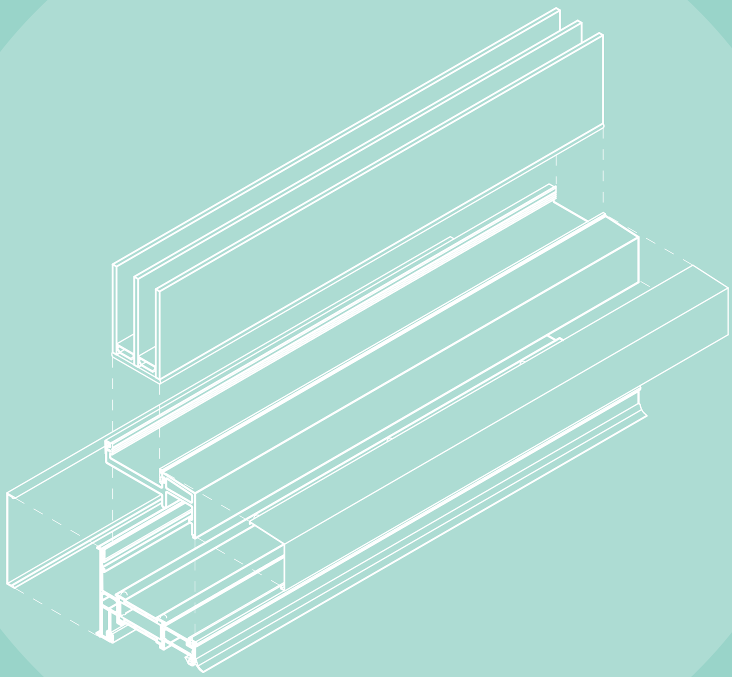
Circular Façade Systems and Construction
Design for Remanufacturing Window Systems



Tania Cecilia Cortés Vargas

MSc Architecture, Urbanism and Building Sciences
Track Building Technology
Delft University of Technology
in cooperation with Kawneer Nederland B.V.

Colophon

MSc Graduation Thesis Report

Version Final P5 Report - 2nd of July 2019

Name: Tania Cecilia Cortés Vargas
Student number: 4747720
Contact: taniaccv@gmail.com

Delft University of Technology (TU Delft)
Faculty of Architecture and the Built Environment
Department of Architectural Engineering + Technology
MSc Architecture, Urbanism and Building Sciences
Track Building Technology

First Mentor: Prof. Dr. Ir. Tillmann Klein	Façade Design
Second Mentor: Dr. David Peck	Climate Design
Guest Supervisor: Wijnand van Manen	Kawneer Nederland B.V.
Board of examiners delegate: Peter Koorstra	Architecture

TU Delft
BK Bouwkunde

KAWNEER
AN ARCONIC COMPANY

Executive Summary

Context

The "take-make-dispose" linear model has proven to be highly unsustainable during the past decades. A circular economy has emerged as a model that is restorative by design, and a response towards the high material and energy intensive linear model. However, a transition to a circular built environment implies a radical change in design and construction. Remanufacturing is one of the three product life extension strategies located in the technical cycles from the circular economy. It is an alternative to demolition, and it allows products to be longer in use, with a constant upgrade. However, for products to be remanufactured, they have to be designed according to certain guidelines, and supported by the application of circular business models.

Kawneer, an American manufacturer of aluminium architectural systems and products, seeks to optimize façade systems to meet the demand for circular building products. This means that the components of the systems should be designed with product properties such as disassembly, modularity, and flexibility, which allows them to be circular. Different (re)life options, such as reuse, remanufacturing, and refurbishment, should also be taken into account from the early design stages. The RT82HI+ window system is one of the most competent products manufactured by Kawneer. However, the only (re)life option currently available is recycling. Therefore, the product is currently unable to meet the requirements of a circular building product.

Objective

The objective of the presented research is to evaluate the performance of the existing façade components of the RT82HI+ window system in a circular economy, and according to such, redesign towards remanufacturing and other product-life extension strategies.

This is done, first, through the understanding of the relationship and dependency among the product design, development, and product-life extension, especially remanufacturing. Secondly, through an analysis of the current lifecycle scenarios of the existing components, and identification of their challenges and potentials in a circular economy. And third, through the ellaboration of three different circular window systems that react upon the main findings from the analysis.

Main findings

Three different designs are explored. The first one is an optimization of the existing RT 82 HI +, where only the critical aspects are redesigned. The second and third are hybrid variants that combine aluminium with wood polymer composite profiles (WPC). These three designs are assessed under the principles of DfD (Design for Disassembly), DfA (Design for Adaptability), and DfRem (Design for Remanufacturing). Additionally, different remanufacturing, reuse, and adaptability scenarios are analysed to understand the performance of the window system in a circular economy.

On the other hand, four main different types of façade systems and construction are reviewed to understand the type of attachment of the window to the construction. This resulted in a critical point because it could affect the performance of the window in terms of circularity.

The results indicated improvements in different aspects. The key one was ease of assembly and disassembly, but also in terms of type of connections, and geometry of product edges. Furthermore, it is discussed how the loop is closed, and the importance of the different stakeholders involved in the façade manufacturing and construction area.

Acknowledgements

I thank my mentors for supporting me throughout the last months of my master studies by guiding me, but mostly, for believing in me. Tillmann Klein has been an inspiring and important role model since I started studying Building Technology, and while his expertise has been highly valuable in the development of this thesis, it was his constant questioning that helped me move forward. He has also supported my academic path through my Honours Programme and involving me as a Student Teaching Assistant for a course on Circularity. David Peck guided me through the challenging area of remanufacturing, but overall, he was one of the few persons that believed that building products have a high potential for being remanufactured. He also understood that this was not an easy task, and through his patience and understanding, I was able to develop my research in the right direction. Wijnand van Manen, the guest supervisor from Kawneer, guided me throughout the company, with his incredible expertise on products, technology, and circularity. He also understood the importance of interviewing and discussing circularity with different stakeholders and helped me arrange meetings with them. Without his help, I would not have been able to have such a deep understanding of the actual practice of circularity. Many thanks also to Andre Smit (Kawneer), Jeroen Boersma (Kawneer), Rob Huvers (Kawneer), Martijn Veerman (Alkondor), and Frank Schotman (Kingspan). These, and many more were some of the important stakeholders that I was able to have interviews and discussions.

I have to especially thank Juan Azcarate Aguerre for being the first person that introduced me to circular façades, and for guiding me through my Honours Programme, which served as the perfect addition to my master's graduation. Thanks to Marcel Bilow, Dr Bucky Lab for helping me disassemble my prototype, and also for explaining the entire process so clearly. This gave me a different perspective of the analysis I did before, and it helped my research go in a different direction. Thanks also to the professors and researchers from the Chair of Building Product Innovation, which hired me as a Student Teaching Assistant for the MOOC about Circular Economy for a Sustainable Built Environment. Being involved in this project gave me a deeper insight into the scale of circularity, and the current critical problems that go beyond product design.

To CONACYT - Alianza FiiDEM 2017 - 2019 for supporting me financially during my master studies.

To my friends in the Netherlands that supported me through these past two years. You have become my little family in Delft and my eternal source of renewable energy. Also thanks to my friends and family back home, who have managed to be present in my life even if I am far away.

Last in this list, but always first in my heart and mind, to my parents, who have challenged and inspired me, always with a guiding hand on my shoulder. My father's stories about his engineering master studies in England, and my mother obtained her PhD in France were some of the main motivations for me to seek graduate studies abroad. Thank you for reading all of my papers, reports, and presentations (and adding all the Oxford commas I always missed), but mostly for supporting me to achieve my goals.
This thesis is dedicated to both of them, engineers at heart, who have done incredible sacrifices throughout my life to help me get here. This achievement is as much yours as it is mine.

Table of Contents

Chapter 1: Research Framework

1.1 Background 10
1.2 Problem Statement 10
1.3 Objective(s) 10
1.4 Focus and Limitations 11
1.5 Research Question(s) 11
1.6 Design Questions 11
1.7 Methodology and Approach 12
1.8 Relevance 12

Chapter 2: Circular Economy

2.1 What is a Circular Economy? 16
2.2 The Principles of a Circular Economy 16
2.3 The Butterfly Diagram 16
2.4 Related Schools of Thought 18
2.5 Related Principles to CE 19
2.6 Circular Business Models and Strategies 20
2.7 Conclusions on Chapter 2 20

Chapter 3: Circular Built Environment

3.1 The theory of levels 24
3.2 Hierarchical Range of Industrial Building Products 25
3.3 Hierarchical Range of Material Building Levels 25
3.4 Circular Building Product Levels 26
3.5 Circular Building Design Principles 26
3.6 Design for Disassembly (DfD) 28
  3.6.1 Available guidelines for Design for Disassembly 28
  3.6.2 The Impact of DfD in the Built Environment 28
3.7 Design for Adaptability (DfA) 29
  3.7.1 Available Guidelines for DfA 29
  3.7.2 The Impact of DfA in the Built Environment 30
3.8 Circular Construction Domain 31
3.9 Conclusions on Chapter 3 32

Chapter 4: Remanufacturing

4.1 Background 36

4.2 The Process Behind Remanufacturing 36
4.3 Barriers Towards Remanufacturing 37
4.4 Types of Remanufacturing Companies 38
4.5 Sources to Retrieve Cores 39
4.6 DfX 40
4.7 Design for Remanufacturing (DfRem) 40
4.7.1 Remanufacturing Product Properties 40
4.7.2 The Impact of DfRem in the Built Environment 43
4.8 Conclusions on Chapter 4 43

Chapter 5: Analysing Kawneer Nederland B.V.
5.1 About the Company 48
5.2 RT 82 HI + system 48
5.2.1 Technical information: 49
5.2.2 Manufacturing and logistics 50
5.2.3 Key Properties 50
5.2.4 Competitors 51
5.3 Current Business Model 52
5.4 Current End-of-Life Scenarios 52
5.5 Circularity Interview and Brainstorming Session 54
5.6 Conclusions on Chapter 5 56

Chapter 6: Window Systems
6.1 Overview: Openings 60
6.2 Evolution 60
6.3 Hardware 61
6.3.1 Functional Hardware 62
6.4 Fitting Glass 62
6.4.1 Window Seals 63
6.4.2 Seals63
6.5 Window Installation 64
6.5.1 Installation with Window Cases 64
6.6 Window Typologies 64
6.7 Window Systems by Material 66
6.7.1 Wooden Windows 66
6.7.2 Steel Windows 68

6.7.3 Aluminium Windows 70
6.7.4 uPVC Windows 72
6.7.5 GRP Windows 74
6.7.6 Aluminium/Wooden Windows 76
6.7.7 Aluminium/uPVC Windows 78
6.8 Comparison Method on Window Systems 80
6.9 State-of-the-Art: Comparison by Materials 82
6.9.1 RT 82 HI + Aluminium Triple Glazed Window Frame 82
6.9.2 CS 104 HI Aluminium Triple Glazed Window Frame 84
6.9.3 AWS 90 SI + Aluminium Triple Glazed Window Frame 86
6.9.4 Opificium TABS Steel Triple Glazed Window Frame 88
6.9.5 uPVC Triple Glazed Prestige Window Frame 90
6.9.6 Titan Aluminium/Wooden Triple Glazed Window Frame 92
6.9.7 GRP Triple Glazed Window Frame 94
6.8.8 PVC/Aluminium/GRP Triple Glazed Window Frame 96
6.10 Conclusions on Chapter 6 98

Chapter 7: Analysis of Existing Design

7.1 Establishing a Reference Project 102
7.2 Function Analysis 103
7.2.1 Function Analysis for Reference Project 104
7.2.2 Hierarchy Definition 104
7.3 Current End-of-life Scenarios for RT 82 HI + 109
7.4 Assessment on Design for Disassembly (DfD) 110
7.4.1 Transformation Capacity Methodology 110
7.4.2 Application of Transformation Capacity Methodology 112
7.4.3 Notes From the Disassembly of the Prototype 115
7.4.4 Steps taken to disassemble the RT 72 Prototype 116
7.4.5 Conclusions on DfD Assessment 116
7.5 Assessment on Design for Adaptability (DfA) 120
7.5.1 Methodology to Assess DfA 120
7.5.2 Application of Methodology for DfA 122
7.5.3 Conclusions on DfA Assessment
7.5.3 Conclusions on DfA Assessment 123
7.6 Assessment on Design for Remanufacturing (DfRem) 124
7.6.1 Methodology to Assess DfRem 124

7.6.2 Application of Methodology for DfRem 124
7.6.3 Conclusions of DfRem Assessment 125
7.7 Conclusions on Chapter 7 126

Chapter 8: Designing a Circular Window System

8.1 Establishing Design Requirements 130
8.2 Design Concepts 131
8.2.1 Optimization of RT 82 HI + 131
8.2.1 Hybrid System Variant A 134
8.2.2 Hybrid System Variant B 138
8.3 Improvements through Material Selection 146
8.3.1 Wood Composite Polymers 146
8.3.3 Bio-based Polymer 146
8.3.4 Phenolic Glass Foam 147
8.4 Improvements on Hardware and Other Elements 147
8.4.1 Handle Connection to Frame 148
8.4.2 Addition of a Sensor 149
8.4.3 Redesign of Corner Cleats 149
8.5 Remanufacturing Scenarios 150
8.6 Reuse Scenarios 152
8.6.1 Brick Cavity Façade System and Construction 152
8.6.2 Passive House Façade System and Construction 152
8.6.3 Residential Storey Floor Façade System and Construction 152
8.6.4 Non-Residential Building Façade System and Construction 158
8.6.5 Conclusions on Reuse Scenarios 158
8.7 Adaptability Scenarios: Overcoming the Fear of Change 158
8.7.1 Refittable - Addition of New Functions 158
8.7.2 Refittable - Change of Aesthetics 158
8.7.3 Convertible - Change of Window Area (+/-) 159
8.8 Maintenance and Warranty 163
8.8.1 Types of Maintenance 163
8.8.2 Durability 163
8.8.3 Warranty 164
8.9 Analysis of Thermal Transmittance 164
8.9.1 Simulation Set-Up and Parameters 164
8.9.2 Results for Hybrid System Variant A 165

8.9.3 Results for Hybrid System Variant B 165
8.9.4 Limitations of Thermal Transmittance Simulation 166
8.10 Conclusions on Chapter 8 167

Chapter 9: Conclusions
9.1 Closing the Loop 170
9.2 Answers to the Research Questions 171
9.3 Answers to the Design Questions 175
9.4 Limitations 177
9.5 Recommendations for Further Research 177
9.6 Reflection 178
9.6.1 Graduation process 178
9.6.2 Societal impact 179

Bibliography 184

Appendix

List of Acronyms

CE	Circular Economy
EMF	Ellen MacArthur Foundation
ERN	European Remanufacturing Network
EOL	End-of-life
EOS	End-of-service
DfRem	Design for Remanufacturing
DfD	Design for Disassembly
DfA	Design for Adaptability
PLE	Product Life Extension
WPC	Wood Polymer Composites

01.

Research Framework

This Chapter introduces the background information on the topic and states the problem that motivated the research. The objective(s), research question(s), and design question(s) are stated, along with the focus and limitations. Furthermore, the three different methods applied to the research are explained, along with a reading guide that illustrates the content of each chapter of this report.

List of Figures:

Fig. 1.0 Disposal of windows. Image by colorado.momentumrecycling.com
Fig. 1.1 Triangulation methodology diagram. Image by author.
Fig. 1.2 Reading guide. Image by author.

Figure 1.0 Disposal of windows. Image by colorado.momentumrecycling.com

1.1 Background

The 20th century was characterised by rapid industrialization and continuous economic growth, but mostly, by remarkable technological advancements. Consequently, it is not surprising that the 21st century faces some of the most crucial environmental problems. Scarcity of resources, ecological degradation, pollution, and health issues are only some of the examples. These can be dated back to the existing, outdated, and linear "extract-produce-use-dump material and energy flow model of the modern economic system" (Korhonen et al., 2018), which has been proven highly unsustainable.

The European construction industry is responsible for 35% of generated waste, and even more, a façade system is usually 25-30% of the embodied energy of a building (Michael, 2016). The circular economy is a response to the resource-intensive linear economic model. It implies the reduction of waste to a minimum, and a variety of (re)life options for materials and products to maintain their value and embodied energy. However, in a linear economy, most of the building products are manufactured, in the best case scenario, by taking into account only one (re)life option: recycling.

1.2 Problem Statement

In a circular economy, the components of a façade are designed according to different (re)life options, therefore, there is an alternative to demolition by entering the closed loops.
On the other hand, remanufacturing has been widely recognised as "an important component of a resource efficient manufacturing industry" (ERN, 2016). However, for a product to be remanufacturable, certain principles need to be taken into account during the early design phasesa. Most of the current products are unable to support the model described above. A demand for a design strategy for façade systems taking into account product life extension strategies, especially remanufacturing, of the components can contribute to sustainable, product life extension scenarios.

Kawneer, an American manufacturer of aluminium architectural systems and products, seeks to optimize façade systems to meet the demand for circular building products. This means that the components of the systems should be designed with product properties such as disassembly, adaptability, and remanufacturability, which allows them to be circular. Different (re)life options, such as reuse, remanufacturing, and refurbishment, should also be taken into account from the early design stages.

The RT82HI+ window system is one of the most competent products manufactured by Kawneer. However, the only (re)life option currently available is recycling. Therefore, the product is currently unable to meet the requirements of a circular building product.

1.3 Objective(s)

Considering the problem definition previously stated, the objective of this research is:

O - To evaluate the performance of the existing façade components of the RT82HI+ window system in a circular economy, and according to such, redesign towards remanufacturing and other product-life extension strategies.

From which, the following sub-objectives derive:

SO1 - To understand the relationship and dependency among the product design, development, and product-life extension, especially remanufacturing.

SO2 - To analyse the current lifecycle scenarios of the existing components, and identify their challenges and potentials in a circular economy.

SO3 - To elaborate a benefit analysis, from an economic and environmental point of view, of the remanufacturing of façade components as a long-term sustainable strategy for Kawneer.

1.4 Focus and Limitations

The stated objective will focus on Kawneer's product, the RT82HI+ aluminium window system, which is the main case study of this thesis. There were two main reasons for selecting this system for the presented research. First, it presents a higher level of complexity at a component level, in comparison with curtain wall systems, for example. Additionally to that, window systems are more demanded in the market than curtain wall systems. Secondly, because the previously reviewed works on circular façade systems by Kim (2013), and Leising (2017) were based on curtain walls. Therefore, the author recognised a gap in the field of research towards window systems.

Moreover, the research and redesign is limited towards the frame elements of window systems. This means that other elements from window systems (for instance, insulating glass units) are not a part of the scope of this research. Additionally, the redesign is oriented towards three main different circular design strategies: Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Remanufacturing (DfRem). This last one as the main focus of the research.

1.5 Research Question(s)

To be able to reach the previously stated objective, the following research question is at the core of the investigation:

RQ - How can Kawneer's façade window systems be improved in terms of circular performance, as a long-term sustainable strategy?

From which, the following sub-research questions derive:

SRQ1 - What are the economic and environmental benefits of implementing product-life-extension strategies in window systems, such as repair, reuse, and especially remanufacturing?

SRQ2 - What are the available guidelines for DfRem (Design for Remanufacturing) and which are the circular business models that support it?

SRQ3 - What are the current end-of-life scenarios for the existing elements of the RT 82HI + system, and which could be the circular (re) life options?

SRQ4 - What is the contribution of improving window and façade systems by applying circular economy principles to the built environment at a larger scale?

1.6 Design Questions

Additionally to the research questions, the following design question is formulated:

DQ - How can façade components of the RT 82HI + aluminium window system be redesigned for scenarios of remanufacturing and circularity?

From which, the following sub-design questions derive:

SDQ1 - Which are the elements and connections that can be redesigned for remanufacturing in a circular economy?

SDQ2 - What is the impact of DfRem strategies on production processes for façade components?

SDQ3 - What is the impact of DfRem strategies on the aesthetics of façade components?

1.7 Methodology and Approach

A triangulation methodology consisting on three different methods was used to realise the presented research. This was based on a (1) Literature Review, (2) Interviews, and (3) Making and Testing. The (1) Literature Review comprises studies on the following topics: Circular Economy, Circular Built Environment, Remanufacturing, and Window Systems. The literature was reviewed by coding the text according to its relevance towards the research questions, new and relevant terminology, and understanding the diverse approaches of different authors. The coding was synthesized into text, and is presented in this report: Chapters 1, 2, 3, 4 and 6.

Furthermore, (2) Interviews were carried out in the company, Kawneer, and also with other important stakeholders, such as a representant from Alkondor Hengelo B.V. (client from Kawneer), and two representatives from Kingspan (supplier for Kawneer). The interview technique was face to face, recorded, blind (the interviewed stakeholders were not aware of the questions before), structured interview, later transcribed into a minute, where the most important findings are written in Chapter 5, and the complete text can be found in the Appendix Section.

The last method was (3) Making and Testing, which consisted of a physical analysis of the window system, especially regarding the disassembly potential, and assessments on DfD, DfA and DfRem. The (1) Literature Review and the (2) Interviews served as main input criteria to do a further analysis and redesign the components. This iterative assessment was aided by an inductive probe, a redesign discussion with the mentors where notes, CAD models and drawings were presented. This was mostly documented in Chapters 7 and 8 of the report.

This triangulation of methods allowed to have an integral research and design, in order to have a more detailed and complete approach of the subjects. Figure 1.1 illustrates the methodology. Figure 1.2 is a reading guide to assist the understanding of the Chapters and their content.

1.8 Relevance

It has been thoroughly proven that the shift from the linear to the circular economy is a radical, yet necessary transition. Remanufacturing is considered a highly important process in the manufacturing industry that uses resources efficiently. Additionally, it follows the Ellen MacArthur Foundation key

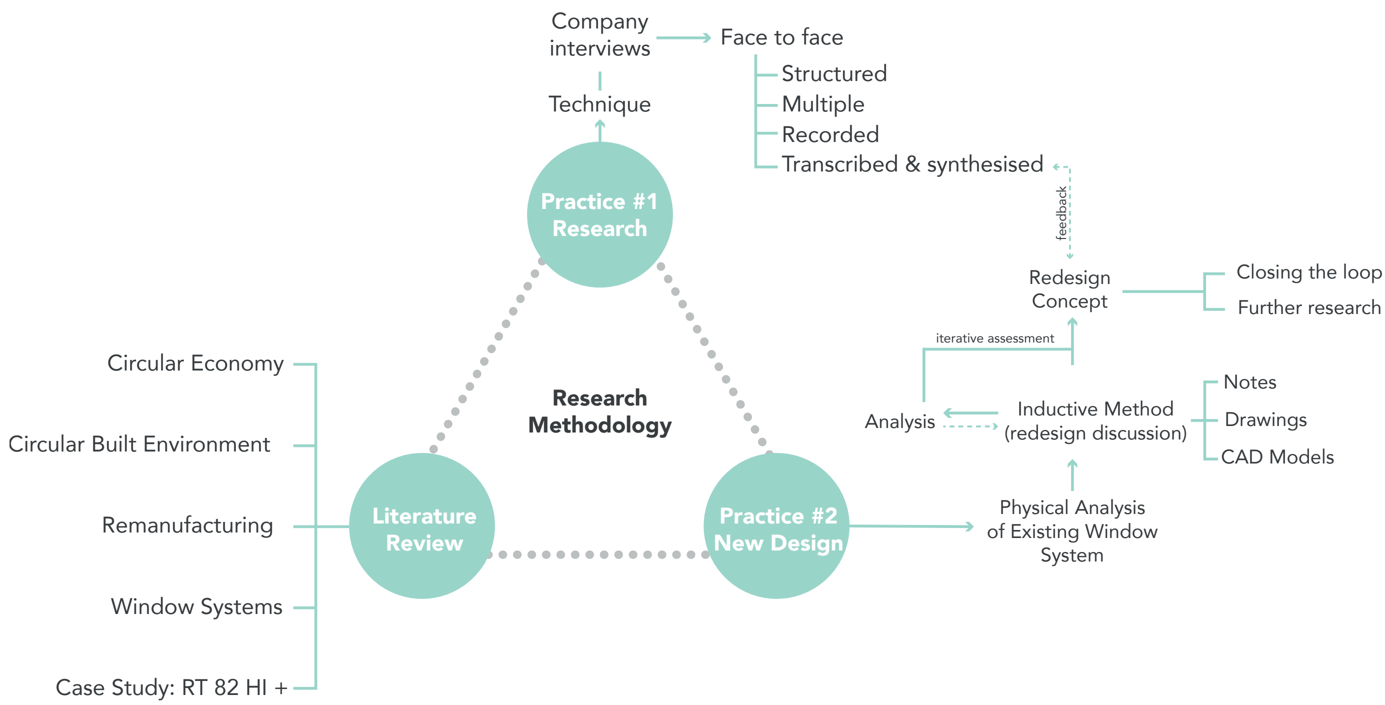


Figure 1.1 Triangulation methodology diagram. Image by author.

principles of a circular economy (2013): “think in systems”, “design out of waste”, “think in cascades”. An important objective for the government of the Netherlands is that the country runs in a circular economy by 2050. Once this is achieved, it is expected that the resource consumption of raw materials will decrease by 50%.

However, for building products to be part of a circular economy, they have to be designed under such principles, particularly in the case of remanufacturing. Therefore, this research aspires to understand the current state of the art in window systems, and the way these systems can shift towards circular design.

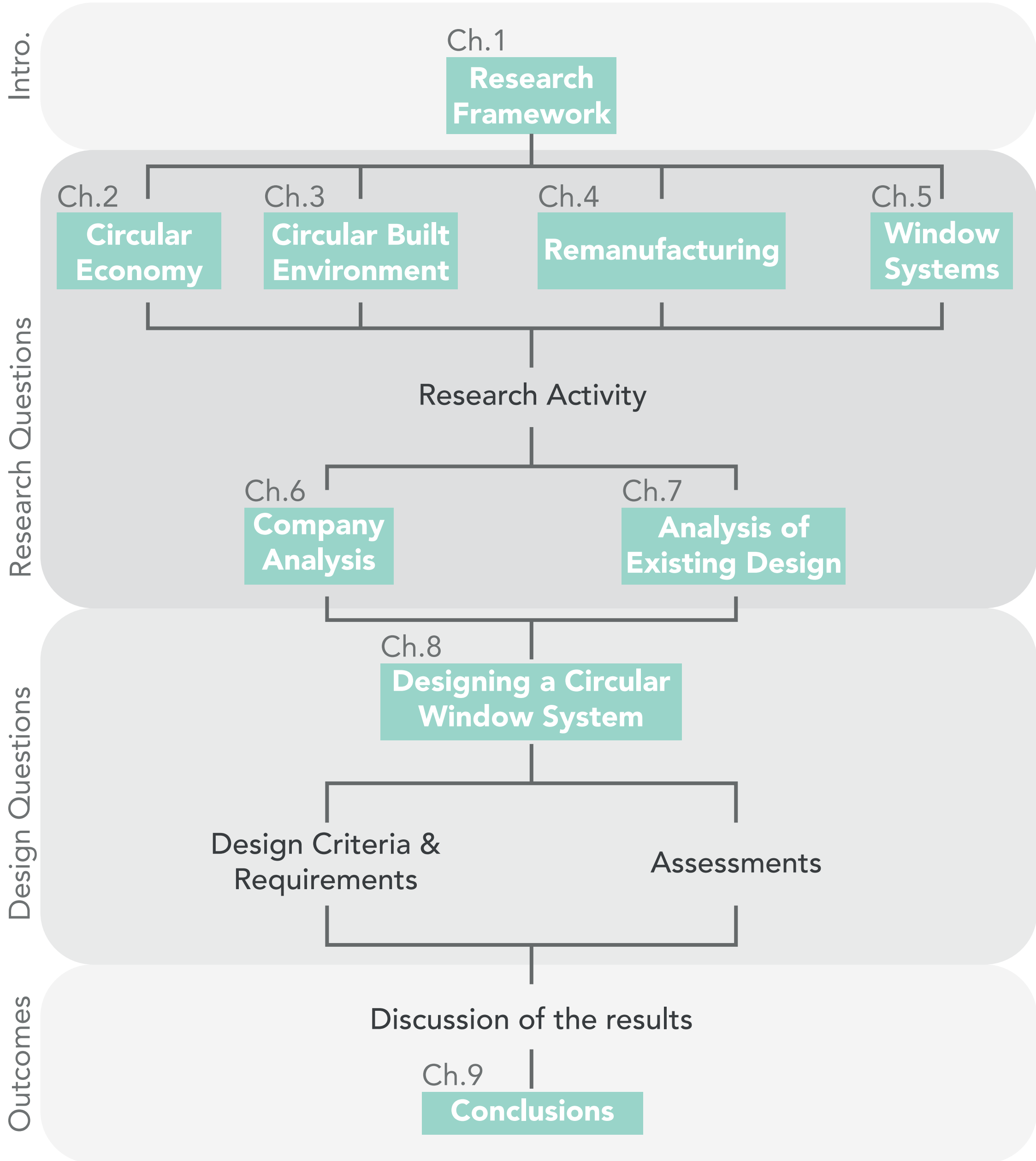


Figure 1.2 Reading guide. Image by author.

02.

Circular Economy

This Chapter introduces the first part of the literature review: the concept of a circular economy. The core of this research was based on the framework by the Ellen MacArthur Foundation. Section 2.1 explains the five main principles of a circular economy. Section 2.3 explains how the butterfly diagram illustrates the principles behind a circular economy. Sections 2.4 and 2.5 explain related principles and schools of thought that might have influenced the framework of the EMF. Finally, Section 2.6 explains the different circular business models and strategies.

List of Figures:

Fig. 2.0 Façade of Bloomberg's headquarters. Image by archdaily.com
Fig. 2.1 Hierarchy of value generation. Image by author.
Fig. 2.2 The Butterfly Diagram. Image by EMF (2013).
Fig. 2.3 Types of loops. Image by Bocken et al. (2015)
Fig. 2.4 Design strategies for slowing resource loops. Image by author.

Figure 2.0 Façade of Bloomberg's headquarters. Image by archdaily.com

2.1 What is a Circular Economy?

The concept of a circular economy has been thoroughly discussed by scholars as early as 1996 by Pearce and Turner. Their research proposed a closed loop system, which leads to other studies in the field and additional interpretations. Further on, the Ellen MacArthur Foundation (EMF) introduced the concept of a Circular Economy in 2010. Such consists of a model of closed loops. As explained by Beurskens and Bakx (2015), "this model is based on living systems as these have proved to be adaptable and resilient, and model the waste equals food relationship very well. The definition of a circular economy proposed by the EMF is as follows:

> *"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems and, within this, business models". (EMF, 2013)*

This definition implies that there is constant conservation of economic and ecological value of both materials and products. This is due to the different types of closed loops that aim to reuse materials and components by allowing them to fall back into the different cycles. The EMF recognises two types of materials in the circular economy: biological and technical. In the first case, the biological cycle's residuals fall back into the biosphere naturally, transforming into natural capital. This principle is similar to the "waste equals food" from the Cradle-to-Cradle model. On the other hand, the technical materials, for instance, fossil fuels, plastics and metals, are finite. The focus is towards the retention of the value and recovering after residual streams.

2.2 The Principles of a Circular Economy

Five main principles established by the EMF (2013) are at the core of a circular economy, and allow it to operate. They are synthesised as follows according to (EMF, 2013):

I. Design out of waste: "Waste does not exist when components are seen as nutrients for the biological or technical material cycles. The product should be designed for remarketing, remanufacture, disassembly, or repurposing. (...) technical nutrients should be designed to be recoverable, refreshable, and upgradable, minimizing the energy input required and maximizing the retention of value".

II. Build resilience through diversity: "Modularity, versatility and adaptivity are prized features that need to be prioritised in an uncertain and fast-evolving world. Production systems should be flexible, able to use many different inputs".

III. Shift to renewable energy resources: "Systems should ultimately aim to run on renewable energy, enabled by the reduced threshold energy levels required by a restorative, circular economy".

IV. Think in systems: "The ability to understand how parts influence one another within a whole, and the relation of the whole to the parts, is crucial. Elements are considered in relation to their environmental and social contexts."

V. Think in cascades: For biological materials, the essence of value creation lies in the opportunity to extract additional value from products and materials by cascading them through other operations".

2.3 The Butterfly Diagram

The Butterfly diagram (Figure 2.2) explains the different biological and technical cycles, and their different loops throughout the economical system. The technical cycles are the core of the presented research, as the materials from the built environment fall into this category. The initial principle is that the tighter the loop, the higher the value retained in the material and/or component. This means that as the loops expand to the outer circles, the value decreases. The EMF establishes that to retain the highest value of the product, there is a hierarchy of value generation. This is depicted in Figure 2.1, and explained as follows: (synthesised from EMF, 2013):

I. Maintenance: Understood as a scheduled regular activity, maintenance is the first and easiest step to retain the product's value. Inspection or service tasks, such as cleaning or tuning the components can even be performed by the user if the manufacturer supplied maintenance instructions.
II. Repair: A product or component is restored after damage or decay.
III. Recondition / Refurbishment: Replacing, rebuilding or repairing major failed components, or close to failure. This activity is a series of constant repairs and maintenance cycles.
IV. Reuse / Redistribution: If a product is in good conditions, without the need for refurbishment, it can redistributed to a new user. Minimal maintenance and cosmetic cleaning can be a part of this process.
V. Upgrade: Parts or components from a product are changed to improve the value, quality or performance of the product. This allows it to continue its service life, and prevents it from becoming obsolete.
VI. Remanufacture: The product is disassembled, cleaned, inspected; and the parts are reconditioned or replenished. The product is then reassembled, and it should return, at least, to its original performance, and with the warranty that it is equal or better than initially. This process will be further explained in detail on Chapter 4.
VII. Recycling: A product is disassembled, and the different parts are classified according to their materials. The materials are recovered and re-introduced as crude feedstock.
VIII. Energy Recovery: The embodied (or at least a part of it) energy can be retrieved before a product is dismissed.
IX. Disposal: This is the last resource in the technical materials flow. The other loops should serve as first options before recurring to the disposal of a product.

