CIRCULAR FACADE REFURBISHMENT

Quirine Henry
TU Delft | February 2018
MSc Building Technology

Title
"Circular Facade Refurbishment"

Personal Information

Name:	Quirine Henry
Student nr.:	4150775
Email:	qshenry2@gmail.com

Members of graduation committee

First mentor:	Dr. Ir. Tillmann Klein T.Klein@tudelft.nl Architecture | AE+T | Facade Design
Second mentor:	Bob Geldermans MSc R.J.Geldermans@tudelft.nl Architecture | AE+T | Climate Design
Third mentor:	Dr. Ing. Thaleia Konstantinou MSc T.Konstantinou@tudelft.nl Architecture | AE+T | Facade Design

Delegate of board of examination

Examiner:	Drs. Kees Dol C.P.Dol@tudelft.nl Architecture | OTB | Housing systems

Delft University of Technology
Faculty of Architecture
MSc Building Technology
Sustainable Design Graduation Studio

Start date:	25 April 2017
Finish date:	1 February 2018

TU Delft

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Preface

During my Masters Building Technology I have got to know the concept of the Circular Economy. After the first encounter during the course Engineering for Sustainable Development, the concept of the Circular Economy has followed me ever since. The concept inspired me, because its idealistic vision has a direct effect on the organisation of the whole world. It strives for a complete change of thinking of humankind: how could we do more with less, or even more with nothing at all. Especially in the built environment, our cities should be shaped in a completely different way, following the vision of the Circular Economy. While I have heard a lot about the concept during the years, from many different people, always bringing up discussions, I had never really understood the practical implementation of the concept. I was very interested to get to know how we, as architectural designers, could make a contribution to the Circular Economy by shaping the built environment according to its principles. How would the "circular cities" of the future look like? Is it only an idealistic movement that will never set foot to ground or does it have the potential to be implemented in real life? I am sure the transition from our current Linear model of take-make-dispose to a Circular Economy in which waste doesn't exist, will take a long time. However, at the moment I have the feeling the Circular Economy is really taking shape and has come close to realisation in certain industries. It feels as if these years the switch in thinking, as some say the development of the third industrial revolution, is slowly happening.

When we look at the history, the development of architecture in the world, from the palaces of Mesopotamia to the Roman Empire that have laid the first stones of the cities that we live in today, from the Renaissance to the Modernism and the Functionalism, we still see the traces of every different building style through the ages. In the form of religious and public buildings where people meet, but also in the form of private houses where people come to rest. All these buildings where built to be long-lasting, to stand there at that location for a whole human lifetime. Some buildings were demolished during wars, others collapsed due to poor construction methods. However, of every period in history some buildings have survived all times, and have been visited or occupied by multiple generations. An example is the Villa Rotonda in Italy, that I have seen when I was an exchange student in Italy. This building has been built in the 16th century and has stayed the same for more than four centuries; the architecture as well as its surroundings have been preserved in its original state. On the contrary, when we follow the lifecycle of the buildings that are being constructed nowadays, some will already be demolished after being in use for ten years, because they no longer meet the requirements or people have just become tired of looking at it. Our current society is one of permanent temporality. The dynamics of our lifestyle have been increased, due to the current globalisation of the world and our high standards of living. While in history the monumental buildings were built as static structures, in accordance with the static lifestyle of the people that were very locally oriented, now we demand for buildings with dynamic structures, that are able to change along with our dynamic lifestyle. A consequence of this change, is the high amount of waste generation that will be brought along with the desire to adapt the static building structures to our dynamic lifestyle. For this reason, the building style that suits our century, is one that enables change. Next to that, we have become more and more aware of the temporary nature of our existence. As a result of our human activities, the global temperature of the earth has risen and the composition of the atmosphere has changed. We, as human beings, realise we are only small figures in comparison with the size of the universe, and can't control nature's forces. The principles of the Circular Economy match this line of thought.

For this reason, I wanted to grab the chance to explore the concept of the Circular Economy during my graduation project. So that, hopefully at the end of my life, when we live in a world where we have all forgotten about the word waste, I will have experienced the transition with my own eyes and even have made a contribution towards the implementation of the ideals of the Circular Economy.

Quirine Henry
18 January 2018

Acknowledgement

With pleasure I finally present to you my graduation project ‘Circular Facade Refurbishment’. Although the project appeared to be challenging sometimes, I have enjoyed the process a lot. I definitely have enriched myself with new knowledge about the concept of the Circular Economy and skills how to apply the principles to the built environment. This results couldn’t have been achieved without the many helping hands during the process.

First of all, I would like to thank my supervisors, Tillmann Klein, Bob Geldermans and Thaleia Konstantinou, for their valuable guidance during the project. I am very gratefull for their support. They have all shown deep involvement in the project and have inspired me a lot with their different insights. Tillmann gave a critical view on the practical implementation of the research results and gave very good advice about the decisions of what direction the project should go into. On the other hand, Bob convinced me to look from a broader perspective to the outcome and take one step back to see whether the decisions still suit the principles of the Circular Economy. Thaleia has shown much help with her detailed knowledge about the 2nd Skin Facade Refurbishment system and motivated me a lot with her positivity to get the best out of the project.

Secondly, I would like to thank the other people involved in the 2nd Skin project: Onno van der Wal, Jasper Sluimer and Rob van Rijs of the contractor company BIK Bouw, and Associate Professor of Industrial Design Dr. Ir. Sacha Silvester. Your interest in the research and enthusiasm to bring the project further, have been very motivating for me during the past nine months. Especially the discussions during the meeting in November with everyone around the table were very constructive for the research. Next to that, your feedback during our final meeting in January on the proposed design was essential for the final development of the concept. Also I would like to thank Jan Floor for the guided tour at the building site of the case study building in Vlaardingen, during which I have learned a lot about the practical challenges of refurbishment. Besides, the meeting with Juan Azcarate-Aguerre about the possible business model around the Circular Facade Refurbishment system have contributed a lot to the development of the last chapter of the research.

Furthermore, the cross-border collaboration with the TU Munchen with Prof. Thomas Auer and David Selje, has been very valuable. I liked it very much to exchange knowlegde about the topic and hear your points of view on the application of the Circulair Economy. I am sure you will be able to bring the research a lot further with your expertise.

Lastly, to be able to complete my Masters degree I would like to thank my friends and family for their unconditional support. They helped me to put the work into perspective and challegned me with surprisingly helpfull discussions about the topic. Also the inspiring coffee breaks at the espressobar at 11 o’clock, in which we did a round the table to give each other feedback on our projects, was very helpfull. You have certainly brought me a lot of joy during the many hours spend at the faculty of Architecture.

Abstract

In de Paris Climate Agreement the goal is set to reach an energy neutral built environment by 2050. As a result, there is a high demand for energy neutral refurbishment of the existing housing stock. With the currently low refurbishment rate is it expected to take around 250 years to reach this goal. Due to the high initial investment costs of refurbishment, spread out over a short period of time, replacement and rebuilding is often the preferred option, while refurbishment is significantly less material consuming. Still the environmental impact of a refurbished building appears to be similar to the environmental impact of a new building, when looking at the material use spread out over the lifetime.

The Circular Economy is a solution to the problem of the current linear lifecycle of refurbishment, because it strives for an increased lifetime of the refurbishment by enabling reuse of components at the end of their functional service life and recycling of materials at the end of their technical service life. The Circular Economy aims to close and extend the loops of material cycles, in order to preserve value of materials, resulting in decreased raw material consumption and waste generation.

In this research the level of circularity of the 2nd Skin Façade Refurbishment system, which is a refurbishment strategy that wraps the building into a second layer of insulation, is examined. The level of circularity of the materials as well as the disassembly potential of the connections between the components and materials, have been analysed. Based on the assessment results, a Roadmap for circular façade refurbishment is developed. As validation of the approach, a design proposal is made for the Circular 2nd Skin Façade Refurbishment system, which is a universal refurbishment system that can be applied to different residential building typologies. The system is designed for future changes, as it enables reconfiguration of the façade arrangement and disassembly at the end of its functional lifetime. Instead of ending up as unrecoverable waste, the circular façade refurbishment system can be reused multiple times for the refurbishment of other residential buildings, exploiting the technical lifetime of the materials to the fullest.

Keywords: Refurbishment, Circular Economy, 2nd Skin Façade, Design for Disassembly, Modularity, Life Cycle

TABLE OF CONTENT

01

INTRODUCTION

This chapter addresses the context of the research, followed by the problem statement. Consequently, the research objectives, methodology and research questions will be explained, ending with the societal and scientific relevance of the research.

In November 2016 200 countries have set the goal to limit the temperature rise below 2 °C by reducing their greenhouse-gas emissions (European Commission, 2017). By 2050 the goal is to reduce the emissions in the building sector by 88-91%, which is the largest of all sectors. This can only be reached when all existing buildings become energy neutral with deep renovation (Konstantinou, 2014). It is important to focus on the existing building stock, because 75-90% of the current building stock will still be there in 2050 (Pomponi & Moncaster, 2017).

During the lifetime of the building, which can be less than 50 years when intended to be temporary or more than 100 years when designed for the long-term (König, Kohler, Kreißig, & Lützkendorf, 2010), the surrounding environment of the building changes. In terms of climate we should look specifically at the global temperature of the earth, which has been fast increasing the last 17 years (NASA/GISS, n.d.) Buildings built before 1975, don't meet the current Dutch building regulations anymore; their energy consumption has become too high, and the thermal insulation of the facade has become too low (Loussos, Konstantinou, Van den Dobbelsteen, & Bokel, 2015). The building envelope is exposed to both the outdoor and indoor environment, and thus is most susceptible to change (Konstantinou, 2014). Every 20-30 years the facade of the buildings will need to be renovated to meet the new building regulations, based on the new climate standards (Konstantinou & Knaack, 2011). The renovation process of demolition, replacement of the facade or addition of new interior or exterior layers, has to start all over again.
In the current building stock, many measures are taken to improve the operational energy efficiency of the building, which has the biggest effect on the total energy consumption of the building (Konstantinou, 2014). Often less attention is given to the building materials themselves, while the production of materials also requires a high amount of energy. Next to that, some virgin materials aren't endlessly available, due to the low turnover rate of the natural resources. The building industry is, after food production, the largest consumer of raw materials in the world, due to the fast rate of demolition and re-building (Pomponi & Moncaster, 2017). When the building reaches zero-energy, the contribution of the embodied energy to the total energy consumption of the building will increase (Konstantinou, 2014).
To be able to decrease the virgin material consumption of the building industry, the material loss during the life cycle of the building needs to be reduced. This could be accomplished by extending the functional lifecycle of the building components by allowing maintenance, repair, replacement, recycling and remanufacturing of building components without the need of demolishing the complete building.

This is where the concept of Circular Economy comes into play. Circular Economy strives for closing and connecting material loops, which means using waste as a resource for the manufacturing of new goods (Geldermans, 2016). Especially during building refurbishment projects, there is a high accumulation of waste materials that are removed from the existing building, while these materials can also be re-processed into new materials or re-used for a new purpose (BAM Bouw en Techniek - Regio Zuidwest, 2015). By maintaining the value of materials and components of the building that are able to be recycled and by extending their life cycle, less material ends-up in the landfill and less virgin materials need to be extracted for the production of new materials (Ellen MacArthur Foundation, 2015).

The building envelope of residential buildings needs to be refurbished on average every 20-30 years (Konstantinou & Knaack, 2011). However, the building envelope is currently built for long durability, with permanent connections between materials and components, and consequently isn't easily adjustable to changing demands during the lifetime of the building. Due to its inflexibility, the refurbishment process of the building envelope is complicated. During the process degradation of materials takes place, due to damaging or functional decline of building components when other components are added or replaced (Durmisevic, 2010). This results in a high amount of material waste on-site that can't be reused and a high demand for new virgin materials to replace the degraded building components.

Problem statement

The problem of the current building refurbishment process, is the high amount of material loss, caused by the inflexibility of the building envelope that can't quickly adapt to the changing demands of new building regulations and new climate standards.

Hypotheses about the problem causes

The facade of the current building stock consists of different components integrated in one single structure, that is impossible to disassemble without damaging the materials. When the building needs to be refurbished to improve its energy performance, the only possibility is to add a new exterior or interior skin to the building.

A recent development in building renovation, is the 2ndSkin Façade Refurbishment concept, that aims to reduce the energy demand of post-war residential buildings to zero, with minimal disturbance of the residents during construction, by adding a new façade structure to the building. The concept is based on the principle of the Three Steps Strategy of increasing the thermal resistance of the façade, reducing the energy demand of the building and using renewable sources (photovoltaics) to generate energy. The 2nd Skin Façade Refurbishment system consists of prefabricated, self-supporting sandwich elements, in which windows, heating and ventilation installations are integrated. The prefabricated façade elements only need to be attached to the existing building envelope by connecting wooden posts to steel U-profiles. Due to the accessibility of the 2ndSkin Façade from the outside of the building, the maintenance of the façade during the lifetime of the building is facilitated. However, at the moment, instead of applying the aforementioned Prefabricated system, another variant of the 2nd Skin Façade Refurbishment system is executed in practice, namely the Exterior Insulation variant. This variant is economically better feasible than the Prefabricated variant. The Exterior Insulation variant consists of a layer of rigid insulation board directly glued to the existing façade of the building (Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017).

The 2nd Skin Façade Refurbishment system is an example of a refurbishment strategy that is a temporary solution. There is a high chance that after 20 to 30 years the 2nd Skin Façade needs to be adjusted again. Expected is that the currently applied Exterior Insulation variant of the 2nd Skin Façade Refurbishment system can't be removed from the existing façade, when the architectural appearance or functional arrangement of the building needs to change. This results in a double amount of material loss; the materials the existing façade of the residential building consists of, as well as the added materials of the refurbishment system. What happens with the materials at the end of the functional lifetime of the refurbishment is an important question when thinking about the life cycle of the building. To be able to decrease the material loss during the next refurbishment process, the 2nd Skin Façade should become circular, which means closing the material loops by enabling reuse of facade components and materials at the end of life of the refurbishment. To be able to make the 2ndSkin Façade circular, we need to look into the properties of the materials that the façade elements consist of, the expected functional and technical lifetime and the end of life scenarios of the materials within the system. Next to that, we need to analyse the connections between the building components and materials, to see to what extent they are they reversible and demountable. Lastly the future scenarios during which the facade refurbishment system is expected to change, should to be investigated to be able to anticipate on this in the design of the 2nd Skin Façade Refurbishment system.

Objectives

The objective of the research is to:
redesign the 2ndSkin Façade Refurbishment system in such a way that re-use and/or recycling of materials and building components is optimised, resulting in a Circular 2ndSkin Façade Refurbishment system.

Necessary is to define assessment criteria for circular building, that can be used to evaluate the level of circularity of the two variants of the 2ndSkin Façade Refurbishment system; the Prefabricated variant and the currently applied Exterior Insulation variant.

Final products

- Assessment methodology to evaluate the level of circularity of façade systems.
- Evaluation of the two variants of the 2nd Skin Façade Refurbishment system
- Redesign of the Circular 2nd Skin Façade Refurbishment system
- Roadmap Circular Building

Hypotheses about the direction of solutions

In general, when designing a circular building, there are three aspects of the building that should be taken into consideration: the main structure, connections and materials.
The main structure should be designed in such a way that separation of building layers is possible (Berge, 2009). In the current 2nd Skin Façade Refurbishment system the prefabricated elements consist of sandwich panels, in which the insulation and ventilation ducts are integrated (Konstantinou et al., 2017). During the research, the 2nd Skin Façade should be examined to see what building layers are integrated in the façade system and whether they can be separated.
The connections between building components should enable fast and easy disassembly of the building components and materials (Durmisevic, 2010). During the research, the connections between the building components have to be analysed to find out whether they are permanent or reversible. It can be expected that for the redesign of the façade system new connection methods have to be designed. A possible solution of the redesign could be to create a demountable timber structure, that allows reconfiguration of open and closed parts of the façade, and provides a framework in which the building components can be individually (re)placed.
Pure materials should be used, of which the virgin materials can easily be separated, enabling optimal recycling (Berge, 2009). The research should take a close look at the materials that the two variants of the 2nd Skin Façade Refurbishment system consists of: whether they follow the technical or biological lifecycle (Ellen MacArthur Foundation, 2013). Both the intrinsic and relational properties of the materials should be examined: the health and quality of the materials as well as their estimated lifetime and applied dimensions (Geldermans, 2016). Based on the research results, alternative materials should be found for the redesign of the 2ndSkin Façade system, that better suit the required characteristics.

Boundary conditions

The research will be focussed on post-war residential buildings, built between 1945-1975. These dwellings cover around 29% of the total housing stock in the Netherlands and have received energy label D or lower (Konstantinou & Knaack, 2011). Especially in Rotterdam, the city that has been completely rebuild after the Second World War, the amount of post-war residential buildings in need of refurbishment is very high. The municipality of Rotterdam states that the city has a surplus of post-war residential buildings for low-income households, while there is a shortage of residential buildings for high- and middle-income households. For this reason, the municipality has decided to demolish thousands of homes (NOS Binnenland, 2016). In the neighbourhood Rotterdam Zuid, the government has decided to replace or refurbish 35000 dwellings before 2030, to improve their energy efficiency and upgrade their quality (Gemeente Rotterdam, n.d.). Due to the high number of dwellings that are in need of refurbishment, the short timeframe and the desired quality increase, these dwellings are interesting case studies for the research.

The research will be based on the research of Thaleia Konstantinou and Tillmann Klein (2017), who have developed the 2nd Skin Façade Refurbishment system in order to decrease the operational energy of post-war residential buildings towards zero. For this reason, the same case study buildings as used in the 2nd Skin Façade Refurbishment project, are chosen for this research: a three-storey tenement house at the Soendalaan in Vlaardingen, built in 1952, and mid-rise apartment block at the Schere in Rotterdam-Zuid, built in 1957. As next step, this research will continue the project by assessing the level of circularity of the 2nd Skin Façade Refurbishment system. During the research, the 2nd Skin Façade Refurbishment system will be evaluated and optimised in terms of circularity, looking specifically at thhe reuse and recycling potential of building materials and components.

Research questions

Taking into account the need to refurbish post-war residential buildings and the importance of integrating the principles of the Circular Economy in the built environment, the research aims at answering the following research question:

Main research question

How can the 2ndSkin Façade Refurbishment system be redesigned into a Circular 2ndSkin Façade Refurbishment system, that optimises reuse and/or recycling of building materials and components?

To be able to answer the main research question, several sub-questions should be answered first, that will be explained in the different chapters in this research:

Sub-questions

- What is in general the current life cycle of post-war residential buildings and what are the most common causes for refurbishment?

- What is the definition of the Circular Economy?
- How can the principles of the Circular Economy be applied to the built environment?
- What different frameworks can be identified that accommodate circularity?

- What assessment methods are currently available, that relate to circularity?
- What assessment methods can be used to assess the level of circularity of the 2nd Skin Façade Refurbishment system?

- How does the Prefabricated variant of the 2nd Skin Façade Refurbishment system work and to what extent is this system "circular"?
- How does the Exterior Insulation variant of 2nd Skin Façade Refurbishment system work and to what extent is this system "circular"?

- How could the 2ndSkin Façade Refurbishment system be redesigned in terms of circularity and to what extent is the redesign of the system "circular"?

Approach and methodology

The research will be based on the following methodology.
As a first step a literature study about the condition of the post-war residential building stock and the concept of the Circular Economy will be done. Precedent analysis is needed to analyse examples of circular building designs. Also the frameworks that relate to certain aspects of the Circular Economy will be investigated, such as Design for Disassembly (DfD) and Cradle-to-Cradle. To be able to assess the level of circularity of the two variants of the 2nd Skin Facade Refurbishment system, existing assessment methods will be analysed. Based on the analysis, one or two assessment methods will be chosen for the circularity assessment of the 2nd Skin Facade Refurbishment system. To be able to redesign the 2ndSkin Façade Refurbishment system, the refurbishment process of the Case Study Building in Vlaardingen, executed by the contractor BIK Bouw, will be followed. The drawings and the mock-up of the Prefabricated variant of 2nd Skin Facade Refurbishment system will be analysed in detail. The involved contractor in the 2nd Skin project, BIK Bouw, will be interviewed to find out the problems of current non-circular renovation systems. Also the material suppliers will be contacted to find out how circular their product already is.

The research will exist of the following steps:

1. Delineate definition of circularity in the built environment.
2. Systematically analyse different frameworks of circularity.
3. Identify design strategies for circular building.
4. Study precedents of circular façades.
5. Analyse assessment methods regarding circularity in the built environment.
6. Define assessment criteria to grade the level of circularity of buildings.
7. Evaluate the Prefabricated variant of the 2nd Skin Facade Refurbishment system (mock-up) in terms of circularity.
8. Evaluate the Exterior Insulation variant of the 2ndSkin Facade Refurbishment system (currently applied to the case study building in Vlaardingen of the housing coorporation Waterweg Wonen) in terms of circularity.
9. Compare the assessment results.
10. Redesign of the Circular 2nd Skin Façade Refurbishment system.

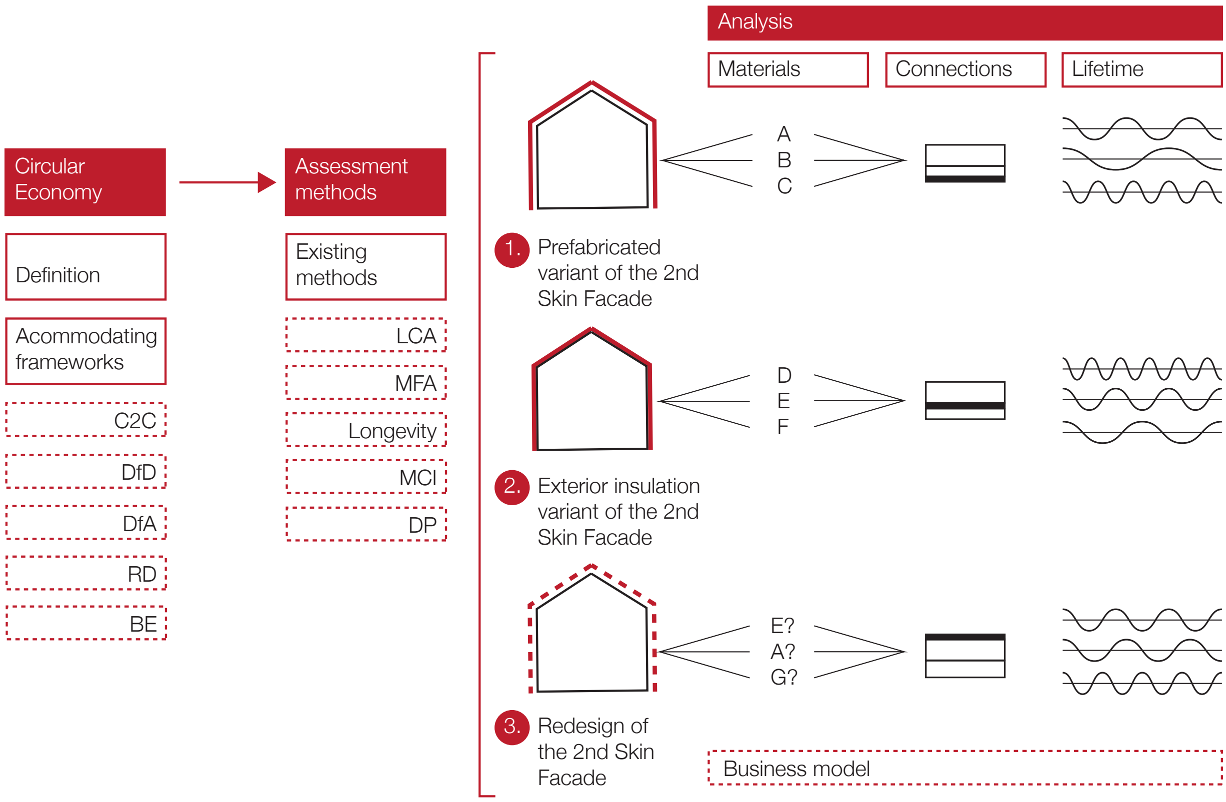


Fig. 1: Research methodology diagram (source: own image)

Relevance

Societal relevance

In the current society, the take-make-dispose model is prevailing in the building industry, resulting in a high amount of material waste accumulated on-site during the construction and demolition of buildings. Especially residential buildings often need to be demolished and rebuilt due to the fluctuating housing demand. At the moment, mainly high- and middle-income households tend to move to the cities, chasing away low-income households. As a result, the residential buildings need to be upgraded in terms of quality of the interior space, façade appearance, energy efficiency etc. Due to the inflexibility of the existing façade, refurbishment of the building is difficult and therefore rebuilding becomes often the more convenient option. To improve the flexibility and sustainability of the renovation process, we need to transform our building method into a circular model, that allows optimal reuse and recycling of materials. When the façade of residential buildings is adaptable to changing user demands and building regulations, the lifetime of the building will increase. The value of the materials will be exploited to the fullest, replacement and recycling of the materials will be facilitated. As a result, the quality of the residential buildings will increase and the amount of material waste will significantly decrease. Thus, the society as well as the environment will benefit from this development.

Scientific relevance

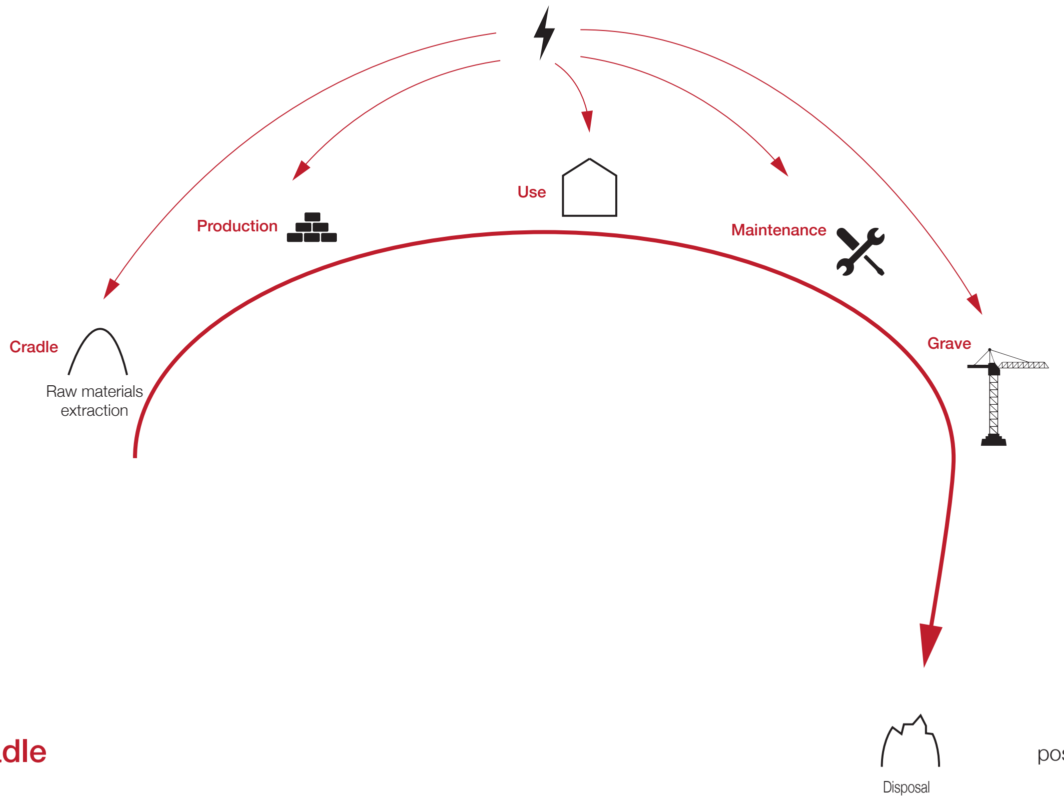
The research adds knowledge on improving the circularity of façade refurbishment systems. The current state of art in research on the Circular Economy in the built environment is focussed on designing new buildings, while the research that applies the theory of Circular Economy to existing buildings, is limited. While, following the Circular Economy principles, it is important to make use of what is already there. To be able to close the material loops of the existing building stock we should start improving the building refurbishment systems, instead of starting from scratch with a new building. Next to that, the circularity assessment of building refurbishment systems is useful for the building industry to understand the practical application of the Circular Economy to the built environment. The research shows the shortcomings and provides solutions to improve the circularity of the façade refurbishment system, resulting in a proposed redesign of the 2ndSkin Façade Refurbishment system. Therefore, the research is relevant for architects, contractors and other stakeholders in the building industry.

Fig. 2: Collage House, S+PS Architects (ArchDaily, 2016)

02

LIFE CYCLE OF POST-WAR HOUSING

Given the task of improving the 2nd Skin Façade Refurbishment system in terms of circularity, the first necessary step that will be undertaken, is to identify and understand the reason of this action. In this chapter, the current life cycle of post-war residential buildings and the importance of refurbishment will be explained. First the phases that the post-war residential buildings go through, from Cradle to Grave, will be described, followed by the most common causes for refurbishment. Lastly will be clarified how circularity could play a role in the refurbishment process of post-war residential buildings.



Cradle

Fig. 3: Current lifecycle of post-war residential buildings (source: own image)

Post-war residential buildings, built between 1950-1975, cover around 29% of the total housing stock in the Netherlands (Konstantinou & Knaack, 2011). The high amount of demolition of buildings during the Second World War (1940-1945), population increase and economic growth led to large housing shortage, resulting in a high demand for rapid construction of new residential buildings in the cities. This so-called construction boom led to new methods of design, manufacture and assembly, applied to the scale of materials as well as building components and complete buildings. It can be seen as a transition point in the management and manufacturing processes in the residential building stock (König, Kohler, Kreißig, & Lützkendorf, 2010). The aim was to make a large number of housing units as quick and economically feasible as possible. The focus of building lay on quantity rather than quality. For this reason, the post-war residential buildings already had bad functional and technical performances from the start. Next to that, at that time the buildings didn't have to meet any building regulations regarding the thermal resistance of the building envelope, since most national building decrees were introduced after the energy crisis in the 1970s, thus most of the post-war residential buildings, constructed before this time, were lacking thermal insulation. On the other hand, the residential buildings built in the period between 1970 and 1990, are reasonably well insulated. The energy performance of the post-war residential also depends on the building typology; the detached single-family houses, terraced houses built in a row or multi-family houses, in which mutiple self-containing housing-units are clustered. The post-war residential building stock in the Netherlands contains many different building typologies with varying shape, size and construction method (Konstantinou, 2014).

Large amounts of virgin materials and energy for the material production were needed as input for the rapid construction of the residential buildings. For the construction "non-traditional" methods were used, influenced by the industrialisation movement. Prefabrication became the state-of-art in north, east and central Europe. In the Netherlands some experimential techniques have been tried out, such as the MUWI building system, consisting of stacked concrete blocks. The main material used for the structure of the residential buildings was reinforced concrete, because of its labour-saving advantages. The concrete structure was either prefabricated or cast in-situ, poured in steel formwork (Konstantinou, 2014). The main material used for the building envelope was brickwork, with or without cavity, and without thermal insulation. Another option for the building envelope was prefabricated concrete panelling. As internal finishing, mostly plaster was used. In general, the window frame was made of wood, containing single or double glazing (Bragança, Wetzel, Buhagiar, & Verhoef, 2007).

Technical decay already started with the inadequate initial quality of the buildings. The fast construction speed had led to insufficient detailing, poor materials were used to decrease the costs and experience with these new building methods was missing. The oil crisis in the 1970s caused a change of mind-set to the building industry. Fossil fuels deficiency led to increased awareness on energy consumption of the building stock. Methods to improve the energy efficiency of buildings were developed and legal building regulations were set, related to insulation and material usage of buildings (Konstantinou, 2014).

Use

In Europe buildings account for 27% of the energy-use induced carbon-emissions. Residential buildings use 2/3 of the total energy consumption of the built environment. Most of the post-war residential building, built after 1945, have an EPC (Energy Performance Certificate) of D or lower (AgentschapNL, n.d.). In 2011 29% of the total building stock in the Netherlands has obtained energy label E, F or G, compared to 14% with energy label A or B (CBS, 2013). During its use, energy is mainly needed for the operation and maintenance of the building.

Operation

Operational energy of residential buildings is used for heating, cooling, DHW, cooking and appliances. In general in the residential buildings in the Netherlands up to 70% from the operational energy is used for space heating. The high energy consumption of the post-war residential buildings is mainly due to the high thermal losses through the building envelope and the use of inefficient building installations.

Currently, the occupants of the post-war residential buildings belong to the socio-economically weaker groups. These low-income households are only able to pay low rents, so it is inevitable they have to live in low-quality housing with accompanying low energy efficiency. Consequently, the operational costs of the residential building are high and increase during the years when the building is badly maintained. As a result, fuel poverty becomes a problem, which has been discovered in 2000; not being able to afford to keep warm in your own house. A household is considered to be fuel-poor when it has to spend more than 10 percent of its income on fuel for adequate heating (BPIE, 2013).

The oil crisis in the 1970s caused a change of mind-set to the building industry. Fossil fuels deficiency led to increased awareness on the energy consumption of the building stock. Methods to improve the energy efficiency of buildings were developed and legal building regulations were set, related to insulation and material usage of buildings. In the past decade, new building products with increased efficiency have been put on the market, such as double glazing and triple glazing. As a result, we are able to build energy neutral homes that generate as much energy as they consume, thus their operational energy reaches zero (Konstantinou, 2014).

Maintenance

Maintenance solely relates to replacement or repair of defected building components. No new components need to be added to the structure. Building components and materials will degrade when approaching the end of their technical lifetime. In general the building envelope suffers most from physical problems. Facade components, such as masonry walls, prefabricated panels, timber, roof and finishes, often show the first signs of natural aging, due to their permanent exposure to the outdoor weather. Outdoor temperature changes could cause shrinkage of materials, resulting in crack formation, deformation and tilt. In the rainy climate of the Netherlands moisture is the most common cause of physical damage to the building envelope; disintegration of masonry units, efflorescence (salt crystallization), and biological growth in the form of plants, mosses, algae and mould on top of the facade. Especially timber components have a high risk of damage, due to the hygroscopic properties of timber. Movements of the foundation of the building could lead to cracks in the façade, bulging walls or sloped floors. Also decay of the joints between building components could be a cause for physical problems of the building.

Lack of proper management of the residential buildings causes bad maintenance of the façade, resulting in an early start of technical decay of the façade. Maintenance costs increase with time, causing the rent prices of the dwellings to decrease. Often the occupants of the residential buildings belong to the low-income groups, that can't afford high rents. As a result, the landlord can't economically invest in the buildings, that need increasingly high expenses for repair during the years. The buildings go more and more into decline. The owners and residents of the buildings get deeper into a negative spiral, caused by a combination of technical, social and financial decay (Konstantinou, 2014).

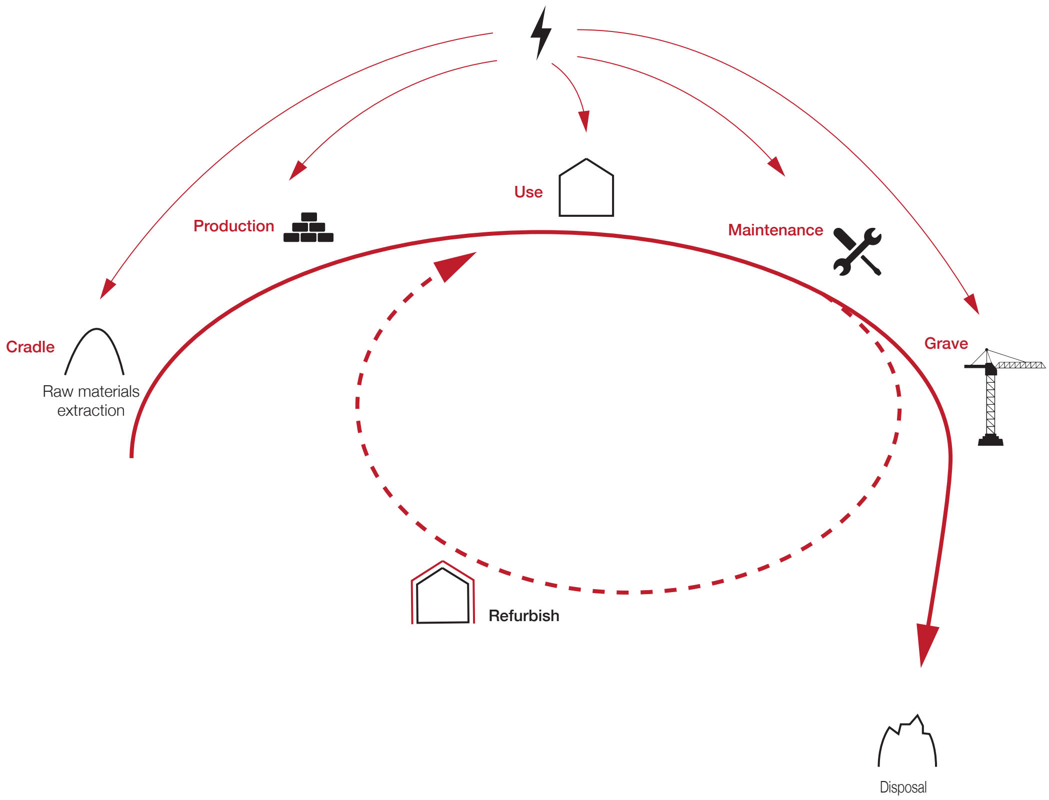


Fig. 4: Current lifecycle of refurbished buildings (source: own image)

Refurbishment

After being in use for a certain period of time, the building could be taken into consideration for refurbishment. The current refurbishment rate of residential buildings is very low. However, no exact number of the amount of refurbishments per year in the Netherlands is available. In 2017 around 30.000 residential buildings have been added to the building stock through production other than new construction. Refurbishment falls under this category, next to residential splitting and function change (CBS, 2017). The replacement rate, however, is calculated to be 0,4%. With this replacement rate, it will take 250 years to renew the complete building stock (Mulder, et al., 2015).
The goal of building refurbishment is to extend the functional service life of the building by replacing and repairing building components that are deteriorated or have become outdated. Different degrees of refurbishment exist, as shown in the supporting diagram (Konstantinou, 2014):

- Refurbishment incorporates the replacement and repair of outdated building components or surfaces, but doesn't include changes to the load-bearing structure of the building. Three degrees of refurbishment can be identified:
    - Partial refurbishment is limited to the repair or replacement of only one building part or component, while the building can still be in use during the process.
    - Normal refurbishment is applied to the entire building or a separate, autonomous part of the building. What is taken into account during normal refurbishment is improved fire safety, acoustics and thermal insulation.
    - Total refurbishment is applied when the building needs to be completely updated to new building requirement standards. The building is then stripped to its load-bearing frame and new components are added to the existing structure.

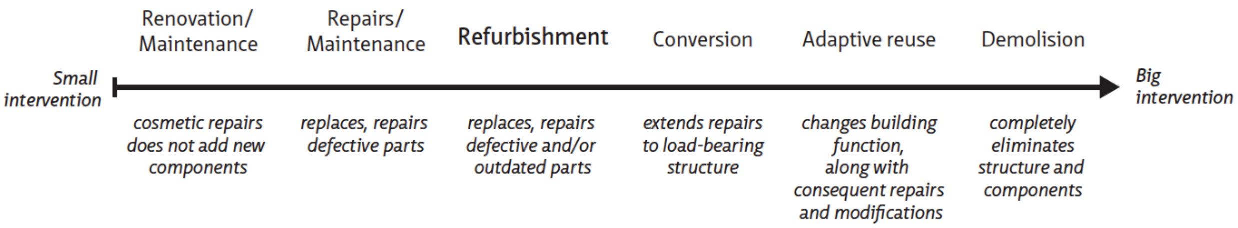


Fig. 5: Levels of Intervention of refurbishment strategies (Konstantinou, 2014)

- Conversion does include repair of the structure of the building, leading to changes of the load-bearing elements and interior layout.
- Adaptive reuse leads to changes of the building function, consequently with repair and modifications of building components

The depth of the refurbishment determines the energy savings on the total energy consumption of the building. Deep refurbishment is spoken of when the interventions lead to energy savings of 60-90%. Another term is major refurbishment, in which the total cost of the refurbishment is higher than 25% of the value of the building, or in which 25% of the building's surface is upgraded. Integrated refurbishment is referred to as a refurbishment strategy in which both the energy efficiency and the physical problems of the buildings will be improved (Konstantinou, 2014).

There are various reasons to choose for refurbishment of in particular post-war residential buildings (Konstantinou, 2014):

1. Technical problems, mainly related to the façade and building services, may require refurbishment. After a certain amount of time, building components and materials become outdated and demand for an upgrade. The climate in the Netherlands is dominated by high amount of rain during the summer and winter, that often leaks into the façade construction of old buildings. Next to water penetration, also moisture and condensation problems lead to damage of building components and materials, like concrete decay or rotten wood. This requires repair or replacement of the building components and materials (Bragança, Wetzel, Buhagiar, & Verhoef, 2007).
2. Another motivation for refurbishment of residential buildings could be functional shortcomings, such as the apartment size and arrangement of the floor plan, depending on the age and lifestyle of the occupants as well as the composition of the family. Research has shown that the space consumption per person in residential buildings have been increased. After the Second World War on average 5-6 persons lived in one dwelling, while in 2002 the number of persons per dwelling have decreased to 2,43 persons (Andeweg, Brunoro, & Verhoef, 2007).
3. Next to that, financial motives play an important role in the decision-making process. Refurbishment will increase the value of the residential buildings, because the change of appearance, function and/or performance increases the attractiveness of the building (Appleby, 2013). As a result, landlords are able to raise the rents of the buildings, consequently leading to social advantages in the neighbourhood. The high rents ask for new tenants with higher incomes, resulting in a restructuring of the socio-economic group living in the residential buildings. Thus refurbishment is a way to regenerate socially problematic residential areas.
4. The last reason for refurbishment is legislations. To be able to reach the goals set by the European Union to decrease the greenhouse gas emissions in the building sector by 88-91% in 2050, national governments have appointed requirements for the energy efficiency of residential buildings. All residential buildings in the Netherlands are obliged to have an energy label, ranging from A (good) to G (bad). This way the government tries to stimulate the landlords to improve the energy efficiency of their building stock through refurbishment (Rijksdienst voor Ondernemend Nederland, n.d.). The landlords can be qualified for a subsidy of the government for the refurbishment of their dwellings (Rijksdienst voor Ondernemend Nederland, n.d.).

Compared to the replacement of the existing structure with a new building, refurbishment of the existing building has the following advantages (Appleby, 2013):

- The construction impacts are reduced, because deconstruction of the existing building is avoided, which means the site doesn't need to be cleared, no pile driving is necessary etc.
- Material costs and embodied energy impacts are lower, because less materials are needed.
- When the refurbishment is executed in phases, continuity of use and income is possible.
- Refurbishment is feasible within shorter programme times.

There are five different strategies for façade refurbishment (Konstantinou, 2014):

- *Replace* deteriorated façade elements with new ones.
- *Add(-in)* a new interior layer to the structure of the building or in the cavity of the facade.
- *Wrap* the building in a second layer.
- *Add(-on)* a new exterior structure onto the existing building, such as a balcony or a greenhouse.
- *Cover* parts or internal/external courtyards and atria with a new roof.

The research will be focussed on the third strategy: wrapping the post-war residential building in a second layer. An example of a refurbishment system that falls under this category, is the 2nd Skin Façade Refurbishment system, developed by Tillmann Klein and Thaleia Konstantinou (2017), which this research elaborates on.

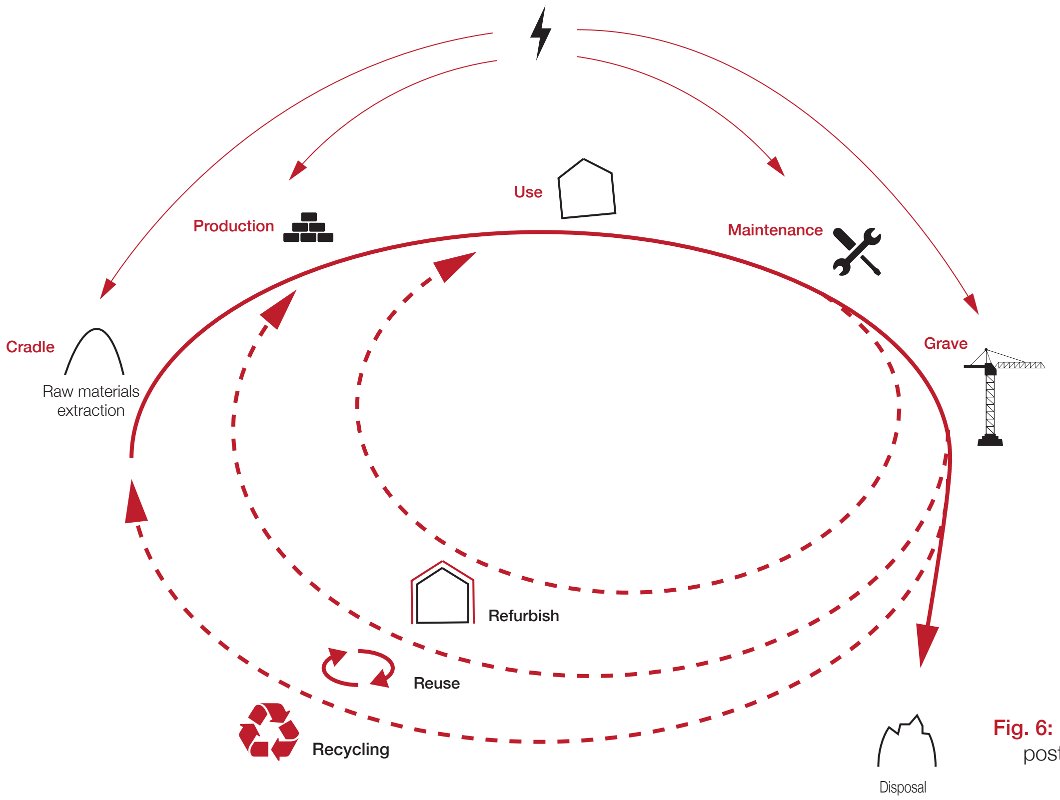


Fig. 6: Desired circular lifecycle of post-ware residential buildings (source: own image)

Grave

The building industry produces yearly 24 million tonnes of waste, accounting for 40% of the total waste production in the Netherlands in 2010. Around 93% of the total construction and demolition waste is recycled as low quality granulate (Ministerie van Infrastructuur en Milieu, n.d.).

When the post-war residential buildings are considered to be neither suitable nor safe for human beings to live in, the final step is deconstruction. The building could be simply torn down or dismantled, making way for a new building to be constructed at the same location. The more durable and long-lasting the materials and components that the building consists of, the less is the need for maintenance and refurbishment and thus the longer it takes before the building needs to be demolished. However, demolition may occur earlier when the intended life of the building is shorter than the physical life of the materials and building components. These valuable materials, such as concrete, steel, aluminium, copper, glass, wood, doors, ceramics, suspended ceilings, PVC, floor covering etc., usually end up as waste that is generated on the building site during the demolition. The waste can either be disposed on the landfill, or be reused or recycled for new purposes (Crawford, 2011). Specialised demolition firms are responsible for the dismantling of the buildings, the separation and the return delivery of the building materials to the suppliers. Research of Deloitte has shown that in 2012 93% of the total construction and demolition waste in the Netherlands has been recovered. 95% of this amount of recovered materials has been recycled, the rest is used for energy recovery. However, most of the recycling refers to down cycling of the material (Deloitte, 2015).

Several reasons can be found to immediately choose for deconstruction, instead of refurbishment of the residential buildings. A disadvantage of building refurbishment is that the possibilities are limited by the existing structure of the building, causing limited scope for enhancing insulation, daylighting or natural ventilation. This is a result of the inflexibility of the existing buildings. When the desired modifications and energy-saving measures of the buildings are too complex and expensive, it could be more convenient to choose for deconstruction and rebuilding, that allows better insulation and more comprehensive building installations. Another reason for deconstruction could be that the existing building contains asbestos or other hazardous materials and refurbishment isn't allowed. Also, demolition and rebuilding is an easy way to get rid of problematic neighbourhoods, that have a negative impact on the urban landscape. Next to that, the current building industry prefers demolition instead of refurbishment, because of its conservative business-as-usual approach (Konstantinou, 2014).

However, according to Thaleia Konstantinou (2014), deconstruction of the post-war residential buildings should be considered as the last resort, when structural problems are non-repairable and when the buildings are located in areas where the demand is significantly higher than the supply. The rest of the buildings should definitely have had the chance to be refurbished before demolition.

Conclusion

This chapter described the current linear life cycle of post-war residential buildings. from Cradle to Grave. Giving the necessity to develop a Circular Façade Refurbishment strategy, identifying and understanding the different phases of the current lifecycle of the post-war residential building stock is essential.

Post-war residential buildings were constructed between 1950-1975 and currently have been in use for around 50 years. Due to the low thermal resistance of the building envelope of the post-war residential buildings and the use of inefficient building installations, their operational energy is very high. Next to that, in general the buildings suffer from physical problems due to poor maintenance. For this reason, most of the residential buildings either need to be refurbished to be able to be in use for another 25 years or deconstructed. The most common causes for refurbishment of the post-war residential buildings are technical, functional, financial or legal. Technical problems relate to deteriorated building components that have reached the end of their technical lifetime. Functional problems relate to the size, floorplan and layout of the building. Financial incentives concern increasing the value of the building. Legal incentives have been formed in the climate agreement of the European Union, in which the goal is set to reach an energy neutral built environment by 2050.
Different degrees of refurbishment can be identified; partial refurbishment, in which only the deteriorated building components will be replaced; normal refurbishment, in which the complete building envelope will be upgraded; and total refurbishment, in which the complete building envelope will be stripped-off and replaced. Different refurbishment strategies have been developed. This research will focus on the refurbishment strategy in which the building is wrapped in a second layer of insulation, as is the case in the 2nd Skin Façade Refurbishment system, developed by Tillmann Klein and Thaleia Konstantinou (2017).
The main disadvantage of refurbishment are the limited possibilities, because the refurbishment has to be adjusted to the existing structure of the building. For this reason, immediate deconstruction and rebuilding is often considered as the most convenient option. Deconstruction of the post-war residential building stock leads to a high amount of construction waste on the building site, resulting in valuable material loss. The life cycle of post-war residential buildings can be improved in terms of circularity by increasing the reuse and recycling possibilities of building components and materials at their end of life.

After the evaluation of the current linear life cycle of post-war residential buildings and discussing the causes for refurbishment, the next step is to think of how to make the change to a circular lifecycle.
Therefore, in the next chapter the concept of the Circular Economy and its application in the built environment will be explained, followed by circularity assessment methods in chapter 4.

03

THE CIRCULAR ECONOMY

The previous chapter explained the importance of refurbishing post-war residential buildings and their current linear process of new build, use, refurbishment and deconstruction. Since the importance of refurbishment of the post-war residential buildings and the linearity of the process is identified, the definition of the Circular Economy and its application in the built environment should be explained.
This chapter will give an answer to the following questions: *What is the definition of the Circular Economy?*, *What are the principles of the Circular Economy?*, and *What different frameworks can be identified that accommodate the Circular Economy?*. Based on the literature research, one definition of the concept of the Circular Economy will be chosen that will be used for the further implementation of the research. Next to that, in the chapter a focus for the research will be chosen within the practical principles of the Circular Economy in the built environment.

Definition of the concept

In the past decade the Circular Economy has become a widespread concept that has gained much attention (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). To be able to apply the concept of the Circular Economy to the refurbishment practice, the definition of the term should be investigated and the application of the concept should be analysed. Research has shown that the term of the Circular Economy can be interpreted in many different ways. To be able to determine the appropriate definition of the Circular Economy for this research, we should first take a look at the historical origins of the concept.

The origins of Circular Economy

The idea behind a Circular Economy arose a long time ago. Some say the idea of Circular Economy originated in 1848, when Hofman, the first President of the Royal Society of Chemistry, introduced the concept of industrial metabolism and waste-is-food. He stated that

"…in an ideal chemical factory there is, strictly speaking, no waste but only products. The better a real factory makes use of its waste, the closer it gets to its ideal, the bigger is the profit."

Others say the founder of the term Circular Economy was Kenneth Boulding, who wrote in 1966:

"Man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy."

Following in 1976, Stahel and Reday-Mulvay where the ones that directly referred to a closed-loop economy. In 1983, Gro Harlem Brundtland was the first person that started formulating long-term environmental strategies for achieving sustainable development in the year 2000 and beyond, in response to the increasing consumption of the neo-liberal society. He mentioned the negative effects of the lifestyle of their society: over-use of natural resources, ineffectual responses to global warming and a lack of focus on social justice. In 1991, Robèrt acknowledged the environmental problems of the current linear processing of materials and recognised the advantages of material processing in cycles (Murray, Skene, & Haynes, 2017).

The person that directly mentioned the term Circular Economy, was Cooper, who wrote in 1999:

"The model of a linear economy, in which it is assumed that there is an unlimited supply of natural resources and that the environment has an unlimited capacity to absorb waste and pollution, is dismissed. Instead, a circular economy is proposed, in which the throughput of energy and raw materials is reduced."

Since then the term is interpreted in many different ways, but in general the term Circular Economy always refers to a cyclical closed-loop system (Murray, Skene, & Haynes, 2017).

Interpretations of the Circular Economy

Many researchers have given a different meaning to the Circular Economy. To be able to form an appropriate definition of the term that can be utilized in this research, it is important to give an overview of all different interpretations of the Circular Economy.

Murray, Skene and Hayes (2017) analysed the meaning of the term Circular Economy in two ways, linguistically as well as descriptive:

Linguistically a Circular economy is the opposite of a Linear Economy that converts natural resources via production into waste. The term Linear Economy is created by the founders of the Circular Economy. While the Linear Economy damages the environment by removing the natural capital of the earth through mining and unsustainable harvesting and reducing the value of the natural capital through waste pollution, the Circular Economy is considered to have no net effect on the environment at all. On the contrary, the Circular Economy is able to restore the damage done during resource extraction and minimise waste generation during the production and life cycle of the product.

The descriptive meaning of the Circular Economy concerns the concept of the cycle; the biogeochemical cycle as well as the idea of recycling products.

- **Biogeochemical cycles:** The earth consists of many basic molecules and atoms that pass through cycles in the planet with a varying time length. One example is water, that takes 9 days to pass through the atmosphere and 37000 years to pass through the oceans to complete the cycle. The complete cycle of phosphorous takes 2000 years, carbon dioxide 4 years and atmospheric oxygen 3.7 million years. Molecules and atoms with fast turnover rates are more sensitive to change. During the past centuries, human activities have made alterations to the biochemical cycles by removing or releasing excessive materials from a cycle. The concept of the Circular Economy could be a solution to restore the fluxes of the biochemical cycles to their natural levels.
- **Recycling:** The Circular Economy also relates to resource recycling. The 3 R's of Reduce, Reuse and Recycle play a central role in the Circular Economy. One approach is the service economy concept, that focusses on Reduction; it slows down the cycles of use and extends the life cycle of products through better manufacturing and maintenance, resulting in lower replacement rates. The Waste-as-food concept focusses on Reuse; unwanted outputs of some industrial processes are reused as input in other processes.

The leader of the Circular Economy in the United Kingdom, the Ellen MacArthur Foundation (EMF), established in 2010, defines the Circular Economy the following (Ellen MacArthur Foundation, 2013):

"A circular economy is one that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles."

Contrary to the linear model of make-take-dispose, in which goods are manufactured from raw materials, then sold on the market, used and finally disposed as waste (Ellen MacArthur Foundation, 2013), the circular model is regenerative, which means using waste as a resource for the manufacturing of new goods (Geldermans, 2016). To be able to function well in the closed, circular system of the earth, the economy and the environment should also be balanced in inputs and outputs (Geissdoerfer et al., 2017).

The linear model that is prevalent in our current society, has brought us many problems. First of all, the model has led to economic losses, due to the high value of materials that is lost, and the high amount of structural waste has accumulated in certain places in the world. This leads to disturbance of the natural systems of the earth, like climate change, biodiversity loss, land degradation and ocean pollution. Secondly, as a result of the depletion of resources and thus the material scarcity, the price and supply risks of materials have increased. There is uncertainty about how many materials are available until what time, and thus materials that are limited available, are sold for high prices. Thirdly, countries have become dependent on other countries for their material supply, what could be a good motive for wars between countries (Ellen MacArthur Foundation, 2013).

There needs to be a radical change in consumption and production from a linear towards a circular model, in order to prevent depletion and wasting of valuable resources (Geldermans, 2016). The objective of the Circular Economy is to achieve optimised production, optimised consumption and minimum waste of materials. So, in general, all activities that reduce, reuse and recycle materials in production, distribution and consumption processes fall under the term Circular Economy. As a result, the Circular Economy will benefit the environment as well as the economy and society (Murray, Skene & Hayes, 2013).

Some see the circular economy as a necessity for sustainable development, as circularity is a means 'to meet the needs of the present without compromising the ability of future generations to meet their own needs'. Both sustainability and the Circular Economy look from a global perspective at the current and future generations and strive for system change through design thinking. However, the difference between sustainability and the Circular Economy is their goals. The goal of sustainable development is open-ended; multiple goals can be reached and they change over time. However, the goal of the Circular Economy is very straightforward; the creation of a closed loop system that eliminates all resource input from the system. Also, the means to achieve this goal are very specific in the Circular Economy; better use of resources, waste reduction and leakage prevention (Geissdorfer, Savaget, Bocken & Hultink, 2016).

Principles of the Circular Economy

To be able to understand the application of the Circular Economy in the built environment, the main principles of the concept should be explained in detail. The Ellen MacArthur Foundation has defined the following three main principles for the functioning of the Circular Economy (Ellen MacArthur Foundation, 2013):

1. Natural capital must be protected and enlarged by:
   a. Keeping track on the finite material stocks
   b. Compensating the demand with renewable resources
2. Resource yields must be increased by keeping products, components and materials at their highest utility and value at all times. Differentiation is made between materials from the technical and biological cycle. Take into account:
   a. Power of the inner circle: the closer the cycles are located near the material source; the more value of the material is preserved.
   b. Power of circling longer: the more frequently the same cycles are performed and the longer the cycles last; the better the material is reused and the longer the lifecycle of the material is extended.
   c. Power of cascaded reuse: in the biological cycle the value of the materials can be extracted by cascading the materials through other applications with lower grades.
   d. Power of pure inputs: the more uncontaminated the input of raw materials is, the more quality is preserved and thus the more efficient the collection and redistribution process will be, resulting in longer product lifecycles and increased material productivity.
3. System effectiveness must be advanced by indicating externalities and preventing them to reoccur.

As can be seen in the diagram (fig. 7) the principles of the Circular Economy can be applied to two different material cycles: the technical (blue) and the biological (green) cycle.

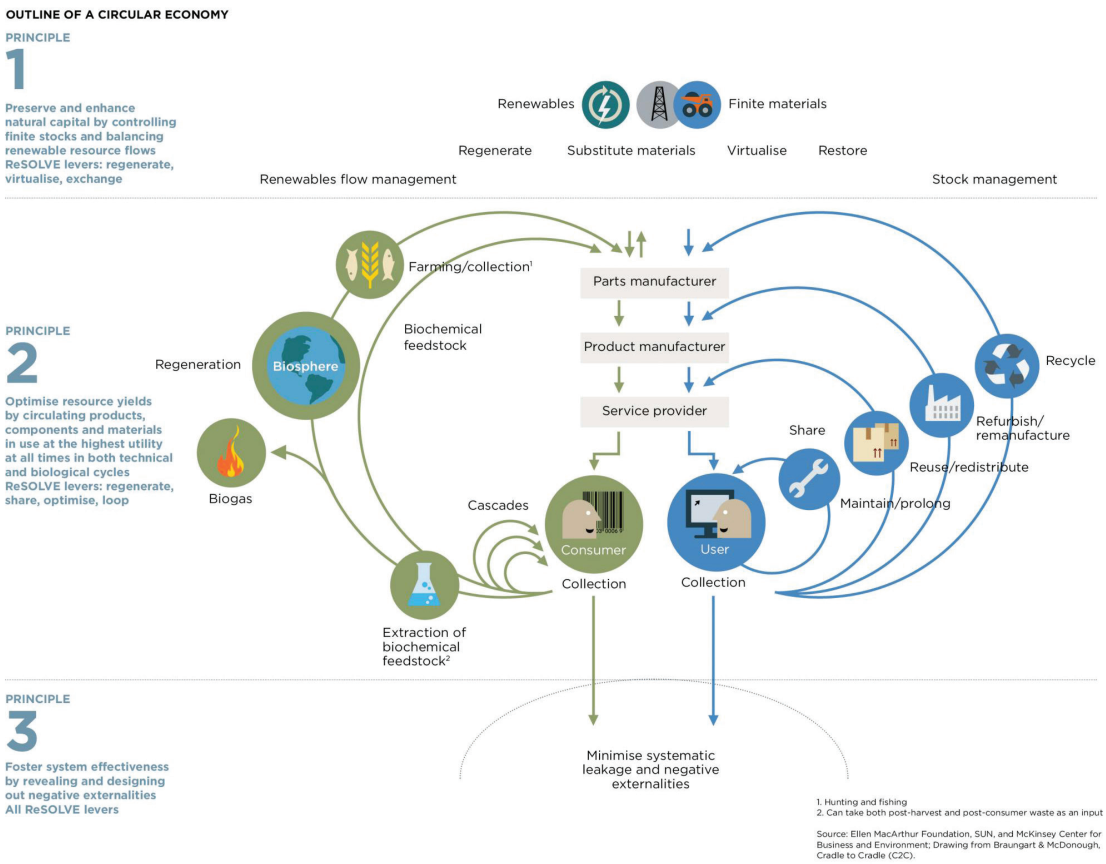


Fig. 7: Outline of the Circular Economy (Ellen MacArthur Foundation, 2013)

Technical cycle
The technical cycle consists of finite materials, that can be recovered and often restored at their end of life. The cycles that the technical materials go through, are the following (Durmisevic, 2010):

1. Design for Maintenance — The first scenario aims to repair components. To enable maintenance of the product or building, the structure should allow removal and replacement of single components.

2. Design for Reuse — The second scenario focusses on extending the lifetime of a complete building, product or component at the end of their functional life cycle, by enabling reuse of the separated components in new configurations (Durmisevic, 2010). The components don't need to be re-manufactured, but can immediately be re-used for similar or different functions. In terms of environment impact, this is the most convenient option, because of the minimal energy and material use.

3. Design for Remanufacture — The third scenario is based on remanufacturing components at the end of their functional life cycle, so that they regain their nearly original condition, "as good as new", and are able to be reused for the same function. Quality control is needed to ensure that the remanufactured components meet the required properties for their function.

4. Design for Recycling — In this fourth scenario components and materials are designed in such a way that they can easily be:
   - recycled into new products (up-cycling)
   - recycled into waste that can safely be disposed (down-cycling).

Biological cycle
The biological cycle consists of renewable materials with biological nutrients, that can be regenerated. The cycles that the biological materials could go through, are the following (Ellen MacArthur Foundation, 2013):

1. Cascading — The first scenario aims to use the biological materials and components for different functions with similar or lower values after their end-of-life. Contrary to technical materials, that can be repaired, biological materials lose their quality over time, because their material order declines along the cascade. By exploiting the cascading cycles, the stored energy that is left in the material will be optimally used and maximum value is extracted from the material.

2. Biochemical extraction — During the second scenario the biological materials are brought to a bio refinery, where conversion processes are applied to the biomass in order to generate electricity and process heat fuels, power and chemical products.

3. Anaerobic digestion — In the third scenario the biological materials are decomposed by microorganisms through a process of anaerobic digestion. As a result, biogas and a solid residual is produced. Biogas is a new energy source, that can be converted into electricity and can be used for heating of buildings.

4. Composting — In the fourth scenario naturally occurring microorganisms, like bacteria, funghi, insects, snails and earthworms, turn the organic left-overs of the biological materials into compost. This way biological nutrients are returned to the soil, and enable new plants to regrow, then be collected and manufactured into new biological materials.

Accommodating frameworks

Several frameworks and design theories relate to the Circular Economy. In this chapter, the different frameworks that accommodate certain aspects of circularity will be explained. Each framework has a different focus point. To be able to place the Circular Economy in its context, it is important to identify the position of its surrounding frameworks.

Cradle-to-Cradle (C2C)
The Circular Economy is inspired by the Cradle-to-Cradle concept, invented by Michael Braungart and William McDonough in 1995 (Geldermans, 2016). Braungart and McDonough stand for a new way of thinking. In their opinion, in our current society we are trying to minimise the negative effects of our actions, while we should make a positive impact with our actions instead. They strive for manufacturing processes "powered by renewable energy, in which materials flow in safe, regenerative, closed-loop cycles" (McDonough & Braungart, 2002). Rather than reducing waste, we should transform our consumption model into a system that creates no waste at all. Contrary to other systems, Cradle-to-Cradle doesn't stand for material efficiency or dematerialisation, but pleads for a system that uses natural materials over and over again (Van Dijk, Tenpierik, & Van Den Dobbelsteen, 2014). What the concept has in common with the Circular Economy, is their regenerative approach (Geldermans, 2016). That is why the three characteristics of Cradle-to-Cradle concept, described below, are also integrated in the principles of the Circular Economy (Ellen MacArthur Foundation, 2013).

The main characteristics of the Cradle-to-Cradle concept are the following (Geldermans, 2009):
1. Waste is food. Biological materials are biodegradable and return to the soil as nutrients for new material lifecycles, after having taken advantage of their cascading possibilities. Technical materials are designed to be maintained, reused, refurbished and recycled for new products with similar or higher grade (up-cycling).
2. Use renewable energy sources. Energy to power the economy shouldn't be derived from finite energy sources, like fossil fuels and nuclear energy, but from renewable energy sources instead, such as the sun and the wind.
3. Celebrate diversity. Similar to nature, diversity is essential for a versatile and resilient economical system. Diversity makes the system stronger, without depleting resources.

The idea of buildings as material banks also originates from the Cradle-to-Cradle concept. Buildings can be seen as depots, that allow temporary storage of valuable materials. This brings along certain criteria that the building materials should meet (Geldermans, 2016):
1. The buildings materials should have a high quality.
2. Only pure materials should be used.
3. The reuse routes of materials should be determined in advance.

However, in the Cradle-to-Cradle concept circularity is not the goal, but a method to make a positive impact. Next to that, the difference with Circular Economy is that not all materials, but only certain materials should be made circular in the Cradle-to-Cradle-philosophy (Geldermans & Jacobson, 2015).

Regenerative Design (RD)
Regenerative Design is derived from the word regenerate, which has the following definition in the American Heritage Dictionary of the English Language: *to give new life or energy to something; to restore it to a better state; to reform spiritually or morally; to improve a place or system*. The concept is inspired by the functioning of the ecosystems of the earth. Human-made systems should be designed based on regeneration instead of depletion of the ecosystems and resources that the earth provides. Instead, human and natural systems should be able to benefit from and strengthen each other (Mang & Reed, 2012). In this theory buildings should function as catalysts that positively support the ecosystem, rather than polluters of the ecosystem (Plessis & Cole, 2011).

Blue Economy (BE)
Blue Economy strives for a system where waste does not exist. Like in nature, the output of every process should be the input for another process. By-products are sources for the manufacturing of new products. In nature, there is always a continuing cascading system of nutrients, matter and energy, resulting in a sufficient to even an abundant amount of resources. This is in contrast with our present economic model, where we experience a scarcity of resources (Pauli, 2010). For this reason, we have to change our economic model into one that reuses all waste of one process as resource for a new process.

Design-to-redesign ideas are closely connected to the Circular Economy. They focus not only on the reduction of pollution, but also on the regeneration of systems by designing better systems. The approach is based on systems rather than components; redesigning rather than improving the efficiency (Geldermans, 2015). Two design-to-redesign concepts, that suit the Circular Economy principles, are Design for Disassembly (DfD) and Design for Adaptability (DfA):

Design for Disassembly (DfD)

This concept can be seen as a tool to reach the Circular Economy. The concept aims to simplify the disassembly process of products. Disassembly is referred to as the method to separate a product into its constituent parts, components, subassemblies or other groups. The reasons for disassembly of a product may be repair or periodic maintenance, or recovery of materials for recycling purposes (Güngör, 2006). In relation to the Circular Economy, Design for Disassembly mainly focusses on the technical possibilities of recycling, but doesn't look at the complete reuse routes of the materials after disassembly of the product or building (Geldermans, 2015).

Especially in the building sector the concept is applicable. To be able to change the linear material flow in the building industry into a circular system the process of demolition has to change into a process of disassembly. The structure of the building needs to enable reuse, reconfiguration and recycling of materials and building components. This calls for a systematic order of assembly of building components, that provides easy maintenance and replacement of every individual component that the building consists of. Important is to think in advance about the causes that would make the building change. For each material the technical lifetime, depending on the structural failure of the materials, as well as the functional lifetime, depending on the use of the component, should be defined (Durmisevic, 2010).

Thus we could say that Design for Disassembly is a key condition for the success of the Circular Economy, and as a result, the disassembly potential has a direct relation with the building's or product's level of circularity.

Design for Adaptability (DfA)

The concept of Design for Adaptability is in line with the Design for Disassembly concept. It is a design methodology that converts products into dynamic adaptable systems, that can be controlled and modified by their users. Because the product is able to respond to changing inputs, the lifetime of the product will consequently increase (Kasarda, et al., 2007). Architect John Habraken applied the concept of DfA to the building industry, as criticism on the monotonous housing developments after the Second World War. He argued for more influence of the users on the design of their dwellings. He proposed to divide the building in two domains: the base building (structure), which is the responsibility of the investor, and the changeable infill of the building, which is the responsibility of the user. The 'open building' approach of Habraken is a solution for the changing occupancy of buildings, and prevents buildings to become outdated (Geldermans, 2016).

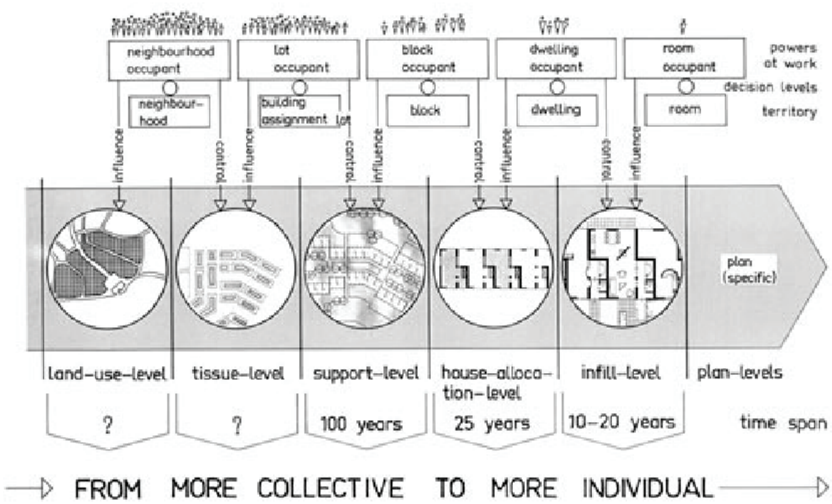


Fig. 8: Levels of decision-making in the Open Building concept (Kendall & Teicher, 2000)

Circularity in the built environment

The built environment is the sector that consumes most raw materials. 25-40% of the global carbon dioxide emissions comes from the built environment. While most of the research aims at developing methods to reduce the operational energy of buildings, less attention is given to the embodied energy of the building materials. The current building process is linear; 90% of the waste production that accounts for 50% of the embodied energy in the building sector, is generated during the demolition of the building (Durmisevic, 2010). 25% of total amount of waste in the Netherlands (24 million out of 60 million tonnes) comes from the building industry (Rijkswaterstaat Ministerie van Infrastructuur en Milieu, n.d.). Now that researchers have started looking at the whole life cycle of buildings, the concept of the Circular Economy is gaining attention.

Pomponi and Moncaster (2017) have given the following definition to a circular building:

"'A circular building' is a building that is designed, planned, built, operated, maintained and deconstructed in a manner consistent with Circular Economy principles."

Circularity can be systematically applied to the built environment at three scale levels (Pomponi & Moncaster, 2017):
- the macro-level (urban cluster of multiple buildings)
- the meso-level (one single building)
- the micro level (one building component).