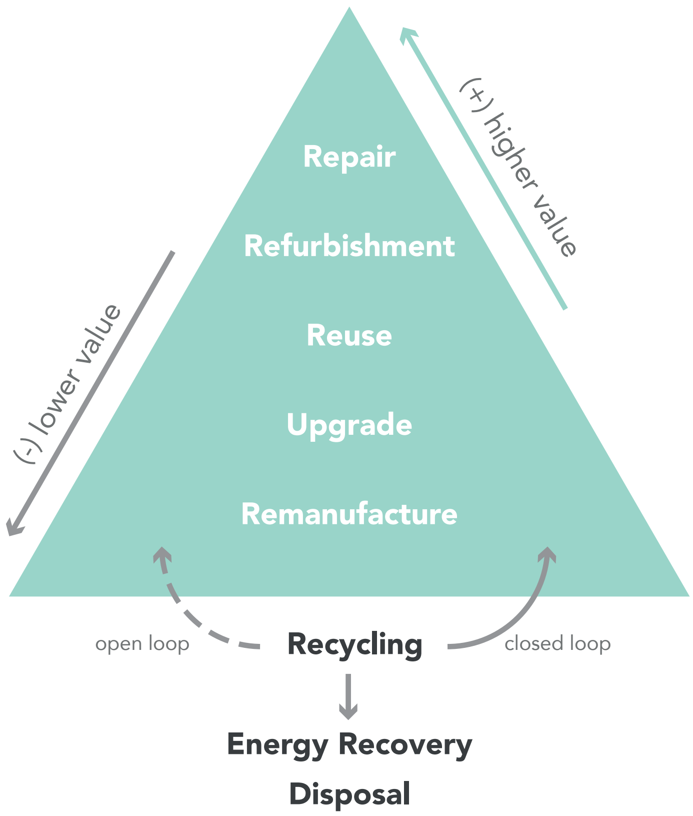


Figure 2.1 Hierarchy of value generation. Image by author.

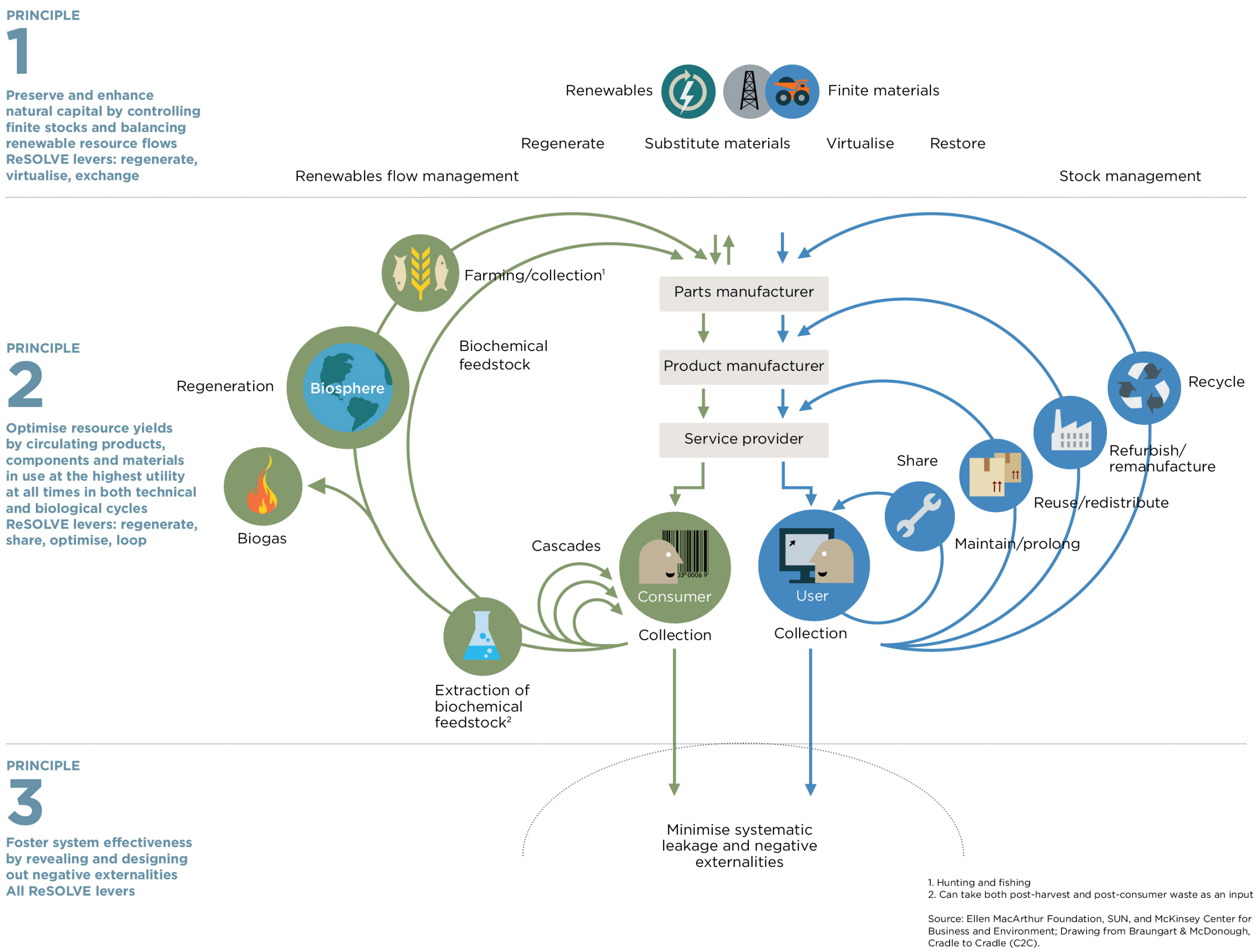


Figure 2.2 The Butterfly Diagram. Image by EMF (2013).

2.4 Related Schools of Thought

Through the last decades, different schools of thought with principles on efficient use of resources, waste reduction and closed-loops, have established certain foundations related to the circular economy. The most relevant are briefly explained (synthesised from EMF, 2013, Leising, 2017):

I. Regenerative Design: Developed by John T. Lule in the 1970s, it establishes that all processes within all systems renew or regenerate their own sources of energy and materials that are consumed. The needs of a society are satisfied within nature's own limits.

II. Performance Economy: Product-life extension, long-life gooWds, reconditioning activities, and waste prevention were some of the principles established by Stahel in his own vision of an economy that worked in loops. Consumers will buy serviced instead of goods, as they will pay for the performance of a product that is delivered. Because ownership is prevented, resources can be used much more efficiently, and waste production is much more controlled.

III. Cradle-to-Cradle: Braungart and McDonough published a book in 2002 explaining a model where materials, in both industrial and commercial cycles, are understood as nutrients. Thus, the entire life-cycle of the product and its materials are considered since the early design process. Some of the relevant principles from the Cradle-to-Cradle are "waste equals good", "celebrate diversity", "use solar income", "separate bio-and technocycle", eco-effectiveness over eco-efficiency".

IV. Industrial Ecology: Refers to the study of energy and material flows in industrial systems. Production processes are understood as living systems where the waste of one might become the input for another system.

V. Biomimicry: Developed by Janine Benyus, it is an approach where humans and processes seek solutions in nature's design. Thus, nature becomes a model (imitation and learning), nature is a measure (norms), and nature is also a mentor (value). This comes from the three point approach to human challenges: society, economy and the environment.

VI. Blue Economy: An economic philosophy by Gunter Pauli, it gains knowledge from the way natural systems are formed, their production, and their consumption. A cascading principle establishes that one's output is another's input.

2.5 Related Principles to CE

Additionally, there are other principles that have a close relationship with a circular economy. Many authors argue that the I-VI principles explained in Section 2.3 are strategies for product life extension (PLE). Furthermore, Bocken et al (2016) distinguishes between two fundamental strategies towards the cycling of resources, as depicted in Figure 2.3:

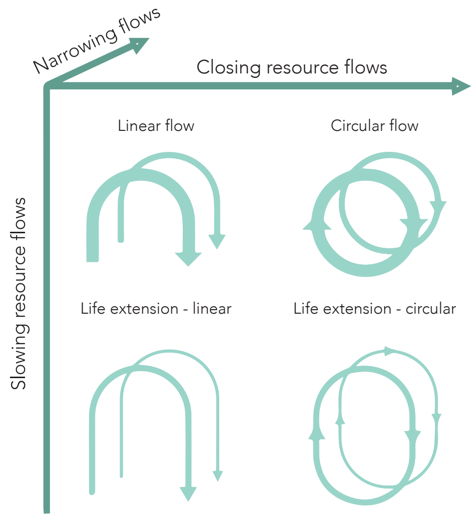


Figure 2.3 Types of loops. Image by author, derived from Bocken et al. (2015)

I. Slowing resource loops: Through the design of long-life goods and product-life extension (i.e. service loops to extend a product's life, for instance through repair, remanufacturing), the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources. Figure 2.4 depicts the different design strategies for slowing resource loops.

II. Closing resource loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources.

Figure 2.4 Design strategies for slowing resource loops. Image by author.

2.6 Circular Business Models and Strategies

Shifting from a linear to a circular economy is one of the most radical changes expected in the 21st century. However, this shift will also impact the way business is made. As technology progresses, business models do so as well. The author has reviewed the work from Boken et al. (2016) and Bakker et al. (2014), which follow the approach between slowing resource loops, and closing resource loops, as it was explained in Section 2.5. For the purpose of the presented research, the focus will be towards slowing resource loops. Three key business model strategies for slowing resource loops are developed by the authors: Access and performance model, Extending product value, and Classic long-life model and encourage sufficiency.

I. Access and performance model: Also known as "Product Service Systems" (PSS), it refers to "a combination of products and services that seek to provide this capability or functionality for consumers while reducing environmental impact is often used to refer to this type of business model and "deliver capability rather than ownership" (Boken et al., 2016). This business model focuses on delivering services instead of the traditional ownership model. The service (cleaning, regular maintenance, and monitoring) is done by the manufacturer or a retailer. The value is created per unit of service. For instance, a laundrette where the customer will pay per washing instead than for the washing machine itself. This product is ideal in a circular economy, because the costs for life-extension are covered by the operating company. They will benefit from this because they can use the product longer. In this model, the customer is able to reduce costs if they reduce the use of a product, and the manufacturer have larger profits from durability, energy efficiency, and reparability. This means that the model itself is able to introduce incentives for slowing resource loops for both the customer and the manufacturer. By nature, it also reduces the need for appliances and goods.

II. Extending product value: This is a model "concerned with exploiting the residual value of products" (Boken et al., 2016). A good example would be when products are recovered at their end-of-service to remanufacture them. This implies the reduction in consumption of new materials, and only energy used for transportation and processing. Remanufacturing is usually done by the original manufacturer. This is highly valuable for the consumer because they are able to purchase affordable products that are "as good as new". It is important to establish services that allow the remanufacturers to have access to the products. Therefore, collection, logistics and labour are important key factors in this process. However, manufacturers have to develop their products in line with reuse and remanufacturing.

III. Classic long-life model and encourage sufficiency: This model focuses mainly on designing long-lasting products. Thus the design is oriented towards durability and high levels of service (maintenance, repairness, cleaning, etc). These are often known as "premium" products, because their costs will cover a prolonged warranty period and long-term service. These costs are absorbed by the manufacturer. Similarly, encourage sufficiency refers to "solutions that actively seek to reduce end-user consumption, in particular through a non-consumerist approach to promotion and sales" (Boken et al., 2016). The principle is as simple as: if users have a products that last as long as possible, they will hold on to them for a longer time. This implies high-levels of service. The approach towards sales by the company is a non-consumerist approach. There are less sales of high quality products, rather than massive sales on products that become obsolete quickly. This business model has proven to encourage an efficient use of resources, promoting a sustainable lifestyle, customer loyalty, as well as encouraging the service industry.

2.7 Conclusions on Chapter 2

The current linear economy model, based on "extract-produce-use-dump" (Korhonen et al., 2018) has proven to be highly unsustainable. The core of this argument lies on the fact that resources are finite, and thus it is unable to meet the environmental challenges of the 21st century. A circular economy model is based on a cyclical flow mode, restorative by design. Energy, labour, and materials are retained through the extension of a product's life, and the principle of treating all materials and components as a valuable source minimize the creation of waste. The framework established by the EMF is at the core of the research, enriched by studies in the similar field that contribute strategic guidelines on the concept.

The five different principles that make the circular economy functional were also explained: design out of waste, build resilience through diversity, shift to renewable energy sources, think in systems and think in cascades. Additionally, the butterfly diagram that makes a distinction between the biological and the technical was analysed. Particular attention was given to the technical cycles because the majority of the materials from the built environment fall into such category. From such, eight different processed are explained: maintenance, repair, refurbishment, reuse, upgrade, remanufacture, recycling, energy recovery, disposal. These different processes can also be classified into two different types of loops in a Circular Economy: slowing resource loops, and closing resource loops.

Moreover, the related schools of thought to the circular economy are briefly explained: regenerative design, performance economy, Cradle-to-Cradle, industrial ecology, biomimicry, and blue economy have all served as initial examples where resource efficiency, waste reduction, and closed loops are the main principles.

03.

Circular Built Environment

This Chapter explains the second part of the literature review, the concept of a Circular Built Environment (CBE). The first Section introduces the theory of levels from Brand (1994). Section 3.2 and 3.4 explain the hierarchical range of industrial building products and material building levels. Furthermore, Section 3.4 discusses the different building product levels, and Section 3.5 explains the main circular building design principles. From this, Section 2.6 and Section 3.7 derive, explaining the principles of Design for Disassembly (DfD) and Design for Adaptability (DfA). Additionally, Section 3.8 explains the circular construction domain.

List of Figures:

Figure 3.0 Façade of Valletta City Gate. Image by designboom.com
Fig. 3.1 CBE Diagram. Image by tudelft.nl
Fig. 3.2 Shearing layers of change. Image by Nederland Circulair (2019)
Fig. 3.3 Hierarchy of building products. Image by Beurskens et Bakx (2015)
Fig. 3.4 Design domain - circular building design principles. Image by Beurskens et Bakx (2015).
Fig. 3.5 Circular building construction model by Beurskens et Bakx (2015), based on the butterfly diagram by the EMF (2013).

Figure 3.0 Façade of Valletta City Gate. Image by designboom.com

3.1 The theory of levels

A Circular Built Environment (CBE) can be understood as a series of different levels: from materials, to components, buildings, and cities; circular design is present on all of these, integrating through technology, flows and resources, society and stakeholders, economy, and management. Figure 3.1 illustrates these relationships. More importantly, a CBE understands that design has another dimension that is not taken into account in a linear economy: time.

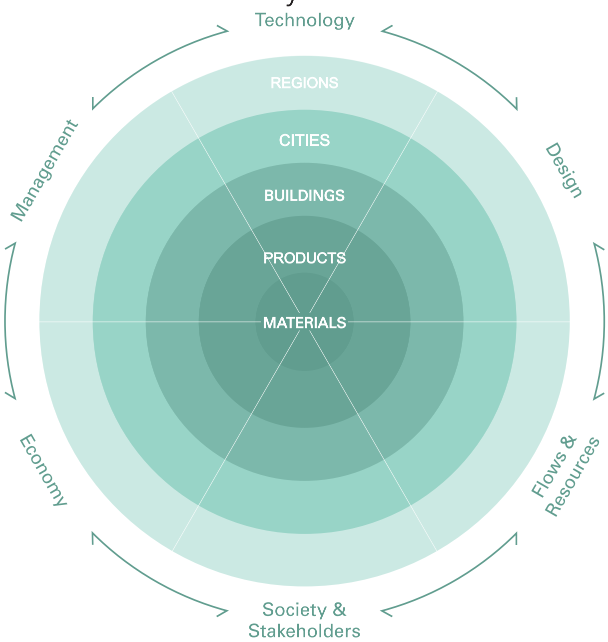


Figure 3.1 CBE Diagram. Image by https://www.tudelft.nl/bk/onderzoek/onderzoeksthemas/circular-built-environment/

A continuous problem seen in the built environment is that buildings are designed as static entities. However, buildings should be able to have a long-term adaptability to the different time frames, changing environmental conditions, and consider the needs of new users. Thus, a building should be understood as "a series of different buildings over time" (Beurskens et Bakx, 2015). However, this conception is not new. Stewart Brand (1994) attempted to integrate time into design, and aspired to define a framework where the built environment can evolve and age gracefully. He identified six different layers of change: site (eternal), structure (30-300 years), skin (20 years), service (7-15 years), space plan (3-30 years), and stuff (daily). His conception of these different layers that are in constant change through time are an important tool for designers to understand the different life-cycles of each layers, and to design them to be independent from each other. Figure 3.2 depicts the shearing layers of change according to Brand (1994).

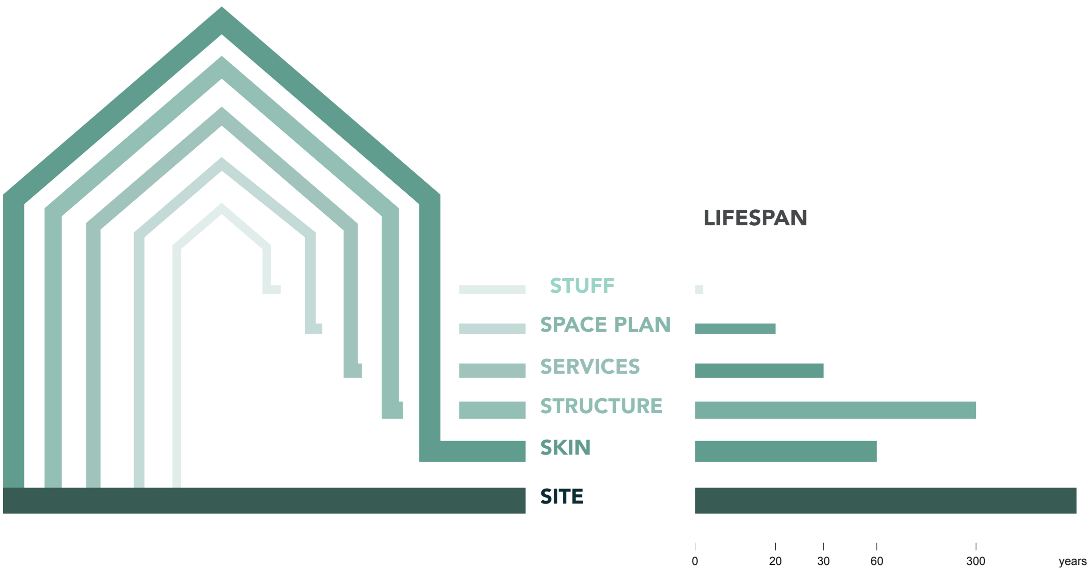


Figure 3.2 Shearing layers of change. Image by author, derived from Nederland Circulair (2019).

3.2 Hierarchical Range of Industrial Building Products

The hierarchical range of industrial building products was developed by Eekhout (2008), further studied by Klein (2013) and adapted to the façade discipline. Figure 3.3 depicts the hierarchical range of industrial building products. Such framework consists of a range that starts with "raw materials" and finished with "building complex". A "range" is a set of items with a defined lowest and highest boundary. The different steps required in the range recieve the name of "product levels". Klein (2013), based on Eekhout (2008) classified the following product levels:

- A **"material"** is understood as the base ingredient that does not require any further production process. Examples include glass or steel. Composite materials can also fall into this category.
- A **"standard material"** is defined as an intermediate good, accessible in standardised forms. For instance, I-beams, tubes, coils, or bricks.
- A **"commercial material"** is the one shaped with a particular purpose of product or project. Examples include extruded aluminium profiles, or rubber gaskets. Both are specifically designed for a particular purpose
- **"Elements"** are understood as different commercial materials. For instance, an insulated glass consists of glass panes, aluminium spacers and silicone.
- A **"sub-component"** refers to a closed assembly of elements with single functional purposes. Examples include window frames, sun-shading devices, etc.
- A **"component"** is described as "an independent functioning building unit, built up from a number of composing elements. Components are assembled off-site, and transported to the site" (Klein, 2013). A good example will be a unitised façade panel.
- A **"building part"** is a collection of elements and components that have the same technical primary function. For instance, a curtain wall, or the primary structure of a building.

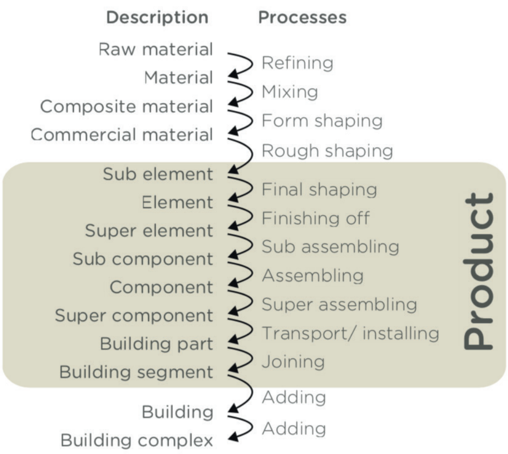


Figure 3.3 Hierarchy of building products. Image by Beurskens et Bakx (2015)

3.3 Hierarchical Range of Material Building Levels

Similar to the previously explained hierarchy from Eekhout (2008), Durmisevic developed an additional framework to understand the technical and physical levels from a building, aside from the functional ones. A deconstructable building structure should be conceived by the designer if there is a full understanding of the hierarchy of such sub-assemblies. This hierarchy of material levels is divided as follows:

- **Building level:** Refers to the group of systems that carry out the main functions of the building, such as enclosure, partitioning, load-bearing, etc.
- **System level:** Refers to the components that carry the system functions. For instance, insulation, finishing, distributing, etc.
- **Component level:** Refers to the assembly of component functions. These are designated through the elements and materials at the lowest level of building assembly.

For instance, in the case of a façade, and according to Brand, its average life-cycle is 20 years, yet the façade consists of different components with different life-cycles. This means that the relationship between the components and materials should be independent from each other to allow easy deconstruction and maintenance. Durmisevic (2006) might be a simpler guide throughout these processes, and it also contains less levels than in Eekhout's (2008) hierarchy.

3.4 Circular Building Product Levels

However, as the analysis and approaches developed by the previous authors (Brand, 1994; Eekhout, 2008; Klein, 2013; Durmisevic, 2006) have proven to be important principles for circular building design, Beurskens et Bakx (2015) recognized the need for an even more specific framework, referred to as "circular building product levels". Such study is also based in three of the previously mentioned authors (Brand, 1994; Eekhout, 2008; and Durmisevic 2006). This approach is also parallel to the "think in systems" principle from the EMF. The "circular building product levels are derived as follows (from top to bottom), derived from (Beurskens et Bakx, 2015):

The building is the assembly of all building systems. From such the following levels derive: "Building Level" (B.): One building divided into building systems. Such systems are strongly linked to the layers of change approach developed by Brand (1994). The four layers of structure, skin, service and space plan are conceived as building systems, and the main systems to be considered in a design of circular building. The "system Level" (S.): derives from the selection of a building level. This system is further on divided on "sub-system level" (SS.). Such system is divided in "component level (C.)", which is then divided into "element level (E.)", and last, the "material level (M.)".

This approach was developed as a guide for designers to understand the different systems of a layer, and to understand their relationship towards change over time and functions. It aims to solve the gap between the abstract principles of the circular economy by the EMF, and applying them towards circular building design.

3.5 Circular Building Design Principles

However, as many designers are familiar with the circular principles described in Chapter 1, there seems to be a gap between these abstract concepts and their applications in the built environment. As a reaction to such, Beurskens et Bakx (2015) established five circular building design principles that are closely related to the circular economy principles from the EMF (2013): be self-sustaining with renewable energy, stimulate diversity, design with sustainable materials, design for disassembly, and design for adaptability, depicted in Figure 3.4. The principles of "Design for Disassembly"(DfD) and "Design for Adaptability" (DfA) are at the core of this research framework, and thus they will be explained in detail, in a separate Section.

I. Be self-sustaining with renewable energy: Such guideline is parallel to the Ellen MacArthur Foundation (2013) principle of "shift to renewable energy sources", along with the Cradle to Cradle "use current solar income" (McDonough et Braungart 2002). By following this principle, buildings do not deplete non-renewable energy sources and reduce the greenhouse gas emissions in the operational phase.

II. Stimulate diversity: This guideline follows also the circular economy principle from the Ellen MacArthur Foundation (2013) "build resilience through diversity", and also the "celebrate diversity" guideline from the Cradle to Cradle framework built by McDonough et Braungart (2002). This guideline consists of two main concepts: biodiversity and conceptual diversity. The first refers to supporting species diversity before development; whereas the latter is regarding the contribution of buildings to the well-being of occupants and their surroundings. Thus, stating that circular buildings should have a positive impact on the environment and the involved stakeholders.

III. Design with sustainable materials: Resource scarcity is one of the most critical problems faced during the 21st century. Availability of materials for construction is an issue that can be addressed since the early design phase. Durable materials that can be reused or recycled is one of the few examples that follow this principle. However, the definition of "sustainable materials" is still a term that has not yet reached a global definition. Yet, it can be strongly linked with the circular economy principles "design out of waste", "think in cascades" and it might also involve "think in systems". It is also parallel to the "waste equals food" principle established by McDonough et Braungart (2002).

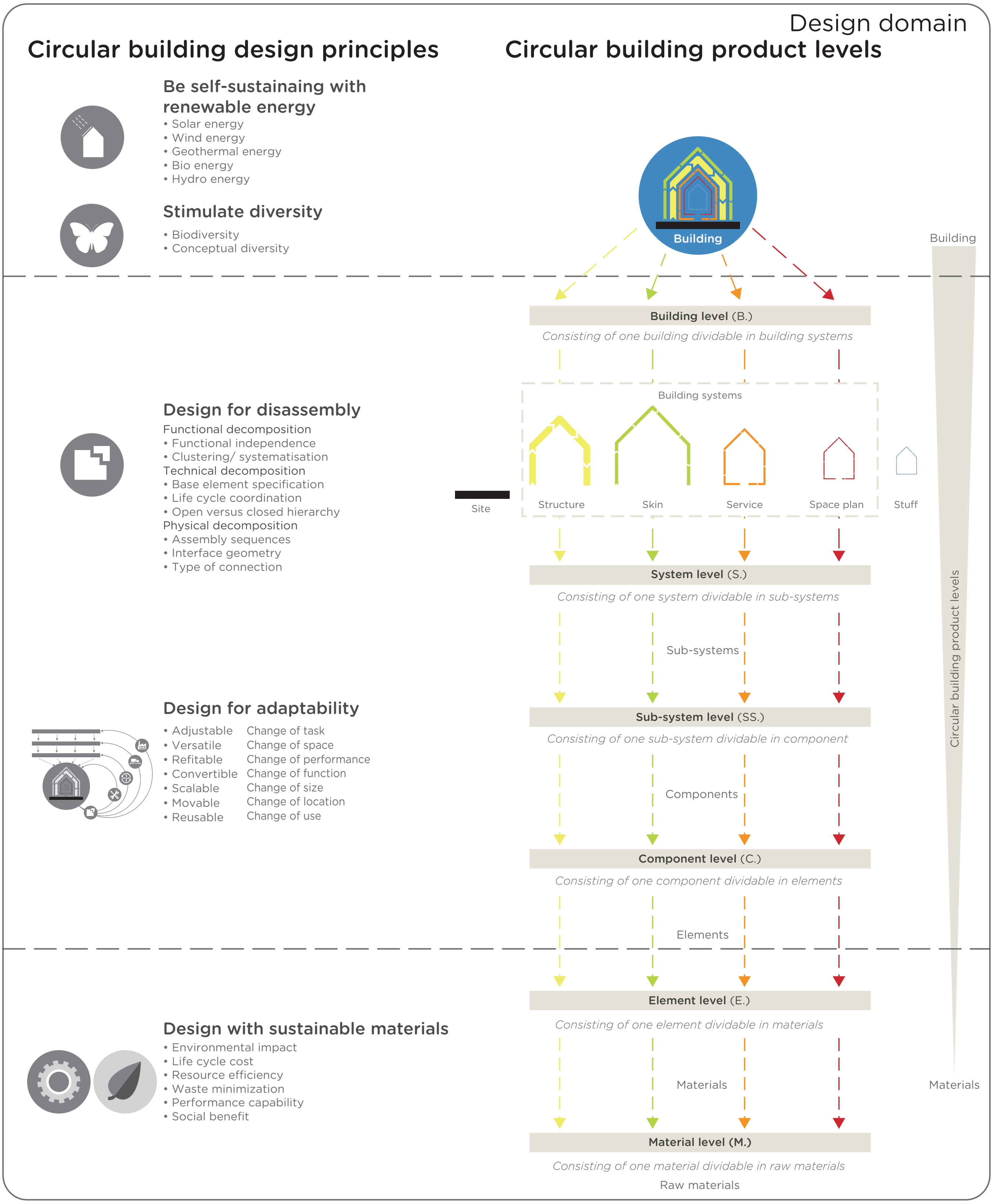


Figure 3.4 Design domain - circular building design principles. Image by Beurskens et Bakx (2015).

3.6 Design for Disassembly (DfD)

Design for Disassembly (DfD) Is a concept where products and buildings are carefully designed for material recovery, value retention, and a meaningful next use. Building components would be able to reach their end-of-service without compromising their end-of-life This means that by disassembling the components, the embodied value is retained and the component can have multiple re(life) options, and by consequence, decreasing the building's industry waste generation. Nevertheless, one of the main barriers towards this type of approach is that components and products are not designed to be easily dismantled, deconstructed, or disassembled. DfD is an approach that "enables products, systems, and components to be carefully and methodically decomposed to recover as many parts as possible" (Deniz and Dogan, 2017).

3.6.1 Available guidelines for Design for Disassembly

Being such a broad topic that can be applied to different disciplines, and also due to its design nature, there is not a single, straight answer. Nevertheless, there are available guidelines that can serve as an initial basis for DfD.The author has synthesised the DfD principles according to the literature review of Deniz and Dogan (2017), Mule (2012), and Durmisevic (2006). As in the framework established by Mule (2012), the summary comprises three different categories: Material selection, Fasteners and connections, and Product structure and component design, as shown in Table 3.1:

Material Selection	• Use as few different materials as possible • Materials that minimize pollution during extraction, processing, deployment, and recycling should be selected • Make inseparable subassemblies from the same material • Avoid secondary finishes, adhesives, and coatings • Material types should have a standard identification • Materials should have a high degree of durability to guarantee that they can withstand the disassembly and have different (re)life options. • Lightweight materials will make both the disassembling, and the transportation easier.
Fasteners and Connections	• Should enable easy and quick disassembly • Use mechanical connections rather than chemical ones • Use joint systems that are used in the standard building practice • Use a minimum number of different types of connections and fasteners • Joints and connections should be able to withstand repeated use • They should be compatible with common hand tools for disassembly. • Specialist technologies should be avoided. • Reduced fastener count and diversity
Product Structure and Component Design	• Overall simplification and standardization of all components through modular, prefabricated systems with a structural grid. • Minimum number of components and connections • Parallel deconstruction should be possible • Open building systems where parts are interchangeable • Assembly methods and sequences should be standard • The system should be designed under a hierarchy of disassembly related to the overall life span of the parts. • All the information on the building manufacturing, along with the assembly and disassembly sequence, should be provided • Selection of components should combine durability and weather control with adaptation and reusability for façades. They should be able to resist the impact of weather. • Trapped building services within the skin should be avoided at all costs. • Inseparable components from the same material will avoid contamination by other materials

Table 3.1 Synthesis of the found guidelines on Design for Disassembly based on Deniz and Dogan (2017), Mule (2012), and Durmisevic (2006)

3.6.2 The Impact of DfD in the Built Environment

DfD in the built environment implies that buildings are understood as a series of independent subsystems, parallel to Brand's (1994) approach. Thus, the skin of the building has a high potential for disassembling, as, according to his theory, it has one of the shortest life cycles, and it can also represent up to 30% of the total embodied energy of the building. Disassembling a façade to recover the different materials and components must be considered as one of the main resources in waste management.

Beurskens and Baxk (2015) recognised DfD under the circular building design principles as "the concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guarantee of the possibility, of all circular building product levels to undergo different (re)life options in a hierarchical way, achieved by implementation of disassembly determining factors in building design". Framing upon such definition, and according to Deniz and Dogan (2017), DfD will potentially increase resource and economic performance, it will reduce the ecological footprint, and will provide different scenarios for reuse, remanufacturing, and recycling. Guy and Shell (2002) described that a continuous practice of DfD in the Built Environment will transform buildings into material banks, which will later on serve as primary sources, instead of mining and harvesting virgin feedstock.