However, creating a circular building is difficult. Buildings are complicated structures that consist of many materials with different life cycles that all interact dynamically in space and time. Next to that, due to their long lifespan, buildings are very apparent to change use during their service life. For these reasons, circular buildings can't be achieved by only reducing resource consumption, improving efficiency and increasing recycling and reuse rates. Two more aspects should be taken into consideration (Pomponi & Moncaster, 2017):
1. Products with a short lifecycle aren't suitable for buildings, because of the significant long-time life span of buildings. On average buildings wear well for 60-90 years. This means 75-90% of the current buildings stock will still be there in 2050. Therefore, it is important to focus on solutions for the existing building stock, instead of new buildings.
2. Buildings consist of many standard manufactured products, that are assembled in a unique way. This makes the disassembly process of every building different.

Frank Duffy and Steward Brand (1994) defined the shearing layers of change of buildings, based on the hierarchy of building components in the structure. In their theory buildings consist of six layers: interior, space plan, services, structure, skin and site (from the inside to the outside). Every layer has a different lifecycle; the interior has the shortest lifecycle and the site the longest (infinite) (Geldermans, 2015). The problem of the current buildings, in which all layers are integrated in one single structure, is that the layers with long-term cycles obstruct the layers with short-term cycles, and, other way around, replacement of the layers with short-term cycles cause damage to the layers with the long-term cycles (Berge, 2009). As a result, Duffy and Brand (1994) discovered that the building is always tearing itself apart.

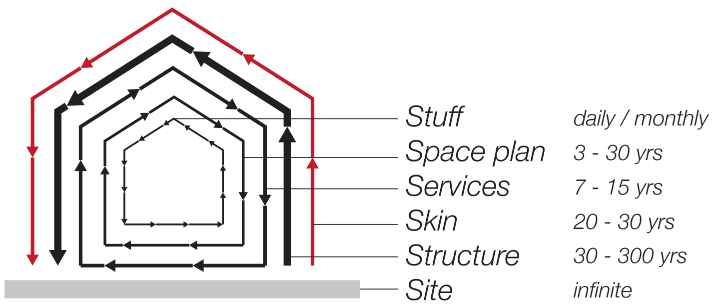


Fig. 9: Shearing layers of change (Berge, 2009)

The building should be redesigned into a structure in which all layers are able to change independently. A cyclic life cycle model enables transformation of materials during different stages of the life cycle of buildings. For the built environment, this means the following: when building materials have lost the required quality for their function in the building, they can be reused for a number of other end-of-life cycle options (Durmisevic, 2010).

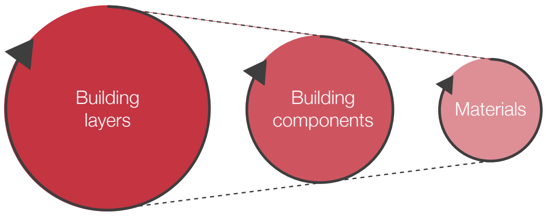


Fig. 10: Diagram of building levels
(source: own image)

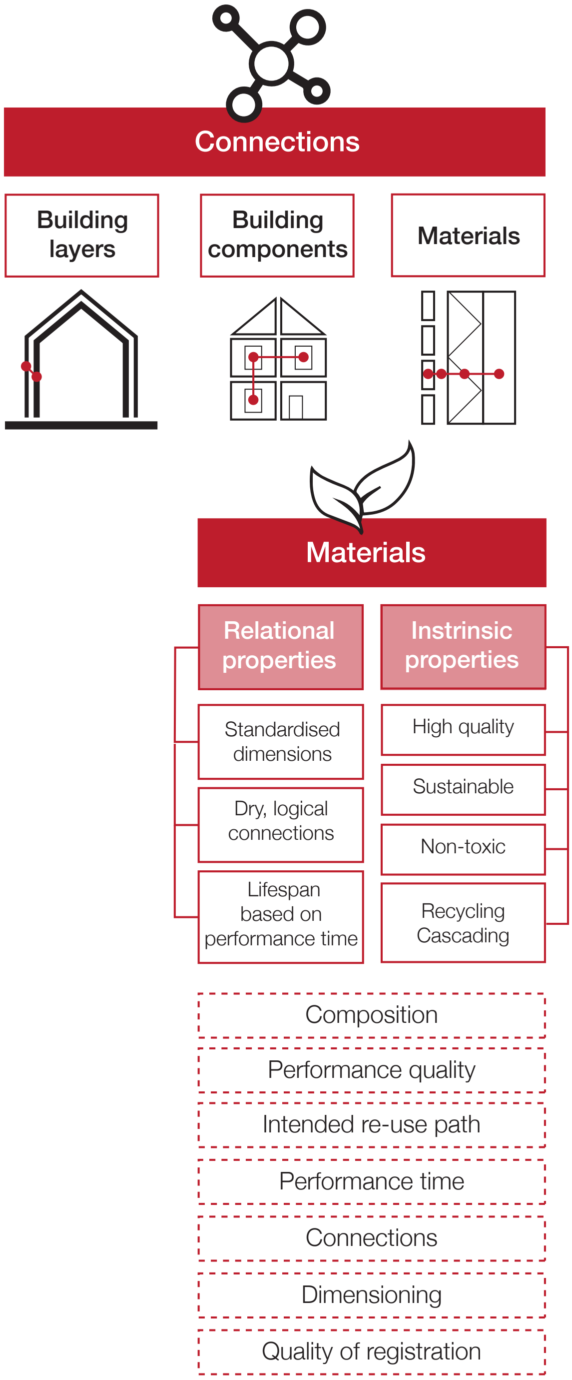


Fig. 11: Diagram of design strategies, based on research of Geldermans (2016)
(source: own image)

Design strategies

The design strategies for circular buildings should be applied to the structure of the building, materials that the building consist of, and the connection between materials and building components. The strategies mainly aim to improve the flexibility and adaptability of the building.

To be able to create a circular building that is designed for easy maintenance, disassembly and efficient re-use of components and materials, the structure of the building should have a high adaptive capacity. Following the principles of the Circular Economy, the structure should enable building components to be eliminated, added, relocated or substituted (Durmisevic, 2010). To increase the adaptive capacity of buildings, separation should be possible at three building levels (Berge, 2009):

1. Seperate building layers: interior, space plan, services, structure, skin and site
2. Separate building components to enable easy disassembly of the building layers.
3. Separate materials; use as much as possible standardized monomaterials, instead of a composition of different materials laminated together.

Materials

While flexibility and adaptability of the building structure are necessary to create a circular building, in the Circular Economy the focus lays on the properties of the used materials: their quality, their recycling possibilities and their health. A division can be made between two types of material properties: intrinsic and relational.

The intrinsic properties of the building materials relate to the chemical composition of the materials. Certain criteria for circular materials are defined (Geldermans, 2016):

1. The material needs to be of high quality, regarding functional performance.
2. The material needs to be of sustainable origin to be able to endlessly provide nutrients for new material life cycles.
3. The material needs to be non-toxic.
4. The material needs to be coherent with the biological cycle and be able to cascade or the material needs to be coherent with one or more technical cycles.

The relational properties of the materials are based on their design and use in the building (Geldermans, 2015):

1. The dimensions need to be standardised, based on the modular coordination and dynamic capacity demands of the buildings.
2. The connections between materials and building components need to be dry and logical.
3. The technical lifespan of the material needs to be based on its functional performance time.

The circular value of a product lays at the intersection of intrinsic and relational properties. In terms of Circular Economy, the value can be defined by looking at the extent in which the product is able to function within the biological or technical cycles. Standardisation of dimensions is a method to increase the reusability of materials or building components in other systems (Geldermans, 2015). However, to maintain diversity in the built environment, standardised elements should enable assembly in different configurations.

Connections

The challenge is how to design building systems that consist of building components that can be replaced several times, without the need to disassemble the whole system. The main technical problem lays in the connection between components, that must be able to provide decomposition, re-composition, incorporation and plugging-in of components. Three design domains, that relate to the type of connections, can be identified. These domains and corresponding subdomains are explained below (Durmisevic, 2010):

- Functional decomposition:
    - Functional independence of materials and building components;
        - How many functions are integrated into one building component?
          Integration of two or more functions with different lifecycles into one component will complicate the disassembly process. Separation of functions in the building component is beneficial for disassembly, because then change or replacement of one function doesn't affect the others.

- Systematisation and modulation of materials and building components;
  - How many building parts are clustered into one component?
    The more building parts are clustered in the factory, the fewer physical connections have to be made on site, and thus the faster the assembly and disassembly process will go. The more steps have to be taken for disassembly, the more attractive becomes demolition. Four types of clustering in the building can be identified: clustering on system, component, element and material level. What materials and elements belong to which cluster, is determined by the functionality of the module. The sequence of the materials and elements in the system is determined by their use and technical life cycles.

- Technical decomposition:
  - Relational patterns between materials and building components:
    - The number of relations: The less building components are integrated into one structure, the better.
    - Hierarchy in the structure: Open hierarchies are preferred to keep building parts independent from each other by only making dependent relations between building components within the assembly.
  - Type and position of relations:
    - Vertical relations take place within one functional group. The building structure becomes dynamic, when its relational diagram is vertically oriented.
    - Horizontal relations take place between different functional groups. Less relations between different functional groups makes replacement and modification of components easier.
  - "Base element" specification: the base element holds all surrounding elements in the cluster together and creates one of the few or only horizontal connections with the other clusters in the dynamic structure. This is the last element that can be disassembled.
- Physical decomposition:
  - Interfaces between materials and components:
    - In as many directions as possible, to prevent damaging of other components.
    - The assembly sequence:
      - Parallel assembly accelerates the process, because more components can be (dis)assembled at the same time.
      - Sequential assembly creates a linear dependency between components, what makes replacement of components difficult.
    - Type of connections:
      - Integral (direct) connections are made by the components edges:
        - Overlapping edges
        - Interlocking edges
      - Accessory (indirect) connections consist of additional parts that form the connection between components:
        - Internal connections are incorporated within the components, which complicates the disassembly process.
        - External connections are independent, which simplifies the disassembly process.
      - Filled connections are made on-site by filling the space between two components with a chemical material. Also welding falls in this category. These connections are permanent and impossible to disassemble.
    - Life cycle coordination:
      - Components and materials with short lifecycles need to be disassembled first and thus assembled last.
      - Components and materials with long lifecycles need to be disassembled last and thus assembled first.
      - The base element should have the longest lifecycle of all components.

Fig. 12: Photos of Alliander Office in Duiven (Henket, 2015)

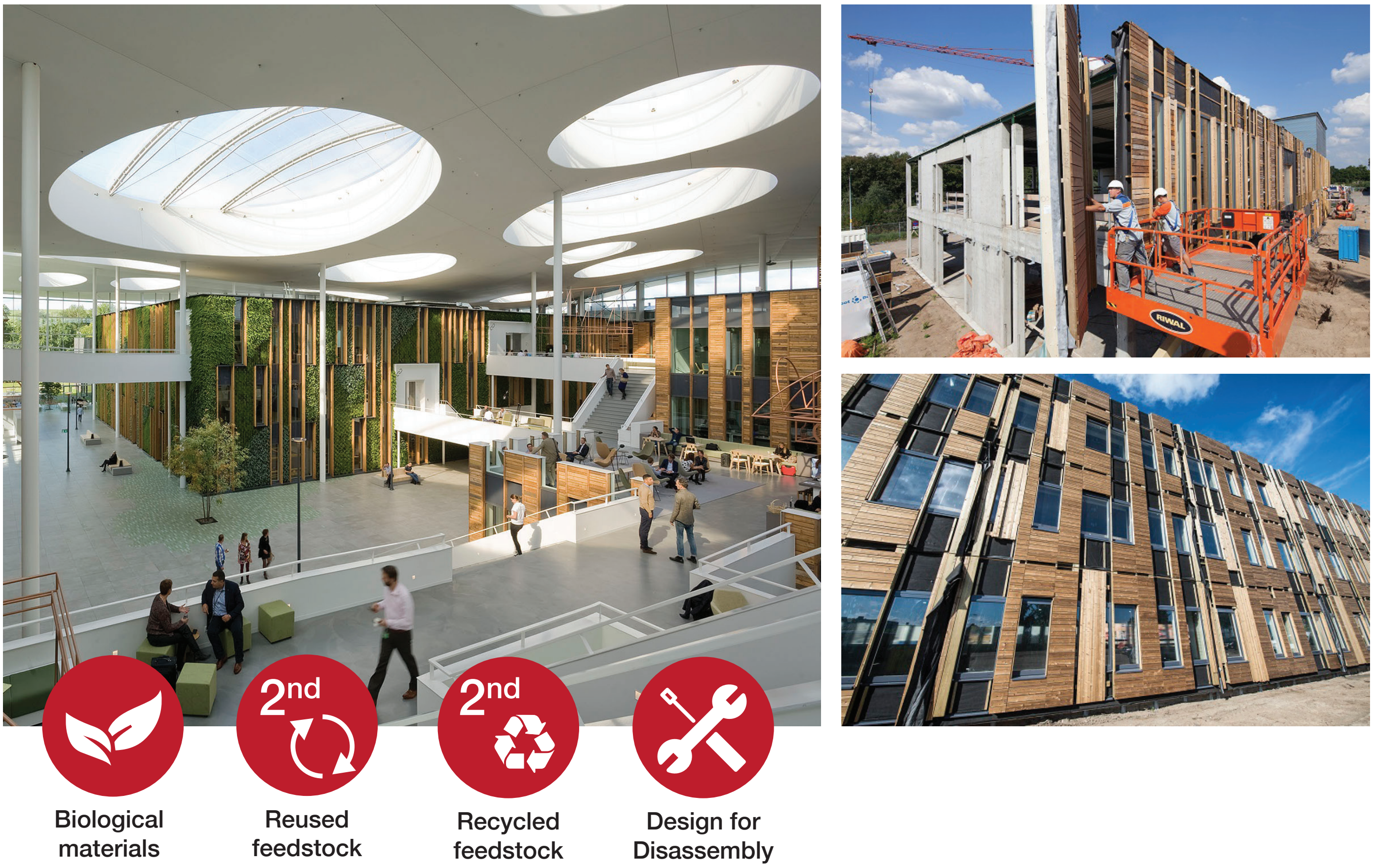


Fig. 13: Photos of the ABN Amro Pavillion in Amsterdam (ArchitectenCie, n.d.)

Precedents

When looking at the façade of a number of precedents, that are called "circular buildings", one should realise that different design principles of the Circular Economy are utilized. The Alliander Office in Duiven, designed by RAU Architects, is an example of a circular building that consists of as much secondary reused and recycled materials as possible. Next to that, the connections between the materials are designed in such a way that they can be disassembled. On the other hand, the ABN Amro pavilion in Amsterdam is made of mainly biological materials, that have as much as possible reuse and recycling possibilities at the end of functional life time of the pavilion. The façade of the City Hall in Venlo mainly consists of technical materials, that have reuse- and recycling possibilities at their end of life, and have connections that are designed for disassembly. The Temporary Courthouse in Amsterdam has been designed for a wide variety of future function, by allowing change of configuration of the facade and structure of the building. In this paragraph the four precedents are described and the integrated principles of the Circular Economy highlighted:

Alliander Office in Duiven (NL), designed by RAU Architects, completed in 2015

The company Liander had the need for expansion of new office buildings with modern workplaces. The company is accustomed to invest for the long-term. Instead of demolishing their six existing office buildings, built in the seventies, in use since 1984, and rebuilding something new, Liander decided to try to reuse as much of the buildings as possible. Also the aim of the architect, Thomas Rau, known as the advocator of the Circular Economy in the Netherlands, was to design a building with as many reused materials as possible, and build in a way that maximum reuse of materials is enabled at the end-of-life of the building. (De Ingenieur, 2015). Because, according to Thomas Rau, reuse of existing buildings is one of the most important methods to get a good score in the field of circularity. To be able to achieve complete circularity of the new office building, all materials of the existing buildings have been analysed in terms of reuse and recycling potential. As a next step, the connection methods were investigated to enable demounting of the materials for next use in the future. Materials of the existing buildings that weren't useful, have been returned to the industry following thirteen different waste flows (Henket, 2015).

As a result, 80% of the materials of the existing office buildings have been reused and registered in the material passport of the new building (De Ingenieur, 2015). The steel support and roof structure, as well as the ceiling elements of the existing buildings, have been reused. Some parts of the existing brick façades have been replaced by a new lightweight ModiWood façade system. Other parts have been maintained and only covered by a new wood facade cladding. The removed bricks have been pulverised and recycled as aggregate for the road of the car park (Henket, 2015). The interior façades are made of waste wood, rescued from the waste incinerator at the other side of the road (De Ingenieur, 2015). Even the insulation of the façade is made of recycled corporate clothing. All buildings are covered by one big roof with an efficient steel construction that saves 20-25% steel consumption.

The office buildings are designed in such a way that they can be completely disassembled at the end of their functional life, enabling reuse of materials as much as possible. As a result, the materials will never turn into waste, but remain raw materials, used for new applications (Henket, 2015). Another aim that the client had set from the beginning was to achieve energy neutrality during the construction as well as the use of the new buildings. Thus solar panels were installed on the roof of the car park and storage, that have provided a positive electricity balance during the firs two years of construction (De Ingenieur, 2015).

ABN AMRO Pavilion in Amsterdam (NL), designed by ArchitectenCie, completed in 2017

As a response to the demolition of their old head office in Amsterdam, that had been in use for only 25 years, ABN Amro decided to build a new circular pavilion at the Zuidas. The pavilion is designed as a living lab, that is able to adapt to changes in use, surroundings and technological developments. According to the architect Hans Hammink, the design of the pavilion is flexible by using fixed dimensions of components and enabling disassembly. As a result, the design is able to cope with functional changes without the need of (partial) demolition of the building. The architect has taken into account the following principles of 'circular building' (Vos, 2017):

- as little use of raw materials as possible
- design and built without waste
- recyclability of used materials
- flexibility and reusability of the interior
- different life cycles of materials and components
- material suppliers as co-makers

The choice of materials and products has been based on their residual value, disassembly potential, recycling potential and maintainability. To decrease their residual value, materials and products aren't covered by finishing layers or integrated in other materials (BAM, 2017).

All materials are registered in the BIM material passport of the building (BAM, n.d.). and thus all materials have reuse potential. To decrease the ecological footprint of the building, the amount of used materials is reduced (BAM Bouw en Techniek bv, 2017) and reused materials have been chosen as much as possible: for example, the concrete that

Fig. 14: Photos of the City Hall in Venlo (Kraaijvanger, n.d.)

Technical materials | Reuse at end of life | Recycling at end of life | Design for Disassembly

Fig. 15: Photos of the Temporary Courthouse in Amsterdam (Cepezed, n.d.)

Technical materials | Reuse at end of life | Recycling at end of life | Design for Disassembly consists for 35% of secondary material (ABN AMRO, 2016). Other examples are the reused window frames of the interior walls in the basement, the reused balustrades, the reused sidewalk tiles for the floor and the reused cable trays, that have been extracted from demolished buildings by the company New Horizon. The acoustic panels have been made of recycled jeans of ABN AMRO and BAM employees (BAM, n.d.). The structure of the pavilion is completely demountable. It is made of cross laminated timber with pinewood from South-Germany at the core and larch wood coating from the Netherlands. To make the connections demountable, the usage of sealant, polyurethane (PUR) and glue has been avoided (BAM Bouw en Techniek bv, 2017). The estimated functional life time of the structure is 30 years, then the wood supplier has to collect the wooden beams for reuse. The beams have been over-dimensioned, in order to enable direct reuse in their commercial size (Wind, 2017). The walls have been made of massive timber. The elevator shaft is also made of wood. The manufacturer Mitsubishi remains owner of the elevators and is paid per transport movement (BAM, n.d.).

City Hall in Venlo (NL), designed by Kraaijvanger, completed in 2016

Four principles of the Cradle-to-Cradle philosophy were the starting points for the design of the new City Hall in Venlo by Kraaijvanger architects: enhanced indoor and outdoor air quality of the building, continuous material cycles, renewable energy that produces more than it uses, and enhanced water quality (Teague, 2016). The concept of circularity has been applied to multiple cycles: materials, water, energy and climate. The main eye catcher of the building is the living green façade on the north that cleans the indoor and outdoor air. The desired results in terms of materials were (C2C-Centre, n.d.):

- Materials are compatible with the technical or biological lifecycle.
- Cradle-to-Cradle certified products are selected.
- Residues are raw materials for new products.
- Products and materials have an added value or users and the environment.

All material suppliers are C2C certified, which means all products and materials are 100% reusable and environmentally friendly in production, use and re-use (ArchDaily, 2017). Products have been chosen based on their embodied energy, the absence of toxins during their complete lifecycle and their recycling and upcycling possibilities (Teague, 2016). To be able to achieve continuous cycles of raw materials, all building components and products can be demounted at their end-of-life. The south façade of the building is made of aluminium, which is completely reusable without quality loss. The green north façade consists of plant trays that are connected to a wooden substructure with low embodied energy and reuse possibilities. The construction is made of 60-70% recycled concrete granulate. The floor tiles in the interior are made of recycled PET bottles. Most of the furniture is made of rubberwood, following the biological material lifecycle (C2C-Centre, n.d.) All used materials are registered in the material passport of the building, specifying their production and origin. At the end of life of the City Hall the suppliers will take their products back to enable high-quality re-use. All building systems can easily be replaced with new sustainable alternatives. The interior is flexible, built independently from the construction, allowing functional change (The Plan, n.d.).

Temporary Courthouse in Amsterdam (NL), designed by Cepezed, completed in 2017

The Temporary Courthouse is designed for a functional lifetime of 5 years. The real estate department of Cepezed is owner and has rented the building to the Rijksvastgoedbedrijf of the government through a Design, Build, Maintain and Remove contract. In order to maximise the residual value of the building at its end of life, the goal for the design of the Temporary Courthouse was to reduce material use, use as much as possible reused “donor materials”, coming from demolished buildings, and recycled materials. The building is completely demountable and as a result completely reusable at another location for various functions. The building can be reconfigured in a different shape. The construction is based on large spans with high columns, in between which additional floors can be placed. A special demountable connection system between the hollow-core floor slabs has been developed in collaboration with the engineering firm IMd (Cepezed, n.d.). According to the architect of Cepezed, Mathieu de Danschutter, the design of the building is autonomous; site and building have been physically as well as aesthetically disconnected. This way a state of permanent temporality is achieved; the building and its value are permanent, while location and use are temporary. The building envelope consists of modular, prefabricated, standardised elements, that can be dis- and reassembled as “a kit of LEGO parts”. Depending on the construction grid, the timber-framed façade elements have a width of 5,40m and a length of 7,20m, connected with screws. The façade cladding is made of lightweight, stretched plastic fabric, that can easily be rolled up and transported. The architect has chosen for technical materials, because of their long lifespan and low maintenance. According to the architect, the main obstacles encountered during the design process, were the structural requirements and the requirements in the field of Building Physics, that prevented the use of recycled and reused materials (De Danschutter, personal communication, November 20, 2017).

Conclusion

Being aware of the many different interpretations of the concept of the Circular Economy, described in the first paragraph of this chapter, it is necessary to utilize one definition of the concept to be able to conduct the research as complete as possible. Thus, based on the above-mentioned interpretations, the following definition of the Circular Economy will be utilized for the research:

Circular Economy aims to close and extend the loops of material cycles, in order to preserve value of materials, resulting in decreased raw material consumption and waste generation in our current society.

This definition for the Circular Economy is chosen, because it incorporates the potential of material reuse, leading to extended material cycles, and the potential of recycling, leading to closed material cycles, as means to decrease raw material consumption and waste generation. To be able to shift from the linear model of take-make-dispose, that is dominant in our current society, to the Circular Economy, products should be designed in such a way that they can be optimally repaired (step 1), reused (step 2) and recycled (step 3), while taking into account minimal embodied energy of the materials. Important to mention is the complexity of the system, due to the large number of actors with different benefits and interests, that are involved and interconnected in the system.

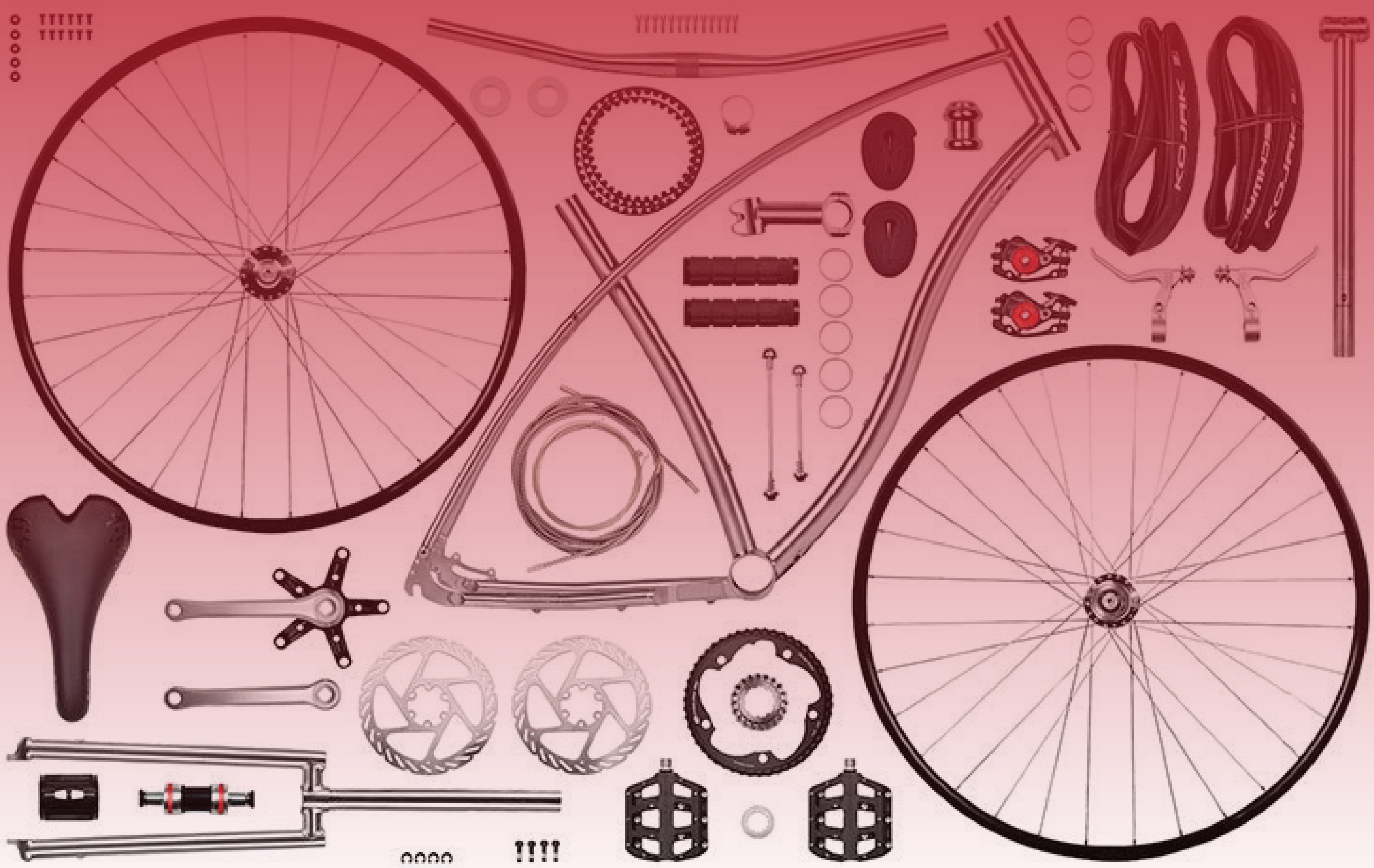
When applying the concept of the Circular Economy to the built environment, the principles affect two main parts of the building(component): materials and connections. Concerning the materials, the intrinsic and relational properties should be taken into account. Concerning the connections, the possibility to dis- and reassemble the building(component) is of main importance, to enable replacement of materials at their end of life without damage. After evaluation of a number of precedents, the principles of the Circular Economy can be applied to circular building in different ways: one could focus on the use secondary materials that consist of reused and/or recycled feedstock, and/or one could focus on increasing the reuse and recycling possibilities of the materials at the end of life. When looking at the different frameworks that accommodate the Circular Economy, the Cradle-to-Cradle philosophy, which is focussed on materials, and the Design for Disassembly (DfD) and Design for Adaptability (DfA) concepts, focussed on connections, are also applicable in the built environment, coherent with the principles of the Circular Economy.

In the next chapter a method to assess the level of circularity of a building or building component, will be developed, based on a combination of existing assessment methods. This circularity assessment method will be used to analyse the level of circularity of the 2nd Skin Façade Refurbishment system.

04

CIRCULARITY ASSESSMENT METHODS

In the previous chapter the definition of the Circular Economy and its application in the built environment are explained. However, methods to assess the level of circularity of buildings or building components don't exist yet. Thus, to be able to identify the assessment criteria for the level of circularity of building(components), first existing assessment methods, that relate to the Circular Economy, will be analysed in this chapter. Based on the literature research a division of assessment criteria is made between materials and connections. As a result a combination of two assessment methods will be chosen for the circularity assessment of the 2nd Skin Façade Refurbishment system, that will be conducted in the next chapter.



Existing assessment methods

While there are many assessment methods on the market that grade the level of sustainability of a building (component), there doesn't exist yet a finalised method to assess its level of circularity. The concept of the Circular Economy has been researched increasingly in the past decade. However, extensive research on how to measure the level of circularity of a product, supply chain or service, is still missing, while this is of main importance for the transition from a circular to a linear economy. To be able to develop a circularity assessment method for this research, first existing environmental assessment methodologies that relate to certain requirements of the Circular Economy, are analysed; the Life Cycle Assessment (LCA), the Material Flow Analysis (MFA), the Longevity Indicator (LI), the Material Circularity Indicator (MCI) and the Disassembly Potential (DP).

The main requirements for the Circular Economy are grouped in the following five categories, that can be measured with different assessment methodologies (Elia, Maria, & Tornese, 2017).:

1. Measure the reduction of input and use of natural resources
2. Measure the reduction of emissions levels
3. Measure the reduction of valuable material losses
4. Measure the increase in share of renewable and recyclable resources
5. Measure the increase in value durability of products

The environmental assessment methodologies will be evaluated on the basis of these five categories. At the end of this chapter, a combination of assessment methods that correspond to most of the requirements, will be chosen for the circularity assessment of the 2nd Skin Facade Refurbishment system, that will be conducted in the next chapter.

Life Cycle Assessment (LCA)
The Life Cycle Assessment tool is used to analyse the environmental impacts of a certain product or process. The entire life cycle of the product or process is taken into account, from cradle, the raw materials extraction, to grave, the final waste disposal (Crawford, 2011). All material and energy flows of the product system are measured and summed up in every life cycle. The LCA calculates the extraction of materials and energy out of the environment (resources) as well as the emissions into the environment. Also the output of other processes that are used as input for new product processes are considered. The system boundaries are defined by the techno sphere and the environment where the effects of the processes are most relevant to the research. The utility unit defines the scope of the assessment. When the whole life cycle of the building has to be taken into account, one representative functional unit in the building will be chosen for the calculation. The LCA assessment can be used to compare different life cycle scenarios of the building. The results of the LCA assessment of the building can be validated by comparing them to the results of a similar building or the total national building stock. The following three phases are taken into consideration in the LCA assessment (König, Kohler, Kreißig, & Lützkendorf, 2010):

1. Pre-use phase; looking at the raw material extraction, material processing, product assembly, packaging, transportation and installation of building components.
2. Use phase: operational energy of the building.
3. Post-use phase: deconstruction of the building, recycling and disposal of the materials.

The Life Cycle assessment results of the building can be improved by replacing materials with a high embodied energy with alternative materials with a lower embodied energy. This could result in a decrease up to 20% of the total cumulative energy, considering a building with a life cycle of 50 years. Another option is recycling of the building materials at the end of the functional service life of the building; this could result in a reduction of 30% of the total life cycle energy and a reduction of 18% of the greenhouse gas emissions of the building (Bribián, Usón, & Scarpellini, 2009).

The following scheme shows a simplification of the general structure of the LCA assessment method (Bribián, Usón, & Scarpellini, 2009):

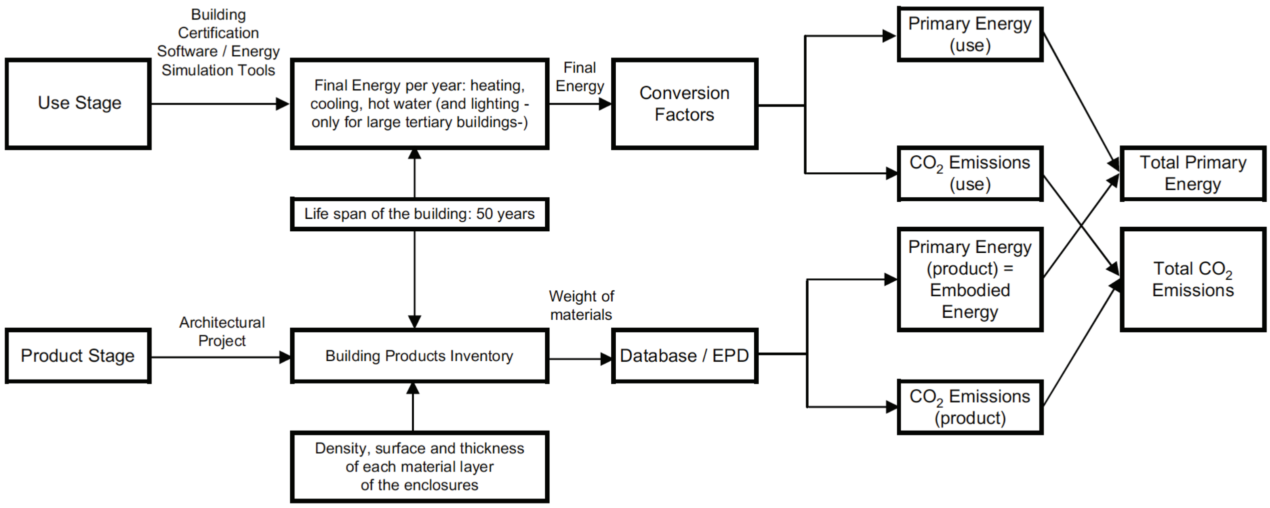


Fig. 16: Simplified visualisation of the LCA (Bribián et al., 2009)

The Life Cycle Assessment method is known to be one of the most complete environmental assessment methodologies, because it includes several impact categories and gives an accurate analysis from different perspectives. However, this also leads to an extensive amount of data that is needed to perform the assessment. When some data is unavailable, the results of the LCA may become uncertain. Next to that, performing the LCA method is time-consuming, compared to other methodologies (Elia, Maria, & Tornese, 2017).
The applicability of the Life Cycle Assessment method to assess the level of circularity of a building product is limited. First of all, the LCA method considers a linear process instead of a circular life cycle of products (Pomponi & Moncaster, 2017). Next to that, the LCA assessment method doesn't take into account the lifetime of products, while this is essential for the circularity assessment (Franklin-Johnson, Figge, & Canning, 2016). Both time and place aren't considered in the Life Cycle Assessment (König et al., 2010).

Summarised, the Life Cycle Assessment method does measure four of the five main requirements of the Circular Economy: the reduction of input and use of natural resources (1), the increase in share of renewable and recyclable resources (2), the reduction in emissions (3) and the reduction of valuable material losses (4). However, it doesn't take into account the increase value durability of products (5).

Material Flow Analysis (MFA)

The Material Flow Analysis investigates the flow and stock of materials entering and leaving a system and subsequently evaluates its environmental performance, based on its environmental burden (Franklin-Johnson, Figge & Canning, 2016). The MFA measures the input and output flows of materials to a system within a specific place and timeframe. The input flows equal the output flows plus the additional materials stored in the system (Rincón et al., 2013).
The Material Flow Analysis suits the principles of the Circular Economy, because it identifies quantifiable imbalances in the input and output of non-renewable resources and their efficiency (Franklin-Johnson, Figge & Canning, 2016). Next to that, the MFA is an interesting instrument to assess the level of circularity of a product or system, because it measures the input of natural resources (1), the use of recyclables (4) and the loss of valuable material (3). However, what the MFA methodology is lacking is information about the quality of the materials flowing through the system. The MFA doesn't take into consideration the reduced quality of secondary materials, compared to the quality of primary materials, which is referred to as down-cycling. Another important requirement of the Circular Economy that is missing, is the measurement of the reduction of emissions; the MFA only focusses on the material flows within the system (Elia, Maria, & Tornese, 2017). Thus, the Material Flow Analysis measures three of the five main requirements of the Circular Economy.

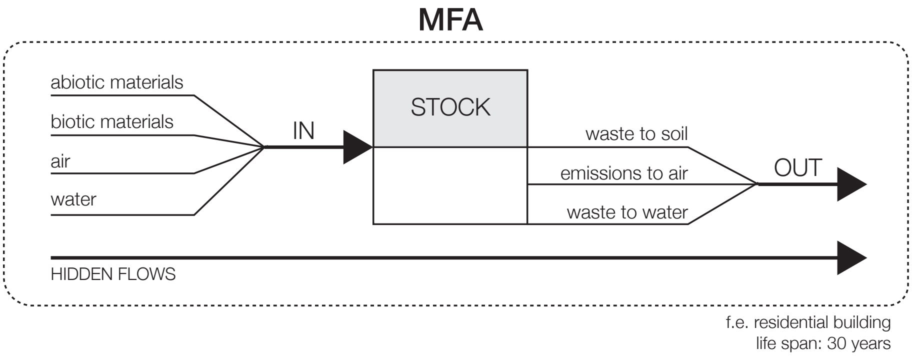


Fig. 17: Visualisation of the MFA (source: own image)

Longevity indicator

The main goal of the Circular Economy can be seen as maintaining materials in use for as long as possible. Because the longer the material is used, the more value is extracted from the material. According to Franklin-Johnson, Figge & Canning (2016), circularity aims to increase the amount of time during which a resource provides value. As a result, they invented the longevity indicator that shows the time length for which a material is kept in a product system, to maximise resource exploitation through product use, product reuse and material recycling. Thus, the longevity of resources indicates the average useful life of products and materials. The longevity indicator can be used to determine the degree of circularity of a product system, by taking into account that a perfectly circular system will be realised when longevity equals infinity.

The longevity indicator is based on temporal calculations, measured in months, and directional calculations, measured in percentages.

- Temporal calculations are used to calculate the lifetime lengths between two developments: such as the initial lifetime (A), the refurbished lifetime (B) and the recycled lifetime (C).
- Directional calculations show the percentages of lost or returned products/materials and refurbished or recycled products. Due to product loss and deficient recycling methods, some resources will disappear at each stage of the cycle.

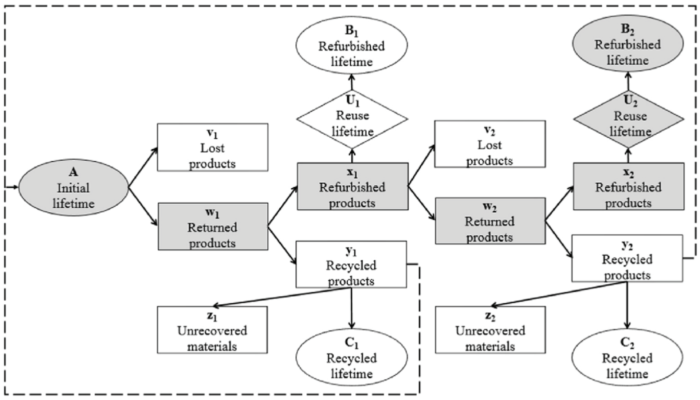


Fig. 18: Visualisation of Longevity Indicator (Franklin-Johnson et al., 2016)

Longevity = initial lifetime (A) + refurbished lifetime (B) + recycled lifetime (C).

The longevity indicator can be applied to any system that consists of use (A), reuse (B) and recycling (C) elements. To calculate the longevity of a system that consists of multiple resources, the longevity of each individual resource needs to be added up. To increase the longevity of a product system, the use of a product should be extended and the recycling or refurbishment of a product should be increased.

The longevity indicator is a simplified method to test the circularity of a product in comparison to an alternative. However, it doesn't consider the complete consumption process; only individual resources are taken into account that are reused in similar product. Also, additional input of raw materials isn't integrated in the model and down-cycling of materials isn't considered. So, it should be developed further and/or combined with other existing indicators that do provide the supplementary information (Franklin-Johnson et al., 2016).

Summarised, unlike the other methodologies addressed in this chapter, the longevity indicator only focusses on measuring the increased durability of products (5). However, it doesn't take into account the quality loss of reuse or recycling of materials over time, while this has a significant effect on the level of circularity of the product.

Material Circularity Indicator (MCI)
The Material Circularity Indicator is initially developed for the product design sector by the Ellen MacArthur Foundation et al. It is a methodology that can be used to assess the level of circularity of products and companies, by showing their position on the transition line from 'linear' to 'circular'. This way the methodology enables comparison between two product designs, regarding circularity. The results can be used as input for new design decisions. The Indicator focusses only on the materials of the technical cycle, that are non-renewable, because their circularity strategies and corresponding business models can be better analysed (Ellen MacArthur Foundation & Granta Design, 2015b).

The Circularity Indicator is based on the following four principles:
1. Use feedstock from reused or recycled sources
2. Reuse components or recycle materials after the use of the product
3. Extend the lifecycle of the products
4. Intensify the use of products

Following the four principles, the Circularity Indicator is based on the following inputs:
1. Input of raw materials in the production process:
   How much raw materials, recycled materials and reused components are needed as input for the production process of the product?
2. Utility during use phase:
   How long and intensely is the product used compared to a product of similar type?
3. Destination after use:
   How much material ends up in landfill? How much material is collected for recycling? Which components are collected for reuse?
4. Efficiency of recycling:
   What is the efficiency of the recycling process; recycled materials for input as well as recycled materials after use?

The difference between the Material Circularity Indicator (MCI) and the Life Cycle Assessment (LCA) is their focus area. Where the LCA looks into the environmental impact of the product during its life cycle, comparing different scenarios, the MFI focusses only on the material flows during the use of the product, Where the LCA balances the environmental impacts of the input and output of the material processes during the life cycle of the product, the MCI concentrates mainly on the use of recycled or reused materials for the production of the product and the reuse and recycling possibilities at the end of use of the product. During the use of the product the MCI values the durability and usage intensity of the product. The environmental impacts of the materials and processes, measured in energy and water, can be calculated complementary to the MCI with a different indicator. Similarities can be found in the data input: many of the required data for the MCI is equal to the LCA. In the future, the two methodologies could possibly be combined and strengthen each other (Ellen MacArthur Foundation & Granta Design, 2015a).

Concluded, the Material Circularity Indicator takes into account four of the five main requirements of the Circular Economy: the reduction of input and use of natural resources (1), the increase in share of renewable and recyclable resources (2), the reduction of valuable material losses (4) and the increase value durability of products (5). However, the only requirement that the MCI doesn't take into consideration, is the reduction in emissions (3).

Disassembly Potential
Unlike the other environmental assessment methods, the Disassembly Potential, developed by Elma Durmisevic (2010), doesn't measure any of the five requirements. However, it is considered to have an indirect effect on all five requirements. According to Elma Durmisevic (2010), the built environment can only become more circular when the transformation of the building is based on disassembly instead of demolition. The current modern building structures are designed to be built, but not to be dismantled at the end of their life. Transformation of the building refers to elimination, addition or relocation of building components and gives an answer to the dynamic behaviours of the owners and users of the building. Life Cycle Analysis results have shown that a higher transformation capacity of buildings leads to a lower environmental impact, because the concept of Design for Disassembly enables more efficient material use and as a result decreased waste generation. This means increased flexibility of the building leads to increased environmental efficiency. To assess the level of circularity of buildings, its Disassembly Potential needs to be taken into account, because disassembly makes reconfiguration, reuse, recycling and replacement of building components and materials possible (Durmisevic, 2010).
To be able to increase the Disassembly Potential of the building, multiple performance criteria have to be taken into account. Buildings are complicated structures, because they consist of many materials with different life cycles. Most of the materials have a longer technical lifecycle than their functional lifecycle. This can be seen as the bottleneck for the transformation of buildings. Next to that, one should look at the dependency between building components and materials in the technical composition of the building. Also the interfaces between the building components and materials should be analysed. When designing for disassembly, the components should be arranged in such a way that they become independent of each other and the interfaces between the components should be designed in such a way that they can be exchanged.

The assessment method of Durmisevic (2010) analyses the functional, technical and physical decomposition possibilities of building structures. Durmisevic (2010) defined the following eight performance criteria to assess the Disassembly Potential of building structures:

Indicators of independency:	
1. Functional decomposition (***FD***)	Material levels
2. Systematisation (***SY***)	
3. Relational Pattern (***RP***)	Technical composition
4. Base element specification (***BE***)	
5. Life cycle coordination (***LC***)	
Indicators of exchangeability	
6. Assembly sequences (***AS***)	
7. Type of connections (***TC***)	Physical integration
8. Geometry of product edge (***GE***)	

The results from the analysis indicate the transformability of the building structure, ranging from static to partly-open to dynamic configurations. Static building configurations are non-transformable and can only be demolished at their end-of-life. Partly-open building configurations consist of both fixed and flexible components, and thus are partly demountable. Dynamic configurations consist of open assemblies in which all building components are independent, materials can easily be exchanged and as a result the complete building can be disassembled without material loss.

Summarised, the Disassembly Potential assessment method, developed by Durmisevic (2010), focusses on the connections between building components and materials, instead of looking at the materials. Therefore, the assessment of the Disassembly Potential should be combined with other assessment methods, that do analyse the materials that the building(component) consists of, in order to provide a complete analysis of the level of circularity of the building(component).

Sustainability labels

As illustration of the practical implementation of the principles of the Circular Economy in the built environment, existing sustainability labels are analysed in terms of circularity. Because circularity in the built environment has gained more attention in the past years, some software has already been developed and used on the market to measure the level of circularity of buildings. Two examples are the software tool GPR Gebouw, and the Roadmap Circular Land Allocation, commissioned by the Municipality of Amsterdam, which will be described in this paragraph.

GPR Gebouw

An example of a management tool for sustainability decision-making, that includes circularity assessment criteria, is the software GPR Gebouw. The software GPR Gebouw measures the level of sustainability of residential and non-residential buildings. The tool is useful in every project phase; from design to realization and refurbishment of the building. The Sustainability Performance (DPG) of the building is based on a combination of the Energy Performance (EPG) and the Environmental Performance (MPG), following five themes: energy, environment, health, consumer quality and future value.
In the past year the subtheme of Circular Material usage has been added to the software. The level of circularity is considered to have a big effect on the level of sustainability of the building. For this reason, the added subtheme has obtained a heavy weighting in the calculation. The results are combined in the Circularity Performance of Buildings (CPG). As the name indicates, the software mainly focusses on the materials that building consists of. However, the connections between the materials are also included in the calculation to a certain extent (W/E adviseurs, 2016).

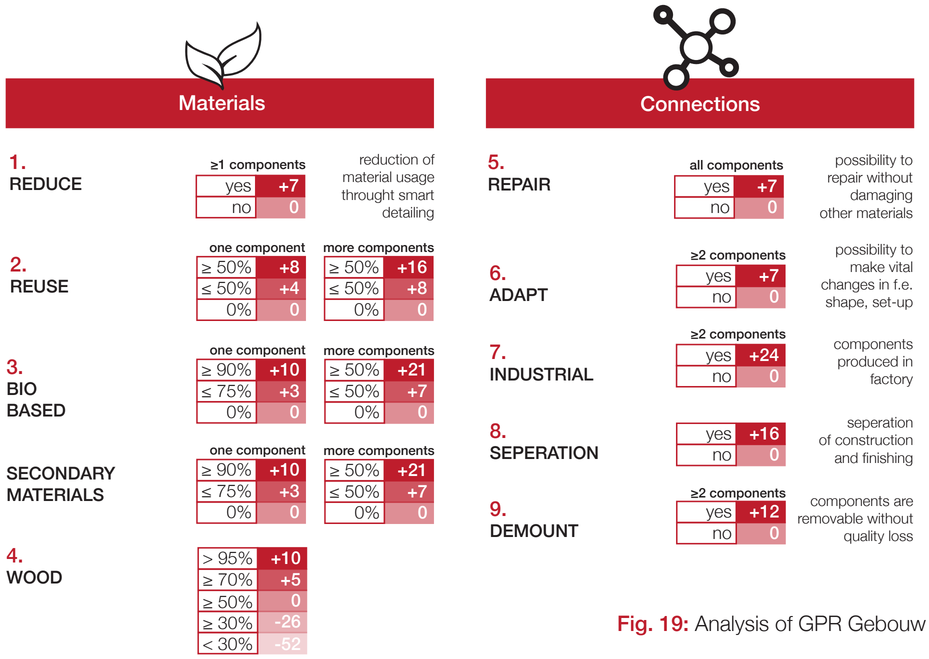


Fig. 19: Analysis of GPR Gebouw Circularity calculation (source: own image)

As can be seen in the diagram (fig. 19), the circularity assessment criteria of the software can be subdivided in two categories; materials and connections. The first category refers to the level of circularity of materials the building consists of; whether the materials have reuse possibilities at their end of life and contain bio based and/or secondary feedstock. The score will increase when more than one building component can be considered circular. The highest scores are given to the components with the highest percentage of bio based and/or secondary feedstock. The material wood is graded separately in the software; when a high percentage of wood in the building comes from sustainably managed forests, the amount of points will increase.
In the second category the connections between the building components are analysed, mainly looking at the building method. The building method should enable efficient material usage and encourage material cycles to occur. For this reason, more points will be obtained when there is a material reduction of 25% in one or more building components through smart detailing, when all components can be repaired without damaging other materials, when the change and/or set up of two or more components can be changed, when two or more components are prefabricated, when the structural and finishing layer of the walls are separated in the detailing and when two or more components are demountable without quality loss. As can be seen in the diagram, most points will be assigned when the building components are prefabricated.

Roadmap Circular Land Allocation

Commissioned by the Municipality of Amsterdam, the companies SGS, Search and Metabolic have developed criteria for circular building, that can be used during tendering for land allocation in the city of Amsterdam. In June 2017, the municipality presented the results to the Dutch Green Building Council, who will attempt to integrate the circularity criteria in the existing sustainability assessment methodology of the Dutch label BREEAM-NL (Dutch Green Building Council, n.d.).

The Roadmap defines criteria for the fives themes: Materials, Adaptivity and resilience, Water, Energy and Ecosystems and biodiversity. In the theme of Materials, the following criteria have been developed, based on the following four principles for circular building (Roemers & Faes, 2017):

1. Reduction
   - of material usage during the life span of the building
   - of environmental impact of the used materials
2. Synergy
   - Design for disassembly
   - Theoretical reusability of materials or components at their equivalent quality level
   - Use of secondary materials for the building process
   - Reuse of materials during the construction phase
3. Production and supply
   - Policy in the field of circular contracting
   - Certification of materials
   - Use and recording of scarce and critical materials
   - Use of renewable materials
4. Management
   - Material passport

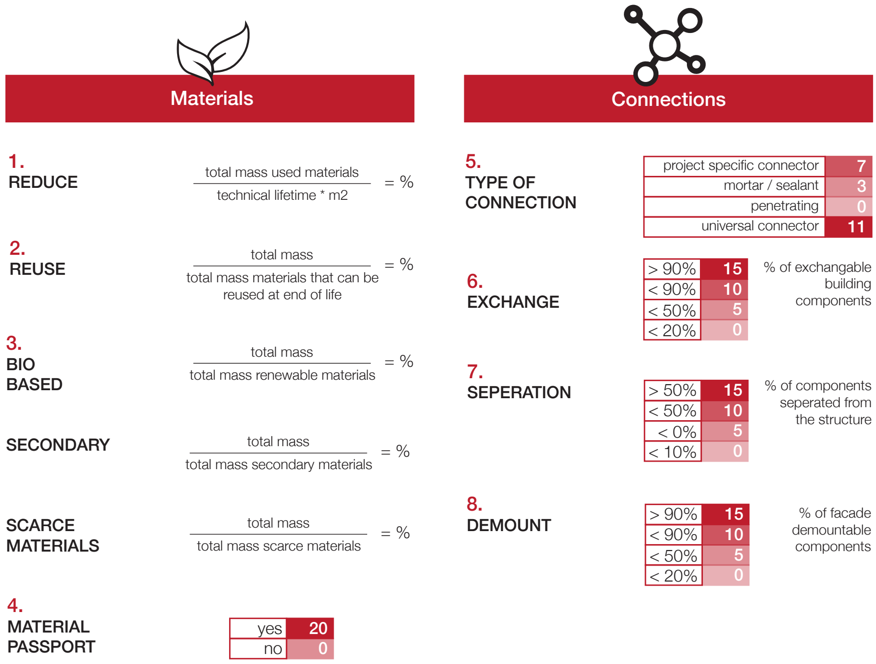


Fig. 20: Analysis of Roadmap Circular Land Allocation (source: own image)

As can be seen in the diagram (fig. 20), the criteria can be subdivided into the two categories: materials and connections. Next to that, the Roadmap also takes into account the process management. The materials are mainly measured in percentages of the total mass, while the connections are measured according to a point score system. Some results are difficult to measure, because they can only be measured at the end of the functional lifetime of the building, such as the percentage of building materials that are actually being reused. The minimum and maximum values for the criteria couldn't be defined, because there isn't yet enough experience in circular building,. For this reason, the criteria are formulated qualitatively as well as quantitatively. The quantitative indicators relate to the performance of the completed building, while the qualitative indicators describe the impact of the different activities and procedures during the process. The data needed for the quantitative indicators mainly comes from BREEAM. The criteria of the Roadmap are still under development. Before implementation they need to be extended, refined and tested in several projects in the coming months. At the moment, the Roadmap could be seen as the first attempt towards circular building (Roemers & Faes, 2017).

Choice of assessment methods

In this chapter one or two assessment methods will be selected to use for the circularity assessment of the 2nd Skin Facade Refurbishment system. The assessment methods that correspond most to the principles of the Circular Economy, will be chosen. The diagram below shows the comparison of the five previously analysed circularity assessment methods: the Life Cycle Assessment (LCA), the Material Flow Analysis (MFA), the Longevity Indicator (Longevity), the Material Circularity Indicator (MCI) and the Disassembly Potential (DP). The comparison is based on the five key requirements of the Circular Economy. The diagram (fig. 21) is derived from the study of Elia, Maria & Tornese (2017):

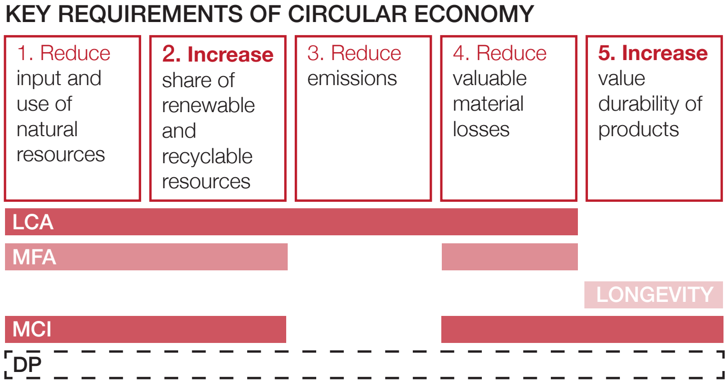


Fig. 21: Comparison of assessment methods (source: own image)

As can be seen in the diagram (fig. 21), the two assessment methods that match with most requirements of the Circular Economy, namely four out of five, are the Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI). The Disassembly Potential is considered to have an indirect effect on all five key requirements, and thus is marked with a dashed line.

According to Elia, Maria & Tornese (2017), the Material Circularity Indicator is a non-standardized index method, which means it measures performances of one specific product or service. Different from the other circularity indicators acting on micro level, the Material Circularity Indicator doesn't only measure the use of recyclable resources and the input of natural resources, but also includes the loss of materials and the product durability. Especially the durability of the product or service isn't taken into consideration in most of the environmental assessment methods, neither at meso nor macro level, while this requirement of the Circular Economy is of high importance to prevent obsolescence of the product or service. The only requirement that isn't included in the Material Circularity Indicator, is the measurement of the reduction of emission levels (Elia, Maria, & Tornese, 2017).
The LCA assessment does measure the reduction of emission levels, but doesn't take into account the durability of products. Next to that the LCA is based on the linear process of produce, use and dispose, instead of the circular life cycle of materials, which is where the Circular Economy is all about. For this reason, to be able to reach complete assessment of the level of circularity of a product, the LCA assessment shouldn't be used for the circularity assessment of the building(component). However, it could be used complementary to the MCI to calculate the energy usage and CO_2 emissions of the product (Ellen MacArthur Foundation & Granta Design, 2015a).
The above-mentioned circularity assessment methods all focus on the materials that the building structure consists of. Studies of Durmisevic (2010) have shown that Design for Disassembly is a prerequisite for circularity in the built environment. The built environment can only become circular when the transformation of buildings is based on disassembly instead of demolition to enable elimination, addition or relocation of materials at the end of their technical or functional lifetime. Increased flexibility of the building structure indirectly leads to increased material efficiency and decreased waste generation. So, next to the reuse- and recyclability of materials, the Disassembly Potential of connections between the materials should be analysed with the methodology of Durmisevic (2010).

Two existing sustainability labels, that have made a first attempt towards the implementation of circularity assessment criteria, have been analysed in this chapter; GPR Gebouw and the Roadmap Circular Land Allocation, commissioned by the municipality of Amsterdam. The two labels have incorporated similar grading systems for the buildings, to assess their circularity performance in terms of materials and connections. Both labels encourage the usage of materials that have reuse and recycling possibilities, and the application of demountable connections that enable disassembly instead of demolition of the building.

For these reasons, analysis of the materials as well as the connections between the building components and materials will be included in the research, to be able to achieve complete assessment of the level of circularity of the 2nd Skin Façade Refurbishment system. Consecutive from the comparison of five existing sustainability assessment methods, relating to certain requirements of the Circular Economy, two assessment methods are chosen to use for the research: the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation (2015b), which will be used to assess the level of circularity of the materials that the building components consists of, and the Disassembly Potential (DP), developed by Durmisevic (2010), that will be used to assess the level of circularity of the connections between the building components and materials. The exact assessment criteria will be explained in the following paragraph.

Formulation of assessment criteria

Material Cirularity Indicator (MCI)

The Material Circularity Indicator will be used to assess the level of circularity of the materials that the building components consist of. During the research, each building component within the façade system will be analysed seperately. The input for the calculation, modelled in Excel, is the following: the amount of virgin feedstock needed for the production of the materials, the reuse and recycling percentages of the materials after use and their recycling efficiency. The functional lifetime of materials and their usage intensity are also integrated in the indicator (fig. 22).
The result of the calculation is a numerical value of the MCI with a number between 0 (linear) and 1 (fully circular). When the MCI-value approaches 0, the building component tends to be linear, meaning most virgin materials that the component consists of, end up as unrecoverable waste in landfill or incineration. When the MCI-value approaches 1, the building component tends to be circular, because the restorative part of the material flow has the upper hand. This means most materials that the building component consists of, come from reused or recycled resources and will be collected for reuse or recycling at their end of life.

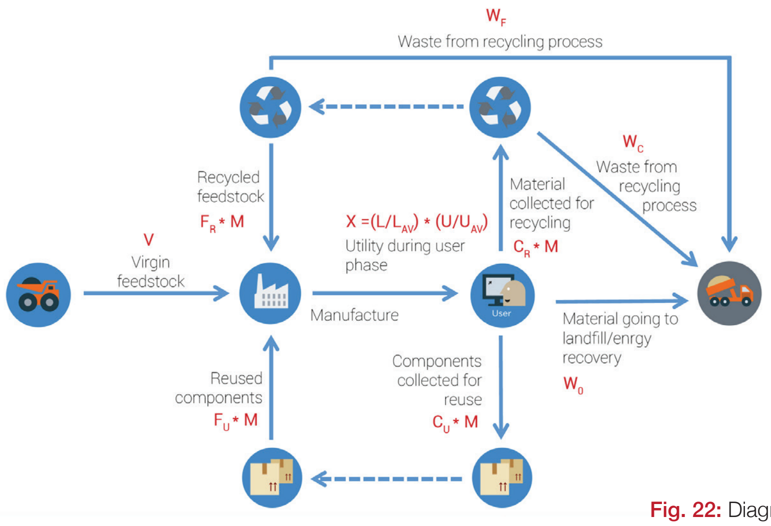


Fig. 22: Diagrammatic representation of the MCI calculation (Leising, 2017)

Important to keep in mind, is that an increased MCI value, calculated with the Indicator, means an improvement of a part of the system, not the whole system. Next to that, material reuse is assumed to have an efficiency of 100% in the calculation, while material recycling is calculated with an efficiency of <100% due to the unavoidable material losses during the recycling process. Next to that, recycled feedstock for the production of new building components doesn't necessarily need to be sourced from the same product cycle, but can also be sourced from another product cycle, retrieved from the open market. During the calculation, actual recycling rates should be used, not the lifetime the product is designed for.

The following pages will describe the exact calculation steps of the MCI Indicator (Ellen MacArthur Foundation & Granta Design, 2015a).

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Calculation

Step 1: Calculate Virgin Feedstock

$$V_{(\chi)} = M_{(\chi)}(1 - F_{R(\chi)} - F_{U(\chi)}) \tag{1.1}$$

Symbol	Definition
$V_{(\chi)}$	Virgin feedstock per subassembly / material
$M_{(\chi)}$	Mass of the product (kg)
$F_{R(\chi)}$	Fraction of mass of a product's feedstock from recycled sources
$F_{U(\chi)}$	Fraction of mass of a product's feedstock from reused sources

$$V = \sum_{(\chi)} V_{(\chi)} \tag{1.2}$$

Symbol	Definition
V	Total amount of virgin feedstock
$V_{(\chi)}$	Virgin feedstock per subassembly / material

Step 2: Calculate Unrecoverable Waste

$$W_{0(\chi)} = M_{(\chi)}(1 - C_{R(\chi)} - C_{U(\chi)}) \tag{2.1}$$

Symbol	Definition
$W_{0(\chi)}$	Mass of unrecoverable waste of a product's subassembly / material that goes into landfill, is used for energy recovery or any other type of process where the materials are no longer recoverable.
$M_{(\chi)}$	Mass of the product's subassembly / material
$C_{R(\chi)}$	Fraction of mass of a product's subassembly / material being collected to go into a recycling process at the end of its use phase
$C_{U(\chi)}$	Fraction of mass of a product's subassembly / material being collected for component reuse

$$W_{C(\chi)} = M_{(\chi)}(1 - E_{C(\chi)})C_{R(\chi)} \tag{2.2}$$

Symbol	Definition
$W_{C(\chi)}$	Mass of unrecoverable waste of a product's subassembly / material generated in the process of recycling parts of a product
$M_{(\chi)}$	Mass of the product's subassembly / material
$E_{C(\chi)}$	Efficiency of the recycling process used for the portion of a product collected for recycling
$C_{R(\chi)}$	Fraction of mass of a product's subassembly / material being collected to go into a recycling process

$$W_{F(\chi)} = M_{(\chi)} \frac{(1 - E_{F(\chi)})F_{R(\chi)}}{E_{F(\chi)}} \quad (2.3)$$

Symbol	Definition
$W_{F(\chi)}$	Mass of unrecoverable waste of a product's subassembly / material generated when producing recycled feedstock for a product
$M_{(\chi)}$	Mass of the product's subassembly / material
$E_{F(\chi)}$	Efficiency of the recycling process of a product's subassembly / material used to produce recycled feedstock for a product
$F_{R(\chi)}$	Fraction of mass of a product's feedstock from recycled sources
$E_{F(\chi)}$	Efficiency of the recycling process used to produce recycled feedstock for a product

$$W = \sum_{(\chi)} (W_{0(\chi)} + \frac{W_{F(\chi)} + W_{C(\chi)}}{2}) \quad (2.4)$$

Symbol	Definition
W	Total mass of unrecoverable waste associated with a product

Step 3: Calculate Linear Flow Index (LFI)

$$LFI = \frac{V + W}{2M + \sum_{(\chi)} \frac{W_{F(\chi)} - W_{C(\chi)}}{2}} \quad (3)$$

Symbol	Definition
LFI	Linear Flow Index
V	Virgin feedstock (*see eq. 1)*
W	Total mass of unrecoverable waste associated with a product (*see eq. 2.4)*
M	Mass of the product
$W_{F(\chi)}$	Mass of unrecoverable waste generated when producing recycling feedstock for a product (*see eq. 2.3)*
$W_{C(\chi)}$	Mass of unrecoverable waste generated in the process of recycling parts of a product (*see eq. 2.2)*

Step 4: Calculate Utility Factor (X)

$$X = (\frac{L}{L_{av}}) \times (\frac{U}{U_{av}}) \quad (4.1)$$

Symbol	Definition
X	Utility Factor
L	Actual average lifetime of a product
L_{av}	Actual average lifetime of an industry-average product of the same type
U	Actual average number of functional units achieved during the use phase of a product
U_{av}	Actual average number of functional units achieved during the use phase of an industry-average product of the same type

$$F_{(\chi)} = \frac{0.9}{X} \quad (4.2)$$

Symbol	Definition
$F_{(\chi)}$	Utility Factor built as a function of the utility x of a product

Step 5: Calculate Material Circularity Indicator (MCI)

$$MCI_P^* = 1 - LFI \times F(\chi) \quad (5)$$

Symbol	Definition
MCI^*_P	Material Circularity Indicator of a product
LFI	Linear Flow Index (*see eq. 3)*
$F_{(\chi)}$	Utility factor built as a function of the utility X of a product (*see eq. 4.2)*

<u>Data source for numerical input</u>

Because the research is focussed on the implementation of the 2nd Skin Façade Refurbishment to post-war residential buildings in the Netherlands, the numerical input for the Material Circularity calculation will be mainly obtained from the Dutch NIBE database Milieuclassificaties Bouwproducten: Gevel en Dak (Haas, 2012). The Dutch Institute of Building Biology and Ecology, NIBE, has been developing environmental classifications of building products since 1992. The institute uses the LCA-method for the environmental classifications of the materials, taking into account all life phases of the materials, from cradle to grave. The data input for the LCA is obtained from the Nationale Milieudatabase, which is a national collection of material data coming from the world's largest transparent life cycle inventory EcoInvent. To be able to make a fair comparison between building products, NIBE takes into account a functional unit with a life cycle of 75 years. The amount of times the building product needs to be replaced during this period, is taken into consideration in its environmental classification. The lifetime of the building product is based on the SBR edition Levensduur voor Bouwproducten (2011).

The numerical values of the NIBE classifications that will be used for this research are:

- the mass of the building product (in kg)
- the lifetime of the building product (in years)
- the end of life scenarios of the building product (in percentages)

When the data of a certain building product couldn't be found in the NIBE database, the data from the website of the material supplier, its umbrella organisation or research institute is used. Since the Utility Factory is created specifically for industrial products, the value for building products is difficult to determine, due to the high amount of building products that are assembled in the building ((Leising, 2017). For this reason, for the calculation of the Utility Factor (X) the estimated lifecycle of the refurbishment, which is 25 years according to the contractor BIK Bouw, is chosen as value for the industry average (Lav), that will be divided by the actual technical lifetime of the building component, as guaranteed by the material supplier (L). This number will then represent the amount of times the building product can be reused when its functional lifetime in the refurbishment has been completed, on the condition that it can be removed undamaged from the existing façade of the refurbished building.

Disassembly Potential

For the circularity assessment of the connections between the building components and materials, the Disassembly Potential, developed by Durmisevic (2010), will be used. The assessment of the Disassembly Potential of the façade system is based on eight performance criteria, visualised in fig. 23.

Criteria 1 and 2 assess the functional decomposition of the system, criteria 3, 4 and 5 assess the technical decomposition of the system, evaluating the hierarchy of components within the configuration, criteria 6, 7 and 8 assess the physical decomposition of the system, looking at the interfaces between the components. The following paragraph gives an explanation of all eight criteria. For each performance criteria, 0 to 10 points can be obtained: 10 points have the best impact on the disassembly potential of the building component, while 0 points have the worst impact. During the circularity assessment of the 2nd Skin Façade Refurbishment system the type of connections (criteria 7) between the materials and the building components will be analysed and graded separately for each building component. The remaining seven criteria will be analysed for the complete façade, following the point system developed by Durmisevic (2010).

1. Functional decomposition

When designing a building for disassembly, important to look at is the functional decomposition of the structure; whether two or more functions are integrated into one building component or whether functions are separated in different components. Independence in the structure can be created with functional separation. First of all, the building should be divided into parts with different functions, performances and life cycles. Four main functions of a building can be identified: supporting, enclosing, servicing and partitioning. These can be subdivided again into the subsystems: foundation, floor, frame, façade, roof etc. Each system behaves differently and causes different effects. What needs to be prevented, is the integration of too many different functions into one system, which may cause components to freeze (Durmisevic, 2010).

When looking at the façade of the building, multiple functions are gathered in one. The main function of the façade is forming the barrier between the indoor and outdoor space. Next to that the façade accommodates insulation and finishing, carries vertical and horizontal loads, and provides daylight. The façade used to be designed as a heavy, static structure. Nowadays, façades develop into more dynamic structures, enabling activities that change frequently.

Four levels of functional incorporation can be defined:

1. Total integration of functions in one component
2. Planned interpenetration of functions in one component
3. Unplanned interpenetration of functions in one component, through for example a free void
4. Total separation of functions in independent components

Instead of integrating all façade functions into one structure, each function should be given an independent component. As a result, change of one function doesn't have any effect on the integrity of the other functions. Another option could be to integrate the functions with similar life cycles into one component.

2. Systematisation

Clustering of building parts into subsystems, according to their life cycle performance, is advantageous in terms of Design for Disassembly, because it prevents too many sequences during (dis)assembly on-site. When the (dis)-assembly process is too time-consuming and extensive, the owner or builder could tend to prefer demolition. Subassemblies are clusters or modules of parts that act as independent building components during (dis)assembly. The more building parts are integrated in one component, that is prefabricated in the factory, the fewer connections need to be made on-site. Two-stage assembly, in which low-level subassemblies are assembled in the factory and only high-level subassemblies on the building site, speeds up the assembly process on-site and increases the efficiency.

Clustering can take place on multiple levels:

1. Clustering on the system levels
2. Clustering on the component levels
3. Clustering on the system, component, element and material levels
4. No clustering.

For example, when a façade system is composed of individual components, that each consist of elements with the same function, the façade becomes easily modifiable. The technical life cycle of the materials determines the sequential order within the component; there should be a separation between fast cycling and slow cycling elements. A prerequisite is that sub-assemblies have dry connections, that allow materials to be separated in the factory. However, prefabricated façade modules, in which all sub-functions are integrated into one composite component (no clustering, integration of all material levels), aren't flexible at all. At the end of life, the façade can only be demolished and all valuable material is lost.

FD Functional Decomposition

Functional dependence

Total separation of functions	++	10
Planned interpenetration of functions	+	8
Unplanned interpenetration of functions	-	2
Total integration of functions	--	1

SY Systematisation

Type of clustering

Clustering on component levels	+++	10
Clustering on element levels	++	6
Clustering on material/element/component	+	4
Clustering on material level	--	1

RP Relational Patterns

Position of relations in relational diagram

Vertical	++	10
Horizontal in lower zone	+	6
Horizontal between upper and lower zone	-	4
Horizontal in upper zone	--	1

BE Base Element

Base Element specification

BE: intermediary between systems/components	++	10
BEt: on two levels	+	6
BE: with two functions	-	4
No Base Element	--	1

GE Geometry

Geometry of products edge

Open - linear	+++	10
Symmetric overlapping	++	8
Overlapping on one side	+	7
Unsymmetric overlapping	-	4
Closed - integral on one side	--	2
Closed - integral on two sides	---	1

Standardisation of products edge

Pre-made geometry	+
Half standardised geometry	
Geometry made on the construction site	-

AS Assembly Sequences

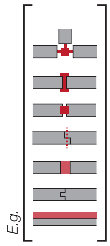
Assembly direction based on assembly type

Parallel – open assembly	+	10
Stuck assembly	+/-	6
Sequential, seq. base element	-	1

TC Connections

Type of connections

Indirect with additional fixing device	+++	10
Indirect via independent third component	++	8
Indirect via dependent third component	+	6
Direct with additional fixing devices	+/-	5
Indirect with third chemical material	-	4
Direct between two pre-made components	--	2
Direct chemical connection	---	1



LC Life Cycle

Life Cycle coordination

Functional life cycle coordination	+	10
Technical life cycle coordination		
Life cycle of components in relation to size	-	1

Fig. 23: Assessment criteria Disassembly Potential, derived from Durmisevic (2010) (source: own image)

3. Relational patterns

The number and type of relations between building elements directly relate to the disassembly potential of the building structure. Two types of relations can be identified: horizontal and vertical relations. Horizontal relations make connections between different functional groups. Vertical relations make connections within one functional group. Different functional groups should not be related directly, because it makes the different groups dependent on each other, complicating modification of only one functional group.
When the relational pattern of the building system is vertically oriented, the system is dynamic. Horizontally-oriented relational patterns lead to static systems, because relations between different functional groups within the building system makes the groups dependent on each other. When the horizontal relations are located in the upper part of the relational pattern diagram, thus at the core of the system, the level of dynamics of the system will decrease significantly. One rule that needs to be taken account when designing a dynamic system, is that the sub-systems can only have relations with the load-bearing system of the structure, so that they can easily be replaced. The horizontal relations that are allowed in a dynamic system, are the relations between the base elements of different sub-assemblies.