A façade can be structured according to a pattern of functional decomposition, and then into different sub-functions that allow it to perform correctly against weather conditions. There also other subfunctions, such as support, control and finishing. The assembly and disassembly sequences of a façade might cause dependencies between its components, and they might affect their ability to be dismantled. Plain, mechanical joints and connections might improve the disassembly potential, along with other simple guidelines related to material selection, and product structure and component design. A façade that is designed for disassembly, where carefully and methodically system parts are recovered as much as possible, is an alternative to demolition. They can enter other (re)life options such as reuse, remanufacturing, and recycling. Because DfD is also an strategy that helps to retain the embodied energy of the components, reuse and remanufacturing are the most desired scenarios. It allows to construct competent recovery methods. It is also one of the most powerful tools towards prevention of material waste.

3.7 Design for Adaptability (DfA)

The guideline is a response towards the constant change in buildings. These should respond as adaptable and resilient as living systems. Thus, this design principle reacts upon changing demands and user requirements. Like the previously explained principle of DfD, DfA is much more efficient if taken into account during the design stage. DfA is also a design principle parallel to the "build resilience through diversity", and taken into account by "think in systems" (Ellen MacArthur Foundation 2013).

As stated by Beurskens and Bakx (2015), "adaptability starts with the understanding of time in architecture". The definition of such principle, applied to a CBE is "the concept of designing buildings with the capacity to accommodate effectively the evolving demands of its context, in which its building products are designed to maximize reusability in initial- and other buildings, to minimize value destruction and thus maximize value through life" (Beurskens and Bakx, 2015). Time needs to be considered as a characteristic in design. To do so, architects and designers need to locate buildings and building products in a context, along with the different changing scenarios it might face throughout its life.

3.7.1 Available Guidelines for DfA

Gereadts et al. (2014) establishes that adaptability comprises three different categories of flexibility, which are:

I. Organizational flexibility: The potential an organization, or a group of users, have to respond towards the changing demands of the built environment.
II. Process flexibility: The ability to react upon dynamic conditions, wishes, or demands throughout

the different phases of building: conceptual phase, design phase, and construction phase.
III. Product flexibility: The capability of a building product to react upon changing conditions, wishes, or demands during the use phase of a building.

Additional to the research of Gereadts et al. (2014), Schmidt (2014) reviews six different adaptability strategies. Beurskens and Bakx (2015) added to Schmidt's (2014) framework a new adaptability strategy: reusable. These strategies are presented in Table 3.2.

Adjustable	The building should be capable of changing its tasks. Non-fixed objects, detachable connections, and operable elements are some examples of this.
Versatile	The ability of a building to change the space. For instance, moveable walls, different room sizes, and frame construction
Refitable	The capability of a building to change its performance. It includes standard shapes, dry connections, access points, among other similar examples.
Convertible	The building should be able to change its function. For instance, loose floors, simple designs, and multifunctional spaces.
Scalable	The ability of a building to change its size. Modularity, divadable rooms, and common product platforms are some of the main examples.
Movable	The capability of a building to change its location. Deconstructable structures, easy connections, or deployability are some of the key aspects.
Reusable	Refers to the ability of building products to change their use to maximize the potential of reusing and minimize value destruction.

Table 3.2 Synthesis of the found guidelines on Design for Adaptability based on Schmidt (2014) and Beurskens and Bakx (2015).

3.7.2 The Impact of DfA in the Built Environment

The need for adaptable buildings has been thoroughly discussed in the past decades, especially in terms of functional and technical performance. The value of DfA applied to a CBE relies on its capability to accommodate future changes that offer high flexibility and economical solutions, different (re) life options when a component or product reaches its end-of-service, and the prevention of discarding building or products because they become obsolete (de Hollander, 2018), (Beurskens and Bakx, 2015). Adaptability is also an important value that will provide a product-life extension principle, because a product or building is able to adapt to change, and overcome it, its value is retained for longer, together with the embodied energy within it. For instance, changing regulations have been one of the main reasons façades have to be replaced. However, if a façade is designed for adaptability, without anticipating the future, but through the use of a modular design, or through convertible assets, the façade can easily be upgraded. This is a huge alternative for demolition or replacement of an existing façade.

If during the early design stages, adaptability is taken into account, the product is able to face obsolescence and enter other (re)life options, which will prevent it from being discarded. Additional to this, adaptability is seen as a key characteristic to the ever changing built environment. However, there are several possible drawbacks. The first one, and most relevant, is the lack of demand for a building to be adaptable. In a linear economy, adaptability is not seen as an important aspect of a product; on the contrary, if a product is required to be constantly replaced, it stimulates the linear flow of such economy. It is also difficult to understand why someone would invest in a façade that can be adaptable if such transformations might come in ten, fifteen, or twenty years. There is no scientific data that enables predicting when a façade will go under a transformation. There is still a long way to go to apply DfA in the area of façade design, especially if a transition towards a CE is to be achieved. The second one is that adaptability might require over dimensioning of components and buildings, which could be translated to a building industry more material intensive. However, this might be justified because products and buildings would be longer in use.

3.8 Circular Construction Domain

The "circular construction domain" aims to demonstrate the functions of a building in a circular economy. Beurskens et Bakx (2015) established a "circular building construction model" which integrates different circular construction principles from the previously stated approach in "circular design domain".

The following principles are at the core of the circular construction domain, and also the most relevant. Some of these were already discussed in Chapter 2. The rest have been synthesised based on Beurskens et Bakx (2015).

I. Material Manufacturer: Is in charge of the transformation of the virgin feedstock into technical or biological materials.
II. Product Manufacturer: Uses the (either technical or biological) materials from the material manufacturer to transform them into building products. Ideally, these should be easy to assemble and to transport to the construction site.
III. Service provider: The service provider is the link between the product manufacturer and the end-user. In a circular economy, it would be ideal that the service provider is connected with the (re) assembler. The service provider is familiar with the principle of selling a product-service system, not a final product where the user retains the ownership.
IV. (Re) Assembler: The service provider will serve to the (re) assembler. This stakeholder is in charge of the disassembly and reassembly of the building systems, and ensuring that they will perform correctly. Constant communication and coordination among architects, engineers and product manufacturers. The reusability and adaptability of all building products should be ensured on all circular building levels.
V. (Re)life Options: In a circular economy, all products and materials have different end-of-life options where their value is retained. These (re)life options run hierarchically from the inner to the outer loops, following the premise that the tighter the loop, the higher the value is retained. Thus, service, recondition, reuse, remanufacture, recycle, cascades and biosphere.
Disassembly: One of the earliest steps in the (re)life options (also known as product-life extension). The disassembly needs to be carried out as neatly as possible to keep the highest value in the building products, components and materials.
VI. Service: This principle consists of different tasks that might be performed to keep building products in an operable condition. The following tasks are part the service premise: monitoring, maintenance, repair, and upgrade. These were previously explained in Chapter 1.
VII. Cascades: This is applied to the biological materials. They will fall into either two types of loops. The first is an open loop, where they will be placed into different use in other sectors. And the second is a closed loop, where they are put into different use, but on the same Section. Closed loop cascading is preferred because it is better to track the material and secure an optimal cascading. The material will eventually return to nature, but to do so, it should be free of any chemical or toxic substances.

Thus, these principles are at the core of the circular building construction model, as seen on Figure. By applying these principles and the processes in the previously described order, the circular construction domain is able to operate correctly. This is a more assertive application of the circular economy in the built environment because it makes important distinctions throughout the processes, materials and it is linked with the circular design phase. Figure 3.5 depicts the circular construction domain, based on the butterfly diagram by the EMF.

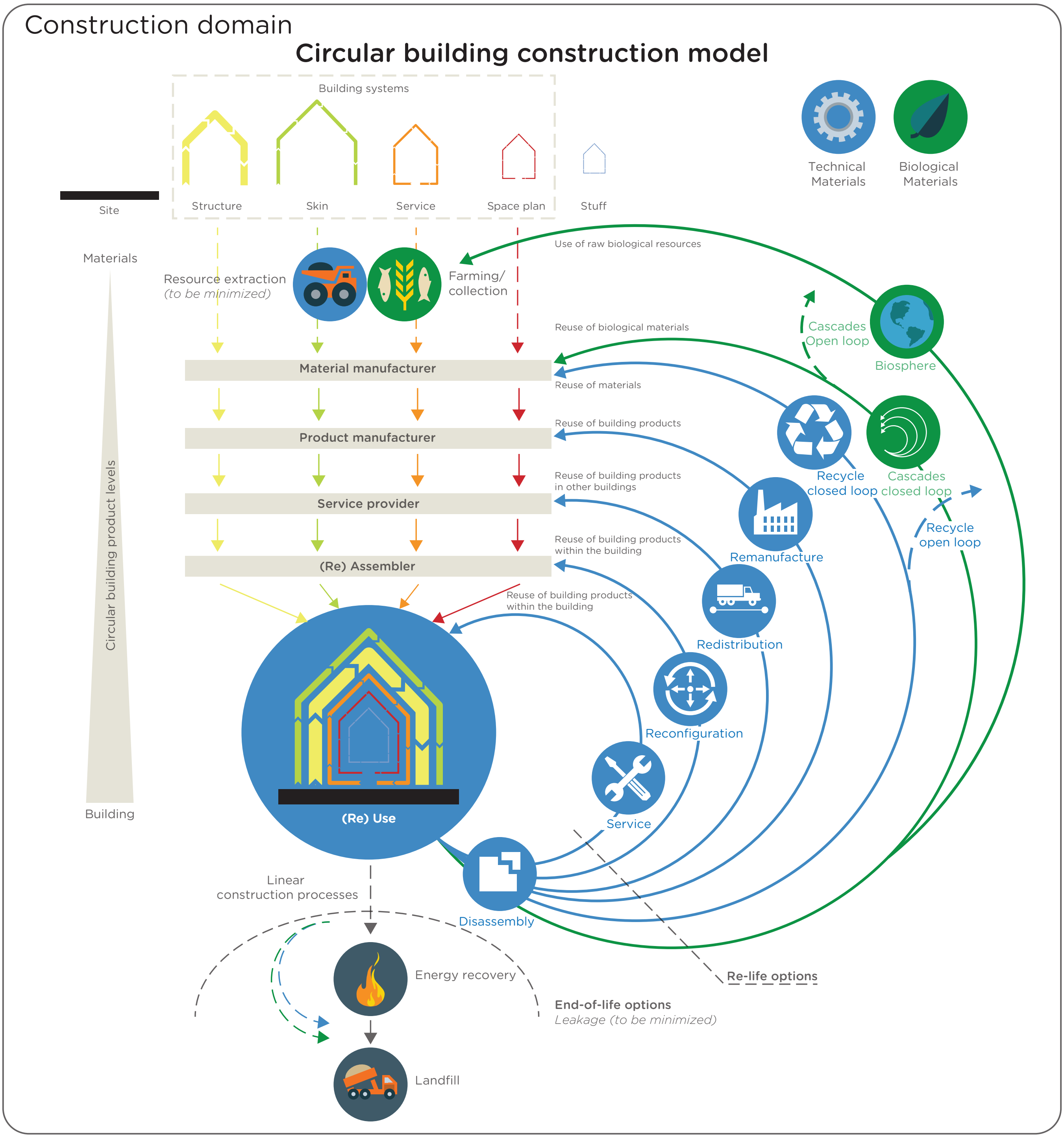


Figure 3.5 Circular building construction model by Beurskens et Bakx (2015), based on the butterfly diagram by the EMF (2013).

3.9 Conclusions on Chapter 3

This Chapter explained how circularity is applied to the built environment. The first three Sections of this Chapter explained how a circular built environment is understood: through a series of levels. Weather this is from a general approach of the CBE, from materials, to components, to buildings, to cities; or from the shearing levels of change from Brand (1994); to the levels of industrial building products (Eekhout, 2008); to material building levels (Durmisevic, 2006). These three different approaches allow to add another dimension to the built environment that will allow them to adapt. The consideration of how a building, or a component evolves through time allows to integrate circular design.

Additionally, the different circular building product levels, based on the theories from Brand, Eekhout and Durmisevic, were explained. From these levels, the circular building design principles derive: be self-sustaining with renewable energy, stimulate diversity, design with sustainable materials, design for disassembly, and design for adaptability. The principles of Design for Disassembly (DfD) and Design for Adaptability (DfA) are at the core of the presented research, and they were further investigated. Design guidelines for DfD and DfA were explained, along with the impact of each design strategy in the built environment. Last, the circular construction domain based on Beurskens & Bakx (2015) was explained, along with the important concepts that will be further applied in this research.

04.

Remanufacturing

This Chapter explains the third part of the literature review: remanufacturing. The first Section of this Chapter introduces the topic, and explains how it has evolved through the years. Section 4.2 describes the process of remanufacturing mechanical systems, and Section 4.3 the barriers towards remanufacturing. Section 4.4 explains the different types of remanufacturing companies, and Section 4.5 the sources to retrieve the cores. Section 4.6 and 4.7 focus on the tools for designers, 'DfX', from which DfRem (Design for Remanufacturing) derives. The available guidelines on DfRem are further explained, along with their impact in the built environment.

List of Figures:

Fig. 4.0 Benefits of bearing remanufacturing. Image by mromagazine.com/
Fig. 4.1 Remanufacturing process for mechanical systems according to ERN (2016), Steinhilper (199). Image by author.
Fig. 4.2 Barriers towards remanufacturing. Image by author.
Fig. 4.3 Sources to retrieve the cores according to ERN (2016), Östlin et al. (2008). Image by author.
Fig. 4.4 RemPro-matrix based on Sundin (2004). Image by author.
Fig. 4.5 Illustrated synthesis of the three business models reviewed in Section 2.6, related to the findings from Sections 4.4 and 4.5. Image by author.

Figure 4.0 Benefits of bearing remanufacturing. Image by mromagazine.com/

4.1 Background

Since the Second World War, remanufacturing processes became a common industrial activity. Nevertheless, it gained academic interest in the 1980s with the studies of Robert Lund (1983). He defined it as:

> *"... an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled, useable parts are cleaned, refurbished, and put into inventory. Then the product is reassembled from the old parts (and where necessary, new parts) to produce a unit fully equivalent and sometimes superior in performance and expected lifetime to the original new product" (Lund 1983).*

However, as this was one of the earliest definitions in the field, it presents certain disadvantages, as it is not specific enough. Boorsma (2016) established a more precise and updated definition of the term:

> *"The process of returning a used product to at least OEM original performance specification from the customers' perspective (Ijomah et al., 2014) by performing "a series of manufacturing steps acting on an end-of-life part or product (Parker, D., Butler, P., 2007), "and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent "(Ijomah et al., 2014) after which the product receives a serial number" (Boorsma, 2016).*

Thus, it is understood by this last definition that the product is upgraded after its end-of-service. Indeed, this is the crucial aspect that is found on remanufacturing: the product value increases, and the embodied energy is conserved. Dr. Nabil Nsar from the Rochester Institute of Technology established that "remanufacturing is the ultimate rebuilding" (Introduction to a Circular Economy, 2018). He explains the main difference between remanufacturing and other slowing-resource loops processes as:

> *"...rebuilding, overhaul and refurbishment, those are basically bringing the product back to a working condition and ensuring that it will function. But it is not like a new condition, like what we do with remanufacturing. Remanufacturing requires to bring the product back to like new condition, from operational specification to life cycle to performance. Basically, you have a rebirth of the product" (Introduction to a Circular Economy, 2018).*

4.2 The Process Behind Remanufacturing

According to the European Remanufacturing Network (ERN, 2016), the number and the sequence of the steps in a remanufacturing process depend directly on the type and function of the product. Because there is a limited knowledge in the case of building products, a general approach towards mechanical products will be applied in this research. The ERN (2016), based on Steinhilper (1999) establishes that there are five steps for remanufacturing mechanical systems:

I. Complete disassembly: In this first step, the cores are disassembled completely. The parts that cannot be repaired or reused are left out. This process is also done manually with as much delicacy as possible, since it is important to preserve the quality of the parts.

II. Thorough Cleaning: Degreasing, deoiling, derusting, and deep cleaning of all parts according to their current state. Depending on the type and level of contaminants, diverse technologies might apply to complete this step.

III. Inspection and Sorting: After the previous steps are completed, the parts are sorted out according to their remanufacturing or reconditioning potentials. All parts are inspected to ensure their final quality, parallel to how it is in the new production of components and products. The classification is according to:

a. Reusable without reconditioning
b. Reusable after reconditioning
c. Not reusable / needs to be exchanged.

IV. Reconditioning and/or Replenishment: Worn out parts are reconditioned through metal treatment processes (examples include drilling, milling, turning, grinding, honing, among others). The parts that are not suitable for reconditioning are exchanged for new parts.
V. Product Reassembly: The last step in the remanufacturing process is the reassembly of parts. This can be done through assembly lines that work with the same tools for small batches. Similar to how it is in manufacturing new products, the remanufactured product is tested to assure its quality. Remanufactured products should have the same, or higher quality of a new product. Figure 4.1 shows the diagram with the steps towards remanufacturing, where quality assurance runs transversal across all of them.

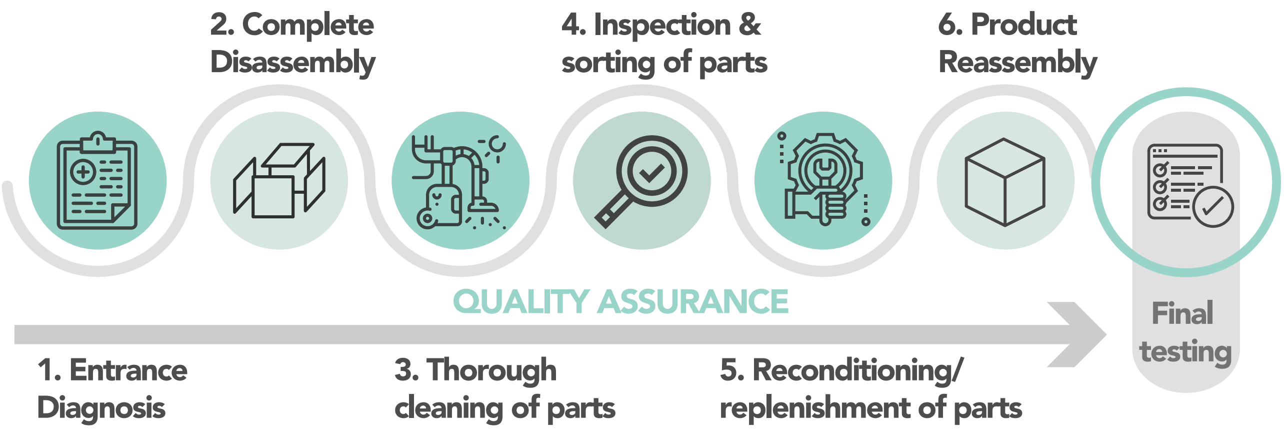


Figure 4.1 Remanufacturing process for mechanical systems according to ERN (2016), Steinhilper (199). Image by author.

4.3 Barriers Towards Remanufacturing

Karvonen et al (2017), organised the barriers towards remanufacturing in three main different groups: business model, DfRem, and process, as depicted in Figure 4.2. This study was conducted after the publication of ERN (2016) in the remanufacturing market study. The author has enriched the approach from Karvonen et al (2017) with the findings from Ijomah et al. (2007), Sundin (2004), Lindkvist et al (2016) in Table 4.1:

Business Model	• Capital investment • Defining remanufacturing • Intellectual property restrictions • Consumer awareness and perception • Institutional barriers • Liability, regulations, legislation, standards • Remanufactured product cost vs new product cost • Market size
DfRem	• Demand for remanufactured products • Investment from the OEM in remanufacturing • Knowledge of DfRem principles • Product design does not integrate end-of-life thinking
Process	• Availability and quality of the cores • Poor control over core availability and collection • Reverse logistics • Elevated technological complexity • Available infrastructure • Process efficiency

Table 4.1 Research results on barriers towards remanufacturing

Figure 4.2 Barriers towards remanufacturing. Image by author.

Regarding the first group, business models, Dr. Nabil Nasr explained (Introduction to a Circular Economy, 2018) that the most crucial barriers are related to perception, where the consumer sees remanufactured products as inferior to a new product. This is a contradiction, and is closely related to lack of awareness of the definition of remanufacturing, as this clearly states that a remanufactured product is "fully equivalent and sometimes superior in performance and expected lifetime to the original new product" (Lund 1983).

Yet, it is important to understand that even if the barriers are organised in three different groups, there is a strong relationship between them. For instance, it has been proven that legislations and regulations have a significant role towards promoting remanufacturing in the industry, and stimulating the market, which falls under the "business model" group. However, this might also interact with some of the other barriers on the list. The "process" barriers are strongly related to an open market access. For instance, constraints towards transporting the cores in between countries might affect the availability of the cores overall.

Additionally, the DfRem group seems to have a shorter list of barriers, but this is because the concept of Design for Remanufacturing is relatively new; and also because it is as simple as if product design does not integrate remanufacturing, this will not be carried out. While it might sound simple, it seems to be one of the most crucial technical barriers, especially because design problems seem to be highly severe in the case of independent remanufacturers. If there is lack of knowledge of DfRem in a product, it is impossible to perform reverse logistics or engineering to remanufacture it.

The lack of application of DfRem principles is mostly reflected in a combination between design and manufacturing, for instance: poor disassembly, and a selection of non-durable materials. Disassembly is one of the key remanufacturing activities, so if a product is not designed for disassembly, is hardly possible that it might be suitable for remanufacturing. Such is because after disassembly, the products can be cleaned, inspected and rectified. Additionally, the linear-economy model has fostered the manufacturing of products that have a short, single life, meaning that they are usually designed with less-durable materials, but with a lower price, thus preferred by consumers ("business model group" and "DfRem"). Furthermore, insufficient integration, or usually, none at all, of end-of-life, or (re) life strategies into the product design. Equally important, the 21st century has been characterised by its increasing technological complexity ("process"). In an era where technology progresses incredibly fast, it is common to find products that become obsolete even before they reach their end-of-life.

4.4 Types of Remanufacturing Companies

The companies that perform remanufacturing can be classified according to their relationship to the product manufacturer, also known by some authors as the Original Equipment Manufacturer (OEM). The ERN (2016), in addition to Lund (1983), Sundin (2004) recognises three types of remanufacturers:

I. Original Equipment Manufacturer/Remanufacturers (OEM/OERs): These companies remanufacture their own products. The cores are retrieved from service centres, trade-ins, or contracts that ended their leasing period.
II. Contracted Remanufacturers (CR): These companies are contracted to remanufacture products from other companies. The OEM might be the owner of the product, but it might outsource the remanufacturing service to offer the products at a lower price. The CR can receive support from the OEM in replacement of parts, design, and testing.
III. Independent Remanufacturers (IR): These remanufacturers might have few or no contact at all with the OEM. They retrieve the cores on their own, and might be compensated by the end-user to source products that have reached their end-of-service. In some cases, a company can act as an IR/CR, which means that for some companies they might collaborate with the OEM, but not in all cases.

4.5 Sources to Retrieve Cores

Many of the current remanufacturers have different sources to retrieve the cores. According to the ERN (2016), based on (Östlin et al, 2008), there are seven main strategies to do this, also depicted on Figure 4.3:

I. Ownership-based: The manufacturer owns the products and the customer operates it. For instance, rental, leasing, or a product-service system.
II. Service contract: A contract that includes remanufacturing is based between a buyer and a manufacturer when the product is purchased.
III. Direct-order: If a remanufacturing operation is possible, the customer will return the product to the remanufacturer, and then sent back.
IV. Deposit-based: A customer purchases a remanufactured product, but they have the obligation of returning a similar one. Therefore, they become a supplier for the remanufacturer.
V. Credit-based: The customer receives a number of credits when they return a product. The credits can be later on used to purchase a remanufactured product.
VI. Buy-back: The remanufacturer buys the wanted used products from a supplier. The latter can either be the end-user, a scrap yard or similar, or a core dealer.
VII. Voluntary-based: The supplier gives the used products to the remanufacturer. The supplier does not necessarily needs to be a customer.

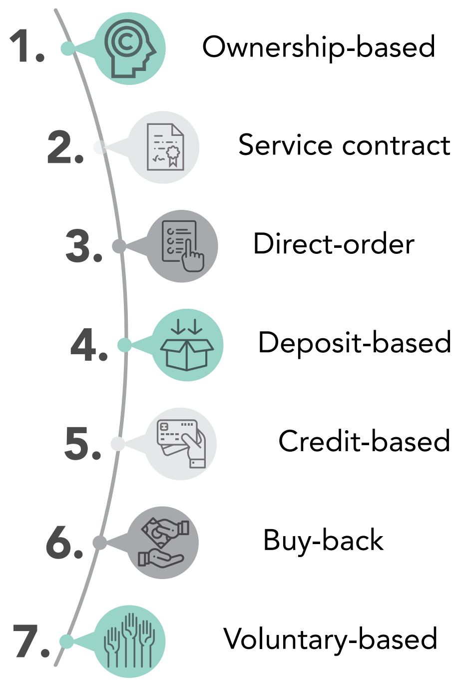


Figure 4.3 Sources to retrieve the cores according to ERN (2016), Östlin et al. (2008).
Image by author.

Some of these might present higher advantages in the relationship that is established between the user and the remanufacturing/manufacturing company. For instance, in the case of "ownership-based" and "direct-order", there is a high control on the core supply since there is a contract involved. Whereas in the case of the voluntary-based, the control on the core supply is quite limited, since the company will receive what the user is willing to give. The "ownership-based" and "service contract" also provide a long-term relationship that can integrate a product and a service, which can assure remanufacturing as a (re)life option. In the case of the "deposit-based" and the "voluntary-based", the relationship focus is lower, because it depends on the customer's operations. The ERN (2016) described that the most common sources to retrieve cores were buy-back, ownership-based, and voluntary based.

4.6 DfX

Additionally, DfRem has been explained by other authors (Charter and Gray, 2008) (Hatcher et al, 2011) as part of the DfX family, where the 'X' stands for different concepts: Design for Adaptability (DfA), Design for Disassembly (DfD), Design for Recycling (DfR), etc. The DfX family has the aim of guiding designers towards a certain goal. However, other authors such as Zwolinski et al. (2006) argue that the DfX principles assume that the entire design process is thoroughly known. Thus, is it important to understand that the DfX activities are mere guidelines and that it is required to consider individual aspects for all processes. Design for disassembly (DfD) and Design for Adaptability (DfA) were already explained in Sections 3.6 and 3.7. However, because of the purpose of this research, Design for Remanufacturing (DfRem) will be thoroughly explained.

4.7 Design for Remanufacturing (DfRem)

As it was established on Section 4.3 Barriers towards remanufacturing, DfRem is one of the key challenges to integrate such process into products. Design for Remanufacturing (DfRem) is a design technique that arises from the recognition that several technical barriers that can be traced back to how the product was designed. But what does DfRem means? Certainly, the goal is to improve the manufacturing potentials. The following definition is constructed based on (Nasr and Thurston, 2006), (Charter and Gray, 2008), (Hatcher et al, 2011):

> *"A combination of design processes whereby an item is designed to facilitate the different steps involved in remanufacturing, considering the product strategy, and the detail engineering of the products in terms of the entire remanufacturing process".*

However, the answer to "how to design for remanufacturing?" is largely broad and vague by nature. Nevertheless, similar to DfD and DfA, there are certain product properties that fall inside the DfRem principles, and that can serve as general guidelines for designers. It is important to note that these product properties are related to the steps required in the remanufacturing process (at least in the generic one).

4.7.1 Remanufacturing Product Properties

Several authors have constructed different approaches towards the desirable properties a product should have for it to be suitable for remanufacturing. One of the most important is the RemPro-matrix, a tool developed by Sundin (2004), and further on reviewed by other authors (Hatcher, 2011), (Lindkvist et al, 2016). Figure 4.4 shows the RemPro-matrix by Sundin (2004).

Different factors that are present in the RemPro-matrix are related to effective product design. Which according to Hatcher (2011), it suggests that the DfRem guidelines are not a "single homogenous task, but actually a collection of many tasks or considerations whose prioritisation will differ

Product Property \ Remanufacturing Step	Inspection	Cleaning	Disassembly	Storage	Reprocess	Reassembly	Testing
Ease of Identification	x		x	x			
Ease of Verification	x						
Ease of Access	x	x	x		x		x
Ease of Handling			x	x	x	x	
Ease of Separation			x		x		
Ease of Securing						x	
Ease of Alignment						x	
Ease of Stacking				x			
Wear Resistance		x	x		x	x	

Figure 4.4 RemPro-matrix based on Sundin (2004). Image by author.

depending on the process of the product". Another benefit from the RemPro-matrix is that it allows the designer to have the whole remanufacturing process in mind. According to the studies conducted by Sundin (2004), the most crucial steps in the remanufacturing process are inspection, cleaning and reprocessing. Therefore, the product properties from the RemPro-matrix are described hierarchically: ease of access and wear resistance are closely related to the previously mentioned steps. In addition, the following properties are prioritized: ease of identification, ease of verification, ease of handling and ease of separation. The reason these are not a first priority is because they do not have a crucial weight on the most delicate steps of the remanufacturing process. Nevertheless, this does not make them less important.

Yet, while the RemPro-matrix is a successful tool when providing guidance and prioritisation of issues, some authors have commented (Hatcher, 2011) that it might be highly-conceptual to apply it to the industry. Probably because the product properties are remarkable subjective, and do not provide a technical application in the field. This is because the RemPro-matrix itself was developed to be a generic tool. Thus, in fact, it aims to be only of general guidance.

Consequently, and based on the studies from Sundin (2004), Ijomah et al. (2007) developed a much detailed approach towards DfRem guidelines. His work focused on developing, among many, two tools that are at the core of his research: first, the identification of design features that affect product remanufacturability; and secondly, detailed examples of high-level remanufacturing guidelines.

On the first tool, Ijomah et al. (2007) maps the different design features: assembly type, product complexity, materials, and design cycle. Along with this, different problems according to each feature are identified, for instance the presence of numerous components, coatings, or internal component arrangements, among others. The design features are graded from 1 - 4, where 4 is the highest impact on affecting product remanufacturability. Table 4.2 explains his approach.

On the second tool by Ijomah et al. (2007), his approach is similar to Sundin's (2004) RemPro-matrix, where the design characteristics are linked to the steps taken in remanufacturing. However, in this case, there is a highly detailed description on each process activity, and a further explanation for each step regarding material properties, assembly technique, and the product structure. This highly detailed approach can also serve as a technical guidance in the design of components and building products. It has been also highly used, and reviewed by other scholars from the field (Hatcher, 2011), (Lindkvist et Sundin, 2016). Because the key purpose of Ijomah's et al. (2007) approach is to provide guidance, it should be applied during the concept generation of the products. This tool is also a ref-

Design features	Problems identified	Severity of impact	Comments: e.g. reasons, explanation, etc
Assembly type		1 - 4	Assembly type might hinder disassembly, an essential and initial activity to the point that remanufacture is impossible.
	Screws	1	Time consuming but generally would not make remanufacturing impossible.
	Rivets	2	Time consuming, but generally would not make remanufacturing impossible.
	Welding	3 - 4	Difficult/impossible to disassemble depending on welding type.
	Strong (e.g. epoxy adhesive)	3	Very strong adhesive can prohibit disassembly.
Product complexity		3	Product complexity may necessitate increased complexity, may require more types of testing, more expensive testing, thus increasing resources used in terms of skills and time.
	Numerous components	2	Numerous components require more resources for testing and remanufacturing
	Product dimension	2	Size and weight of product can be detrimental e.g. by making access to damaged components difficult
	Internal component arrangement	2 - 3	May lead to wear because of friction between parts. May make remanufacturing more complex and expensive because of difficulty in accessing damaged parts. Caused by ineffective communication between end-user, remanufacturer, manufacturers and designers.
	Coatings		Unnecessary and ineffective coatings can inhibit remanufacturing and may even be detrimental in the long run, e.g. flaking teflon coating might leave debris that might damage components.
Materials		4	Non-durable materials cannot be remanufactured. Banned materials deters remanufacture.
Design cycle		3	Resource expected to keep pace with modernity.

Scale showing severity of problem's impact on remanufacturing

1 low impact → 2 → 3 → 4 → 4 very high impact

Table 4.2 Design features affecting product remanufacturability according to Ijomah et al. (2007).

erence, qualitative tool based on a collection of different simple principles. The table by Ijomah et al. (2007) with the high-level remanufacturing guidelines can be found in the Appendix.

However, the question also remains for the products that are not in the concept development stage. Are these also suitable for remanufacturing? Can remanufacturing be retroactive? Although this is not recommended, since remanufacturing should be taken into account since the early design stages, the shift towards a circular economy will require to test if existing products can be remanufactured. Vogtländer et al (2017) established an eight-point criteria to determine such:

I. The product is durable
II. The product functionality can be recovered
III. The product design is standardised and modular
IV. The value at the EOL is high enough to prevent discarding
V. The cost to obtain the core is low if compared with the potential intrinsic value
VI. The product's basic hardware technology is relatively stable over a period of time that exceeds the product lifetime

VII. The consumer should be informed about the opportunity to return the core and about the availability of remanufactured products in order to create an adequate supply and demand
VIII. The product is DfD

This eight-point criteria can also serve as a series of guidelines for remanufacturers/manufacturers and designers in the case of an existing product, or even during the concept development stage (although the previously mentioned tools might be a better, highly detailed example).

4.7.2 The Impact of DfRem in the Built Environment

If DfRem is applied as a regular practice to all building components, its impact in the built environment will most likely be related to the input in raw material, labour and energy. This can later on translate to the economy. A reduction in the input of raw materials into the chain will also mean that we will keep products longer in use, and companies will most likely shift towards business models focused on providing a service instead than a product. However, there could be possible drawbacks on this. For instance, if companies now rely on making profit from remanufacturing activity, "the paradox of circling faster" might come into place. This means that the product might be designed to be remanufactured earlier than necessary with the purpose of demanding a service that will create value for companies.

Additionally, the process of remanufacturing, and DfRem has a high focus on design for disassembly. This might also mean that the industry might become highly labour intensive, which can be translated into the creation of new highly skilled jobs.

Another "possible" drawback might be that keeping a product in use might block innovation. However, this is not entirely true, because as it is explained in Section 4.7.1, the product's technology should be stable for it to be remanufactured.

Overall, the building industry will become more material efficient, products that are suitable for remanufacturing will be kept longer into place, allowing them to have different (re)life options. Consumers would be able to have low-cost remanufactured building products with a warranty equal or higher than new ones. This would build a strong relationship between the OEM and remanufacturing companies, where a service is continuously provided.

4.8 Conclusions on Chapter 4

This Chapter aimed to answer SRQ2: "What are the available guidelines for DfRem (Design for Remanufacturing) and which are the circular business models that support it?". A short literature review on the field was analysed, describing the approaches by the different authors, their key purpose, and more importantly, at which stage they should be applied. In the case of the RemPro-matrix, developed by Sundin et al. (2004), there is a cross-relationship between the product properties and the remanufacturing process. This is one of the key aspects of this tool, since many of the technical barriers are related to the concept development phase. The RemPro-matrix focuses on nine crucial product properties: ease of identification, verification, access, handling, separation, securing, alignment and stacking; along with wear resistance. These are later on cross-related towards seven remanufacturing steps recognised by Sundin (2004): inspection, cleaning, disassembly, storage, reprocess, reassembly, and testing. This qualitative tool provides guidance, but more importantly, a prioritisation of issues that might be presented during the remanufacturing process. It also has the advantages of being simple, and easy to apply during the early design stages. However, due to the same, it can present the disadvantages of being too broad, and highly subjective.

Based on the RemPro-matrix by Sundin (2004), Ijomah et al.(2007) developed a robust set of DfRem guidelines. His initial approach is towards identifying design features that affect product remanufacturability. He identifies them through four main design features: assembly type, product complexity, materials, and design cycle. A scale showing the level of impact on remanufacturing, where 1 is the lowest, and 4 is the highest, is used to prioritise the product properties. Additionally, he comments on the impact of such, and elaborates on the factors that cause the problem. From the identification of such problems, he develops a second tool: high-level remanufacturing guidelines where he links three product properties: material, assembly technique and product structure; with the three remanufacturing process activities, product disassembly, cleaning, and remanufacturing (includes testing). Similar to the RemPro-matrix, such qualitative approach, a set of guidelines, are to be applied during the early design stages. It presents the advantages of being simple, yet more technical and precise. However, Hatcher (2011) commented on it as still presenting the problem of being subjective, like its predecessor, RemPro-matrix. Another important disadvantage is that it does not take into account lifecycle thinking, and it is unknown if it has been applied to the industry.

Additionally, the eight-point criteria established by Vogtländer et al (2017) serves also as a general guideline, especially in the case where remanufacturing is applied retroactively. Similar to the other two tools previously reviewed, this approach can also serve as general guidance for the designers, manufacturers, and remanufacturers. This approach is the only of the three reviewed that takes into account lifecycle thinking, and the consumer's experience. However, similar to the other two tools, it can seen as subjective and too general.

This Chapter can strongly relate back to Section 2.5, where, as it was explained, remanufacturing is considered as one of the "slowing resource loops". Additionally, Section 2.6 also stated three of the circular business models for slowing resource loops. These models are directly related to Sections 4.4 and 4.5 in this Chapter, as they have a strong relationship with the business models previously explained. Figure 4.5 depicts a small synthesis of the business models reviewed in Chapter 2, and how these relate the contents described in this Chapter, taking into account the type of remanufacturing company, and the sources to retrieve the cores.

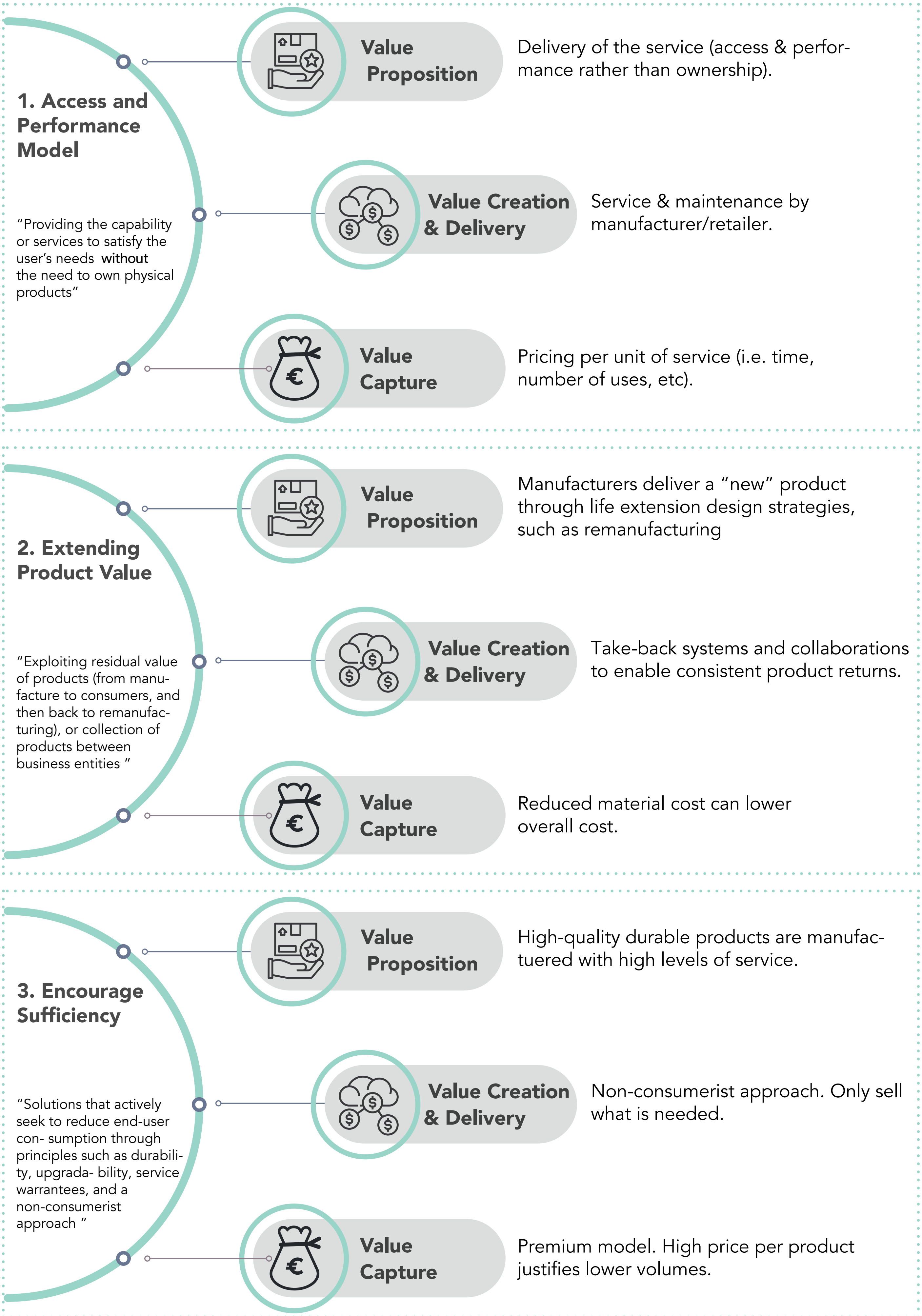


Figure 4.5 Illustrated synthesis of the three business models reviewed in Section 2.6, related to the findings from Sections 4.4 and 4.5. Image by author.

05.

Analysing Kawneer Nederland B.V.

This Chapter analyses the company Kawneer Nederland B.V. in different aspects. The first Section explains the vision of the company, and its role in the façade industry. Section 5.2 explains the selected case study for the research: the RT 82 HI + system. The technical information, key properties, and competitors of the product are analysed. Furthermore, Section 5.3 explains the current business model through the tool of the business model canvas. Section 5.4 explains the current life cycle of Kawneer's products. Finally, Section 5.5 summarises the outcome of a circularity interview and brainstorming session held with three important stakeholders.

List of Figures:

Fig. 5.0 View of Kawneer Nederland B.V. headquarters in Harderwijk. Image by stedebouwarchitectuur.nl
Fig. 5.1 Scheme of the relationship of stakeholders. Image by Klein (2013).
Fig. 5.2 RT 82 HI + Window system. Image by Kawneer (2018)
Fig. 5.3 Top view of the RT 82 HI +. Image by Kawneer (2018).
Fig. 5.4 Benchmark of high insulating aluminium windows. Image by author.
Fig. 5.5 Business Model Canvas according to the current linear business model from Kawneer Nederland. Image by author.
Fig. 5.6 Diagram of the current life cycle of products from Kawneer. Image by author.

Figure 5.0 View of Kawneer Nederland B.V. headquarters in Harderwijk. Image by stedebouwarchitectuur.nl

5.1 About the Company

Kawneer is an American manufacturer, leader of architectural aluminium products and systems. It is part of the Arconic's Building and Construction Systems (BCS) business. High-thermal performance, hurricane resistance and blast mitigation are some of the key innovations developed by Kawneer in the past years. The company has an extensive range of products: curtain walls, framing systems, doors and windows.

Klein (2013) explains that in the façade building industry, the project phases have different stakeholders related to it. The processes of each stakeholder is also separated, which makes the supply chain even more complex. Kawneer can be understood as a 'system supplier', according to the separated stakeholder process analysed by Klein (2013), as seen on Figure 5.1. In other words, it can be understood as a 'system integrator', meaning that they specialize in bringing together different elements to create components or systems.

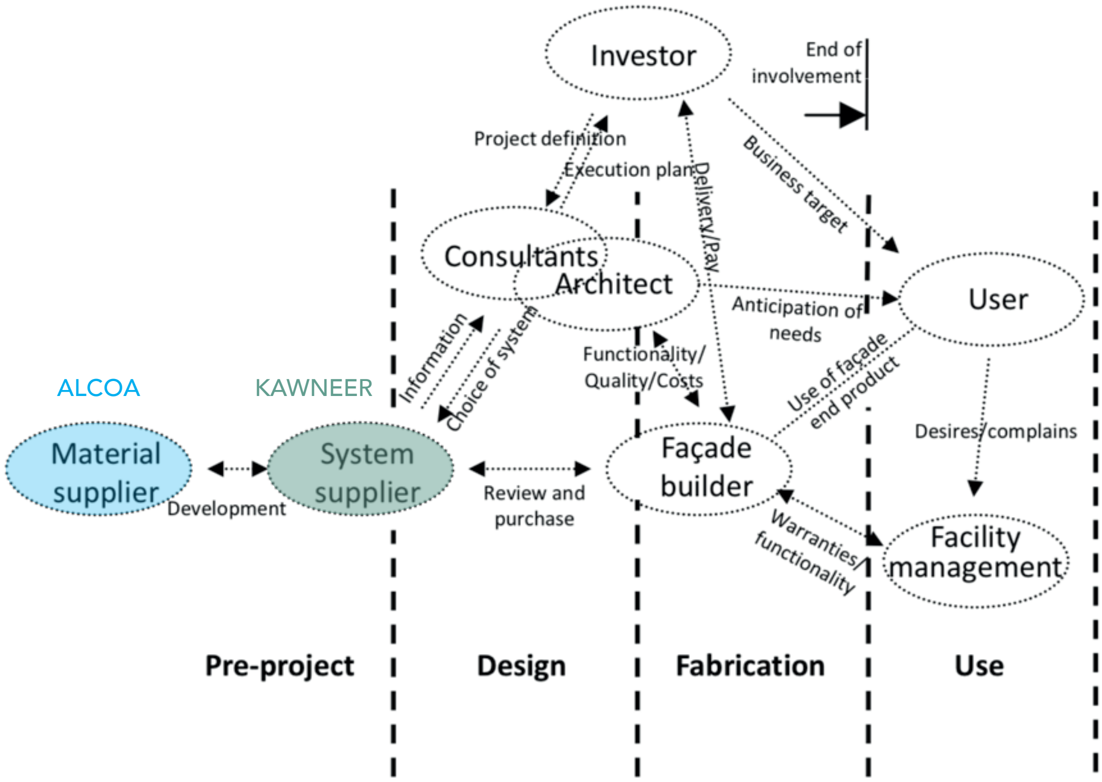


Figure 5.1 Scheme of the relationship of stakeholders. Image by Klein (2013).

5.2 RT 82 HI + system

The RT 82 HI + aluminium system is characterised by having high insulation values. It is also certified Passive House phB, and it is manufactured in eight different variations. Highly attractive for the market, the system has a U-value of 0.79 W/m2, mostly due to the AlcoaTherm insulation material. Because the system is modular, it is possible to have different variations on the same according to the architectural demand. The outer shell of the system can be adjusted according to the required design, without affecting the functional properties. Double glazing and triple glazing can also be adjusted according to the thermal insulation requirements

The RT 82 HI + system (Figure 5.2) is part of the modular series of window systems. The RT 52, RT 62, and RT 72 have the same product architecture, where the main difference is the width of the thermal break. As the series goes up (from 52 to 82), the thermal break becomes wider, making the RT 82 HI + series the one with the widest thermal break (44 mm).

Additionally, it is important to mention that Kawneer is not the direct builder of the window system. They supply the different elements of the window, door, or curtain wall components, and their clients, a façade builder, will manufacture the façade and its components, including the full window assembly, according to each project.

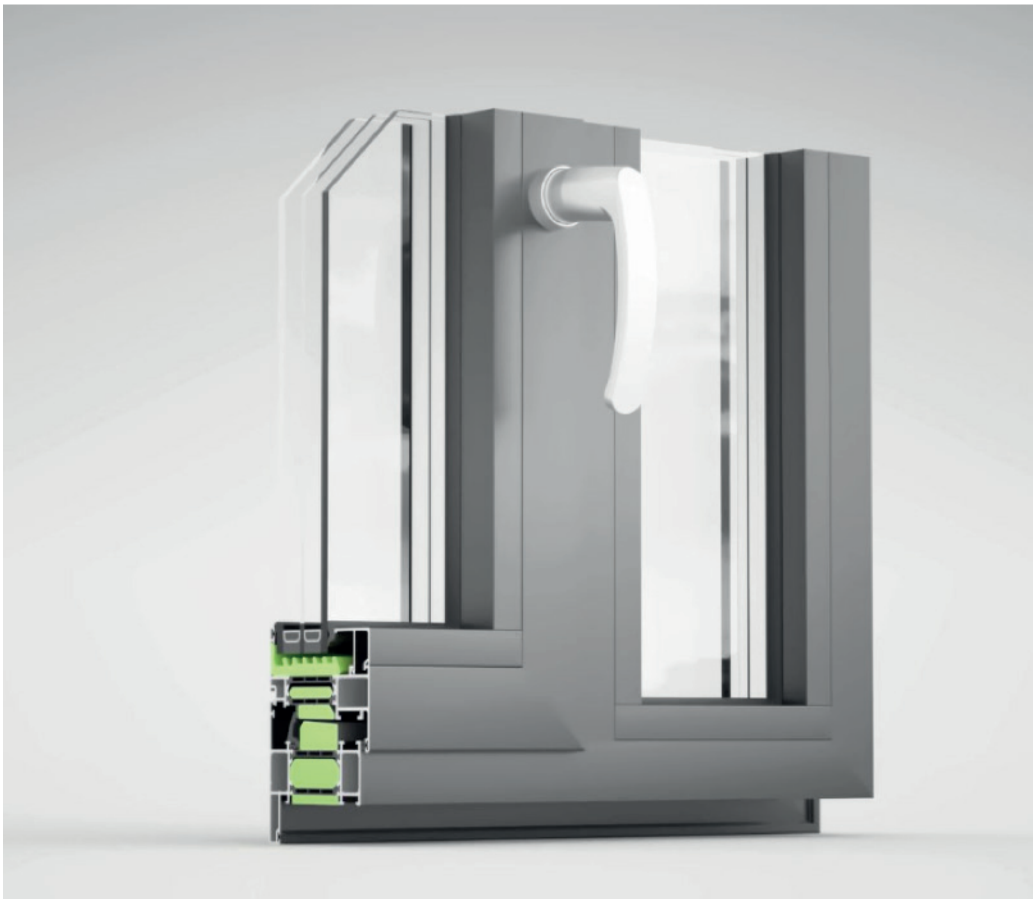


Figure 5.2 RT 82 HI + Window system. Image by Kawneer (2018)

5.2.1 Technical information:

Kawneer (2018) establishes the following:

System features

- Material: Aluminum extrusion profile
- Alloy: EN AW 6060 T 66 according to EN 573 anodising quality
- Construction: Symmetrical 3 chamber system
- Frame depth: 82 mm, variable, depending on required strength
- Wing depth: 90 mm
- Insulator: 45 mm plastic thermal break with patented AlcoaTherm filling
- Glazing capacity: Up to 66/74 mm

System options

- Water drainage: Concealed / visible water drainage
- Glazing: Indoor and exterior glazing
- Seals: Continuous vulcanised corners and / or frames

Model characteristics

- Design: Standard surface, concealed wing, renovation and / or custom made
- Windows: Straight vent or softline for internal and external turning
- Hinges and locks: System-related with Euro- utility and A-line handles
- Accessories: System-specific accessories as per regulation Kawneer
- Surface treatment: Anodising (20 or 25 micron), powder coating, pre-treatment 6-fold chromate, 60 micron with gloss level 30 or 70%. Other combinations on request

5.2.2 Manufacturing and logistics

Alcoa, the mining company, extracts the aluminium from America, and transforms it into the 6060 alloy through the addition of chromium, copper, iron, magnesium, and other chemical elements (AEC, 2018). This makes the 6060 alloy part of the wrought aluminium-magnesium-silicon family (6000 series). This alloy is further on processed into billets, which later on go through the extrusion process by heating the 6060 alloy to 300 - 600 °C. After the profiles have been created through extrusion, they are sent to Kawneer's factory in Harderwijk. There, they are assembled into the full window or curtain wall frame, by adding a polyamide thermal break. This process is done with a knurling machine where the aluminium profiles (called at this point 'baby profiles', Figure 5.3) are rolled with the polyamide thermal break. After they have been assembled, they can no longer be separated without breaking the elements. The assembled profile is then tested to ensure quality and building regulations. This last process of assembling the baby profiles with the thermal break is the only one taking place at Harderwijk. The profiles, along with the hardware, and other accessories, are then packed and shipped to the client.

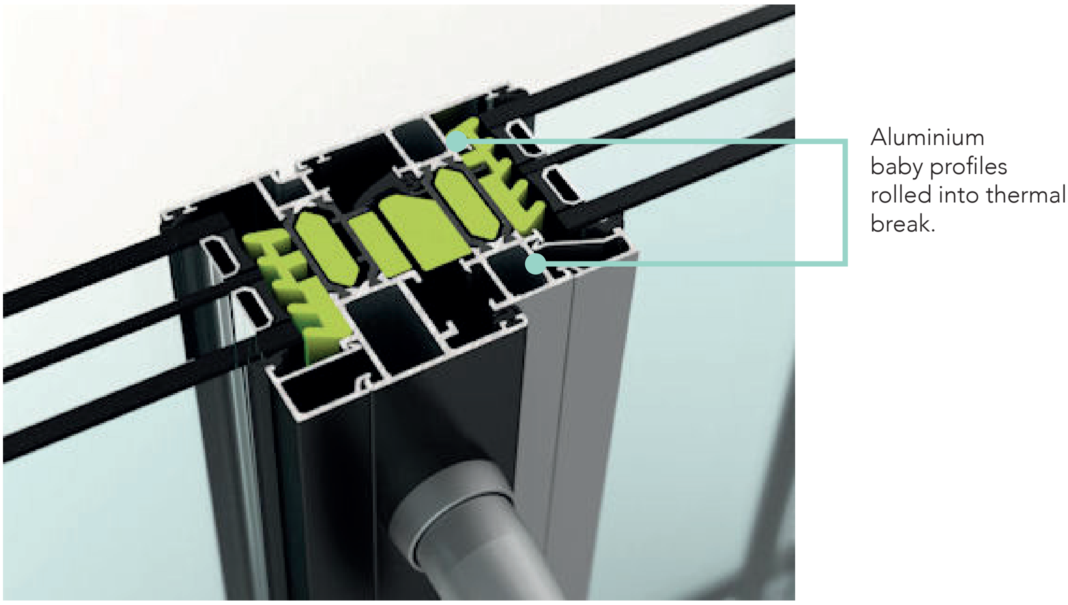


Figure 5.3 Top view of the RT 82 HI +. Image by Kawneer (2018).

5.2.3 Key Properties

Some of the key properties are derived from the material and production process, and others are attributed to the product design itself.
Material and production process properties: Aluminium, along with aluminium extrusion process present different advantages to designers and consumers. These are synthesised as follows from the Aluminum Extruders Council (AEC, 2018)

(a) Material Advantages:

- Recyclable
- Lightweight
- Strong
- High strength-to-weight ratio
- Resilient
- Corrosion resistant

(b) Extrusion Process advantages:

- Wide range of finished
- Virtually seamless
- Complex integral shapes
- Fastening and assembly
- Joinable

- Cost-effective
- Short lead times

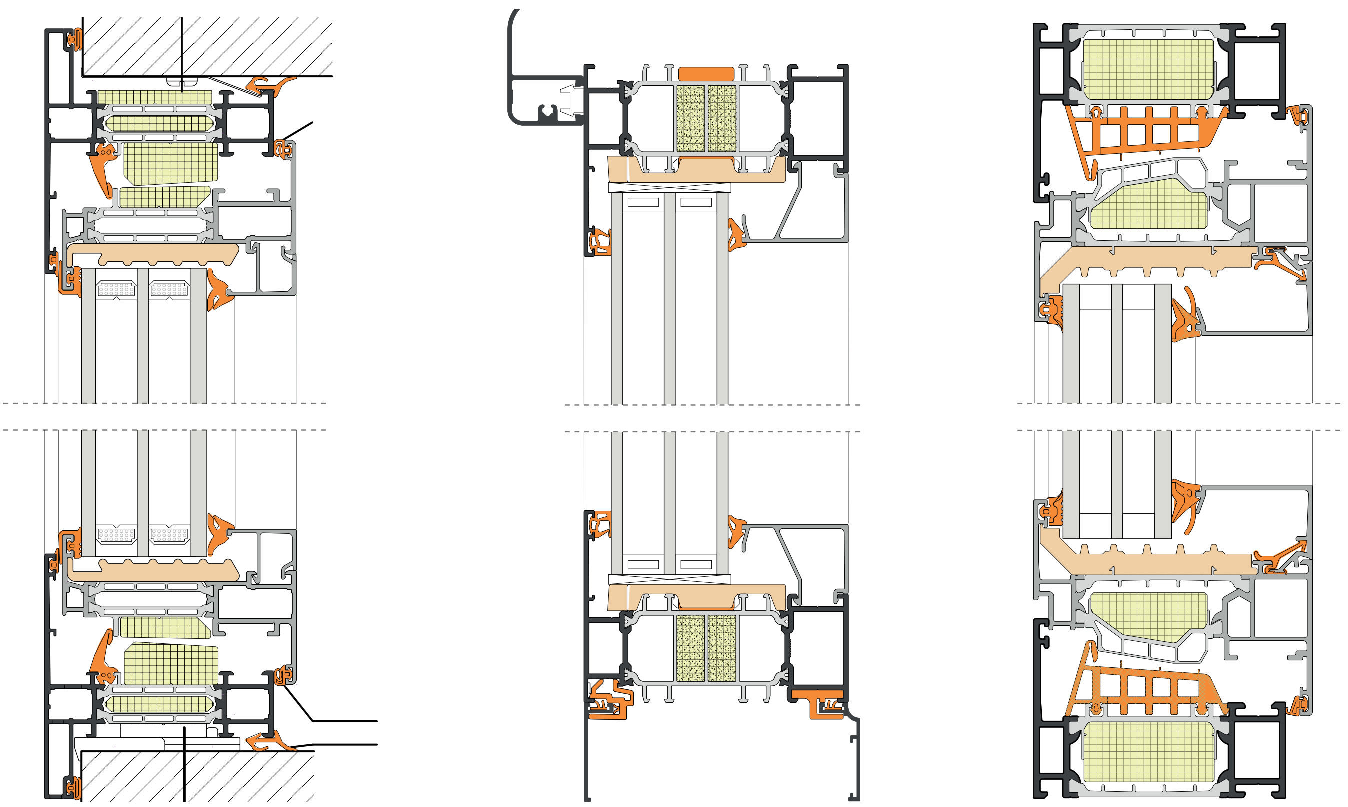
These key properties attributed to aluminium window systems will be further discussed on Chapter 6 Window Systems, where different Window Systems and materials are compared

(c) Product Design Properties: Additionally, the window design of the RT 82 HI + attributes other key properties that are important to discuss. According to van Manen (2019), Sustainability and CE expert at Kawneer (and guest supervisor), the RT 82 HI + system has the lowest U-value in the market, with the slimmest frame, and with a Passive House certification to phB level. In conclusion, the product design properties focus on a high thermal insulation, but with a very slim frame. This allows the client to have large glazing surfaces with high thermal insulation.

5.2.4 Competitors

The main competitors for Kawneer, and the RT 82 HI + in particular, are Reynaers Aluminum (Belgium), and Schüco International (Germany). These two companies manufacture aluminium products (in the case of Schüco they also use other materials), and have similar products that compete against the RT 82 HI + (Figure 5.4). These products, which are highly insulated aluminium window systems with a Passive House certification are:

- CS 104 HI by Reynaers
- AWS 90 SI + by Schüco



RT 82 HI + Aluminium Triple Glazed Window Frame - Kawneer

CS 104 HI Aluminium Triple Glazed Window Frame - Reynaers

AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco

Figure 5.4 Benchmark of high insulating aluminium windows. Image by author.

Their product properties, technical performance, and key properties are thoroughly explained in Chapter 6 Window Systems.

5.3 Current Business Model

It is not surprising that Kawneer, as most of the companies in the world, operates under a linear economy system. However, before analysing the many different opportunities that a circular business model could provide, it is important to understand the current business model of the company first. The tool used to analyse this is the Business Model Canvas (as depicted in Figure 5.5), and it will be explained as follows:

I. Value proposition:

(a) Product: reliable aluminium systems with high thermal insulation and performance. Service: Technical support, advice during project development, and technical guidance.
(b) Customer Segments: Façade manufacturers, architectural firms, and consultants.
(c) Customer Relationships: Long term relationships built through dedicated personal assistance.
(d) Value for Customer: They receive high quality individual window elements that are assembled by the façade manufacturers (main client).

II. Value creation and delivery:

(a) Key Activities: product design, product integration, purchasing of hardware and other accessories/elements, assembling elements into products, product testing, packaging and shipping.
(b) Key Resources: technical an d product design knowledge, distribution network, storage facility, testing facility, software, website.
(c) Distribution channels: trade fairs, office fairs (OE), advertisement, e-commerce.
(d) Key Partners: Suppliers (hardware, insulation, accessories, etc), Alcoa and Arconic (parent company), façade builders, Universities (TU Delft, BK).

III. Value Capture

(a) Cost Structure: Fixed costs (overhead), variable costs (procurement).
(b) Revenue Streams: creation of value through a single sales of products

5.4 Current End-of-Life Scenarios

According to Wijnand van Manen (sustainability and circularity expert for Kawneer, and guest supervisor), and Jeroen Boersma (team leader of European Product Development), it was informed that currently, only 3-4% of the products by Kawneer are directly reused, and there is no current activity by the company on remanufacturing. However, there is a high recycling rate on the 6060 aluminium profiles. Figure 5.6 illustrates the current end-of-life scenarios of the products, along with the involved stakeholders (blue), and their role in the process (green).

The current life cycle of Kawneer's products can be divided into four different stages by the author: sourcing, production, use, and end-of-life. The first stage, sourcing, takes place in the American continent, where aluminium is extracted as virgin feedstock by Alcoa. After this, the virgin materials are transformed into processed materials by a material manufacturer. During this process, the aluminium profiles are extruded from billets. Afterwards, they are sent to Kawneer, the system supplier, who assembles the aluminium "baby" profiles with polyamide thermal breaks, and the hardware pieces and accessories are assembled in the factory, as explained in Section 5.1.2 Manufacturing and Logistics. Next, façade builders, receive the different components, and assemble them to manufacture a complete façade system. The final product is then delivered to the user/owner, who is responsible for

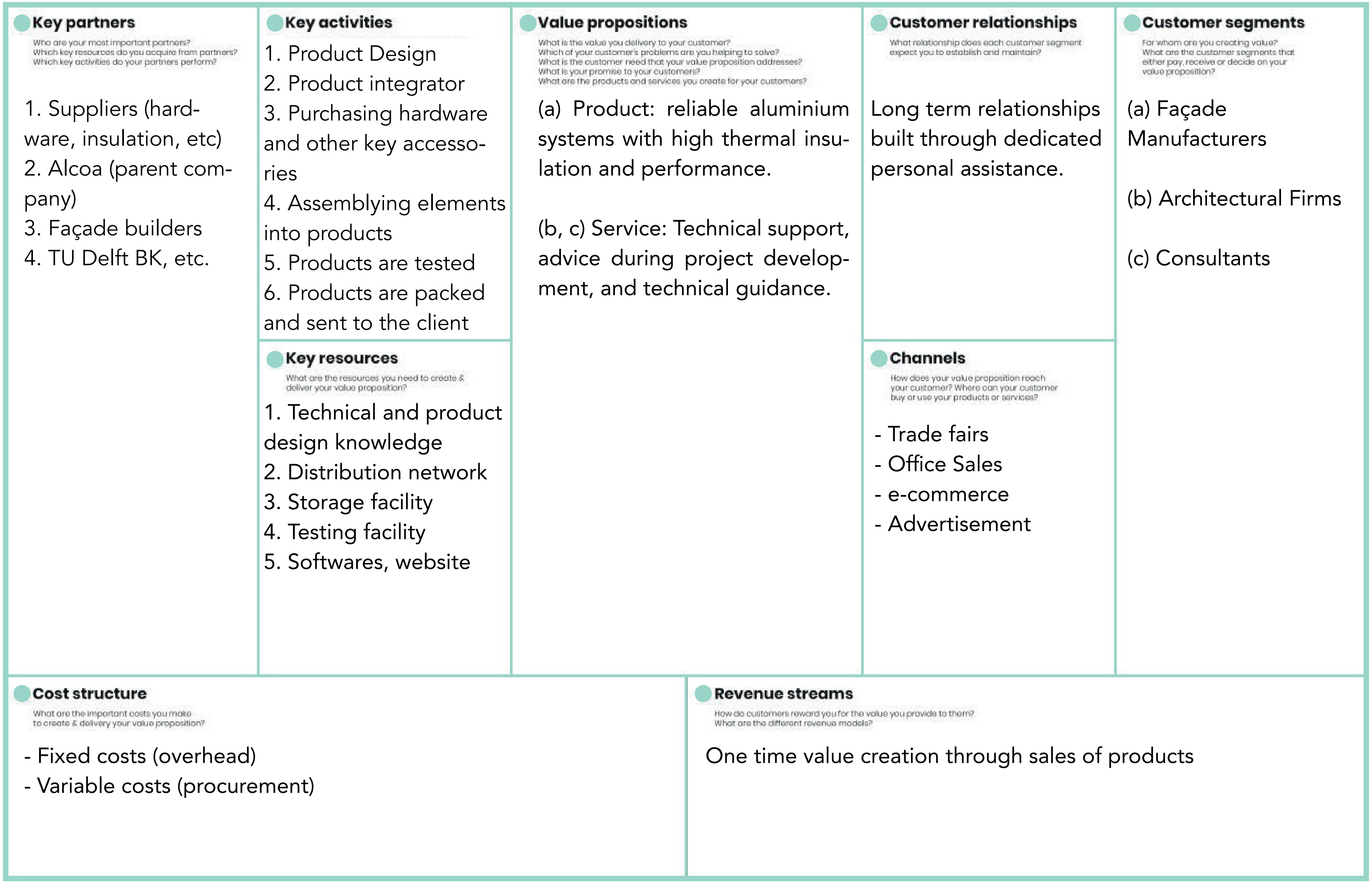


Figure 5.5 Business Model Canvas according to the current linear business model from Kawneer Nederland. Image by author.

maintenance. When the product reaches its end-of-life, there is an alternative to demolition: recycling.