4. Base element specification

The base element is a third independent part that integrates all surrounding elements of the cluster. The base element connects elements within independent assemblies and/or performs as an intermediary with other clusters. Next to that, the base element can take over the load bearing function of the component, this way creating independency within the structure. Important to keep in mind is that the base element should be made of a material with a long life cycle, that lasts longer than the connected elements.

5. Geometry

The geometry of the edges of the product plays an important role in the disassembly potential of connections. The products edges can vary between open geometry, that allows disassembly in all directions, which is most favourable for disassembly, to interpenetrating geometry, that only allows disassembly in one direction and is thus less favourable. The worst situation is when the connected elements need to be demolished to make disassembly possible.

6. Assembly sequence

To prevent demolition of the building and decrease the amount of waste generation on the building site, the assembly and disassembly sequence should be simple and efficient. The assembly sequence determines the number of dependencies between building elements. A parallel assembly sequence links less building elements together, and thus leads to an increase in speed of the (dis)assembly process. A sequential assembly sequence links more building elements together, resulting in a decrease in (dis)assembly speed and creating difficulties for substitution of elements.

7. Connections

The type of connections is the most important aspect regarding Design for Disassembly, because the connection determines the degree of freedom of components. When the connections allow disassembly, each building component becomes replaceable and each material becomes recyclable. The connections make decomposition, re-composition, incorporation or plugging-in of elements either possible or impossible. The disassembly potential of a connection depends on the number of components that need to be connected, the type of material used to make the connection and the shape of the component’s edges.

A distinction can be made between three connection types: direct (integral), indirect (accessory) and filled. Integral connections don’t consist of an additional connection piece, but let the geometry of the components make the connection. These can be divided in overlapping connections, which are often used for vertical external façade components, and interlocking connections, that are connected internal through the geometry of the components’ edges and only allow sequential assembly. Accessory connections need one or more additional pieces to make the connection. These additional pieces can be placed internal, which means inserted into the geometry of the components, or external with applied cover strips and/or frame. The accessory connections are more favourable for disassembly, because additional pieces make dismantling of elements easier. The filled connection type is made on site with chemical material, which makes disassembly impossible. Welding and concrete filling fall under this category, and thus needs to be prevented at all times when designing for disassembly.

These two main criteria for connections are important to remember:

- Elements need to be kept separated.
- Dry-jointing techniques need to be used, instead of chemical connection techniques.

8. Life Cycle Coordination

The functional life cycle of buildings ranges from 5-75 years. Also the materials that the building components consist of, have varying life cycles. In the current building industry, these material life cycles aren't often taken into consideration, resulting in assembly sequences in which materials with short life cycles are placed first. However, materials with short life cycles must be replaced quite regularly, so in this case all other elements of the structure need to be disassembled first before being able to replace them. It would be much more efficient to assemble the materials with the longest life cycle first and the materials with the shortest life cycle last. Materials with short life cycles, that need to be replaced soon, have to be disassembled first, and materials with long life cycles, that don't need regularly replacement, should be disassembled last. A distinction should be made between the functional and technical life cycle: materials have to be replaced when the material doesn't meet its functional requirements anymore or when the material is simply worn out. The life cycle of the materials also depends on the size of the components. Small components are preferably made of materials with short life cycles, because they can easily be replaced. On the other hand, big components shouldn't be made of materials with long life cycles, because in general replacement of big components in the structure is more complicated.

Conclusion

This chapter discussed several circularity assessment methods, that measure one or more of the following key requirements of the Circular Economy in the built environment:

1. Measure the reduction of input and use of natural resources
2. Measure the reduction of emissions levels
3. Measure the reduction of valuable material losses
4. Measure the increase in share of renewable and recyclable resources
5. Measure the increase in value durability of products

Thus far there doesn't yet exist a finalised circularity assessment method. Two examples of sustainability labels, that have made a start assessing the level of circularity of buildings, have been analysed: the software tool GPR Gebouw and the Roadmap Circular Land Allocation of the municipality of Amsterdam. Interesting to see, is that the circularity assessment criteria of the two examples fit in the two categories, described in chapter 3: materials and connections. GPR Gebouw makes use of a point system to grade the level of circularity of the buildings. On the other hand, the Roadmap Circular Land Allocation makes use of percentages of the total mass to grade the level of circularity of the materials, and a point system to grade the level of circularity of the connectioins.

Based on the comparison results, two assessment methods are chosen to assess the level of circularity of the 2nd Skin Façade Refurbishment system. The Material Circularity Indicator will be used to assess the materials each separate building component consist of, while complementary the Disassembly Potential will be used to assess the connections between the materials and separate building components within the façade system.

The Material Circularity Indicator is based on the calculation of the virgin feedstock, mass of unrecoverable waste and lifetime of the material. The result of the calculation is a numerical value between 0 and 1. When the building component obtains a score close to 0, the building product tends to be linear. When the MCI-value approaches 1, the building component tends to be circular.
The Disassembly Potential is based on eight performance criteria, measuring the functional, technical and physical decomposition of the building component with a point score system. Obtaining 10 points for each category has the best impact on the disassembly potential of the building component, while obtaining 0 points has the worst impact. The type of connection between the materials each facade component consists of, will be analysed separately.

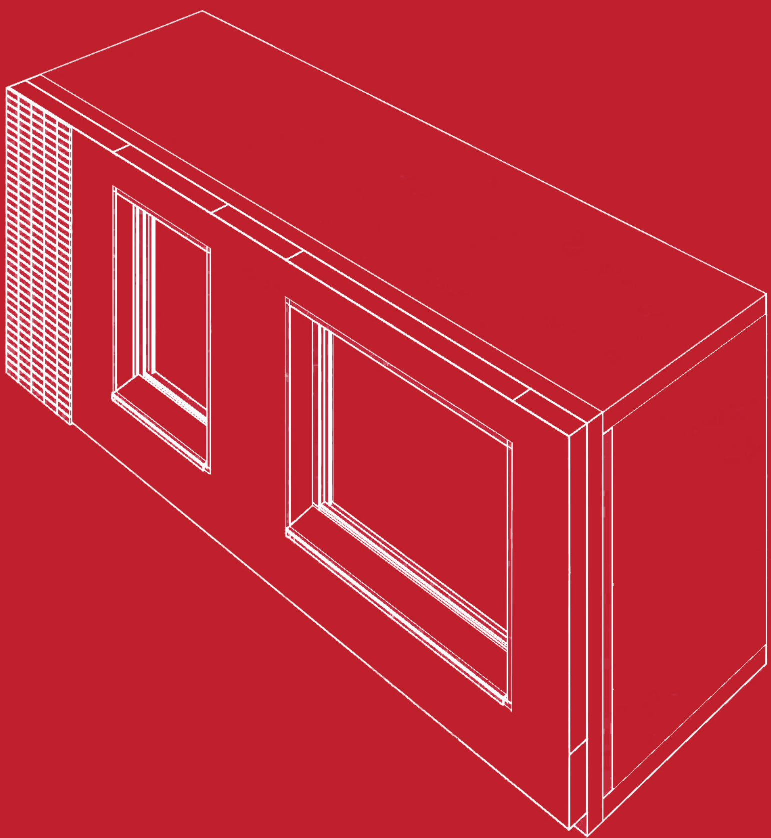
In the next chapter the circularity assessment of the 2nd Skin Façade Refurbishment system will be conducted. First each component the 2nd Skin Façade Refurbishment system, consists of, will be analysed separately in terms of materials with the Material Circularity Indicator and in terms of connections with the Disassembly Potential. Thereafter, the complete façade system will be analysed with a combination of the Material Circularity Indicator and the Disassembly Potential.

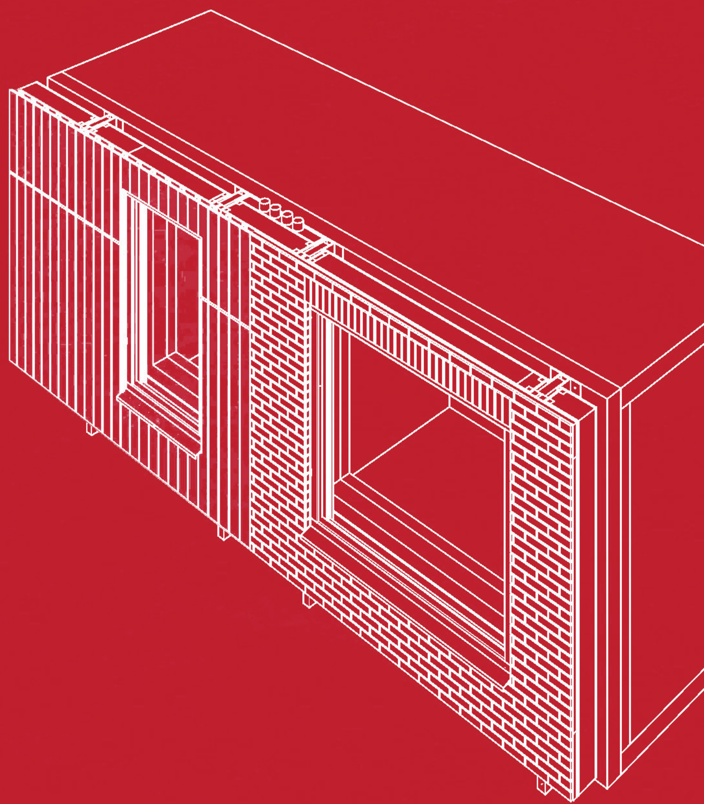
05

CIRCULARITY ASSESSMENT OF 2ND SKIN REFURBISHMENT

In this chapter, the level of circularity of the 2nd Skin Façade Refurbishment system will be assessed. Two variants of the 2nd Skin Façade Refurbishment system will be analysed in terms of materials and connections: the Prefabricated variant and the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system. The Material Circularity Indicator of the Ellen MacArthur Foundation and Granta Design (2015) is used for the material assessment. The Disassembly Potential, developed by Elma Durmisevic (2010), is used for the assessment of the connections.

At the end of the chapter the two variants will be compared in terms of circularity. Based on the comparison, the changes that need to be made to improve the level of circularity of the two variants





Framework

The circularity assessment will be conducted to evaluate the 2nd Skin Façade Refurbishment system. The 2nd Skin Façade Refurbishment system, developed by Thaleia Konstantinou, Tillmann Klein et al. (2017), is a refurbishment strategy for the façades of post-war residential apartment buildings with energy label D or lower, with the aim to decrease their operational energy towards zero by wrapping the building in a second layer of insulation. The principle of the system is based on the Trias Energetica: prevent the use of energy (1), use sustainable energy sources as much as possible (2), and, if necessary, use fossil energy sources as efficient as possible and compensate with 100% renewable energy (3) (Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017).

These objectives have led to the following solutions:

1. Increase the thermal resistance and airtightness of the existing façade of the building, by replacing the existing windows and adding insulation layers on top of the closed parts of the façade and roof of the building (walls Rc = 6,5 m^2K/W; windows Rc = 1,135 m^2K/W; window frames Rc = 0,8 m^2K/W; ground floor Rc = 3,5 m^2K/W and roof Rc = 4,5 m^2K/W).
2. Reduce the energy demand for heating while providing adequate indoor air quality by installing a central ventilation system with heat recovery in the building.
3. Generate renewable energy by installing photovoltaic (PV) panels on the roof.

Another objective for the development of the 2nd Skin Facade Refurbishment system was to minimize disturbance of the occupants of the buildings by preventing relocation and decreasing the construction time during the refurbishment process. This is needed to lower the costs of the process and gain user acceptance of occupants and owners. At least 70% of the tenants need to have agreed to the change, before the refurbishment of the buildings is allowed to proceed.

Two variants of the 2nd Skin Façade Refurbishment system can be distinguished:

- The Prefabricated variant of the 2nd Skin Façade Refurbishment system consists of prefabricated façade modules that are connected to the existing façade through a substructure. This variant has been tested in a mock-up, executed by façade contractor Rollecate (Guerra-Santin, Silvester, & Konstantinou, 2015). This variant will be described and assessed in paragraph 5.1.
- The Exterior Insulation variant consists of an exterior insulation system that is directly glued to the façade of the residential building (Azcarate-Aguerre, et al., 2017). This variant is now being applied to the case study building in Vlaardingen, executed by the contractor BIK Bouw. The Exterior Insulation variant will be described and assessed in paragraph 5.2.

The leading research questions for the circularity assessment of the two variants is:

To what extent is the Prefabricated variant of the 2ndSkin Façade Refurbishment system "circular"?
To what extent is the Exterior Insulation variant of the 2ndSkin Façade Refurbishment system "circular"?

In order to answer the research questions the two variants will be analysed, following two steps:

1. Each individual component that the façade system consists of, will be analysed separately:
    a. The Material Circularity Indicator (fig. 22) will be used to assess the level of circularity of the materials each individual component consists of, based on the material feedstock, end of life scenarios and lifetime of the component. The data is obtained from the Dutch database NIBE Milieuclassificaties Bouwproducten. The result will be a numerical value for the Linear Flow Index, ranging from 0 (circular) to 1 (linear), the Utility Factor, ranging from <1 (when the component needs to be replaced during the functional life time of the 2nd Skin Facade Refurbishment system) and >1 (when the lifetime exceeds its functional lifetime), and the Material Circularity Indicator, ranging from 0 (linear) to 1 (circular). For the calculation of the Utility Factor a functional life time of 25 years is used, because this is the estimated lifetime of the complete 2nd Skin Facade Refurbishment system, taken into account by BIK Bouw.
    b. The Disassembly Potential will be used to assess the level of circularity of the type of connections between the materials within each component, looking at the demountability of the interfaces. The result will be an indication of the effect of the connection on the disassembly process, with --- indicating the worst and +++ the best effect (fig. 20).

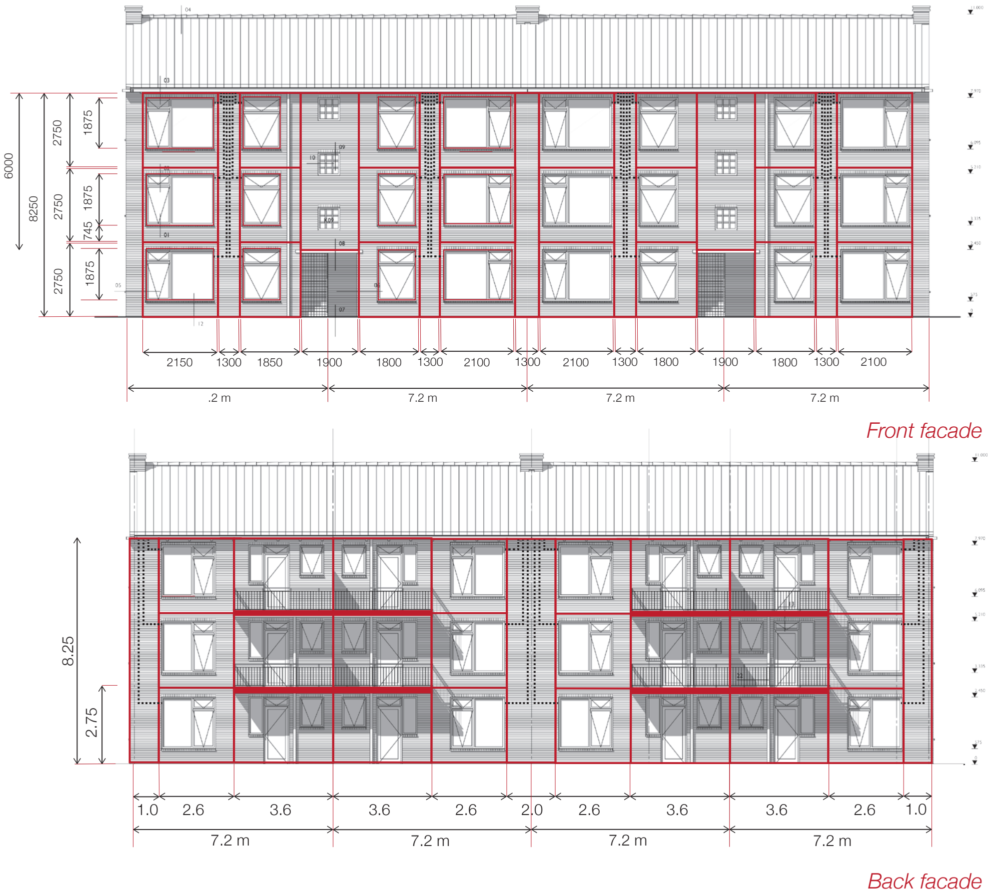


Fig. 24a Case study building, with applied modules of the Prefabricated variant of the 2nd Skin Facade (source: own image)

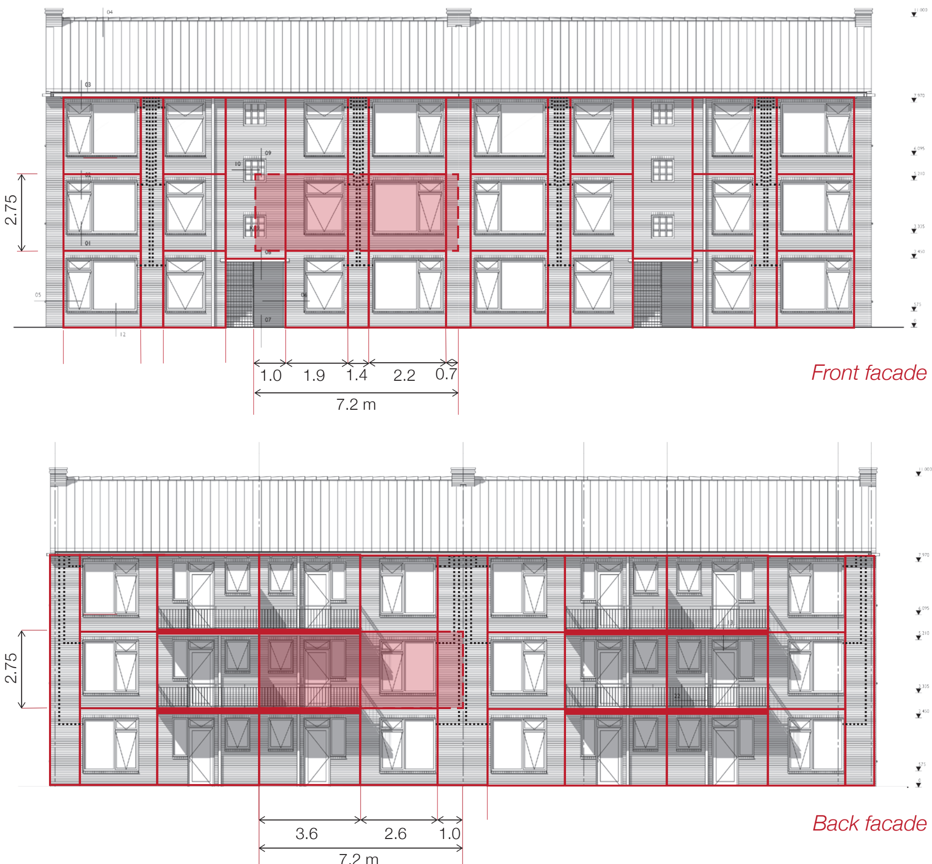


Fig. 24b: Indication of the functional unit for the circularity assessment (source: own image)

2. The complete façade system will be assessed in terms of Disassembly Potential:
   a. The eight performance criteria of the Disassembly Potential assessment will be evaluated for the complete façade system, looking at the functional decomposition, the systematisation, the relational patterns, the base element specification, the geometry, the assembly sequence, the type of connections and the life cycle coordination. These criteria will be assessed with the use of a function structure, connection analysis and relational diagram.

In paragraph 5.3 the results of the circularity assessment of the two variants of the 2nd Skin Façade Refurbishment system, the Prefabricated variant and the Exterior Insulation variant, will be compared, looking at the assessment results of the Material Circularity Indicator and the Disassembly Potential.
Based on the comparison, the changes that need to be made to improve the level of circularity of the two variants of the 2nd Skin Façade Refurbishment system, will be determined. Subsequently a Circularity Roadmap will be developed, that will help the architect and contractor with decision-making during the refurbishment process.

Case Study building
The research focusses on multi-residential buildings in the Netherlands, built after the war (1945-1975), because in general these buildings are in high need of refurbishment. Multi-family housing is a common Dutch typology that accounts for more than 20% of the Dutch housing stock (Bragança, Wetzel, Buhagiar, & Verhoef, 2007). For the circularity assessment of two refurbishment systems, the Prefabricated variant and the Exterior Insulation variant, a case study building is chosen that is planned to be refurbished with the Exterior Insulation variant. The choice of the case study building is determined by the 2nd Skin Façade project (Klein & Konstantinou, 2017), that this research will elaborate on.

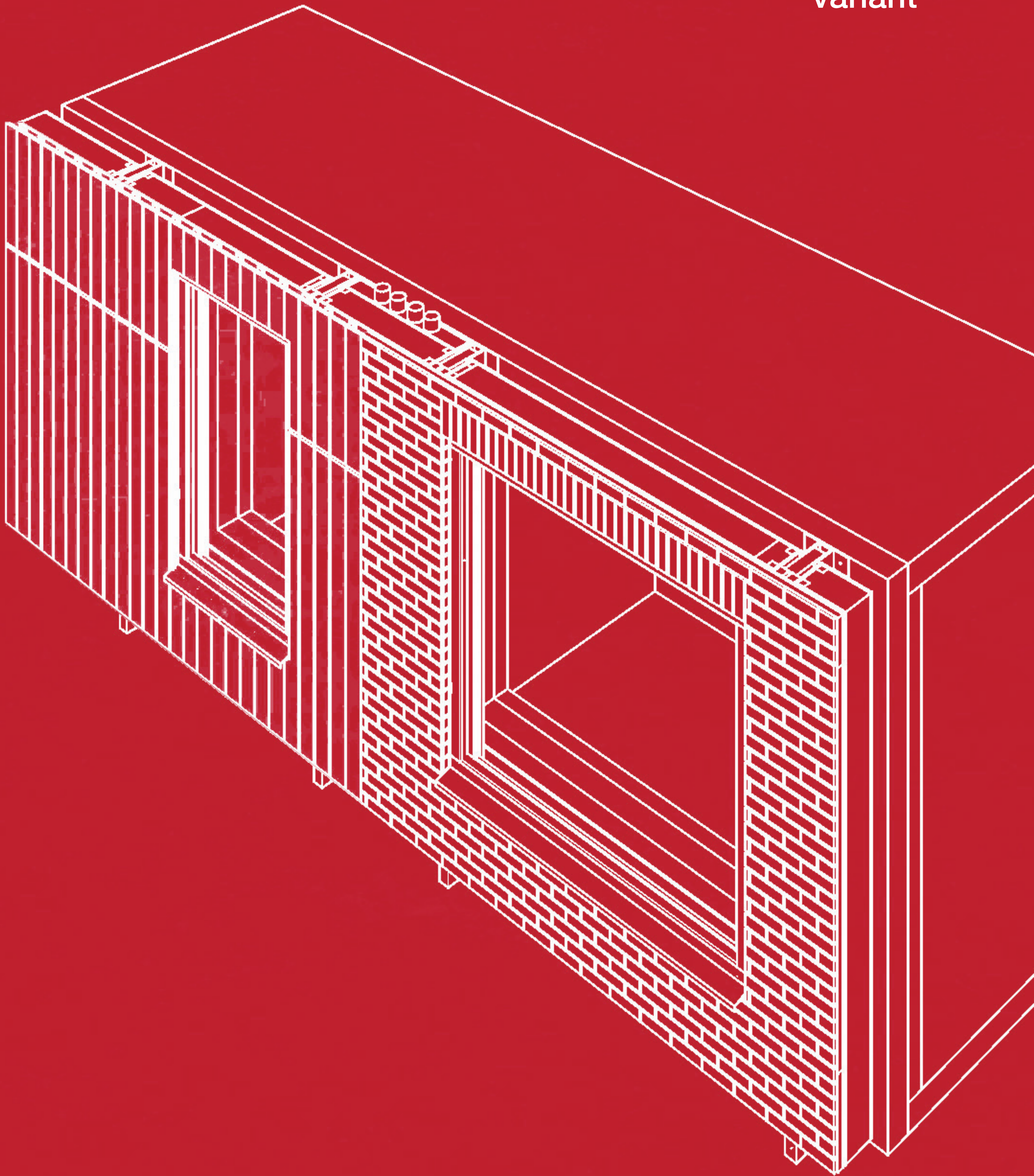
The case study building is a three-storey tenement house in Vlaardingen at the Soendalaan, built in 1952. The typology is a multi-family house, containing four housing units per floor. thus 12 housing units in total. The length of the building is 28,8m, the width is 9,0 m and the height is 11,0 m. The building has a gable roof (fig. 25). Each housing unit consists of one hallway of 5,1 m^2, one kitchen of 5,1 m^2, one living room of 17,2 m^2, one bathroom of 3,5 m^2 and two bedrooms of resp. 7,2 m^2 and 12,2 m^2. On the back façade, each dwelling contains a balcony next to the kitchen. The two entrances at the street give access to the common staircase, from which all dwellings are accessible.
The building envelope is insulated, consists of an exterior wall of brickwork with a cavity and an interior wall of concrete with plaster finishing. The window frames are made of wood (KAW Architecten, 2017). One representative dwelling, situated in the middle of the building, is chosen as functional unit, where the two refurbishment systems will be applied to. The façade fragment has a length of 7,2 m and a height of 2,75 m. The façade fragment contains one window of 2,5 m by 1,9 m, one window of 1,4m by 1,9m and one small window cut in two. The last window will be neglected during the analysis (fig. 24b).

The building is owned by the housing corporation WaterWeg Wonen. WaterWeg Wonen has a portfolio of around 11000 tenement houses in Vlaardingen. Most of the dwellings are intended for people with low incomes. The planned traditional refurbishment will be managed by the contractor BIK Bouw; a firm that focusses on sustainable solutions for new buildings, refurbishment and maintenance of existing buildings. Other stakeholders involved in the project are the research institution of the TU Delft, the material supplier Sto Isoned (brick strips), Itho Daalderop (climate services) and Kingspan (insulation) (WaterWeg Wonen, 2017).

Fig. 25: Photos of the case study building Soendalaan, Vlaardingen (KAW Architecten, 2017)

5.1

Prefabricated variant



Description

The Prefabricated variant of the 2nd Skin Façade Refurbishment system is a self supporting system, independent from the underlying structure of the existing building. The system consists of prefabricated floor-height elements in which new windows and building systems for heating, ventilation and energy generation are integrated. These façade elements need to be attached to the existing facade of the building through a substructure of wooden posts. This makes the building systems easily accessible from the outside of the building, facilitating easy maintenance of the facade. It also provides the opportunity to replace the building services with better alternatives during the use of the building (Guerra-Santin, Silvester, & Konstantinou, 2015). The ventilation pipes are embedded in insulation board, attached to the opaque façade elements of the 2nd Skin Facade (Klein & Konstantinou, 2015): the inlet of fresh air is led through the façade, the outlet through the existing ventilation shafts of the building (Klein & Konstantinou, 2017). The photovoltaic panels and heat recovery installations for ventilation are placed on the roof.

The flexibility of the 2nd Skin Façade Refurbishment system increases the time-span of the initial investment, resulting in lower rent or living costs of the occupants of the building. Next to that, customisation of the façade refurbishment system for different types of buildings in different climate zones is possible (Guerra-Santin, Silvester, & Konstantinou, 2015).

Assembly sequence

<u>Step 1:</u> Installation of the substructure of the 2nd Skin Facade, by attaching vertical wooden posts to the existing façade of the building, using steel U-profiles and bolts.

<u>Step 2:</u> Placement of the central opaque prefabricated façade elements with integrated ventilation pipes, using timber sticks to bolt onto the wooden substructure.

<u>Step 3:</u> Placement of the left and right transparent prefabricated façade modules with integrated windows and shading devices, using timber sticks to bolt onto the wooden substructure.

<u>Step 4:</u> Installation of the internal lining of the windows and placement of airtight sealing between the prefabricated façade modules.

<u>Step 5:</u> Finishing with the façade cladding, that can be of various materials, such as bamboo, aluminium sheets or brickwork. Some cladding materials can be attached in the factory, others can be applied only on the building site.

<u>Step 6:</u> Placement of an extra insulation layer on the roof.

<u>Step 7:</u> Finishing with roof cladding material.

<u>Step 8:</u> Installation of the photovoltaic panels on the roof, to be able to reach the zero energy targets.

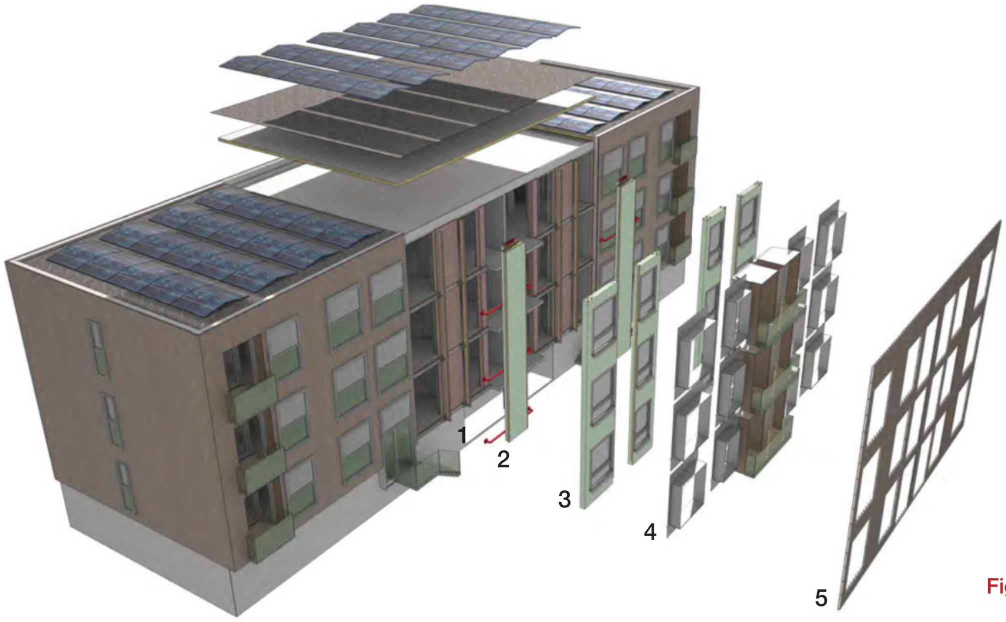


Fig. 26: Exploded view Prefabricated variant of the 2nd Skin Facade (Klein & Konstantinou, 2015)

Option 1: Brick cladding

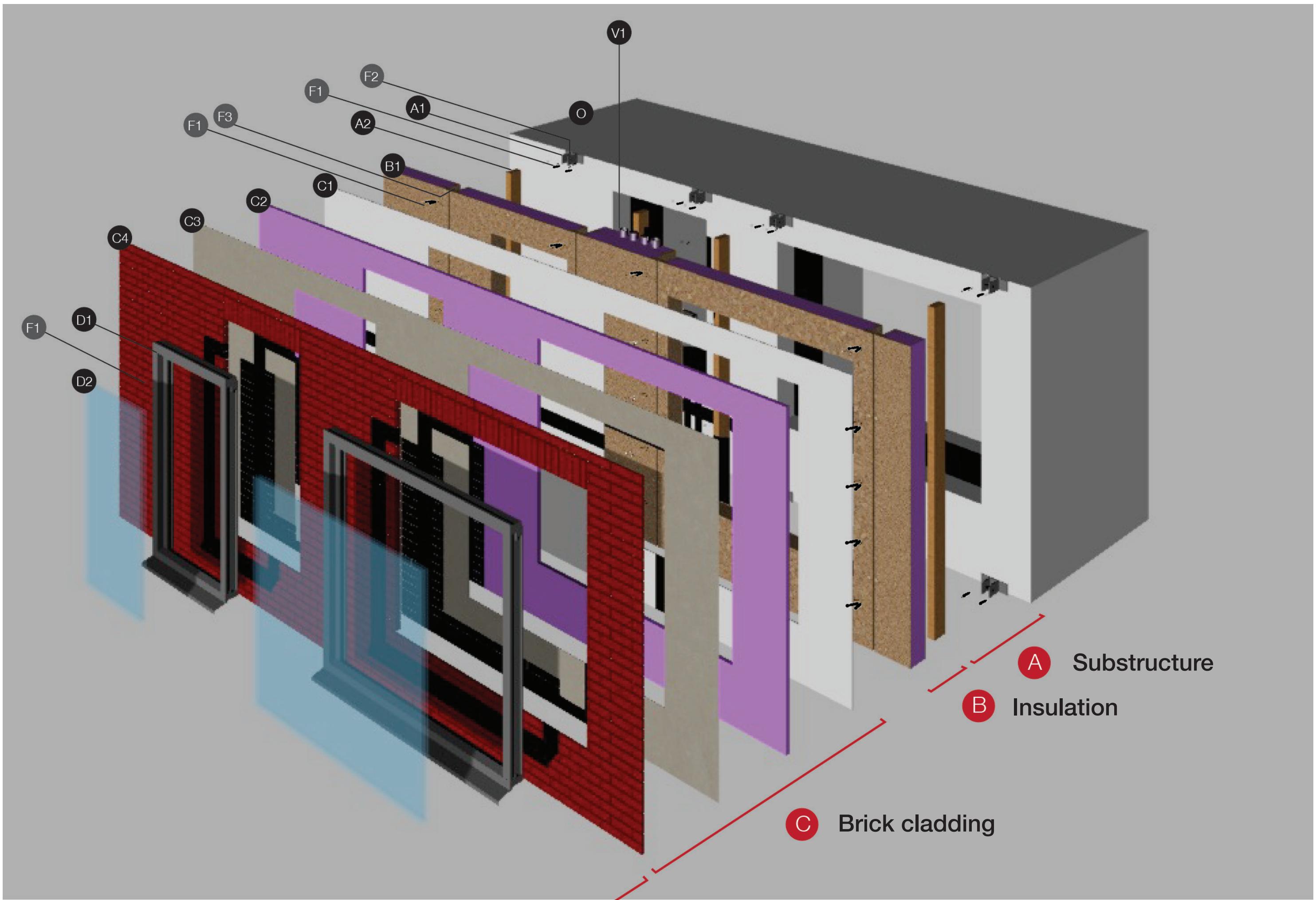


Fig. 27: Exploded view functional unit Prefabricated variant, Option 1 (source: own image)

<u>Components:</u>

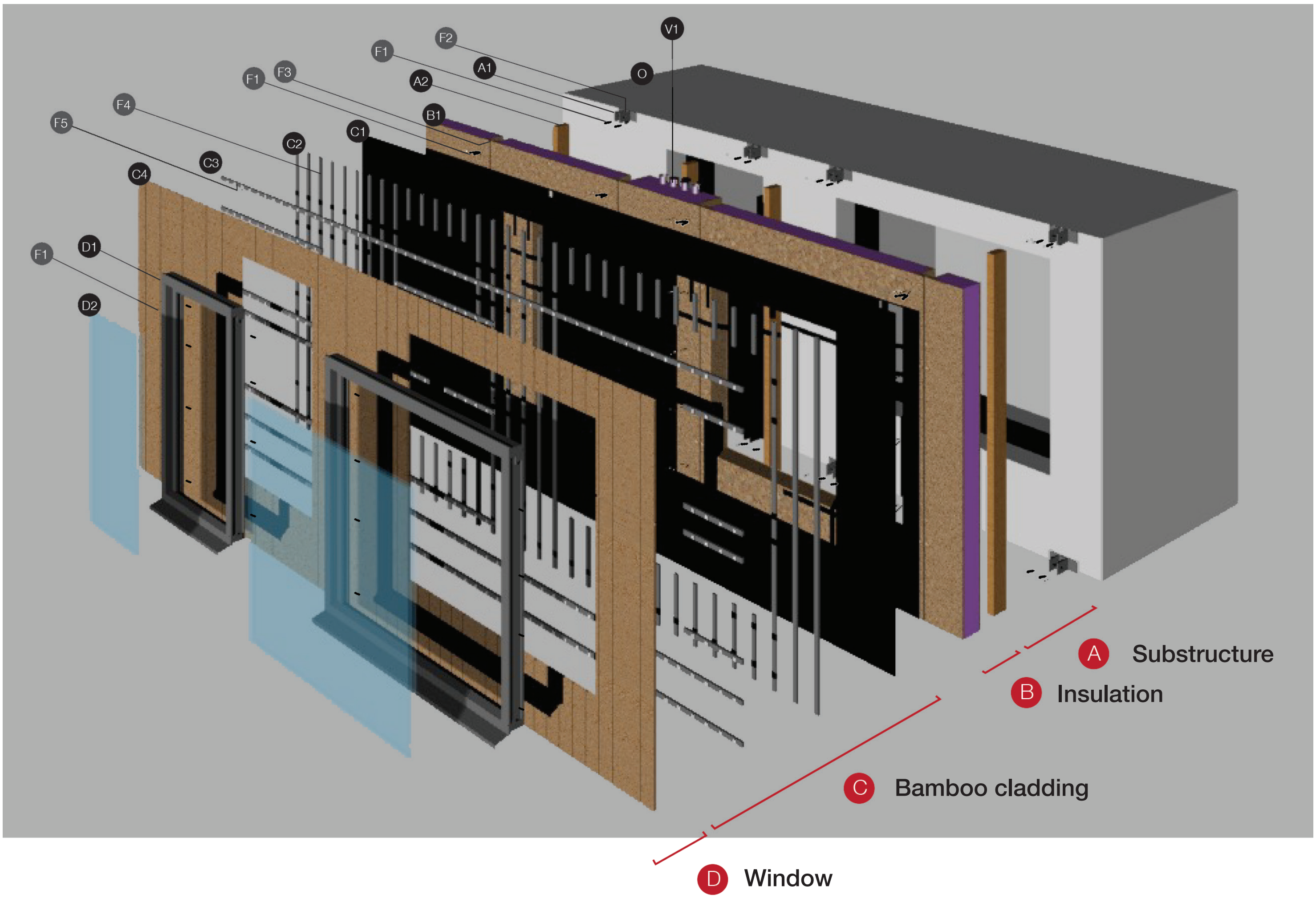
O	Existing facade
A1	U-profiled anchor
A2	Vertical post
B1	Structural Insulated Panel (SIP)
C1	Adhesive
C2	Insulation
C3	Fibre cement
C4	Brick strips
D1	Window frame
D2	Triple glazing
V1	Ventilation duct

<u>Fixing devices:</u>

F1	Screw
F2	Bolt
F3	Sealant

For this research two cladding options for the Prefabricated variant of the 2nd Skin Façade will be taken into account: one option with brick strips cladding and the second option with bamboo cladding. When looking at the exploded view of the two options of the 2nd Skin Façade (fig. 27 and 28), the system can be subdivided into four seperate components: the substructure (A), the insulation layer (B), the cladding (C) and the windows (D). For the circularity assessment of the 2nd Skin Façade, each individual component will be analysed in terms of materials, using the Material Circularity Indicator, and connections, following the analysis of the Disassembly Potential. The circularity assessment of the complete system will be based on these assessment results.

Option 2: Bamboo cladding



<u>Components:</u>

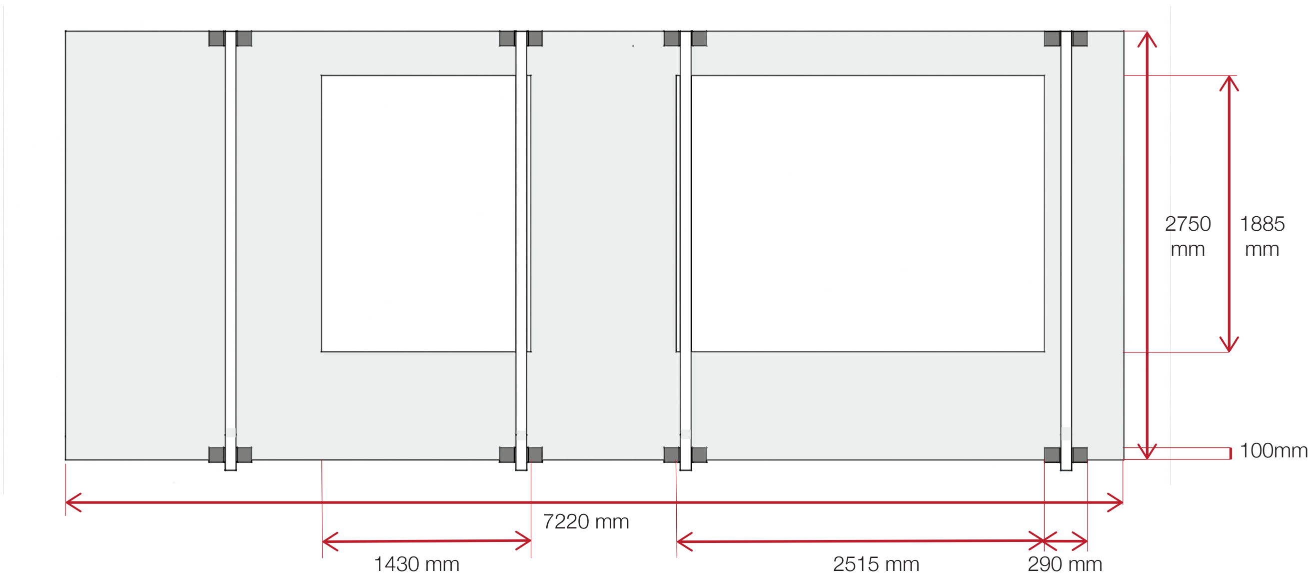
O	Existing facade
A1	U-profiled anchor
A2	Vertical post
B1	Structural Insulated Panel (SIP)
C1	Water tight, damp open foil
C2	Vertical studs
C3	Profile
C4	Bamboo slats
D1	Window frame
D2	Triple glazing
V1	Ventilation duct

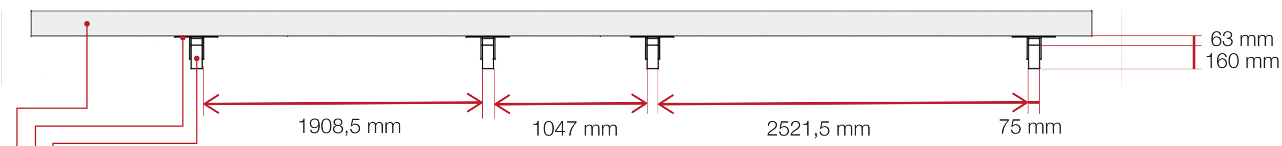
Fig. 28: Exploded view functional unit Prefabricated variant, Option 2; (source: own image)

<u>Fixing devices:</u>

F1	Screw
F2	Bolt
F3	Sealant
F4	Nail
F5	Clip

Substructure

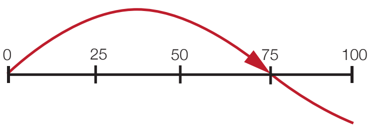




Life cycle (yrs)

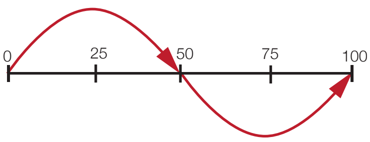
End of life scenarios

A2
Pinewood posts
75 x 160 mm



0% | 5% | 10% | 85%

A1
Stainless-steel
U-profile



12% | 87% | 1% | 0%

O
Existing facade

Fig. 29: Photos Mock-Up; connection method substructure (Konstantinou, n.d.)

The substructure of the Prefabricated variant consists of vertical timber studs, attached to the existing façade of the residential building with stainless-steel U-profiles. The vertical studs have a width of 75 mm, a length of 2750 mm and a thickness of 160 mm. The studs are made of treated pinewood with an increased durability. The sticks are covered by the SIP-panels, protected against the weather and not exposed to moisture. In the Nationale Milieudatabase pinewood ribs are analysed in a roof element for refurbishment, which is comparable to the function and location of the pinewood studs in the Prefabricated variant of the 2nd Skin Façade system. In this case the pinewood studs have a lifespan of 75 years, a recycling rate of 5%, 85% incineration and 10% landfill (Stichting Bouwkwaliteit, 2017). The pinewood needs to be replaced earlier when the material is damaged by insects and fungi, depending on the moisture content of the wood. The lifetime can be extended by applying a layer of paint on the wood. However, depending on the type, the painting can have a negative effect on the recycling possibilities at the end of life. A more sustainable method of curing the wood is thermal modification, then the wood maintains fully recyclable (Geldermans, 2009).

On average a stainless-steel profile is made for 60% of recycled material and the recycling efficiency of stainless steel is 100% (Bureau of International Recycling, n.d.). According to research of Bouwen Met Staal, steel that is used for light applications, such as window frames and profiles, has a recycling rate of 87% and a reuse rate of 12% (Bouwen met Staal, 2013). A lifespan directive of at least 50 years is taken into account for stainless steel, applied in the dry side of the construction behind the waterproof and damp tight layer. The main problem of stainless steel in terms of corrosion is pitting (Kettlitz, 2011).

Material Circularity Indicator (MCI)

Results:

LFI = 0,66

X = 3,0

MCI = 0,80

Calculation:

Step 1: Calculation of the mass of the component

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
Pinewood	0,132	460	60,720
Stainless steel	0,005	7880	41,922

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
Pinewood	Biological	0	0	60,720
Stainless steel	Technical	59%	0	17,188

Step 3: Calculation of unrecoverable waste of the materials

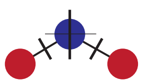
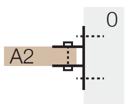
Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
Pinewood	5% (efficiency 100%)	0%	57,684
Stainless steel	87% (efficiency 100%)	0%	0,419

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

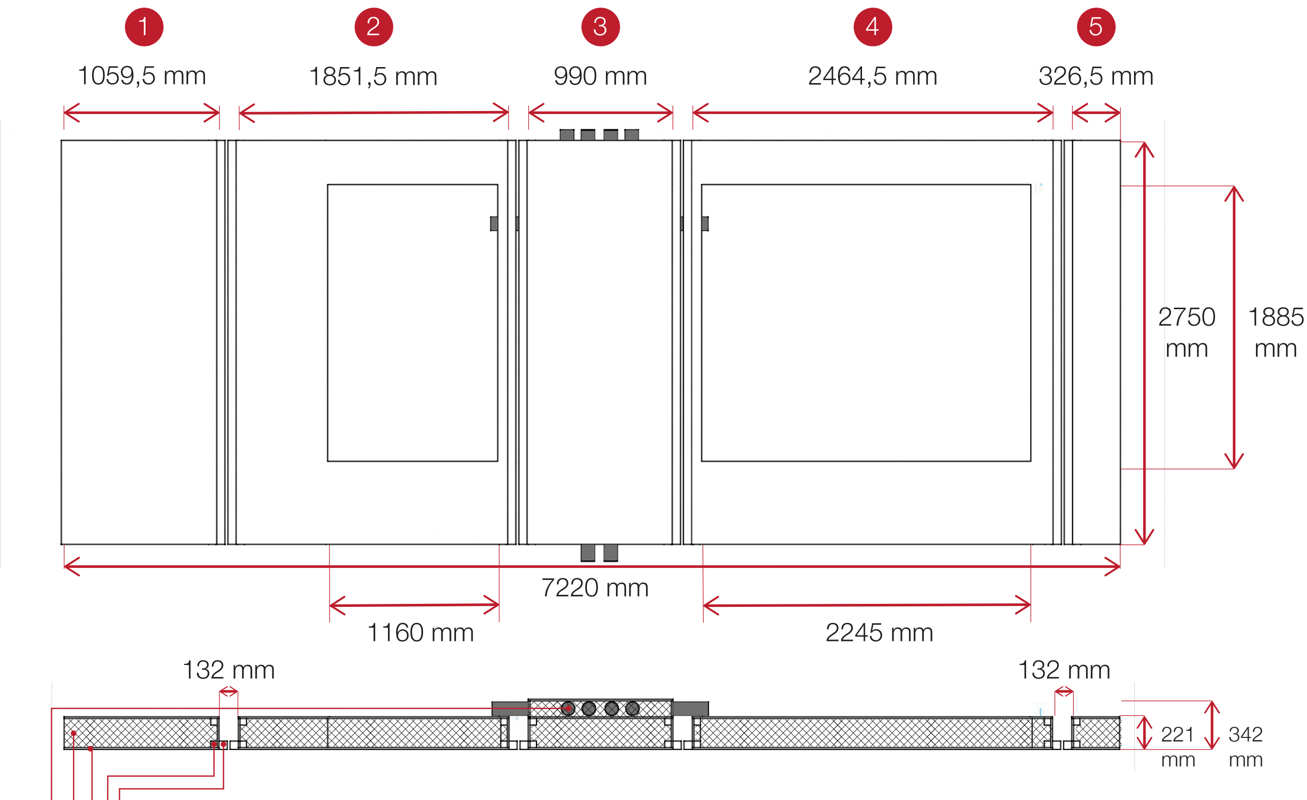
Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Substructure	0,66	3,0	0,80

Disassembly Potential (DP)

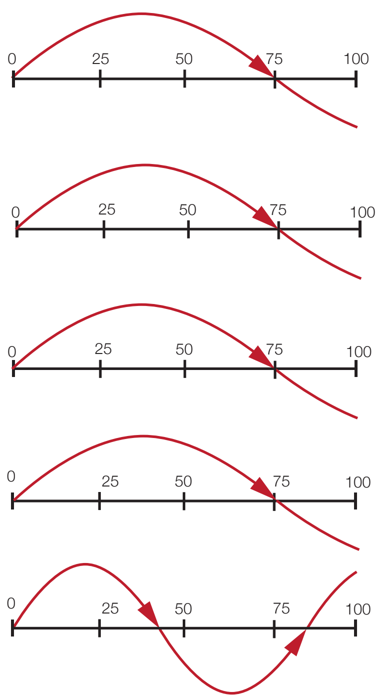
Connection analysis:

CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
0 - A2 (A1 = third component)			1. Indirect 2. Additional fixing device	1. Screwed 2. Bolted	+++

Structural Insulated Panels (SIP)



Life cycle (yrs)



End of life scenarios

B4 Pinewood sticks 56 x 56 mm	0%	5%	10%	85%
B3 Pinewood stiffeners 44 x 44 mm	0%	5%	10%	85%
B2 Chipboard P5 12mm	0%	10%	5%	85%
B1 EPS insulation 197 mm	0%	5%	5%	90%
V1 PVC pipes Ø 90 mm	0%	90%	0%	10%

The main components of the 2nd Skin Façade system are the left, right and central Structural Insulated Panels (SIP), produced by Kingspan. These panels consist of a core of 197 mm EPS Platinum insulation, surrounded by layers of chipboard, type P5, with a thickness of 12 mm. Inside the SIP panel 4 integrated pinewood sticks ensure the stiffness of the panel. The bonding between the materials is made with adhesives over the complete surface area. Two other pinewood sticks are fixed on the side of the panel and make the connection with the substructure possible. The dimensions of the SIP-panels are limited, due to the production method of the supplier Kingspan. Minimum length of the panels is 0,3m and maximum length 6,3m. The minimum width of the panels is 0,3m and maximum width 1,2m. When the height of the building is max. 20m, the width of the openings have a maximum dimension of 2,26m, leaving a width of 1,020m of the SIP-panel on the left and right side of the opening. Screws can be applied unlimited at any location on the exterior chipboard layer of the panels. The SIP-panels are damp-open elements and are applied to the façade without vapour tight layer (Kingspan, 2015).

Behind the central SIP-panel an extra layer of 107mm EPS insulation is added, in which the ventilation pipes are integrated. These pipes are connected to the heat recovery ventilation units, that are placed on the rooftop (Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017). The shape of the ventilation pipes is cut out of the EPS insulation plates, so the connection between the pipes and EPS insulation is made through pre-made shape geometry. The ventilation pipes are made of PVC, have a life expectancy of 30 years and high recycling rate of 90% (NIBE, 2017). When PVC is pulverized to powder at the end of life, it can be reused for the production of new PVC pipes. PVC can be recycled up to 7 times (Bureau Leiding, n.d.)
EPS is a synthetic insulation material. The virgin materials used for the production of EPS, expanded polystyrene, are ethylene and pentane. Pentane is added as leavening and consequently the ethylene starts to expand. The EPS insulation plates are created when the ethylene becomes hard foam during the cooling process in the mould. When the EPS plates maintain undamaged after disassembly of the building, they can be 100% reused. Because EPS has a high energetic potential, incineration is often the preferred option at the end of life (Hildebrand, 2014). According to NIBE the end of life scenarios of EPS insulation plates account for 5% landfill, 90% incineration and 5% recycling (Haas, 2012).
Chipboard is a wood-based material, but can't be considered as a biological material, because of the presence of chemical resins in the material. Chipboard is a type of wood fibre board that is made of the by-products of the production of sawn wood; small wood shavings with a length of 1,3-1,8 mm. The chipboard is produced by bounding the wood shavings into wooden composites with the use of resins, accounting for 5-10% of the total mass (Hildebrand, 2014). In general chipboard consists of 75% recycled wood (Centrum Hout, 2015). For the SIP panel chipboard type P5 is used. This type of chipboard is bonded with MUF (Melamine-Urea-Formaldehyde) adhesive (Drieplex, n.d.). According to NIBE the end of life scenarios of chipboard account for 5% landfill, 85% incineration and 10% recycling (Haas, 2012). Chipboard belongs to wood class B (wood that is glued, painted or varnished) and thus has a recycling efficiency of 100% (Recycling.nl, n.d.).
The 4 integrated stiffeners and the 2 connection sticks are made of untreated pinewood. The average density of pinewood (Picea abies) is 460 kg/m3 (Haas, 2012). Because the pinewood stiffeners are integrated in the SIP panels they are protected against moisture and sunlight, so they fit in risk class 1. This leads to an increased lifespan (Stichting Probos, 2009). According to the Nationale Milieudatabase the pinewood stiffeners that are integrated in sandwich elements for roofs, which are comparable to the SIP panels, have a lifespan of 75 years. The recycling rate is 5%, 85% is incinerated and 10% ends up in landfill (Stichting Bouwkwaliteit, 2017). At the end of life the recycled pinewood will be cut into small pieces and can then be reused for the production of chipboard (Splunter, 2016).
The 2 timber sticks that connect the SIP panels to the substructure are made of the same type of untreated pinewood as the substructure. The pinewood sticks are positioned underneath the waterproof layer, and thus also fit in risk class 2. Similar to the substructure, the pinewood sticks also have a lifespan of 35 years, a recycling rate of 0%, 95% incineration and 5% landfill (Stichting Bouwkwaliteit, 2017).

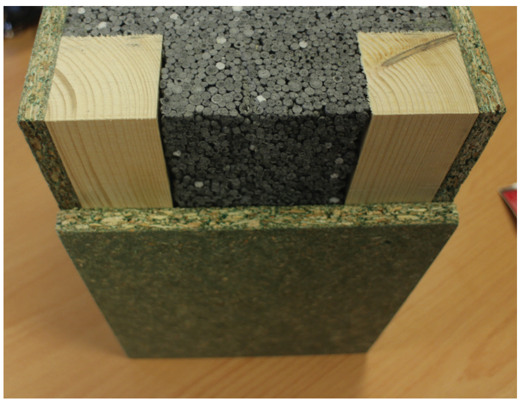



Fig. 30: Photos Mock-up;
Left: assembly of SIP-panels
Right: section SIP-panel
(Konstantinou, n.d.)

Calculation:

Step 1: Calculation of the mass of the component

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
EPS	7,563	15	113,452
Chipboard	0,482	600	289,069
Pinewood (uncured)	0,084	460	38,843
Pinewood (cured)	0,069	460	31,736
PVC	7,820 (m)	1,42 (kg/m)	11,104

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
EPS	Technical	0%	0%	113,452
Chipboard	Technical	75%	0%	72,267
Pinewood (uncured)	Biological	0%	0%	38,843
Pinewood (cured)	Biological	0%	0%	31,736
PVC	Technical	0%	0%	11,104

Step 3: Calculation of unrecoverable waste at the end of life of the materials

Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
EPS	5% (efficiency 100%)	0%	107,780
Chipboard	10% (efficiency 100%)	0%	260,162
Pinewood (uncured)	5% (efficiency 100%)	0%	36,901
Pinewood (cured)	5% (efficiency 100%)	0%	30,150
PVC	90% (efficiency 100%)	0%	1,110

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
SIP panels	0,73	3,0	0,78

In a telephone conversation with the Project manager Renovation of Kingspan, Rolf Pennings, the circularity assessment of the SIP-panels is discussed. In general, a technical lifecycle of 75 years is taken into account for the SIP-panels, when protected against the weather with a waterproof layer. For the production of the SIP-panels a high amount of virgin material is consumed. Waste within the production process is immediately reused. The material supplier Kingspan takes into account a take-back period of 30 years. At the end of life of the SIP-panels, the EPS can be removed from the chipboard with burning iron wire. During the process, valuable material loss can't be prevented. As a result, the EPS can be recycled up to 7 times in applications where the material isn't direct load-bearing, because of its decreased compressive strength. However, there is no demand for reused EPS material in this condition, so usually the SIP-panels are incinerated at the end of life. The chipboard, when cleared from EPS remains, will be brought back to the pallet industry for reuse or recycling purposes. Kingspan is working on the development of a demountable sandwich panel. Nonetheless, for the sandwich technology the use of adhesives is required to guarantee the strength and air-tightness of the panel. The type of used adhesive foams and expand, closing off the joints between the elements. A demountable connection method that ensures the same strength and air-tightness as the adhesives, hasn't yet been developed for the sandwich panels (Pennings, personal communication, December 18, 2017).

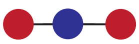
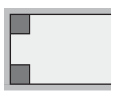
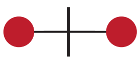
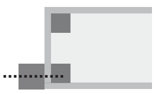
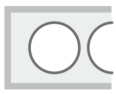
Material Circularity Indicator (MCI)
Results:

LFI
= 0,73

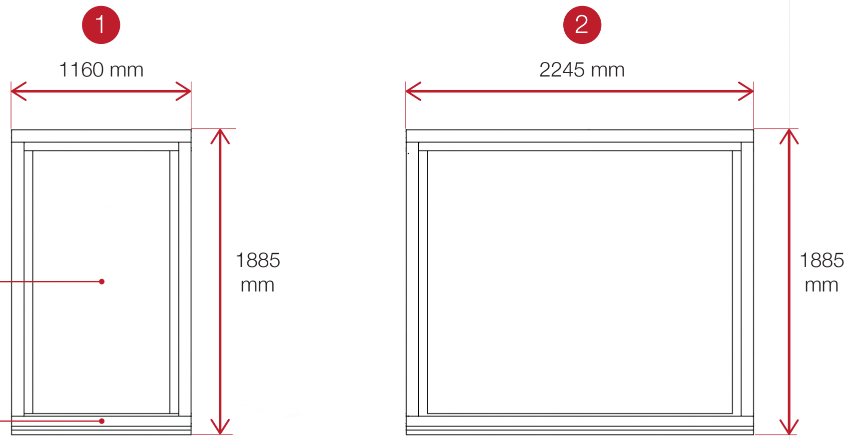
X
= 3,0

MCI
= 0,78

Disassembly Potential (DP)
Connection analysis:

CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
B1 - B2 B1 - B3 B2 - B3			1. Indirect 2. Chemical	1. Surface contact	-
B4 - B2 B4 - B3			1. Indirect 2. Additional fixing device	1. Screwed	+/-
V1 - B1 V1 - B2			1. Direct 2. Premade components	1. Surface contact	--

Window



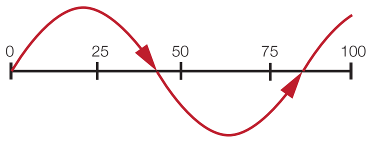
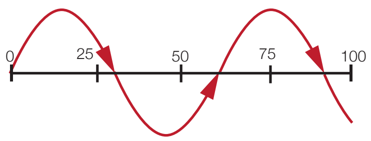
	Life cycle (yrs)	End of life scenarios			
D2 PVC on steel core		0%	77%	8%	17%
D1 Triple glass HR++		0%	70%	30%	0%

Fig. 31: Photos Mock-up: installlation of the K-Vision PVC window frame (Konstantinou, n.d.)

According to the Nationale Milieudatabase, HR++ double glazing with coating and argon filling, comparable to the HR++ triple glazing that is used in the 2nd Skin Façade, has a lifespan of 30 years, a recycling rate of 70% and 30% ends up in landfill (Stichting Bouwkwaliteit, 2017). The triple glazing can be removed from the window frame without damage. However, direct reuse of the triple glazing is impossible because of the varying dimensions of the glass. On the other hand, the glazing can be melted and recycled for the production of new glass. For the production of float glass 10-20% of the final product consists of recycled scrap glass, called cullet (PPG Industries, 2010). For the MCI calculation, a recycled content of glass of 10% is taken into consideration.

The window frames, produced by material supplier K-vision, are made of PVC with a steel core. According to NIBE, the life span of this type of window frame is 40 years. The steel core is made of 37% recycled content. According to the Product Manager of the supplier K-vision, Jelmer Bijlsma, in general 10% recycled PVC is used for the production of the window frames, applied in the rotating profiles of the frame (Bijlsma, personal communication, January 9, 2018). At the end of life, 77% of the window frame can be used for recycling, 8% ends up in landfill and 15% is incinerated (Haas, 2012). The supplier K-vision takes into account a lifespan of 30 to 50 years of their PVC window frames. The VKG Vereniging voor Kunststof Gevelelementenindustrie (translated: Association for Plastic Façade elements industry), guarantees a 100% return policy of the PVC window frames, that can be recycled up to 10 times for the production of new window frames (MRPI, 2015). For the recycling of PVC the following technique is used: after disassembly of the old PVC window frames, the PVC and steel can be completely recycled. The PVC will be shredded to granulate. After removal of the pollution, the PVC granulated can used in the production process of new window frames. The efficiency of the PVC recycling process is 100% (Inoutic, 2017).

Material Circularity Indicator (MCI)

Results:

LFI = 0,76

X = 1,2

MCI = 0,43

Calculation:

Step 1: Calculation of the mass of the component

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
PVC	14,350 (m)	2,3 (kg/m)	33,005
Steel	14,350 (m)	1,37 (kg/m)	19,660
Glass	0,063	2500	157,19

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
PVC	Technical	10%	0%	29,705
Steel	Technical	37%	0%	12,385
Glass	Technical	10%	0%	141,47

Step 3: Calculation of unrecoverable waste of the materials

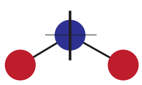
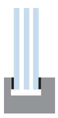
Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
PVC	77% (efficiency 100%)	0%	7,591
Steel	77% (efficiency 100%)	0%	4,522
Glass	7% (efficiency 20%)	0%	93,137

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

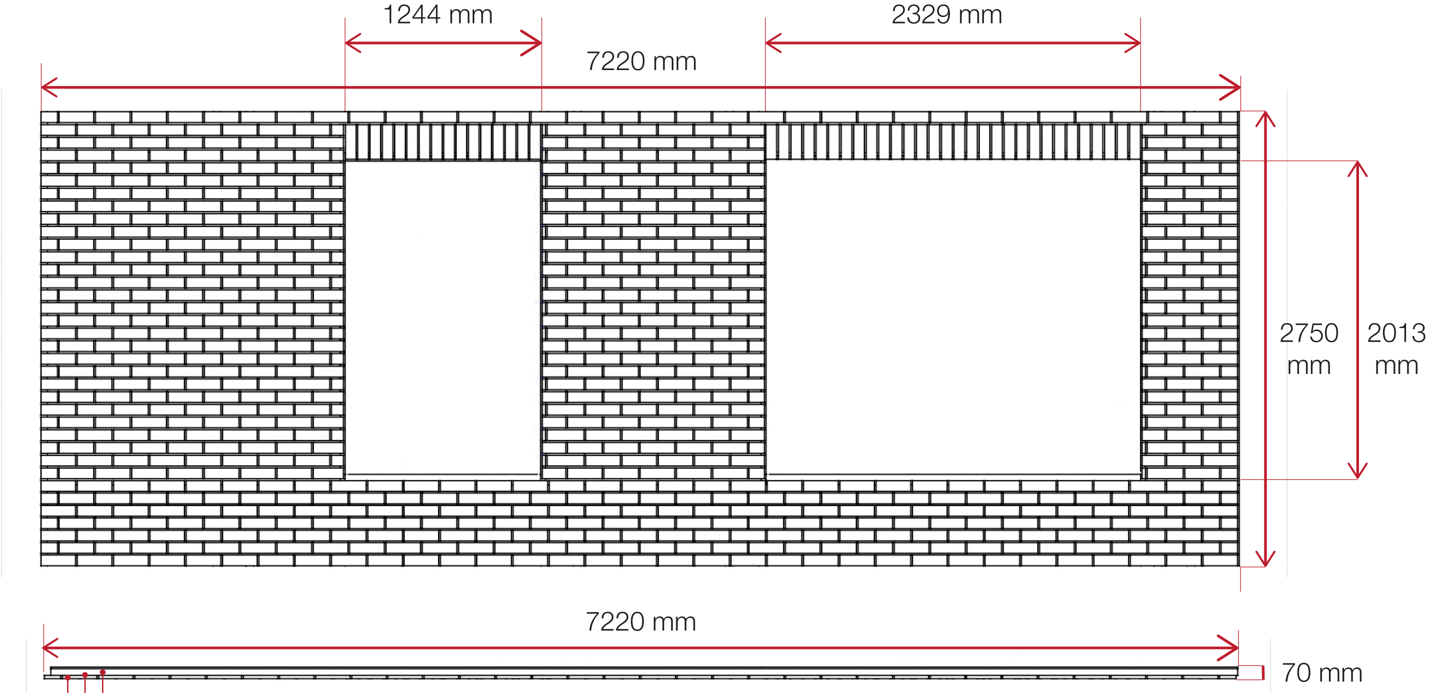
Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Window	0,76	1,2	0,43

Disassembly Potential (DP)

Connection analysis:

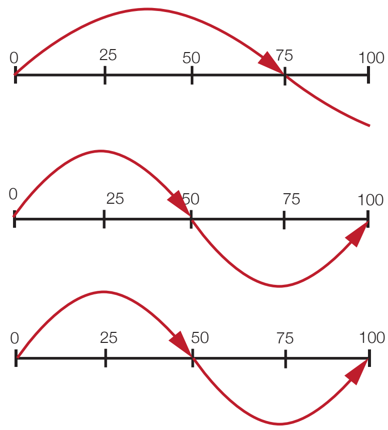
CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
D1- D2 (gasket = third component)			1. Indirect 2. Third independent	1. Surface contact	++

Cladding option 1: Brick strips



Life cycle (yrs)

End of life scenarios



C2 EPS insulation 40 mm	0%	0%	5%	95%
C3 Fibre cement 10 mm	0%	0%	5%	95%
C4 Brick strips 210 x 65 x 20mm	0%	0%	91%	9%

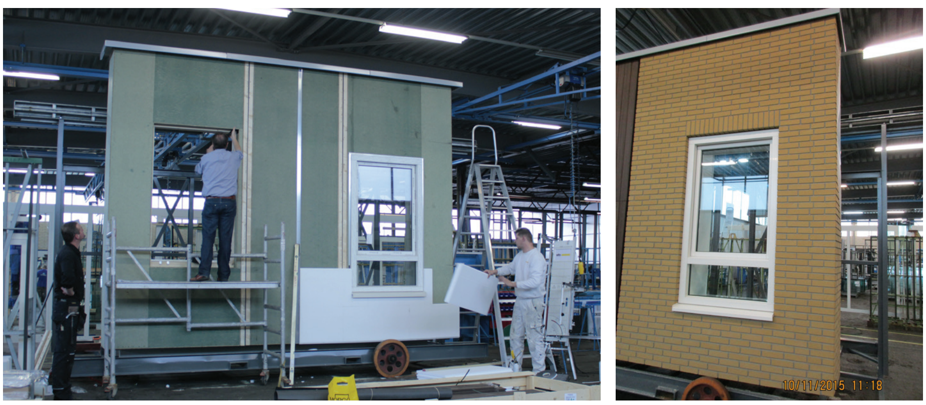


Fig. 32: Photos Mock-Up; StoTherm Classic, brick strips cladding (Konstantinou, n.d.)

This first facade cladding option is brick strips, produced by the material supplier Sto Steenstrips. The brick cladding system, named StoTherm Classic, consists of brick strips with a thickness of 20 mm, attached to a layer of 40 mm EPS insulation and 10 mm fibre cement. In general, bricks have a long lifespan of 100 years and recycling rate of 77% (Haas, 2012). However, the material supplier Sto guarantees a lifespan of 50 years for the complete brick strips cladding system. In the environmental product sheet of Sto Steenstrips is stated that reuse and recycling of the brick strips is impossible (Sto Isoned bv, 2017). According to the called contact person of the company Sto, Rudy Jansen, the brick strips can't be removed purely from the facade cladding system without residues of the surrounding materials (Jansen, personal communication, December 15, 2017). For this reason, the brick strips are expected to end up in landfill, based on the percentages of NIBE (Haas, 2012). Also the fibre cement layer, named Stolevell Uni, has a lifetime of 50 years and recycling rate of 0% (Sto Isoned bv, 2017). According to NIBE, in general fibre cement will be mainly incinerated (95%) at the end of life (Haas, 2012).

The brick cladding is connected to the underlying SIP panels with adhesives. First the EPS insulation will be placed, internally connected with an integral form-connection at the top and bottom edges. When the EPS plates are placed, glued to the existing facade, a reinforcement layer of fibre cement with integrated mesh is spread over the EPS plates to enable the connection with the bricks strips. Then the brick strips are placed on top of the façade. The joints between the brick strips are filled with a type of adhesive mortar. The mortar bonding reduces the reuse potential of the bricks and the EPS insulation. In general, mortar can be removed from bricks through thermal or chemical treatment. But after the treatment the bricks will have different colours and dimensions. The bricks and the mortar can be completely reused and the mortar recycled. Another option is to crush the masonry debris into fine grain fractions and then mix them with clay to produce new bricks with recycled content (Van Dijk, 2014). However, according to the supplier, the brick strips have no reuse and recycling potential (Sto Isoned bv, 2017). Probably this is due to the chemical connection to the EPS insulation layer, that can't be removed from the brick strips.