There is a collection and separation of the materials to group the 6060 aluminium products that have the potential to be recycled. HKS is the recycling company in charge of this. The products are then melted into aluminium billets in the Netherlands. After that, they are shipped to Belgium where the aluminium profiles are extruded, and then supplied again to Kawneer. While this is a much better option than waste or demolition, the products have a much larger potential to have other (re)life options that just recycling. As it was stated in Chapter 2, recycling is the last option in the diagram for a circular economy. It should be further studied which would be the other possible end-of-life/end-of-service scenarios for Kawneer products, and find a long-term sustainable solution.

5.5 Circularity Interview and Brainstorming Session

On the 27th of February, an interview and brainstorming session was held at Kawneer Nederland B.V. headquarters in Harderwijk, Netherlands, with Wijnand van Manen (sustainability and circularity expert for Kawneer, and guest supervisor), Andre Smit (project manager for Kawneer), and Martijn Veerman (specialist on circular façades at Alkondor Hengelo B.V.). The aim of this meeting was to interview these three different stakeholders that have expertise on circular façades. The full transcript of the interview can be found at the Appendix. The following were some of the key remarks from this interview and brainstorming session:

> *"Nowadays we see maintenance as 'corrective maintenance', which means that we do something when it's too late. There is a linear way of thinking if you do it like this. It is very expensive to come everytime back when the product is not working anymore [...] So this pushed us to move forward to 'predictive maintenance'". - M. Veerman*

> *[talking about market demand for remanufactured windows] "But then an important point is who is our potential client for the second-use façade? Maybe it is not an architect, but it is a real-estate owner." - M. Veerman*

> *[talking about disassembly] "Sorry, but on the other hand you throw away money. And this is also one of the principles of the CE: to keep the value as it is. So first, you want to keep the materials of course, but then someone from Alkondor took the time in making that corner connection. And if you take the parts apart to make a new one, then you throw away the effort put into creating this existing corner connection. That is why it is really interesting that if you are able to use the first option of the complete window. That is the way we throw away the least." - A. Smit*

> *"So then it is important to be as flexible as possible, easy to upgrade the system, but also the value of this element. Everything is about the money. And when it is the price in this 15-30 years or 45 years, when the price is totally less than on the way as we work in this time, then it is easier to sell it. Because the materials are not so expensive, but the working hours of the people, these are expensive." - W. van Manen*

> *"A circular façade is a service which is delivered as a sub-solution of building as a service, in which it is more about the function and the performance, than the product itself. A circular façade is delivered to the large cycle of the building, or the function of the building, and it follows a series of loops in a chain where it always comes back, not as waste, but as raw material." - M. Veerman, Alkondor*

> *"A circular façade is designed carefully, along with the building products in it. It should be cheap, conscientiously used, constantly maintained, and not damaged; so it can live for as long as possible. If the façade is no longer in use, it should be given to a new user. It should be reused for as long as possible". - A. Smit, Kawneer.*

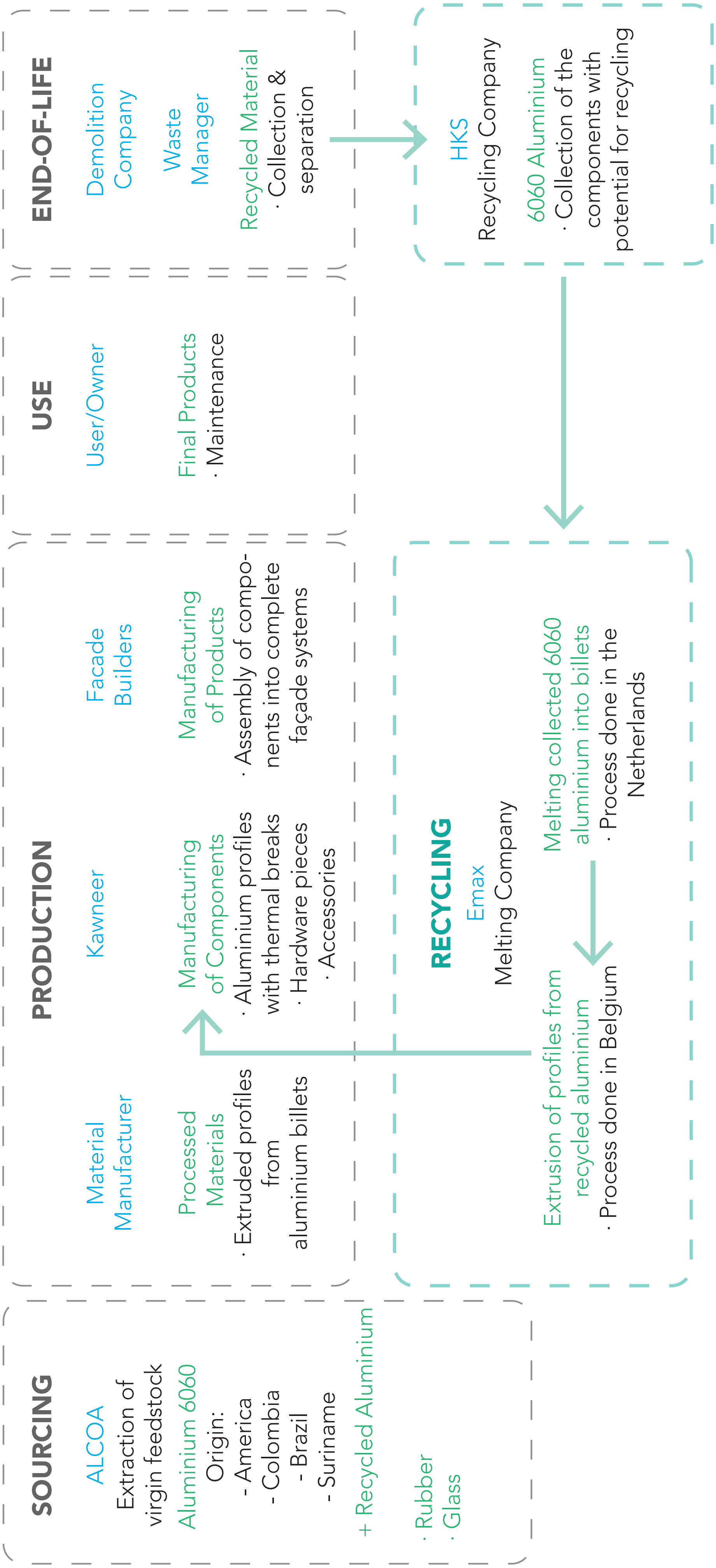


Figure 5.6 Diagram of the current life cycle of products from Kawneer. Image by author.

The feedback given by these three important stakeholders served as important input for the design process, which will be further explained in Chapter 8 Designing a Circular Window System.

5.6 Conclusions on Chapter 5

In this Chapter, different aspects from the company were analyzed. First, the company's vision and strategy that at the moment, aims to shift from a linear to a circular model. Then, the RT 82 HI + was described, along with its relationship with the other window series from Kawneer, like the 52, 62, and 72. The RT 82 HI + stands out from the rest of the series because it has the higher level of insulation, and it also holds a Passive House certificate, and with an extremely slim frame. The current manufacturing and logistics of the company was also analysed through understanding it into four different segments: sourcing, production, use and end-of-life. During the sourcing, the raw material is extracted by the parent company, Alcoa. The production process starts when the raw material is processed into billets, and then extruded into profiles, which are sent to Kawneer. The aluminium profiles are rolled with the thermal breaks at Kawneer's factory, and then sold to façade manufacturers disassembled.

According to the façade design, the client assembled the profiles, hardware and other accessories, and the façade system is installed. During the use phase, it receives service through a maintenance company. Once the product reaches its end of life, the only (re) life option is recycling. This is done by HKS, a recycling company, that collects the 6060 aluminium alloy, and then in remelted by Emax, a melting company. The 6060 alloy is then reintroduced into the chain as virgin feedstock, and the product process restarts from this point.

The current business model was analysed by applying a Business Model Canvas, where it was found that the current business model is linear, and there is room for improvement towards a circular business model, already reviewed on Chapters 2 - 4.

The analysis presented in this Chapter will also serve as important input towards the redesign of the system, as well as the development of a business model that supports remanufacturing. This will be further explained in Chapter 8 Designing a Circular Window System.

06.

Window Systems

This Chapter is the fifth part of the literature review: window systems. An overview and evolution on windows is presented in the first two Sections. Section 6.3 explains the different types of hardware, while Section 6.4 describes how glass is fitted through seals, aided by Section 6.5, window installation. Section 6.6 explains five different types of window typologies. Section 6.7 explains thoroughly the different types of window systems by material: wood, steel, aluminium, uPVC, GRP, and two hybrid types (aluminium/wood and aluminium/uPVC). Section 6.8 compares the findings on each window system by material through a Harris Profiles matrix. Section 6.9 is a state-of-the-art on window systems by material, similar to Section 6.7, but by presenting specific products from different providers. Section 6.10 concludes the findings through the elaboration of an element-function matrix.

List of Figures:

Fig. 6.0 View of Bettenhous SHK by GBK Architekten. Image by gbk-architekten.de
Fig. 6.1 Internal view of façade from Notre Dame du Haut in Ronchamp, France, by Le Corbusier. Image by archdaily.com
Fig. 6.2 Window hinge. Image by eraeverywhere.com
Fig. 6.3 Window seal. Image by feldcocedarrapids.com
Fig. 6.4 Collection of images of window typologies. Top left: Punched windows. Top right: Window Strip. Center left: French window. Center right: Window - wall. Bottom: Curtain wall. Images by: pixabay.com; france-voyage.com; balconette.co.uk; remi.com; designingbuildings.co.uk
Fig. 6.5 3D view of a wooden window in a brick cavity wall. Image by Watts (2014).
Fig. 6.6 Double glazed steel frame. Image by Watts (2014).
Fig. 6.7 Collection of images of Kawneer's aluminium window frames. : Top: Exploded axonometry of the RT 82 HI + Aluminium Window System. Bottom: Front view of the RT 52/62/72/82.
Image by Kawneer Nederland (2018)
Fig. 6.8 Collection of images of uPVC frames. Top: Isometric view, image by archiexpo.com ; bottom: origin-global.com
Fig. 6.9 Collection of images of GRP frames. Top image: installation of a GRP window. Bottom: GRP profiles. Image by fiberline.com
Fig. 6.10 Collection of images of an Aluminium/Wooden window. Image by: pinus-window.com
Fig. 6.11 Collection of images of two different Aluminium/uPVC windows. Top image by archiproducts.com bottom image by cdn.finstral.com
Fig. 6.12 Analysis on the RT 82 HI + window frame. Image by author
Fig. 6.13 View of the CS 104 HI window system. Image by Renaers (2019).
Fig. 6.14 Analysis on the CS 104 HI window frame. Image by author.
Fig. 6.15 View of the AWS 90 SI + Window System. Image by Shüco (2019).
Fig. 6.16 Analysis on the AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco. Image by author
Fig. 6.17 Axonometric view of the Opificium TABS window system. Image by Palladio (2019)
Fig. 6.18 Analysis on the Opificium TABS Steel Triple Glazed Window Frame - Palladio. Image by author
Fig. 6.19 Image by uPVC Triple Glazed Prestige Window Frame. Image by Inoutic (2019).
Fig. 6.20 Analysis on the uPVC Triple Glazed Prestige Window Frame. Image by author, based on Fradelou (2013).
Fig. 6.21 View of the Titan Aluminium/Wooden Triple Glazed Window Frame. Image by Josko (2019).
Fig. 6.22 Analysis of the Titan Wooden/Aluminium Triple Glazed Window Frame. Image by author, based on Fradelou (2013).
Fig. 6.23 View of the GRP Triple Glazed Window Frame. Image by Ecliptica (2019).
Fig. 6.24 View of the GRP Triple Glazed Window Frame by Ecliptica (2019). Image by author, based on Fradelou (2013).
Fig. 6.25 View of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame. Image by Josko (2019).
Fig. 6.26 Analysis of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame. Image by author based on Fradelou (2013).
Fig. 6.27 Matrix on the analysis of the different element-functions of the eight window systems. Image by author.

Figure 6.0 View of Bettenhous SHK by GBK Architekten. Image by gbk-architekten.de

6.1 Overview: Openings

A space is defined by floor, walls and ceilings, but also by the position and type of its opening. The location of such openings in a façade is also closely related to the height and width of a room. Additionally, the type and location of openings are also closely related to human activities such as resting, walking, standing still (French windows, for instance), sitting, and working (longitudinal windows). The type of user is also important, for example, in a Kindergarten, windows might be lower for the kids. The design of components such as the height of a parapet and lintel is highly crucial to understand in the design of a window. Rebates, or the reveals of an angle are other important factors that might affect the quality of outlook and light influx (Hochberg et al, 2009).

The function of a building also determines specific requirements for a façade, and thus, its openings. Residential buildings, for instance, might have different requirements for each area (living room, bedroom, etc), depending on the legislation, level of privacy, and climate conditions. Office workspaces have a high demand for illumination and glare protection at the same time. Industrial buildings have a high demand for lighting but no outside views. These type of requirements for each opening also give each building a different character.

Figure 6.1 Internal view of façade from Notre Dame du Haut in Ronchamp, France, by Le Corbusier. Image by archdaily.com

6.2 Evolution

According to Hochberg et al. (2009), the opening has evolved from the archetypal hole or slit to a complex architectural component: the window. This complex change is integral with the rapid changes in technology, construction, new materials and production processes. “The history of Architecture is the history of the window”, Le Corbusier (Figure 6.1) declared in the 20th century (Hochberg et al., 2009). Innovations in steel, glass, and reinforced concrete in the 19th century lead to a greater spatial freedom.

Structural frames liberated the envelope from the load bearing structure, and the level of transparency in façades increased dramatically. The window transformed into a wall, or rather the wall into a window. The transparent wall with glass separating wild nature and domesticity provided safety and protection, while still creating a connection with the outdoor environment. Panoramic windows, strip windows, bay windows and glass walls are new elements that add a new spatial dimension. The improvements in glass manufacturing also became a turning point, as float-glass technology lead towards larger glazing surfaces. The liberation of the façade from the structural functions of the building also allowed to treat openings as a design concept considering its construction, proportion, and protection; along with other architectural qualities such as patterns and composition of a façade.

Openings lead to a series of negative and positive spaces that interplay between solid and void surfaces. Therefore, windows become part of a living concept that "unites personal living space, with the outside world, and bringing sight of the environment into the living spaces" (Hochberg et al., 2009). Today, the design possibilities of windows seem limitless. There are windows for different functions, climates, made out of different materials, and they might have a high importance in the character of the building.

During the last decades, higher water and air tightness barriers have been incorporated to window design. Air infiltration in the opening has been considerably reduced by adding rubber-based seals held in place through aluminium clips. They can easily be replaced when the seals are worn out. Watertightness has also been highly improved with the addition of pressure equalised rebates in the window Section. This way, when the water enters the profiles at the sides, it will be drained away from the cavity, but without being drawn into the inner seal, between the inside and outside frame (Watts, 2014). The outer seal will prevent the excess infiltration of water, and the inner seal also has an acoustic barrier function.

6.3 Hardware

Window hardware refers to the collection of parts that allow the window system to operate. This means, it allows it to open, close, lock, or hold together certain pieces. Knaack et al. (2007), states that "fittings such as hinges and stays are the connection between the element and the façade construction, and are used at the exterior interface between secondary structure and infill elements". Hardware components are usually available in standard solutions, and they should be coordinated with the structure of the selected façade system.

Hinges (as seen in Figure 6.2) are the moving connection among the sash and the window frame. Commonly, hinges are composed of two parts, and they can either be called 'drill-in hinges', 'surface hinges' (screwed or nailed in place), or a 'mortise hinge' (butt hinge), or 'lift-off hinge' (notched in). The selection of the hinge type depends on the weight of the frame and glass that needs to be supported. They can also have more than one part, if the load is too high. Hinged fittings are also commonly manufactured in steel or aluminium, and the fixing method might depend on the material of the frame. For instance, in the case of wood, they are drilled, mortised or routed; where in the case of plastic, drilled or screwed. Additionally, in the case of aluminium, they can be either clamped, or welded in place, but also screwed.

However, the finishing of the material is also important, because the hinges are usually visible for the user, and they affect the general aesthetics of the window. The different finishes currently available in the market are matt-nickel plated, chromium plated, stainless steel, and standard color plastic coatings. However, while the finish might be important due to the aesthetic qualities, it is also related to the durability of the hinge, which might be even more important. The hinges should be corrosion resistant, like anodised aluminium, or stainless steel.

Hochberg et al. (2009) classifies the different hinges types in the following four categories:

I. Mortise hinges: They have two plates that are mortised to the frame. The bottom one with the pintle on the window frame, and the top one with a gudgeon on the sash. A routing machine makes slots on the frame, and then the mortise hinge is introduced. Metal pins are inserted through the frame to fix the hinge in place. Screws can also be used. Mortise hinges are only used with rebated windows.
II. Drill-in hinges: These hinges are fixed with the use of drill-in studs. These are drilled into the window frame through jigs or templates. The drill-in hinge has a leave which is attached by screws to the frames.

Figure 6.2 Window hinge. Image by eraeverywhere.com

III. Pivot hinges: This type of hinge allows the designer to create hidden openings. Angle hinges and/or corner hinges might be used to attach a sash, and also to strengthen it.
IV. Strap and snake hinges: These have different variations in geometry, from an 'S' shape or a rounded shovel. They follow the same principle as angle corner hinges.

6.3.1 Functional Hardware

If the window is required to perform a movement more complex than pivoting of the sash, then functional hardware is required. Hochberg et al. (2009) classifies functional hardware in six different types: rooflight fittings, tilt-turn, horizontally pivoting, sliding window, vertically pivoting, and intrusion resistant fittings (mushroom-head locking points).

Tilt-turn fittings were popularized in Germany by post-war buildings, and then introduced by the DIN 68121 in 1968. This hardware design allows window sashes to be operated through a handle and brought into a pivoted position; or, through a scissor mechanism, into a tilted setting. If the user desires limited ventilation, the window is opened by tilting the sash. This position can be held for long through the use of a simple side-hung casement window, and there is a special hook and eye fitting. This is an easy way to ventilate the space without completely opening the window, called 'gap ventilation'. After a long period of time, gap ventilation can be as effective as cross ventilation.

The most popular functional window hardware element is the turning handle. There are different functions that can be performed with the simple movement: opening, closing, and tilting. Single armed levers were introduced recently as a new form of window lock, and they allow the user to apply a stronger force when the inner mechanism is moved, and it also gives a visual indicator if the sash is locked. This type of hardware is fixed by using simple elements, such as bolts (drawn or slid into position), a quarter-turn sash fastener, or a single or double armed (clamped by friction to a wire stirrup at the top of the side). Other types of window locks are wing hooks, pivoting bolts, drop latches, turning bolts or espagnolettes, and lever bolts.

6.4 Fitting Glass

The connexion between the glazing or fitting panels strengthens the sash of a window. The weight of the glass should be transferred equally through support packers. The bottom sash hinge carries the weight of the glass, and when the glass is inserted into the frame, it is important that no part of

Figure 6.3 Window seal. Image by feldcocedarrapids.com

the pane is in direct contact with the frame. The previously mentioned support packers, which are the element responsible for carrying evenly the weight of the glass pane, should be positioned in a way that the frame of the sash is not damaged. Support packers are commonly found in the market in forms of hardwood or plastic (usually polypropylene). The forces from the glass panes are transferred through compression to the support packers. Additionally to the support packers, the space packers in the glass pane serve as spacers that maintain an even distance between the glass and the frame. The packers also serve the important function of providing ‘restraint free support’, which ensures that the inevitable movements of the elements in a window system occur evenly without damaging the fragile glass panes, especially in cases of thermal expansion or moisture. A glazing bead can be fixed by nailing or screwing in place the inner face of the window. This will press the glass panes against a rebate, which keeps the elements in place.

6.4.1 Window Seals

Previously, the seal for the glazing and the frame was done with stiff putty. However, over the years putty might dry out, creating cracks along its surface and cause damage. Modern construction has followed the sequence of attaching a glazing bead against a glazing strip with a wet seal (usually silicone, acrylate, polysulfide and polyurethane sealant), or in other cases, a dry seal. Dry seal systems can be understood as prefabricated gaskets, extruded with complex profiles from synthetic rubber, as seen in Figure 6.3. Nevertheless, over time, gaskets can also shrink and create gaps at the joints, which allows water to penetrate.

6.4.2 Seals

The seals in a window are important because they ensure air-and-water tightness, so they must be flexible to fulfill this function. For example, the joint between the sash and the window frame is a functional joint called ‘rebate seal’. Another important seal in a window is the wind stop, which must be easily replaceable, continuous peripheral, and it should not be displaced.

Seals are usually found in the form of PVC or rubber gaskets. The type of shape is closely related to the material they are being used on: wood, plastic or metal. These type of shapes allow the seal to deform, and go back to its original form, allowing flexibility. Seals need to be cleaned regularly and maintained, and therefore, installed in a way that they are easy to remove. Other types of seals are:

sash rebate seals, projecting seals, window frame seals, and double rebate seals.

6.5 Window Installation

The degree of thermal and acoustic insulation a window can provide is also highly determined by the way it is attached to the construction. The fixing method and connections depend directly on the material of the window and the wall is connected to. Window openings might have an internal rebate, external rebate, or in other cases, none at all. The window frame should be attached to the construction in 80 cm intervals, with a rigid connection that allows movement. These connections, aside from holding the window in place, also have the function of transferring the forces safely into the building. A secondary frame, or a window case can also be used to allow easy replacement of a window. Dowels, straps, fishtails and angles, which are the common fixing elements, are able to carry horizontal forces. Screws, and other fixing elements that are installed should also be corrosion resistant.

The joint between the window and the wall should be carefully designed. This joint is formed with a flexible sealant that allows movement. Two seals are placed in the wall: one on the inside and one on the outside. On the inside, the sealant should be continuous and against water vapour. On the outside, it must protect against the climate, especially water penetration. It is common to use foam in situ to provide insulation for the joint. This material adjusts easily and fills uneven connection surfaces (i.e. brickwork). However, it is important to understand that a foam is not a sealant, and it is also not able to carry load.

6.5.1 Installation with Window Cases

A mounting window case is described by Hochberg et al. (2009) as "an auxiliary construction that separates the formation of the window joint from the main processes of building, and permits easy removal of the window when it requires replacement". This element has two important functions: it fixes the window to the construction, and it transfers the load from it. The window cases are usually installed during the 'finishing' phase of the building's construction. The cases should be designed and installed to ensure that the sealing fulfills all requirements, so for example, thermal expansion or floor deflections should be taken into account. Additionally, the case should not reduce the thermal insulation of the window frame, so it should be taken into account when doing thermal calculations. The window case simplifies the building processes, saves time and makes the replacement more precise.

6.6 Window Typologies

Hochberg et al. (2009) classifies window typologies into five according to their design form, architectural characteristics, and the type of construction needed to install them: punched windows, window strips, french windows, window-wall, and curtain wall. Figure 6.4 depicts the five typologies.

I. Punched windows: constructed with a lintel at the top, a window sill at the bottom, and with reveals on the sides. The area of the wall is commonly significantly larger than the opening area.

II. Window strips: consists of a series of window elements (usually punched windows) aligned horizontally next to each other on the same floor. They are used when sill panels are not compulsory due to architectural or structural reasons. They also allow a more flexible distribution of space. The 'tongue-and-groove' principle is commonly used as a joining method to the window frame and its sides. The sides of the frames are also joined to other parts of the building (like partition walls). Top and bottom connections are like standard punched windows.

III. French window: also called "window-door" is an opening component that starts at a floor level, and is also used as a door.

IV. Window-wall: A window wall system is a room high element consisting of different windows and doors combined together. The DIN 18056 states that it includes a windowed area built with frames, mullions, rails, filling panels (glazing or opaque), with minimum measurements of 9.00 m long and 2.00 m high.

Figure 6.4 Collection of images of window typologies. Top left: Punched windows. Top right: Window Strip. Center left: French window. Center right: Window - wall. Bottom: Curtain wall. Images by: pixabay.com; france-voyage.com; balconette.co.uk; remi.com; designingbuildings.co.uk

V. Curtain wall: external wall construction, usually for framed buildings. The curtain wall is placed in front of the construction, commonly anchored at the floor slabs. It usually consists of storey-high components, or a single load-bearing structure with vertical and horizontal rails. Solid panels and glazing are then fixed to this construction.

6.7 Window Systems by Material

Window systems can also be analysed according to their frame material. This analysis might be more complete than Hochberg et al. (2009) five typologies because it will allow the understanding of each material's properties that affect the window design. In the following Section, five different window materials are analysed (wood, steel, aluminium, uPVC, and GRP) along with case studies of each. Window systems that combine two of the five analysed materials are also presented (aluminium and wood, and aluminium and uPVC). For each window system, their manufacturing process, material properties, and the advantages and disadvantages of each, will be discussed.

6.7.1 Wooden Windows

Wooden windows are probably one of the oldest systems used in façade construction. There is a large range of design variations available in the market, and they have a high-aesthetic value. Wooden Sections form the full structural support of the glazing, which is then later on secured with glazing beads (Watts, 2014). Figure 6.5 provides a 3D view of a wooden window in a brick cavity wall.

(a) Manufacturing Process: The frames and sashes of a wooden window can be made from solid wood, laminated wood, and other materials. Common wood types are pine, spruce, teak, afrormosia, agba, redwood, sipo, etc (Hochberg et al., 2009). The wood is then milled into the profile shape that it is required by the manufacturer or client. Later on, the profiles will require to be impregnated with a wood preservative. This will protect it from mold and insect infestation. These surfaces will further on require regular maintenance and recoating. Detailing is highly important when designing wooden windows, because water should be drained immediately. However, if the window is well maintained, it can last for a really long time (Knaack et al, 2007).

(b) Material Properties: Wooden frames have great thermal insulation values. They do not require a thermal break in the profile, and they can reach a U-value from 0.3 to 0.5 W/m2K. Careful design should be taken into consideration, because if the wood profiles are not tied together, they can twist or warp when they are exposed to outside elements. Even if the surface is treated with paint or varnish, any movement related to moisture can crack the outer finish and provoke further movement inside (Watts,2014). They also require high maintenance.

(c) Advantages:
- If well maintained, durable
- High thermal performance
- Wood is a highly available material
- Easily customized
- Variety in finishes
- Low embodied energy
- Renewable resource (if there is a certification that ensures sustainable cultivation)
- Easily repaired
- Low production cost

(d) Disadvantages:
- High maintenance (for example, regular painting every 3-5 years, and complete repaint every 10)
- If the maintenance is not properly done, it can rot, break, or warp
- Low weather resistance
- Low fire resistance
- It cannot be recycled, but only downcycled.

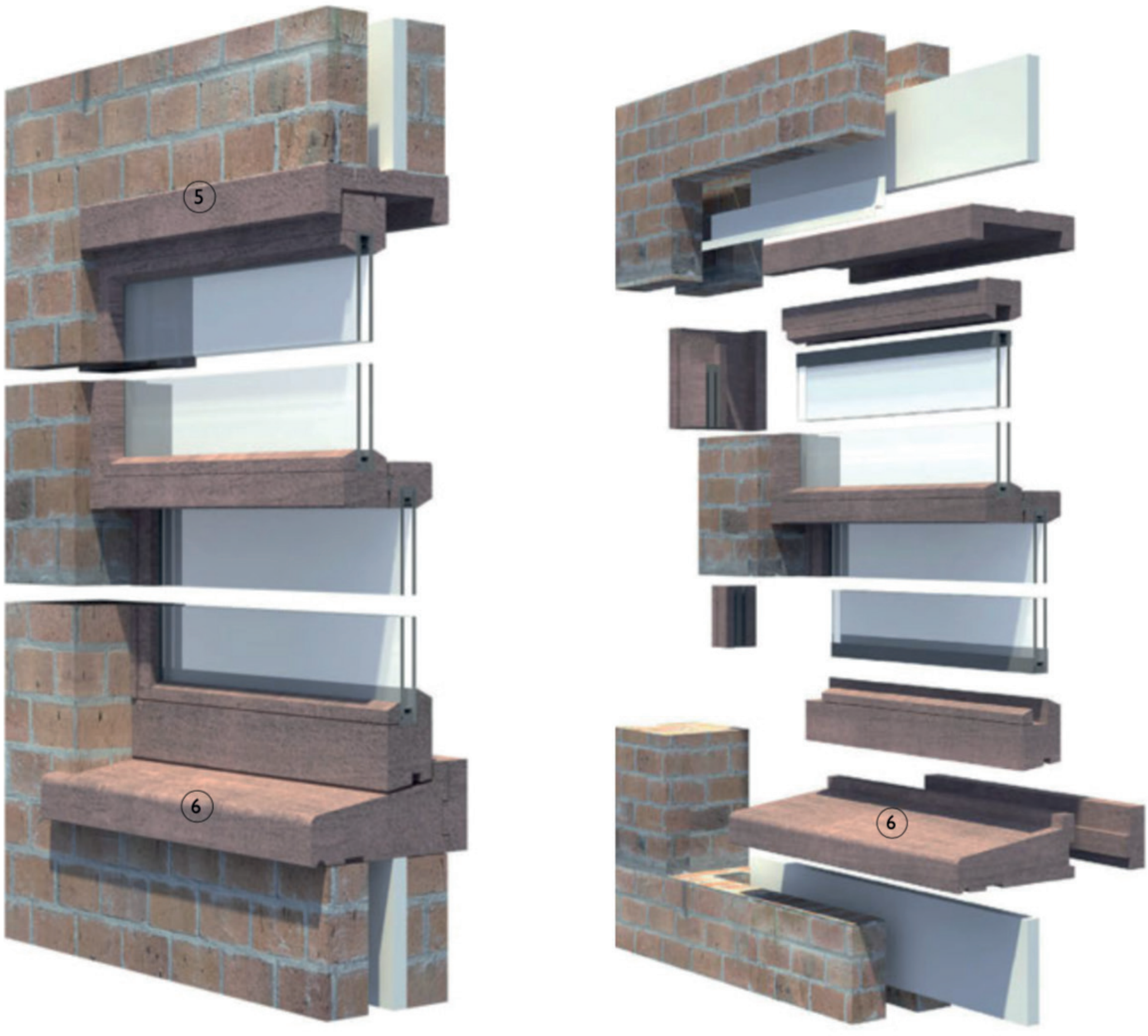


Figure 6.5 3D view of a wooden window in a brick cavity wall. Image by Watts (2014).

6.7.2 Steel Windows

(a) Manufacturing process: With the technological innovation of the 19th century, cast iron became a popular material. By the mid-twentieth century, stainless steel frames had acquired a high popularity, and thus, slender steel frames became an important characteristic of Modernism. Steel frames are commonly manufactured by combining recycled steel and virgin feedstock. They can also be produced from stainless steel, steel alloys or corten steel. The steel profiles are produced by folding metal sheets, resulting in cold-rolled hollow Sections in T-, Z-, I-, or L- shapes. Because of the nature of this production process, it is not possible to manufacture profiles with too much detail, contrary to the case of aluminium. However, in terms of accuracy, it will remain high, "with close tolerances and recesses for weather-strip rubber seals, glazing, and thermal breaks" (Watts, 2014). Figure 6.6 shows a double glazed steel frame.

(b) Material Properties: Steel windows are commonly used when fire-resistant properties are important. They provide structural integrity during a fire. However, it will not give thermal insulation to counter the heat generated by the fire (Watts, 2014). Steel frames will provide a high structural strength and stiffness, so they are ideal to cover large spans. However, steel profiles require to be thermally broken, since steel has a high thermal conductivity. The frame is divided in two parts, inner and outer, and connected through an insulating material that acts as a thermal break. The high thermal conductivity also causes water condensation in the profiles, which can be solved by detailing water collection channels in the internal window sills. Steel is also one of the heaviest materials, so this should be considered when selecting this type of frame. Additionally, it can corrode. However, if treated properly against corrosion, it can last for a long time with hardly any maintenance.

(c) Advantages

- High strength and stiffness
- Highly durable
- Low maintenance
- Slim-line frames
- Easy to clean
- If designed correctly, it can be reused or recycled
- Fire resistant

(d) Disadvantages

- High thermal conductivity, therefore, thermal breaks are necessary
- Poor resistance to condensation
- Risk of corrosion
- Heavy material

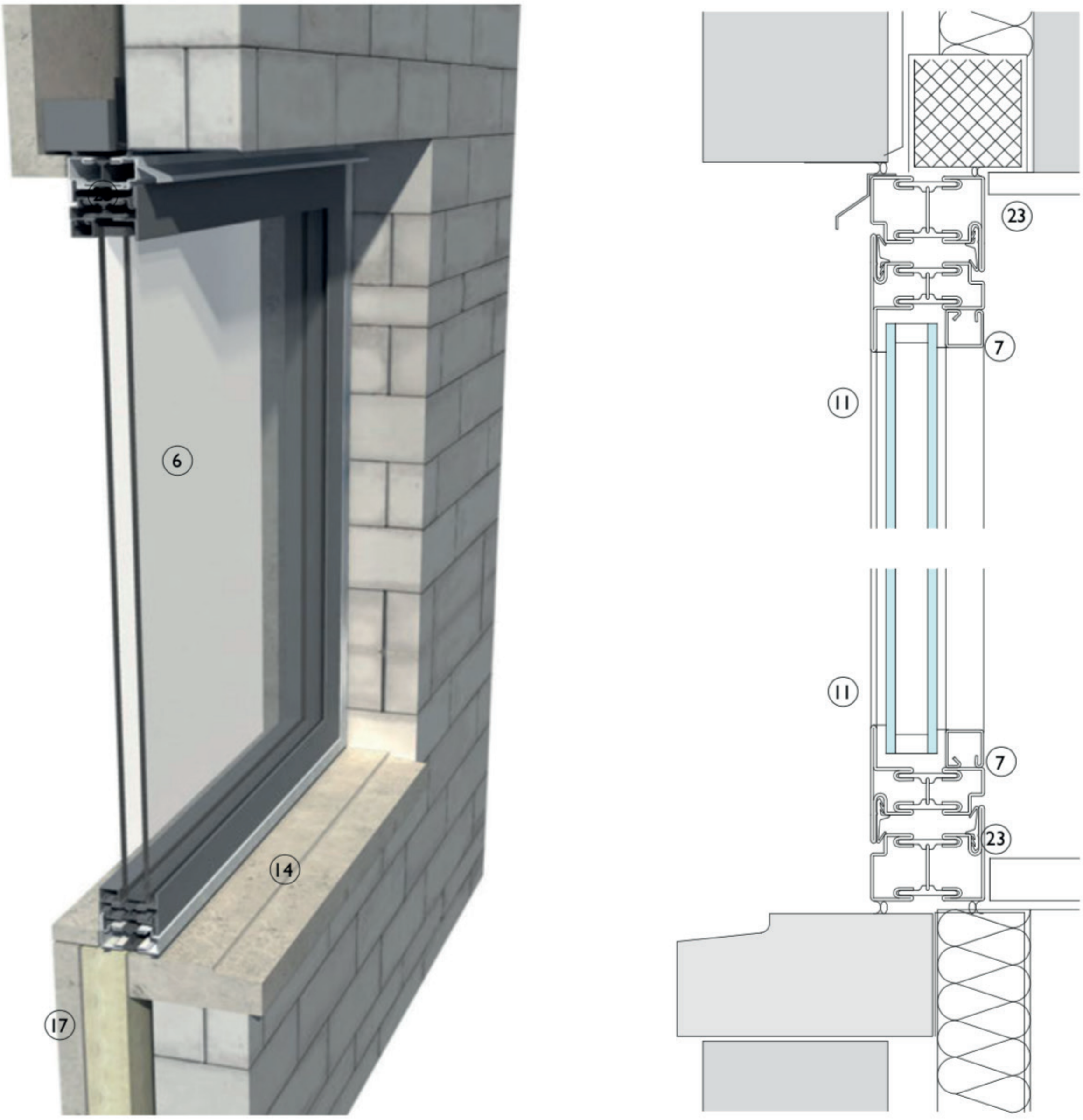


Figure 6.6 Double glazed steel frame. Image by Watts (2014).

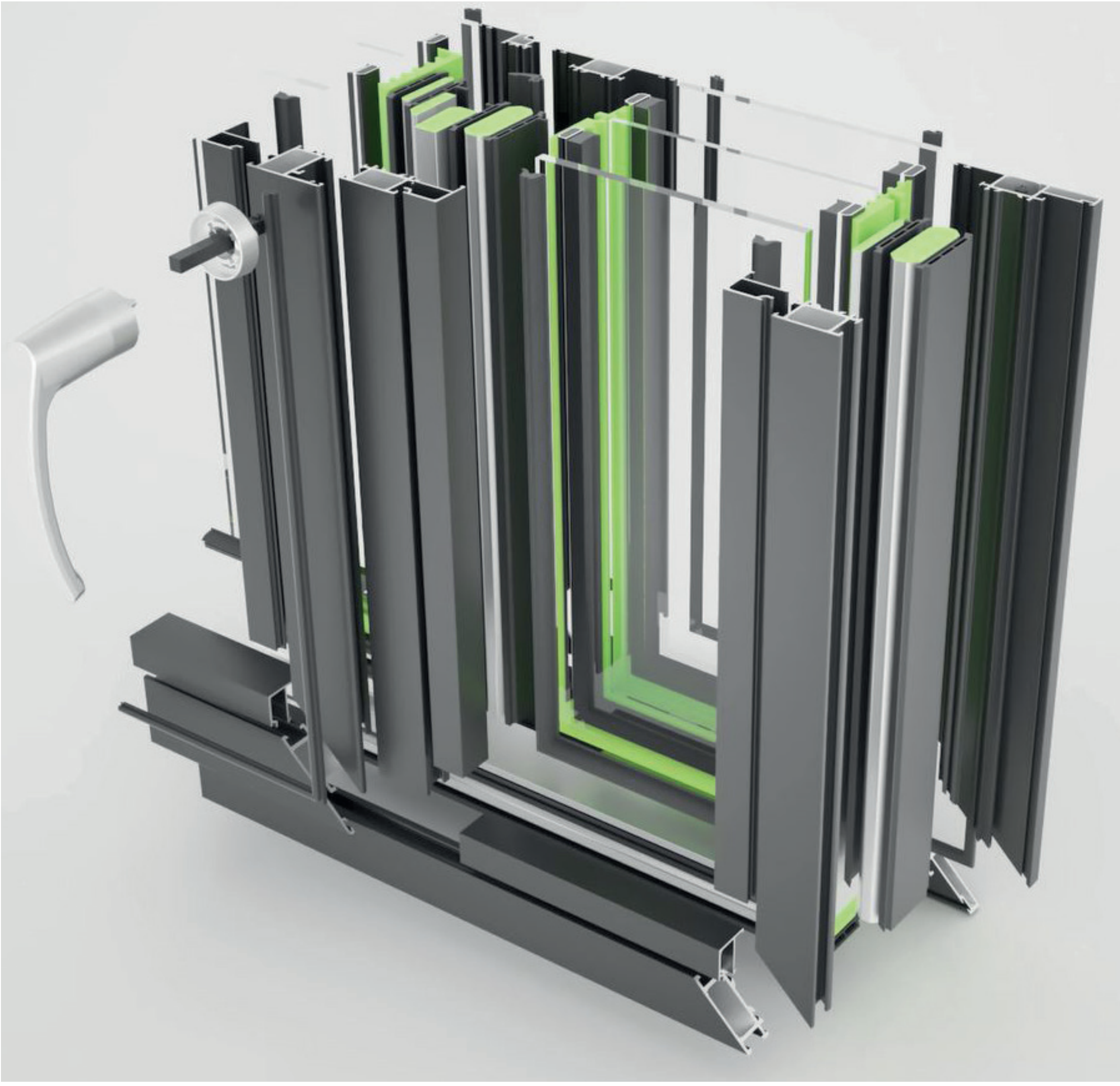
6.7.3 Aluminium Windows

(a) Manufacturing process: Aluminium is one of the most recyclable materials in the built environment. The aluminium scrapes, along with virgin feedstock, are both melted to form billets. The billets then go through an extrusion process, which allows the frame to be highly detailed and with complex shapes. The profiles can later on be finished through anodising, coating, or painting. To form the thermal break, polyamide strips and the aluminium profiles go inside a knurling machine to form the full thermally-broken frame. Unfinished aluminium can oxidise, and therefore, the profiles are treated with methods such as grinding, brushing, polishing or electrochemical process such as anodising. Powder coated processes are also applied, and these might be baked in a special oven at a temperature of 180 °C. The aluminium profiles are then connected together to form the complete frames with screwed or bolted joints.

(b) Material Properties: Aluminium frames are lightweight, strong, and stiff. It is also corrosion resistant and highly durable, thus, the frames require very little maintenance. However, aluminium has a high thermal conductivity, and that is the reason the design of the thermal breaks is highly important, as it reduces the heat from the inside to the outside. The thermal break also contributes highly to the reduction of the U-vale, from 2.0 (non-thermally broken) to 1.0, or even 0.5 W/m2K. This might increase the cost and the width of the window. Contrary to wood and steel, aluminium combines low weight with a high construction accuracy, but it might also expand more than other materials due to its high thermal conductivity. Tolerances of 1-1.5 mm/m length should be considered when designing the profiles. Figure 6.7 shows different window frames by Kawneer, where the bottom image shows a series of windows there the thermal break increases 10 mm for each series (RT 52/62/72/82).

(c) Advantages:
- Lightweight
- High strength and stiffness
- Durability (up to 70 years)
- Low maintenance
- Water and corrosion resistance
- Easy to clean
- Low cost
- Highly recyclable
- High manufacturing accuracy
- Easy to install

(d) Disadvantages
- High thermal conductivity, thus, thermal breaks are necessary
- Low condensation resistance
- High primary embodied energy



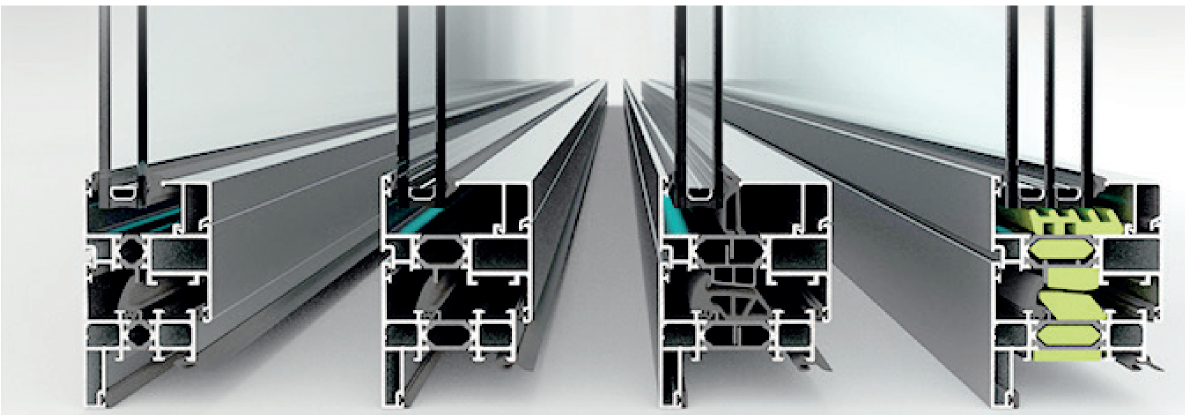


Figure 6.7 Collection of images of Kawneer's aluminium window frames. : Top: Exploded axonometry of the RT 82 HI + Aluminium Window System. Bottom: Front view of the RT 52/62/72/82.
Image by Kawneer Nederland (2018)

6.7.4 uPVC Windows

(a) Manufacturing Process: The materials needed are unplasticized polyvinyl chloride, which is heated up, and then extruded to form a shape. The profiles of a uPVC frame are hollow, and might require stiffening steel or aluminium Sections to increase the stability and load bearing capacity. The stiffeners are either riveted or screwed into the profile, but they might also increase the thermal conductivity. Because the profiles are extruded, it is possible to manufacture complex shapes and high details.

(b) Material Properties: PVC profiles have a lower stiffness, and are not recommended for large spans. They are also easy to handle during the installation and assembly, mostly due to its lightweight. They have a great thermal performance because uPVC has a low thermal conductivity, so there is no need to add a thermal break. The inside of a uPVC profile might have chambers to improve the thermal performance, and such chambers can also be filled with insulation, resulting in an even higher performance than wooden frames. The colour and texture are given to the frame during the production process, which means that the frame will require hardly any maintenance or extra finishing coating. Plastic can also creep under constant loads, which can lead to deformation if the profile is not properly reinforced. Figure 6.8 depicts two different types of uPVC frames.

(c) Advantages:

- High thermal insulation
- Lightweight
- Low maintenance
- Resistant to corrosion
- Easy to install
- Lower cost
- Complex shapes / high detail
- Low cost

(d) Disadvantages:

- Low stiffness
- High environmental impact
- Reinforcement might be required
- High thermal expansion
- Low fire resistance
- Low radiation exposure resistance
- With low or high temperatures, there can be loss of mechanical properties

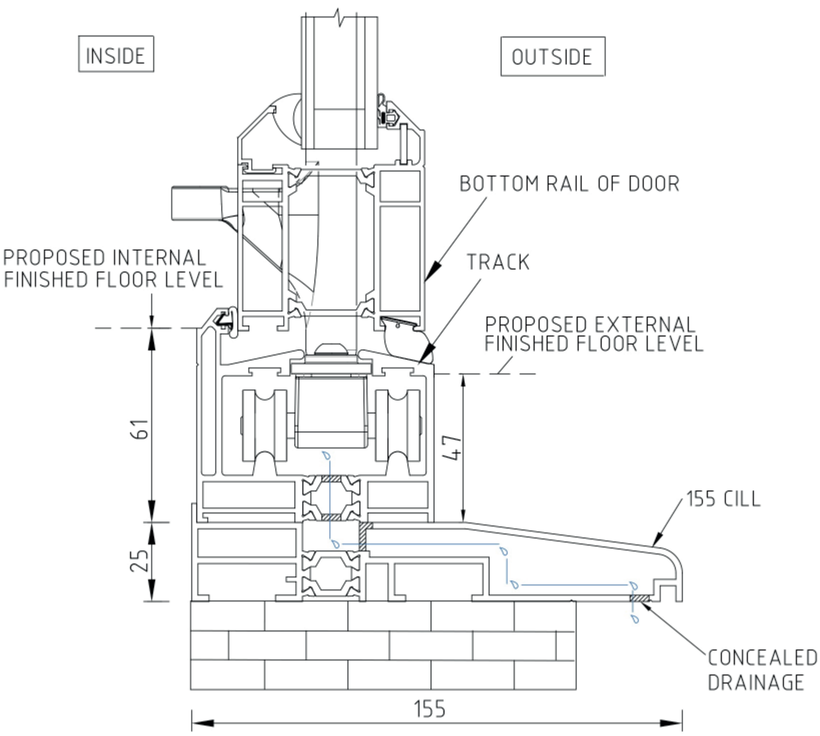


Figure 6.8 Collection of images of uPVC frames. Top: Isometric view, image by archiexpo.com ; bottom: origin-global.com

6.7.5 GRP Windows

(a) Manufacturing Process: Glass Reinforced Polymer (GRP) is pultruded to create profiles for the frames. Due to the nature of its production process, the frames can be highly detailed and complex shapes are possible. This is a relatively new material in the construction sector, but it offers endless possibilities in means of shapes and colours. It has been called by many as "the future material in the façade sector" (Fradelou, 2013). Colours are added during the production process, which means the frame does not require any further finishing. However, this production process is highly expensive and time consuming. Customization, while is possible due to the production process, is highly costly. This makes the final product very expensive

(b) Material Properties: GRP frames are highly stiff and strong, due to the nature of the glass reinforcement. Similar to other composite materials, they do not decay, and have low maintenance requirements. GRP frames are durable, have high corrosion resistance, and low thermal conductivity and thermal expansion. Therefore, it does not require a thermal break. Additionally, the air cavities inside the frame can be filled in with insulation. However, GRP frames are not easily repaired. They are highly fragile and should be carefully transported and installed. Figure 6.9 depicts different GRP frames.

(c) Advantages

- Superior thermal insulation
- Lightweight
- Durable
- High stiffness
- Low maintenance
- Water and corrosion resistance
- Easy to clean
- Available in complex shapes
- Smaller profiles in comparison to other materials
- Low thermal expansion
- Low thermal conductivity

(d) Disadvantages

- Not reusable
- High production cost
- Low fire resistance
- Difficult to repair
- Fragile product
- Limited availability by producers

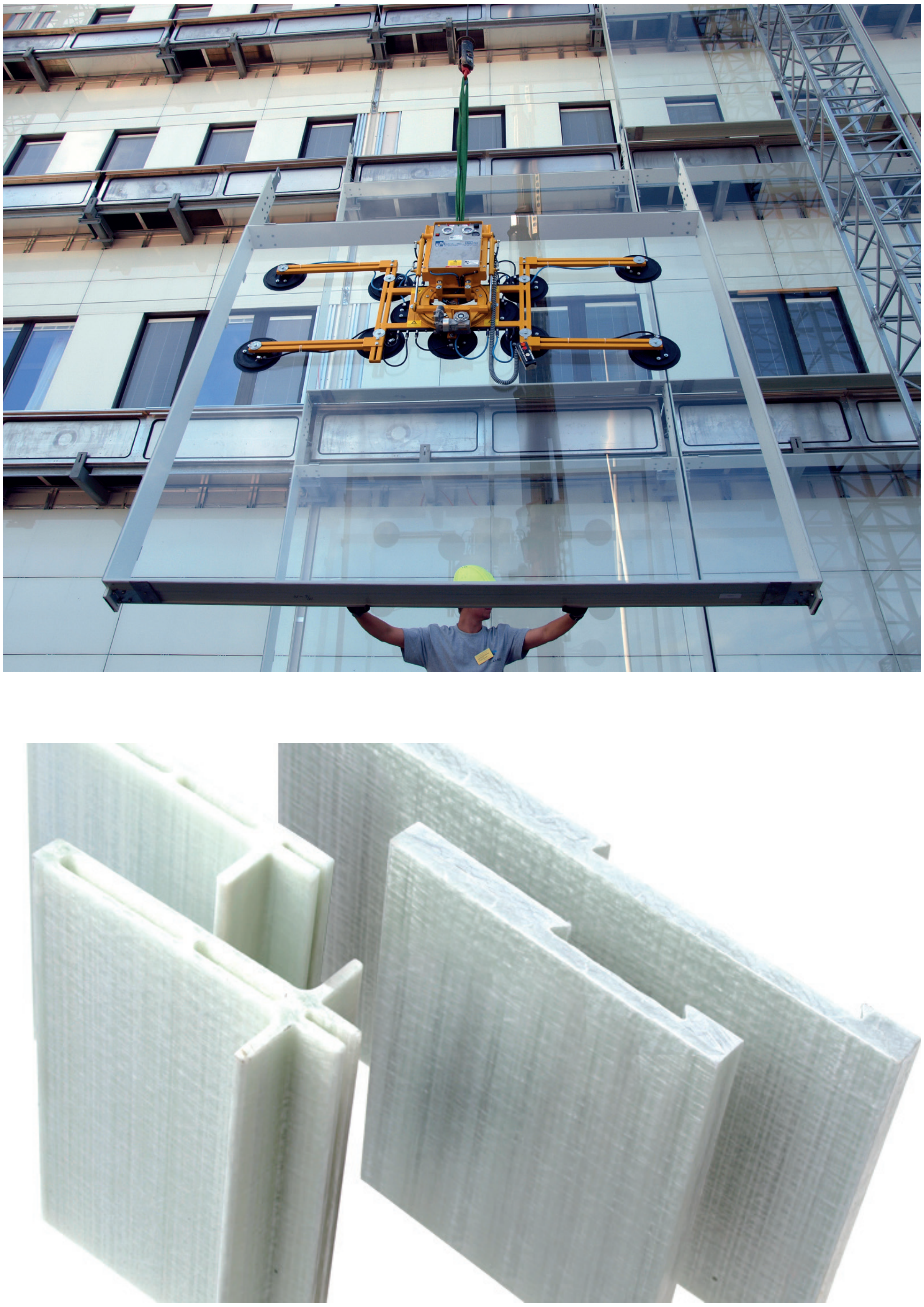


Figure 6.9 Collection of images of GRP frames. Top image: installation of a GRP window. Bottom: GRP profiles. Image by fiberline.com

6.7.6 Aluminium/Wooden Windows

(a) Manufacturing process: The system consists of a wooden load bearing frame, produced like normal wooden profiles, which is then covered with an aluminium weatherboard.

(b) System Properties: The combination of wood and aluminium have created a new type of frame that benefits from a double material solution. The aluminium weatherboard protects the wooden frame from the weather, increasing the durability of the product. Maintenance requirements are also lower in this case, due to the high durability of the aluminium protecting the wood. The thermal performance of the window remains relatively high, as wood has a low thermal conductivity, and the aluminium cover does not affect this. The aesthetic quality of a wooden window is preserved on the inside. However, some of the possible drawbacks are that the wooden frames might contract and expand during changes in temperature, which means that the gap in between the two materials should allow for this tolerance. Additionally, because of the combination of these two materials, the thermal performance might decrease if the detailing is not accurate. The cost of this system is also higher compared to normal window frames, particularly because of the aluminium. Figure 6.10 depicts an aluminium/wooden window.

(c) Advantages:

- High durability (especially compared to full wooden frames)
- High thermal performance
- Easy to customise
- Recyclable and reusable (if properly designed and disassembled)
- Low embodied energy (especially if compared to full aluminium windows)
- Easy to repair
- Low maintenance
- Impact and scratch resistance

(c) Disadvantages:

- Low fire resistance
- Higher cost
- If it is not properly detailed and maintained, it can swell, rot or warp
- Required stain or paint every 5 years approximately

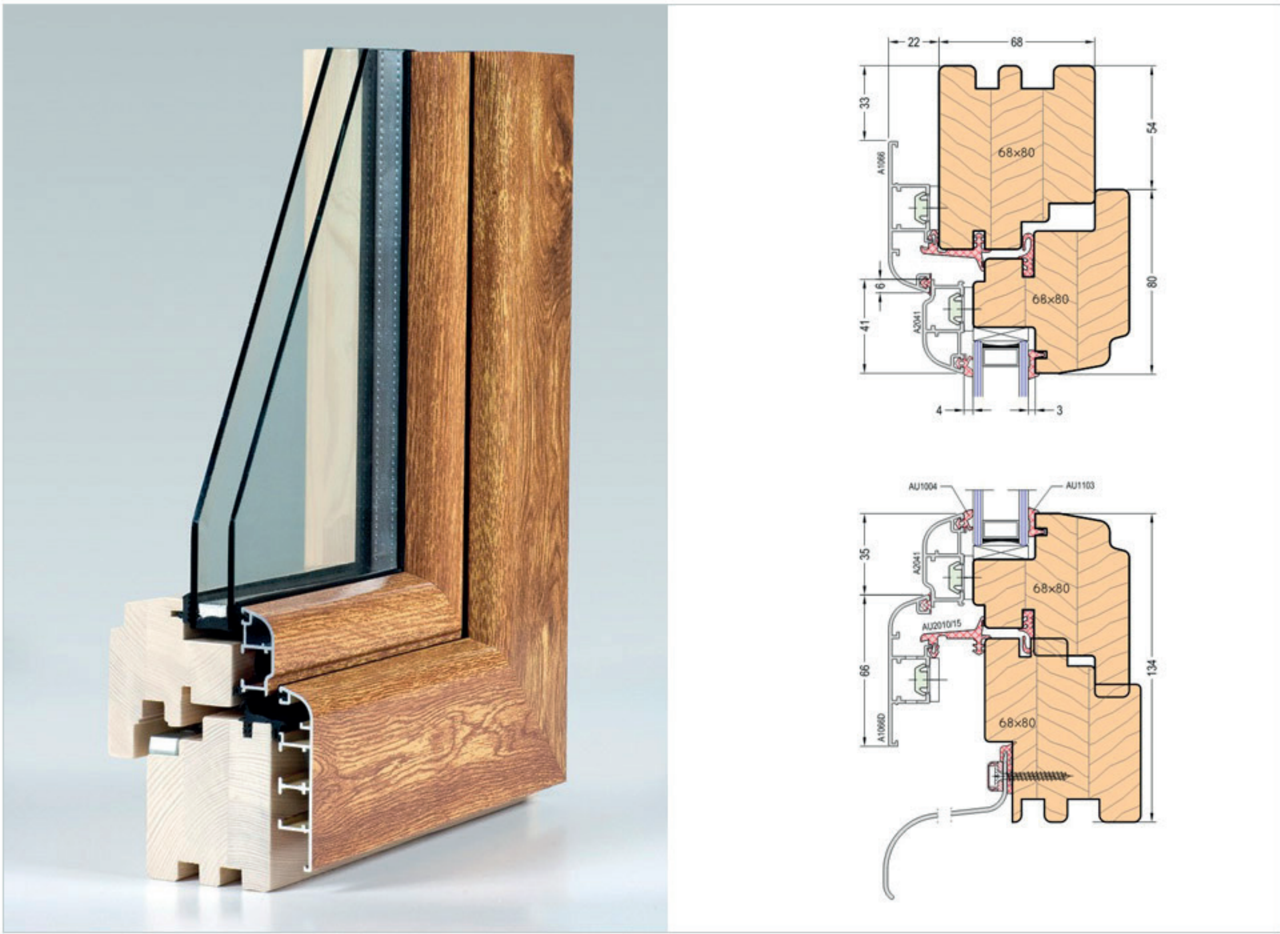


Figure 6.10 Collection of images of an Aluminium/Wooden window. Image by: pinus-window.com

6.7.7 Aluminium/uPVC Windows

(a) Manufacturing Process: Similar to Aluminium/Wooden windows, uPVC/Aluminium window systems consist of a combination of a uPVC profile that is covered with an aluminium weatherboard. The profiles are extruded from uPVC, as well as the aluminium covers, which are then placed covering the profile to create the hybrid system.

(b) System Properties: The combination of uPVC and aluminium allows the system be light-weight, stiff and strong. The external aluminium cover allows the uPVC profile to have higher durability and weather protection, making it easier to maintain. However, the combination of these two materials also has possible drawbacks. For instance, the thermal expansion of aluminium is different to the one for uPVC which can cause uneven movements. Figure 6.11 depicts two different aluminium/uPVC frames.

(c) Advantages:
- High thermal insulation
- Lightweight
- High durability
- Low maintenance
- Resistant to corrosion
- Resistance to warping and sticking

(d) Disadvantages:
- Not possible to reuse
- Low fire resistance
- Low stiffness

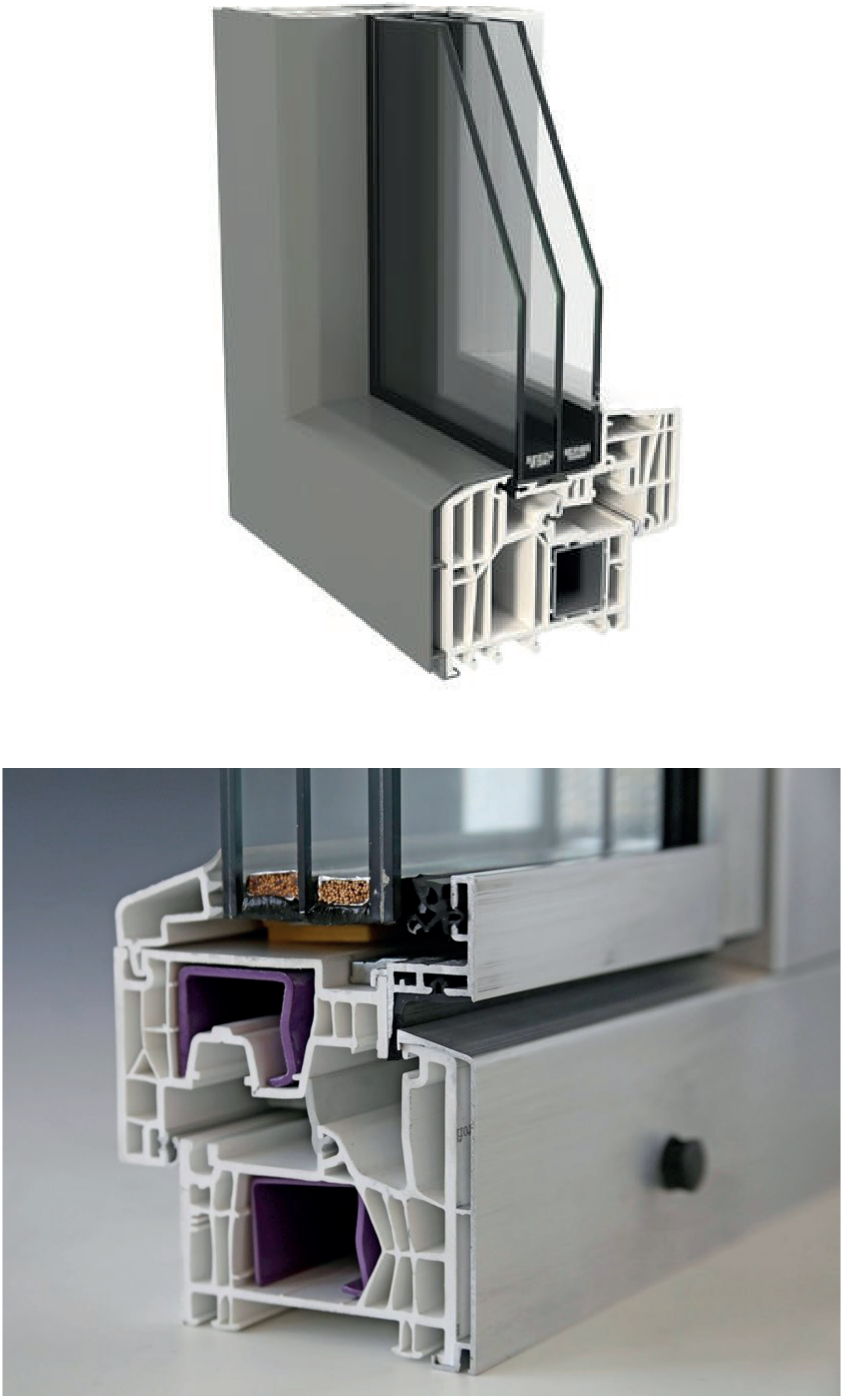


Figure 6.11 Collection of images of two different Aluminium/uPVC windows. Top image by archiproducts.com bottom image by cdn.finstral.com

6.8 Comparison Method on Window Systems: Harris Profiles Matrix

The characteristics of each window system will be assessed through a quantitative comparison: a weighted average that will determine the most suitable material for a circular window system. Different characteristics are considered, however, they are not equally weighted (from 1 - 5, 1 being the less important, and 5 the most important). This is because some properties might have higher importance than others in terms of circularity. Further explanation for the characteristics with the highest weighted values are provided as follows:

- **Cyclability:** The material/product is able to circulate hierarchically between the loops for product life-extension of repair, reuse, and remanufacture.
- **Low maintenance:** The product/material is easy to maintain through regular service checks, cleaning, and small repairs.
- **Low primary embodied energy:** Primary embodied energy refers to the total sum of all the energy required to produce any product or service, from manufacturing to transportation. This is one of the many ways the environmental impact can be measured.
- **Recyclable:** When the product reaches its end-of-life, the materials can be broken down, processed, and new materials can be created out from it.
- **Ease of repairness:** The product can be easily repaired to return it to working conditions

The matrix shows that Aluminium/Wood, Aluminium, and Steel have the highest weighted average, while U-PVC and GRP systems seem to have the lowest. Wood also scores quite high on its own, along with Aluminium/uPVC window systems. However, looking closer at the table, GRP scores higher than uPVC systems. Mostly because of the stiffness, low thermal conductivity, and low maintenance. It is important to understand that while GRP has high score for many of the properties evaluated, but in those that are weighted higher because they are related to circularity, it scores lower (except in low maintenance). This is also one of the reasons the difference between each material is so low.

While this Harris Profile Matrix is a rough approach to a quantitative method for measuring the performance of each system, it is important to understand that a limitation to this assessment might be that the score given to each property and material can be subjective, as it is focused on circularity. Perhaps for other scenarios, the materials would have a higher score. For instance, cyclability refers to the material to be able to circulate hierarchically in the loops of product life extension; while durability means that the material should last for as long as possible. However, the cyclability has a higher weight than durability. This is because durability does not ensure that the product is able to circulate. By looking closely at the table, it can be seen that in the case of GRP, the material is extremely durable, but it cannot be repaired, and if it is not installed properly, it can break, making it less suitable for a circular project, and scoring considerably low in the cyclability aspect.

The assessment weighted average matrix for each window system, where weight is: 1-2-3-4-5 ; very unimportant - unimportant - neutral - important - very important.

Materials' score is: 1-2-3-4-5-6-7 ; very unsatisfactory - unsatisfactory - slightly unsatisfactory - neutral - slightly satisfactory - very satisfactory.

The matrix shows that the best system is the hybrid variation of Aluminium/Wood, followed by aluminium window systems. Also, according to this matrix, u-PVC and GRP seem to be the worst materials, particularly because they are not able to circulate hierarchically. This will be taken further into consideration in Chapter 8. Designing a Circular Window System.

Material	Weight	Aluminium	Steel	Timber	uPVC	GRP	Al/Wood	Al/PVC
Lightness	3	6	1	4	6	7	5	6
Durability	3	7	7	6	3	7	7	7
Cyclability	5	7	7	5	2	1	7	4
High strenght	2	6	7	6	2	7	6	7
Low maintenance	4	7	6	3	6	7	7	7
Low thermal conductivity	3	1	2	7	5	7	7	4
Low initial cost	3	6	3	7	7	1	5	4
Complex shapes	1	7	5	3	7	4	3	6
Low primary embodied energy	4	1	6	7	3	5	5	4
Reusable	5	7	7	7	4	1	7	4
Ease of repairness	5	7	7	5	4	1	6	4
No need for a thermal break	x	x	x	○	○	○	○	○
Total		**5.68**	**5.60**	**5.47**	**4.27**	**4.37**	**5.96**	**5.17**

Table 6.1 Harris Profiles Matrix on the eight different window systems analysed.