Material Circularity Indicator (MCI)

Results:

LFI = 1,00

X = 2,0

MCI = 0,55

Calculation:

Step 1: Calculation of the mass of the component

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
EPS	0,507	15	7,598
Fibre cement	0,127	1070	135,489
Brick strips	0,222	1600	355,555
Mortar	0,031	1750	54,301

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
EPS	Technical	0%	0%	7,598
Fibre cement	Technical	0%	0%	135,489
Brick strips	Technical	0%	0%	355,555
Mortar	Technical	0%	0%	54,301

Step 3: Calculation of unrecoverable waste at the end of life of the materials

Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
EPS	0%	0%	7,598
Fibre cement	0%	0%	135,489
Brick strips	0%	0%	355,555
Mortar	0%	0%	54,301

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

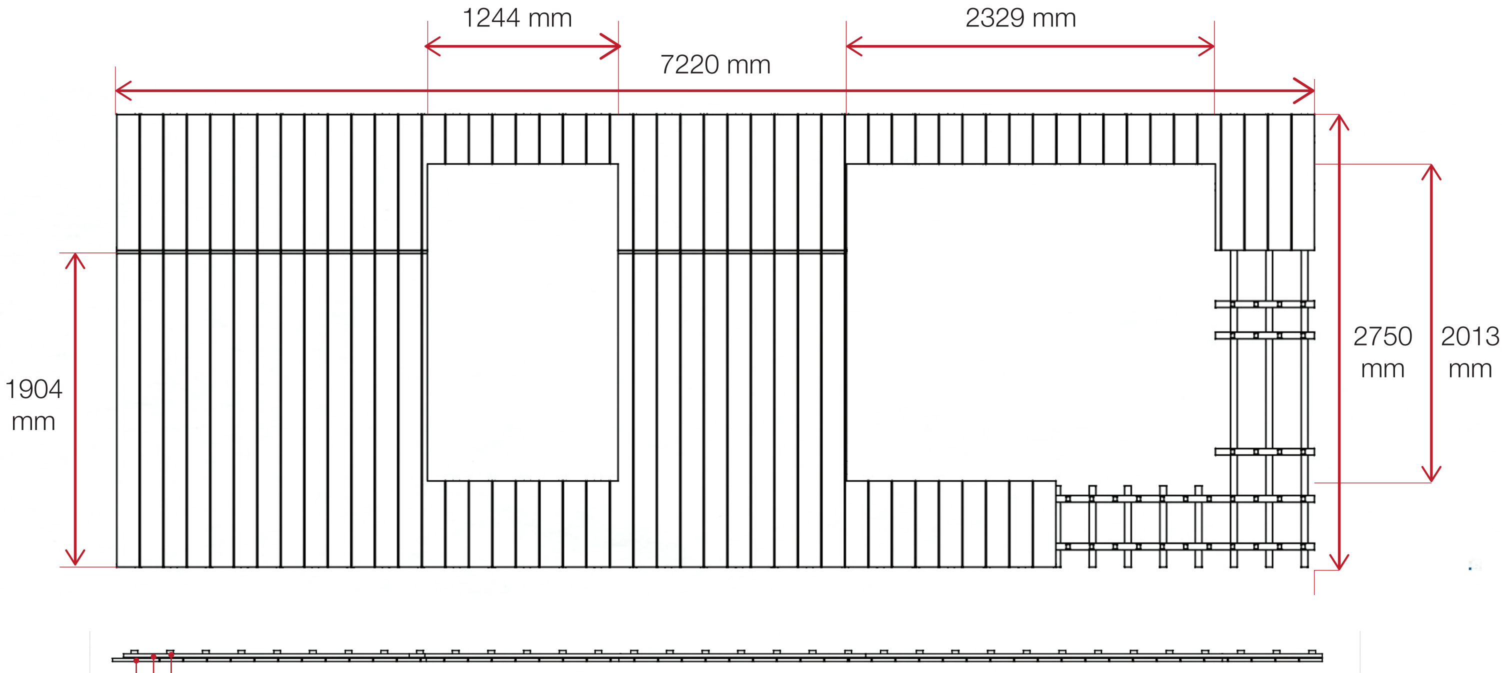
Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Brick cladding	1,00	2,0	0,55

Disassembly Potential (DP)

Connection analysis:

CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
C4 C4 - C3 C3 - C2			1. Direct 2. Chemical	1. Surface contact	-
C2			1. Direct 2. Integral; interlocked	1. Surface contact	--

Cladding option 2: Bamboo



	Life cycle	End of life scenarios			
C3 Aluminium profile 20 mm		0%	90%	5%	5%
C2 Stainless steel clips 40 mm		0%	90%	5%	5%
C1 Bamboo slats 137 x 18 mm		0%	0%	5%	95%

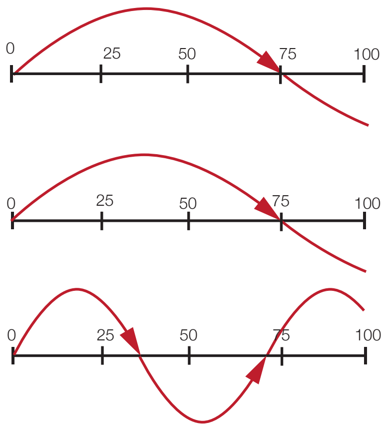


Fig. 33: Photos Mock-Up; MOSO Bamboo Xtreme cladding (Konstantinou, n.d.)

The second option is the bamboo cladding, called Bamboo Xtreme delivered by the material supplier MOSO. The façade cladding system consists of solid bamboo planks, made for 92-95% of thermally modified, compressed bamboo strips, coming from sustainably managed production forests in China. As a result, the bamboo planks are extremely durable (class 1) and hard. Bamboo is a renewable material with a fast turnover rate; after 4-5 years the bamboo stems are ready for harvest (CAPEM, 2017). The façade supporting system is developed by Derako Solid Wood Systems. The supporting system consists of vertical wooden posts, that are connected to the underlying SIP panels with screws. Horizontal aluminium profiles, with integrated façade clips, are attached to the vertical posts with screws. The bamboo planks, with a width of 137 and a thickness of 18 mm, consist of vertical grooves, that fit exactly into the geometry of the stainless-steel façade clips. The façade clips are made of stainless-steel type 301 and have a weight of 7880 kg/m3 (AK Steel, 2012). Based on the Inventory of Carbon & Energy (ICE) published by the University of Bath, the average recycled content of steel in Europe is 59% (Hammond & Jones, 2008). The aluminium profiles have a density of 2700 kg/m3 and have an average recycled content of 47% (Haas, 2012).

The façade supporting system with the aluminium profiles and stainless-steel clips have a long durability and don't need technical maintenance during their lifetime. The system is completely demountable, resulting in 100% recyclable materials (Derako Façade Systems B.V., 2016). According to the Environmental Product Declaration of MOSO, the façade cladding system has a lifespan of 35 years. The bamboo slats consist for 92-93% of renewable materials and for 7% of other substances (phenol formaldehyde, used to glue the strips together). In general, at the end of life stage 95% of the total amount of bamboo, used in the Netherlands, will be incinerated and 5% dumped at the landfill (Haas, 2012). Most of the aluminium profiles and stainless-steel clips will be recycled (90%) (CAPEM, 2017). Research of Rombach has shown that the overall recycling efficiency rate for the production of recycled aluminium is 74,4% (Rombach, 2013). The efficiency of the recycling process used for the portion of a product collected for recycling, is 20% (Frischknecht, 2010). In the Nationale Milieudatabase pinewood sticks are analysed in a fibre cement cladding system, which is comparable to the function and situation of the vertical pinewood posts in the bamboo cladding system. In this case the pinewood studs have a lifespan of 35 years, a recycling rate of 0%, 95% incineration and 5% landfill (Stichting Bouwkwaliteit, 2017).

Material Circularity Indicator (MCI)

Results:

LFI = 0,77

X = 1,4

MCI = 0,51

Calculation:

Step 1: Calculation of the mass of the component

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
Pinewood	0,046	460	20,948
Aluminium	0,004	2700	11,696
Stainless steel	0,009	7880	68,452
Bamboo	0,230	1150	265,049

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
Pinewood	Biological	0%	0%	20,948
Aluminium	Technical	33%	0%	7,837
Stainless steel	Technical	59%	0%	28,065
Bamboo	Biological	0%	0%	265,049

Step 3: Calculation of unrecoverable waste at the end of life of the materials

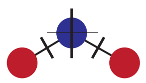
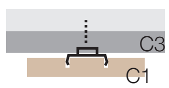
Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
Pinewood	0%	0%	20,948
Aluminium	90% (efficiency 20%)	0%	6,044
Stainless steel	90% (efficiency 100%)	0%	6,845
Bamboo	0%	0%	265,049

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Bamboo cladding	0,77	1,4	0,51

Disassembly Potential (DP)

Connection analysis:

CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
C1 - C3 (C2 = third component)			1. Indirect 2. Additional fixing device	1. Integral; interlocked 2. Screwed	+++

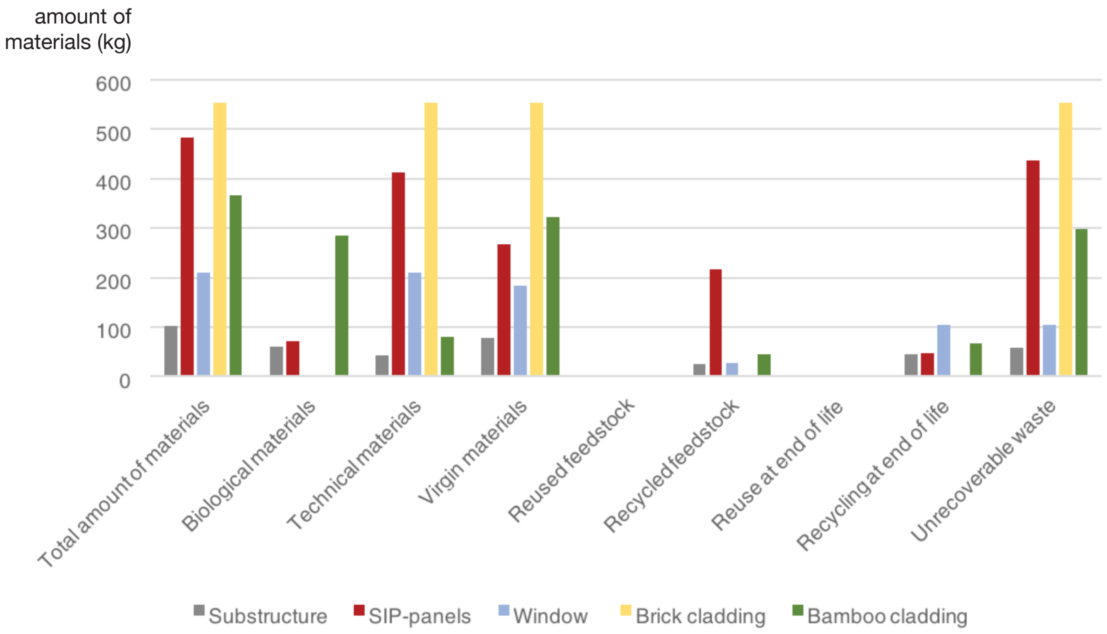


Fig. 34: Graph MCI assessment results Prefabricated variant (source: own image)

Material analysis

When comparing the MCI assessment results of the separate building components the Prefabricated variant of the 2nd Skin Facade Refurbishment system consists of, the following conclusions can be drawn, based on the graph shown above (fig. 34):

- The component that contains the highest amount of materials, when comparing the mass, is the brick cladding system. The second component that also contains a high amount of materials, is the SIP panelling system. The component with the lowest material usage, is the substructure.
- The facade refurbishment system mainly consists of technical materials. The cladding option that contains the highest percentage of biological materials that are renewable, is the bamboo cladding, while the brick cladding only consists of technical materials.
- When comparing the amount of virgin materials used for the production of the components, the brick cladding system only consists of virgin materials and doesn't contain any recycled content. Also the bamboo cladding system consists of a high amount of virgin materials, in relation to the other components in the system. The component that consumes the least amount of virgin materials, is the substructure.
- The facade refurbishment system doesn't consist of any reused components.
- The component that contains the highest amount of recycled feedstock in the system, is the SIP-panel.
- At the end of life, the amount of unrecoverable waste of the system is relatively high. The component that generates the highest amount of waste, is the brick cladding option. Also the SIP-panelling system has a low recycling potential and thus generates a high amount of unrecoverable waste at the end of life.
- The components with a high recycling percentage at the end of life, are the substructure and the window frame. Also the supporting structure of the bamboo cladding has recycling potential at the end of life.

For these reasons in the MCI assessment results can be seen that the brick cladding system has obtained a LCI-value of 1, which means the product is completely linear. On the other hand, the LCI-value of the bamboo cladding is 0,77. Due to the effect of the longer lifespan of the brick cladding system, the MCI-value of both cladding systems is comparable. The component with the lowest LFI-value and highest MCI-value is the substructure. Due to the presence of recycled feedstock and the long lifespan of the product, the SIP-panels have reached an LFI-value of 0,73 and a MCI-value of 0,78.

Assessment of the complete system

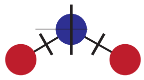
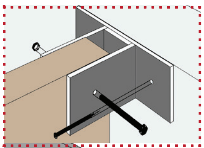
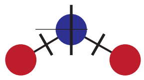
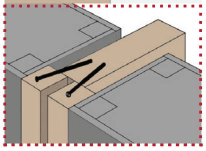
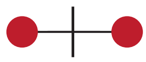
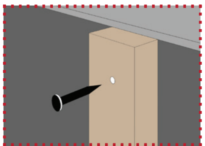
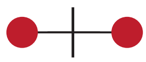
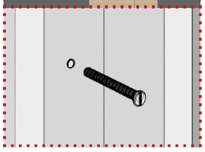
CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
A - O			1. Indirect 2. Additional fixing device	1. Screwed 2. Bolted	+++
B - A			1. Indirect 2. Additional fixing device	1. Screwed	+++
C - B (option 1)			1. Indirect 2. Chemical material	1. Surface contact	-
C - B (option 2)			1. Direct 2. Additional fixing device	1. Nailed	+/-
D - B			1. Direct 2. Additional fixing device	1. Screwed	+/-

Fig. 35: Connection analysis Prefabricated variant (source: own image)

Connection analysis
As can be seen in the diagram (fig. 35) most components are connected through dry interfaces. Indirect dry interfaces with additional fixing devices are preferred when designing for disassembly. The substructure (A) is indirectly connected to the existing façade (O) through a stainless-steel U-profile (A1), that enables a screwed connection with the existing façade and a bolted connection with the vertical posts (A2) of the substructure. Consequently, the Structural Insulated panels (B) are indirectly connected to the substructure (A) through wooden connection sticks (B4), that are connected to the SIP-panels and screwed to the vertical posts (A2) of the substructure. The windows (D) are directly connected to the chipboard of the SIP-panels (B2) with screws. For the cladding the two options have different connection methods: the insulation layer of the brick cladding (C2) is connected to the underlying SIP-panel (B) with the use of adhesives. On the other hand, the mounting profile of the bamboo cladding (C2/3) is directly connected to the SIP-panels (B) with screws. The components that are screwed into place, are decoupled: the interfaces allow the components to be exchanged in case of damage (Klein, 2013). This makes the bamboo cladding favourable, instead of the brick cladding. The bamboo cladding is connected to the SIP-panel through a decoupled interface; the clips and the aluminium mounting frame. On the other hand, the brick cladding can't be removed without damaging the underlying SIP-panels, due to the irreversible chemical connection.

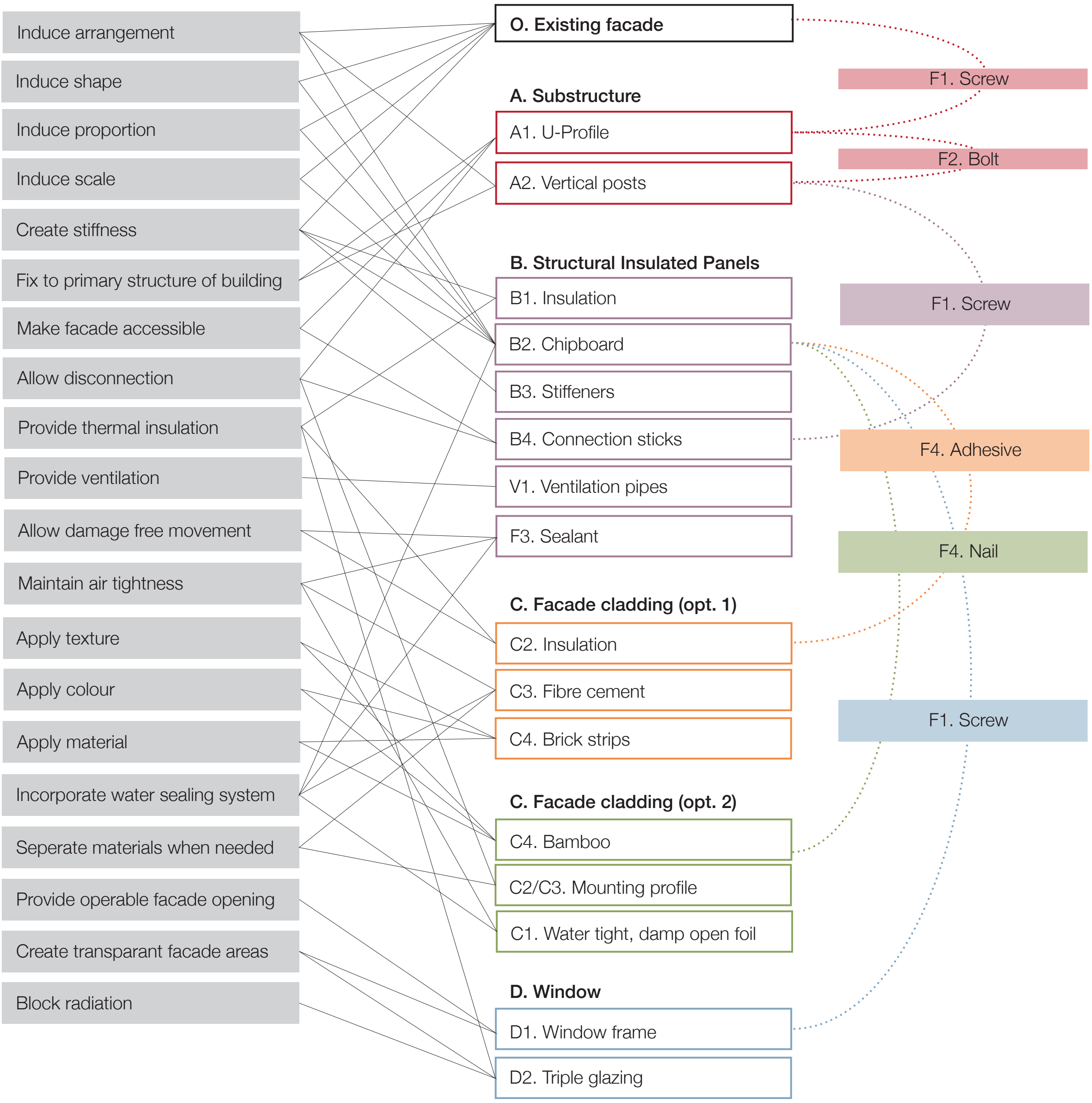


Fig. 36: Function structure Prefabricated variant (source: own image)

Function structure

The function structure, illustrated in fig. 36, shows the support functions each façade element of the Prefabricated variant of the 2nd Skin Façade Refurbishment fulfils. As can be seen in the diagram, the main functions of the substructure are the fixation of the 2nd Skin to the primary (existing) structure of the building, as well as making the 2nd Skin Façade accessible from the outside and allowing disconnection from the existing facade. The diagram shows that the Structural Insulated Panels copy most functions from the existing façade. The Structural Insulated Panels take over the arrangement, shape, proportion and scale of the existing facade. Also, the SIP-panels provide the stiffness of the 2nd Skin Façade, independent from the existing façade. The main function of the SIP-panels is providing insulation, which is a function the existing façade doesn't meet. The insulation material also ensures waterproofing of the façade. Next to that, the ventilation pipes are integrated in the SIP-panels, thus the ventilation is also provided by the SIP-panels. Both cladding options, brick and bamboo, apply texture, colour and material to the façade. The main function of the window is to create transparent façade areas, at the same location as the replaced original windows of the existing facade.

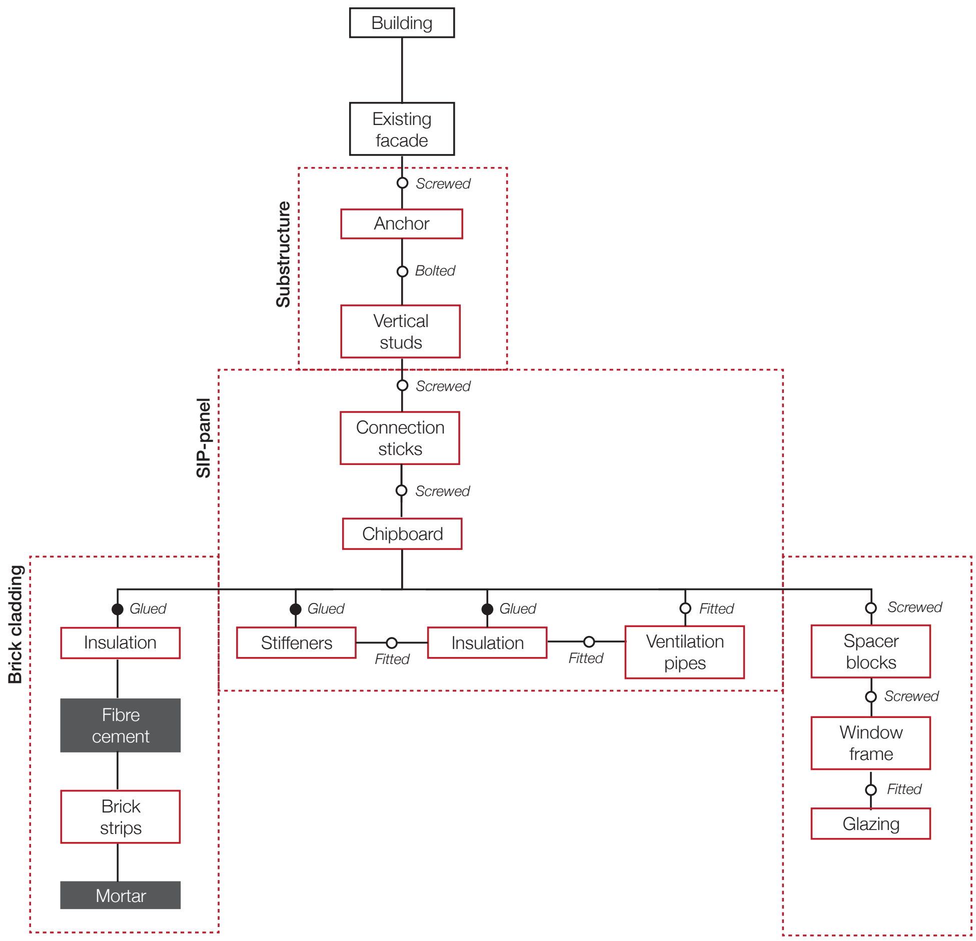


Fig. 37: Relational diagram
Prefabricated variant Option 1
(source: own image)

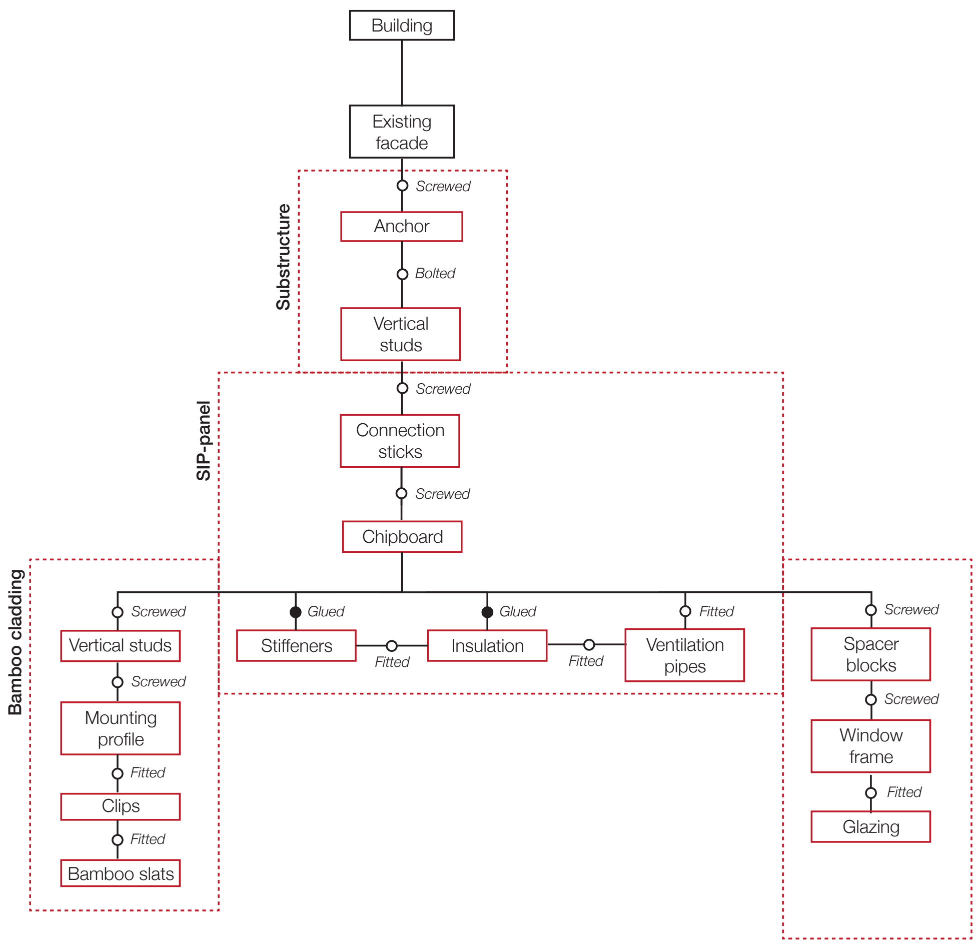


Fig. 38: Relational diagram
Prefabricated variant Option 2
(source: own image)

Disassembly Potential

Functional decomposition (FD)

There is planned interpenetration of functions in the SIP-panels. The main function of the SIP-panels is to provide additional thermal insulation to reach energy neutrality of the residential building. The EPS insulation boards contain pre-made holes, in which the wooden stiffeners and ventilation pipes are placed. The wooden sticks are incorporated in the SIP-panels to provide stiffness. Relocation or resizing of the ventilation pipes or stiffeners have consequences on the other functions; the thermal insulation and stiffness of the panel. The chipboard plates determine the position of the façade openings and thus define the arrangement of the façade, as well as the size and thus the shape, proportion and scale of the facade. Because the central SIP-panel consists of double layered insulation, in which the ventilation pipes are integrated, a void is created between the existing façade and the 2nd Skin Façade. This free zone is still empty and only creates a separation between the two facades. However, a possibility could be to use the free zone for services, resulting in unplanned interpenetration of functions.

For the façade cladding, there are 2 options: brick and bamboo.

- The brick cladding system consists of multiple layers, that are connected permanently through layers of fibre cement and mortar, so the brick cladding should be seen as one component in which multiple functions are integrated. Next to the architectural functions (adding texture, colour and material to the façade), the brick cladding contributes to the provision of thermal insulation with the 40 mm EPS insulation, which is originally needed to enable thermal expansion of the brick during temperature change. The brick cladding is chemically connected through adhesives to the underlying SIP-panels. When the brick cladding needs to be removed when the architectural appearance of the building has to change, the underlying component will be damaged.
- The bamboo cladding has as only function the architectural appearance of the facade. The mounting profile and clips make disassembly of the cladding possible, to enable change of cladding and thus change of architectural appearance of the building without damaging the surrounding components.

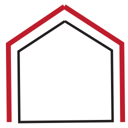
Concluded, the 2nd Skin system could be classified as planned interpenetration of some functions as well as unplanned interpenetration of other functions. *(Score: 5)*

Systematisation (SY)

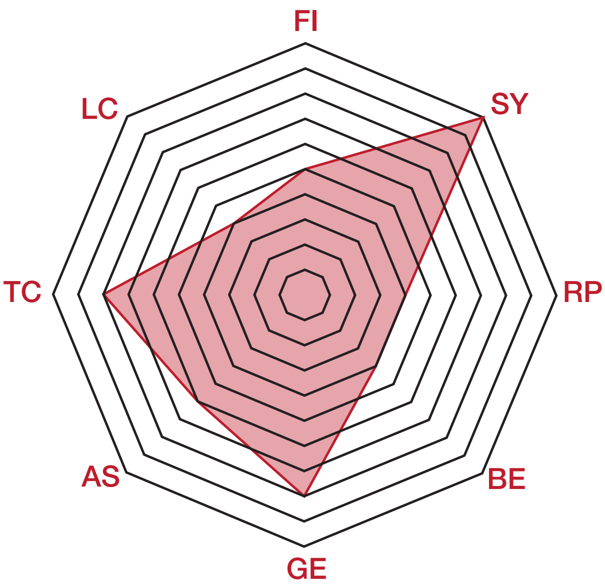
The Prefabricated variant of the 2nd Skin Façade Refurbishment system consists of 4 clusters on component level, grouped according to their sub-function: substructure, insulation, cladding and windows. The substructure needs to be completely assembled on-site, because this is the component that is directly connected to the existing façade. The insulation layer, namely the SIP-panel, is completely prefabricated in the factory. The cladding needs to be assembled on-site, because the cladding has to cover the joints between the prefabricated SIP-panels. The windows are also prefabricated, bespoken to the varying dimensions of the façade openings of the different residential buildings, already include triple-glazing and can immediately be placed on-site. The division of the 2nd Skin Façade into separate components increases the flexibility and consequently the Disassembly Potential of the system. However, the components are assembled in a defined order, so when an element of one component needs to be replaced, some other elements and components that cover the chosen component need to be disassembled as well. Next to that, within the component some connections between elements aren't demountable. Mainly the insulation and cladding materials contain permanent connections. When one element is deteriorated, the complete component has to be replaced. Because of the clustering of the system on component level, the systematisation 2nd Skin Façade is graded the highest. *(Score: 10)*

Relational Patterns (RP)

The relational diagram of the Prefabricated variant of the 2nd Skin Façade Refurbishment system (see fig. 37 and 38) is mainly closed and static; the replacement of one element has a direct effect on its surrounding elements. The separate components are horizontally connected; screwed or bolted with additional steel profiles. This makes the components functionally dependent on each other. Within the components the relational patterns differ. The relational diagram of the SIP-panels is mainly horizontally oriented; many elements are integrated and interconnected within the component, resulting in a closed assembly. The relational diagrams of the substructure, windows and cladding, brick and bamboo, are mainly vertically oriented; the different elements are assembled successively, resulting in a layered assembly. The elements with most connections to the surrounding components, are the chipboard elements within SIP-panels. As a result, in the middle zone of the relational diagram, the clustered components are horizontally connected to each other, which complicates the disassembly process. For this reason, the category Relational Patterns is graded the low. *(Score: 4)*



1. **Prefabricated variant**



FI	Functional Independence
SY	Systematisation
RP	Relational Patterns
BE	Base Element Specification
GE	Geometry of the Edge
AS	Assembly Sequence
TC	Type of Connection
LC	Life Cycle coordination

Fig. 39: Disassembly Potential evaluation of the Prefabricated variant (source: own image)

Technical lifetime

- 75 years
- 50 years
- 40 years
- 30 years

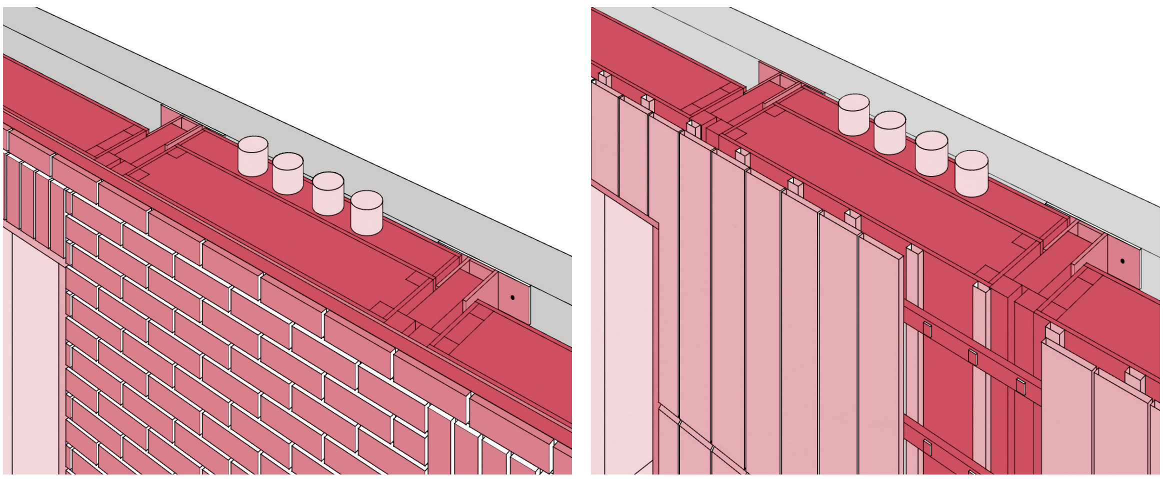


Fig. 40: Life Cycle Coordination of the Prefabricated variant
Left: cladding option 1, brick
Right: cladding option 2, bamboo
(source: own image)

Base Element specification (BE)
On component level, the SIP-panel can be considered as the base element of the Prefabricated variant of the 2nd Skin Façade Refurbishment system, because this component is connected to all other three components of the system; the substructure, the façade cladding and the window. On element level, the supporting structure of the façade cladding and the window frame are connected to the chipboard elements of the SIP-panel. The substructure of the 2nd Skin Façade is connected to the pinewood connection sticks, that are fixed to the chipboard elements with screws. Directly or indirectly, all components are connected to the chipboard elements of the SIP-panels. Within the SIP-panels the EPS insulation plates can be seen as the base element, to which all other elements of the SIP-panels are glued. However, the chipboard elements are situated at the surface of the SIP-panels, and thus these specific elements should be considered as the base elements of the 2nd Skin Façade system. Next to the base element, the main function of the chipboard is to induce the arrangement of the 2nd Skin Façade. So, the system consists of a base element with multiple functions. *(Score: 4)*

Geometry (GE)
The SIP-panels of the 2nd Skin Façade are symmetric overlapping with the substructure, so the panels can be disassembled in two directions. The geometry of the edges of the prefabricated windows are overlapping on two sides and fit precisely in the openings of the SIP panels at the position of the old window frames of the existing façade with the use of wood adjusting blocks. The façade cladding options both have open, linear geometries, so the components can be disassembled in all directions. The connection of the vertical studs with the steel anchors of the substructure is closed, integral on one side, so can only be disassembled in one direction. Within the SIP-panels the connection between the elements is mainly closed, integral on two sides. The wooden stiffeners and the ventilation pipes are stuck between the chipboard and EPS insulation plates. Most of the components are prefabricated, only the assembly is done on-site. This is convenient for the disassembly of the system. For this reason, the geometry of the components is graded high. *(grade: 8)*

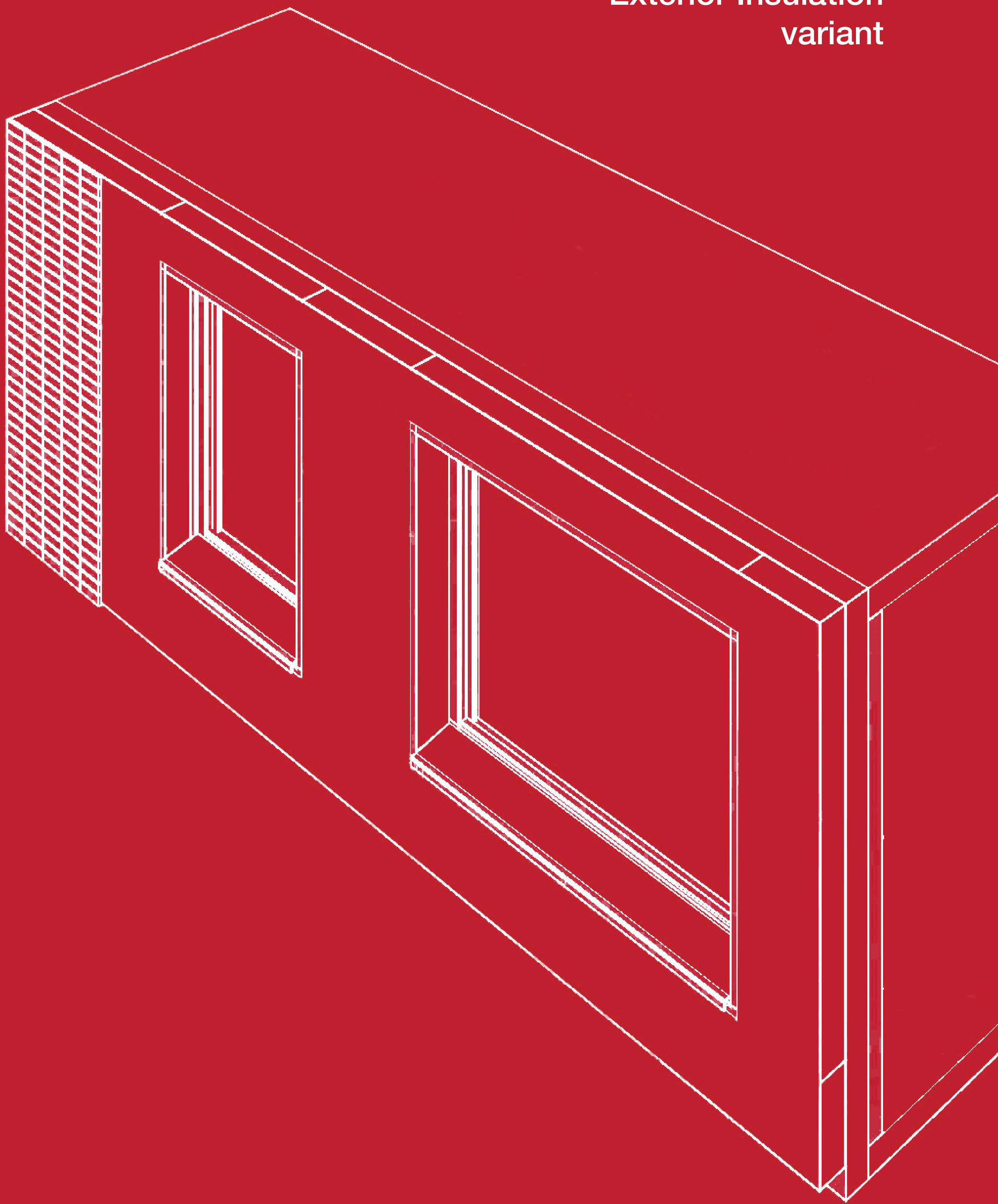
Assembly Sequences (AS)
The assembly of the complete 2nd Skin Façade is partly sequential, partly overlapping. The first step is the connection of the substructure to the existing façade of the residential building. The steel anchors are screwed to the façade, then the vertical wooden studs can be attached to the anchors. Meanwhile in the factory, the SIP-panels will be assembled, the ventilation pipes will be integrated in the EPS-insulation and the PVC windows can already be placed in the openings of the SIP-panels. On-site the prefabricated SIP panels with integrated windows will be attached to the vertical studs of the substructure with screws. The airtight sealing between the panels and the internal lining of the windows will be placed on-site. The final step is the assembly of the cladding on the façade; some cladding materials can already be attached to the SIP-panels in the factory (bamboo), other cladding materials need to be installed on-site (brick). Summarised, most of the assembly of the façade elements into components is done in the factory, while the assembly of the components to build the 2nd Skin Facade is done on-site. This means each component is fixed on place by the later assembled components, resulting in linear dependencies between the components in the 2nd Skin Façade system. This means in the assembly components, such as the SIP-panels and the substructure, get stuck. *(grade: 6)*

Type of Connections (TC)
Most of the connections between the separate components within the 2nd Skin Façade system are directly or indirectly connected with additional fixing devices. The connection between the SIP-panels and the substructure as well as the connection between the substructure and the existing façade are made with independent third components, namely the connection sticks and stainless-steel anchors. Only the brick façade cladding is chemically connected to the surface of the SIP-panels. The elements within the SIP-panels, however, are all chemically connected. Also the elements of the brick façade cladding are connected with a third chemical material, which is unsuitable for disassembly. The substructure, the window and the bamboo façade cladding are dryly connected, which is preferable for disassembly of the facade system. For this reason, in general, the type of connections of the Prefabricated variant of the 2nd Skin Façade are suitable for disassembly, especially the option with bamboo cladding. *(grade: 8)*

Life Cycle Coordination (LCC)
The elements of the 2nd Skin Façade with the shortest life cycle, are the PVC ventilation pipes, with a technical lifetime of 30 years and an estimated functional lifetime of 15 years. The PVC ventilation pipes are situated within SIP-panels, integrated into the EPS-insulation layer with a lifetime of 75 years. The ventilation pipes are stuck in the pre-made geometry of the EPS insulation and thus can't be replaced without damaging the EPS insulation. The element with the second shortest lifetime is the bamboo cladding with a lifetime of 35 years. The bamboo slats, however, are situated at the outermost façade surface and have a dry connection with the supporting cladding structure, thus the bamboo slats can easily be replaced. For these reasons, the Life Cycle Coordination of the Prefabricated variant of the 2nd Skin Façade is graded relatively low. *(grade: 4)*

5.2

Exterior Insulation variant



Description

The Exterior Insulation variant of the 2nd Skin Facade Refurbishment system consists of an exterior insulation layer that is directly glued to the existing façade of the residential building. This variant is now being applied to the case study building in Vlaardingen, executed by the contractor BIK Bouw. It is a standard solution that is currently most often used to improve the energy performance of post-war residential buildings, also referred to as the External Insulation Finishing System (EIFS). In this variant, a layer of rigid exterior insulation, such as EPS board, is applied to the existing façade and roof of the residential buildings, finished with a layer of plasterwork to seal the surface and define the architectural appearance. Next to that, the existing windows are replaced by new triple glass windows and mechanical ventilation systems with heat recovery are installed on the balcony for every apartment. Only the existing heating system, gas boiler and radiators, will be maintained. Unlike the Prefabricated variant, the ventilation ducts aren't integrated in the insulation board, but instead placed in a separate installation unit in front of the façade, situated between the balconies (Azcarate-Aguerre, et al., 2017).

The façade consists of the following layers:

- 190 mm rigid EPS insulation is connected to the existing façade of the residential building with 3 mm PU112-adhesive (Kingspan, n.d.)
- 1,5 mm organic plaster, type Stolit K (Sto Isoned bv, 2017), which is connected the EPS insulation layer with 3 mm organic primer, type Sto Putzgrund (Sto Isoned bv, 2017).

As concluded from the conversation with the contractor Jan Floor from BIK Bouw, who managed the process on the building site, this assembly sequence has been followed for the realisation of the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system at the case study building in Vlaardingen (Floor, personal communication, November 15, 2017):

Assembly sequence

<u>Step 1:</u> The existing façade of the residential building will be made ready for refurbishment by cutting off the existing balconies and cleaning the façade with a high-pressure sprayer.

<u>Step 2:</u> The foundation for the new balconies will be laid out.

<u>Step 3:</u> To define the ground floor level of the façade (level 0), the first line of EPS insulation will be placed, glued to the existing façade and finished with primer to make it watertight.

<u>Step 4:</u> The existing roof will be removed and then made wind and watertight with foil. The existing purlins of the roof will be maintained and strengthened to attach the prefab insulated sandwich panels of Kingspan to with screwed connections. On top of the insulated roof panels, the photovoltaic panels will be installed. The waste materials of the roof will be separated and brought to the recycling industries.

<u>Step 5:</u> After removal of the glass, the new PVC window frames will be attached to the existing wooden window frames of the building with a screwed connection. The existing window frames will be maintained to prevent the need of interior finishing.

<u>Step 6:</u> Consequently the 2nd Skin Façade will be applied by gluing the EPS insulation board on top of the existing façade of the residential building with PU-adhesives. The insulation board will be cut on-site to the right dimensions. Then the layer of organic primer will be applied to the surface of the insulation board to make the façade immediately waterproof.

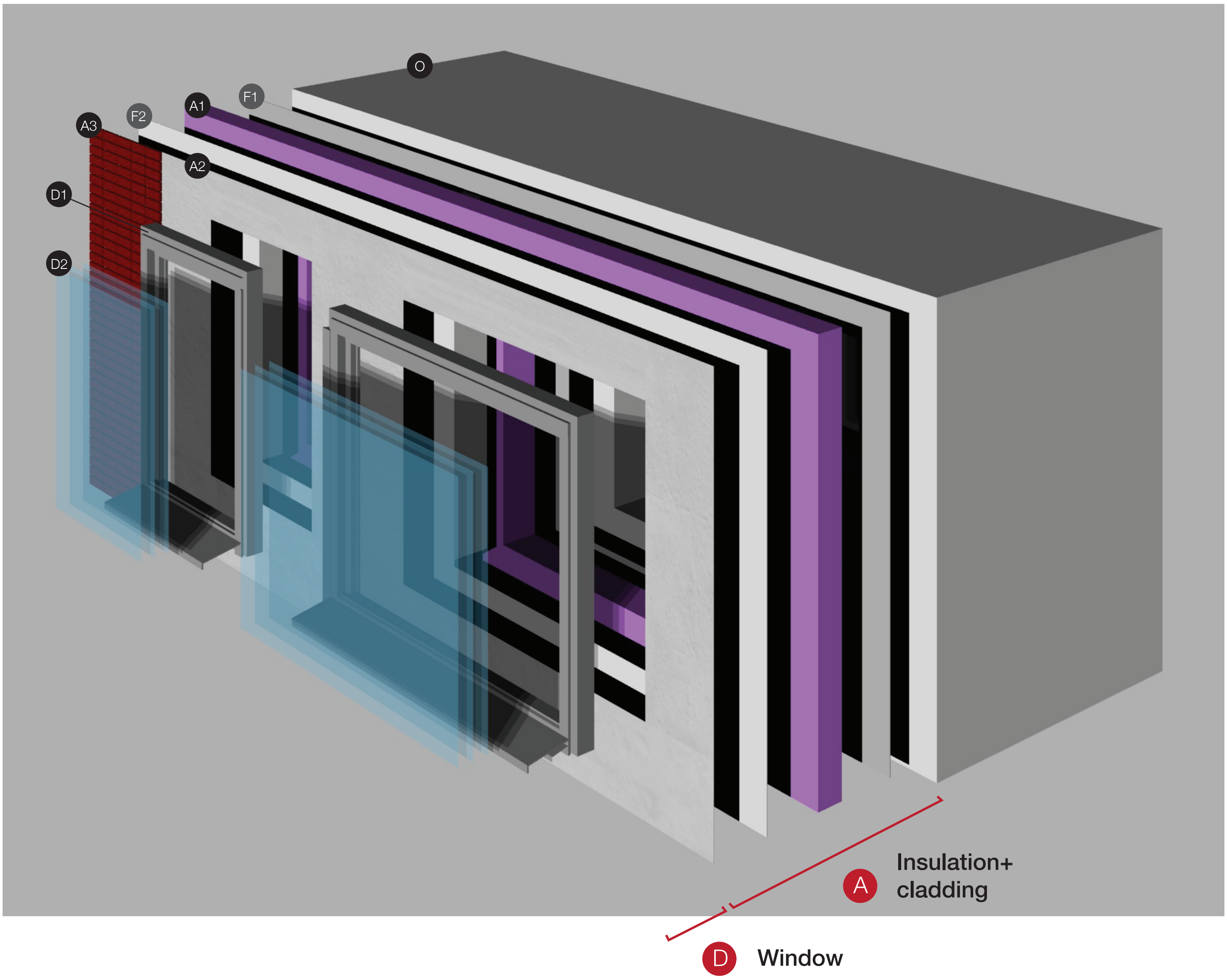
<u>Step 7:</u> Then the finishing layer of plaster and at certain locations brick strips will be applied to the surface of the EPS insulation board, connected with meshed mortar.

<u>Step 8:</u> The new balconies will be placed, supported by steel columns. The balconies will still be connected to the existing façade through anchors with a thermal break.

<u>Step 9:</u> Lastly, the separate installation unit with will be built. The unit is made of a timber framed structure and can be built quickly in one week. The facade cladding of the unit will connected to the timber frame with Aqua panels. These panels enable removal of the plaster and brick cladding without damaging the timber frame structure.

Fig. 41: Visit building site Vlaardingen (18-11-2018)
(source: own photos)

Because most elements the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system consists of, are chemically connected, the elements can't be removed separately. Only the window is connected directly to the existing façade, separately from the rest of the façade. For this reason, in the circularity assessment of the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system, the insulation and cladding are considered as one façade component and the window as the second facade component.

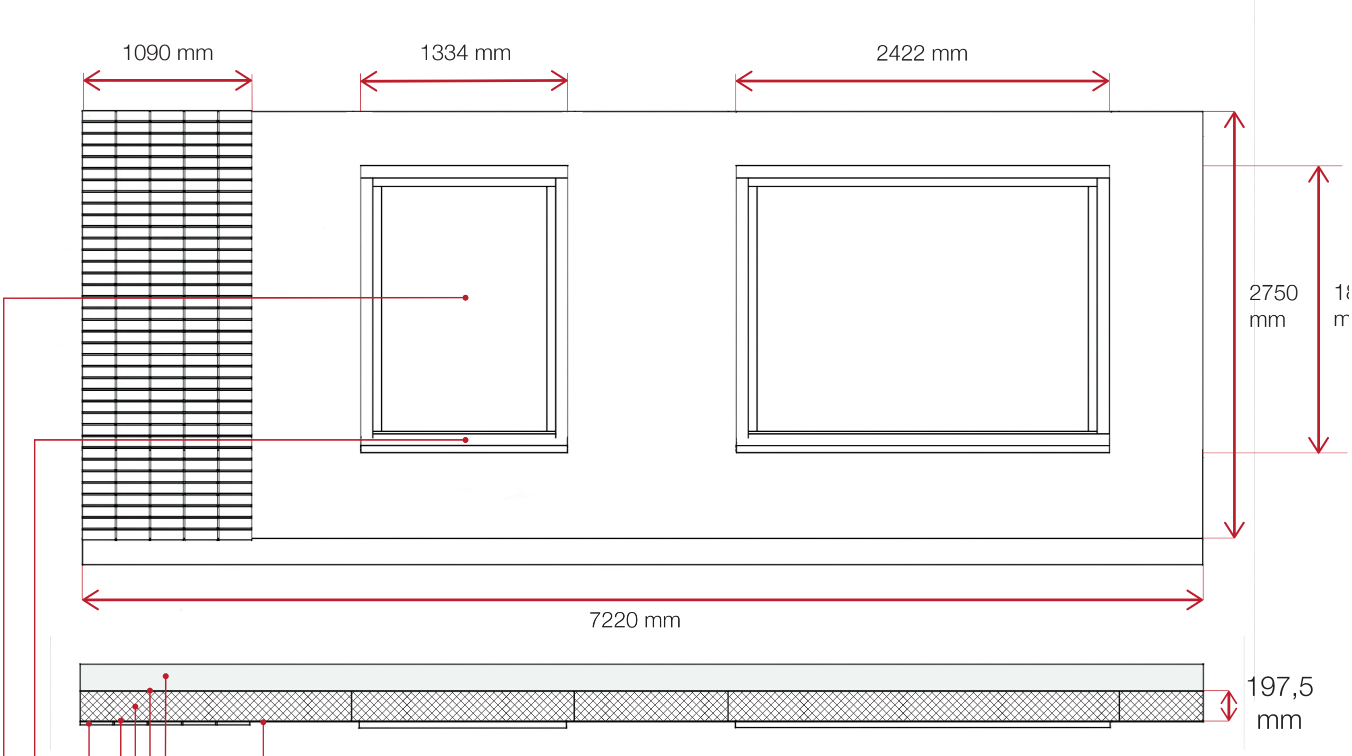


<u>Components:</u>

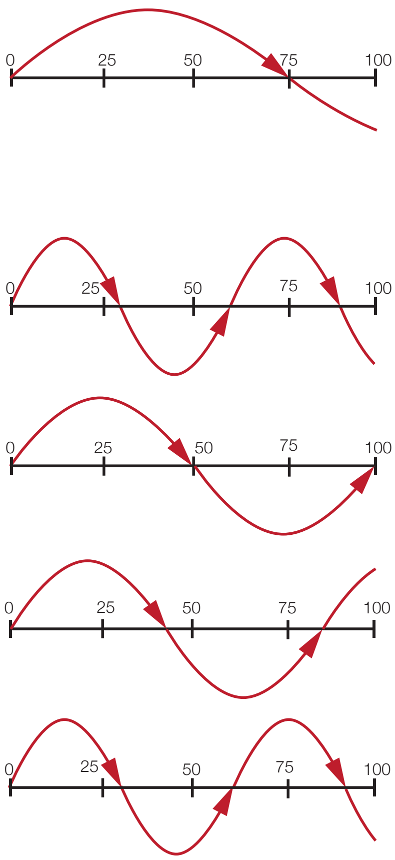
O	Existing facade
A1	Insulation
A2	Plaster
A3	Brick strips
D1	Window frame
D2	Triple glazing

<u>Fixing devices:</u>

F1	Adhesive
F2	Mortar
F3	Screw



	Life cycle (yrs)	End of life scenarios			
O Existing facade					
F1 PU-adhesive 3 mm					
A1 EPS insulation 190 mm		0%	5%	5%	90%
F2 Mortar 3 mm					
A2 (1) Organic plaster 1,5 mm		0%	0%	10%	90%
A2 (2) Brick strips 20 mm		0%	0%	91%	9%
D1 PVC on steel core		0%	77%	8%	17%
D2 Triple glass HR++		0%	70%	30%	0%



Assessment of the complete system

The main materials the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system consists of, is EPS insulation board, plaster and brick strips.

For the insulation layer the synthetic, rigid material EPS (expanded Polystyrene) is chosen. EPS insulation boards are available in the following dimensions: 1000 x 500mm, 1000 x 1000mm, 2000 x 1000mm and 2000 x 1250 mm. The EPS boards will be connected to the existing façade with PU112-adhesives. The EPS insulation boards are integral connected through the geometry of the components' edge to prevent water leakage into the structure. When the EPS board maintain undamaged after disassembly of the building, it can be 100% reused (Kingspan, n.d.). However, tests on the building site at the Soendalaan in Vlaardingen has proven that the EPS-insulation can't be removed undamaged from the existing façade, due to the strength of the PU-adhesive. The PU-adhesive leaves traces behind on the surface of the existing façade, that are difficult to remove (fig. 42). However, when the EPS is still considered to be recyclable, Kingspan will collect the EPS waste material and use it for the production of new EPS boards (Kingspan, n.d.). When recycling of the EPS is impossible, incineration will be the preferred option at the end of life (Haas, 2012).

The organic plaster Stolit K, produced by material supplier Sto, consists of 5% organic substance. The plaster is applied to the wall on top of the organic primer with a RVS trowel. Then the plaster needs to dry for 14 days. After around 30 years the plaster has reached the end of its technical life (Sto Isoned bv, 2017), which can be recognised when the plasterwork is tearing and peeling off. However, none of the material can be reused or recycled, because the high level of conflation between the organic plaster, primer and insulation layer prevents disconnection (Hildebrand, 2014). The plaster can be removed by milling, grinding, brushing, polishing or blasting, but damaging of the surrounding materials is unavoidable. When removal of the plaster is impossible, the plaster will be disposed together with the primer and insulation material, ending up in landfill or incineration (Zelger, Figl, Scharnhorst, Lipp, & Waltjen, 2017).

The only façade component that can be removed and reused or recycled at the end of the functional life of the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system, is the PVC window frame. The PVC window frame is the only component that is separately attached to the existing wooden window frame of the residential building with a screwed connection. According to the Nationale Milieudatabase, in general around 70% of the HR++ double and triple glazing, used in the Netherlands, will be recycled. The PVC window frames with a steel core, made of 37% recycled content, have a recycling rate of 77% (Haas, 2012). According to the material supplier, K-vision, the PVC material can be reused up to 10 times for the production of new window frames ((K-vision, 2017).

Fig. 42: Photos visit building site Vlaardingen (18-11-2018); placement and removal of EPS insulation board, (source: own photo)

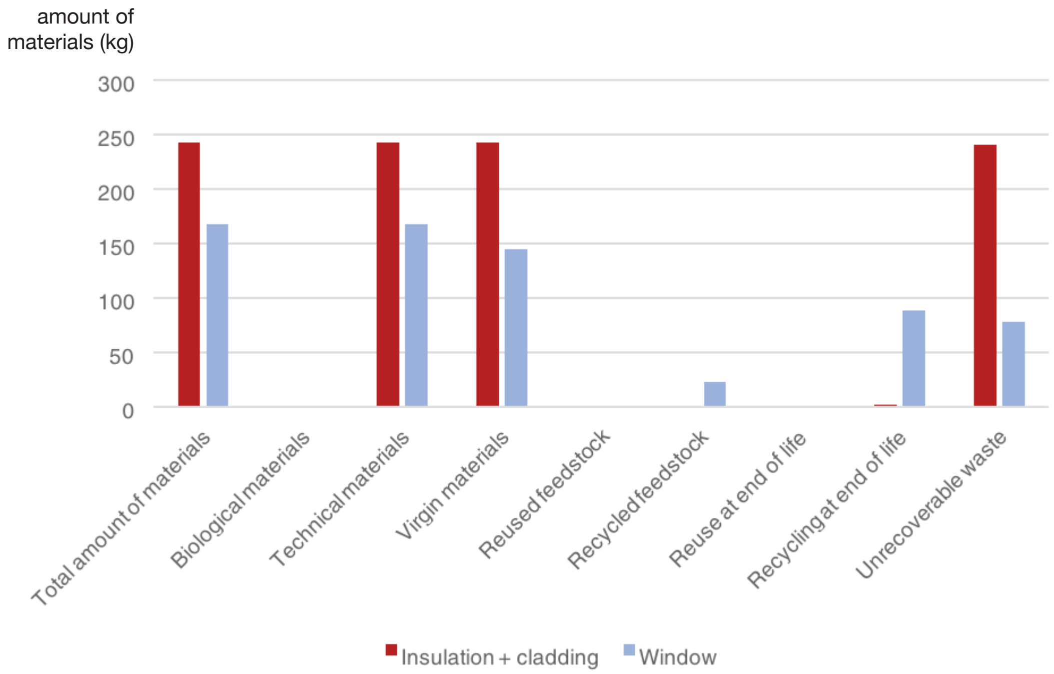


Fig. 43: Graph MCI assessment results Prefabricated variant (source: own image)

Material analysis

When comparing the MCI assessment results of the separate building components the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system consists of, the following conclusions can be drawn, based on the graph shown above (fig. 43):

- In the facade refurbishment system all used materials are technical, and thus non-biodegradable.
- The materials, used for the exterior insulation layer and cladding package, don't contain any reused or recycled feedstock, but are completely made of virgin materials. On the other hand, the window frame and glazing does contain a certain percentage of recycled feedstock.
- At the end of life none of the materials of the insulation layer and cladding package can be reused or recycled, but all end up as unrecoverable waste, due to the irreversible chemical connections between the elements. The window frame can be removed from the facade without damage at its end of life and does have recycling potential.

For these reasons in the MCI assessment results can be seen that the insulation and cladding package have obtained a LCI-value of 1, which means the product is completely linear. Due to the effect of the relatively long technical lifespan of the component, compared to the expected functional lifetime of the refurbishment system, the MCI-value of the insulation and cladding package is 0,25, which means the product can't be considered circular (MCI<0,5). The window has obtained a lower LCI-value of 0,61, due to its percentage of recycled feedstock and recycling potential at the end of life. For this reason, the window can be considered to be more circular than linear (MCI>0,5).

Material Circularity Indicator (MCI)

Results:

Insulation + cladding

LFI
= 1,0

X
= 1,2

MCI
= 0,25

Window

LFI
= 0,61

X
= 1,2

MCI
= 0,54

Calculation:

Step 1: Calculation of the mass of the materials

Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)
Insulation			
PU-Adhesive	0,037	1200	44,707
EPS	2,360	15	35,393
Cladding			
Mortar	0,037	1500	55,884
Plaster	0,014	1800	25,437
Brick	0,051	1600	80,808
Window			
PVC	15,430 (m)	2,300 (kg/m)	35,489
Steel	15,430 (m)	1,370 (kg/m)	21,139
Glass	0,067	2500	110,258

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
Insulation				
PU-Adhesive	Technical	0%	0%	44,707
EPS	Technical	0%	0%	35,393
Cladding				
Mortar	Technical	0%	0%	55,884
Plaster	Technical	0%	0%	25,437
Brick	Technical	0%	0%	80,808
Window				
PVC	Technical	10%	0%	35,489
Steel	Technical	37% (efficiency 100%)	0%	13,318
Glass	Technical	10% (efficiency 80%)	0%	99,232

Step 3: Calculation of unrecoverable waste at the end of life of the materials

Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
Insulation			
PU-Adhesive	0%	0%	44,707
EPS	5% (efficiency 100%)	0%	33,624
Cladding			
Mortar	0%	0%	55,884
Plaster	0%	0%	25,437
Brick	0%	0%	80,808
Window			
PVC	77% (efficiency 100%)	0%	8,162
Steel	77% (efficiency 100%)	0%	4,862
Glass	70% (efficiency 20%)	0%	65,328

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Insulation + cladding	1,00	1,2*	0,25
Window	0,61	1,2	0,54

*The shortest lifespan of the materials, which is the lifespan of the mortar and the plaster, is chosen as lifespan for the complete façade component in the calculation, because when these materials have to be replaced, the other materials probably need to be removed as well due to the high chance of damage.

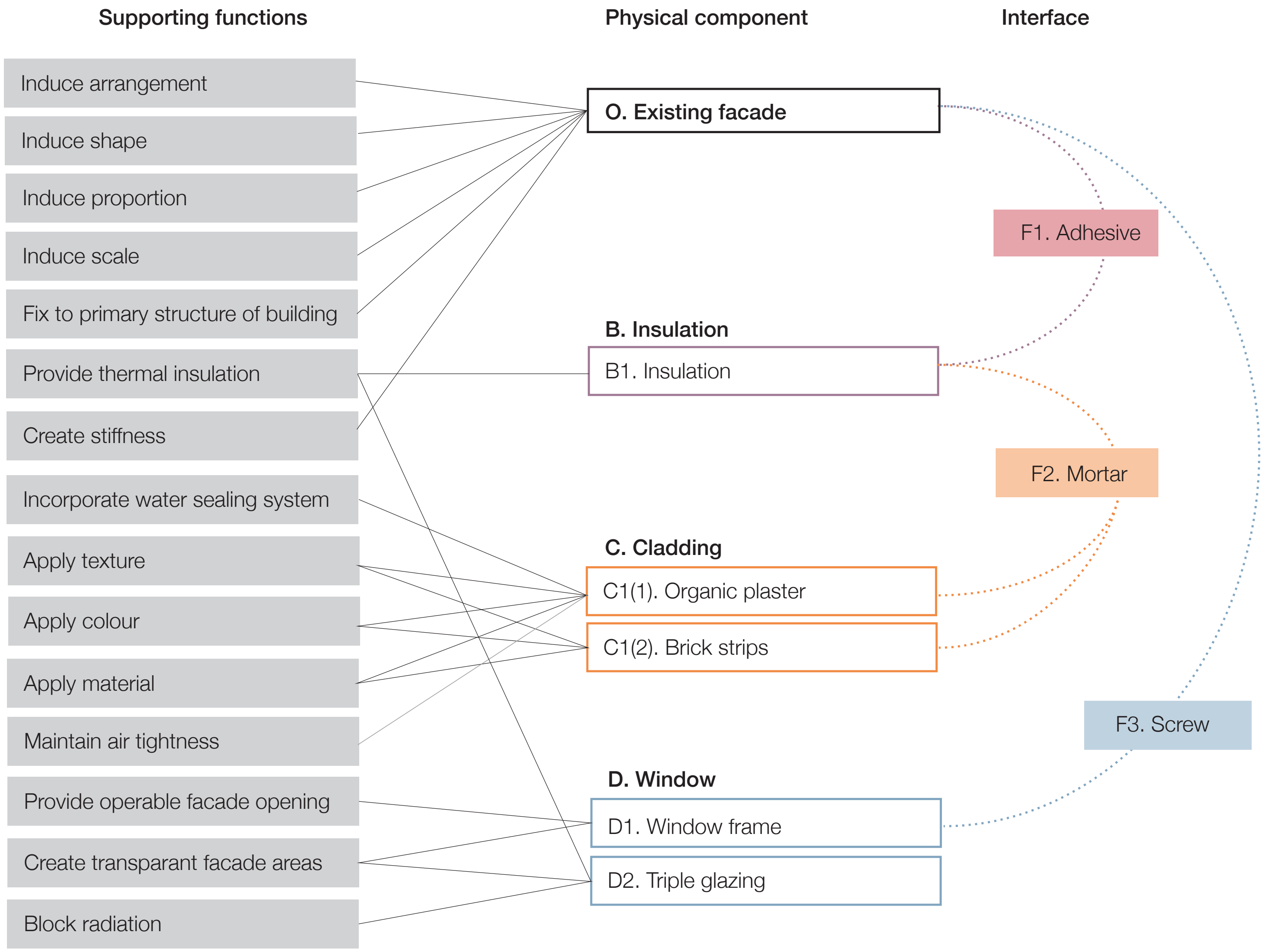


Fig. 44: Function structure Exterior Insulation variant (source: own image)

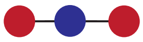
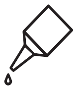
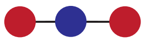
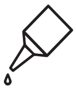
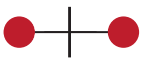
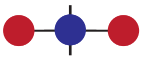
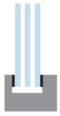
CONNECTION	CONNECTION DIAGRAM	INTERFACES	TYPE	ASSEMBLY	GRADING
A1 - O (F1 = connection material)			1. Indirect 2. Chemical material	1. Surface contact	-
A2(1) - A1 (F2 = connection material)			1. Indirect 2. Chemical material	1. Surface contact	-
A2(2) - A1 (F2 = connection material)			1. Indirect 2. Chemical material	1. Surface contact	-
D1 - O			1. Direct 2. Additional fixing device	1. Screwed	+/-
D1 - D2 (gasket = third component)			1. Indirect 2. Third independent	1. Surface contact	++

Fig. 45: Connection analysis of the Exterior Insulation variant (source: own image)

Function structure

The function structure, illustrated in fig. 44, shows the support functions each façade element of the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system fulfils. As can be seen in the diagram, the main function of the added layer is the provision of thermal insulation, induced by the EPS insulation boards. The existing façade still maintains its original functions of inducing arrangement, scale and proportion, next to creating stiffness and making the connection to the primary structure of the building. The plaster and brick strips cladding apply texture, colour and material to the new façade. Next to that, the plaster makes the new façade waterproof and airtight. The main function of the new window is to create transparent façade areas, at the same location as the original windows of the existing facade. Next to that, the triple glazing increases the thermal resistance of the open parts of the façade, and thus also fulfils the function of providing thermal insulation.

Connection analysis

As can be seen in the diagram (fig. 45) most materials within the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system, are connected through wet interfaces, while dry connections are preferred when designing for disassembly. The EPS insulation layer (A1) is connected indirectly to the existing façade with the use of a third chemical material, PU-adhesive (F1). Consequently, the cladding materials, the plaster (C1(1)) and brick strips (C1(2)), are also connected with a third chemical material, namely mortar (F2), to the EPS insulation layer. Only the PVC window frame (D1) is attached to the existing window frame (O) with a dry connection method (F3). The triple glazing (D2) is hold into place in the window frame by the use of gaskets. Due to the high amount of chemical connections, the cladding and exterior insulation layer can't be removed from the existing façade without damaging the underlying structure. Only the triple glazing and window frames can be removed and disassembled to enable reuse.