6.9 State-of-the-Art: Comparison by Materials

For a further understanding of the different types of window frames and their properties, a state-of-the-art that analyses existing frames in the market was realised. The selected frames are:

I. RT 82 HI + Aluminium Triple Glazed Window Frame - Kawneer
II. CS 104 HI Aluminium Triple Glazed Window Frame - Reynaers
III. AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco
IV. Opificium TABS Steel Triple Glazed Window Frame - Palladio
V. PVC Triple Glazed Prestige Window Frame - Inoutic
VI. Titan AluminiumWooden Triple Glazed Window Frame - Josko
VII. GRP Triple Glazed Window Frame - Ecliptica
VIII. Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame - Josko

6.9.1 RT 82 HI + Aluminium Triple Glazed Window Frame - Kawneer

(a) System Description: This thermally broken aluminium window frame is the most innovative and modular system from Kawneer (2018). This window frame is the most slender in the market with the highest insulation value due to the Alcoatherm insulation technology. It also holds a Passive House phB certificate. It is possible to connect different systems of Kawneer with the RT 82 HI + due to its modular nature. In conclusion, this system offers a large variety of designs, the highest insulation value, and flexibility. Figure 6.12 is an analysis of the system.

(b) System Characteristics:
Material: Aluminium extruded profile
Alloy: EN AW 6060 T 66 (according to EN 573 anodising quality)
Construction: Symmetrical 3 chamber system
Frame depth: 82 mm (it can vary depending on the strength)
Insulation: 45mm plastic thermal break filled with AlcoaTherm insulation
Glazing capacity: Maximum 66/74 mm
Surface treatment: Anodizing (20-25 microns), powder coating, pre-treatment of 6-fold chromate, 60 microns with a gloss level of 30 or 70%.

(c) System Performance:
Insulation value: Uf = 0.79 W/m2k (according to EN 10077-2)
Certification: Passive House phB certificate
Airtightness: Class 4 (according to EN 12207)
Water resistance: 9A (according to EN 12208)

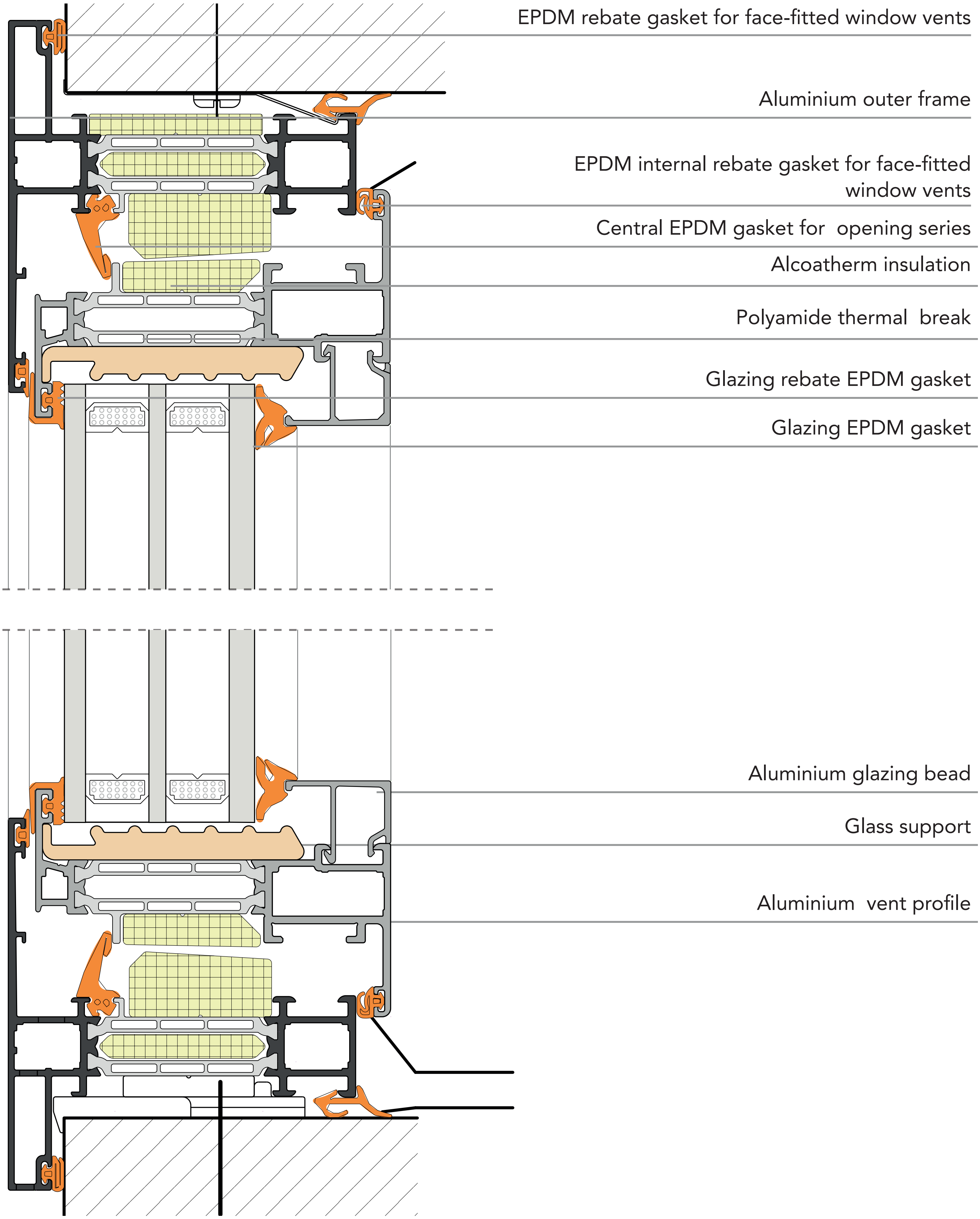


Figure 6.12 Analysis on the RT 82 HI + window frame. Image by author

6.9.2 CS 104 HI Aluminium Triple Glazed Window Frame - Reynaers

(a) System Description: The CS 104 HI aluminium frame is the solution by Reynaers for passive buildings. With the aid of a patented insulation technology which is introduced inside the thermal break, the system achieves a high thermal insulation value. Gaskets were especially redesigned for this system to achieve a higher level of wind and water tightness. The built-in depth of the profiles also provides higher strength and stability. This gives the architectural freedom of building large glazed surfaces. In conclusion, this system provides a high thermal insulation, a strong system, and high values for air, wind and water tightness. Figure 6.13 depicts the system, and Figure 6.14 is an analysis of the system.

(b) System Characteristics:
Material: Extruded aluminium
Alloy: EN AW 6060 (according to EN 573 anodising quality)
Construction: Symmetrical 3 chamber system
Frame depth: 95 mm
Insulation: 59 mm fibreglass reinforced polyamide strips
Glazing capacity: 65 mm
Surface treatment: Anodized or powder coated.

(c) System Performance:
Insulation value: Uf = 0.88 W/m2K (depending on the frame/vent combination)
Certification = None
Airtightness = 4 (600Pa) (EN 1027; EN 12208)
Watertightness: E900 (900 Pa) (EN12211; EN 12210)
Wind load resistance: 5

Figure 6.13 View of the CS 104 HI window system. Image by Renaers (2019).

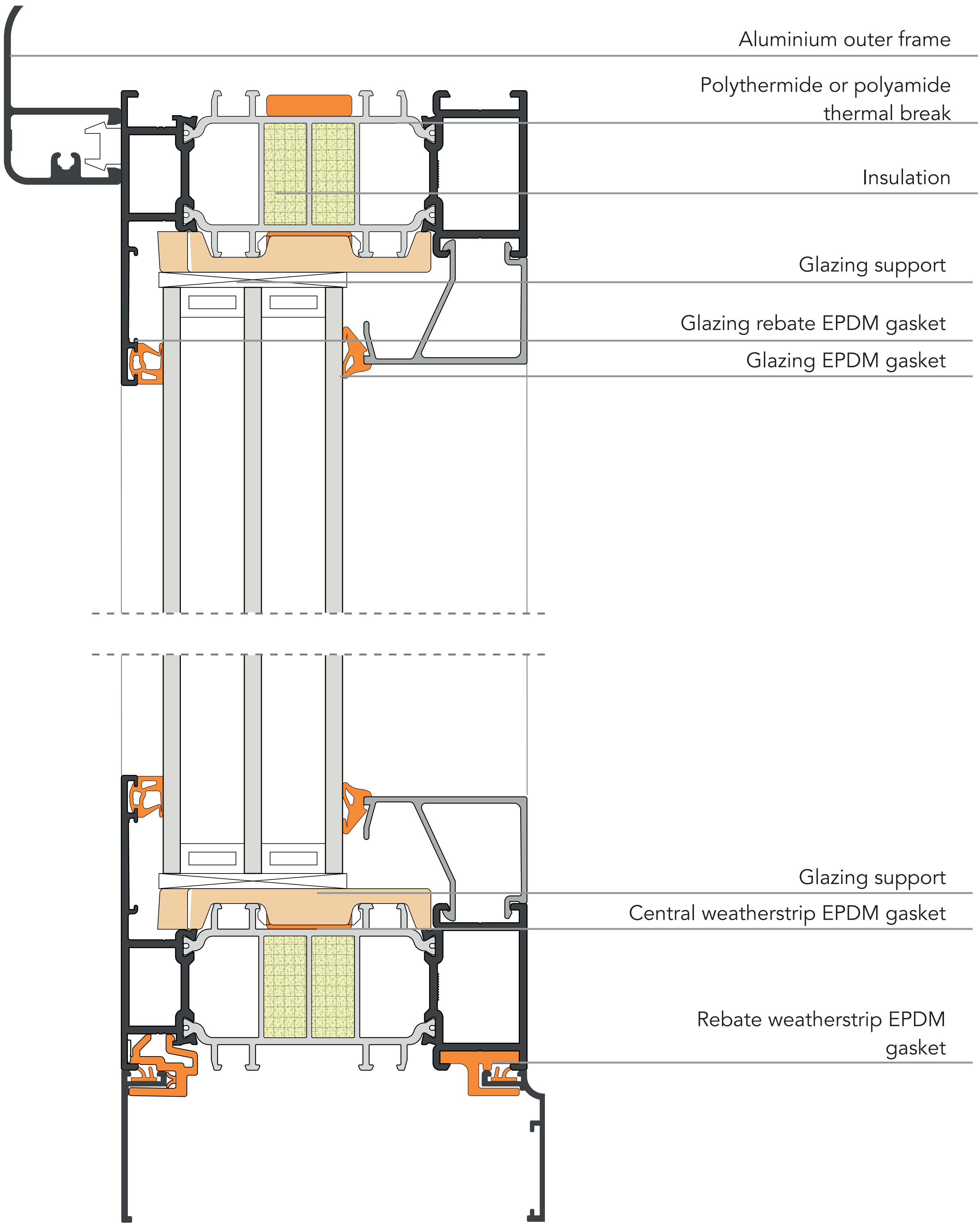


Figure 6.14 Analysis on the CS 104 HI window frame. Image by author.

6.9.3 AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco

(a) System Description: This frame system offers a modular solution with high thermal insulation values. Referred to as a "block system", the slender frames can be customisable between single and double-vent designs. If the frame is designed carefully, it is possible to achieve a passive house standard. A variation in this system is available, AWS 90 SI + Green, which uses castor oil instead of polyamide thermal breaks. In conclusion this system offers flexibility, ease of customisation, and innovative sustainable solutions. Figure 6.15 depicts the system, and Figure 6.16 is an analysis of the system.

(b) System Characteristics:
Material: Extruded aluminium
Alloy: EN AW 6060 (according to EN 573 anodising quality)
Construction: Symmetrical 3 chamber system
Frame depth: 77 mm
Insulation: 62 mm fibreglass reinforced polyamide strips (possible castor oil if upgraded to AWS 90 SI + Green)
Glazing capacity: 68 mm
Surface treatment: Powder coated, anodised, painted, duraflon, colour ranges

(c) System Performance:
Insulation value: Uf = 0.8 W/m2K (depending on the frame/vent combination), average Uf value = 1.0 W/m2K
Certification = Passive House
Airtightness = 4 (600Pa) (EN 1027; EN 12208)
Watertightness: 9A
Wind load resistance: C4/B4

Figure 6.15 View of the AWS 90 SI + Window System. Image by Shüco (2019).

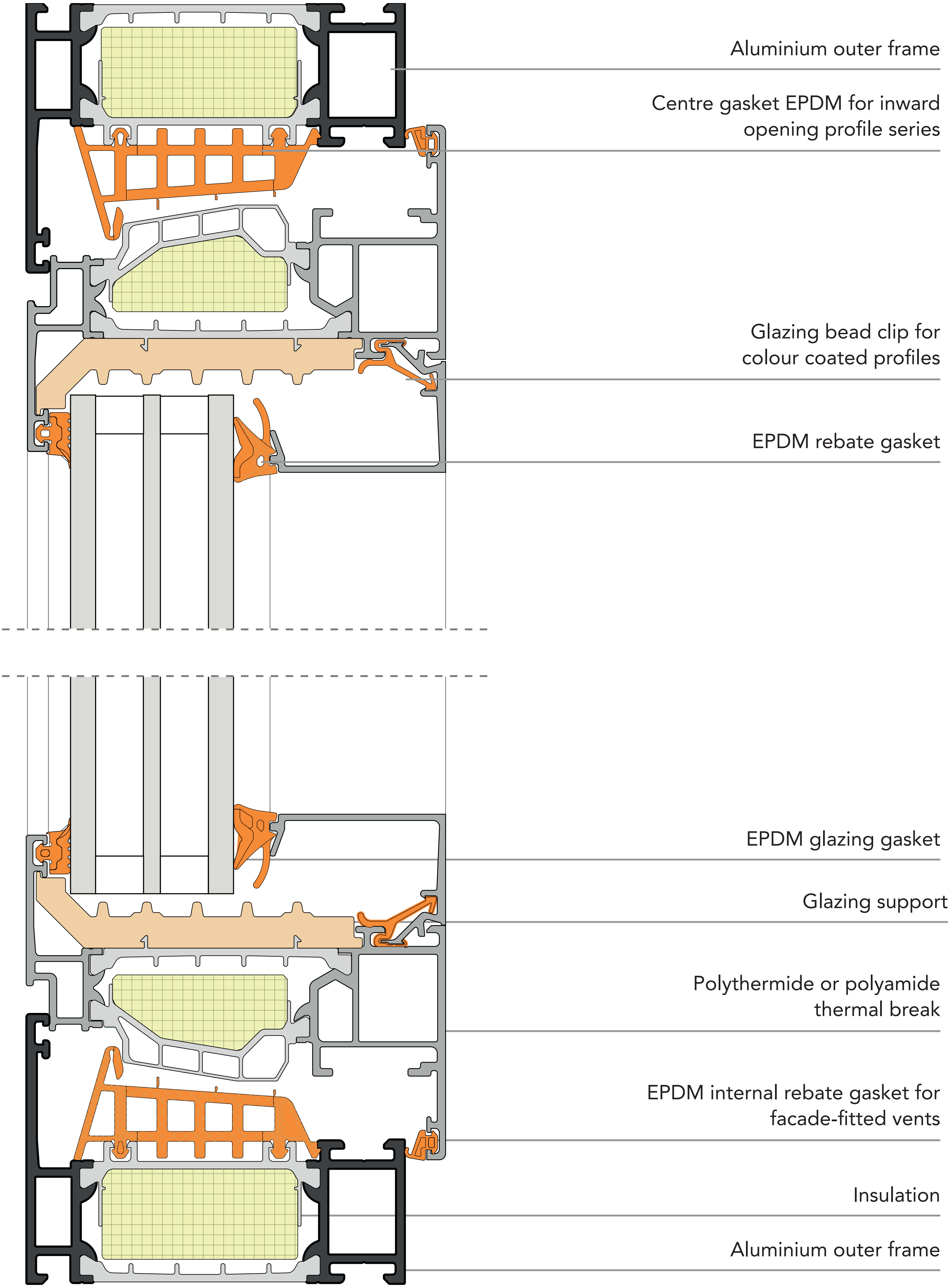


Figure 6.16 Analysis on the AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco. Image by author

6.9.4 Opificium TABS Steel Triple Glazed Window Frame - Palladio

(a) System Description: This system proposes a new type of architecture: a steel frame with a ventilated thermal break. The profiles have slots along their entire surface, and their shape and size allow the circulation of air needed to stop heat and cold transmission from one side of the profile to other. Studies showed that because of this ventilated thermal break, the dispersion of heat is limited. Because the slots in the frame allow the circulation of air, the convective movement stops or disperses the heat/cold coming from the outside. The movement of air also keeps glasses and frames dry, preventing corrosion, oxidation and moulds. The system is available in stainless steel and steel, and it is possible to combine it with further finishes, for instance, the addition of a wooden cover for the inside, extra insulation on the outside (thermal shield), or even a ballistic system. The frame becomes "a body shell, a dummy which dress can be changed according to the needs and taste of the moment" (Palladio, 2019). In conclusion, this is an innovative system which offers different possibilities to customise the frame, through a new innovative way of providing insulation. Figure 6.17 depicts the system, and Figure 6.18 is an analysis of the system.

(b) System Characteristics:
Material: Rolled steel/stainless steel
Construction: L-, T-, and Z- profiles with 20 mm thickness.
Frame depth: 60 mm (average)
Insulation: ventilated thermal break
Glazing capacity: 62 mm
Surface treatment: painted steel, pickled or mirrored steel, corten, copper, brass. Possible to add wood, artificial marble, leather, and even fabric as a cover.

(c) System Performance:
Insulation value: Lowest possible is Uf = 1.9 W/m2K (depending on the frame/vent combination, and glass thickness), average Uf value = 3.6 W/m2K
Certification = None
Airtightness = 4 (EN 102601)
Watertightness: E1500 (higher than the maximum 9A); (UNI EN 1027/01)
Wind load resistance: C5 (UNI EN 12211/01)

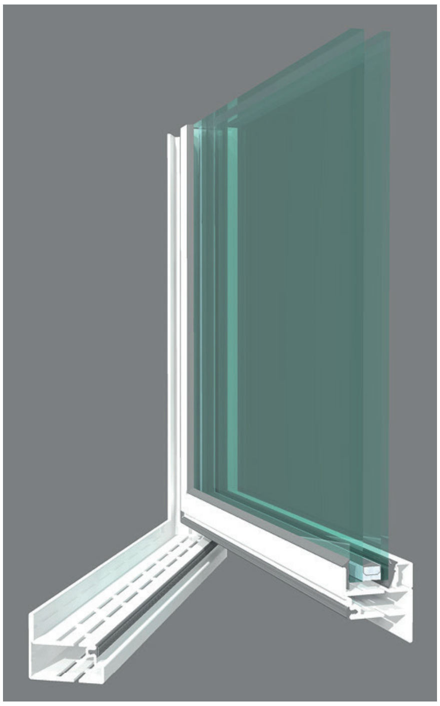


Figure 6.17 Axonometric view of the Opificium TABS window system. Image by Palladio (2019)

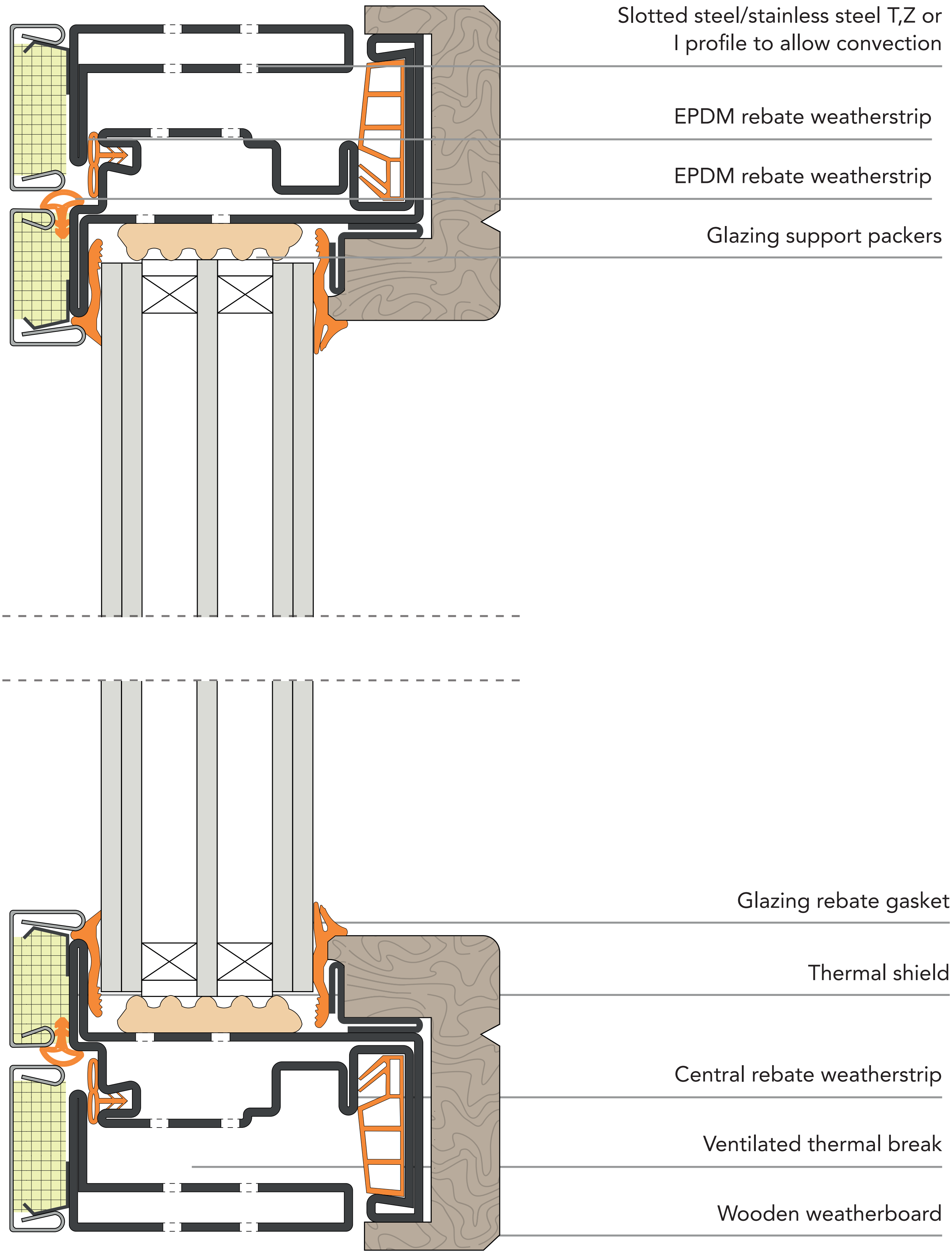


Figure 6.18 Analysis on the Opificium TABS Steel Triple Glazed Window Frame - Palladio. Image by author

6.9.5 uPVC Triple Glazed Prestige Window Frame - Inoutic

(a) System Description: This system offers the combination of being slender and highly insulating in terms of acoustic and thermal. This is achieved through a six-chamber design and a profile depth of 76 mm. This product also satisfies the latest requirements for the Energy Saving Regulation (ENEV 2014). The window profile is available in four different design variants, different colours, and even aluminium cappings. It can also be reinforced for extra stiffness in case the glazing surfaces need to be larger. In conclusion, this system offers a high insulation, with different customisation options and finishes. Figure 6.19 depicts the system, and Figure 6.20 is an analysis of the system.

(b) System Characteristics:

- Material: Extruded PVC profiles
- Construction: Six chamber, 2.8 mm thick
- Frame depth: 76 mm
- Insulation: Six chamber technology
- Glazing capacity: 44 mm
- Surface treatment: 40 different laminated foil colours

(c) System Performance:

- Insulation value: Lowest possible is Uf = 1.1 W/m2K (depending on the frame/vent combination, and glass thickness)

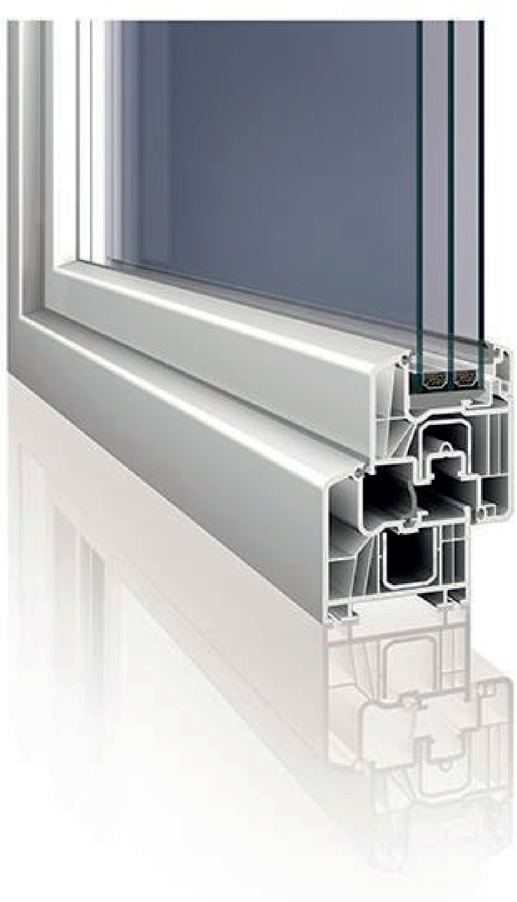


Figure 6.19 Image by uPVC Triple Glazed Prestige Window Frame. Image by Inoutic (2019).

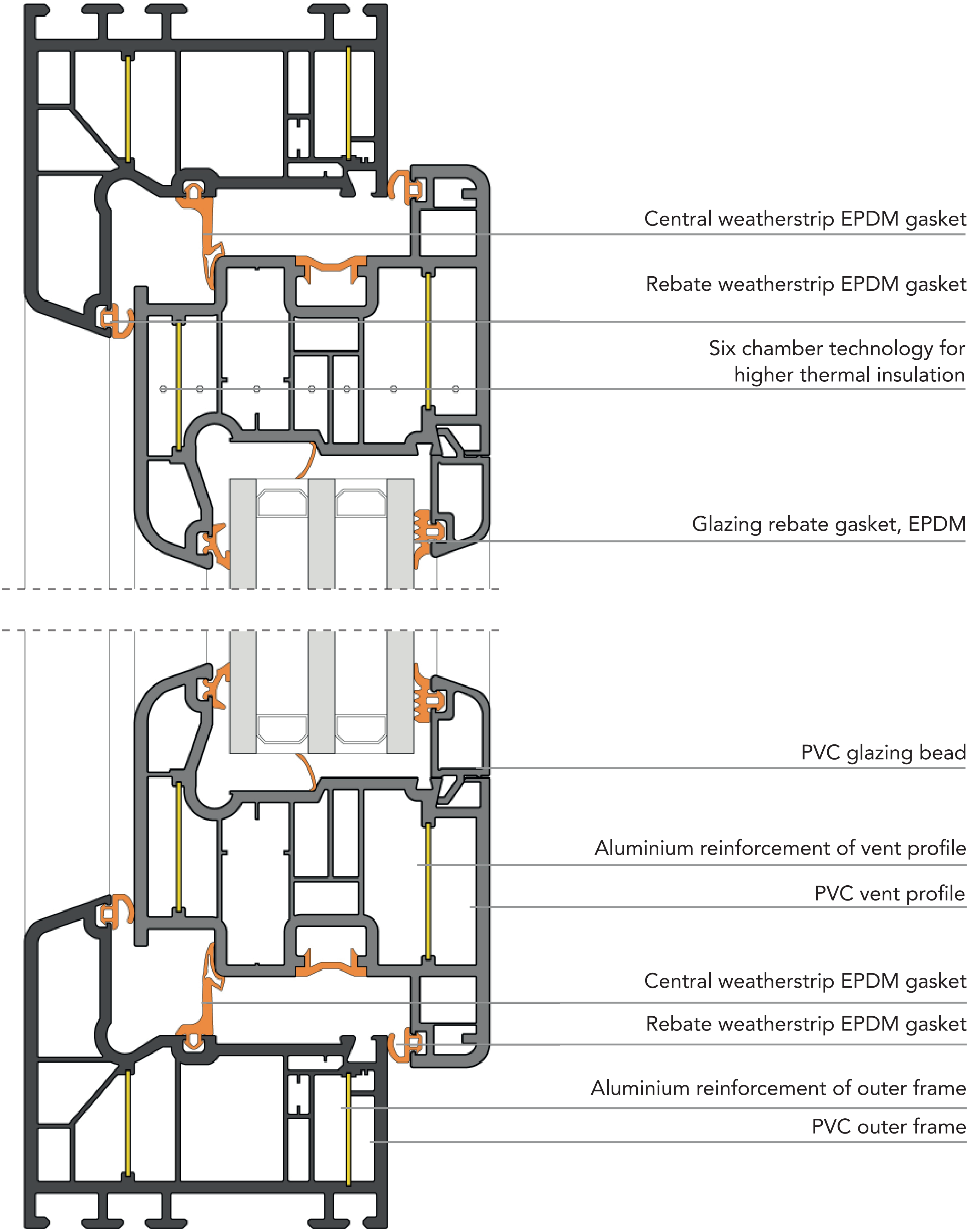


Figure 6.20 Analysis on the uPVC Triple Glazed Prestige Window Frame. Image by author, based on Fradelou (2013).

6.9.6 Titan Aluminium/Wooden Triple Glazed Window Frame

(a) System Description:

This product was designed to fit passive house standards, while still manufacturing sustainably. The frame is composed of two parts, a wooden frame made, which is then covered with an aluminium weatherboard. In between these two materials, there is an insulation foam. In conclusion, because this system combines the properties of two materials, it achieves a very low insulation value, while still maintaining a slender frame, which has the aesthetic qualities of wood. Figure 6.21 depicts the system, and Figure 6.22 is an analysis of the system.

(b) System Properties:

- Material: Spruce or oak, covered frame with aluminium weatherboard
- Construction: Solid wooden asymmetrical frame
- Frame depth: 103 mm (where 32 mm is highly efficient thermofoam)
- Insulation: Thermofoam, 32 mm
- Glazing capacity: 60 mm
- Surface treatment: Varnished wood covered with aluminium weatherboard

(c) System Performance:

- Insulation value: Lowest possible is Uf = 0.67 W/m2K
- Certification: Passive House-certified, PH Institute Darmstadt, Germany

Figure 6.21 View of the Titan Aluminium/Wooden Triple Glazed Window Frame.
Image by Josko (2019).

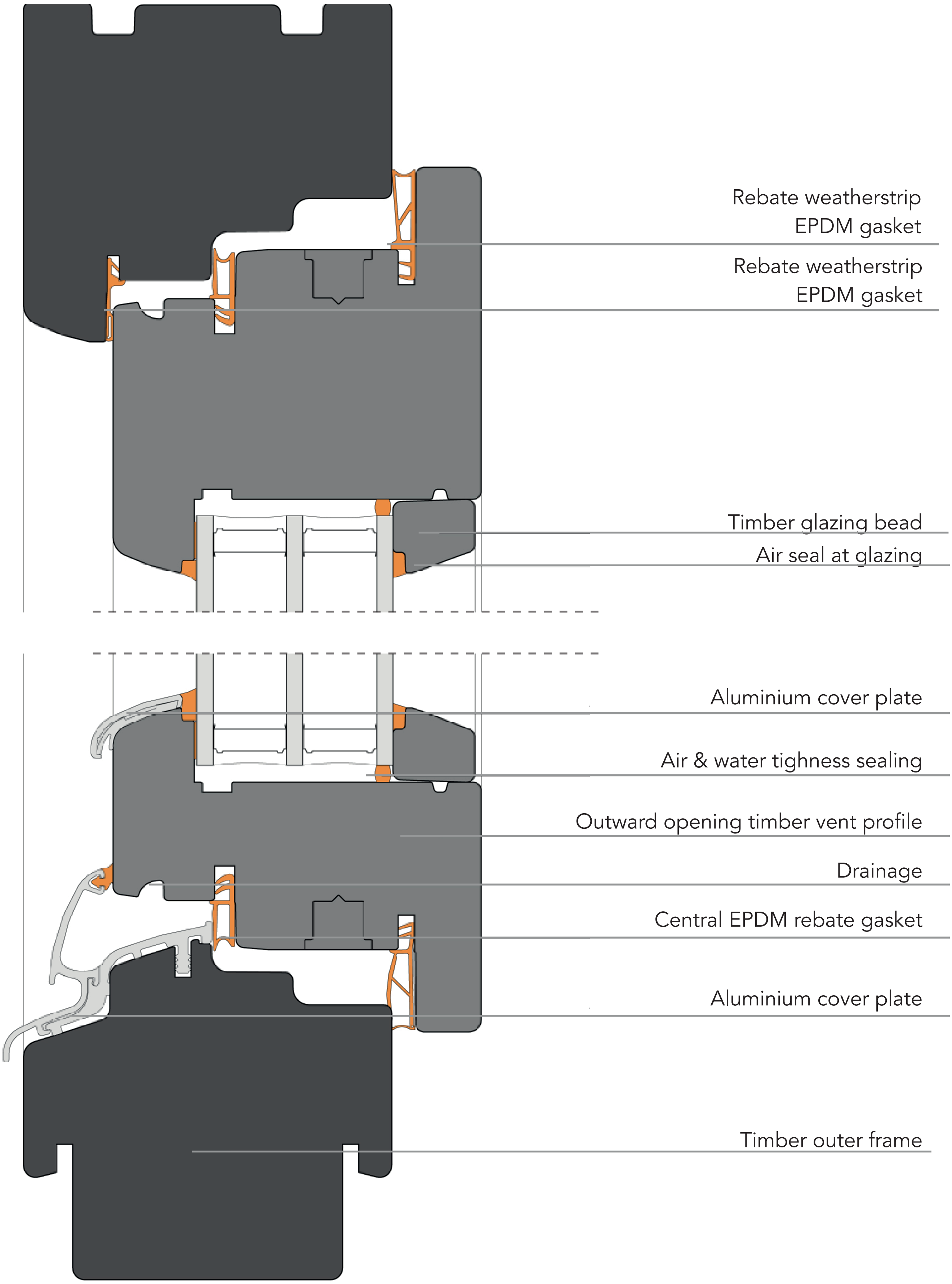


Figure 6.22 Analysis of the Titan Wooden/Aluminium Triple Glazed Window Frame. Image by author, based on Fradelou (2013).