Disassembly Potential

Functional decomposition (FD)
There is a high level of functional integration in the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system. The EPS insulation layer is directly chemically connected to existing façade. The brick and plaster cladding is directly chemically connected to the EPS insulation. For this reason, the combination of the insulation layer and the cladding should be considered as one façade component that serves multiple functions: providing thermal insulation as well as providing air- and water tightness and applying texture, material and colour to the façade. A separate component of the Exterior Insulation variant is the window, which is individually connected to the existing window frame of the façade. The Exterior Insulation variant can't exist independently from the existing façade of the residential building. The existing façade still fulfils most of the functions. For these reasons, the added 2nd Skin façade becomes static and fixed, resulting in a low level of functional decomposition. *(Score: 1)*

Systematisation (SY)
The Exterior Insulation variant of the 2nd Skin Facade Refurbishment system consists of two clusters. The window can be considered as one high level sub-assembly on component level, which is pre-assembled in the factory, bespoken to the varying dimensions of the façade openings of the different residential buildings and installed as a completed product on-site, including triple-glazing. The combination of insulation and cladding can be considered as a sub-assembly on material level. The insulation and cladding materials need to be dependently arranged on-site to form the additional façade, chemically connected with adhesives to the existing façade. The insulation and cladding materials need to be assembled in a defined order and form an inseparable package with the existing façade. When one material needs to be replaced, the complete package needs to be removed from the façade and there is a high chance all materials will be damaged an have to be replaced. Concluded, the systematisation of the Traditional Refurbishment system takes place at material and component level, which is inconvenient for disassembly of the façade. *(Score: 3)*

Relational Patterns (RP)
The relational diagram of the Exterior Insulation variant is mainly vertically oriented. The plaster and brick cladding are directly connected the EPS insulation, which is in turn directly chemically connected to the existing façade. The triple glazing is directly connected to the window frame, which is in turn separately connected to the old window frame of the existing façade. The existing façade forms the horizontal connection between the two clusters. The relation diagram leads to a shared assembly. This open hierarchy within the system, is convenient for the disassembly of the façade, because the two clusters can be independently removed. Because of the vertical relational patterns between the two clusters, the Traditional Refurbishment scores high in this category. *(Score: 10)*

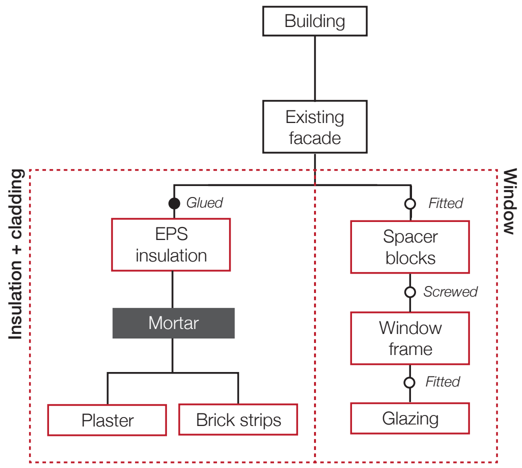


Fig. 46: Relational Pattern of the Traditional Refurbishment System (source: own image)

Base Element specification (BE)
The Exterior Insulation variant of the 2nd Skin Facade Refurbishment system lacks a base element. The two clusters are directly connected to the existing façade, without the intervention of a third independent component. When the existing façade of the residential building will be removed, the additional 2nd Skin façade of the Exterior Insulation variant can't stand on its own. The missing third base element in the system complicates the disassembly of the 2nd Skin façade system. *(Score: 1)*

Geometry (GE)
The geometry of the edges of the materials of the Exterior Insulation variant is different for every element. The EPS insulation plates have grooved edges, that slide into each other. The connection between the plates is integral and interlocking on two sides. The mortar and plaster are just spread over the EPS insulation and thus have an open, linear geometry. Also the bricks, that are chemically connected with mortar, have a linear geometry. Only the prefabricated window frame has symmetric overlapping edges, that fit precisely in the existing wooden window frame with the use of wood adjusting blocks. The geometry of the EPS plates, the brick strips and the windows is made in the factory. The geometry of the plaster cladding is done on-site. This means the geometry is half-standardised, which is inconvenient for the disassembly of the system. *(Score: 5)*

Assembly Sequences (AS)
The assembly of the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system is mainly sequential, partly overlapping. The window is prefabricated in the factory and delivered as a complete package on-site, including triple-glazing. First the new PVC window frame is installed at the location of the existing window frame. Then the additional layer of EPS insulation is glued on top of the existing façade. Thereafter the plaster is connected to the EPS insulation through a layer of reinforced mortar. The brick strips need to be placed last, embedded in the mortar. Each material is fixed on place by the later assembled materials, so they can't be replaced without the removal of the other materials. The sequential assembly of the Traditional Refurbishment system leads to a relatively low grade in this category. *(Score: 3)*

Type of Connections (TC)
Almost all connections in the Exterior Insulation variant are wet and chemical. The chemical material that is used for the connection of the EPS insulation to the existing façade is PU-adhesive. The EPS insulation can only be removed mechanically, leading to a high chance of damaging the existing façade. The EPS insulation plates are connected to each other through integral, interlocking edges. The plaster and brick cladding are chemically connected to the EPS insulation with mortar. Only the window frame is dry connected to the existing window frame with the use of wooden adjusting blocks as independent third material. The glazing is also indirectly dry connected to the window frame with gaskets. The use of chemical connections need to be prevented when designing for disassembly. For this reason, the Traditional Refurbishment system will obtain a low score in this category. (Score: 2)

Life Cycle Coordination (LCC)
The materials of the Exterior Insulation variant with the shortest technical life cycle, are the plaster and the underlying mortar. The plaster is situated at the outermost surface of the façade, so is uncovered. When the plaster needs to be removed, there is a high chance of damaging the EPS insulation layer, which as the longest life cycle of the system of 75 years, underneath the plaster. Also the triple glazing has a lifetime of 30 years. Because the window frame is connected directly to the existing façade, the glazing can be removed without touching the insulation layer and cladding of the 2nd Skin facade. The EPS insulation has the longest lifespan and is situated closest to the existing façade. This is convenient in terms of Design for Disassembly. (Score: 8)

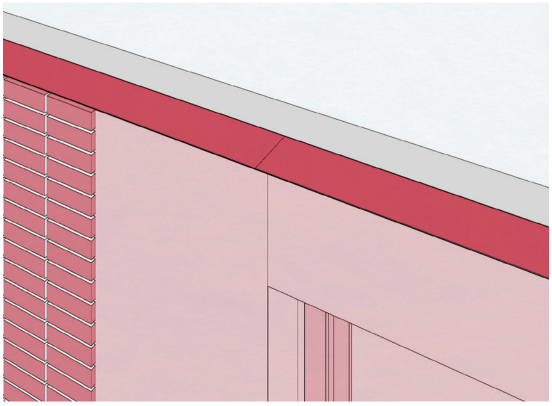
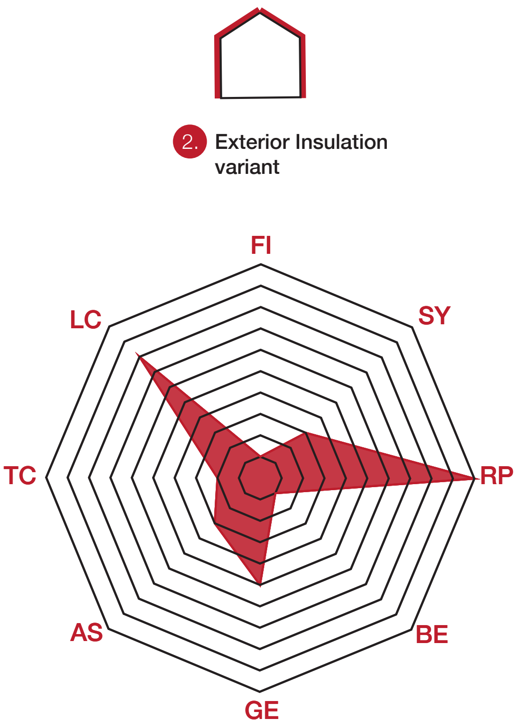


Fig. 47: Life Cycle Coordination of the Exterior Insulation variant (source: own image)

Technical lifetime
75 years
50 years
40 years
30 years



FI Functional Independence
SY Systematisation
RP Relational Patterns
BE Base Element Specification
GE Geometry of the Edge
AS Assembly Sequence
TC Type of Connection
LC Life Cycle coordination

Fig. 48: Disassmbly Potential evaluation of the Traditional Refurbishment system (source: own image)

		1. Prefabricated variant		2. Exterior Insulation variant
		Option 1: Brick cladding	Option 2: Bamboo cladding	
	Mass	1350 kg	1163 kg	409 kg
Feedstock	Biological	31%	61%	0%
	Technical	69%	39%	100%
	2nd Reused feedstock	0%	0%	0%
	2nd Recycled feedstock	19%	26%	4,6%
End of life scenarios	Reuse	0,4%	0,4%	0%
	Recycling	14%	22%	22%
	Landfill	35%	9%	31%
	Incineration	48%	64%	39%
Material Circularity Indicator	LFI (Linear Flow Index)	0,84	0,76	0,83
	X (Utility factor)	2,0	1,4	1,2
	MCI (Material Circularity Indicator)	0,62	0,51	0,38

Fig. 49:
Comparison of the MCI assessment results (source: own image)

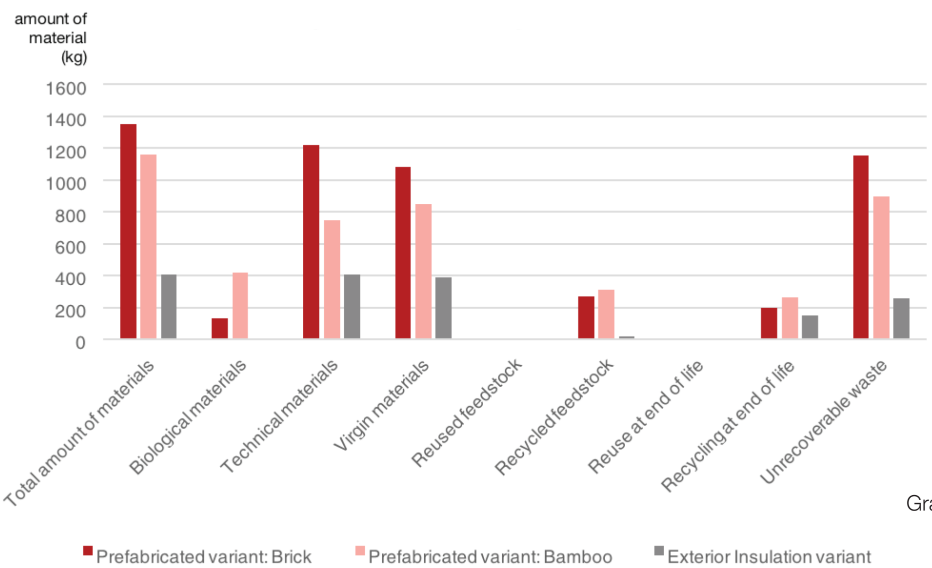


Fig. 50:
Graph calculation results MCI assessment (source: own image)

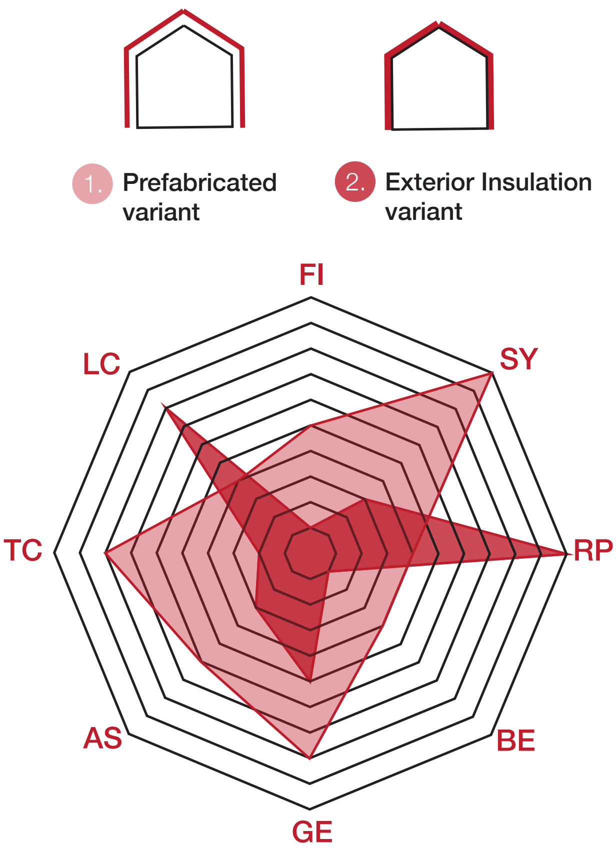
Comparison

Material Circularity Indicator
From the material circularity assessment of the two variants, the Prefabricated variant and the External Insulation variant of the 2nd Skin Façade Refurbishment system, performed with the Material Circularity Indicator, developed by the Ellen MacArthur Foundation and Granta Design (2015), the following conclusions can be drawn:
First of all, important to take into account is that the mass of the External Insulation variant of the 2nd Skin Facade Refurbishment system is significantly lower than the mass of the Prefabricated variant. Next to that, certain materials are used in both variants; the EPS insulation, the PVC window frames and HR++ triple glazing. The External Insulation variant contains a similar type of brick strips cladding as the first cladding option of the Prefabricated variant, only in a smaller amount.

Feedstock
When comparing the mass of the two variants, the External Insulation variant consumes considerably less virgin materials than the Prefabricated variant. The materials that are used in the External Insulation variant all belong to the technical cycle in the diagram of the Ellen MacArthur Foundation (see fig. 7, page 29). The Prefabricated variant consist of certain materials from the biological cycle, namely pinewood, that are part of the substructure and the Structural Insulated Panels. The two cladding options also make a difference: the bamboo cladding consists for a big part of materials from the biological cycle, while the brick cladding consists of only materials from the technical cycle. The percentage of secondary feedstock is also substantially higher in the Prefabricated variant, compared to the Exterior Insulation variant. The materials that contain secondary feedstock, are the chipboard in the Structural Insulated Panels, the stainless-steel anchors in the substructure, the steel core of the PVC window frame and the triple glazing. Next to that, the aluminium mounting profile and the stainless-steel clips of the bamboo cladding also contain secondary recycled feedstock, which explains its higher percentage compared to the brick cladding option. None of the two variants contain reused materials.

End of life scenarios
When looking at the amount of unrecoverable waste at the end of life of the two variants, remarkable are the equivalent percentages of the Prefabricated variant option 1 (brick cladding) and the Exterior Insulation variant. The cladding of the Exterior Insulation variant consists of materials with similar end of life scenarios as the brick cladding of the Prefabricated variant option 1. Due to the irreversible connection of the bricks strips to the EPS insulation underlayer, the brick cladding system can't be recycled. The plaster, that is used as cladding in the Exterior Insulation variant, also can't be recycled and at the same time limits the recycling possibilities of the other materials. For this reason, the recycling percentage of the Exterior Insulation variant is lower than the Prefabricated variant. The recycling percentage of the Prefabricated variant with bamboo cladding is higher than the Prefabricated variant with brick cladding, because the supporting structure of the bamboo cladding has a high recycling potential. However, the bamboo slats will be incinerated at the end of their technical lifetime for energy revoery. The only elements of the Prefabricated variant that have reuse potential, are the stainless-steel anchors. Their weight is relatively low compared to the total weight of the system. For this reason, the reuse percentage of the complete system is very low. None of the materials of the Exterior Insulation variant can be reused. Most of the unrecoverable waste of the two refurbishment systems will be incinerated at the end of the functional life of the 2nd Skin Facade Refurbishment system. The Prefabricated variant with the bamboo cladding, that contains most biological materials, also has the highest percentage of waste incineration.

MCI-value
When looking at the LCI-values, both variants tend to be more linear than circular. The LCI-values of the two variants are high, ranging from 0,76 to 0,84; all three come closer to 1 (= fully linear) than to 0 (= fully circular). The second option of the Prefabricated variant has the lowest LCI-value, because the bamboo cladding system has a significantly higher recycling percentage and thus a lower percentage of unrecoverable waste than the brick cladding. The first option of the Prefabricated variant with the brick cladding has the highest LCI-value, because the brick cladding system contains neither recycled feedstock nor has the recycling potential at the end of life. The Exterior Insulation variant has a slightly lower LCI-value. When taking into consideration the lifespan of the two variants, the MCI-value of the Exterior Insulation variant is the lowest (0,38). The plaster cladding of the Exterior Insulation variant has a very short lifespan of 30 years. Because the plaster is directly chemically connected to the other materials, the complete façade needs to be removed at the end of life of the plaster. The bamboo façade cladding also has a short lifespan of 35 years, but the bamboo slats can be removed from the facade without damaging the surrounding facade components. The Prefabricated variant with brick cladding has the highest MCI-value of 0,62, due to its long lifespan.



FI	Functional Independence
SY	Systematisation
RP	Relational Patterns
BE	Base Element Specification
GE	Geometry of the Edge
AS	Assembly Sequence
TC	Type of Connection
LC	Life Cycle coordination

Fig. 51:
Comparison of the results of the connection assessment (source: own image)

Disassembly Potential
When looking at the circularity assessment of the connections, on the basis of the eight criteria of the Disassembly Potential tool, developed by Durmisevic (2010), some notable differences can be found between the Prefabricated variant and the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system:

Functional independence (FI)
When looking at the analysis of the functional independence of the two variants, the Prefabricated variant scores best. However, in both variants there is a considerably high level of functional integration, which is inconvenient for the transformation of the facade. In the Exterior Insulation variant most functions are integrated in one façade package, with the exception of the window. In the Prefabricated variant there is better separation of functions, but there is still functional integration within components of the system. Most functions are integrated in the Structural Insulated panels; the ventilation pipes, insulation and stiffeners. For this reason, the SIP-panels are considered as the weakest element of the Prefabricated variant in terms of functional independence.

Systematisation (SY)
In terms of systematisation, the Prefabricated variant of the 2nd Skin Façade Refurbishment system has reached the highest score, while the Exterior Insulation variant scores lowest. Systematisation of the Exterior Insulation variant takes place at material level, which needs to be prevented when designing for disassembly. On the contrary, systematisation of the Prefabricated variant takes place at component level, which is the preferred level for disassembly. The four components that the Prefabricated variant consists of, are prefabricated in the factory, while the elements of the Exterior Insulation variant mainly need to be assembled on-site. Pre-made geometry is preferred to increase the level of standardisation of the product.

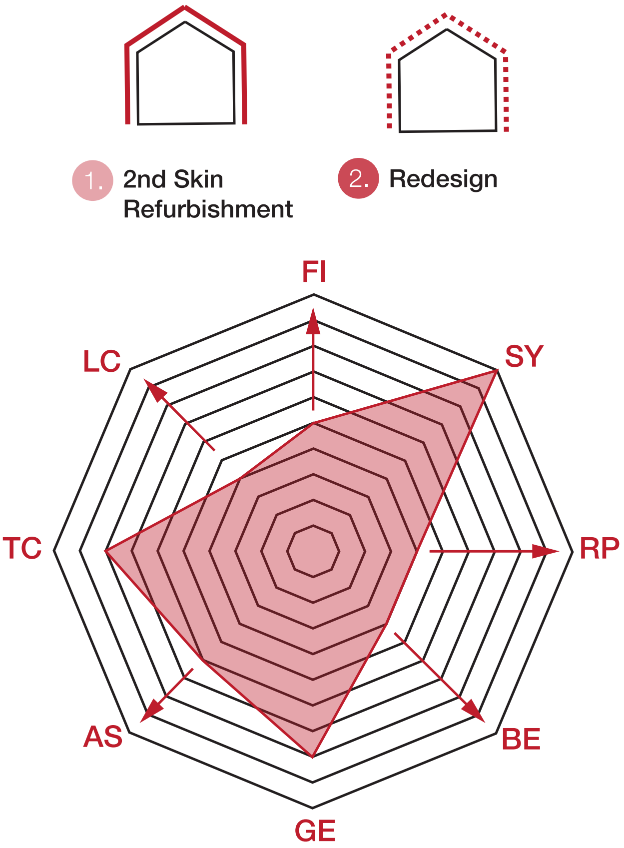
Relational Patterns (RP)
When looking at the Relational Patterns of the two variants, the Exterior Insulation variant has reached the highest score and the Prefabricated variant a lower score. This difference is caused by the position of the relationships between the components in the relational diagram. The components of the Prefabricated variant are all horizontally connected to each other in the middle part of the diagram. The main connection element between the components is the chipboard, which is part of the SIP-panels. On the contrary, the relational diagram of the Exterior Insulation variant is completely vertically oriented. The two clusters (window and insulation + cladding) are independently connected to the existing façade in a shared assembly, which is convenient for the disassembly of the system.

Base Element specification (SY)
The difference between the two variants in this category, is that the Prefabricated variant contains a base element, while the Exterior Insulation variant lacks an independent base element. The base element of the Prefabricated variant is the chipboard, which is part of the SIP-panels. However, the chipboard fulfils other functions, so the grading of the Prefabricated variant in this category isn't the highest.

Geometry (GE)
The geometry of the components of the Prefabricated variant is pre-made in the factory and most of the components are also pre-assembled in the factory. In the Exterior Insulation variant, most components are assembled on-site. Only the windows are prefabricated. Half-standardised geometry is considered to be inconvenient for the Disassembly Potential of the system, so in this field the preference will go to the Exterior Insulation variant.

Assembly Sequence (AS)
The assembly sequence of the Exterior Insulation variant is mainly sequential. Due to the high level of prefabrication, the assembly sequence of the Prefabricated variant is partly overlapping. The prefabricated components of the Prefabricated variant only have to be connected to the existing facade on-site. However, each component is fixed on place by the later assembled components, resulting in linear dependencies between the components in the Prefabricated variant. This means some components, such as the SIP-panels and the substructure, get stuck in the assembly. For this reason, the assembly sequence of the Prefabricated variant has to be improved, when designing for disassembly.

Type of Connections (TC)
The Exterior Insulation variant of the 2nd Skin Façade Refurbishment system mainly consists of wet, chemical connections, that are difficult to break without damaging the surrounding materials. The connections between the four different components of the Prefabricated variant are all dry, which is preferred for the disassembly of the system. However, some connections within the components, such as the SIP-panels, are chemical and have to be improved.



FI	Functional Independence
SY	Systematisation
RP	Relational Patterns
BE	Base Element Specification
GE	Geometry of the Edge
AS	Assembly Sequence
TC	Type of Connection
LC	Life Cycle coordination

Fig. 52:
Ambitions for the redesign of the Prefabricated variant of 2nd Skin Facade Refurbishment system (source: own image)

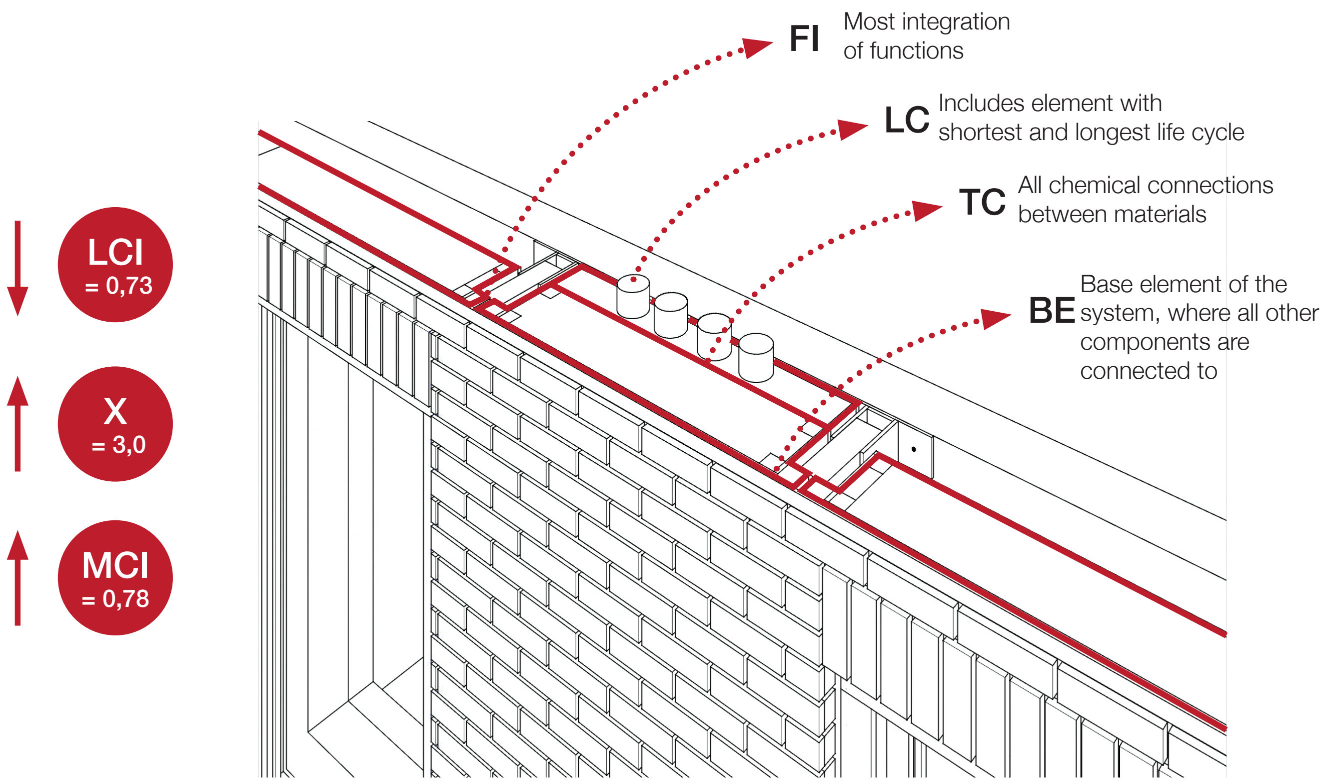


Fig. 53:
Opportunities for the redesign of the Structural Insulated Panels (source: own image)

Life Cycle Coordination (LC)
The main weakness of the Prefabricated variant in terms of Life Cycle Coordination, is the position of the building services within the Structural Insulated Panels. The ventilation pipes have the shortest technical life cycle of the complete system, but are situated the farthest from the surface and thus are most difficult to reach. In the Exterior Insulation variant the Life Cycle Coordination is better organised; materials with the shortest lifespan are positioned at the outermost surface of the facade, while the materials with the longest lifespan are positioned close to the existing façade.

Conclusion

In this chapter, the circularity assessment of the two variants of the 2nd Skin Façade Refurbishment system, the Prefabricated variant and the Exterior Insulation variant, is conducted. The materials that the two variants of the 2nd Skin Façade Refurbishment system consist of, have been assessed with the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design (2015). The connections between the materials and components that the two variants consist of, have been assessed on the basis of the eight performance criteria of the Disassembly Potential, developed by Durmisevic (2010). As a result, we are now able to say to what extent the Prefabricated variant and the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system are considered to be “circular”.

The Prefabricated variant is considered to be more “circular” in terms of materials and connections, than the Exterior Insulation variant, because the Prefabricated variant has obtained a MCI-value of >0,5. This is mainly due to the amount of recycled feedstock present in the chipboard, that the Structural Insulated Panels consist of, and the stainless-steel anchors, that connect the 2nd Skin Façade to the existing façade. When comparing the two cladding options, the bamboo cladding option results in a higher MCI-value, because of its high recycling percentage and dry connection method. The brick cladding option has obtained a lower MCI-value, because most materials the brick cladding system consist of, end up in landfilll. When looking at the Disassembly Potential, the Prefabricated variant is designed for disassembly to some extent. Because of its high level of prefabrication, the extensive use of dry connections between the components and the systematised clustering of materials, the Prefabricated variant is the favourable option in terms of disassembly.

The Exterior Insulation variant is considered to be more “linear” in terms of materials and connections, compared to the Prefabricated variant. However, the system consumes significantly less virgin materials, due to its low weight, compared to the Prefabricated variant. The MCI-value indicates a grade <0,5, so follows a more “linear” than “circular” lifecycle. The reasons for the low MCI-value, are the small amount of reused and recycled feedstock, which is only present in the materials of the window frame, the short lifetime of the system and the impossibility to reuse components at the end of life. Also in terms of Disassembly Potential, the extensive use of wet connections between the materials has a negative effect on the disassembly potential at the end of life of the refurbishment system. Next to that, there is no clustering of materials and functional independence, so we could say the Exterior Insulation variant isn’t designed for disassembly.

Concluded, especially the Prefabricated variant has most potential to be optimised its level of circularity, as its MCI-value approaches 1 and many points are obtained for certain performance criteria of the Disassembly Potential. The component within the Prefabricated variant that has most potential to be improved, is the Structural Insulated Panel. The Exterior Insulation variant should be improved significantly, to be able to increase its level of circularity: in terms of connections, change from wet to dry, and in terms of materials, increase the amount of recycled and/or reused feedstock and increase the reuse and/or recycling possibilities of the materials at the end of life.

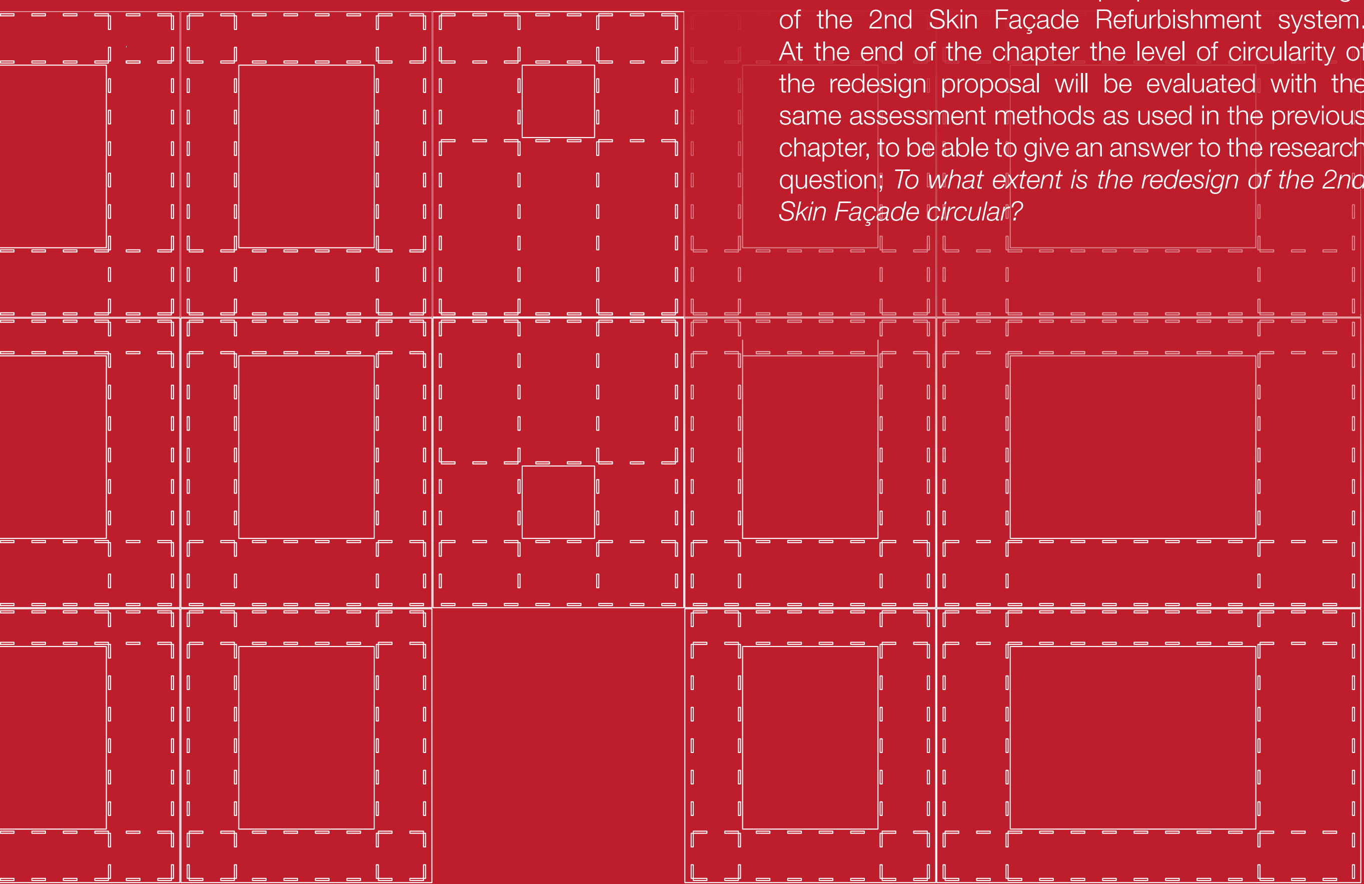
The next chapter will present improvement methods of the 2nd Skin Façade Refurbishment system, in the form of a Roadmap towards Circular Refurbishment and a proposal for the redesign of the Prefabricated variant of the 2nd Skin Façade Refurbishment system.

06

DESIGN PROPOSAL

The previous chapter elaborated on the circularity assessment of the two variants of the 2nd Skin Façade Refurbishment system, in terms of materials with the Material Circularity Indicator (MCI) and connections with the Disassembly Potential (DP).

In this chapter, based on the theoretical background regarding the principles of the Circular Economy in the built environment and the results of the circularity assessment of the two variants, a Roadmap for Circular Façade Refurbishment is developed. The Roadmap will give an answer to the research question; *How could the level of circularity of the 2nd Skin Façade be improved in terms of materials and connections?*. The Roadmap will be validated on the basis of a proposal for a redesign of the 2nd Skin Façade Refurbishment system. At the end of the chapter the level of circularity of the redesign proposal will be evaluated with the same assessment methods as used in the previous chapter, to be able to give an answer to the research question; *To what extent is the redesign of the 2nd Skin Façade circular?*



Limitations
The circularity assessments of the two variants of the 2nd Skin Façade Refurbishment system have shown that the Prefabricated variant has most potential to be optimised in terms circularity, due to the choice of materials and the used connection methods. However, the system has scored a MCI-value of 0,62 (option 1) and 0,51 (option 2), so there still is room for improvement when looking at reuse- and recyclability of the materials. While there is already a high level of prefabrication, systematisation and use of dry connections between the components, the Disassembly Potential of the system can still be improved when looking at the Functional Independence (FI), Relational Pattern (RP), Base Element Specification (BE) and Assembly Sequence (AS) of the system.
When zooming into the different components of the 2nd Skin Facade, there is much difference in MCI-value, ranging from 0,43 (windows) to 0,80 (substructure). Also the type of connections between the elements within each component differs from dry to wet connections. When looking at the Disassembly Potential, the Structural Insulated Panels are considered to be the weakest link of the Prefabricated variant of the 2nd Skin Façade Refurbishment system. Most connections between the elements within the SIP-panels are chemical. Next to that, most functions are integrated in the SIP-panels, it includes the material with the longest (EPS insulation) and shortest lifecycle (PVC ventilation pipes) and it is the base element of the system to which all other components are connected.
For these reasons, the design proposal for the redesign of the Prefabricated variant of the 2nd Skin Façade Refurbishment system will be focussed on the optimisation of the Structural Insulated Panels (SIP), in terms of reuse- and recyclability of materials and reversibility of connections.

Problem statement
The problems of the Structural Insulated Panels, that shape the Prefabricated variant of the 2nd Skin Façade Refurbishment system, are the following:

- The dimensions and arrangement of the SIP-panels depend on the existing façade of the residential building. This interferes with the reusability of the SIP-panels on different facades of other post-war residential buildings. The dimensions of the panels can only be reduced by cutting off material. However, this would lead to valuable material loss, so should be prevented. And this would affect the accuracy of the dimensions and the stiffness of the panel. Thus the standardisation of the elements should be improved to increase their reuse potential.
- The materials used in the SIP-panels have limited recycling possibilities. Most of the material will be considered as unrecoverable waste and needs to be incinerated at the end of life. Only the PVC-pipes have a high recycling potential, when they can be removed undamaged from the panels. Next to that, the amount of reused and recycled feedstock for the production of the materials the SIP-panels consist of, is low. Only the chipboard contains a certain percentage of recycled wood shavings.
- The connections between the chipboard, EPS insulation and the pinewood stiffeners are all chemical. This type of connection is irreversible, thus limit the Disassembly Potential of the system. The ventilation pipes are connected to the EPS insulation through premade geometry, so they are impossible to remove from the SIP-panels without damaging the surrounding EPS insulation board.
- The functional lifespan of the SIP-panels is the highest of all components in the 2nd Skin Refurbishment system. An important part of the strategy of the 2nd Skin Façade is to integrate the building services in the façade to make them easily accessible from the outside. However, the services have the shortest functional lifespan of the system. This material combination conflicts in terms of Life Cycle Coordination.
- The element of the SIP-panel that functions as base element of the complete system, is the chipboard. All other components of the 2nd Skin Facade Refurbishment system are directly or indirectly connected to this element. However, the chipboard isn’t an independent element, that allows components to be replaced without any effect on the other components.

Objective
The objective of the redesign of the 2nd Skin Façade Refurbishment system is to improve the connections of the Structural Insulated Panels, to allow dis- and reassembly, while also increasing the reuse- and recyclability of the materials that the SIP-panels consist of. The design proposal of the SIP-panels will be applied to two case study buildings with different facade arrangements: the case study building in Vlaardingen (p. 64-65) and another case study building in Rotterdam (p. 112-113). The aim is to enable exchange of façade components, in this case only the SIP-panels, between the two case study buildings. For this design proposal, the following steps will be taken:

1) Find alternative materials for the SIP-panels with better reuse- and recycling possibilities.
2) Redesign the connections between the elements of the SIP-panels and the surrounding components within the 2nd Skin Façade Refurbishment system.
3) Increase the standardisation of the elements within the SIP-panels to enable component exchange between two different existing façades of residential buildings that are in need of refurbishment.

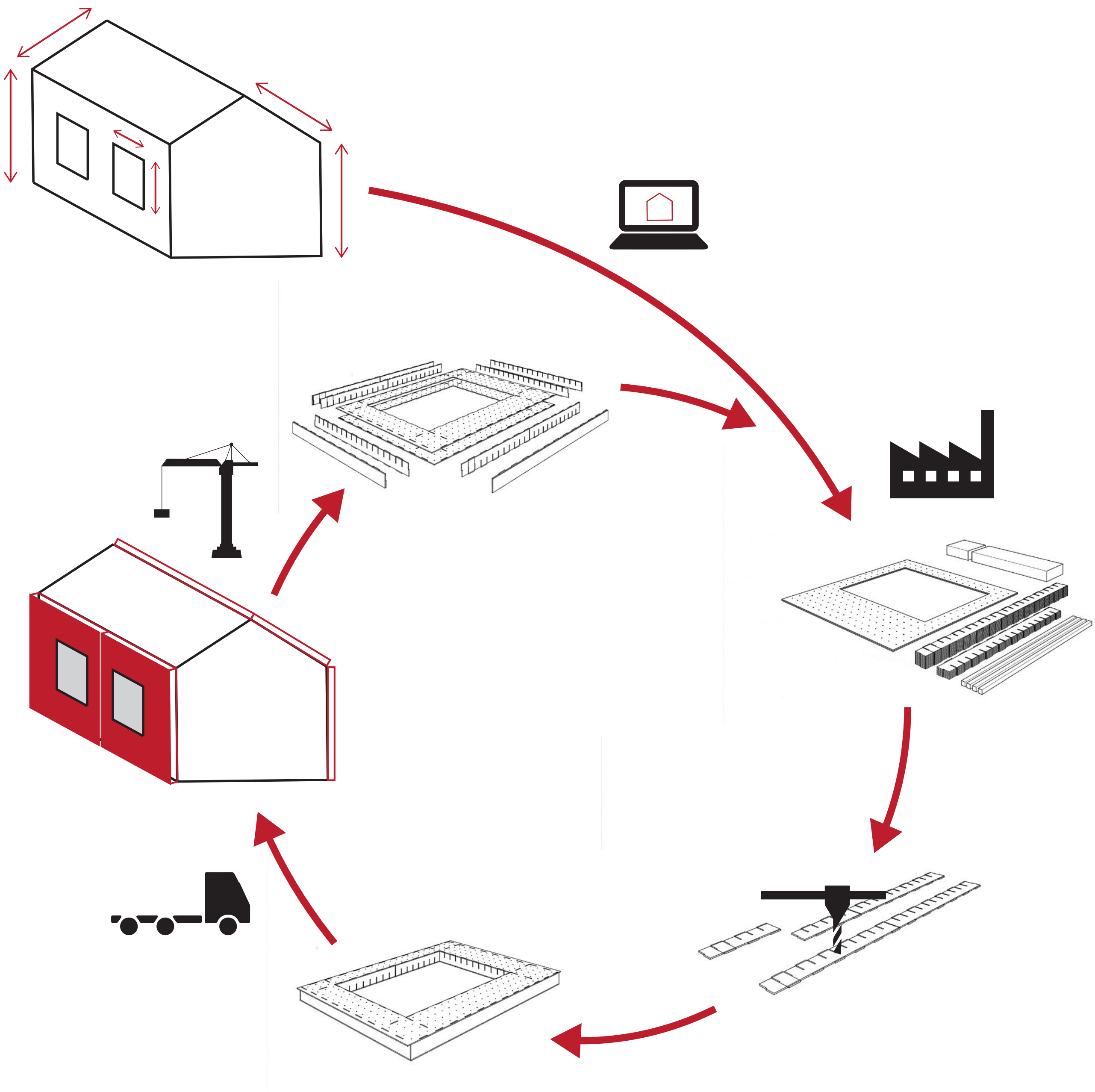


Fig. 54:
Daigram, explaining the concept
(source: own image)

Concept

The aforementioned problems of the 2nd Skin Facade Refurbishment system, in specific the Structural Insulated panels, leaded to the objectives for the redesign. These criteria will be translated into a design concept, that will form the basis for the development of a Circular 2nd Skin Facade Refurbishment system.

When hearing the vision of the contractors BIK Bouw, that are now in the process of refurbishing the case study building in Vlaardingen, their interest in upscaling the refurbishment system to the complete housing stock of the housing cooperation WijWonen became apparent. The housing corporation owns a high number of post-war residential buildings, around 180 dwellings, that are in need of deep refurbishment to meet the current energy requirements, appointed by the national building decree Bouwbesluit. Fellow housing corporations struggle with the same problem and miss the time and financial possibilities that a deep refurbishment of their housing stock needs.The main difficulty of upscaling the refurbishment to their complete housing stock, appeared to be the big differences in size and layout of the various post-war residential building typologies (BIK Bouw, personal communication, November 13, 2017).

Inspired by this demand, the idea arose to design a universal façade refurbishment system, that can be applied to any type of post-war residential buildings. One of the core principles of the Circular Economy is to enable direct reuse of components at the end of their functional lifetime, in order to extend the material loops without value loss. Preferred is to first encourage reuse within the same industry. For this reason, the concept of a facade refurbishment system is developed with a high level of standardisation to increase the reusability of components. The idea is that these standardised components will be stored in a central warehouse. When a residential building is in need of refurbishment, as a first step the exact dimensions of the building will be measured, using digital technologies. The overall format of the building, including the dimensions and positions of the facade openings, will be taken into account. Digital 3D laser scanners, that are able to measure a high amount of points in a short timeframe with an accuracy of 2 to 4 mm, do already exist and have been used by the construction company BAM to measure buildings for the refurbishment-project De Stroomversnelling (BAM, 2015). Based on these accurate measurements, the dimensions of the prefabricated modules, that shape the 2nd Skin Facade Refurbishment will be defined, the frame as well as the infill of the modules, in accordance with a universal grid, that fits to all formats of all post-war residential building typologies. The standardised elements, that the prefabricated modules consist of, will be stored in the central warehouse, when the refurbished building has to be deconstructed at the end of its functional lifetime. When another residential building needs to be refurbished, as much as possible standardised elements from previously refurbished buildings, will be collected, assembled in new configurations, matching the different dimensions and format of the reference building. The prefabricated modules will be assembled off-site, including insulation, windows and cladding, then transported to the building site, where the modules will be attached to the existing facade of the building. At the end of its functional life, the added 2nd Skin Facade will be disassembled and the standardised components will be brought back to the warehouse, waiting to be reused for the refurbishment of the next residential building.

To demonstrate the applicability of a universal facade refurbishment system, a facade design is made for two case study buidings. Next to the case study building in Vlaardingen, introduced in chapter 5 (p. 64-65), a second case study building is chosen; a post-war residential building in Rotterdam with a different typology and facade arrangement (p. 112-113). Based on the facade arrangement of the two case study buildings, a grid will be defined that fits to the existing facade of both case study buildings. As a next step, the standardised elements, that the prefabricated modules consist of, will be designed, starting with the materialisation of the elements, followed by the design of the connections. As a result, the exact shape of the elements will be developed and the level of standardisation determined. The aim is to achieve as much as possible direct reuse of elements for the refurbishment of the two case study buildings, with as little remanufacturing as possible.

Case Study Building 1: Vlaardingen

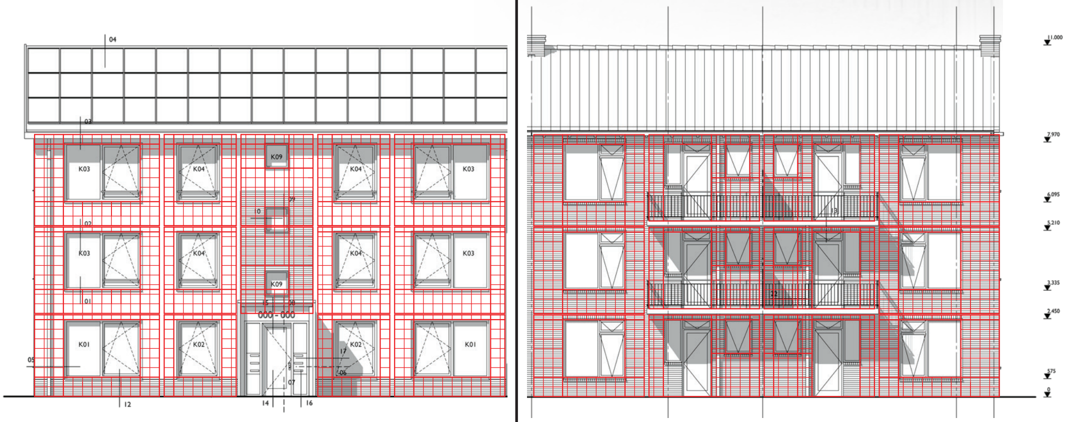


Fig. 55:
Front facade (left), back facade (right) with applied grid, Case Study Building 1 scale 1:200 (source: own image)

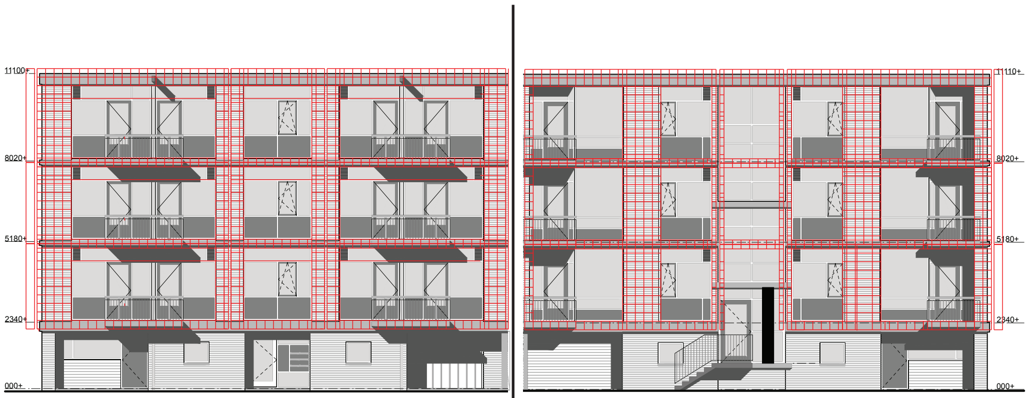


Fig. 56:
Front facade (left), back facade (right) with applied grid, Case Study Building 2, scale 1:200 (source: own image)

Case Study Building 2: Rotterdam

Case Study Building 2

In continuation of the 2nd Skin Façade Refurbishment project of Thaleia Konstantinou, Olivia Guerra-Santin et al., the same case study buildings are chosen for this research. The second case study building is situated in Rotterdam at the Schere (fig. 57). This type of post-war residential building is considered to be the most common type in the area of Rotterdam-Zuid and offers the best market for carbon reduction opportunities, due to the low thermal performance of the facade and the high number of residential buildings, built according to this building method.

The case study building is a mid-rise apartment block with a central staircase, accessible from the front façade. The building is three-story high and consists of four apartments per floor. The building is built in 1957, according to the Basisregistraties Adressen en Gebouwen (Kadaster, n.d.) The façade of the building is non-insulated and consists of a massive concrete wall of 100mm, a cavity and brick cladding. The floors are made of concrete reinforced slabs, that continue uninterrupted into the balconies. Lightweight parapets are incorporated in the large windows (Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017).

Similar to Case study building 1 in Vlaardingen, Case study building 2 in Rotterdam is calculated to need an additional 197 mm exterior insulation (0,040 W/mK), to be able to increase the thermal resistance of the building envelope to Rc = 6,5 W/m^{2}K. Therefore, for the design of the prefabricated modules, that will be applied to both case study buildings, an insulation thickness of 197 mm is taken into account.

Fig. 57:
Photos of Case Study Building 2 (Konstantinou et al., 2017).

Grid selection

To be able to design a universal facade refurbishment system, applicable to the existing facades of the two chosen post-war housing typologies, case study building 1 and 2, a grid has to be defined that fits to both facade arrangements. Façade analysis of the two case study buildings has proven the applicability of a grid of 150 by 150mm. The two different façade arrangements fit in the proposed grid within a tolerance of max. 60 mm, compensated by decreasing the size of the window openings.
As a next step, the façades of the two case study buildings are divided into separated prefabricated modules, in accordance with the existing facade arrangement, matching the proposed grid. The dimensions of the prefabricated modules are determined, based on the preferred position of the substructure and the symmetry of the existing façade (fig. 55 and 56).

ELEMENT	SPECIFICATIONS
Roof	Rc 4.5
Facade elements	Rc 6.5
Ground floor	Rc 3.5
Window frames	Rc 0.8
Double glazing	U 0.8 (1.135) g_g o,8
Infiltration	0.4 dm^3/s.m2
Ventilation system	Balanced ventilation efficiency 0.75

Fig. 58:
Input for building simulation software after renovation of building (Konstantinou et al., 2017).

Roadmap

Explanation of use
Given the necessity of keeping the circularity principles already in mind during the early design phases of the façade refurbishment of post-war residential buildings, a Roadmap is developed that helps architects and contractors during the decision-making process of refurbishment projects. The Roadmap points out what design decisions have a direct and/or indirect effect on the level of circularity of the façade refurbishment system and what options should be considered. The design questions relate to the materials the façade consists of, as well as the disassembly potential of the connections between the materials within the façade system. For each design decision, two, three or four options are given, ranging from "good" options (red), that have a positive effect on the level of circularity of the building product, to "bad" options (grey), that need to be prevented when designing a circular façade refurbishment system.

The Roadmap should be used to evaluate every individual façade component separately:
- the substructure, that connects the 2nd Skin Façade to the existing façade of the building
- the insulation layer, that provides additional thermal insulation to improve the energy performance of the building
- the window, that replaces the existing window of the building
- the cladding, that applies a new architectural appearance to the building

The Roadmap takes into account key considerations when designing for circularity and helps to determine the relevant options. It can be used to compare different building products in order to select the most circular. Probably in some cases the most circular option can't be chosen, due to technical, financial or other reasons. Still eventual disadvantages of the chosen product in terms of circularity should be kept in mind. For these reasons, the Roadmap should be used as a support tool during the design process.

For the validation of the Roadmap, a proposal for a redesign of the 2nd Skin Façade Refurbishment system is introduced. Design decisions are made stepwise on the basis of the roadmap, starting with the choice of materials, followed by the design of the connections and the composition of the façade system, to show how the Roadmap should work in practice.

QUESTIONS	OPTIONS	EXPLANATION
What type of material is used for the component?	Biological material / Technical material	Biological materials are renewable and can be regenerated, while technical materials are finite and can only be recovered.
What type of feedstock does the material consist of?	2nd Reused feedstock / 2nd Recycled feedstock / All virgin materials	Best situation is when the component consists of secondary materials and no virgin materials need to be extraced for the production of the component. Reused feedstock is a better option than recycled feedstock, because no additional energy is needed for the production process.
What is the end of life scenario of the component?	Reuse / Recycling / Incineration / Landfill	Best situation is when the component can immediately be reused for a new or similar function and its lifetime is extended. For the recycling of materials additional energy is needed for the production process, so isn't preferable. Incineration should be prevented, due to the valuable material loss, while landfill is the worst end of life scenario.
What is the life time of the component?	50-75 yrs / 25-50 yrs / 0-25 yrs	When the component has a long technical life time, it doesn't need to be replaced often. When the functional life time of the component has passed, the component can be reused in another configuration.
How is the component connected to its surrounding components?	Indirect + third component / Direct + additional fixings / Direct through premade geometry / Chemical connection	Wet chemical connections between the components should be prevented, because these are difficult to remove. Dry connections with additional fixing devices should be used, preferable with a third independent component that makes the connection between the components indirect.
What does the geometry of the component's edge look like?	Open - Linear / Symmetric overlapping / Closed - Integral	When the geometry of the edges is open and linear, components can easily be disassembled without damaging its surrounding components. When the geometry of the edges is closed, damaging other components is unavoidable.
Does the component represent only one function?	yes / no	If not, then change or replacement of one function does affect the other functions that the component represents.
Are multiple elements clustered into the (prefabricated) component?	yes / no	If there is no clustering of building elements, more connections have to be made on-site and thus the slower the assembly and disassembly process of the facade willl go.
Can the component be removed from the facade without damaging other components?	yes / no	If not, then when one component needs to be replcaced, all other components that are directly connected to the component need to be removed as well.
Is there a base element, to which all facade components are connected, present in the facade?	yes / no	If not, then independency between the different components is difficult to achieve, because an intermediary is missing.
Is the assembly sequence parallel, meaning multiple components can be placed at the same time?	yes / no	If not, then a sequential assembly sequence links more building elements together, resulting in a decrease in (dis)assembly speed and creating difficulties forthe replacement of elements.
Is the component with the shortest lifetime situated closest to the outer surface and the component with the longest lifetime farthest?	yes / no	If not, then replacement of the component with the shortest lifetime is most difficult to replace, because all components with longer lifetimes need to be disassembled first.

Materials

As followed from the research, circular building materials consist of secondary feedstock, coming from reused or recycled sources, and will be restored at the end of life through preferably reuse and/or recycling. Linear building materials consist only of raw materials and lose their value at the end of life through incineration or landfill. In this chapter alternative, circular building materials will be chosen to replace the linear building materials used in the existing 2nd Skin Façade Refurbishment system. The circular building materials will be chosen based on the following six questions:

1. *What type of material is used for the component?*
    a. *Biological material*, that is renewable and contains biological nutrients.
    b. *Technical material*, that is man-made, extracted from finite sources, and can only be recovered and often restored at the end of life.

2. *What type of feedstock does the material consist of?*
    a. *Reused feedstock*, that concerns components from other products, used directly in a new product without the need of remanufacturing.
    b. *Recycled feedstock*, that can be sourced from the same product cycle or the open market.
    c. *All virgin material*, that hasn't been used or consumed before.
    This option should be prevented when designing for circularity.

3. *What is the end of life scenario of the component?*
    a. *Reuse*, which means the lifetime of the component is extended to be reused for a similar or new function without the need of remanufacturing.
    b. *Recycling*, which means recovering the materials that the component consists of for its original or other functions through processing.
    c. *Incineration*, which means burning the materials at the end of life for energy recovery.
    d. *Landfill*, where the unrecoverable waste materials will be brought to be buried.
    The last two options should be prevented when designing for circularity.

4. *What is the technical lifetime of the component?*
    a. *50 to 75 years*, which means the component can be reused up to three times, taking into account the estimated functional lifetime of the 2nd Skin Refurbishment of 25 years.
    b. *25 to 50 years*, which means the component can be reused up to two times, taking into account the estimated functional lifetime of the 2nd Skin Façade Refurbishment of 25 years.
    c. *0 to 25 years*, which means the component precisely meets the functional lifetime or has to be replaced during the estimated functional lifetime of the 2nd Skin Façade Refurbishment of 25 years.

5. *How is the component connected to its surrounding components?*
    a. *Indirect + third component*, that enables easy replacement of the components without disassembling and damaging the surrounding components.
    b. *Direct + additional fixing devices*, that enables easy replacement of the component but does damage the surrounding components.
    c. *Direct through premade geometry*, that only allows disassembly of the complete structure.
    d. *Chemical connection*, that is irreversible and thus hinders the disassembly process.
    This option should be prevented when designing for circularity.

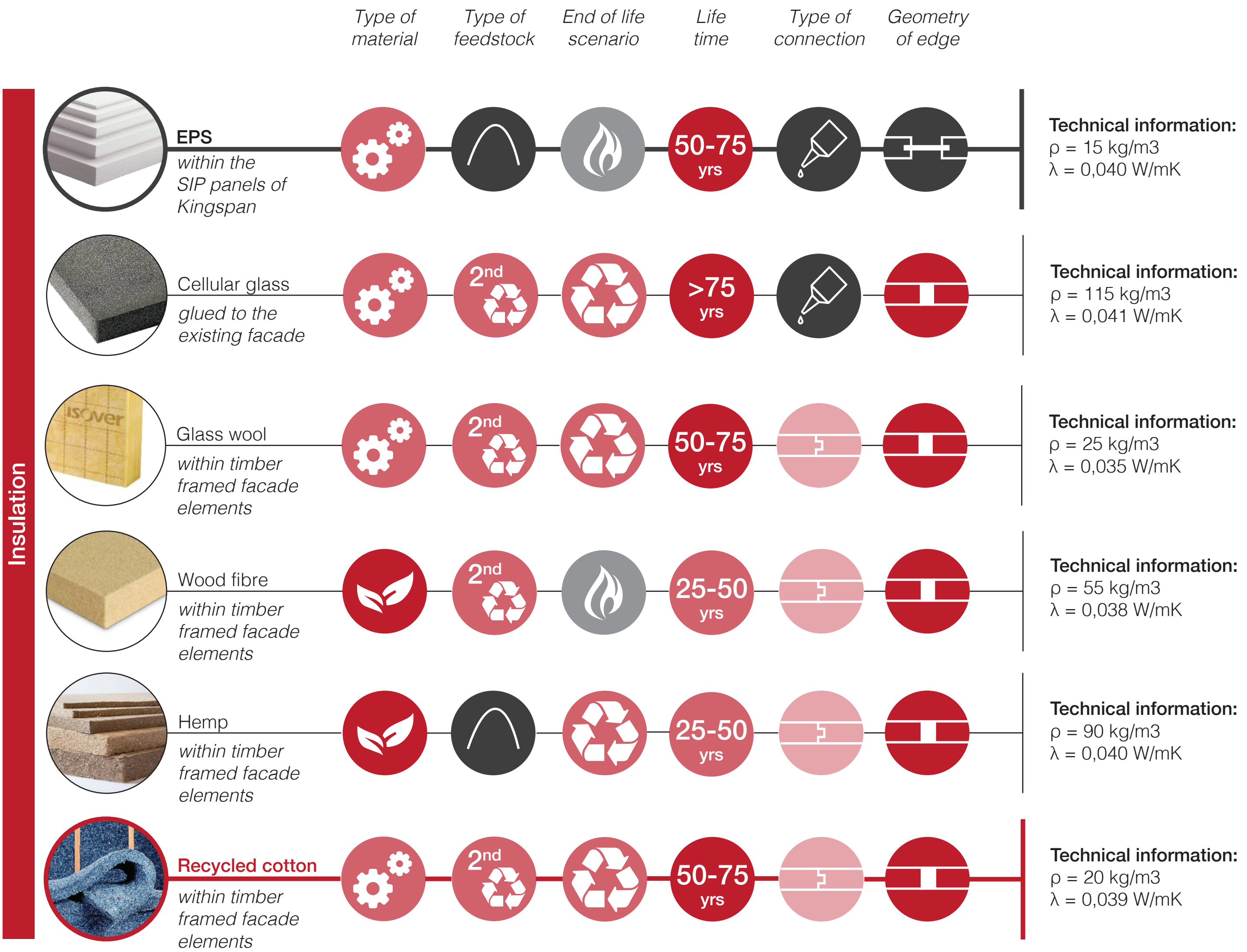
6. *What does the geometry of the components edge look like?*
    a. *Open – linear*, that allows disassembly in three directions.
    b. *Symmetric overlapping*, that allows disassembly in two directions.
    c. *Closed – integral*, that only allows replacement of the component by demolition of the surrounding components. **This option should be prevented when designing for circularity.**

Insulation

In the two variants of the 2nd Skin Façade Refurbishment system the material EPS (Expanded Polystyrene) is used as insulation material. However, this material is considered to be linear because it completely consists of virgin materials and can only be incinerated at the end of life, due to the permanent chemical connection with its surrounding components.

When looking at the NIBE B2B-factor, that gives an indication to what extent the building product meets the Cradle-to-Cradle principles (see chapter 3), three alternative conventional insulation materials are chosen to be analysed. These insulation materials score best in the category of Material Reutlisation (H), that takes into account the recycling percentages of the building product. The amount of recycled material, used for the production of the product, accounts for 1/3 of the percentage, the amount of material that can be recycled at the end of life, accounts for 2/3 of the percentage (NIBE, 2017). Two other insulation materials, hemp and recycled cotton, that aren't included in the NIBE database and are less commonly used, but do have circular characteristics, are analysed as well.

The comparison of the alternative insulation materials is based on the first 6 questions of the Toolbox, that define to what extent the building material is circular. Next to that, the density and thermal resistance of the material will be taken into account in the decision-making process, because these factors have most influence on the functioning and dimensioning of the 2nd Skin Façade Refurbishment system.



Cellular glass
Cellular glass is the insulation material, that has obtained the highest score in the category Material Reutilisation (H) of the NIBE B2B-factor. (NIBE, 2017). Cellular glass consists of 66% recycled glass, coming from the car industry. During the production the glass powder, mixed with sand, dolomite, chalk and other substances, is reboiled in the oven with a temperature of 850° and glass bubbles arise. These bubbles give the material its strength and thermal insulating qualities. Next to that, the closed cell structure makes the material waterproof, damp tight and funghi-resistant. At the end of life cellular glass can be recycled as granulate for street covering or as filling material in sound-absorbing walls. However, the connection of the cellular glass to the substructure needs to be chemical with PC-adhesives, which complicates the disassembly process. The production process of the cellular glass is energy-consuming, but has been reduced by the industry with 50% since 1950. An advantage of the product is its long lifespan of around 100 years, which has a positive effect on the ecological profile of the material (Foamglas, n.d.).

Glass wool
An alternative conventional insulation material, that can be considered circular, is glass wool. Glass wool is made of glass scrap and natural sand, that are transformed into long glass wool fibres through a centrifugation and blowing process. The fibres are bounded with resins. Glass wool is insensitive to high temperatures and moisture (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016). Currently glass wool consists for more than 70% of recycled content (Vlakglas Recycling Nederland, n.d.). Glass wool can be recycled multiple times for the production of new insulation material, when the wool is dry, chemically pure and free of other waste material (OVAM, n.d.). However, research of Schiavoni et al. (2016) has shown that glass wool is one of the insulation materials with the highest embodied energy and global warming potential, when considering a functional unit of material mass needed to obtain a thermal resistance of 1 m^2K/W for a 1 m^2 panel. For this reason, the material can't be considered to be sustainable, but rather circular when the material will be recycled multiple times at the end of life.

Wood fibre insulation
A biological alternative insulation material, that can be considered circular, is wood fibre insulation. For the production of wood fibre insulation waste materials of the sawmill industry are used, that are then shredded and bonded with wet fibres. When the material is kept in a dry environment, the wood fibre insulation has an infinite lifetime (Van Leemput & Heuts, 2007). In general, wood fibre insulation is considered to have a lifetime of 40 years. Most of the wood fibre insulation (96%) used in the Netherlands is incinerated at the end of life (Haas, 2012). However, at the end of life the wood fibres can be easily recycled (Schiavoni et al., 2016). The material needs to be placed in a timber-framed element through friction-fit. The plate of wood fibre insulation needs to have 10 mm extra on the sides to be able to clamp the material within the structure. Advised is to use 2x100mm wood fibre insulation, instead of 1x200mm, to facilitate the assembly process (STEICO, n.d.). A disadvantage of the material is its high embodied energy, due to its high energy consumption during production.

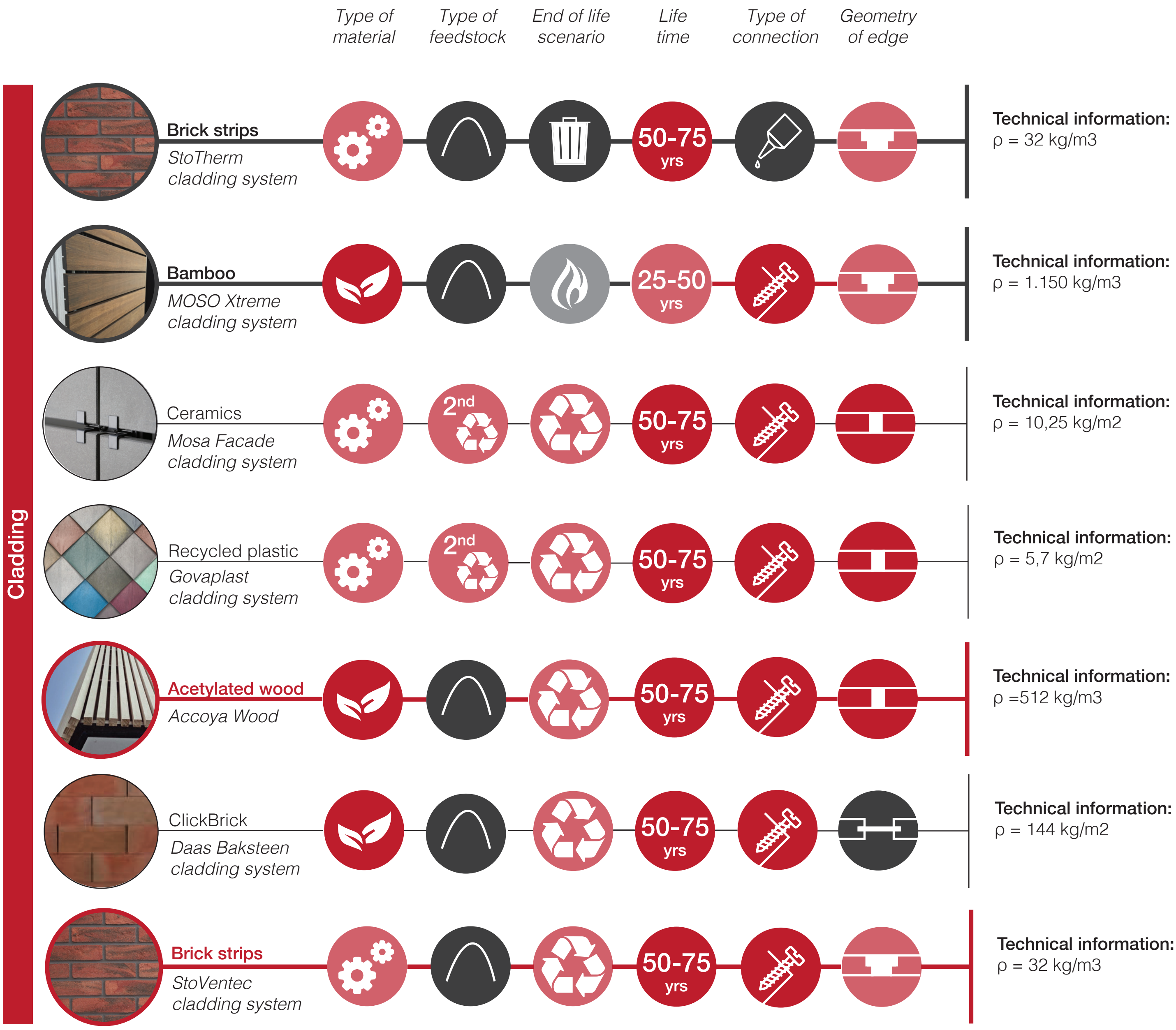
Hemp
The renewable textile fibre hemp is used as resource for the production of damp open insulation material, often mixed with polyester fibre and fire retardants. Hemp is a natural material, coming from a plant that is easy to grow, and suits well the function of a thermal insulator due to its low thermal conductivity. However, when hemp absorbs water from the air, its thermal conductivity will increase, so it should be protected from moisture and free water within the structure (Schiavoni et al., 2016). Hemp insulation is available in rolls, with a thickness ranging from 3 to 8 cm, and plates, with a thickness ranging from 3 to 19 cm. At its end of life, hemp is completely recyclable. Next to that, the material is resistant to fungi and has a similar insulating value as glass wool (Isolatie-info.nl, n.d.).

Recycled cotton
An innovative insulation material, whose properties haven't yet been deeply analysed, is Metisse insulation, that consists of 77% recycled cotton. Locally collected old clothes are sorted in social workshops, washed and then processed into cotton fibres. These fibres are then treated with fire retardant and biocide, combined with polyester fibres (15%) and converted into plate insulation material. According to its Environmental Product Declaration, recently published in September 2017, the product Métisse RT has an estimated lifetime of 75 years and has the potential to be recycled at the end of life, while there isn't yet developed a functioning end of life programme for the material. The Metisse insulation should be applied within a timber framed structure, attached to the substructure with nailed connections (VRK-isolatie, 2017). The recycled cotton isn't waterproof, so should be kept in a dry environment. For this reason, the exterior has to be covered with a damp open, water- and windproof material, such as a wood fibre cement plate. The recycled cotton insulation is available in plates for vertical applications and flakes for horizontal applications (Willaert, 2011).

Cladding

In the Prefabrication variant of the 2nd Skin Façade Refurbishment system two cladding materials were applied: brick strips, produced by supplier Sto, and bamboo, produced by supplier MOSO. Both materials can be considered as linear, because they completely consist of virgin material and need to be either incinerated at the end of life or buried in landfill. Due to the chemical connection of the brick strips to the under layer of EPS, that is glued to the substructure, recycling of the brick strips is impossible. On the other hand, the bamboo cladding is dry connected to the substructure through the use of stainless-steel clips and aluminium supporting profiles. Next to that, the bamboo cladding is a biological material, that can be regenerated at the end of life. Thus, the bamboo cladding can be considered to be more circular than the brick cladding.

For the redesign of the 2nd Skin Façade Refurbishment system, several alternative cladding materials are investigated. The comparison of the cladding materials is based on the six questions, that define to what extent the material is circular. Next to that, the density of the cladding material will be taken into account in the decision-making process, because this factor has most influence on the dimensioning of the 2nd Skin Façade Refurbishment system.



Ceramics
The ceramic tiles, produced by Mosa, are made of natural raw materials; clay and sand. These raw materials are sourced from quarries in the Netherlands, Germany and France, located within a radius of 500 kilometre from the production plant in Maastricht (NL). The tiles contain a percentage of 16-25% of recycled feedstock, obtained from the residual waste of the stone industry. According to material supplier Mosa, the tiles have a technical lifetime of hundreds of years. In the Environmental Product Declaration of the Mosa wall tiles a lifespan of 75 years is taken into account. At the end of life, the ceramic tiles can be recycled. Currently the material supplier Mosa is investigating a tile return system, in which the used tiles can be returned to Mosa for reuse (Koninklijke Mosa B.V., 2011). The tiles are attached to the underlying structure with a bolted connection to aluminium anchors, that can be visible or hidden from view. The anchors are supported by aluminium Omega-, T- or L-profiles that are dryly connected to the sandwich panels with screws (Koninklijke Mosa B.V., n.d.).

Recycled plastic
For the Dutch Design Week in 2017 the architects SLA and Overtreders W designed a temporary pavilion, that is considered to be 100% circular. All materials needed for the construction of the pavilion were borrowed from material suppliers, producers and inhabitants of the city of Eindhoven. The façade was made of recycled plastic shingles, that were produced of the plastic waste of the inhabitants. When the temporary pavilion needed to be disassembled at the end of the event, every inhabitant that had contributed to the project, received one plastic shingle. The shingles are connected to a welded mesh with the use of additional fixing devices; tie wraps, drawn through one small opening in the top of the shingle. Consequently, the welded mesh is also connected to the underlying secondary steel façade support structure with tie wraps (De Architect, 2017). The shingles are produced by the Govaplast, the supplier of recycled plastic plates and profiles. They mainly use recycled plastic from the food and packaging industry, composed of the materials PE and PP. During the production process these materials are grinded, mixed, melted at high temperatures and then pressed into moulds. According to Govaerts, the shingles are 100% recyclable at the end of life. With a thickness of 4 mm and a density of 950 kg/m3, the weight of the recycled plastic shingle is 5,7 kg/m2 (Govaplast, n.d.).

Accoya wood
A renewable alternative for the bamboo façade cladding, which does have recycling possibilities at the end of life, is the thermally modified wood type Accoya, made through the process of acetylation. Accoya wood is made of the fast-growing Radiata Pine, that has an increased strength and durability when chemically treated with acetic anhydride. As a result, the material has reached the highest durability class and a technical lifetime of 60 years is guaranteed for outdoor applications. While the material is completely made of virgin materials, its renewable properties with fast turnover rate increases its level of circularity. At the end of life the Accoya Wood can be recycled and used for the production of a certain type of MDF wood, named Tricoya. Another option is composting the wood at the end of life, which is harmless for the environment, due to the absence of toxic materials in the wood (Accoya, n.d.).

ClickBrick
A brick cladding variant is the ClickBrick system, developed by the Dutch brick supplier Daas. The ClickBrick is a dry stacking system without the use of mortar or adhesives. The bricks consist of a groove, in which an RVS clip fits. This means the geometry of the edges of the bricks is integral; one single brick can't be removed from the façade, without disassembling the complete brick facade. The RVS clip is the third component that connects the bricks to each other and the underlying structure through an anchor with screw thread ((Daas Baksteen, n.d.). The bricks are completely made of virgin materials from the biological cycle, namely clay, and have an expected lifetime of 100 years. At the end of life, due to the dry stacking system, the bricks and stainless-steel clips are completely recyclable (C2C-Centre, n.d.). With a thickness of 90 mm and density of 1600 kg/m3, the bricks will have a weight of 144 kg/m2.

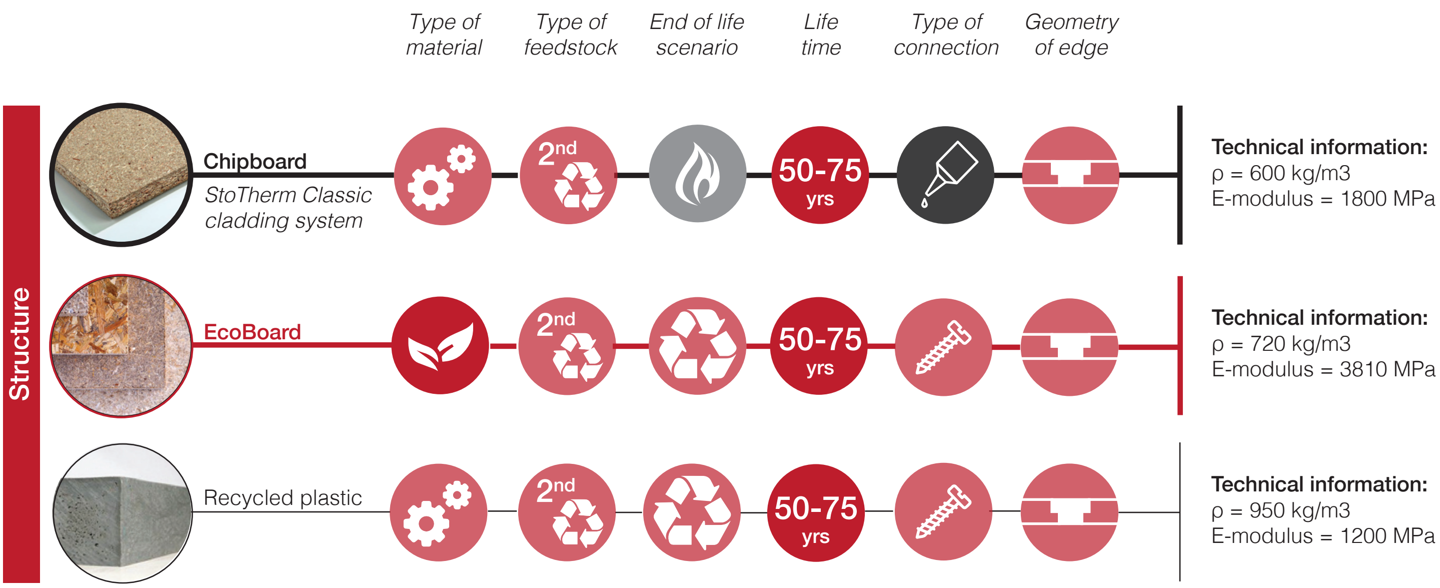
Brick strips
Another product of Sto Steenstrips is the StoVentec brick cladding system. Instead of gluing, which is the case with the used StoTherm cladding system, in this system the cladding is dryly connected to the underlying structure with an aluminium and stainless-steel supporting structure. The brick strips are chemically connected to a fibre cement plate, which is in turn connected with screws to the supporting structure (Sto Isoned bv, 2017). In this ventilated system, the cladding can be removed from the façade without damaging the surrounding components. However, the brick strips are still chemically connected to the fibre cement plate, so can't be separated. At the end of life, the cladding can be crushed into fine grain fractions and be recycled for the production of new bricks or granulate. Stonecycling is an example of a start-up company that produces bricks with various recycled content (StoneCycling, n.d.). A disadvantage of the StoVentec system, compared to the StoTherm system, is the increased material use. The difference between the two systems, is the use of an aluminium supporting structure with the StoVentec system, and the use of an EPS insulation under layer with the StoTherm system.

Structure

The current Structural Insulated panels are made of sheets of chipboard, connected to pinewood stiffeners. Chipboard is a technical material, that consist of 75% recycled wood shavings and 5-10% chemical resins. Despite the presence of recycled feedstock in the material, the chipboard is a linear building material, because it needs to be incinerated at the end of life. The E-modulus of 12 mm P5 chipboard is 1800 MPa (Jan Smulders Triplex bv, n.d.). For this reason, several alternative materials for the structure of the SIP-panels are investigated for the redesign of the 2nd Skin Façade Refurbishment system. The comparison of the materials is based on the six questions, that define to what extent the material is circular. Next to that, the density and strength of the material will be taken into account in the decision-making, because these factors have most influence on the functioning of the 2nd Skin Façade Refurbishment system.

ECOBoard
The sheet material ECOBoard is a biological material, that is renewable. ECOBoard consists for 97% of recycled feedstock, namely agricultural waste material, such as straw and reed, bonded with lignin with 3% additive pMDI (Kennisbank Biobased Bouwen, n.d.). At the end of life of the ECOBoard is 100% biodegradable and 100% recyclable to the same product. Next to that, the ECOBoard has a good performance on fire and weather resistance (Materia, n.d.). However, the board needs to be protected against direct water, which can cause shrinkage or expansion of the material. Test results have shown that the density of ECOBoard Standard is 720 kg/m3 and the E-modulus is 3810 MPa (ECOBoard, n.d.). To make the material waterproof, a biobased coating, made of bioplastic and biomass, is being developed by ECOBoard International. However, this variant of the product hasn't been brought to the market yet, but is still under development.

Recycled plastic
An alternative technical material for the structural sheet within the SIP-panels, is recycled plastic, produced by the material supplier Govaplast. Govaplast delivers high quality boards, posts and beam, completely made of recycled plastic. These boards are used for the production of for example outdoor benches, air conditioning units and scaffold boards. They can be made with integrated grooves to enable easy installation. Similar to wood products, the recycled plastic boards can be screwed, nailed, sawed, milled, drilled, stapled, etc. According to Govaplast, the sheets are 100% recyclable at the end of life. With a thickness of 12 mm and a density of 950 kg/m3, the weight of the recycled plastic board is 11,4 kg/m2. The E-modulus of recycled plastic board is 1600 MPa (Govaplast, n.d.)



Choice of material

Based on the explained material analysis on the previous pages, the following materials have been chosen for the redesign, by looking at their percentage of recycled content, recyling possibilities at the end of life and technical lifetime:

Insulation

Based on the comparison results, the circular building material recycled cotton, called Metisse, is chosen as insulation material, because it contains a high percentage of recycled feedstock (77%), coming as waste material from the clothing industry. Next to that, the material can be recycled repeatedly at the end of life for the production of new insulation material and has a long lifespan of 75 years. Next to that, the insulation material is soft, thus can be compressed to the right dimensions, which is a beneficial for the reuse possibilities in different facade arrangements.

Fig. 59: Metisse recycled cotton insulation (VRK-Isolatie, 2017)

Structure

Based on the comparison results, for the material of the structural frame of the prefabricated panels is chosen for ECOBoard, which is the biodegradable variant of chipboard. ECOBoard contains of a high percentage of recycled feedstock (97%), coming as waste material from the agricultural industry. At the end of life ECOBoard is competely recyclable and can be used for the production of new ECOBoard. When the material is treated with biobased coating, made of bioplastic and biomass, the material will become waterproof and its technical lifetime is expected to increase up to 75 years. This product is, however, still under development by ECOBoard International.

Fig. 60: ECOBoard (Materia, n.d.)

Cladding

Based on the comparison results, as cladding material is chosen for acetylated wood, delivered by the supplier Accoya. Due to its renewable properties, its recyclability and biodegradability at the end of life, Accoya Wood is considered to be a more circular alternative to replace the MOSO bamboo cladding.

Fig. 61: Accoya Wood (Accoya, n.d.)

When the architectural appearance of the existing façade needs to be preserved, proposed is to choose for a different type of brick cladding system (StoVentec), in which the brick strips are chemically connected to a fibre cement board, which is in turn mechanically connected to a supporting structure. This way the cladding can be removed from the prefabricated panels without damaging the surrounding components, which was the case in the original situation. Because the brick strip supplier Sto hasn't yet been able to develop a circular system that makes reuse or recycling of the brick strips possible, this is considered to be the most circular option at the moment.

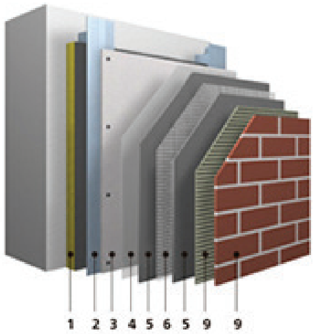


Fig. 62: StoVentec system (Sto Isoned bv, 2017)

Connections

Subsequently, as followed from the research, the connections between the components and the materials within the components need to be redesigned to enable disassembly of the 2nd Skin Façade Refurbishment system at the end of the functional lifetime of the post-war residential building. Due to functional or technical decline at a certain moment the building needs to be de- or reconstructed, while certain materials the 2nd Skin Façade Refurbishment system consist of, still have a remaining technical service life. For this reason, the connections between the components and materials should be demountable. According to Durmisevic (2010) the connections between the components must be able to provide decomposition, re-composition, incorporation and plugging-in of components. Based on the eight criteria for disassembly, developed by Durmisevic (2010), the following questions are included in the Roadmap, that will help during the decision-making process for the redesign of the connections of the 2nd Skin Façade Refurbishment system:

5. *How is the component connected to its surrounding components?*
   a. *Indirect + third component*, that enables easy replacement of the components without disassembling and damaging the surrounding components.
   b. *Direct + additional fixing devices*, that enables easy replacement of the component but does damage the surrounding components.
   c. *Direct through premade geometry*, that only allows disassembly of the complete structure.
   d. *Chemical connection*, that is not reversible and thus hinders the disassembly process. This option should be prevented when designing for circularity.

6. *What does the geometry of the components edge look like?*
   a. *Open – linear*, allowing disassembly in three directions.
   b. *Symmetric overlapping*, allowing disassembly in two directions.
   c. *Closed – integral*, only allowing replacement of the component by demolition of the surrounding components. This option should be prevented when designing for circularity.

7. *Does the component represent only one function?*
   If not, then change of one component does affect the other functions that the component represents.

8. *Are multiple elements clustered into the component?*
   If not, then more connections have to be made on-site and thus the slower the assembly and disassembly process will go.

9. *Can the component be removed from the façade without touching other components?*
   If not, then when one component needs to be replaced, all other components that are directly connected to the component need to be removed as well.

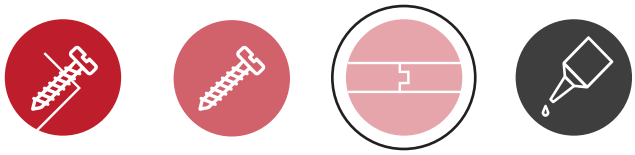
10. *Is there a base element, to which all façade components are connected?*
    If not, then independency between the different component is difficult to achieve, because an intermediary is missing.

11. *Is the assembly sequence parallel, meaning multiple components can be placed at the same time?*
    If not, then the assembly sequence is a sequential, which means more components are linked together, resulting in a decrease in (dis)assembly speed and creating difficulties in the replacement of elements.

12. *Is the component with the shortest lifetime situated closest to the outer surface and the component with the longest lifetime farthest from the outer surface of the façade?*
    If not, then for the replacement of the component with the shortest lifetime, all components with longer lifetimes need to be disassembled first.

Type of connections

How is the component connected to its surrounding components?



As concluded from the circularity assessment of the Prefabricated variant of the 2nd Skin Facade Refurbishment system, the Structural Insulated panels have most potential to be improved in terms of Disassembly Potential, because all connections between the elements are chemical and thus irreversible. The SIP-panels can't be disassembled at the end of their functional lifetime and thus the materials, that the SIP-panels consist of, can't be separated in its purest form. As a result, none of the materials can be reused or recycled. For this reason, the redesign of the SIP-panels is focussed on changing from wet to dry connection types. To prevent the use of adhesives and other additional fixing devices that damage the material, decided is to let the geometry of the components' edges form the connections. The disadvantages are that this type of connection only allows sequential assembly and can only be disassembled completely (Durmisevic, 2010). However, as long as the connections tolerate repeated assembly and disassembly and maintain their strength, connections with premade geometry are considered to be even more useful than direct connections with additional fixings.

Inspiration for the connection redesign is found in the WikiHouse concept, developed by Alastair Parvin. WikiHouse is an open-source modular building method, that can be built by everyone. An example of the application of the building method, is the pioneer dwelling in Almere, built by the Dutch branch of the organisation WikiHouseNL (WikiHouseNL, n.d.) (fig. 63). Part of the WikiHouse concept is the usage of circular materials and flexible building modules with elements that can be independently altered, substituted or upgraded. However, important to notice, is that circularity wasn't the main aim, but rather an unforeseen outcome of the concept. The main ambition of the WikiHouse movement was to make the design of low-cost, low-energy, high-performance homes accessible to everyone by making use of digital technologies (WikiHouse, n.d.).
Another source of inspiration for the redesign was the Delft Product Development Lab, built in front of the Faculty of Architecture in Delft. The pavilion is made according to the building system Fabfield, developed by Pieter Stoutjesdijk (The New Makers, n.d.) (fig. 64). The pavilion consists of prefabricated façade and floor components, that precisely fit into each other, using CNC-milling technology. As a result, no foil, sealants and PUR is needed (Technische Universiteit Delft, n.d.). The prefabricated floor components contain protruding notches at the top and bottom, that precisely fit into the grooves of the façade components. To secure the connection, an additional nut and bolt are integrated in the component. The chosen material for the façade components is 18mm OSB board. The façade cladding consists of aluminium composite panels. The efficient building method leads to decreased material usage and decreased waste generation on the building site. When the functional lifetime of the building has ended, the components can be disassembled and reused in other building projects (Van der Knaap, 2016).
Also the Circular Building, developed by Arup for the 2016 London Design Festival, was taken as an example for the connection redesign (fig. 65). This pavilion is considered to be one of the first buildings in the United Kingdom, that meets the Circular Economy principles. The aim was to design the components in such a way that their fullest potential for the duration of their complete lifecycle is reached. The façade is made of prefabricated SIPS-panels, that are self-

Fig. 63: WikiHouse (WikihouseNL, n.d.)

Fig. 64: PD-lab (Bilow, n.d.)

Fig. 65: The Circular Building (Arup Associates, n.d.)

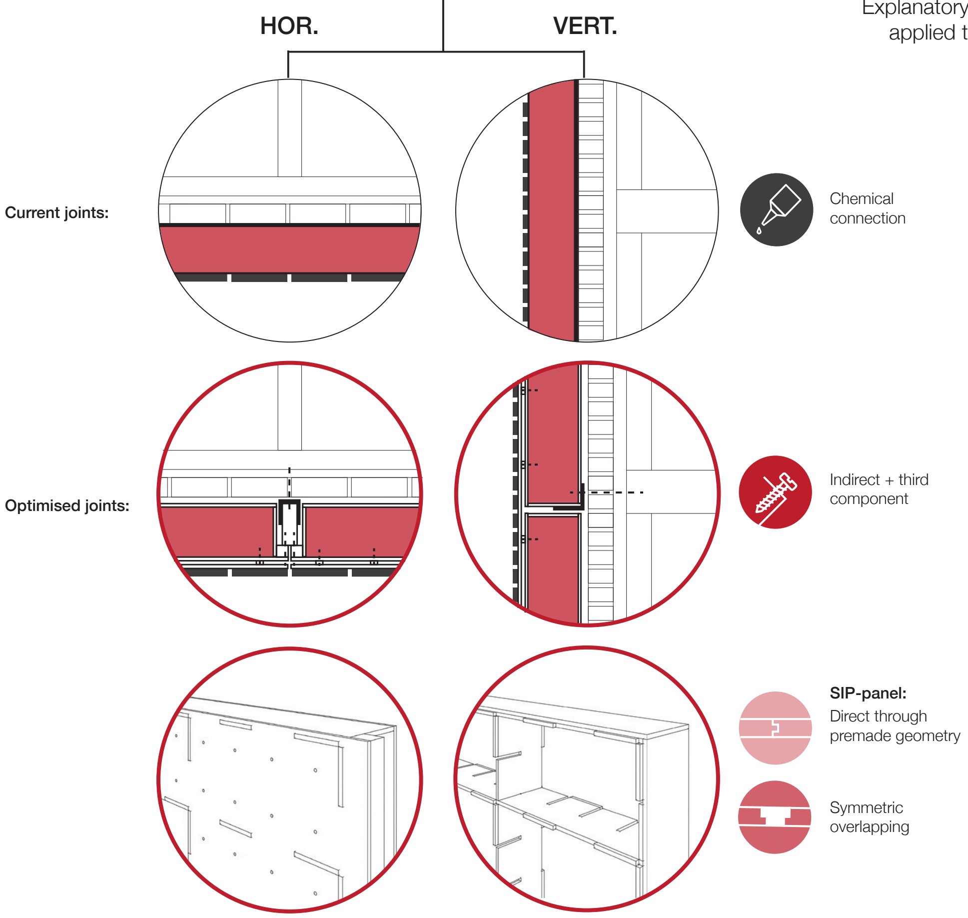


Fig. 66:
Explanatory section of the redesign, applied to Case Study Building 1 (source: own image)

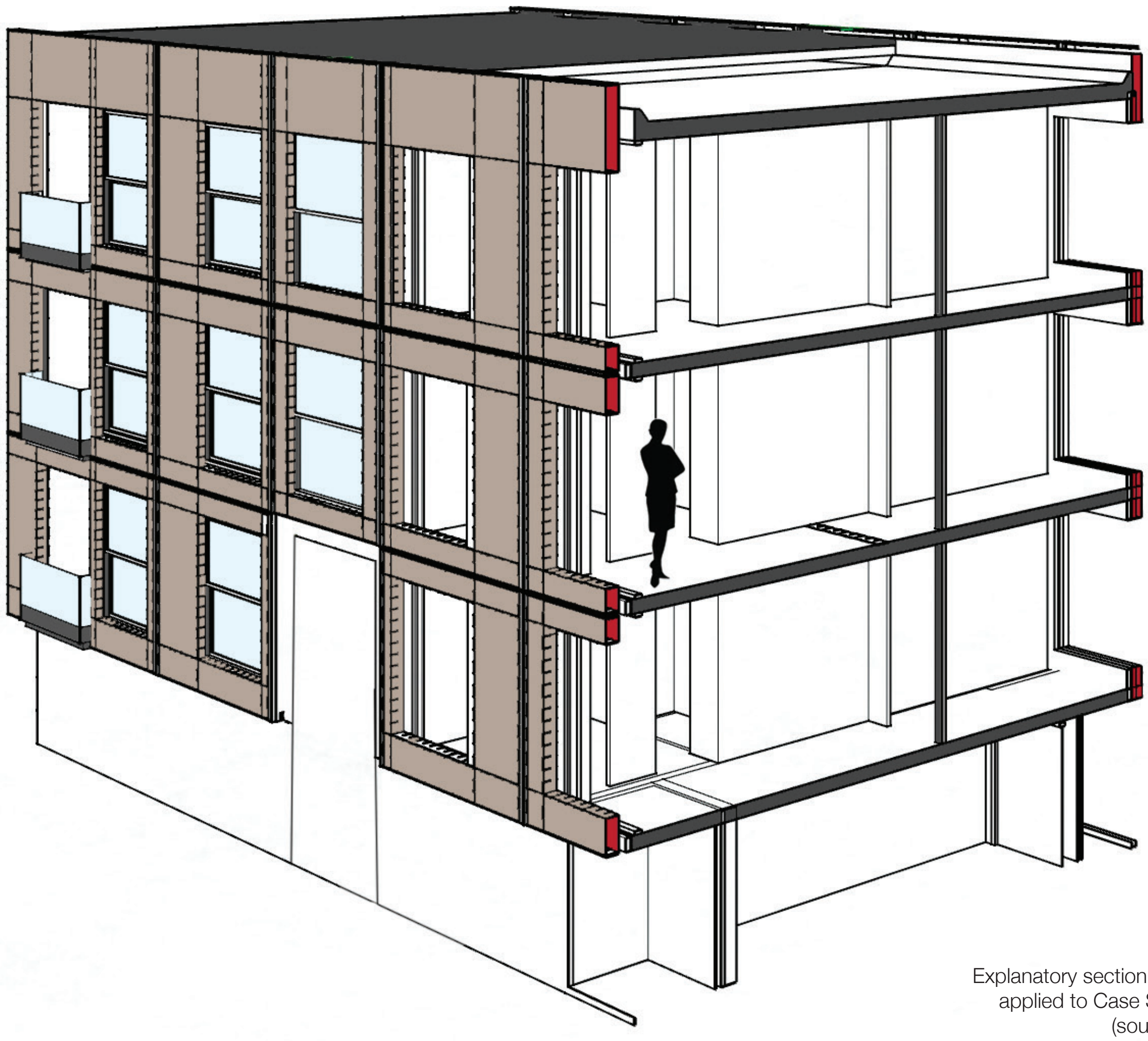
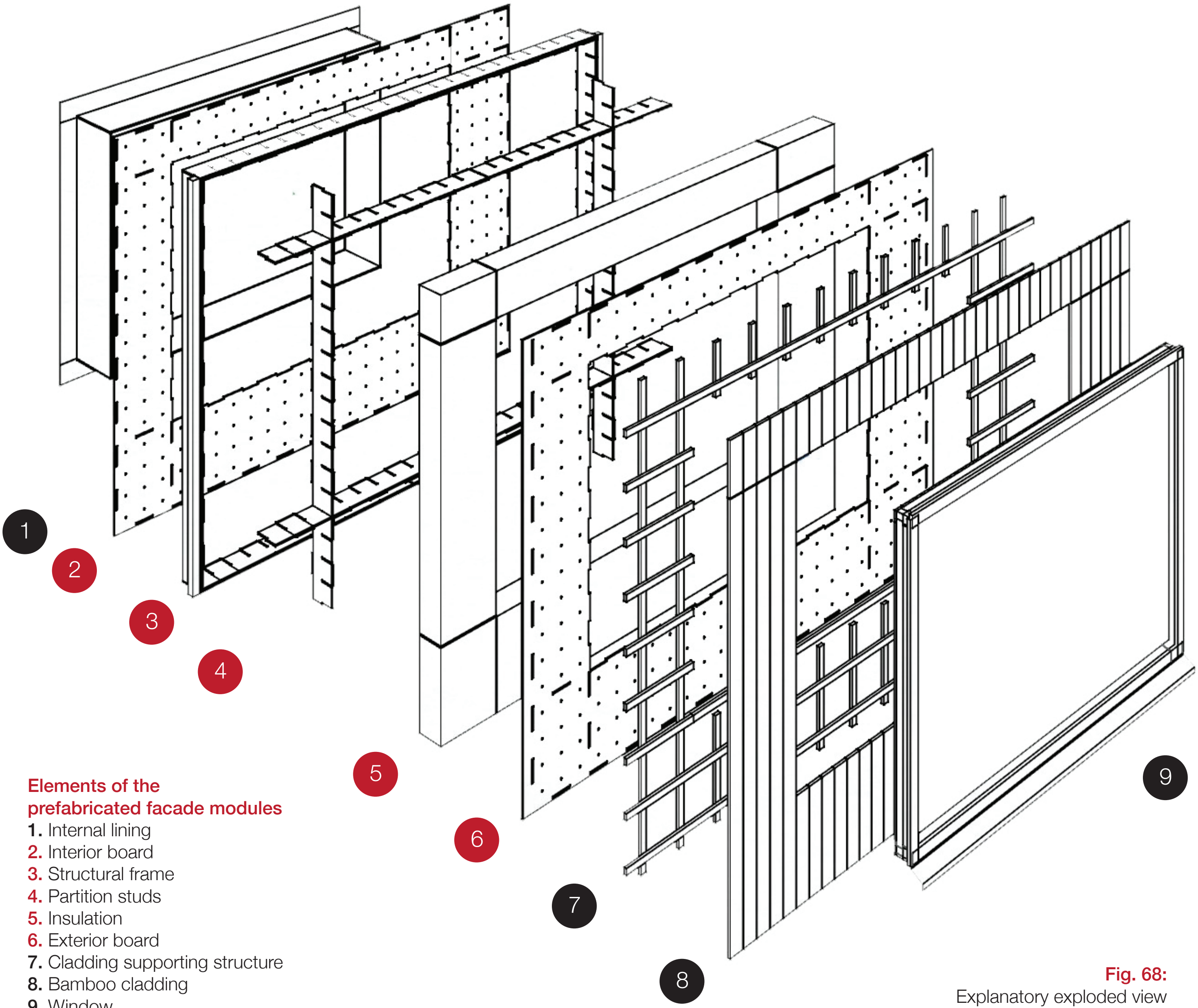


Fig. 67:
Explanatory section of the redesign, applied to Case Study Building 2 (source: own image)

supporting and demountable. Instead of mechanical fixings, the connections are made through pre-made geometry. Each element had been designed to fit in a specific location, repeated as often as possible. Every element contains a QR-code, that can be used to track the materials through its lifetime. As a result, all components can be repurposed in the future (Arup Associates, n.d.)

As can be seen in fig. 66 and 67, when comparing the Redesign to the Exterior Insulation variant of the 2nd Skin Façade Refurbishment system, the type of connection has changed from a wet to a dry connection. Instead of using a chemical connection between the added exterior insulation layer and the existing façade, which is irreversible, there is chosen for an indirect connection with the use of third independent component. Similar to the Prefabricated variant of the 2nd Skin Façade Refurbishment system, in the redesign the prefabricated modules are connected to the existing façade through a substructure of vertical wooden posts, that are connected with screws to the existing façade with the use of an independent stainless-steel anchor (see p. 70-71). As is the case in the Prefabricated variant, the window frames will be connected with screws to the prefabricated modules, that will then be delivered as one package to the building site.

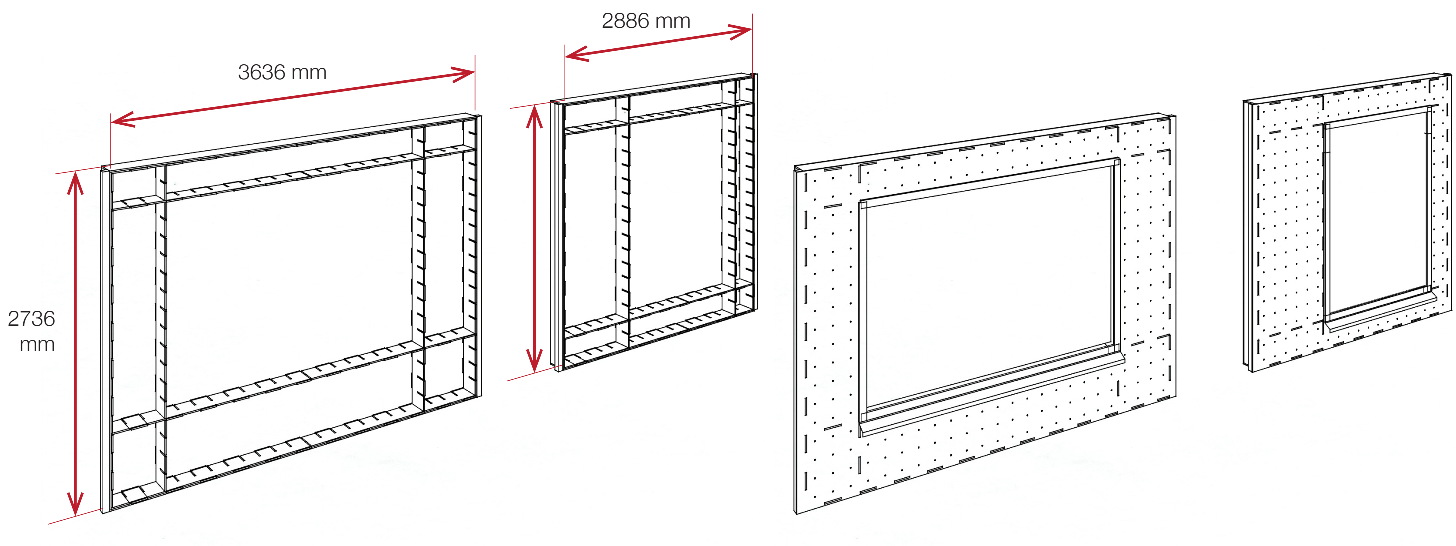
Different from the Prefabricated variant of the 2nd Skin Façade Refurbishment system, the connections between the materials within the Structural Insulated panels have changed from wet to dry. Following from the connection analysis of the previously mentioned references, a connection type is designed that is shaped by the geometry of the components edges. Every element that SIP-panel consist of, contains grooves and protruding notches at certain locations, that precisely into each other. As a result, the SIP-panels can be assembled without the use of adhesives or other additional fixing devices. Instead of gluing the insulation material to the surrounding chipboard, the insulation is stuck within the structure. Also the facade cladding will be connected to the prefabricated modules via a dry connection method, that will be explained on the following page.



Elements of the prefabricated facade modules

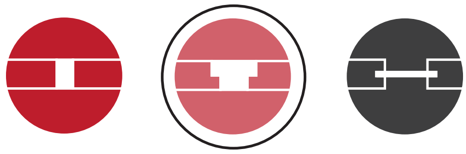
1. Internal lining
2. Interior board
3. Structural frame
4. Partition studs
5. Insulation
6. Exterior board
7. Cladding supporting structure
8. Bamboo cladding
9. Window

Fig. 68:
Explanatory exploded view of one facade module (source: own image)



Geometry of the component's edge

What does the geometry of the component's edge look like?



When choosing for connections through pre-made geometry, important is to design the component's edges in such a way that the geometry is either symmetric overlapping or linear. When the geometry is closed and integral, the component can only be disassembled by damaging certain elements. For this reason, geometry of the component's edges is designed to be symmetric overlapping, because then the geometry still holds the elements in place, but also enables disassembly without damage of the surrounding elements.

As shown in fig. 68, the frame of the prefabricated modules consist of horizontal and vertical studs, that contain grooves and protruding notches at certain locations. The type of connection between the vertical and horizontal studs within the module is integral and symmetric overlapping. Through premade CNC-milled grooves, the studs are slid into one another and hold into place through friction-fit. This way the modules can be rearranged, just by pulling the studs loose and sliding them into another groove. With the chosen geometry of the edges, the studs can only be moved in one direction. Similar to timber-frame building systems, the insulation material will be stuck in the frame. The exterior and interior board of the prefabricated modules contain grooves at the exact position of the protruding notches of the vertical and horizontal studs of the frame, and thus fit precisely on top of the frame. At the top and bottom the exterior and interior board stick out to enable the joint between the prefabricated modules. At the left and right side of the module, the connection sticks will be directly attached to the exterior board of the module with screws to form the connection to the substructure.
The connection between the prefabricated modules and the façade cladding is also incorporated in the premade geometry. The exterior board of the prefabricated modules contain small perforations, that are the size of a screw. The holes are positioned at a distance of 150 mm, because most cladding materials need to be fastened to the substructure at a centre-to-centre distance of 300 to 600 mm. Due to the varying position of the window in the facade of different typologies of post-war residential buildings, a tolerance of 150 mm is taken into account. In the redesign, the supporting structure of the cladding will be connected to the prefabricated modules with the use of screws/bolts, and can in turn be removed easily from the board without damaging the board of the prefabricated modules, and be replaced with another type of cladding, fastened at the same position as the previous cladding supporting structure. Also the interior board of the prefabricated module contains perforations, to which the buildings services that need to be integrated in the 2nd Skin Facade, such as the ventilation shafts, can be attached.

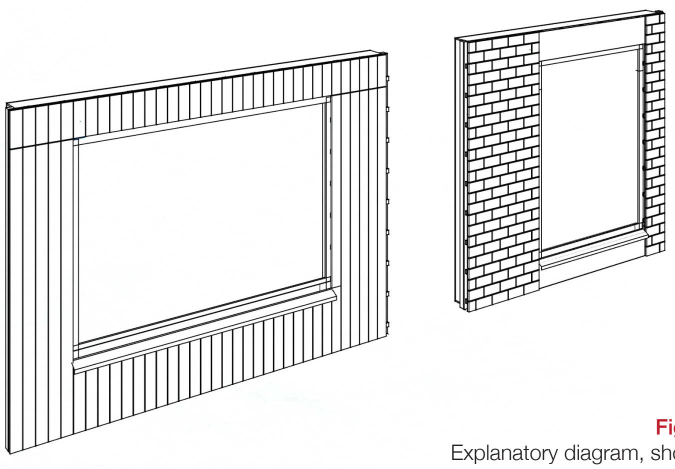


Fig. 69:
Explanatory diagram, showing different arrangements within the module
1) facade frame
2) closure with board
3) cladding
(source: own image)

As shown in fig. 69 the prefabricated modules can be arranged in different configurations. When the window of the existing façade is located at a different position, the horizontal and vertical slats can be rearranged to be able to suit the particular arrangement of the reference façade. When the dimensions of the prefabricated modules need to change, the slats have to be cut to size. Important is to choose for a soft insulation material, that can be squeezed into any dimension. There may be chosen for a similar cladding material as the existing façade or a change in architectural appearance of the building with a different cladding material. All cladding materials, that have the possibility to be dry connected via a substructure to the prefabricated modules, can be applied to this system.

Final design

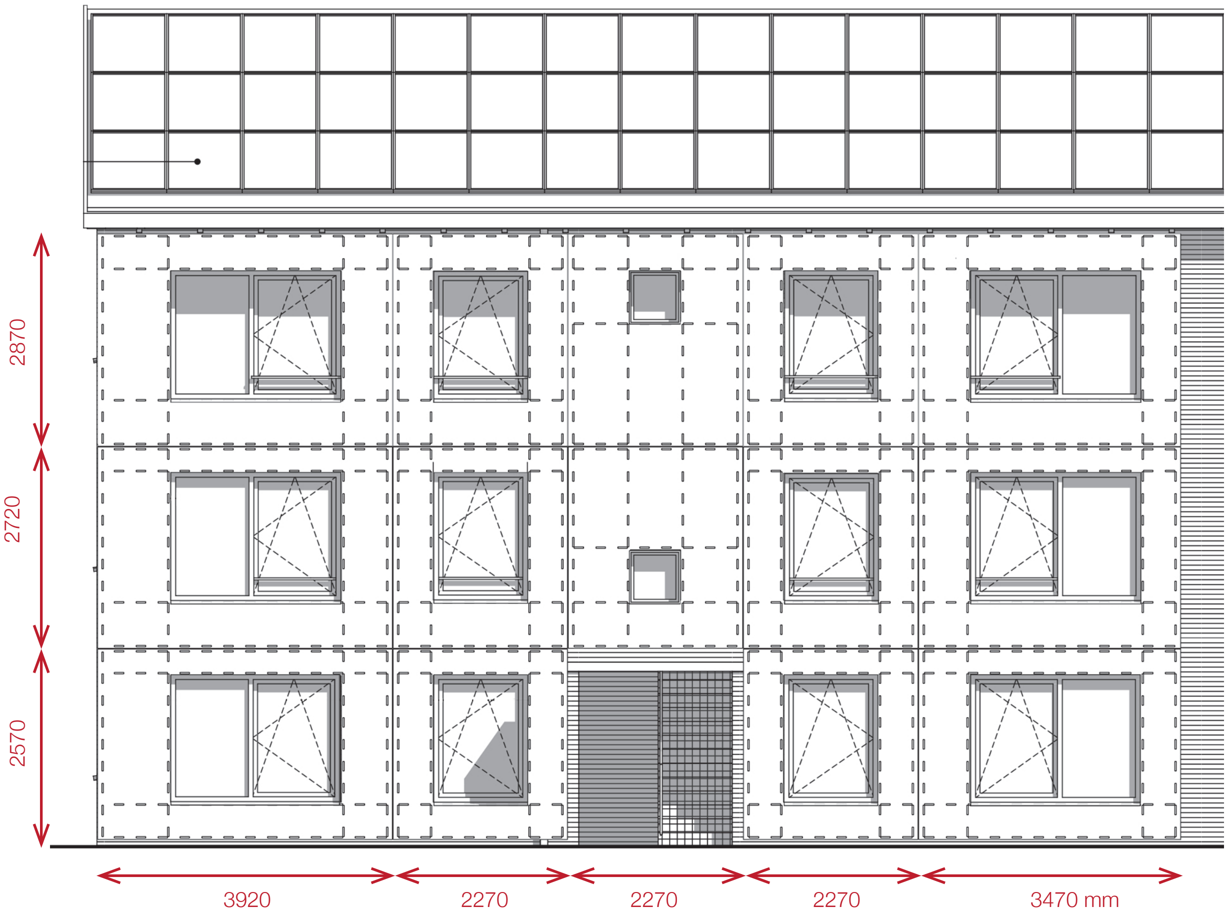


Fig. 70:
Case Study Building 1
Front facade, scale 1:100
(source: own image)

Final design

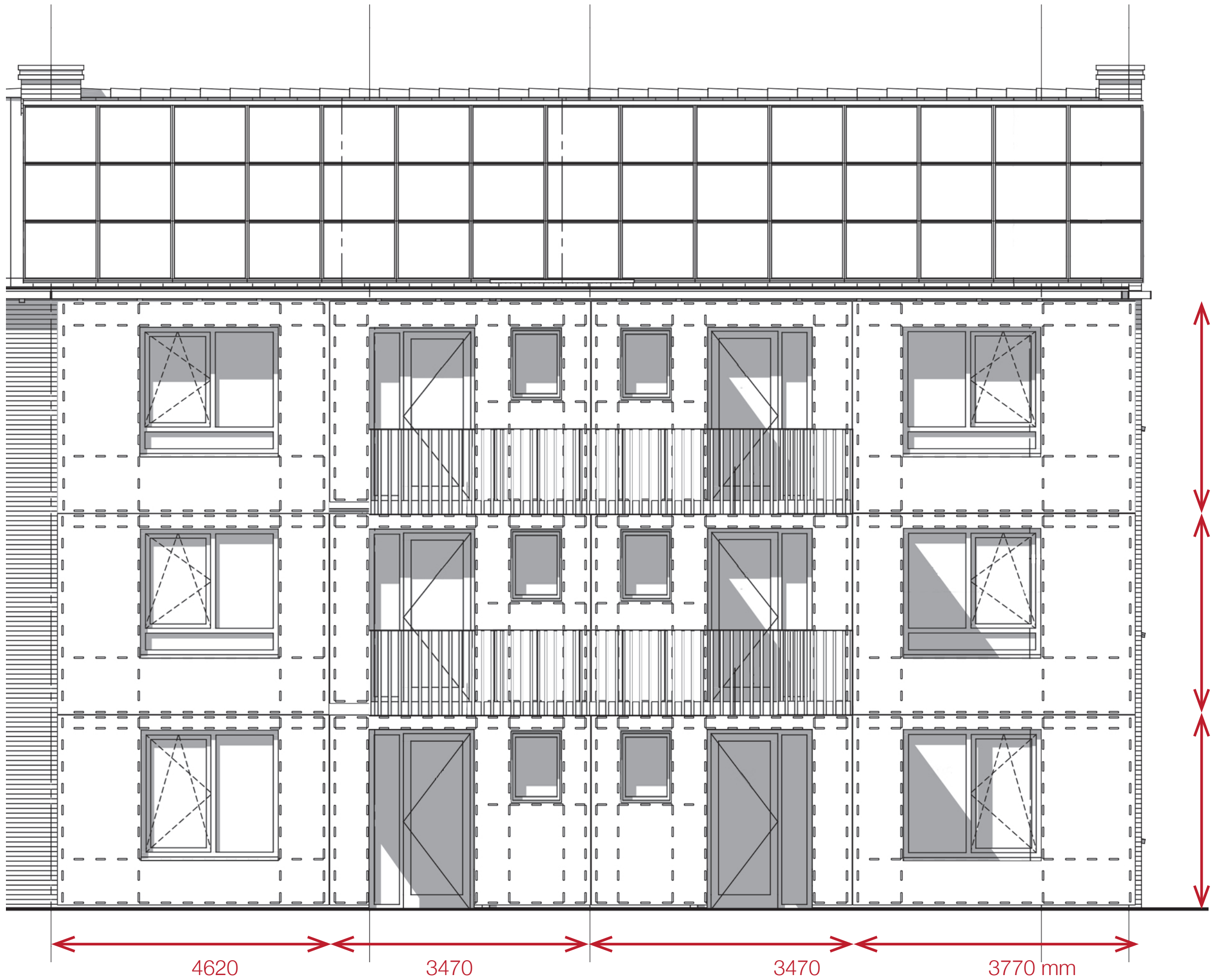


Fig. 71:
Case Study Building 1,
Back facade, scale 1:100
(source: own image)

Final design

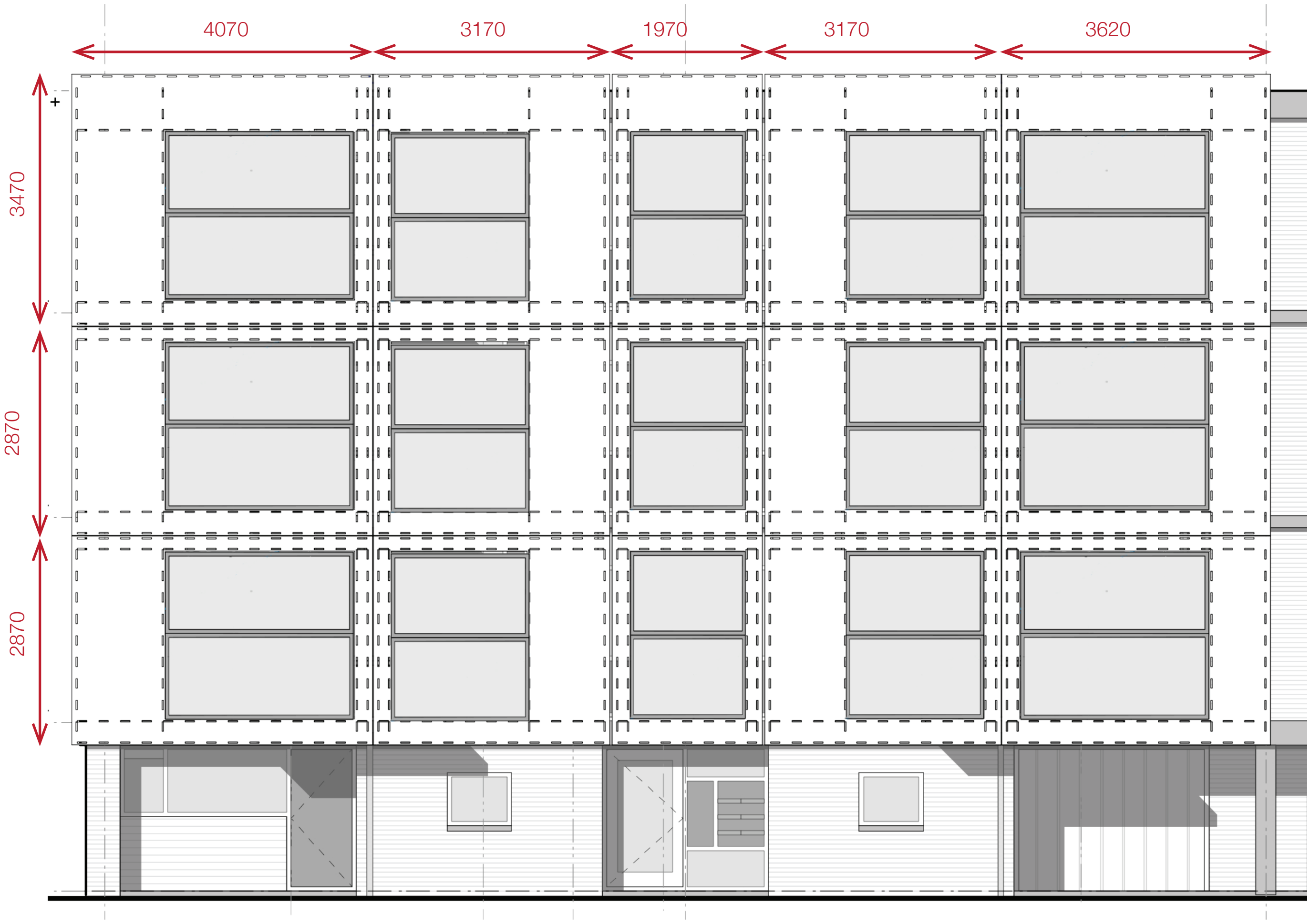


Fig. 72:
Case Study Building 2
Front facade, scale 1:100
(source: own image)

Final design

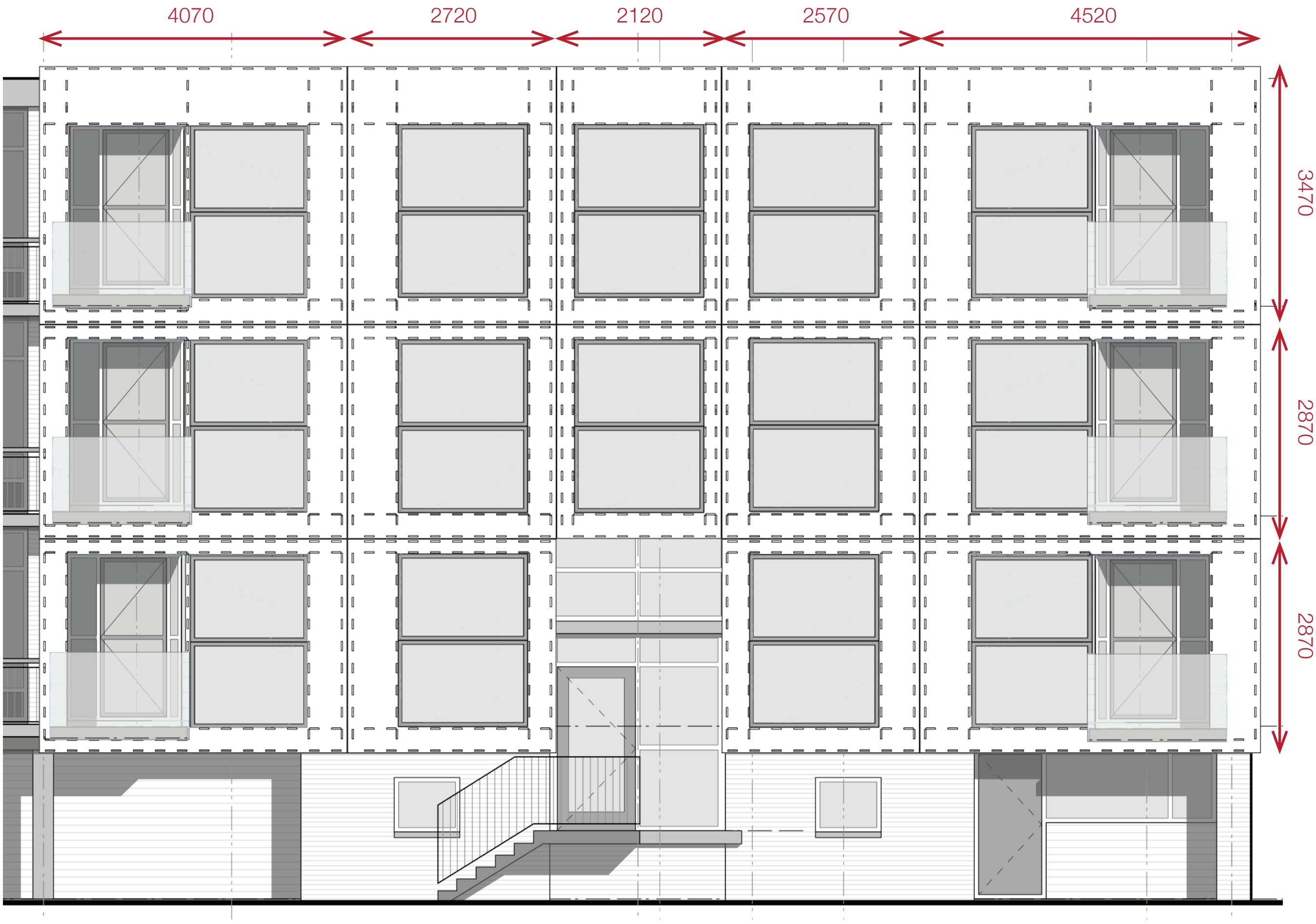


Fig. 73:
Case Study Building 2,
Back facade, scale 1:100
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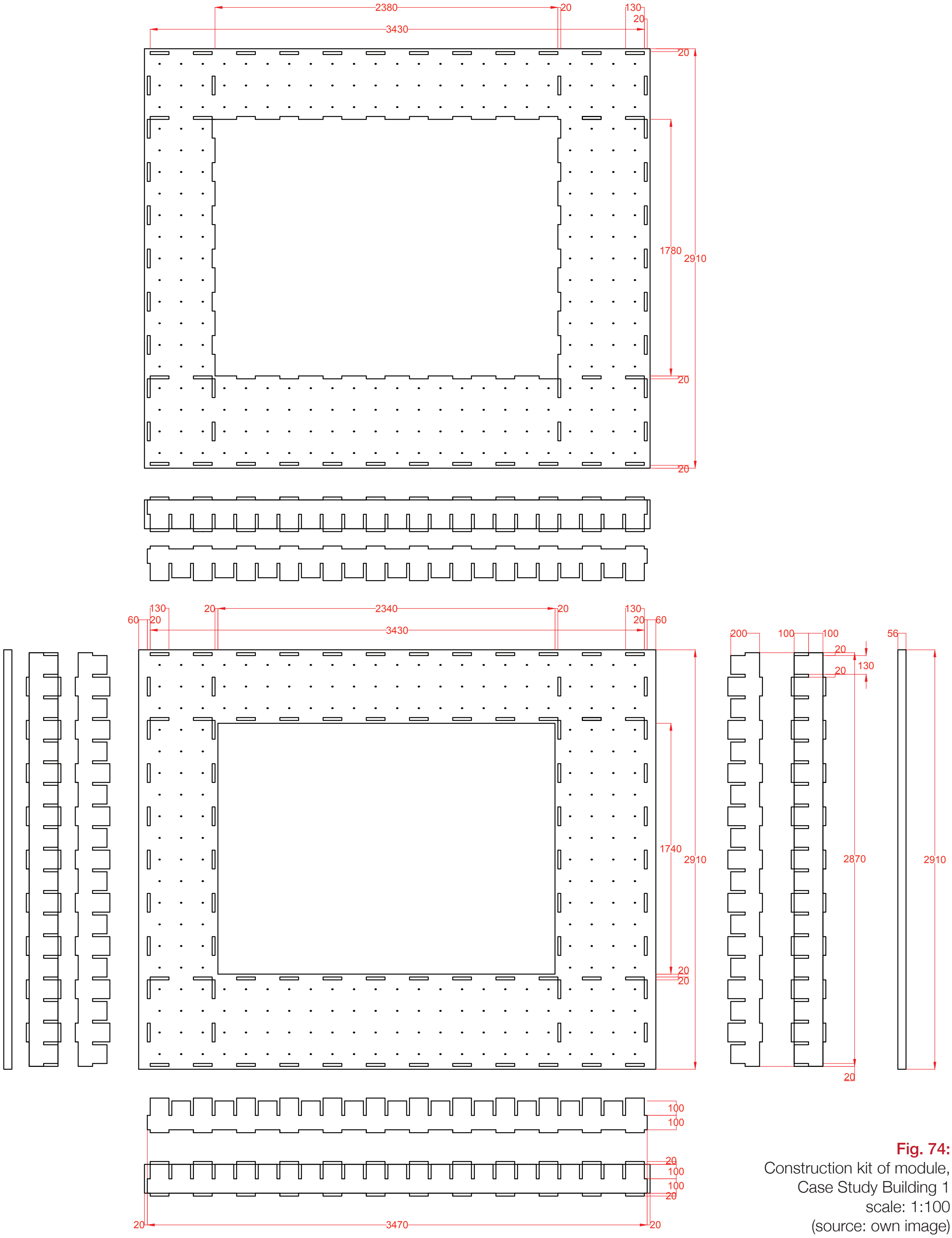


Fig. 74:
Construction kit of module,
Case Study Building 1
scale: 1:100
(source: own image)

Dimensioning

Fig. 74 and 75 show the construction kit of one prefabricated façade module of Case Study building 1 and one prefabricated façade module of Case Study building 2. As can be seen in the drawings, the construction kit consists of a set of two horizontal and two vertical partitioning studs that will be positioned at the location of the facade opening, two horizontal and two vertical structural studs that define the frame of the prefabricated module, an exterior and an interior board and two wooden posts of 56 x 56 mm that make the connection of the prefabricated module with the substructure, which is in turn connected to the existing façade of the residential building. All elements have a thickness of 18 mm, similar to the design of the prefabricated modules of the facade of PD-lab (see p. 125), because this thickness is tested to be structurally strong enough in this situation (Van der Knaap, 2016). Due to time limitations of the research, structural performance of the proposed design of the prefabricated modules haven't been tested, so it could be that the studs require an increased thickness. Both the partitioning and structural horizontal

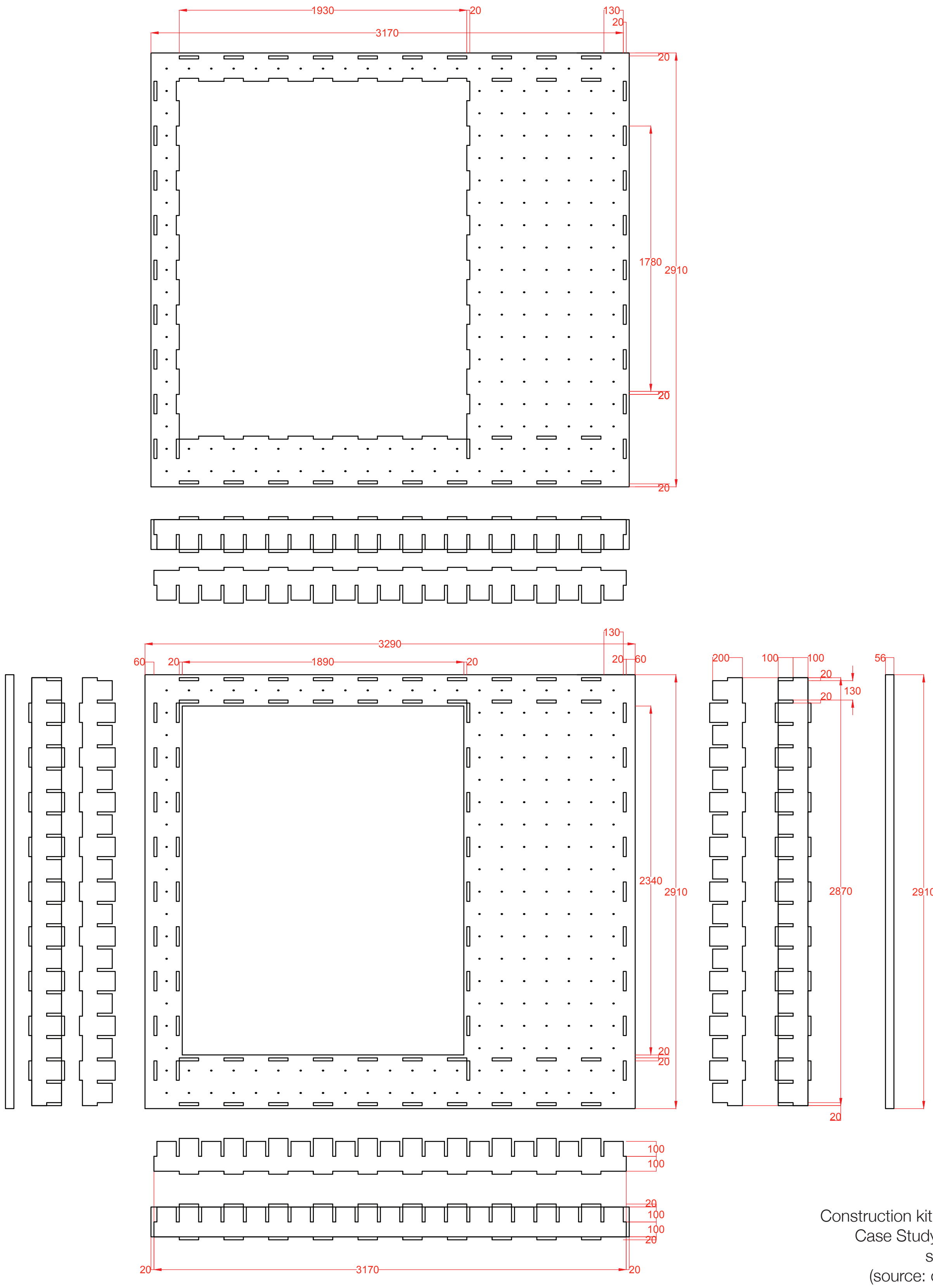


Fig. 75:
Construction kit of module,
Case Study Building 2
scale: 1:100
(source: own image)

and vertical studs contain grooves at a centre-to-centre distance of 150mm in the length. The grooves have a length of 100mm and a width of 18mm, based on the thickness of the partitioning studs. The partitioning and structural studs have a width of 200mm, determined by the required additional insulation thickness to make the residential building energy neutral. This thickness is based on the calculations of Thaleia Konstantinou, to achieve a thermal resistance of the facade of Rc = 6,5 W/m2K when an insulation material is applied with a thermal resistance of 0,040 W/mK (Konstantinou, 2014). When another type of insulation is used with a higher or lower thermal resistance, the thickness of the studs has to respectively increase or decrease. At every 300mm the studs have a bigger width with an additional 18mm on both sides, to be able to make the friction-fit connection with the interior and exterior board of the module. The partitioning and structural studs differ in thickness. The partitioning studs are single-layered. The structural studs are double-layered; they have an additional back plate of 18mm to increase their stiffness and to enable the connection with the exterior and interior board of the façade module.

Case Study Building 1

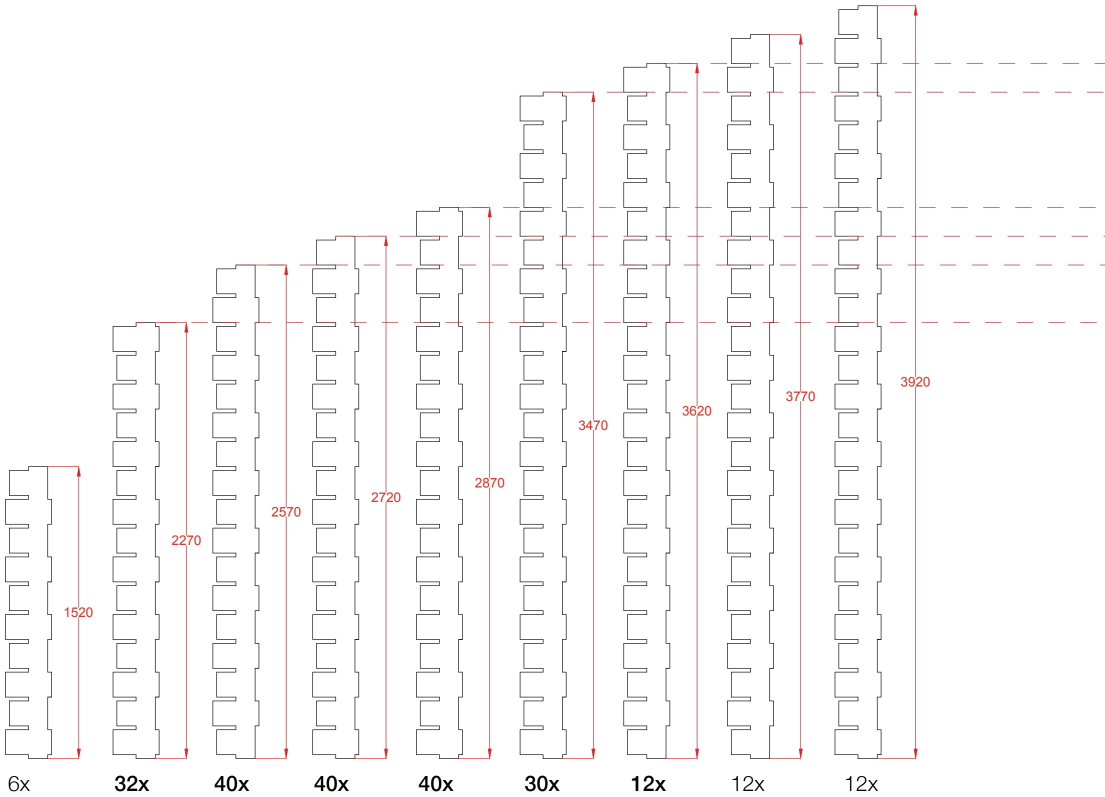


Fig. 76:
Kit of standardised parts
Case Study Building 1
(source: own image)

Case Study
Building 2

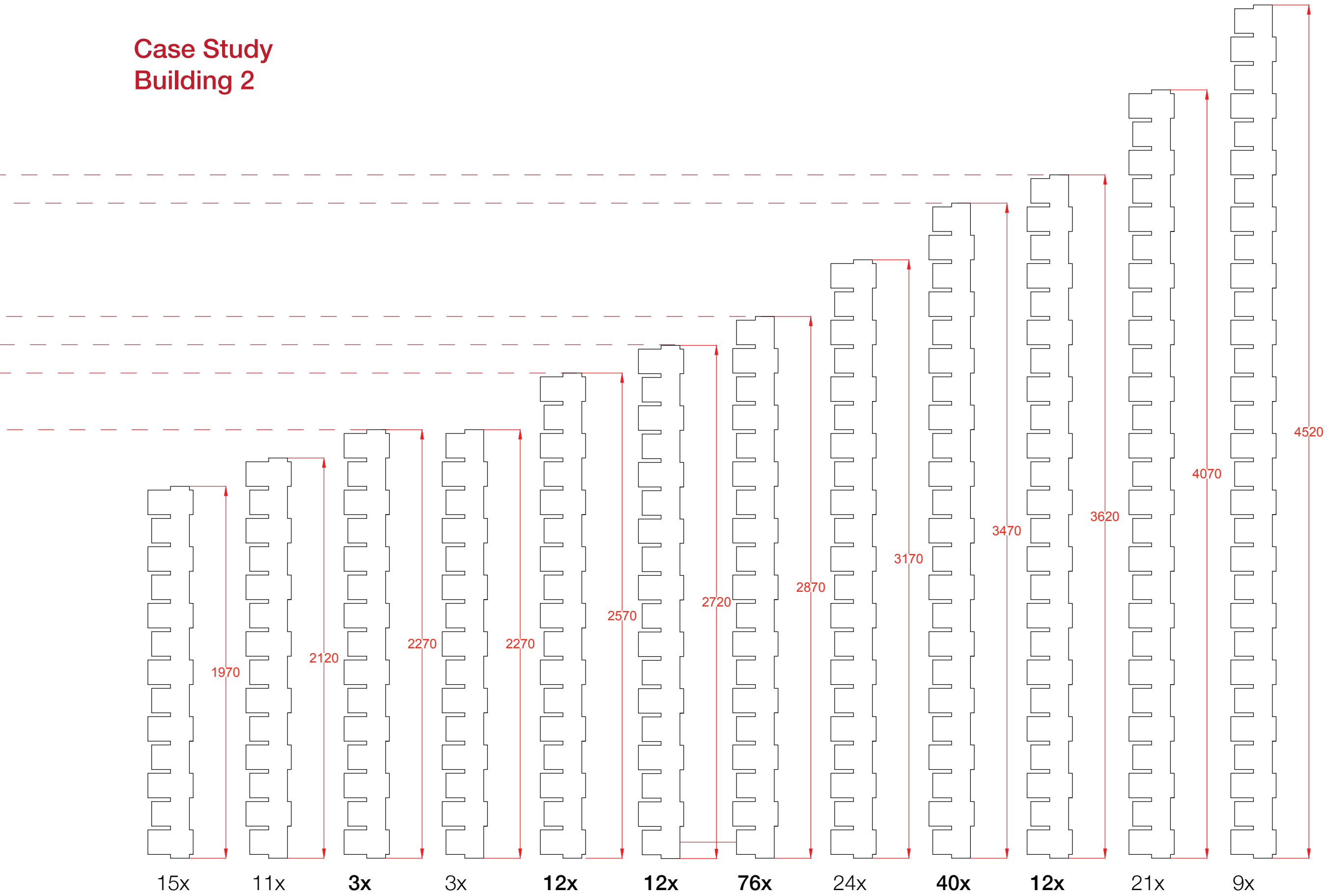
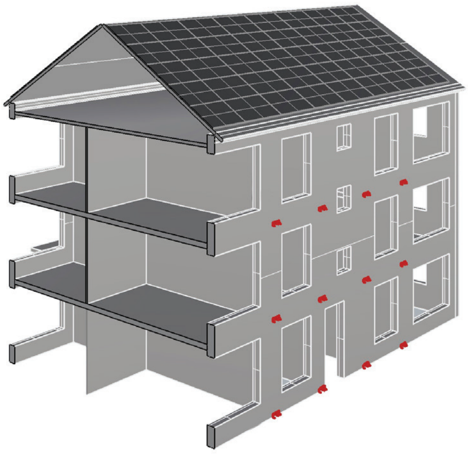


Fig. 77:
Kit of standardised parts
Case Study Building 2
(source: own image)

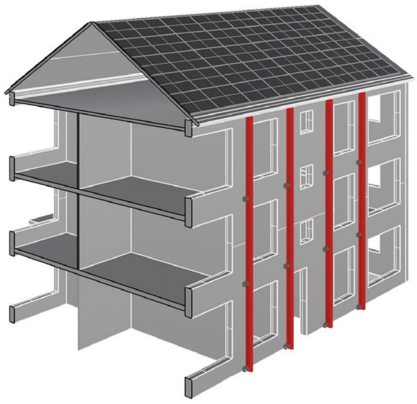
Standardisation

Fig. 76 and 77 represent the two construction kits of horizontal and vertical partitioning and structural studs, that are needed for the assembly of the prefabricated modules that shape the complete 2nd Skin Façade Refurbishment system of respectively Case Study Building 1 and 2. When comparing the two construction kits, the studs have varying dimensions. As can be seen in the diagrams, one set of studs, with a height of 3612 mm, can be reused directly without adjustment. For Case Study Building 1 and 2 these studs will be used repetitively 24 times, applied to 12 prefabricated modules. The other sets of studs have different dimensions and need to be adjusted for reuse. Adjustment of the studs means cutting off a piece of 150/300/450mm. These left-overs could be recycled for the production of new studs or reused in other industries. Eventually, when a high number of residential buildings will be refurbished with the same system, expected is that some studs with a certain dimension will be most often (re)-used for the refurbishment of multiple buildings. As a result, these studs will be considered as the most standardised and will consequently be produced in a higher number. Studs with other dimensions should be considered as deviating from the standard size, and will be produced less frequently. Consequently, the system will further evolve and minimum and maximum dimensions of the studs will be determined, because at a certain moment the studs will have been cut to the smallest size and obviously can't be enlarged. As a result, the 2nd Skin Facade Refurbishment system of the reference building will be subdivided into prefabricated modules, based on the minimum and maximum dimensions of the studs.

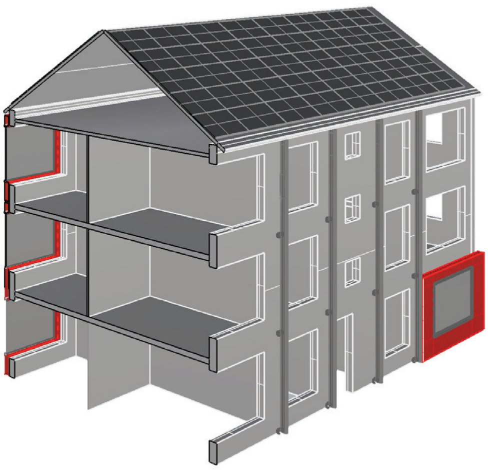
The redesign proposal doesn't take into account the standardisation of the exterior and interior board of the modules, because expected is that these boards can't be standardised to a high level. Next to that, the interior and exterior board contribute to the stiffness of the panel and thus can't be subdivided into separate smaller elements. The façade arrangements of the two Case Study Buildings already vary too much. When the arrangement of the façade module changes, the interior and exterior board have to be adapted to the new layout. This can be done by cutting the window openings to the right size and milling new grooves in the board at the changed position of the horizontal and vertical studs. However, this is only possible to a certain extent. When the window opening has to become smaller, the board can't be reused, because the size of the opening in the board can't be decreased. However, when the system will be applied on a large scale, there is a high chance that some boards have the potential to be reused on different façades of residential buildings with the same typology. Post-war residential buildings, located in the same neighbourhood, often have similar façade arrangements. In these cases, the interior and exterior board do have direct reuse potential without any adjustments.



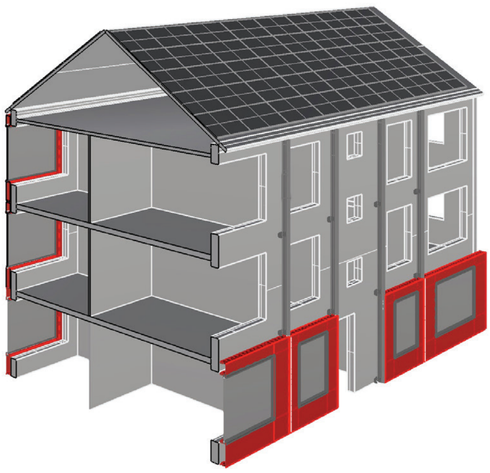
1.
Placement of the stainless-steel anchors, screwed to the existing facade



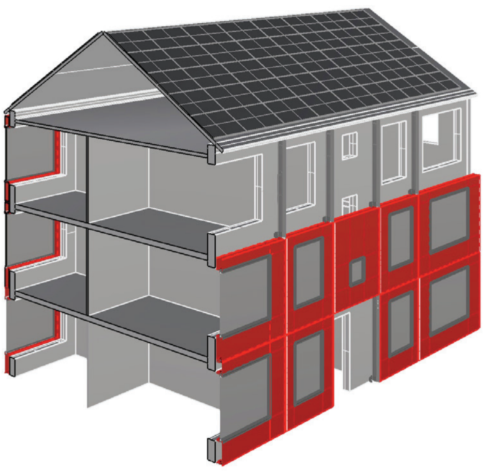
2.
Placement of the vertical wooden posts, attached with a bolted connection to the anchors.



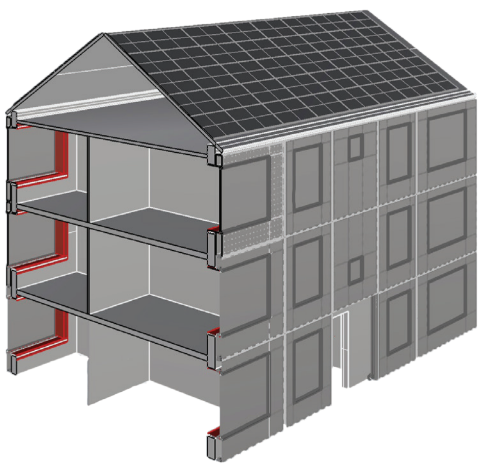
3.
Installation of the first prefabricated module, connected to the vertical posts of the substructure with screws.



4.
Installation of the first line of prefabricated modules at ground floor level. The support structure of the facade cladding has already been attached to the modules.



5.
Installation of the rest of the prefabricated modules, line by line.



6.
When one module is placed, the internal finishing in the room can already be installed.

Assembly sequence

Is the assembly sequence parallel, meaning multiple components can be placed at the same time?

yes no

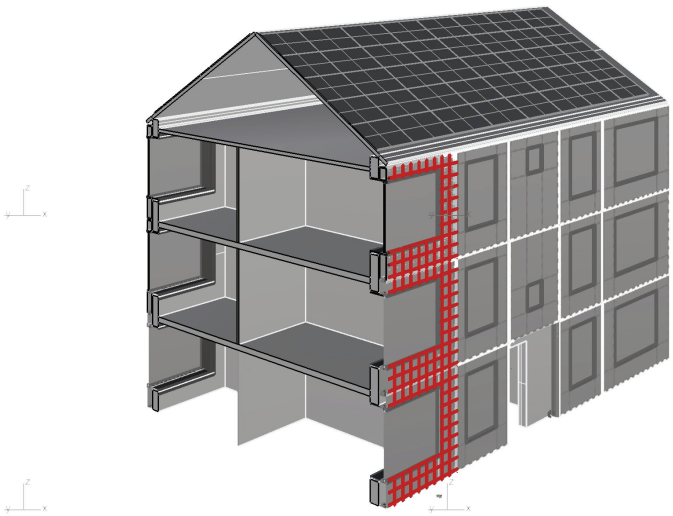
Can the component be removed from the facade without damaging other components?

yes no

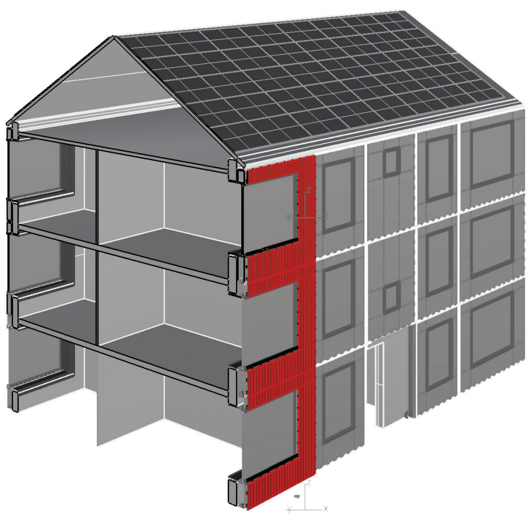
As can be seen in fig. 78 the assembly sequence of the redesigned 2nd Skin Facade Refurbishment system is sequential. While multiple prefabricated modules can be assembled parallel off-site, on the building site the prefabricated modules can only be installed one after another. The prefabricated modules have to be installed at a certain distance from each other, to be able to perfectly match the arrangement of the existing facade. Thereafter, the joints between the prefabricated elements need to be filled with additional insulation and sealed waterproof. Already in the factory the supporting structure of the facade cladding will be attached to the prefabricated modules. To conceal the joints, the facade cladding will be installed on-site, with an additional connecting piece of the supporting structure, spanning from module to module. As a result, when one facade module needs to be removed from the facade, the facade cladding material has to be removed first. Next to that, when a certain element within the prefabricated module has to be replaced, the complete module has to be taken off the facade. The rearrangement of the module should be done at a place where the module can be laid down horizontally, because the module loses its stiffness when the exterior board is removed.

The assembly of the prefabricated module itself, is also sequential. As a first step, structural studs that define the outer frame of the module should be placed at the right position in the grooves of the interior board. Then the partitioning studs, that define the position of the façade opening, will be placed successively. As a next step, the soft insulation material will be pressed within the closed parts of the frame. Then the exterior board will be placed on top of the frame with the grooves at the exact position of the protruding notches of the frame. The wooden sticks, that connect the prefabricated modules to the substructure, had already been attached to the exterior board. When the exterior board is placed, the wooden sticks will also be screwed to the frame to ensure the connection to the prefabricated module. Then the modules will be lifted to stand vertically. As a final step, the window frame will be installed in the module, the cladding supporting structure will be attached to the exterior board and the ventilation shafts to the interior board of the module.

Fig. 78:
Assembly sequence
(source: own image)



7.
When all modules are connected to the existing facade with sealant at the joints, the support structure of the facade cladding can be placed,



8.
Finally, the facade cladding material, in this case bamboo, can be attached to the facade, spanning from module to module.

Detailing

On the basis of detailed drawings (scale 1:10), the Disassembly Potential of the proposed redesign of the 2nd Skin Facade Refurbishment system will be analysed, by answering the final five questions of the Roadmap.

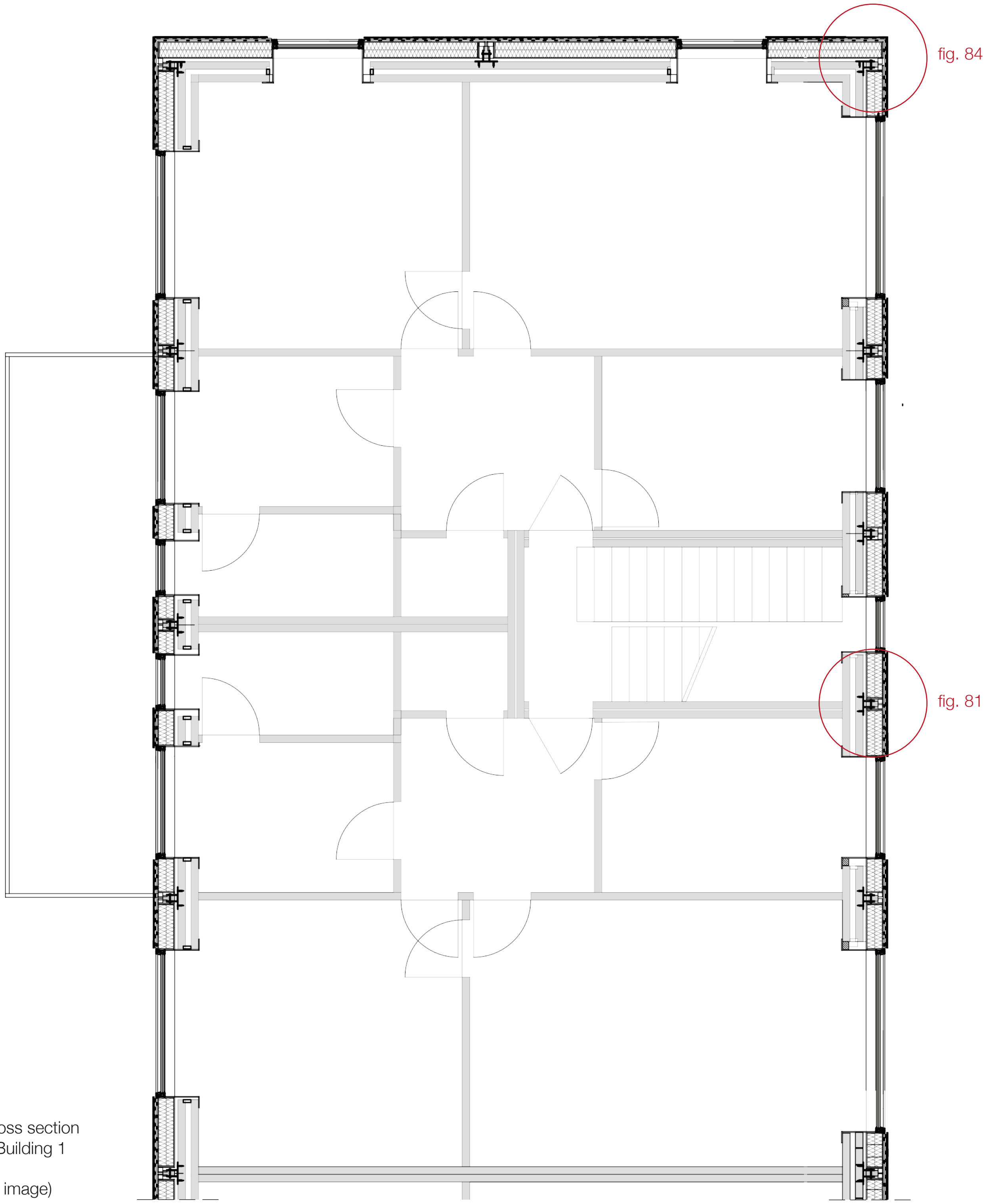


Fig. 79:
Horizontal cross section
Case Study Building 1
scale 1:100
(source: own image)

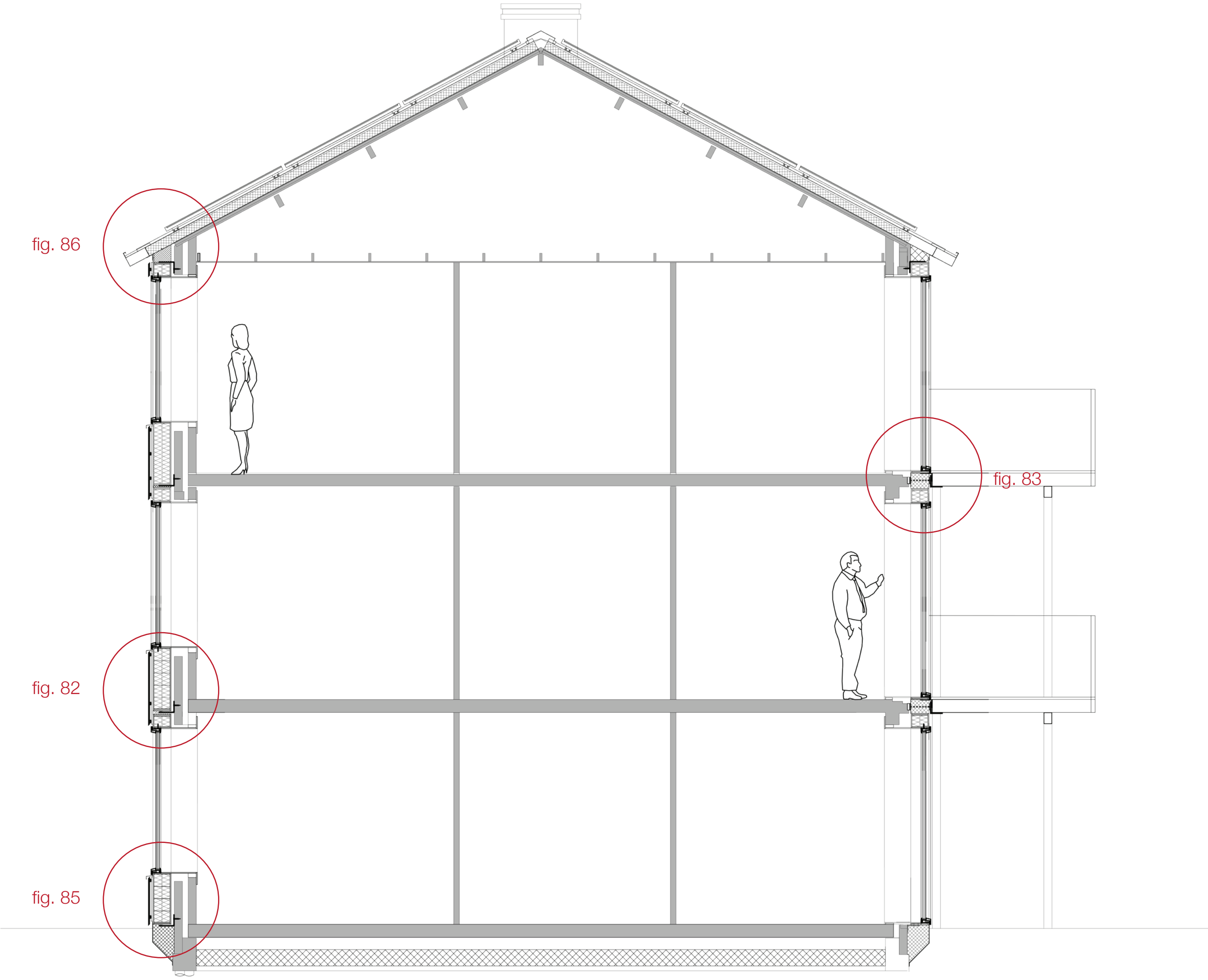


Fig. 80:
Vertical cross section
Case Study Building 1
scale 1:100
(source: own image)

Hor. connection facade modules

Does the component represent only one function?

yes no

As can be seen in the horizontal connection detail of the prefabricated facade modules to the existing facade, many functions are incorporated into the prefabricated facade modules. The insulation layer is integrated in the prefabricated module, so it provides the additional thermal insulation of the facade. Next to that, the prefabricated facade modules take over the arrangement, shape, proportion and scale of the existing facade. Also the prefabricated modules provide the stiffness of the added 2nd Skin Facade. Adaptation of the arrangement of the prefabricated module will have a direct effect on the thermal resistance of the facade. When the size of the facade openings has to increase or decrease, the thermal resistance of the complete facade will become relatively lower or higher, because of the low Rc-value of the double glass windows (Rc = 1,135 W/m^{2}K) in comparison with the closed parts of the facade (Rc = 6,5 W/m^{2}K). Next to that, rearrangement of the module will have a direct effect on the stiffness of the module; when the size of the window increases, the structural frame of the window has to support bigger loads. These situations need to be taken into account in the dimensioning of the elements.

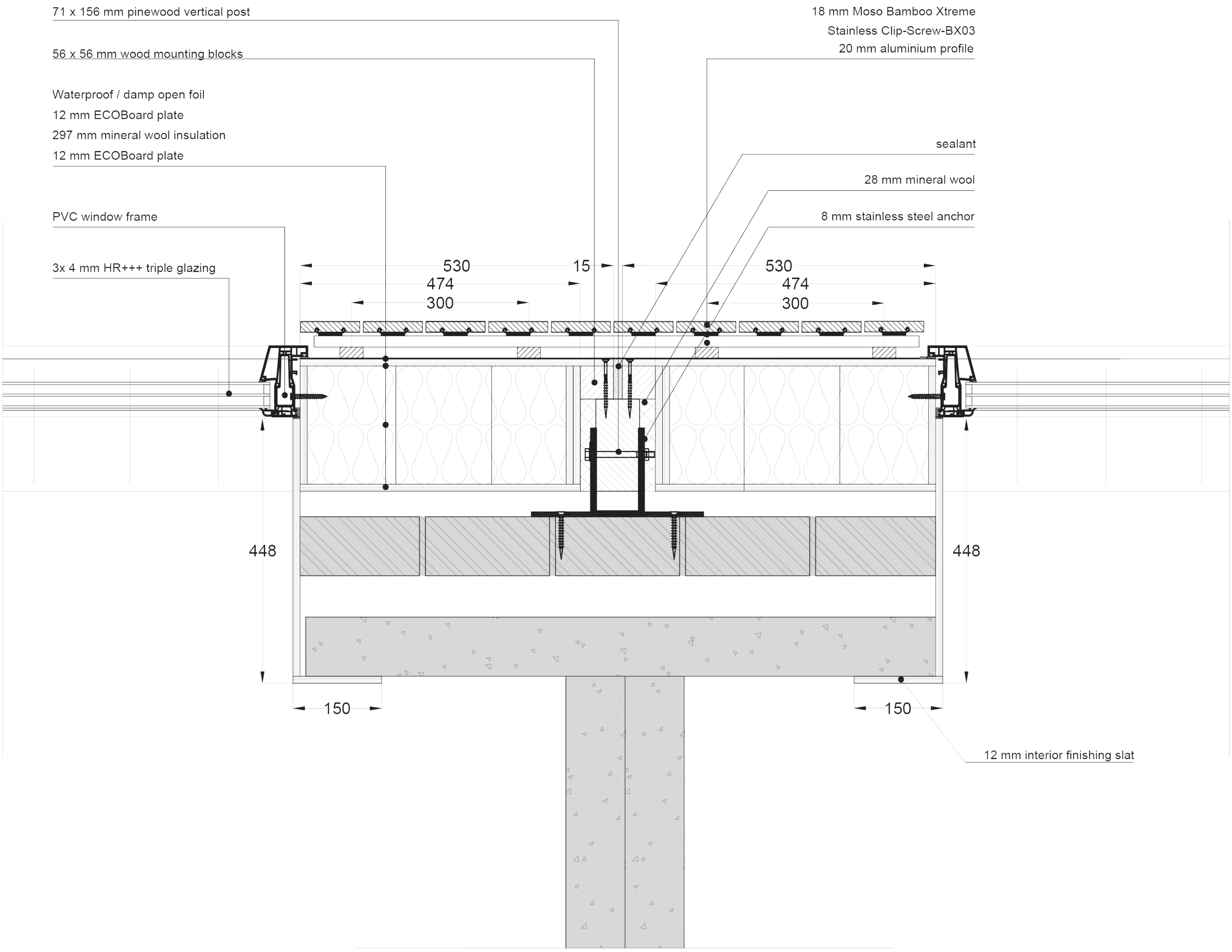


Fig. 81:
Horizontal detail
connection window frame
scale 1:10
(source: own image)

Vert. connection facade modules

Are multiple elements clustered into the (prefabricated) component?

yes no

Most elements that the 2nd Skin Facade Refurbishment system consists of, are integrated in the prefabricated modules. The prefabricated modules will be delivered on-site with insulation, support structure of the cladding, ventilation shafts (when needed) and window frames integrated. The facade cladding will be delivered seperately and needs to be attached to the support structure on-site. Also the interior finishing has to be placed on-site, to accomodate the tolerances of the existing facade. The interior finishing could also be prefabricated in the factory.

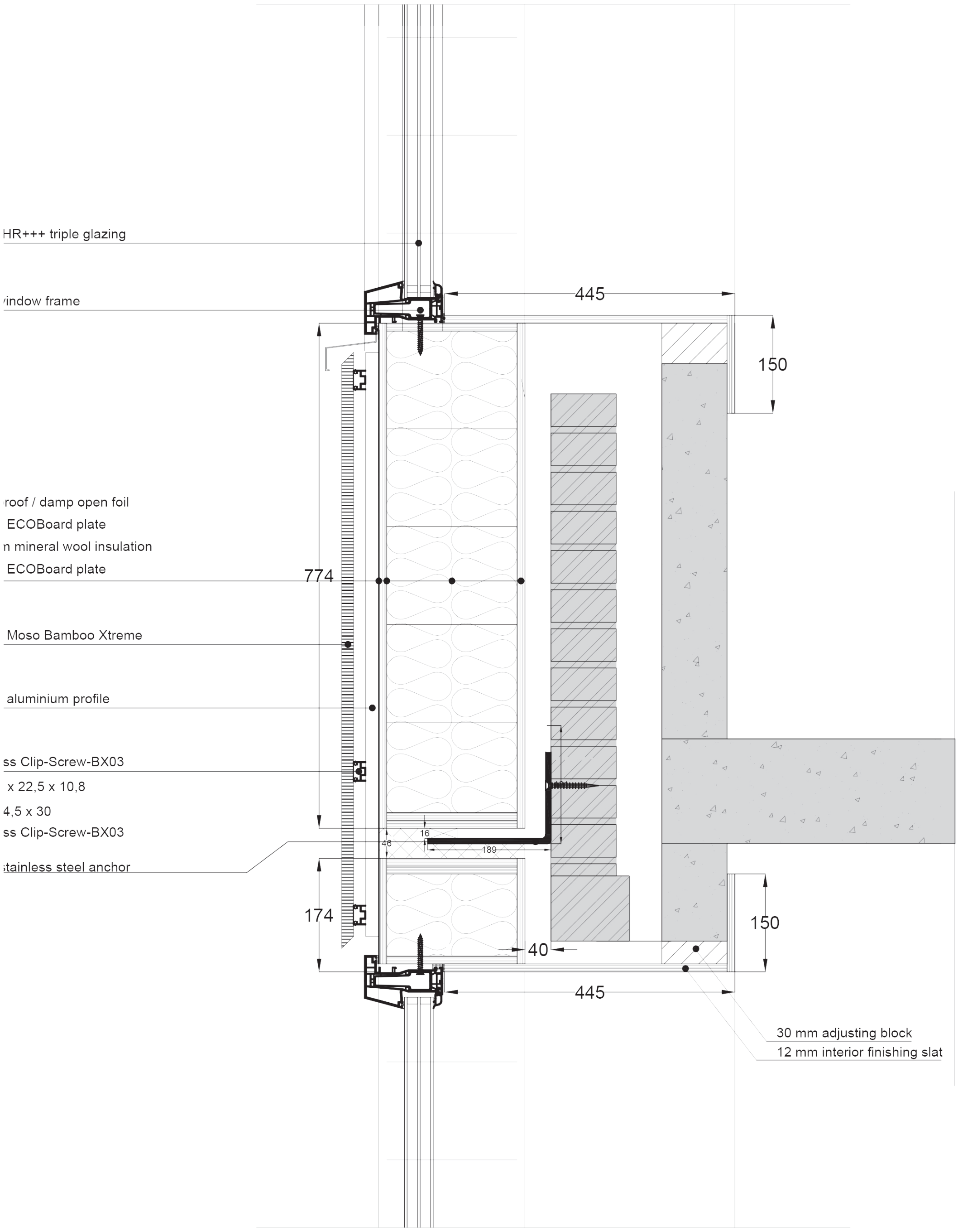


Fig. 82:
Horizontal detail
connection at the corner
scale 1:10
(source: own image)

Hor. connection balcony

Is there a base element, to which all facade components are connected, present in the facade?

yes no

The prefabricated facade modules form the base elements in the 2nd Skin Facade Refurbishment system, to which the other facade components are connected. The building services will be connected to the interior board of the prefabricated facade modules and the cladding will be attached to the exterior board of the prefabricated modules. The insulation layer will be stuck between the interior and exterior board of the facade modules. The connection of the modules to the existing facade is made through the substructure via the connection sticks that are in turn connected to the exterior board. As can be seen in the horizontal detail of the balcony connection, the balcony support is combined with the stainless steel anchors that support the prefabricated modules and make the connection to the existing facade.

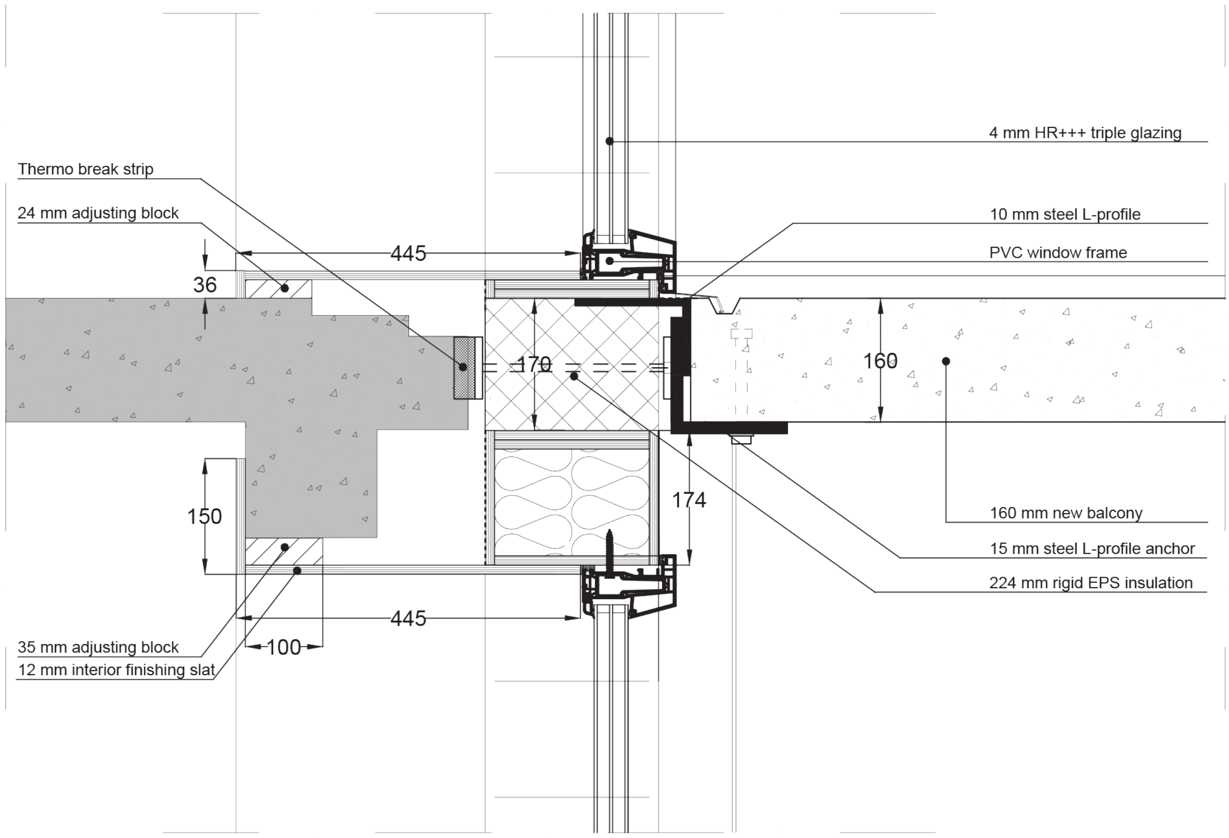


Fig. 83:
Vertical detail
connection balcony
scale 1:10
(source: own image)

Hor. connection corner

Is the component with the shortest lifetime situated closest to the outer surface and the component with the longest lifetime farthest?

yes no

The Life Cyce Coordination of the 2nd Skin Facade Refurbishment system hasn't been improved in the redesign, compared to the Prefabricated variant. The composition of the facade has stayed the same; the building services, that have the shortest technical and functional lifetime of the system, are still placed closest to the existing facade. The ventilation shafts have become better to reach, because they aren't placed within the prefabricated modules, but at the outside. Next to that, the connection of the ventilation shafts to the interior board of the prefabricated modules is mechanical and demountable.

As can be seen in the horizontal connection detail at the corner (fig. 84), the substructure carries the load of the prefabricated modules and transfers these to the ground. The existing wall of the building isn't strong enough to carry the additional weight of the 2nd Skin Facade. For this reason, a seperate foundation wall should be used, connected in the ground to the existing foundation of the building. This means additional ground works should be done on-site.

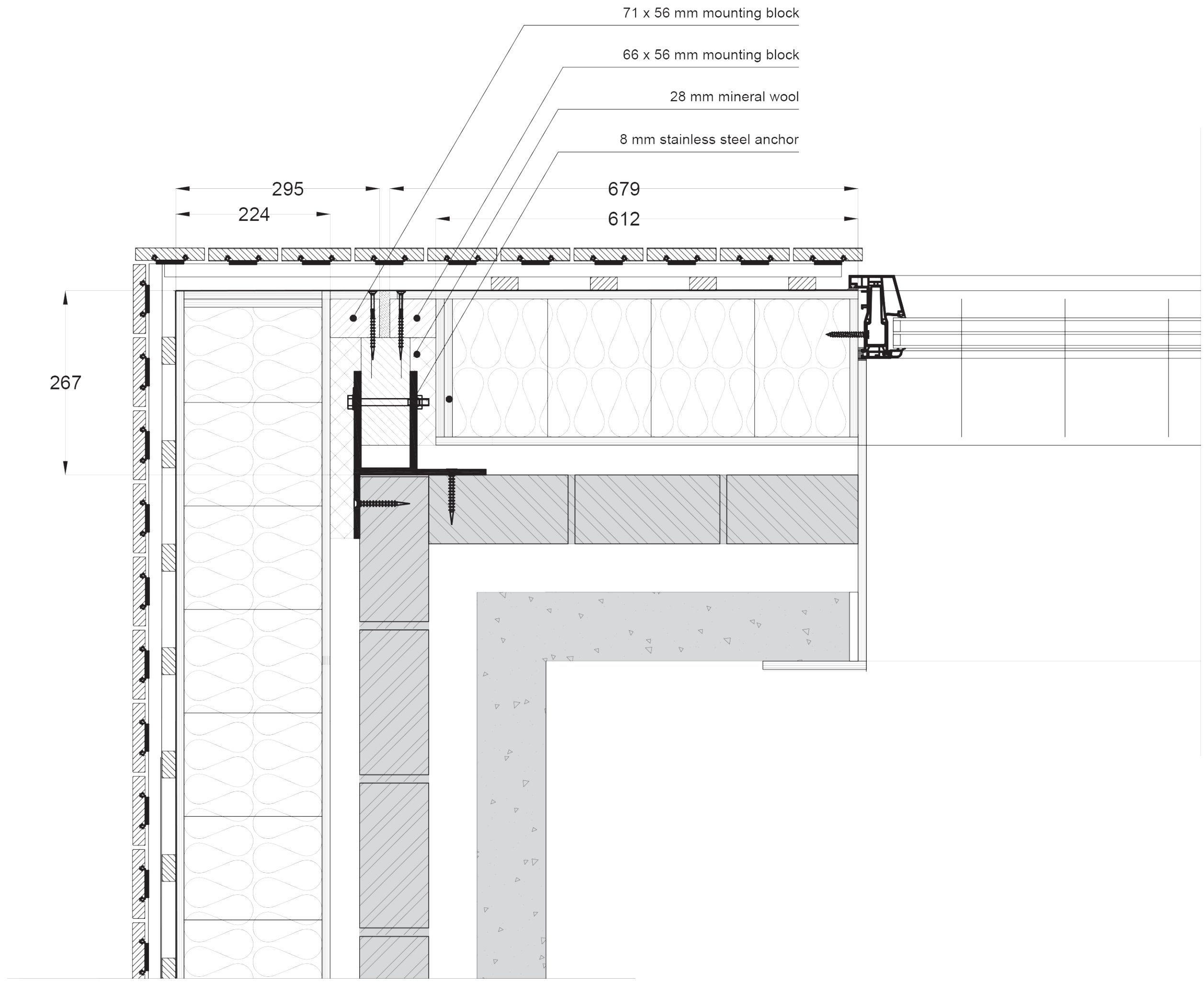


Fig. 84:
Vertical detail
connection window frame
scale 1:10
(source: own image)

Vert. connection foundation

As can be seen in the vertical connection detail of the foundation, the prefabricated modules hang above ground.To prevent thermal leakage through the ground, additional rigid EPS insulation with a layer of bitumen emulsion has to be placed on top of the existing facade that lies underground, depending on the ground water level. The connection with the prefabricated modules will be made waterproof by connecting the remaining foil of the prefabricated modules with the EPS insulation layer.

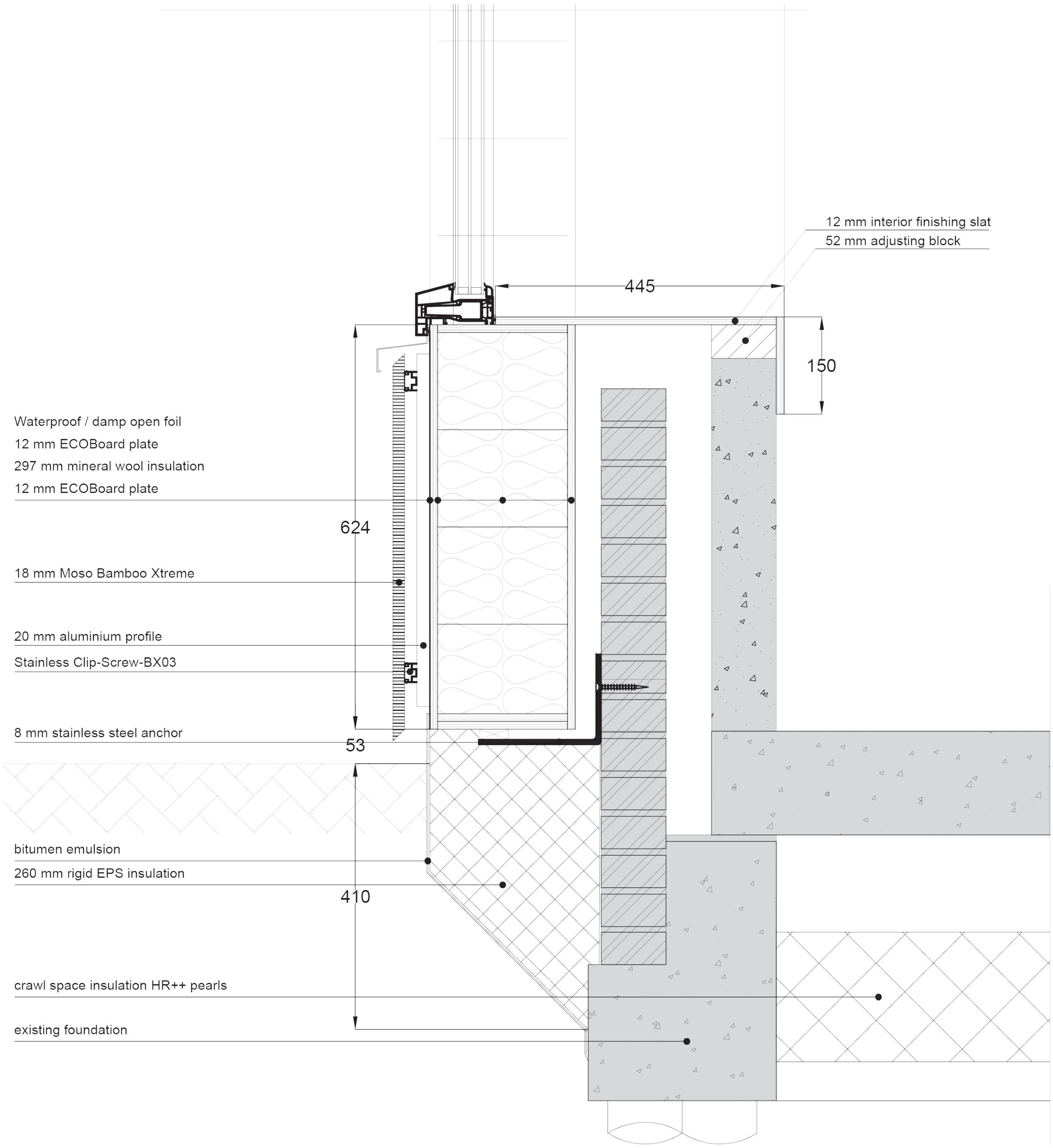


Fig. 85:
Vertical detail
connection foundation
scale 1:10
(source: own image)

Vert. connection roof

Next to that, to be able to let the thermal line continue uninterrupted, additional EPS insulation is needed at the location of the connections of the prefabricated modules to the roof, because the prefabricated modules can't complement precisely the edge of the gabled roof of the residential building. These additional EPS plates shouldn't be glued to the existing facade, but they should be clamped beteen the protruding edges of the frame of the prefabricated modules.

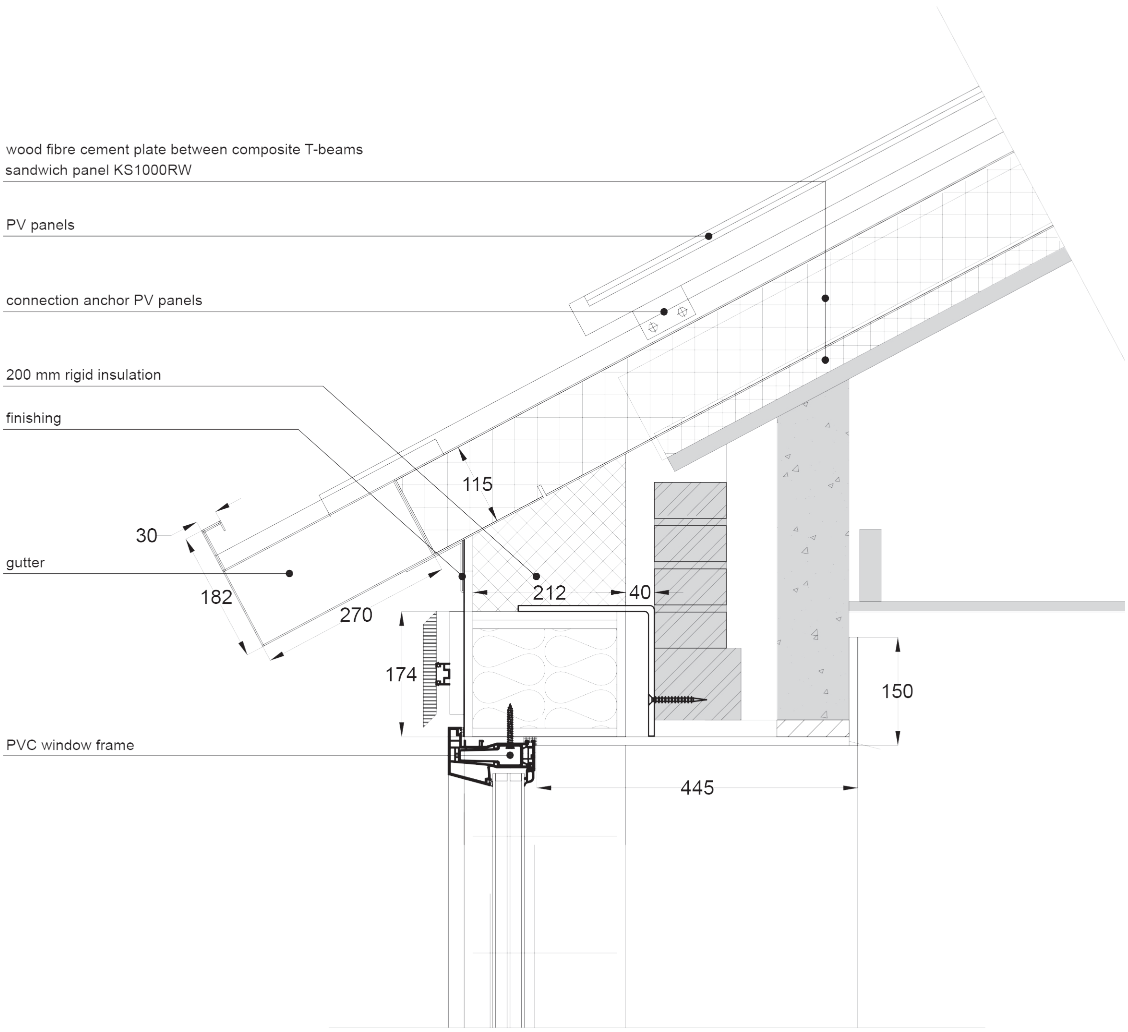


Fig. 86:
Vertical detail
connection roof
scale 1:10
(source: own image)

Scenarios of change

The contractor BIK Bouw delivers the 2nd Skin Facade Refurbishment system as a complete package: they take care of the design and installation of the refurbishment system, applied to the reference building, as well as the monitoring and support during the service life of the refurbishment system. This means that the contractor will be hold responsible for the maintenance of the refurbishment for the period after installation of the system. Consequently, it is in the best interest of the contractor to provide the refurbishment system for its complete service life at the lowest possible price. For this reason, the contractor will mainly look from a financial and sustainable perspective to the system. On the one hand, he is interested in new technology investments that give him a faster return by reducing his costs; such as the upgrading of energy-generation technologies with higher efficiencies after 20 years (Azcarate Aguerre, 2014). An estimated service life of 25 years is taken into account for the refurbishment of the case study building in Vlaardingen. As key performance indicators for circularity, the following future scenarios will considered for the 2nd Skin Façade Refurbishment system, based on the discussion with the contractor BIK Bouw (BIK Bouw, personal communication, November 13, 2017):

Scenario 1: Building stays for another 25 years
When the refurbished building is qualified to be maintained for another 25 years, only the building components and elements that have reached the end of their functional and/or technical service life, need to be replaced. In the case of the Circular 2nd Skin Façade Refurbishment system, the first elements that need to be replaced after 30 years, are the building services. There is even a high chance that the building services need to be replaced with installations with higher efficiencies, already during the first period of use of the refurbishment system, considering the average functional lifetime of services of 7-15 years (Berge, 2009). The second component that will need to be replaced, is the cladding. The external envelope of the facade is expected to become obsolete after 20-30 years (Konstantinou & Knaack, 2011). Based on this observation, we could expect the façade cladding to be changed after 25 years. The technical lifetime of the bamboo slats will be ended after 35 years, while the aluminium mounting profile is still sufficient to use for another 50 years. Thus there is potential in replacing the bamboo cladding with a different cladding material, that can be supported by the same mounting profile. The substructure and SIP-panels can be maintained for a second period of use of the 2nd Skin Façade, because of their long technical lifetime of 50-75 years.

Scenario 2: Function changes
The second scenario that could occur after 25 years, is function change of the building. When the function changes, there is a high chance the façade arrangement and shape of the building has to be altered. Reason for function change could be the wish of the housing corporation to attract a new target group to the area, for example change from social rent housing to higher incomes classes. The municipality of Rotterdam states that the city has a surplus of post-war residential buildings for low-income households, while there is a shortage of residential buildings for high- and middle-income households. For this reason, the municipality has decided to demolish thousands of homes (NOS Binnenland, 2016). As reaction to these urban developments, the 2nd Skin Facade should enable upgrading or reconfiguration of the facade as a means to change along with the supply and demand of the neighbourhood. The appearance of the building can be upgraded by changing cladding material. As a next step, the 2nd Skin Facade can be altered by decreasing or increasing the size of the window openings and repositioning of the windows. However, consequence is that the existing facade of the building has to change along with the refurbishment system. Thus, when the function of the building changes, the existing facade should have to be removed. When the structure of the existing building will be maintained, the prefabricated modules of the 2nd Skin Facade can still be reused on the same building by rearranging the horizontal and vertical slats of the module. Only the windows will need to be replaced in this situation.

Scenario 3: Deconstruction
After 25 years the post-war residential building needs to be deconstructed. Reasons for deconstruction could be that the existing facade and/or structure of the residential building has reached the end of its technical service life or that the building no longer meets the living standards of the residents. At the end of its functional life, the 2nd Skin Façade Refurbishment system has to be removed.

1) One option is to reuse the complete system by placing the same prefabricated modules of the 2nd Skin Façade Refurbishment system in front of the existing façade of another (post-war) residential building that is in need of refurbishment, which has a similar facade arrangement as the deconstructed residential building

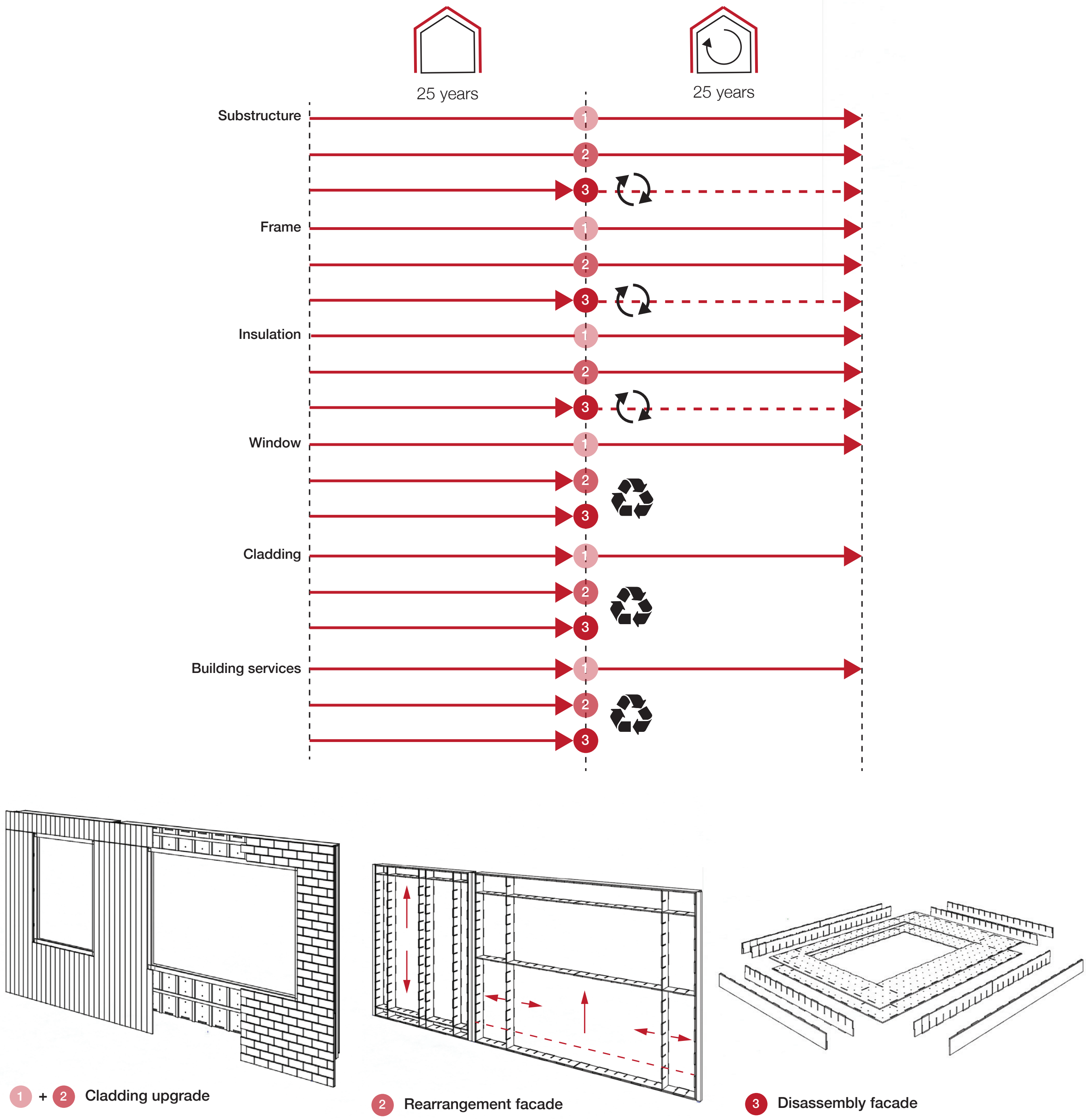


Fig. 87:
Future scenarios
Circular 2nd Skin Facade
(source: own image)

2) The second option is to reuse the separate components that haven't reached the end of their technical service life, and reuse them in a different configuration and/or combination. The components that can be considered for reuse after 25 years, are the substructure, the frame of the prefabricated panels, the insulation material and the supporting profile of the cladding, which all three have a remaining technical service life of 50 years. For the components, a new reuse destination should be found that requires as little as possible adjustments to the original configuration of the component. The materials that have reached the end of their technical lifetime, such as the window, cladding and building serivce, should be recycling for the production of new components.

Design evaluation

Material Circularity Indicator

When comparing the proposed redesign with the Prefabricated variant of the 2nd Skin Facade Refurbishment system, the focus lays on the prefabricated SIP-panels. With the Material Circularity Indicator one facade module of ca. 3,6 by 2,7m is assessed. Based on the assessment results, shown in fig. 88, the following conclusions can be drawn:

- In the redesign, the prefabricated module has a 1,16x higher mass than the SIP-panel of the Prefabricated variant, due to the increased thickness and density of the ECOBoard that replaces the Chipboard and the increased density of the Metisse insulation that replaces the EPS insulation.
- The redesign consists of a high amount of biological materials, that are renewable and biodegradable, while the SIP panel of the Prefabricated variant consists of mainly technical materials, that can't decay naturally.
- The chosen materials of the redesign contain a high amount of recycled feedstock, while in the SIP-panel of the Prefabricated variant most materials contain virgin feedstock, only the chipboard contains a certain percentage of recycled feedstock.
- At the end of life, all components of the redesign can be reused, due to the demountable connections. When reuse is impossible, all materials can be 100% recycled. On the other hand, the SIP-panel can't be disassembled or reconfigured at the end of life due to the chemical connections, so doesn't have any reuse or recycling potential. The only option is incineration of the complete panel.
- When comparing the Linear Flow Index of the redesign to the SIP-panel of the Prefabricated variant, the LFI-value of the redesign is very low, because the percentage of recycled content comes close to 100% and the reuseability of the system is 100%. The LFI-value of the SIP-panel is high, because the materials are for 50% sourced of virgin resources, which all end up as unrecoverable waste when the functional lifetime of the panel has been reached.
- While both system have the same technical lifetime of 75 years, their Utility Factor differs. At the end of the expected functional lifetime of the refurbishment system of 25 years, the complete module of the redesign can be reused 3 times before reaching the end of its technical lifetime. However, due to its inflexibility, the SIP-panel of the Prefabricated variant can't be reused at the end of its functional service life of 25 years, despite its remaining technical service life of 50 years. For this reason the Utility Factor of the SIP-panel of the Prefabricated variant is 1 and the Utility Factor of the redesign 3.
- The MCI-value is based on the LFI and the Utility Factor of the component. Because the redesign consist of almost only recycled content and can be completely reused at the end of life, the MCI-value reaches almost 1, thus can be considered to be a circular product. The MCI-value of the SIP-panel is <0,5, and thus a linear product, due to the high amount of unrecoverable waste at the end of life and use of a high amount virgin material for the production.

		1. SIP panel (Prefabricated variant)	2. Redesign
	Mass	158,3 kg	184,2 kg
Feedstock	Biological	25%	89%
	Technical	75%	11%
	2nd Reused feedstock	0%	0%
	2nd Recycled feedstock	49%	92%
End of life scenarios	Reuse	0%	100%
	Recycling	0%	0%
	Landfill	0%	0%
	Incineration	100%	0%
Material Circularity Indicator	LFI (Linear Flow Index)	0,75	0,04
	X (Utility factor)	1,0	3,0
	MCI (Material Circularity Indicator)	0,32	0,99

Fig. 88: Results MCI assessment (source: own image)

1. SIP panel (Prefabricated variant)

Step 1: Calculation of the mass of the component

Material	Volume (m³)	Density (kg/m³)	Mass (kg)
EPS	0,976	15	14,64
Chipboard	0,173	600	104,0
Pinewood (uncured)	0,086	460	39,73

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
EPS	Technical	0%	0%	14,64
Chipboard	Technical	75%	0%	25,99
Pinewood (uncured)	Biological	0%	0%	39,73

Step 3: Calculation of unrecoverable waste at the end of life of the materials

Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
EPS	0%	0%	14,64
Chipboard	0%	0%	104,0
Pinewood (uncured)	0%	0%	39,73

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
SIP panel	0,75	1,0	0,32

2. Redesign

Step 1: Calculation of the mass of the component

Material	Volume (m³)	Density (kg/m³)	Mass (kg)
Metisse insulation	0,993	20	19,87
ECOBoard	0,217	720	156,4
Pinewood (uncured)	0,017	460	7,963

Step 2: Calculation of the virgin feedstock of the materials

Material	Cycle	Recycled feedstock (%)	Reused feedstock (%)	Virgin materials (kg)
Metisse insulation	Technical	85%	0%	2,980
ECOBoard	Biological	97%	0%	4,691
Pinewood (uncured)	Biological	0%	0%	7,963

Step 3: Calculation of unrecoverable waste at the end of life of the materials

Material	Fraction collected for recycling (%)	Fraction collected for reuse (%)	Unrecoverable waste, immediately going to landfill / incineration (kg)
Metisse insulation	0%	100%	0,000
ECOBoard	0%	100%	0,000
Pinewood (uncured)	0%	100%	0,000

Step 4: Calculation of MCI-value of the component (0 = linear; 1 = circular)

Component	Linear Flow Index (LCI)	Utility factor (lifespan / 25)	Material Circularity Indicator (MCI)
Prefab. modules	0,04	3,0	0,99

Fig. 89:
Calculation results MCI assessment (source: own image)

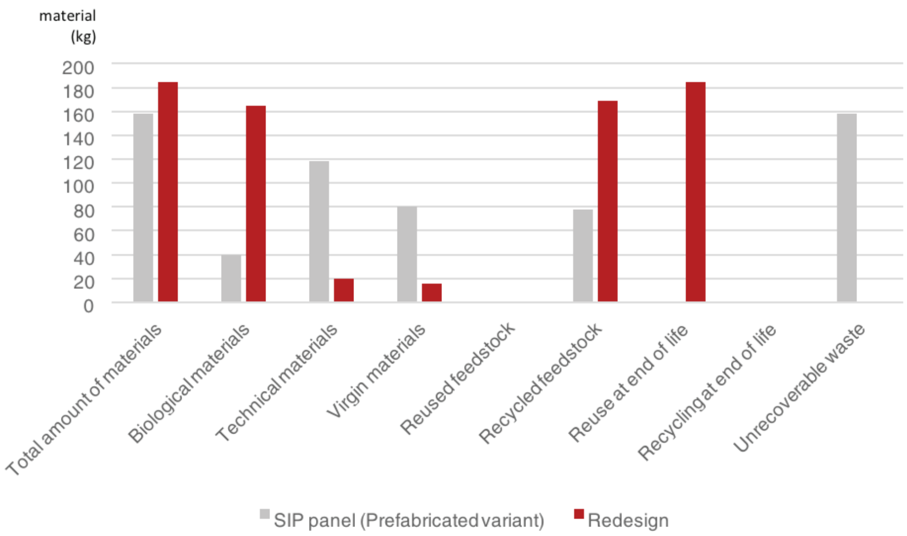


Fig. 90:
Calculation results MCI assessment, presented in graph
(source: own image)

Disassembly Potential

When evaluating the Disassembly Potential of the proposed redesign, compared to the Exterior Insulation Variant and the Prefabricated variant of the 2nd Skin Facade Refurbishment system, on the basis of the eight criteria developed by Durmisevic (2010), the following conclusions can be drawn:

Functional independence (FI)
When looking at the functional independence, the redesign still has obtained the same grade as the Prefabricated variant, because the redesigned prefabricated modules fullfill the same functions as the SIP-panels of the Prefabricated variant. *(grade: 5)*

Systematisation (SY)
In terms of systematisation, the redesign has maintained the same score as the Prefabricated variant, because the four clusters of elements of the substructure, insulation, cladding and window, haven't been changed. *(grade: 10)*

Relational Patterns (RP)
When looking at the Relational Patterns, the redesign has been improved, compared to the Prefabricated variant. Due to the demountable and reversible connections, adjustment of elements within the prefabricated modules is possible, so the transformation capacity of the system has been increased. *(grade: 8)*

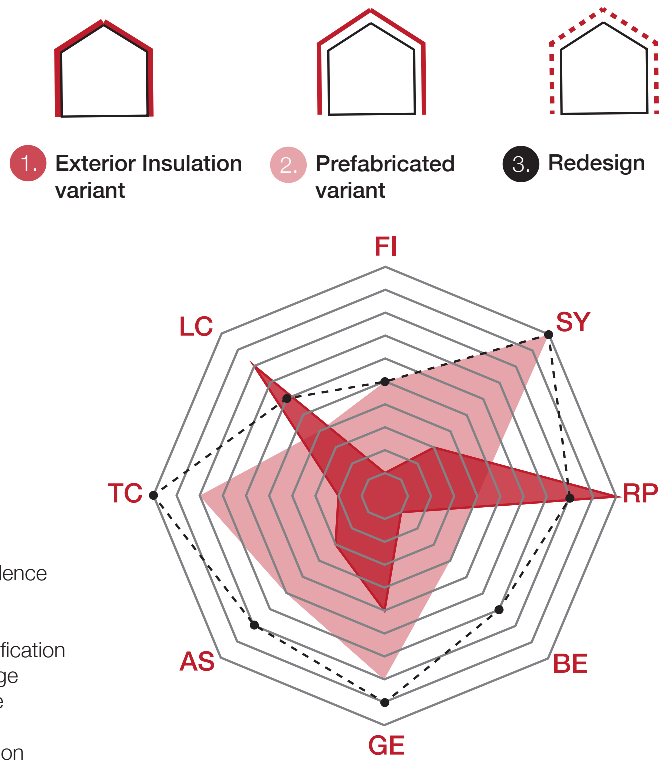
Base Element specification (SY)
In the redesign the exterior board of the prefabricated modules has become the Base Element of the system, similar to the Prefabricated variant. However, as an improvement the redesigned exterior board contains premade geometry, to which the other components can be attached. As a result of the reversible connections, the Base Element won't be damaged when the surrounding components need to be replaced. *(grade: 7)*

Geometry (GE)
Similar to the Prefabricated variant, in the redesign the geometry of the component edges is pre-made and most of the components are pre-assembled in the factory. The level of standardisation has been improved in the redesign. *(grade: 9)*

Assembly Sequence (AS)
The assembly sequence is still mainly sequential in the redesign. However, the level of prefabrication has been increased, so less components need to be assembled on-site, compared to the Prefabricated variant. *(grade: 8)*

Type of Connections (TC)
In the redesign, no chemical connections are present in the system. The connections within the SIP-panels, that were all chemical in the Prefabricated variant, have all been changed to dry connections through premade geometry. *(grade: 10)*

Life Cycle Coordination
In terms of Life Cycle Coordination, the redesign hasn't been changed. The building services with the shortest life cycle are still located closest to the existing facade, but they have become better accessible, due to the dry connection to the interior board of the prefabricated modules. *(grade: 6)*



FI	Functional Independence
SY	Systematisation
RP	Relational Patterns
BE	Base Element Specification
GE	Geometry of the Edge
AS	Assembly Sequence
TC	Type of Connection
LC	Life Cycle coordination

Fig. 91:
Results DP assessment
(source: own image)

Conclusions

Design advantages

The main advantage of the proposed system, is that the elements that the prefabricated modules consist of, have become reusable at the end of their functional service life. By enabling reuse, the lifecycles of the materials within the same system have been extended. Instead of a custom-made solution for a specific residential building, the facade refurbishment system has become universal. The high level of standardisation makes reuse of elements for the refurbishment of a second or even a third residential building with a different facade typology possible.
Next to that, the change from wet to dry connection methods between the elements makes separation of materials in its purest form possible. At the end of their technical lifetime, the materials that the prefabricated modules consist of, can all be recycled for the production of new building products. By letting the geometry of the component form the connection, assembly and disassembly of the system has been simplified. Besides, reconfiguration of the facade is enabled without having the need to disassemble the complete system. The geometry of the prefabricated modules allows changes to be made to the position of the horizontal and vertical grids of the facade, then define the position of the windows. This way the facade can be adapted to functional changes in the future.
Lastly, replacement of components, that have reached the end of their technical lifetime during their functional service life, such as the facade cladding and building services, have been enabled by making the components easy accessible. The perforations of the interior and exterior board of the prefabricated modules allows components to be replaced multiple times by predefining the connection points to which the component can be screwed or bolted.

Design limitations

The main drawback of the system is the increased material usage. The research has shown that a high level of prefabrication consequently leads to an additional amount of materials that need to be used to provide stiffness of the prefabricated modules during transportation and assembly. When the 2nd Skin Facade has to be self-supporting, being able to stand independently from the existing facade, the amount of structural elements in the system will increase. As a result, the increased mass of the Prefabricated 2nd Skin Facade modules causes higher pressure on the existing facade, that has to transfer the loads to the ground. For this reason, not all existing facades can be taken into consideration for this system, because not all are able to support the high mass of the prefabricated modules.
Next to that, the system could only work if it is applied on a big scale. To enable direct reuse of components, the stock of standardised elements should be substantial. When the system is applied to a housing stock of 200 buildings, the chance of simularities in facade arrangement of the different building typologies will be increased. As a result, there is a higher chance that certain components the 2nd Skin Facade Refurbishment system consists of, will be similar for the facade refurbishment of multiple buildings. Certain dimensions of the components will become standard and will be produced in a higher number. Other dimensions will be less frequently applied, deviating from the standard size.
Probably the proposed system will be more expensive than the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system, that is being applied to the case study building in Vlaardingen at the moment. The initial investment costs at the start will be significantly higher. However, the high level of prefabrication is expected to lead to significantly less labour on-site. The construction time on-site will be decreased and consequently the occupants will experience less disturbance of the refurbishment process. However, the more often the system will be reused, the lower the costs over the lifetime of the system. Next to that, the higher level of standardisation will improve the financial feasibility of the system.

Recommandations for further development

First of all, the structural performance of the prefabricated modules should be tested, to be able to determine the exact thickness of the horizontal and vertical studs, based on the maximum span that is possible in the module. Also, the system should be further developed in terms of (embodied) energy; what amount of energy is needed for the production of the components, looking at the energy consumption of the CNC-milling machine, what amount of energy is needed for the transportation of the prefabricated modules from the central warehouse to the building site and the assembly of the system? Based on this research, the most strategic location of the central warehouse in the city should be defined. The embodied energy in relation to the extended lifetime of the components should be compared to the Exterior Insulation variant of the 2nd Skin Facade Refurbishment system.
Next to that, in the redesign only the prefabricated modules have been improved in terms of circularity. To let the complete refurbishment system become circular, the other components, such as the brick facade cladding, should also be designed for disassembly. Besides, the standardisation possiblilities of the interior and exterior board of the prefabricated modules requires further research, to increase the reuseability of the complete system.
Lastly, the material choice for the frame of the prefabricated modules could be further investigated. Based on the increased functional lifetime of the system, another type of material with a longer lifetime and higher strength could be chosen. An example of an alternative material that suits these characteristics is recycled plastic.

07

THE BIGGER PICTURE

In the previous chapter the design proposal of the Circular 2nd Skin Facade Refurbishment system is explained on the basis of a Roadmap for Circular Building. The design has been evaluated in terms of materials with the Material Circularity Indicator (MCI) and connections with the Disassembly Potential (DP).

To be able to understand the importance and applicability of this research, the study will be placed in the wider context. This chapter will look at the intermediate steps that need to be taken in the refurbishment practice before being able to implement the proposed circular facade refurbishment strategy. Also the business model that should be developed to make the proposed refurbishment strategy feasible, will be investigated, analysing the challenges that need to be addressed to get there. Therefore, an approach to reach a complete circular built environment will be developed.

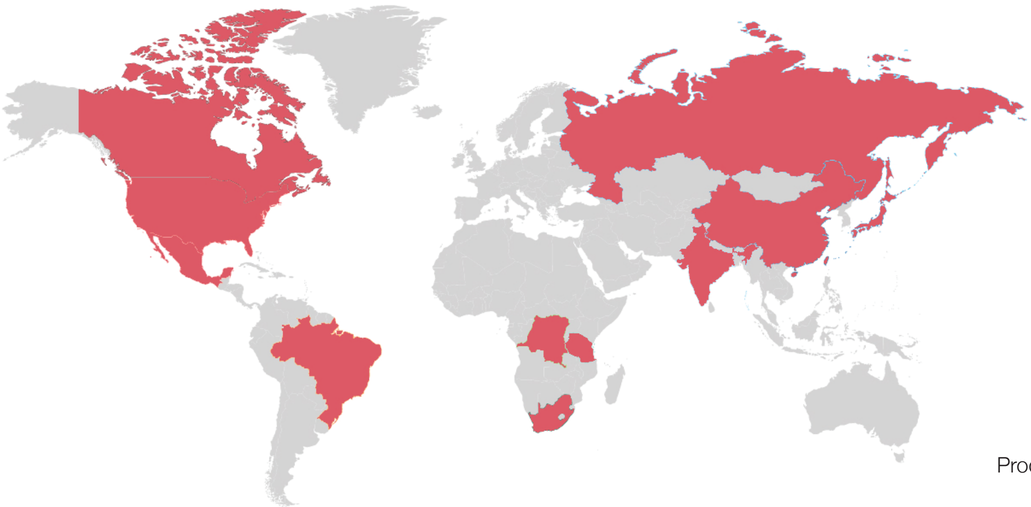


Fig. 92:
Production concentration of critical materials (Rijksoverheid, 2016)

Nederland Circulair

On the 15th of January 2018, the Dutch State Secretary of Infrastructure and Water Management, Stientje van Veldhoven, has received the plans for a sustainable, circular economy in the Netherlands in 2050, concerning the sectors Biomass & Food, Building, Consumer Goods, Plastics and Manufacturing (Rijksoverheid, 2018). While the energy transition has been translated into concrete goals at European and national level, as set in the Paris Climate Agreement in 2015, the plans for the transition to the circular economy, as stated in the national program Nederland Circulair in 2050, developed in in 2016, haven't been concretised yet (Van Santen & Pelgrim, 2018). However, the circular economy makes a positive contribution to the climate goals of the Paris Climate Agreement, because more efficient use of materials and resources is calculated to lead to a reduction of 70 megatons CO2-emissions per year, accounting for 9% of the total CO2-emissions of the Netherlands. In the national program Nederland Circulair in 2050, the ambition of the government is set to use 50% less virgin materials by 2030 (mineral, fossil and metals) in order to realise a circular economy in the Netherlands by 2050, in which products and materials are designed in such a way that they can be reused with as little as possible value loss and without harmful emissions to the environment. The virgin materials that are still necessary, should be extracted through sustainable methods (Rijksoverheid, 2016). According to Van Veldhoven, the agenda for the transition to the circular economy has to be finalised before the summer of 2018 to be able to make the climate plans for 2030 realizable. State Secretary Van Veldhoven affirms in a newspaper that, when the government starts purchasing at least 10% "circular products" that are either recyclable, reused or resource-saving, a reduction of 1 megaton CO2-emissions can already be achieved by 2022. To make the transition to the circular economy possible, companies should be stimulated to consume less virgin materials. According to State Secretary Van Veldhoven and Employers President Hans de Boer, the government should give priority to "circular" companies. The idea is that via the investment bank Invest-NL, that is now being established, "circular" projects and companies could get a loan of the government (Van Santen & Pelgrim, 2018).

One of the main reasons for the need to transition to the circular economy, is the explosive demand for virgin materials of our current society (fig. 93). Research has shown that the world population now uses 34 times more virgin materials than at the beginning of the century (Sociaal-Economische Raad, 2016). This development can be explained by the global population growth, from approximately 3 billion people in 1950 to a projected 9 billion people in 2050, the fast-growing middle class in emerging countries, from 2 billion people in 2010 to 5 billion people in 2030 (Guldager Jensen & Sommer, 2016), and the application of new technologies that demand for specific virgin materials. As a result of this explosive demand for virgin materials, the environmental pressure on the earth has been increased significantly, leading to resource depletion and degradation, biodiversity loss and climate change. Consequently, the Netherlands has become reliant on other countries for their virgin material supply. 68 percent of the material supply of the Netherlands is retrieved from foreign countries, as shown in fig. 92 (CBS, 2011). Certain materials that are limited available, are sold for increasingly higher prices, resulting in reduced security of supply. The accompanying geopolitical tensions have a direct effect on the stability of the Dutch and European economy.
The concept of the circular economy is a solution to these problems, because it strives for more efficient usage of materials, alongside increased usage of renewable materials that are unlimited available. Transition to the circular economy lessens the environmental pressure on the earth by preventing resource depletion and degradation. The circular economy also offers economic opportunities for the Netherlands, because it makes the country less reliant on the import of scarce materials from other countries. Next to that, more efficient use of virgin materials is needed to be able to keep feeding and providing the necessary goods for the next generations on earth. However, one must realise that the circular economy as a complete closed system is impossible and absolute global decoupling from the linear model seems to be only feasible in the long term (Rijksoverheid, 2016).

Effect on the building sector

The building sector has been given priority over the other sectors for the transition to the circular economy, because the sector consumes a high amount of raw materials and has a big impact on the Dutch economy (Rijksoverheid, 2016). Construction and demolition waste accounts for 41.6% of the total waste production in the Netherlands (CBS, 2015). While around 93% of the total construction and demolition waste is recycled (Deloitte, 2016), it mainly refers to down cycling at a lower level, such as the processing of construction waste into granulate for road filling. Next to that, the building sector is responsible for 35% of the total CO2-emissions (Ellemmi, 2013). At the moment the building sector is most focussed on decreasing energy and CO2-emissions, while there is still much to be gained in the area of material efficiency and waste reduction (Rijksoverheid, 2016).

The following strategic ambitions have been set for the Building sector in the national program Nederland Circulair in 2050 (Rijksoverheid, 2016):

- Residential and non-residential buildings, as well as civil construction works, make use of mainly renewable materials.
- Material use is optimised over the complete lifetime of the building (value retention, less costs, more reuse and less environmental impact).
- The building sector reduces as much as possible CO2-emissions, in the production and construction phase as well as in the use phase.
- The building sector is an innovative sector that proactively anticipates to changes in society and the demand of the market and the consumer.

The main action point in the transition agenda of the Building sector, is to develop a measurement system to determine the level of circularity of a building (Van Santen & Pelgrim, 2018). The government wants the building sector to take its own responsibility, while stimulating pilot projects. Next to that, the aim is to reach as much as possible synergy of the circular economy with the energy transition in the built environment (Rijksoverheid, 2016).

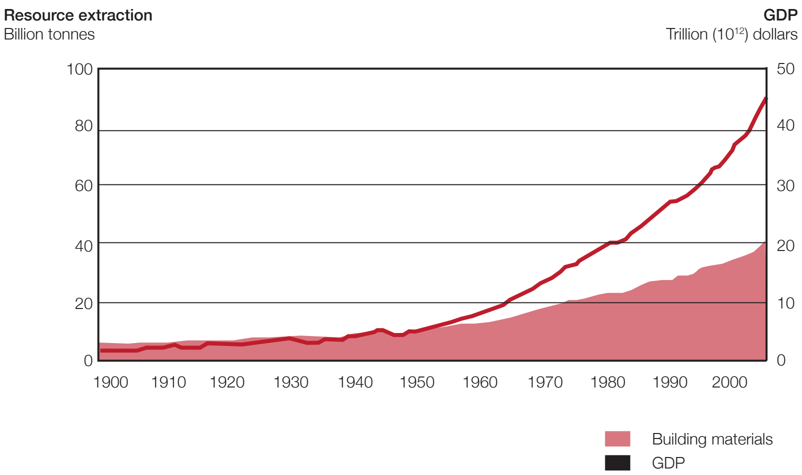


Fig. 93:
Graph of worldwide resource extraction in billion tonnes, 1900-2005 (Rijksoverheid, 2016)

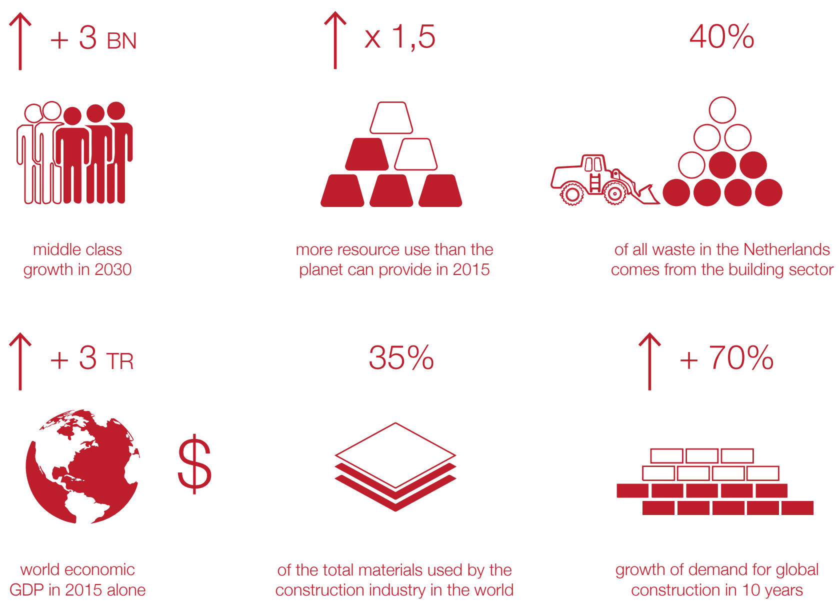


Fig. 94:
Global challenges for the building sector (Guldager Jensen & Sommer, 2016)

Effect on the refurbishment practice
When looking at the refurbishment and transformation of the existing building stock, the efforts to create an energy neutral and circular built environment have the potential to be combined (Rijksoverheid, 2016).

As stated before, tn the ambitions of the Paris Climate Agreement of 2015, the goal is set to reach an energy neutral built environment by 2050. To be able to achieve this, yearly 300.000 residential buildings need to be refurbished. With the current refurbishment and replacement rate of 0,4%, it is expected to take 250 years to reach this goal (Mulder, et al., 2015). The low rate is mainly due to high initial investment costs of refurbishment. Acoording to research of BPIE, financial funding is often missing (BPIE, 2013). Energy costs cover in general only 3-4% of the total expenses of the households, and thus aren't considered as a major concern, especially since the payback period may be longer than the period the residents are planning to stay in the house. The degree of privatisation also determines the willingness to refurbish, while for housing corporations it has proven to be difficult to achieve resident's consensus. The main barrier for refurbishment is the 'split incentives barrier', which occurs when one party has to invest in the energy-saving refurbishment measures, while another party gets the financial profit from the intervention (Konstantinou, 2014).
From the interview with Onno van der Wall of the contractor company BIK Bouw, who is responsible for the refurbishment of the case study building in Vlaardingen (as analysed in chapter 5.1), appeared that in practice the main problem of the current refurbishment practice is stagnation in the start-up phase. Many building products for the refurbishment of residential buildings are available on the market. Instead of choosing for one product, contractors tend to choose a combination of building products from different manufacturers, resulting in a custom-made assembly of different products for the refurbishment of every particular residential building. Consequently, the preparation and design time of every refurbishment project is increased. Also the logistics on the building site have become more complex, due to the many different material suppliers and subcontractors involved in the process (Van der Wal, personal communication, January 3, 2018).

When looking at the material efficiency, refurbishment is significantly less material consuming than demolition and replacement with a new building, because part of the existing building structure will be maintained. However, at the end of life of the refurbishment, when the existing building has reached the end of its technical or functional service life, double the amount of waste will be generated; the waste materials coming from the added facade refurbishment system as well as the waste materials coming from the existing façade. The environmental impact of a refurbished building is similar to the environmental impact of a new building, when looking at the material use spread out over the lifetime (Mulder, et al., 2015). A refurbished building has a shorter lifespan than a new building, but also makes use of a smaller amount of materials.

The Circular Economy could be seen as a solution for the problems that the high demand for energy neutral refurbishment of residential buildings brings along. In the Circular Economy restoration and regeneration of materials through design is the focus of attention. As concluded from the literature review in chapter 2, the Circular Economy aims to close and extend the loops of material cycles, in order to preserve value of materials, resulting in decreased raw material consumption and waste generation. The concept of the Circular Economy is relevant for the refurbishment practice, because it strives for an increased lifetime of the refurbishment by enabling reuse of components at the end of their functional service life and recycling of materials at the end of their technical service life. As proposed in the redesign of the Circular 2nd Skin Facade Refurbishment system in chapter 6, when the lifetime of the refurbishment system is increased by allowing the same system to be reused for the refurbishment of multiple residential buildings, the initial investment costs of the refurbishment system will be spread out over a longer period of time. Next to that, an increased level of standardisation of components will result in an universal refurbishment system, that can be applied to any type of residential building. As a result, the design phase that is currently needed to design a custom-made solution for every specific residential building, will be less time-consuming.

Application of the Circular Economy

The company Arup has made a start implementing the principles of the Circular Economy to the built environment with a system-approach for commercial property. In order to see where the circular approaches have the biggest opportunity to increase material efficiencies and reduce costs and environmental impacts, they sketched a possible application of the circular economy, shown in fig. 95 (Arup, 2016). The proposed refurbished system of this research (see chapter 6) is considered to fit in this model, as it also takes into account material sourcing of reused components from the same or other industries, as well as enabling reuse of components after disassembly of the building(system). For this reason, on the basis of the model developed by Arup (2016), step by step the functioning of the system, but then applied to the refurbishment practice with the proposed Circular 2nd Skin Façade Refurbishment system, will be investigated.

0. Ecosystem

"In the circular Economy, buildings will be designed for a whole lifecycle and not simply an end use" (Arup, 2016).

To ensure that this happens, full life cycle contracts, from design to operation and disassembly, should be implemented, encouraged by the government. Instead of purchasing, clients will lease products through performance-based contracts. In the circular economy, the building sector will have to collaborate with other industries to exchange resource and reuse cycles. Buildings will have to make mainly use of renewable resources that are locally available, to make the industry more resilient and lower the investment risks (Arup, 2016).

When looking at the proposed Circular 2nd Skin Façade Refurbishment System, we can see that the design is made for a whole lifecycle and not simply an end use. Instead of ending up as unrecoverable waste at the end of its functional service life, the circular refurbishment system is designed in such as way that it can be reused a second or maybe even a third time for the refurbishment of another residential building, until the technical lifetime of the materials has been reached.

A suggestion for the business model around the circular refurbishment system, is to enable leasing of the system for a period of time, after which the components the refurbishment system consists of, will be given back to the owner. Two types of leasing business model can be identified (Azcarate Aguerre, 2014), applicable to the proposed Circular 2nd Skin Façade Refurbishment system:

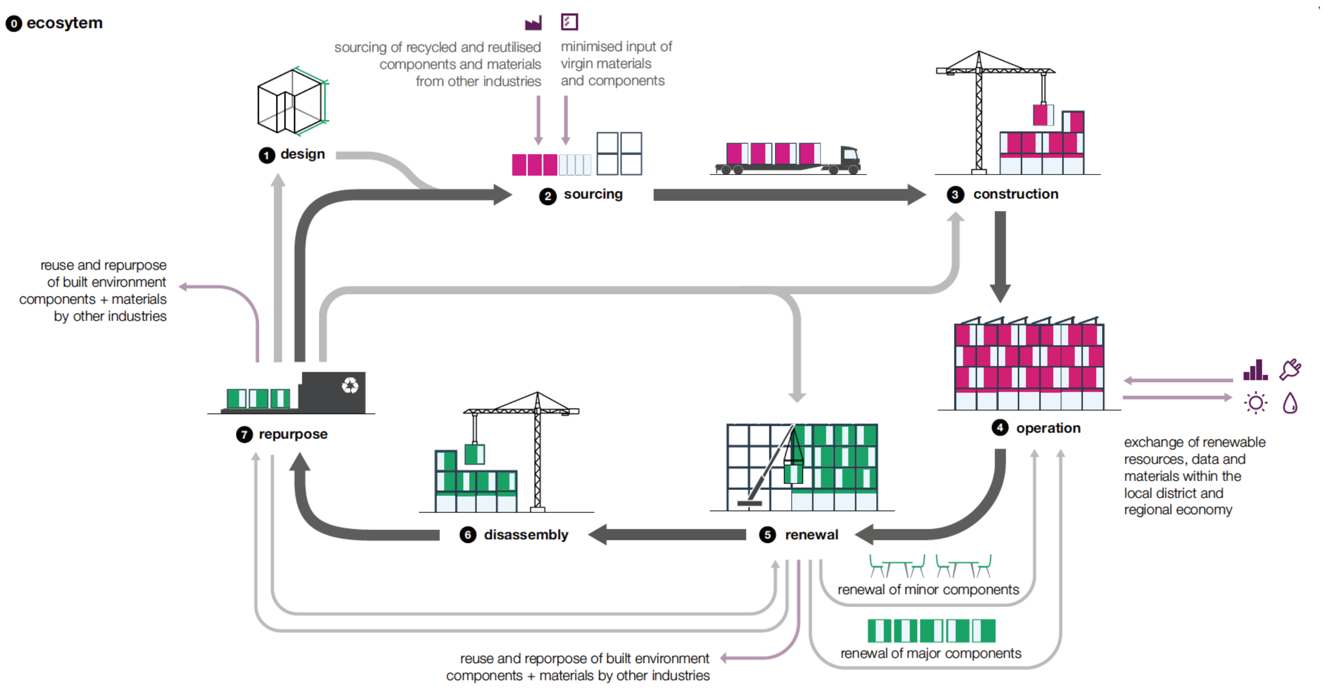


Fig. 95: Application of CE Principles to Commercial Property (Arup, 2016)

1) The type of business-to-client model that could be applied with the Circular Façade Refurbishment system, is Technological Leasing, in which the product and service provider retains ownership of the assets. For the client, in this case the owner of the residential building(stock), it offers the advantage to pay for the refurbishment system as a service instead of a product. Consequently, the owner of the residential building doesn't risk the chance that the façade refurbishment system will eventually become obsolete, due to for example changing requirements in the national building decree. For the provider of the façade refurbishment system it offers the advantage of achieving a long-term relation with the client. Instead of risking the chance that the client will hire maintenance and buy products from other suppliers, the provider will be assured that the client keeps making use of his services. The provider of the circular façade refurbishment system will be responsible for the functioning of the system, as well as the maintenance of the system and the replacement of parts, which will be incorporated in the monthly fees of the system. It will be in the best interest of the provider to enable reuse of components and recycling of materials for the production of new components, because he stays the owner of the product, also at the end of the functional service life of the refurbishment (Azcarate Aguerre, 2014).

2) The concept of leasing could also be taken one step further, by using a Product-Service System agreement (fig. 97). In this business model, the client doesn't only lease the product, in this case the façade refurbishment system, but he will be leasing the service, in this case of "having an energy neutral home". This means the provider of the service has to ensure the thermal resistance of the façade is increased to the right value, the most efficient climate installations are installed and the architectural appearance of the building is maintained. The Product-Service System Provider should know what specific combinations of products and services are needed to achieve the desired result. Their profit will increase when they charge the service for a certain price, while decreasing the costs to deliver it. As a result, to still be able to provide the required service they will strive for resource usage in the most efficient way. This will encourage the providers to keep upgrading their technologies and extending the service-life of the system by enabling reuse. This business model is also advantageous for the client, because the initial high investment costs will be spread out over the service life of the product, in this case the façade refurbishment system. Next to that, the risks and liability will be outsourced to the provider. An example of an application of the Product-Service System is the mobile industry. Instead of a month-to-month financing structure, also the market model that allows upgrading of the product over-time, could be suitable for the Circular 2nd Skin Façade Refurbishment system. In this model, the basic system will be sold for initial low-costs, which could then be upgraded over time by buying add-ons to the system. An example of such a system is the jewellery brand "Pandora" (Azcarate Aguerre, 2014).

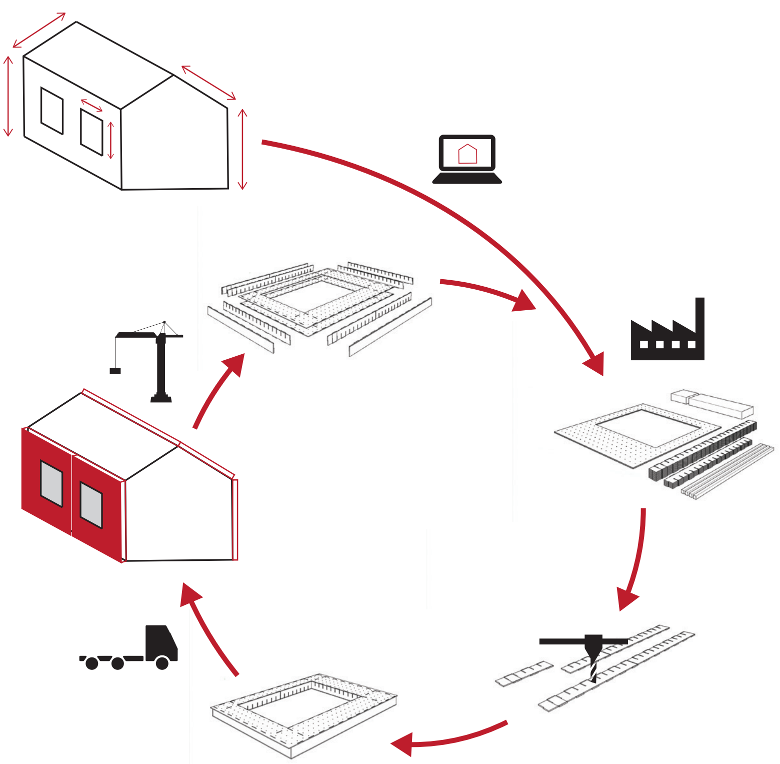


Fig. 96:
Concept of the Circular 2nd Skin
Facade Refurbishment system (source: own image)

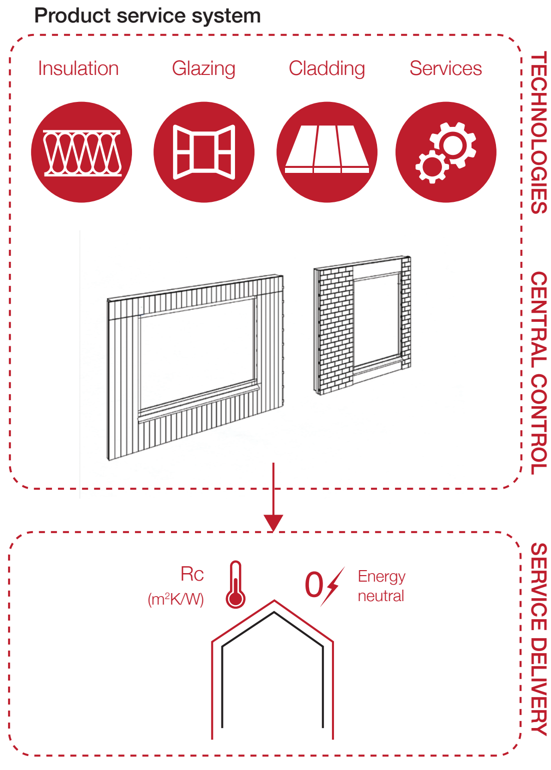


Fig. 97:
Business model proposal
(source: own image)

The contractor could be the provider of the Circular 2nd Skin Façade Refurbishment system. Also, for example the insulation material supplier, that delivers the main component that shapes the facade refurbishment system, in this case the SIP panels Kingspan (see chapter 5), could be the system provider. To be able to provide this service, multiple product manufacturers have to cooperate. The supplier of the insulation materials has to ensure the thermal resistance of the existing façade is increased to the required value, the supplier of the building services has to ensure the most efficient climate installations are applied, and the supplier of the cladding materials has to ensure the architectural appearance of the building is maintained. Whether the refurbishment system contains reused or new components, doesn't matter for the client, as long as it functions and still meets the requirements. With performance-based contracts the material suppliers have the responsibility over the functioning of their products during the complete service life of the refurbishment.

1. Design

"A circular building will be more than just a structure providing space and shelter; it will accommodate future change, such as remodelling, expansion or disassembly" (Arup, 2016).

In the circular economy designs should be made open-source to make it standard practice. Architects, engineers and designers should collaborate and built on each other's work. The change of mind-set will cause them to first think of reuse and retrofitting possibilities of the existing building before considering new buildings. Instead of looking at the design of the building as an end-result, the operation and performance during its lifetime should be followed (Arup, 2016).

The proposed Circular 2nd Façade Refurbishment system is designed for future changes, as it enables reconfiguration of the façade arrangement and disassembly at the end of its functional lifetime. Despite the high level of standardisation of the proposed Circular 2nd Skin Façade Refurbishment system, the refurbishment system still needs to be adapted to the façade arrangement of the particular residential building typology it will be applied to. Based on the digital measurements of the building the exact dimensions of the standardised components the façade refurbishment system consists of, will be defined. These elements will be searched for in the central warehouse of components that have already been used. The geometry of the standardised components should become open-source, so that architects, designers and engineers will always first look at already available reused components before considering new components. This way the architects learn how to design with the standardised components without limitations.

2. Sourcing

"Modularity and adaptability will be key components of design in a circular built environment" (Arup, 2016).

Buildings should be designed with flexible, durable, reused and reusable parts. As extraction of virgin materials is expected to be significantly reduced in the future, gradually the remaining materials and components of the linear economy will disappear, by first enabling as much as possible reuse (Arup, 2016). According to the Dutch government, the transition to the circular economy asks for international collaboration, as the Netherlands is reliant on international material flows. To strengthen the market for secondary and renewable resources, international agreements should be made. At the moment non-sustainable products are less expensive than sustainable alternatives, because the environmental impact hasn't yet been incorporated in the price of the product. To decrease the amount of virgin material usage and waste generation at the end of life, the Dutch government is planning to investigate the implementation of legal agreements with the product manufacturers about the amount of reused (recycled or bio-based) materials used for their products (Rijksoverheid, 2016). When every product is legally obliged to contain a certain percentage of recycled or reused content, the market will be forced to move towards the circular economy.

For the Circular 2nd Skin Façade Refurbishment system, at the start of the implementation of the system all components still need to be manufactured new, containing as much as possible recycled content from the waste of other industries. After 10 years can be expected that the first buildings that are refurbished with the system, will need to be deconstructed. The components the refurbishment system consists of, will be disassembled. The components that haven't been damaged during disassembly and have maintained their strength (let's say for instance 90% of all components), will be stored at the warehouse, ready to be reused for the next refurbishment. The components that have been broken or damaged and can't be considered for reuse (let's say for instance 10% of all elements), will be recycled for the production of new components. Consequently, the components will be assembled in a new configuration, that matches the existing façade of another residential building that is in need of refurbishment. We could expect 80% of the façade refurbishment system of another residential building to consist of reused components, while 20% of the components are deviating in size and need to be manufactured new. When the system is applied on a large scale, we could expect that the percentage of reusable components will increase, due to the increased chance of similarities in façade arrangement of the different residential buildings. To encourage the use of reused components, these should be sold for a lower price than the new components, based on their remaining technical lifetime.

3. Construction

"The world construction in a circular world will be used in the context of assembly" (Arup, 2016).

In the Circular Economy, there will be spoken of assembly instead of construction of buildings. Off-site manufacturing and prefabrication will become the state-of-the-art instead of casting on-site.

For this reason, also the refurbishment practice is expected to move to prefabrication. At the moment most buildings are refurbished with bespoke elements cut on-site, resulting in a high amount of construction waste generated on the building site. As shown in this research (see chapter 6), when the refurbishment system consists of prefabricated elements that are dimensioned in the factory beforehand, designed with smart detailing and standardised dimensions to minimise material use, less valuable material will be wasted. Also, the labour costs of assembly on-site will be lowered, because the construction time will be decreased significantly.

4. Operation

"All buildings and structures will be designed to high efficiency standards, minimizing externalities and environmental impacts." (Arup, 2016).

Buildings will need to exploit internal resource cycles to the fullest and become net producers of energy. The service life of the buildings will be extended with preventative maintenance techniques (Arup, 2016)

The ambition is set to design buildings in the future with high efficiency standards. By 2020 all new buildings added to the building stock have to be energy neutral, according to the Dutch national climate agreement Energieakkoord. By 2050 also the existing building stock has to become energy neutral (Sociaal-Economische Raad, 2013). What isn't yet incorporated in the objectives of the Energieakkoord, is the complete life cycle energy of the building, consisting of three energy types; embodied energy, operational energy and demolition energy. When the operational energy of the residential building has been decreased to zero, the effect of the embodied energy, which is the quantity of energy necessary for the production, maintenance and refurbishment of the building, and demolition energy, which is the quantity of energy needed for the deconstruction of the building at the end of its functional lifetime, on the total energy consumption of the building will be increased (Loussos, Konstantinou, Van den Dobbelsteen, & Bokel, 2015). For this reason, the environmental impact over the complete lifecycle of the refurbishment system has to be taken into account. By enabling replacement of components without damaging other components, the circular refurbishment system is designed in such a way that preventative maintenance is facilitated.

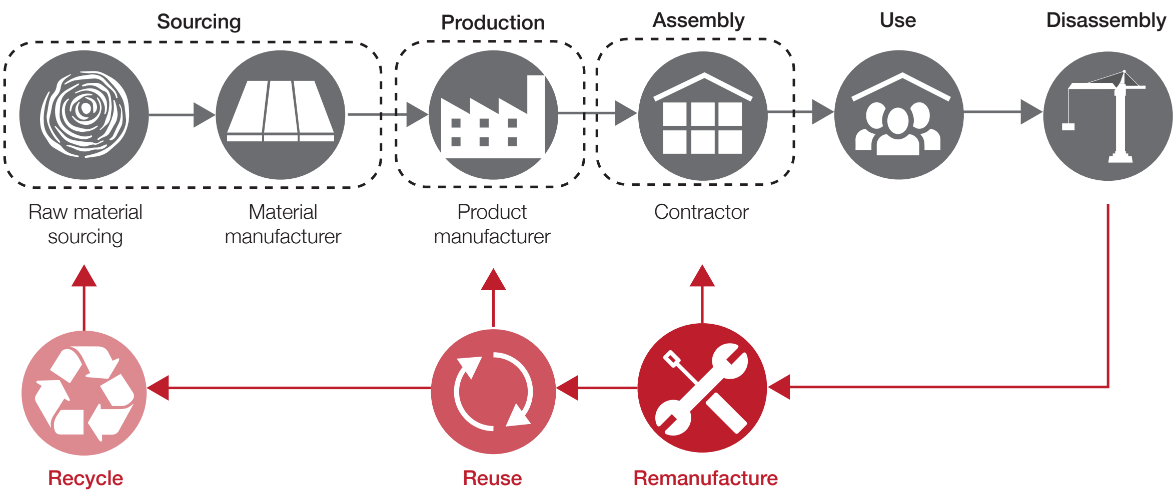


Fig. 98::
Supply chain analysis of refurbishment system (source: own image)

5. Renewal

"The functions of, and demands made on, buildings and structures are constantly changing and yet today they are static and rigid by design" (Arup, 2016).

In the Circular Economy, buildings should be designed as dynamic structures that have constantly changing functions and demands. For this reason, the adaptability and flexibility of building structures should be improved. Design of new constructions as well as refurbishment systems need to allow easy access to building services and be demountable and reconfigurable (Arup, 2016).

When the Circular 2nd Skin Façade Refurbishment system, placed on top of the existing façade of the residential building, is able to change along with the existing building, its functional service life is increased. When the function of the residential building changes, for example occupants with higher incomes will be attracted to the neighbourhood, the refurbishment system is ready to be upgraded. When the existing building needs to be deconstructed and replaced, the refurbishment system is able to be reused for the façade of the new construction with a different arrangement. Consequently, the amount of waste generated on the building site and the time and costs for renewal will be decreased, because components can be reused directly in a second service life.

6. Disassembly

"Demolition will be minimized in a circular world" (Arup, 2016).

Instead of demolition, in the Circular Economy one must speak of disassembly. Lifecycle BIM-models could facilitate the dis- and re-assembly process by allowing stakeholders to redesign the system using the same components. Instead of static and rigid buildings, buildings change into highly mobile, versatile and flexible structures that can be transported to different locations (Arup, 2016).

On that account, the working method of demolition firms should change drastically. This could be seen as one of the biggest challenges. Research at the TU Delft has shown that the costs for disassembly of a concrete structure, taking into account dis- and reassembly, adaptation, transportation and storage, are 3,5 times as big as the costs for demolition (Glias, Pasterkamp, & Peters, 2014). For this reason, the Circular 2nd Skin Façade Refurbishment system is designed in such a way that the disassembly method is simplified and evident. Again, legal and financial obligation is expected to be the crucial incentive for this change in mentality within demolition companies. The government is planning to develop circular business models that will make disassembly financially more attractive than demolition. Also redefining waste is a necessary step to stimulate companies to prevent waste generation (Rijksoverheid, 2016).

7. Repurpose

"The circular built environment will make maximum use of components and materials, circulating them between buildings and projects and maintaining them at the highest possible value and performance." (Arup, 2016).

When after a certain amount of time the components can't be reused for an equal function, the materials the components consist of, should be recycled and remanufactured for the production of new components for the application in the same or another industry. This model requires full-system collaboration and information exchange between all stakeholders involved in the refurbishment process. Financial incentives are expected to play the most important role in this system change, because suppliers should gain financial benefits from the retaking and repurposing of their products at the end of the functional lifetime of the refurbishment system (Arup, 2016).

As is the case in the Circular 2nd Skin Façade Refurbishment system, the structural frame and insulation material has most reuse potential and thus should have a long technical service life to be able to make as many iterations during its functional service life as possible. All components the system consist of, should be tracked during its complete lifecycle to minimise value loss and enable numerous repurpose cycles. A way to enable this, could be making use of material passports. The past, current and future usage of materials should be taken into consideration already from the start of the refurbishment project onwards.

Intermediate steps

The above-described future for the built environment seems like an ideal vision that can only be reached through drastic changes of the current society. The main question that has remained unanswered is: *How to start the transition from a linear to a circular system, when looking at the refurbishment practice in particular?* Especially for the involved contractor BIK Bouw, who is responsible for the realisation of the 2nd Skin Facade Refurbishment and interested in contributing to the Circular Economy, this question is of main importance.

In chapter 6, the principles of the Circular Economy have been translated to practical points of attention for the stakeholders involved in the refurbishment process, in the form of a Roadmap. The proposed redesign of the Circular 2nd Skin Façade Refurbishment system, as explained in chapter 6, is an example of a circular refurbishment system, but hasn't been developed in this research far enough to be implemented in the market. For this reason, the intermediate steps that can be undertaken by the stakeholders involved in the refurbishment process, to initiate the transition process from a linear to a circular economy, with the currently available products on the market, will be proposed on this section.

The research has shown that the principles of the Circular Economy and the theory of Design for Disassembly (see chapter 2) have lead to a façade refurbishment system consisting of prefabricated modules, attached to the existing façade with dry, reversible connection methods. The Prefabricated variant of the 2nd Skin Façade Refurbishment system, tested in a mock up, can be considered as an improvement in terms of circularity, compared to the Exterior Insulation variant, which is now most often applied in practice. However, the prefabricated Structural Insulated Panels (SIP) that are applied in the Prefabricated variant, contain irreversible wet connections between the materials. None of the materials can be reused or recycled, because they can't be separated from the panels in its purest form. The type of adhesive has to be strong enough to guarantee the required stiffness and airtightness of the sandwich panel. A demountable variant of the sandwich panel that guarantees the same stiffness and airtightness, hasn't been developed yet.

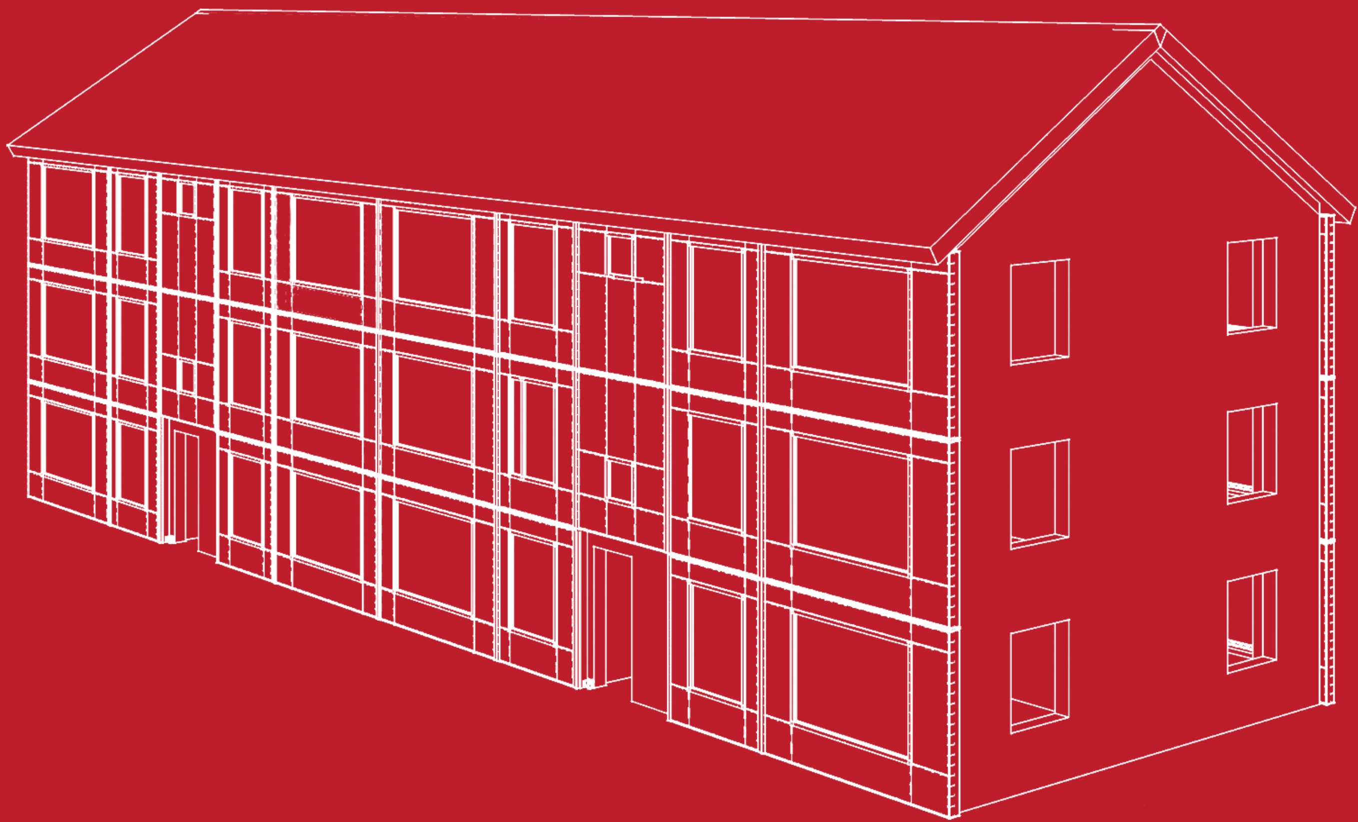
Before being able to implement the proposed Circular 2nd Skin Façade Refurbishment system (see chapter 6), advised is to choose for a refurbishment product that can be applied to the existing façade of the residential building with a dry connection method, that allows removal of the panels from the existing façade at the end of its functional lifetime. An example of a building method with dry connections between its components, is timber-framed building, in which a stud wall, covered with wooden plates, holds the insulation in place. The TEK building system of material supplier Kingspan is an example of a refurbishment system with timber-framed elements, similar to the Structural Insulated Panels used in the Prefabricated variant of the 2nd Skin Façade Refurbishment system (Kingspan, n.d.). While these timber-framed elements can't be reconfigured at the end of their functional lifetime, they can be disassembled in the factory of Kingspan with some material loss, as followed from an interview with the Project manager Renovation of Kingspan, Rolf Pennings (Pennings, personal communication, December 18, 2017). To enable direct reuse of the prefabricated panels, the panels should be dimensioned in such a way that they can be applied to multiple different building typologies. For this reasons, contractors and architects will be advised to analyse the façade arrangement of a certain stock of residential buildings, for example the total building stock of the involved housing corporation, and to develop standardised dimensions of the panels, based on the façade analysis.

The practical guidelines of the principles of the Circular Economy, as visualised in the Roadmap, encourage material suppliers to rethink about their production process and the end-of-life scenarios of their product. When the stakeholders involved in the refurbishment process, such as the contractor or the architect, demand for a circular building product, material suppliers will be forced to redevelop and improve their product in terms of circularity. Because the Circular Economy causes change of the complete system, all stakeholders involved in the process have a shared responsibility. For this reason, the ambitions of the building project should be made clear at the beginning of the process, to ensure all heads will be pointed in the same direction.

08

CONCLUSIONS

This final chapter provides an answer to the main research question, based on the answers of sub-questions. Subsequently, the recommendations for further research are defined, followed by the author's reflection on the graduation project and process.



Conclusions

Sub-questions

- What is in general the current life cycle of post-war residential buildings and what are the most common causes for refurbishment?

Post-war residential buildings have been constructed between 1950-1975 and in use for a period of time, in general around 50 years. Due to the high construction speed, the buildings were designed with insufficient detailing, poor materials were used to decrease the costs and experience with the new building methods used, such as prefabrication, was missing. For this reason, technical decay of the buildings was already visible from the beginning. Now most of the residential buildings either need to be refurbished to be able to be in use for another 25 years, or deconstructed. The most common causes for refurbishment of the post-war residential buildings are technical, functional, financial or legal. Technical problems mainly relate to the façade components and building services of the residential buildings, that have become outdated and demand for an upgrade after a certain amount of time. Functional shortcomings could be another motivation for refurbishment, because the building doesn't meet with the current living standards of the occupants. Financial reasons relate to a desired increase in value of the building. At the moment, the main cause for refurbishment is legal, concerning the new requirements for the energy efficiency of residential buildings (Konstantinou, 2014). In the Energieakkoord an agreement signed in 2013 by 40 organisations, is stated that in 2030 all buildings in the Netherlands need to have at least energy label A. Next to that, in the Paris Climate Agreement the goal is set to reach an energy neutral built environment in 2050. To be able to reach that goal, 300.000 residential buildings need to be refurbished anually. With the current refurbishment and replacement rate of 0,4% it is expected to take 250 years to make the complete residential building stock energy neutral (Mulder, et al., 2015).

- What is the definition of the Circular Economy?

Many different interpretations of the concept of the Circular Economy have been developed in the past decade. Based on the analysed literature, the following definition is utilized for this research: The Circular Economy aims to close and extend the loops of material cycles, in order to preserve value of materials, resulting in decreased raw material consumption and waste generation in our current society. This definition for the Circular Economy is chosen, because it incorporates the potential of reuse, which leads to extended material cycles, and the potential of recycling, which leads to closed material cycles, as means to decrease raw material consumption and waste generation. To be able to shift from the linear model of take-make-dispose, that is dominant in our current society, to the Circular Economy, products should be designed in such a way that they can optimally be repaired (step 1), reused (step 2) and recycled (step 3), while taking into account minimal embodied energy of the materials. Important to mention is the complexity of the system, due to the large number of actors with different benefits and interests that are involved and interconnected in the system (Ellen MacArthur Foundation, 2013).

- How can the principles of the Circular Economy be applied to the built environment?

When applying the concept of the Circular Economy to the built environment, the principles affect two main parts of the building(component): materials and connections. Concerning the materials, the intrinsic and relational properties should be taken into account (Geldermans, 2016). Concerning the connections, the possibility to dis- and reassemble the building(component) is of main importance to be able to replace materials at the end of their functional and technical lifetime without damage (Durmisevic, 2010). After observation of a number of precedents, the principles of the Circular Economy can be applied to circular building in different ways: one could focus on the use secondary materials that consists of reused and/or recycled feedstock, and/or one could focus on increasing the reuse and recycling possibilities of the materials at the end of life.

- What different frameworks can be identified that accommodate circularity?

When looking at the different frameworks that accommodate the Circular Economy, the Cradle-to-Cradle philosophy, which is focussed on materials, the Design for Disassembly (DfD) and Design for Adaptability (DfA) concepts, that are focussed on connections, are also applicable in the built environment, coherent with the principles of the Circular Economy.

- What assessment methods are currently available, that relate to circularity?
    - Life Cycle Assessment (König et al., 2010).
    - Material Flow Analysis (Rincón et al., 2013).
    - Longevity Indicator (Franklin-Johnson et al., 2016).
    - Material Circularity Indicator (Ellen MacArthur Foundation, 2015b).
    - Disassembly Potential (Durmisevic, 2010).

- What assessment methods can be used to assess the level of circularity of the 2nd Skin Façade Refurbishment system?

Based on the comparison results of the above-mentioned assessment methods, evaluated on the basis of the five key requirements of the Circular Economy, two assessment methods are chosen to assess the level of circularity of the 2nd Skin Façade Refurbishment system: the Material Circularity Indicator, developed by the Ellen MacArthur Foundation (2015b), and the Disassembly Potential, developed by Durmisevic (2010). Different from the other assessment methods, the Material Circularity Indicator doesn't only measure the use of recyclable resources and the input of natural resources, but also includes the valuable material loss and the product durability. The only requirement that isn't included in the Material Circularity Indicator, is the measurement of the reduction of emission levels. Studies of Durmisevic (2010) have shown that Design for Disassembly is a prerequisite for circularity in the built environment. The built environment can only become circular when the transformation of buildings is based on disassembly instead of demolition to enable elimination, addition or relocation of materials at the end of their technical or functional lifetime. For these reasons, for the assessment of the 2nd Skin Façade Refurbishment system, the Material Circularity Indicator will be used to assess the level of circularity of the materials each separate building component consists of, while complementary the Disassembly Potential will be used to assess the connections between the materials and the separate building components within the façade refurbishment system.

- How does the Prefabricated variant of the 2nd Skin Façade Refurbishment system work and to what extent is this system "circular"?

The Prefabricated variant of the 2nd Skin Façade Refurbishment system consists of prefabricated floor-height Structural Insulated Panels in which new windows with triple glazing and building systems for heating, ventilation and energy generation are integrated. These prefabricated panels are attached to the existing façade through a substructure of wooden posts, connected to the existing façade with stainless-steel anchors (Guerra-Santin, Silvester, & Konstantinou, 2015). Two cladding options are analysed: brick strips and bamboo.

When looking at the MCI value of 0,62 (brick cladding) and 0,51 (bamboo cladding), derived from the calculation of the Material Circularity Indicator, the Prefabricated variant shouldn't be considered as a completely linear product (MCI = 0), and neither a completely circular product (MCI = 1). From 19% (brick cladding) to 26% (bamboo cladding) of the feedstock for the production of the materials comes from secondary resources and between 22% (bamboo cladding) and 14% (brick cladding) of the materials will be recycled at the end of life. More than half of the materials will be considered as unrecoverable waste and will be either incinerated or disposed at the landfill at the end of life. Only the stainless-steel anchors of the substructure have the potential to be reused and the supporting structure of the bamboo cladding and the window frame have the potential to be recycled at the end of life.

When analysing the Disassembly Potential of the system, the Prefabricated variant is designed for disassembly at the end of life to a certain extent. An advantage of the Prefabricated variant is the high level of systematisation on component level. Next to that, the high amount of prefabrication increases the (dis)assembly speed. Also the connections between the components are mainly dry through the use of additional fixing devices. However, a disadvantage is the high level of functional integration within the Structural Insulated Panels, which is undesirable in terms of disassembly. The elements within the SIP-panels are all chemically connected with adhesives and thus irreversible. Next to that, when looking at the life cycle coordination within the system, the component with the shortest life cycle, which is in this case the ventilation duct, is most difficult to replace, because it is covered with materials with longer lifecycles.

- How does the Exterior Insulation variant of 2nd Skin Façade Refurbishment system work and to what extent is this system "circular"?

The Exterior Insulation variant of the 2nd Skin Façade Refurbishment system consists of a layer of rigid exterior EPS insulation board, that is directly glued to the existing façade, finished with a layer of plasterwork to seal the surface (Azcarate-Aguerre, et al., 2017).

When looking at the MCI value of the Exterior Insulation variant of 0,38, derived from the calculation of the Material Circularity Indicator, the Prefabricated variant is considered as a more linear product than circular (MCI < 0,5). The reasons for the low MCI-value, are the small amount of reused and recycled feedstock, that is only present in the PVC window frame, the short lifetime of the system and the impossibility to reuse or recycle components at the end of life. Most of the materials, that the Exterior Insulation variant consists of, need to be incinerated at the end of life, with the exception of the PVC window frame.

Also in terms of Disassembly Potential, the extensive use of wet connections between the existing façade, the insulation layer and the cladding material has a negative effect on the disassembly process at the end of life of the refurbishment system. Next to that, there is no matter of clustering of materials and functional independence. As a result, the Exterior Insulation variant can't be disassembled at the end of life without valuable material loss. However, the system consumes significantly less virgin materials, compared to the Prefabricated variant, due to its low weight.

- How could the 2ndSkin Façade Refurbishment system be redesigned in terms of circularity and to what extent is the redesign of the system "circular"?

The circularity assessment of the two variants of the 2nd Skin Façade Refurbishment system has shown that the Prefabricated variant has most potential to be improved in terms circularity, due to the choice of materials and the used dry connection methods. However, the Structural Insulated Panels have most potential to be optimised in terms of reuse- and recyclability of materials and reversibility of connections.

To improve the level of circularity of the 2nd Skin Façade Refurbishment system, the proposed redesign is made on the basis of a Roadmap, that supported the decision-making process. In the Roadmap, the principles of the Circular Economy have been translated into practical guidelines, that can be utilised during the design process.
As a first step, alternative materials are chosen for the redesign of the 2nd Skin Façade Refurbishment system, that consist of secondary feedstock and have the potential to be restored at the end of life through preferable reuse and/or recycling. In the redesign the EPS insulation will be replaced by Metisse insulation, that consists of recycled cotton, coming as waste stream from the clothing industry. The structural frame of the prefabricated panels will be made of ECOBoard instead of chipboard, because ECOBoard mainly consists of agricultural waste feedstock and is biodegradable and recyclable at the end of life. As cladding material is chosen for Accoya wood, instead of bamboo, due to its dry connection method and its biodegradability at the end of life. When the architectural appearance of the existing façade needs to be preserved, proposed is to choose for a different type of brick cladding system, in which the brick strips are chemically connected to a fibre cement board, which is in turn mechanically connected to the facade supporting structure. This way the cladding can be removed from the prefabricated panels without damaging the surrounding components, which was the case in the original situation.

In the redesign, the type of connections within the prefabricated panels has been changed from wet to dry connections. Instead of using a chemical connection between the insulation and the structure of the prefabricated panels, the connections have been made with premade geometry, that enables easy reconfiguration and replacement of elements within the module without the need to disassemble the complete module. Next to that, the standardisation of the elements is increased to enable direct component exchange between two case study buildings that are in need of refurbishment. The horizontal and vertical studs of the prefabricated modules are dimensioned on the basis of a grid of 150 x 150 mm that fits to the façade arrangement of both case study buildings. This way direct reuse of the horizontal and vertical studs is possible for the same application, with as little adjustments as possible.
When comparing the circularity assessment results of the redesign to the Structural Insulated Panels of the Prefabricated variant of the 2nd Skin Façade Refurbishment system, the MCI-value of the redesign reaches almost 1 (MCI = 0,99) and thus should be considered as a circular product, while the MCI-value of the Structural Insulated Panels approaches 0 (MCI = 0,32) and thus should be considered as a linear product. The main advantage of the proposed redesign in terms of circularity, is that the elements that the prefabricated modules of the redesign consist of, have become reusable at the end of their functional service life. The high level of standardisation makes reuse of elements for the refurbishment of a second or even a third residential building with a different facade typology possible. At the end of their technical lifetime, the materials that the prefabricated modules consist of, can all be recycled for the production of new building products. Besides, reconfiguration of the facade is enabled without having the need to disassemble the complete system. Replacement of components that have reached the end of their technical lifetime during their functional service life, have been enabled by making the components easy accessible. For these reasons, the Disassembly Potential of the system has been increased by allowing elimination, addition or relocation of building components without damage.

Main research question

- How can the 2ndSkin Façade Refurbishment system be redesigned into a Circular 2ndSkin Façade Refurbishment system, that optimises reuse and/or recycling of building materials and components?

The proposed redesign of the 2nd Skin Façade Refurbishment system is made on the basis of a Roadmap. The Roadmap addresses the key principles of the Circular Economy, applied to the built environment, in the form of practical questions. The Roadmap points out what design decisions have a direct and/or indirect effect on the level of circularity of the façade refurbishment system and what options should be considered. The Roadmap is developed to help architects and contractors during the decision-making process. For the validation of the Roadmap a proposal for a redesign of the 2nd Skin Façade Refurbishment system is developed. Design decisions are made stepwise on the basis of the Roadmap, starting with the choice of alternative circular building materials, followed by the redesign of the connections and increasing the level of standardisation of the façade system. The design proposal shows how the Roadmap should work in practice.

As followed from the research, to optimise reuse of building materials and components, the Circular 2nd Skin Façade Refurbishment should consist of standardised components that can be reused at the end of their functional service life for the refurbishment of a second or even a third residential building with a different façade typology. By enabling reuse the lifecycles of the materials have been extended within the same system. To optimise recycling of building materials and components, the change from wet to dry connection methods between the elements makes separation of materials in its purest form possible. As a result, at the end of their technical lifetime, the materials that the Circular 2nd Skin Façade Refurbishment system consist of, can all be recycled for the production of new building products without valuable material loss. By letting the geometry of the components' edges form the connection, assembly and disassembly of the system has been simplified. This way the design allows elimination, addition or relocation of every building component without damage to the surrounding components. Therefore, the proposed Circular 2nd Skin Façade Refurbishment system contributes to the closure of multiple material cycles and the extension of the cycles by increasing the functional lifetime of the system, resulting in decreased raw material consumption and waste generation during the refurbishment process of the post-war residential buildings.

Fig. 99::
Visit of the building site Case Study Building 1, Vlaardingen, 15/11/2017 (source: own image)

Recommandations for further research

Besides the circularity assessment of the two variants of the 2nd Skin Façade Refurbishment system, the Prefabricated variant and the Exterior Insulation variant, the main outcome of this research is the Roadmap to circular façade refurbishment, validated by the design proposal of the Circular 2nd Skin Façade Refurbishment system. The circularity assessment method and the developed Roadmap take into account two aspects, regarding the practical implementation of the Circular Economy in the built environment: the level of circularity of materials the building components consists of, and the disassembly potential of the connections between the building components and materials.

The Roadmap, which is based on the circularity assessment method used in the research, is focussed on the technical implementation of the principles of the Circular Economy. The calculated level of circularity of the two variants of the 2nd Skin Façade Refurbishment system is based on the Material Circularity Indicator, which assesses the materials the building components of the system consists of, and the Disassembly Potential, which assesses the connections between the components and materials within the system. What haven't been incorporated in the assessment method, are the embodied energy of the used materials of the 2nd Skin Façade Refurbishment system and the CO_2-emissions of the production, recycling and remanufacturing processes. The main focus of the research was to improve the level of circularity of the 2nd Skin Facade Refurbishment system by closing and extending material cycles. However, this approach doesn't necessary lead to a higher level of sustainability of the proposed system. For this reason, the Roadmap should be further developed by taking into account the effect of the embodied energy and CO_2-emissions over the extended lifetime of the refurbishment. Further research should look into the involvement of the Life Cycle Assessment in the used circularity assessment method of this research.

Consequently, further research should be done into the development of the business model around the proposed circular façade refurbishment system. To enable the transition from the linear process of take-make-dispose of the refurbishment system into a circular process with the proposed Circular 2nd Skin Façade Refurbishment system, research into the supply chain management should be conducted. The possibilities of implementing leasing or hiring business models in the refurbishment practice, should be examined. The potential of reselling components via secondary markets should be analysed and the financial incentives for stakeholders to participate in the proposed circular facade refurbishment system should be investigated, looking at the cost and payback time. Also, the financial feasibility and the market potential of the proposed Circular 2nd Skin Façade Refurbishment system should be examined by looking at the need and necessity of a reusable and adaptable refurbishment system, based on the expected future scenarios of refurbished buildings. Next to that, analysis of the logistics on the building site during dis- and reassembly of the refurbishment system should be included.

The end result of the proposed Circular 2nd Skin Façade Refurbishment system can't be called 100% circular, because the research doesn't take into consideration the whole system around the product 2nd Skin Facade Refurbishment. However, what the research has tried to demonstrate is that the principles of the Circular Economy and the high demand for energy neutral refurbishment of the post-war residential building stock have the potential to be combined and strengthen each other, whereby the proposed Circular 2nd Skin Facade Refurbishment system is presented as a possible outcome of this approach.

Reflection

In this section, the graduation project will be reflected on two aspects: the graduation process and the societal impact. The reflection will give an answer to the main question: *How and why did the used approach work or did not work and to what extent?* This first part will focus on the used research methodology. The second part focusses on the research within the wider social context.

Graduation process

The graduation project started with the existing research project 2nd Skin Façade Refurbishment of Thaleia Konstantinou and Tillmann Klein. In this existing research project a refurbishment strategy for post-war residential buildings was developed, in which the residential building is wrapped in a second layer of exterior insulation with integrated ventilation ducts and photovoltaics on the roof, in order to reach energy neutrality of the building. The aim of the graduation project was to further develop the façade refurbishment system in terms of circularity. The end result would be the redesign of the Circular 2nd Skin Façade Refurbishment Facade Refurbishment system, that creates no waste. The hypothesis leaded to the use of recycled and bio based materials in the redesign, that could be disassembled at the end of the functional lifetime of the refurbishment.

The following methodology was used for the research. First, based on intensive literature research, the definition of the Circular Economy and its application in the built environment was determined to get familiar with the concept. Then the accommodating frameworks around the Circular Economy, were analysed to be able to identify the coherence. Next, the design strategies for circular building were developed, based on literature research and analysed precedents. The second step was the assessment of the level of circularity of buildings. A complete circularity assessment tool didn't yet exist, so several sustainability assessment methods were analysed. The two methods in which most of the principles of the Circular Economy were integrated, were chosen and the exact assessment criteria were defined. These assessment criteria were then used to evaluate the level of circularity of the 2nd Skin Façade Refurbishment system. To be able to make a comparison, two variants of the 2nd Skin Façade Refurbishment system were analysed: the Prefabricated variant, that consists of prefabricated modules connected to the existing façade with a substructure, and the Exterior Insulation variant, that consists of exterior insulation board glued to the existing facade. Originally, also the existing façade of the case study building was planned to be evaluated, but that appeared not to be useful for the research, because the existing façade would be maintained during the refurbishment process. The redesign of the 2nd Skin Façade Refurbishment system was based on the comparison results of the two refurbishment systems. To be able to make the redesign of the 2nd Skin Façade, a Roadmap was created to help making decisions for the redesign. This wasn't incorporated in the initial research methodology, but appeared to be necessary for the translation of the research results into a new design proposal.

The chosen research methodology did work out to a certain extent, because the comparison of the assessment results of the two variants did lead to practical points of improvements that needed to be implemented in the design in order to increase the level of circularity of the 2nd Skin Façade Refurbishment system. However, important to mention are the limitations of the chosen methodology. As stated in the research framework, the assessment focusses on the technical aspects of the implementation of the Circular Economy in the built environment. The proposed methodology can be used to assess the level of circularity of the materials the 2nd Skin Façade Refurbishment system consist of, and the Disassembly Potential of the connections between the façade components and materials. What the approach doesn't take into consideration, is the analysis of the supply chain and business model around the refurbishment process of the post-war residential building, while this is also of high importance when implementing the Circular Economy into practice. Next to that, the embodied energy of the materials and the transportation distances from the factory to the building site isn't incorporated into the methodology, while these aspects also have an impact on the level of circularity of the system. Originally planned was to incorporate also the embodied energy of materials into the methodology. However, this aspect was considered to be more related to the level of sustainability than the level of circularity of the system. For these reasons, the research can't state that the redesign of the 2nd Skin Façade Refurbishment system should be considered as 100% circular, because not all aspects of the Circular Economy were taken into account. The graduation process has shown the complexity and the widespread definition of the Circular Economy, that has an effect on many fields of study within the wider socio-economic system, leading to a concept difficult to grasp completely within the timeframe of the graduation process.

This methodology enabled the connection between research and design. All decisions for the redesign of the façade system were based on the research results, in which the two variants of the 2nd Skin Facade Refurbishment system were assessed in terms of circularity. The decision-making process was facilitated by translating the research results into a Roadmap, that explains with questions step by step how to design a circular façade. This roadmap can be seen as an additional result of the graduation project, that can be used by architects, contractors and material suppliers. The conducted literature research showed the necessity to implement the principles of the Circular Economy into practical guidelines that can be applied in practice. This proposed Roadmap should be seen as a way to communicate these.

The relationship between the theme of the graduation lab, Sustainable Design Graduation studio, and the chosen subject, Circular Façade Refurbishment, is clear. Circularity is strongly interlinked with sustainability, because the Circular Economy is seen as a new approach towards sustainability. Next to that the research had to fit within two of the four tracks of the master Building Technology: Façade, Structural, Climate and Computational design. The chosen tracks for this graduation project were Façade and Climate design. In terms of Façade Design the graduation project delivers a detailed façade system, that can be used to refurbish different typologies of post-war residential buildings. In terms of Climate design, the focus lays on sustainability; providing a system to improve the energy efficiency of residential buildings within the framework of the Circular Economy.

Societal impact

The results of the graduation results are applicable in practice, because the project provides a practical Roadmap for circular façade design, that can be used by architects, contractors and material suppliers during the design process. The roadmap can be used for the design of a façade refurbishment system, which was the topic of this research, but also for the design of the façade of new buildings. The proposal for the redesign of the 2nd Skin Façade Refurbishment system can't yet be applied to practice, because the design needs to be elaborated further. During the graduation project the system is applied to two case study buildings. However, to make the system feasible, more case study buildings with different typologies should be examined in detail.

The projected innovation, however, has been achieved. The aim of the project was to develop a new circular façade refurbishment system, that has the potential to be brought to the market. From the feedback of the contractor, that was involved in the project of the 2nd Skin Façade Refurbishment system, clearly emerged the necessity of a universal façade refurbishment system, that can be applied to any post-war residential building. Because of the currently low refurbishment rate of post-war residential buildings, the ambition of the Paris climate agreement to reach energy neutrality of the built environment in 2050 can never be reached. These developments in the building industry ask for an innovative solution, that would give a helping hand in increasing the refurbishment rate of the high number of post-war residential buildings with bad energy performance.

The project has a clear impact on sustainability, because it offers a practical solution to the problem of the current linear take-make-dispose model that is prevailing in the current building industry. During construction, demolition and refurbishment of buildings a high amount of valuable material waste is accumulated on-site. Due to the inflexibility of the building envelope the refurbishment of the residential building is complicated and demolition and reconstruction is often the preferred option. The developed façade refurbishment system can be disassembled and reassembled to enable refurbishment of multiple residential buildings with the same system. The system will be applied from the outside, to avoid disturbance of the inhabitants. With the 2nd Skin Refurbishment system the building will become energy neutral, creating a comfortable interior climate in the building. Next to that, the proposed redesign increases the flexibility of the façade, so the façade is able to go along with the changing demand of the people living in the building. Consequently, the project has made an effort to translate the concept of the Circular Economy in practical building guidelines, that can be applied to the building industry.

09

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10

APPENDIX

MCI Calculation

Prefabricated variant

Material Circularity Indicator
2nd Skin Facade Refurbishment

Option brick		Option bamboo	
Thickness	0,293	Thickness	0,283
Length	7,220	Length	7,220
Height	2,750	Height	2,750
Openings	7,192	Openings	7,192
Volume	**3,710**	**Volume**	**3,584**

Components

Material properties

Component	No.	Material type	Part	Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m3)	Mass (kg)
Structural Insulated Panel	**1**	EPS insulation			2,726	1,048	0,197	1,115	15	16,718
		Chipboard	Top / bottom	2	1,060	0,221	0,012	0,011	600	6,744
			Left / right	1	2,726	0,197	0,012	0,006	600	3,867
			Front / back	2	2,726	1,0595	0,012	0,069	600	41,590
		Pinewood stiffeners		2	2,726	0,044	0,044	0,011	460	4,855
		Pinewood (cured) sticks		1	2,750	0,056	0,056	0,009	460	3,967
									total	**77,740**
	2	EPS insulation			2,726	1,828	0,197	1,942	15	29,126
		Chipboard	Top / bottom	2	1,852	0,221	0,012	0,020	600	11,784
			Left / right	2	2,726	0,197	0,012	0,013	600	7,733
			Front / back	2	2,726	1,8515	0,012	0,069	600	41,192
			Opening (T/B)	2	1,885	0,197	0,012	0,009	600	5,347
			Opening (F/B)	2	1,160	0,197	0,012	0,0055	600	3,291
		Wooden stiffeners		4	2,726	0,044	0,044	0,021	460	9,711
		Timber sticks		2	2,750	0,056	0,056	0,017	460	7,934
									total	**116,118**
	3	EPS insulation			2,726	0,966	0,197	1,016	15	15,246
		Chipboard	Top / bottom	2	0,990	0,221	0,012	0,011	600	6,301
			Left / right	2	2,726	0,197	0,012	0,013	600	7,733
			Front / back	2	2,726	0,990	0,012	0,065	600	38,862
		Wooden stiffeners		4	2,726	0,044	0,044	0,021	460	9,711
		Timber sticks		2	2,750	0,056	0,056	0,017	460	7,934
									total	**85,787**
	4	EPS insulation			2,726	2,441	0,197	2,600	15	39,001
		Chipboard	Top / bottom	2	2,465	0,221	0,012	0,026	600	15,686
			Left / right	2	2,726	0,197	0,012	0,013	600	7,733
			Front / back	2	2,726	2,465	0,012	0,060	600	35,804
			Opening (T/B)	2	1,885	0,197	0,012	0,009	600	5,347
			Opening (F/B)	2	2,245	0,197	0,012	0,0106	600	6,369
		Wooden stiffeners		4	2,726	0,044	0,044	0,021	460	9,711
		Timber sticks		2	2,750	0,056	0,056	0,017	460	7,934
									total	**127,585**
	5	EPS insulation			2,726	0,315	0,197	0,327	15	4,908
		Chipboard	Top / bottom	2	0,327	0,221	0,012	0,003	600	2,078
			Left / right	1	2,726	0,197	0,012	0,006	600	3,867
			Front / back	2	2,726	0,327	0,012	0,021	600	12,817
		Wooden stiffeners		2	2,726	0,044	0,044	0,011	460	4,855
		Timber sticks		1	2,750	0,056	0,056	0,009	460	3,967
									total	**32,492**
	5	EPS insulation			2,726	0,966	0,107	0,564	15	8,453
		Chipboard	Top / bottom	2	0,990	0,119	0,012	0,006	600	3,393
			Left / right	1	2,726	0,107	0,012	0,004	600	2,100
			Back	1	2,726	0,990	0,012	0,032	600	19,431
		PVC ventilation pipes			7,820				1,42	11,104
									total	**44,481**

Component	Material type	Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m3)	Mass (kg)
Substructure	Pinewood studs	4	2,750	0,075	0,16	0,132	460	60,720
	Stainless steel U profiles	8	0,665	0,1	0,01	0,005	7880	41,922
Cladding (option 1)	Fibre cement (Sto Levell Uni)		2,750	7,22	0,01	0,127	1070	135,489
	EPS insulation		2,750	7,22	0,04	0,507	15	7,598
	Bricks	814	0,210	0,065	0,02	0,222	1600	355,555
	Mortar				0,02	0,031	1750	54,301
Cladding (option 2)	Vertical wooden posts	23	2,750	0,04	0,018	0,046	460	20,948
	Horizontal aluminium profile	5	7,220	0,08	0,0015	0,004	2700	11,696
	Stainless steel AISI 301 clips	254	0,045	0,019	0,04	0,009	7880	68,452
	Bamboo	27	1,905	0,137	0,018	0,127	1150	145,865
		27	0,825	0,137	0,018	0,055	1150	63,170
		24	0,523	0,137	0,018	0,031	1150	35,596
		24	0,300	0,137	0,018	0,018	1150	20,418
						0,230		

Component	No.	Material type	Material	Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m)	Mass (kg)
Window	1	Window frame	PVC		6,090	0,080	0,120	0,058	2,3	14,007
			Steel		6,090	0,080	0,120	0,058	1,37	8,343
		Triple HR++ glass	Glass	3	0,918	1,769	0,004	0,019	2500	48,718
	2	Window frame	PVC		8,260	0,080	0,120	0,079	2,3	18,998
			Steel		8,260	0,080	0,120	0,079	1,37	11,316
		Triple HR++ glass	Glass	3	2,044	1,769	0,004	0,043	2500	108,475

Lifetime (yrs)		Waste scenarios (%)				Feedstock materials (%)		Efficiency recycling process (%)	
Technical	Functional	Landfill	Incineration	Recycling	Reuse	Recycling	Reuse	Recycling	Feedstock
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0	100	100
75		10	85	5	0	0	0	100	100
75		10	85	5	0	0	0	100	100
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0		
75		10	85	5	0			100	100
75		10	85	5	0	0	0	100	100
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0	100	100
75		10	85	5	0			100	100
75		10	85	5	0	0	0	100	100
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0	100	100
75		10	85	5	0			100	100
75		10	85	5	0	0	0	100	100
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0	100	
75		10	85	5	0			100	100
75		10	85	5	0	0	0	100	100
75		5	90	5	0	0	0	100	100
75		5	85	10	0	75	0	100	
30		0	10	90	0	0	0	100	100
75		10	85	5	0	0	0	100	100
50		1	0	87	12	59	0	100	100
50		5	95	0	0	0	0	100	100
75		5	90	0	0	0	0	100	100
50		91	9	0	0	0	0	100	100
50		91	9	0	0	0	0	100	100
35		5	95	0	0	0	0	100	100
75		5	5	90	0	33	0	20	74,4
75		5	5	90	0	59	0	100	100
35		5	95	0	0	0	0	100	100

Lifetime (yrs)		Waste scenarios (%)				Feedstock materials (%)		Efficiency recycling process (%)	
Technical	Functional	Landfill	Incineration	Recycling	Reuse	Recycling	Reuse	Recycling	Feedstock
40		8	15	77	0	10	0	100	100
40		8	15	77	0	37	0	100	100
30		30	0	70	0	10	0	20	80
40		8	15	77	0	10	0	100	100
40		8	15	77	0	37	0	100	100
30		30	0	70	0	10	0	20	80

Step 1: Calculate virgin feedstock		Renewable content	M(x) (kg)	FR(x)	FU(x)	V(x) (kg)
SIP panels	EPS	Tech	113,452	0	0	113,452
	Chipboard	Tech	289,069	0,75	0	72,267
	Pinewood	Bio	38,843	0	0	38,843
	Timber	Bio	31,736	0	0	31,736
	PVC (ventilation)	Tech	11,104	0	0	11,104
Substructure	Pinewood	Bio	60,720	0	0	60,720
	Stainless steel	Tech	41,922	0,59	0	17,188
Brick cladding	Fibre cement	Tech	135,489	0	0	135,489
	EPS	Tech	7,598	0	0	7,598
	Brick	Tech	355,555	0	0	355,555
	Mortar	Tech	54,301	0	0	54,301
Bamboo cladding	Pinewood	Bio	20,948	0	0	20,948
	Aluminium	Tech	11,696	0,33	0	7,837
	Stainless steel	Tech	68,452	0,59	0	28,065
	Bamboo	Bio	265,049	0	0	265,049
Window	PVC	Tech	33,005	0,1	0	29,705
	Steel	Tech	19,660	0,37	0	12,385
	Glass	Tech	157,193	0,1	0	141,474
option 1: Brick cladding			1350 kg			1081,818 kg
option 2: Bamboo cladding			1163 kg			850,774 kg

Step 2: Calculate unrecoverable waste		M(x) (kg)	CR(x)	CU(x)	W0(x)	EC(x)	WC(x)	EF(x)	WF(x)	W	C(landfill)
Sandwich panels	EPS	113,452	0,05	0	107,780	1	0	1	0	107,780	0,05
	Chipboard	289,069	0,1	0	260,162	1	0	1	0	260,162	0,05
	Pinewood	38,843	0,05	0	36,901	1	0	1	0	36,901	0,10
	Timber	31,736	0,05	0	30,150	1	0	1	0	30,150	0,10
	PVC ventilation	11,104	0,9	0	1,110	1	0	1	0	1,110	0,00
Substructure	Pinewood	60,720	0,05	0	57,684	1	0	1	0	57,684	0,10
	Stainless steel	41,922	0,87	0,12	0,419	1	0	1	0	0,419	0,01
Brick cladding	Fibre cement	135,489	0	0	135,489	1	0	1	0	135,489	0,05
	EPS	7,598	0	0	7,598	1	0	1	0	7,598	0,05
	Brick	355,555	0	0	355,555	1	0	1	0	355,555	0,91
	Mortar	54,301	0	0	54,301	1	0	1	0	54,301	0,91
Bamboo cladding	Pinewood	20,948	0	0	20,948	1	0	1	0	20,948	0,05
	Aluminium	11,696	0,9	0	1,170	0,2	8,421	0,744	1,328	6,044	0,05
	Stainless steel	68,452	0,9	0	6,845	1	0	1	0	6,845	0,05
	Bamboo	265,049	0	0	265,049	1	0	1	0	265,049	0,05
Window	PVC	33,005	0,77	0	7,591	1	0	1	0	7,591	0,08
	Steel	19,660	0,77	0	4,522	1	0	1	0	4,522	0,08
	Glass	157,193	0,7	0	47,158	0,2	88,028	0,8	3,930	93,137	0,30
					1106,419 kg		88,028 kg		3,930	1152,398 kg	
					847,488 kg		96,450 kg		5,258	898,342 kg	

W(landfill)	C(inc)	W(inc.)
5,673	0,9	102,107
14,453	0,85	245,709
3,884	0,85	33,016
3,174	0,85	26,976
0,000	0,1	1,110
6,072	0,85	51,612
0,419	0	0,000
6,774	0,95	128,715
0,380	0,9	6,838
323,555	0,09	32,000
49,414	0,09	4,887
1,047	0,95	19,901
0,585	0,05	0,585
3,423	0,05	3,423
13,252	0,95	251,796
2,640	0,15	4,951
1,573	0,15	2,949
47,158	0	0,000
465,170		640,869
103,354		744,135

Step 3: Linear Flow Index (LFI)		V	W	M	WF(x)	WC(x)	LFI
Sandwich panel	EPS	113,452	107,780	113,452	0	0	
	Chipboard	72,267	260,162	289,069	0	0	
	Pinewood	38,843	36,901	38,843	0	0	
	Timber	31,736	30,150	31,736	0	0	
	PVC ventilat	11,104	1,110	11,104	0	0	
		267,403	436,102	484,204	0	0	0,73
Substructure	Pinewood	60,720	57,684	60,720	0	0	
	Stainless ste	17,188	0,419	41,922	0	0	
		77,908	58,103	102,642	0	0	0,66
Brick cladding	Fibre cemen	135,489	135,489	135,489	0	0	
	EPS	7,598	7,598	7,598	0	0	
	Brick	355,555	355,555	355,555	0	0	
	Mortar	54,301	54,301	54,301	0	0	
		552,943	552,943	552,943	0	0	1,00
Bamboo cladding	Pinewood	20,948	20,948	20,948	0	0	
	Aluminium	7,837	6,044	11,696	1,328	8,421	
	Stainless ste	28,065	6,845	68,452	0	0	
	Bamboo	265,049	265,049	265,049	0	0	
		321,899	298,887	366,146	1,328	8,421	0,85
Window	PVC	29,705	7,591	33,005	0	0	
	Steel	12,385	4,522	19,660	0	0	
	Glass	141,474	93,137	157,193	3,930	88,028	
		183,564	105,250	209,858	3,930	88,028	0,76
		1081,818	1152,398	1349,647	3,930	88,028	0,84
		850,774	898,342	1162,850	5,258	96,450	0,77

Step 4: Utility Factor (X)	Lav	L	U	X
Sandwich panel	75	25	1	3,0
Substructure	75	25	1	3,0
Brick cladding	50	25	1	2,0
Bamboo cladding	35	25	1	1,4
Window	30	25	1	1,2
Option 1: Brick cladding	50	25	1	2,0
Option 2: Bamboo cladding	35	25	1	1,4

Step 5: Material Circularity	LFI	F(x)	MCI
Sandwich panel	0,73	0,3	0,78
Substructure	0,66	0,3	0,80
Brick cladding	1,00	0,45	0,55
Bamboo cladding	0,85	0,6	0,45
Window frame	0,76	0,8	0,43
	0,84	0,5	0,62
	0,77	0,6	0,51

Exterior Insulation variant

Material Circularity Indicator
Traditional Refurbishment

Thickness	0,198
Length	7,220
Height	2,750
Openings	7,436
Volume	**2,453**

Components

Material properties

		Material type	Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m3)	Mass (kg)
Fastening		Adhesive (type PU112)		2,750	7,220	0,003	0,037	1200	44,707
Insulation		EPS		2,750	7,220	0,190	2,360	15	35,393
Cladding		Mortar (Putzgrund)		2,750	7,220	0,003	0,037	1500	55,884
		Plaster		2,750	6,130	0,0015	0,014	1800	25,437
		Brick strips	185	0,210	0,065	0,020	0,051	1600	80,808
Window	1	*Opening*		*1,885*	*1,430*		*2,696*		
		PVC		6,630				2,300	15,249
		Steel		6,630				1,370	9,083
		Glass	3	1,632	1,179	0,004	0,023	2500	57,724
	2	*Opening*		*1,885*	*2,515*		*4,741*		
		PVC		8,800				2,300	20,240
		Steel		8,800				1,370	12,056
		Glass	3	1,632	2,252	0,004	0,044	2500	110,258

Step 1: Calculate virgin feedstock			Renewable	M(x) (kg)	FR(x)	FU(x)	V(x) (kg)
Fastening		PU adhesive	Tech	44,707	0	0	44,707
Insulation		EPS	Tech	35,393	0	0	35,393
Cladding		Mortar	Tech	55,884	0	0	55,884
	-1	Plaster	Tech	25,437	0	0	25,437
	-2	Brick strips	Tech	80,808	0	0	80,808
Window		PVC	Tech	35,489	0,1	0	31,940
		Steel	Tech	21,139	0,37	0	13,318
		Glass	Tech	110,258	0,1	0	99,232
				409	**kg**		**386,720 kg**

Step 2: Calculate unrecoverable waste			M(x) (kg)	CR(x)	CU(x)	W0(x)	EC(x)	WC(x)	EF(x)	WF(x)	W	C(landfill)	W(landfill)
Fastening		PU adhesive	44,707	0	0	44,707	1	0	1	0	44,707	0,1	4,471
Insulation		EPS	35,393	0,05	0	33,624	1	0	1	0	33,624	0,05	1,770
Cladding		Mortar	55,884	0	0	55,884	1	0	1	0	55,884	0,1	5,588
	-1	Plaster	25,437	0	0	25,437	1	0	1	0	25,437	0,1	2,544
	-2	Brick strips	80,808	0	0	80,808	1	0	1	0	80,808	0,91	73,535
Window		PVC	35,489	0,77	0	8,162	1	0	1	0	8,162	0,08	2,839
		Steel	21,139	0,77	0	4,862	1	0	1	0	4,862	0,08	1,691
		Glass	110,258	0,70	0	33,077	0,2	61,744	0,8	2,756	65,328	0,3	33,077
						286,562 kg		**61,744 kg**		**2,756**	**318,812**		**125,515**

Step 3: Linear Flow Index (LFI)			V	W	M	WF(x)	WC(x)	LFI
Fastening		PU adhesive	44,707	44,707	44,707	0	0	1
Insulation		EPS	35,393	33,624	35,393	0	0	0,98
Cladding		Mortar	55,884	55,884	55,884	0	0	
	-1	Plaster	25,437	25,437	25,437	0	0	
	-2	Brick strips	80,808	80,808	80,808	0	0	
			242,230	**240,460**	**242,230**	0	0	**1,00**
Window		PVC	31,940	8,162	35,489	0	0	
		Steel	13,318	4,862	21,139	0	0	
		Glass	99,232	65,328	110,258	2,756	61,744	
			144,490	**78,352**	**166,886**	**2,756**	**61,744**	**0,61**
			386,720 kg	**318,812 kg**	**409,116 kg**	**2,756 kg**	**61,744 kg**	**0,83**

Step 4: Utility Facto	Lav	L	U	X
Fastening	75	25	1	**3,0**
Insulation	75	25	1	**3,0**
Plaster cladding	30	25	1	**1,2**
Brick cladding	50	25	1	**2,0**
Window frame	30	25	1	**1,2**
	30	**25**	**1**	**1,2**

Step 5: Material Circularity Indicat	LFI	F(x)	MCI
Fastening			
Insulation			
Cladding	1,00	0,8	**0,25**
Window	0,61	0,8	**0,54**
	0,83	**0,8**	**0,38**

Lifetime (yrs)			Waste scenarios (%)					Feedstock materials (%)			Efficiency recycling proc	
Technical	Functional		Landfill	Incineration	Recycling	Reuse		Recycling	Reuse		Recycling	Feedstock
75			10	90	0	0		0	0		100	100
75			5	90	5	0		0	0		100	100
30			10	90	0	0		0	0		100	100
30			10	90	0	0		0	0		100	100
50			91	9	0	0		0	0		100	100
40			8	15	77	0		10	0		100	100
40			8	15	77	0		37	0		100	100
30			30	0	70	0		10	0		20	80
40			8	15	77	0		10	0		100	100
40			8	15	77	0		37	0		100	100
30			30	0	70	0		10	0		20	80

C(inc)	W(inc.)
0,9	40,237
0,9	31,854
0,9	50,296
0,9	22,893
0,09	7,273
0,15	5,323
0,15	3,171
0	0,000
	161,046

Redesign

Material Circularity Indicator

Redesign

			Amount	Height (m)	Width (m)	Area (m2)
Components	Window opening		1	1,820	2,570	4,677

Material properties

	Material type		Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m3)	Mass (kg)
Redesigned modules	Metisse insulation			2,688	3,588	0,200	0,993	20	19,87
	ECOBoard	Horizontal studs	4	3,620	0,024	0,018	0,006	720	4,504
		Vertical studs	4	2,720	0,024	0,018	0,005	720	3,384
		Structural studs (hor.)	2	3,620	0,024	0,018	0,003	720	2,252
		Structural studs (vert.)	2	2,720	0,024	0,018	0,002	720	1,692
		Interior board	1	2,760	3,660	0,018	0,098	720	70,30
		Exterior board	1	2,760	3,770	0,018	0,103	720	74,23
	Pinewood connection sticks		2	2,760	0,056	0,056	0,017	460	7,963
									184,193

Step 1: Calculate virgin feedstock			M(x) (kg)	FR(x)	FU(x)	V(x) (kg)
Redesigned modules	Metisse	Tech	19,87	0,85	0	2,980
	ECOBoard	Bio	156,4	0,97	0	4,691
	Pinewood	Bio	7,963	0	0	7,963
			184,2 kg			**15,63** kg

Step 2: Calculate unrecoverable waste		M(x) (kg)	CR(x)	CU(x)	W0(x)	EC(x)	WC(x)	EF(x)	WF(x)	W	C(landfill)	W(landfill)	C(inc)	W(inc.)
Redesigned modules	Metisse	19,869	0	1	0,000	1	0	1	0	0,000	0	0,000	0	0,000
	ECOBoard	156,4	0	1	0,000	1	0	1	0	0,000	0	0,000	0	0,000
	Pinewood	7,963	0	1	0,000	1	0	1	0	0,000	0	0,000	0	0,000

			Amount	Height (m)	Width (m)	Area (m2)
Components	Window opening		1	1,820	2,570	4,677

Material properties

	Material type		Amount	Length (m)	Width (m)	Thickness (m)	Volume (m3)	Density (kg/m3)	Mass (kg)
SIP panels	EPS insulation			2,686	3,586	0,197	0,976	15	14,64
	Chipboard	Left / right plate	2	3,620	0,197	0,012	0,017	600	10,27
		Top / bottom plate	2	2,720	0,197	0,012	0,013	600	7,716
		Front / back plate	2	2,710	3,610	0,012	0,123	600	73,52
		Opening (top / bottom)	2	2,570	0,197	0,012	0,012	600	7,291
		Opening (left / right)	2	1,820	0,197	0,012	0,009	600	5,163
	Pinewood connection sticks		2	2,710	0,056	0,056	0,017	460	7,819
	Pinewood stiffeners (vert.)		8	2,686	0,044	0,044	0,042	460	19,14
	Pinewood stiffeners (hor.)		4	3,586	0,044	0,044	0,028	460	12,77
							0,173		**158,3 kg**
							0,086		

Step 1: Calculate virgin feedstock			M(x) (kg)	FR(x)	FU(x)	V(x) (kg)
SIP panels	EPS	Tech	14,64	0	0	14,64
	Chipboard	Tech	104,0	0,75	0	25,99
	Pinewood	Bio	39,73	0	0	39,73
			158,3 kg			**80,36** kg

Step 2: Calculate unrecoverable waste		M(x) (kg)	CR(x)	CU(x)	W0(x)	EC(x)	WC(x)	EF(x)	WF(x)	W	C(landfill)	W(landfill)	C(inc)	W(inc.)
SIP panels	EPS	14,641	0	0	14,64	1	0,000	1		14,64	0	0,000	1	14,64
	Chipboard	104,0	0	0	104,0	1	0,000	1	0,000	104,0	0	0,000	1	104,0
	Pinewood	39,729	0	0	39,729	1	0,000	1	0,000	39,73	0	0,000	1	39,73
		158,3			**158,3**		**0,000**		**0,000**	**158,3**		**0,000**		**158,3**

Step 3: Linear Flow Index (LFI)		V	W	M	WF(x)	WC(x)	LFI
SIP panels	EPS	14,64	14,64	14,64	0,000	0,000	
	Chipboard	25,99	104,0	104,0	0,000	0,000	
	Pinewood	39,73	39,73	39,73	0,000	0,000	
		80,36	**158,3**	**158,3**	**0,000**	**0,000**	**0,75**

Step 4: Utility Factor (X)	Lav	L	U	X
SIP panels	25	25	1	1,0

Step 5: Material Circularity Indicat	LFI	F(x)	MCI
Sandwich panel	0,75	0,9	**0,32**

Lifetime (yrs)	
Technical	Functional
75	
75	
75	

Waste scenarios (%)			
Landfill	Incineration	Recycling	Reuse
0	0	0	100
0	0	0	100
0	0	0	100

Feedstock materials (%)	
Recycling	Reuse
85	0
97	0
0	0

Efficiency recycling process (%)	
Recycling	Feedstock
100	100
100	100
100	100

Step 3: Linear Flow Index (LFI)		V	W	M	WF(x)	WC(x)	LFI
Redesigned modules	Metisse	2,980	0,000	19,87	0,000	0,000	
	ECOBoard	4,691	0,000	156,4	0,000	0,000	
	Pinewood	7,963	0,000	7,963	0,000	0,000	
		15,63	**0,000**	**184,2**	**0,000**	**0,000**	**0,04**

Step 4: Utility Factor (X)	Lav	L	U	X
Redesigned modules	75	25	1	3,0

Step 5: Material Circularity Indicat	LFI	F(x)	MCI
Redesigned modules	0,04	0,3	**0,99**

Lifetime (yrs)	
Technical	Functional
75	
75	
75	
75	
75	

Waste scenarios (%)			
Landfill	Incineration	Recycling	Reuse
5	**90**	5	0
5	**85**	10	0
10	**85**	5	0

Feedstock materials (%)	
Recycling	Reuse
0	0
75	0
0	0

Efficiency recycling process (%)	
Recycling	Feedstock
100	
0	0