6.9.7 GRP Triple Glazed Window Frame - Ecliptica

(a) System Description: This system is a new type of architecture that combines a strong, durable material with a very good thermal insulation, 700 times better than aluminium, and 4 times stronger than wood. What is even more attractive is that the window frame is much more slender, making the glazing area bigger and much more attractive. The product also follows a waste recycling concept called "CompoCycle", where full material and energy recovery are assured, according to the European Waste Directive. In conclusion, this system provides a new approach to window manufacturing, with an innovative material, with superior thermal insulation and stiffness. Figure 6.23 depicts the system, and Figure 6.24 is an analysis of the system.

(b) System Properties:
Material: Pultruded GRP profile
Construction: Asymmetrical frame
Frame depth: 45 mm
Insulation: GRP is an insulating material by itself
Glazing capacity: 60 mm

(c) System Performance:

Figure 6.23 View of the GRP Triple Glazed Window Frame.
Image by Ecliptica (2019).

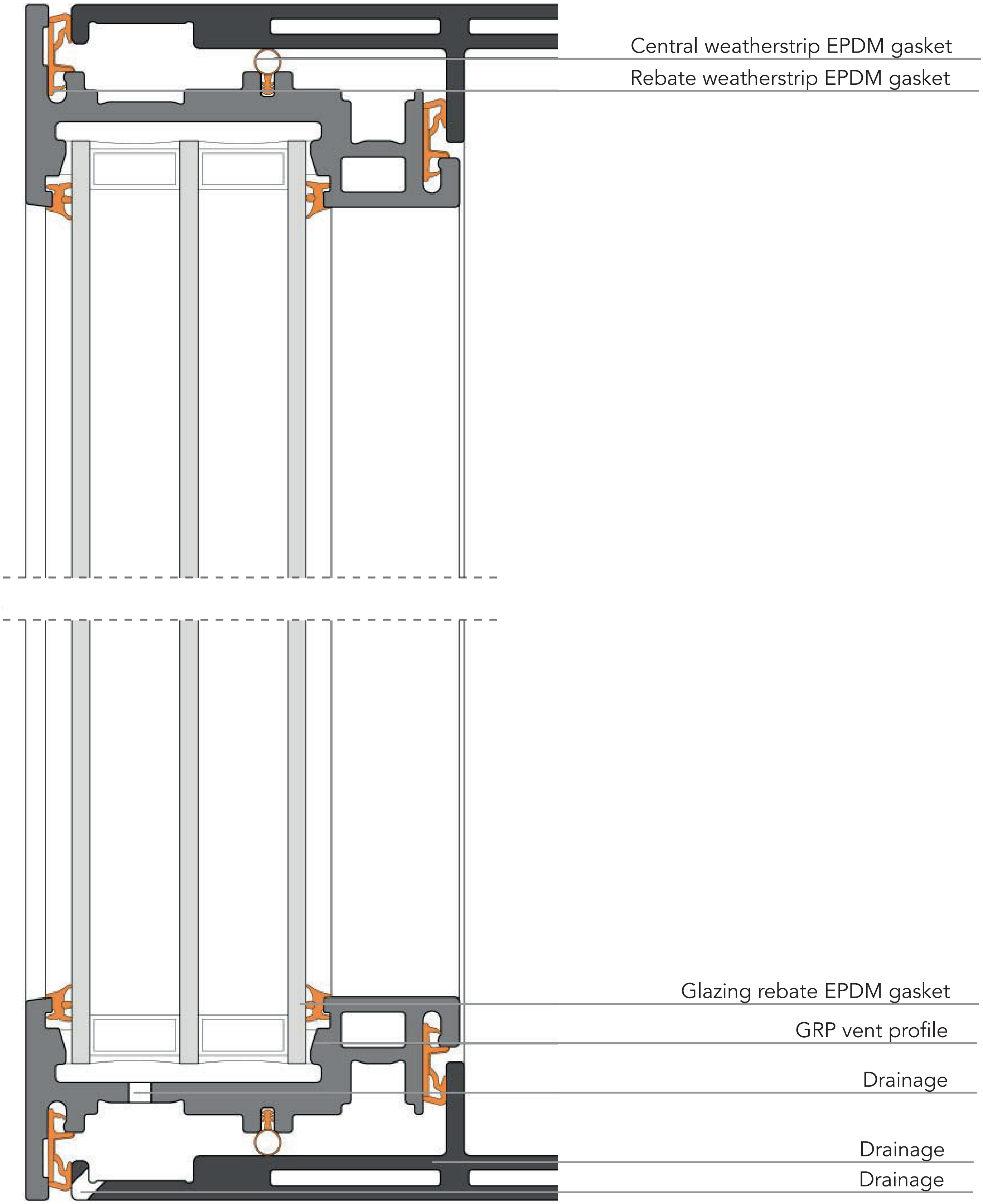


Figure 6.24 View of the GRP Triple Glazed Window Frame by Ecliptica (2019). Image by author, based on Fradelou (2013).

6.8.8 Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame - Josko

(a) System Description: The combination of these materials result in a window frame with high thermal insulation, strong, and slim at the same time. Because of the PVC construction, this frame is much lighter, but because the frame is covered in an aluminium weatherboard, it is also durable and easy to maintain. The window sash is made of GRP, which makes it more secure, lighter, and less prone to distortion. In conclusion, this frame benefits from the different properties of three materials: thermal insulation provided by PVC and GRP, stiffness (GRP), and durability (Aluminium weatherboard). Figure 6.25 depicts the system, and Figure 6.26 is an analysis of the system.

(b) System Properties:
Material: Extruded PVC profile covered with aluminium weatherboard, GRP window sash
Construction: Six chambers
Frame depth: 100 mm
Insulation: Six chamber technology. The main chamber can also be filled with thermal insulation.
Glazing capacity: 60 mm

(c) System Performance:
Insulation value: Lowest possible is Uw = 0.67 W/m2K
Certification: None

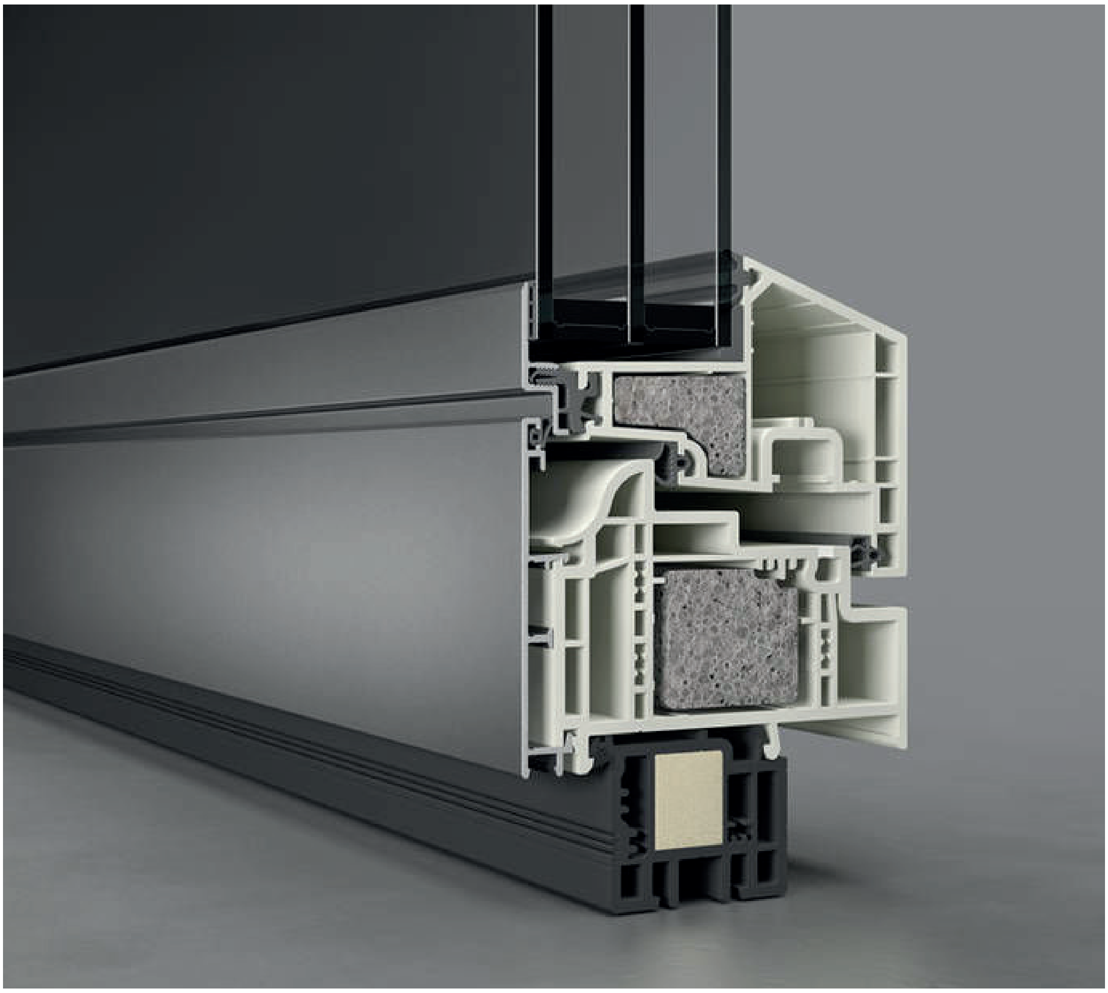


Figure 6.25 View of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame.
Image by Josko (2019).

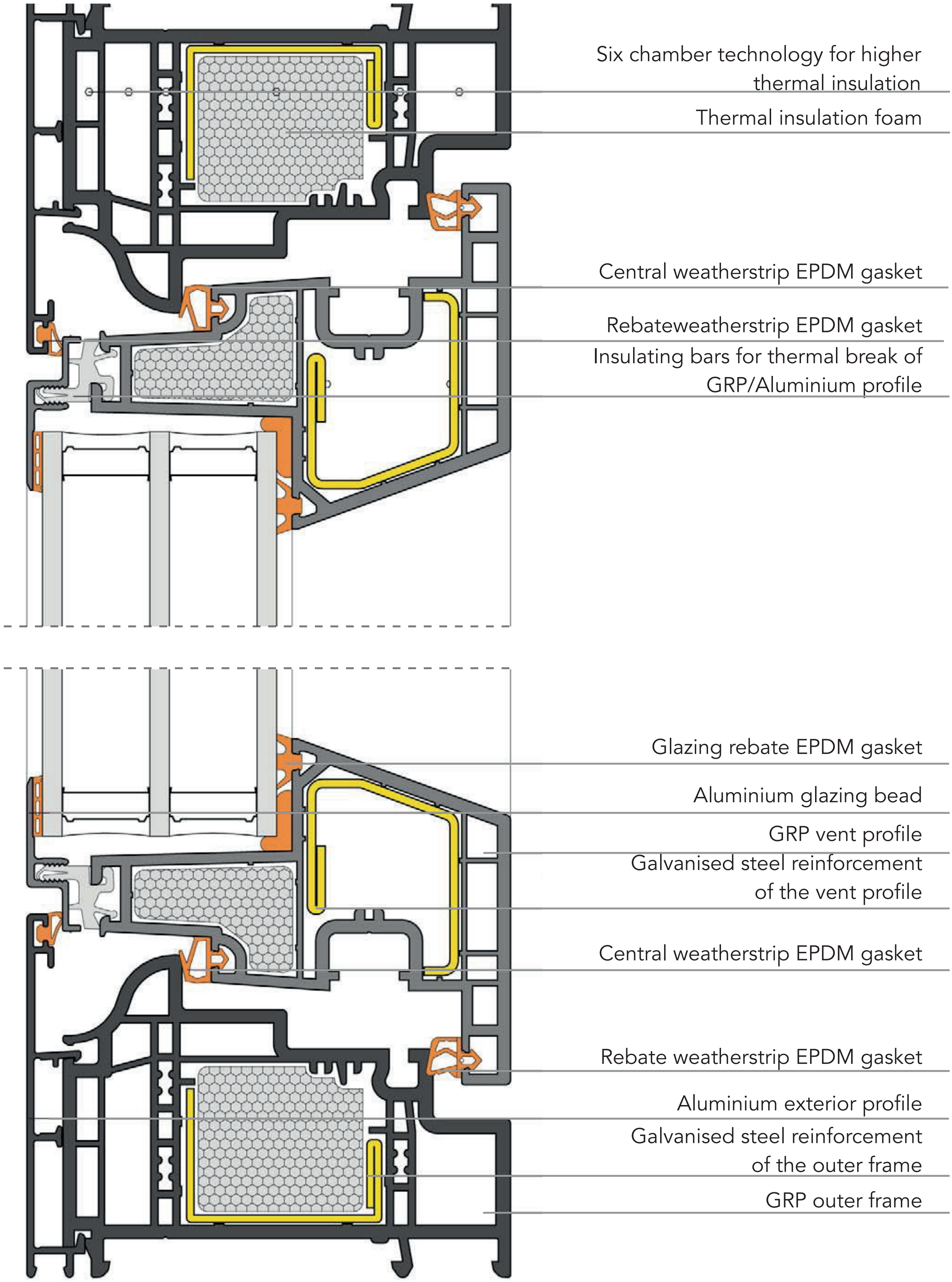


Figure 6.26 Analysis of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame. Image by author based on Fradelou (2013).

6.10 Conclusions on Chapter 6

This Chapter discussed the different types of window systems, along with the different available materials in the market: wood, aluminium, steel, PVC, and GRP. Hybrid variants were two or even more of these materials are included were also discussed: aluminium/wooden frames, and aluminium/PVC frames. Additional to the analysis of each system, a specific product was selected to do a further analysis and comparison. The following function-element matrix (Figure 6.27) was done with the purpose of analysing how each element interacted with five of the different window functions: thermal insulation, drainage, stiffness, sound insulation, and adjustable glazing width.

(a) Thermal insulation: As it can be seen, in the case of the three aluminium windows, the thermal insulation is provided through a thermal break, because these materials have a high thermal conductivity. On the other side, PVC, GRP, and wooden frames do not require any thermal break, due to their low conductivity. In the case of the steel window, because of this particular product, the insulation is created through convective movements around the profile. The slots in the profile allow for convection, and thus the profile itself is the element that fulfills this function. PVC frames insulate the window system through chambers, the higher the number of these chambers, the better the insulation value. GRP and aluminium do not require an additional element to insulate.

(b) Drainage: Aluminium frames have a small hole for drainage in the profile. They also have small 'noses' in the inner part of the profile to stop the water from coming in. The case is similar to PVC, steel and GRP. The gaskets are also an important element for this function.

(c) Stiffness: Aluminium and steel frames provide structural strength due to their material properties. Same is the case with GRP and wood. However, PVC needs strengthening through the addition of steel bars, placed on the inside.

(d) Sound Insulation: In almost all cases, sound insulation is provided by the outer weather gaskets, and the inner chambers (for aluminium and PVC). GRP and wooden frames have their fulfill their insulating functions through the frame itself.

(e) Adjustable glazing width: For the case of aluminium and PVC frames, the glazing beads can be removed and replaced to adjust the glazing width. This is also the case for some of the wooden frames. For the analysed steel system it is unclear how the glazing width can be adjusted, since it had no glazing beads.

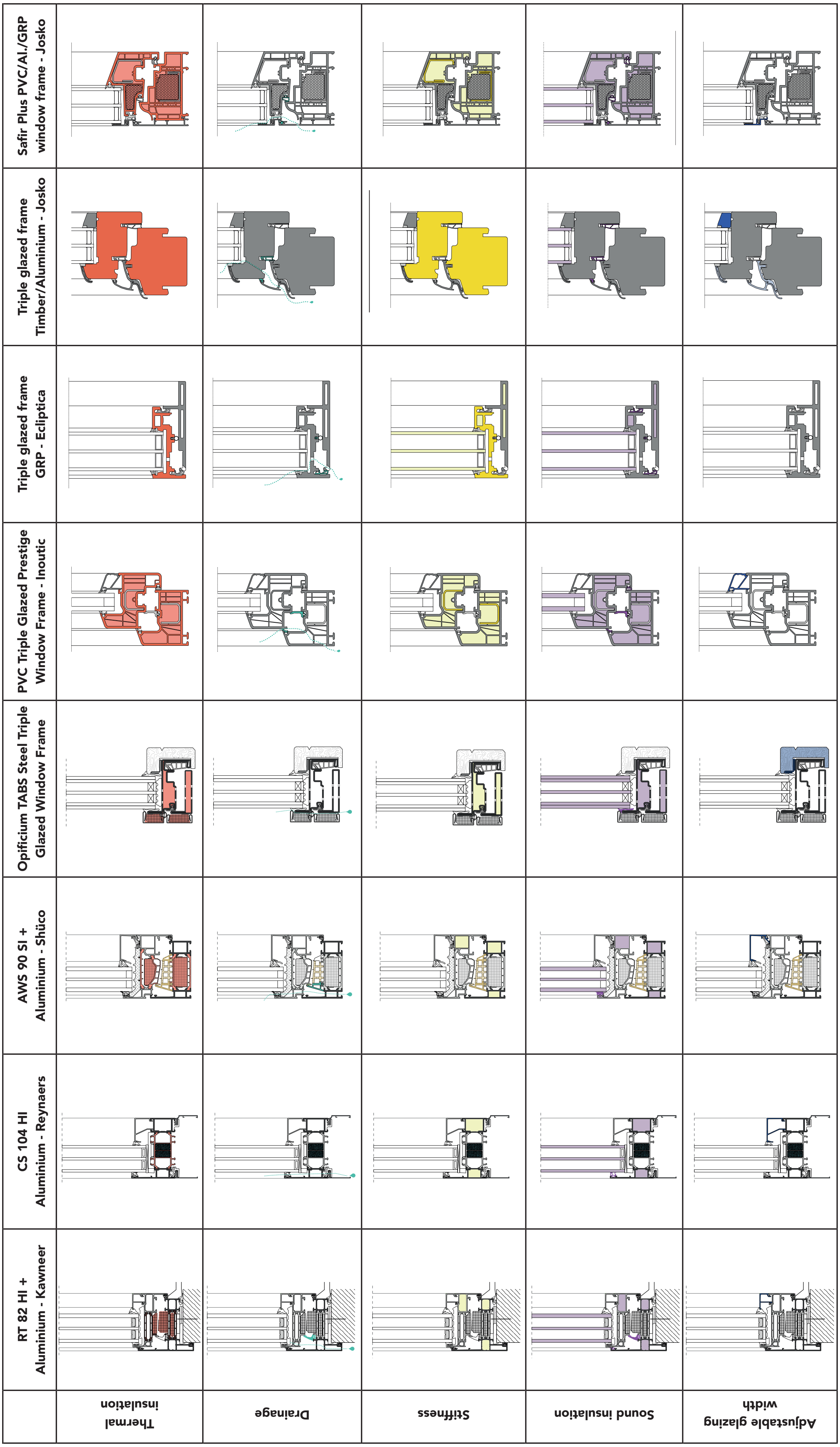


Figure 6.27 Matrix on the analysis of the different element-functions of the eight window systems. Image by author.

07.

Analysis of Existing Design

This Chapter analyses the RT 82 HI + according to an established reference project. A function analysis according to the façade function tree is analysed to understand the different façade requirements. Then, the current end-of-life scenarios for the elements of the RT 82 HI + are analysed. Assessments for DfD, DfA, and DfRem are done through the use of three different methodologies found through the literature review. Each of the three methodologies are then applied to the RT 82 HI + to understand its challenges and potentials. The disassembly process of a physical prototype is also explained in this Chapter.

List of Figures:

Fig. 6.0 View of Bettenhous SHK by GBK Architekten. Image by gbk-architekten.de
Fig. 6.1 Internal view of façade from Notre Dame du Haut in Ronchamp, France, by Le Corbusier. Image by archdaily.com
Fig. 6.2 Window hinge. Image by eraeverywhere.com
Fig. 6.3 Window seal. Image by feldcocedarrapids.com
Fig. 6.4 Collection of images of window typologies. Top left: Punched windows. Top right: Window Strip. Center left: French window. Center right: Window - wall. Bottom: Curtain wall. Images by: pixabay.com; france-voyage.com; balconette.co.uk; remi.com; designingbuildings.co.uk
Fig. 6.5 3D view of a wooden window in a brick cavity wall. Image by Watts (2014).
Fig. 6.6 Double glazed steel frame. Image by Watts (2014).
Fig. 6.7 Collection of images of Kawneer's aluminium window frames. : Top: Exploded axonometry of the RT 82 HI + Aluminium Window System. Bottom: Front view of the RT 52/62/72/82.
Image by Kawneer Nederland (2018)
Fig. 6.8 Collection of images of uPVC frames. Top: Isometric view, image by archiexpo.com ; bottom: origin-global.com
Fig. 6.9 Collection of images of GRP frames. Top image: installation of a GRP window. Bottom: GRP profiles. Image by fiberline.com
Fig. 6.10 Collection of images of an Aluminium/Wooden window. Image by: pinus-window.com
Fig. 6.11 Collection of images of two different Aluminium/uPVC windows. Top image by archiproducts.com bottom image by cdn.finstral.com
Fig. 6.12 Analysis on the RT 82 HI + window frame. Image by author
Fig. 6.13 View of the CS 104 HI window system. Image by Renaers (2019).
Fig. 6.14 Analysis on the CS 104 HI window frame. Image by author.
Fig. 6.15 View of the AWS 90 SI + Window System. Image by Shüco (2019).
Fig. 6.16 Analysis on the AWS 90 SI + Aluminium Triple Glazed Window Frame - Schüco. Image by author
Fig. 6.17 Axonometric view of the Opificium TABS window system. Image by Palladio (2019)
Fig. 6.18 Analysis on the Opificium TABS Steel Triple Glazed Window Frame - Palladio. Image by author
Fig. 6.19 Image by uPVC Triple Glazed Prestige Window Frame. Image by Inoutic (2019).
Fig. 6.20 Analysis on the uPVC Triple Glazed Prestige Window Frame. Image by author, based on Fradelou (2013).
Fig. 6.21 View of the Titan Aluminium/Wooden Triple Glazed Window Frame. Image by Josko (2019).
Fig. 6.22 Analysis of the Titan Wooden/Aluminium Triple Glazed Window Frame. Image by author, based on Fradelou (2013).
Fig. 6.23 View of the GRP Triple Glazed Window Frame. Image by Ecliptica (2019).
Fig. 6.24 View of the GRP Triple Glazed Window Frame by Ecliptica (2019). Image by author, based on Fradelou (2013).
Fig. 6.25 View of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame. Image by Josko (2019).
Fig. 6.26 Analysis of the Safir Plus PVC/Aluminium/GRP Triple Glazed Window Frame. Image by author based on Fradelou (2013).
Fig. 6.27 Matrix on the analysis of the different element-functions of the eight window systems. Image by author.

Figure 7.0 View of RT 72 prototype disassembled. Image by M. Bilow (2019).

7.1 Establishing a Reference Project

To design and assess a circular window system, it is important to establish a reference project. The current market for the RT HT 82 HI + is 100% residential in the Netherlands. Therefore, a brick cavity wall was taken as the construction system, which is the common system for residential buildings. This reference project was drawn according to standard details for Dutch construction, depicted in Figure 7.1. The analysed façade segment will measure 3.00 m x 3.00 m, with an aluminium window of 1.20 m x 1.20 m. This reference project will be further analysed in the following Sections.

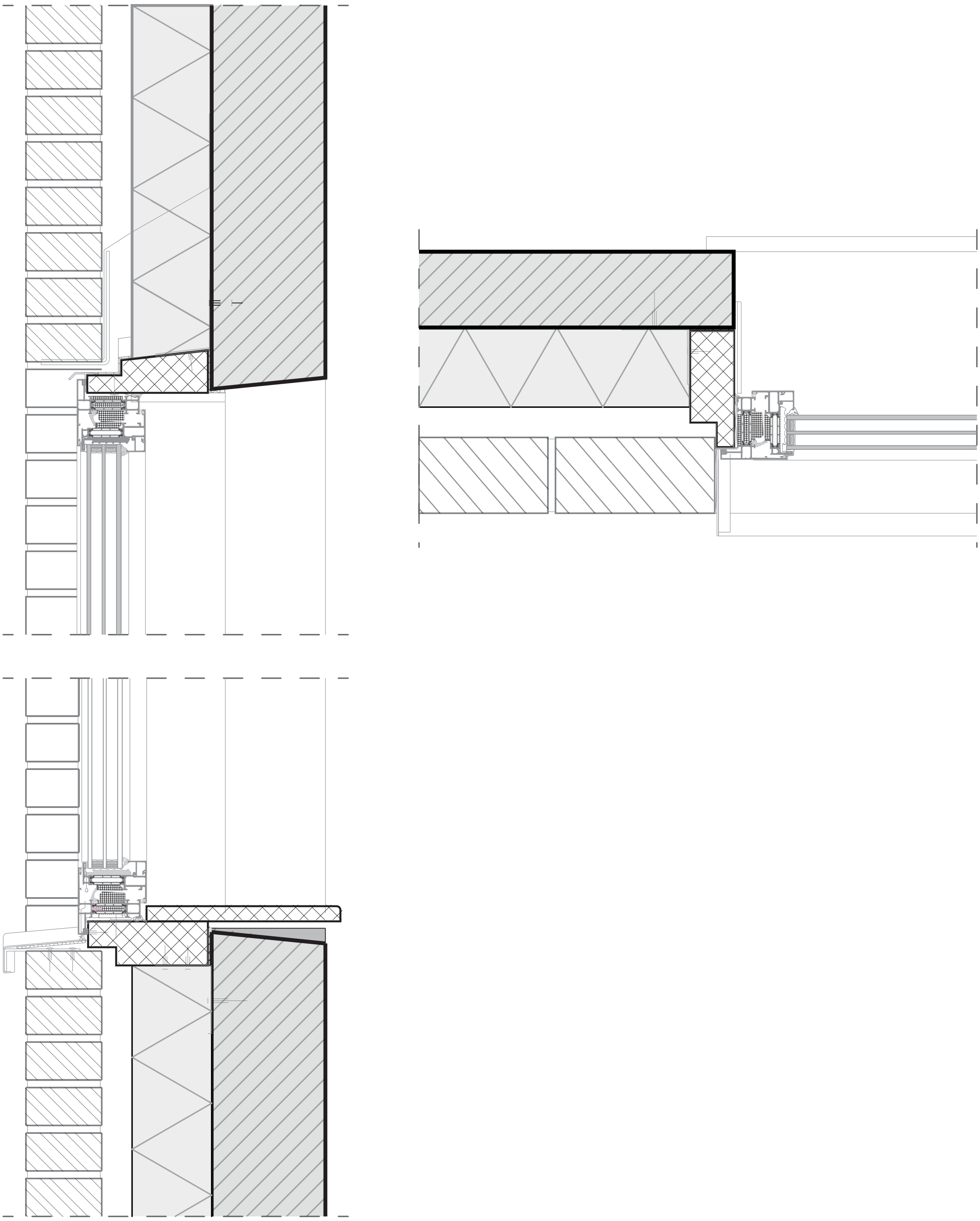


Figure 7.1 Detail of the reference project, brick cavity wall with the RT 82 HI +. Image by author.

7.2 Function Analysis

The main function a façade fulfills is to separate the "usable interior space from the outside world" (Knaack et al., 2007). Architecturally speaking, the façade states the aesthetic of a building, its identity, it provides views to the exterior, is resistant to wind loads, and carries its own weight. Façades also provide sun protection, while still allowing light to illuminate the building. It also provides thermal and acoustic insulation, and resists rain and humidity. These functional requirements should be taken into account since the early conceptual stages to the final construction.

According to Knaack et al. (2007), a façade has three main construction areas: primary structure, secondary structure, and infill elements. The functions are distributed along the different components of these three categories. They are depicted in Figure 7.2, and described as follows:

- **Primary structure:** The main load bearing function component, which transfers the loads from the façade system to the foundation of the building.
- **Secondary structure:** It encompasses the load bearing functions of the façade, transferring them to the primary structure. This structure also connects the elements between different levels.
- **Infill elements:** Elements such as glazing or panels are mounted in the façade. These have complex functions, such as providing outside views, protect from the water, provide sound and thermal insulation, etc.

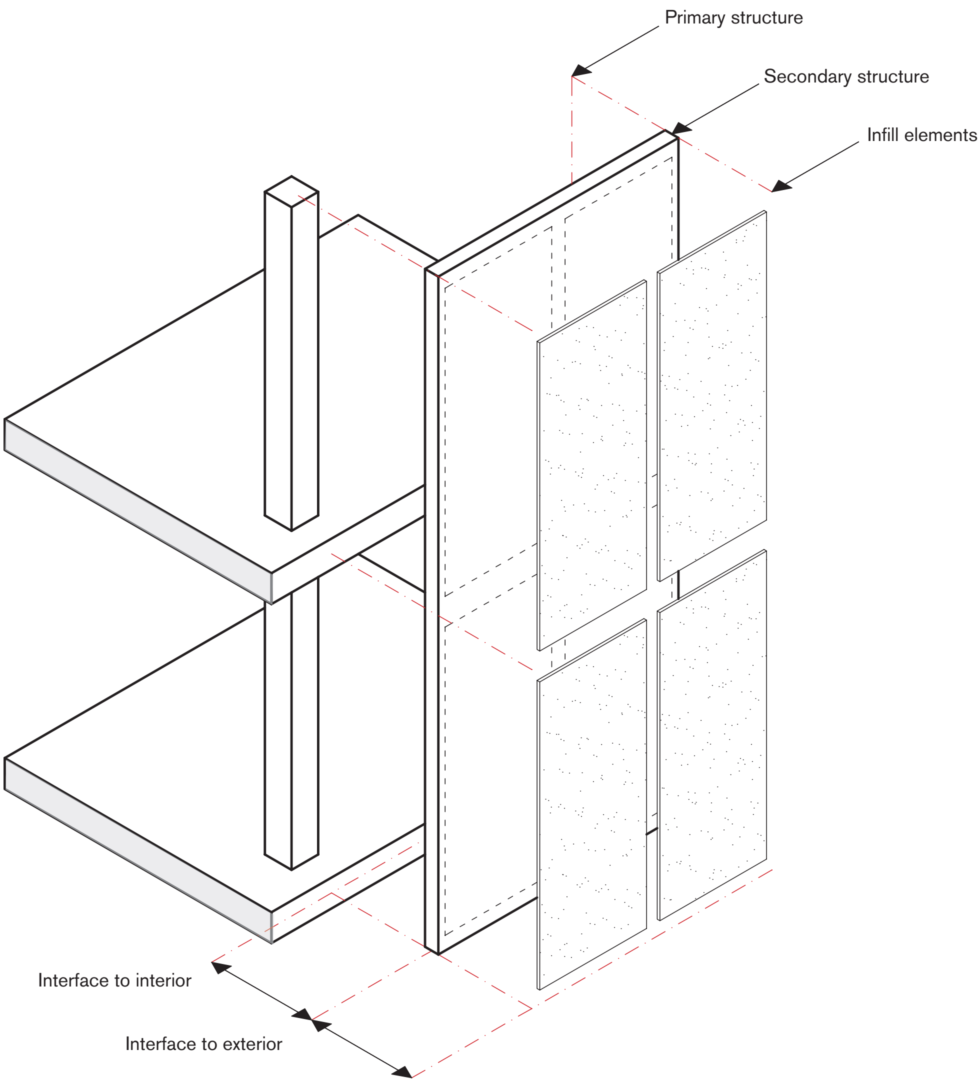


Figure 7.2 Main areas of construction of a façade. Image by Knaack et al. (2007).

However, with the incredibly fast technological improvements, the functions a façade can fulfill have become even more complex. Herzog et al. (2004) describe in the "Façade Construction Manual" a brief representation of the different façade functions, divided mostly between outside functions, inside functions, but also the functions of separating components. To fulfill the requirements of a façade, Herzog et al. (2004) assign to the different façade components protective and regulatory functions, as seen on Figure 7.3.

Another important approach towards the function analysis of a façade is the '"Façade Function Tree" developed by Klein (2013), depicted in Figure 7.4. This approach starts with a five category division from which the level of detail increases gradually: main function, primary and secondary function, supporting functions, and detailed supporting functions. The first three illustrate a general function description. The overall function derives from Herzog et al. (2004) approach: "Separate and filter between nature and interior spaces". However, Klein (2013) recognises that the functions of a façade might be multifaceted, and thus the primary functions are derived. Klein (2013) based this on Vitruvius' concept that a building should be durable ("durable construction", "reasonable building methods", "handling of sustainability"), convenience ("comfortable interior climate", "use of the building"), and beauty ("spatial formation of façade"). As the tree goes on, it can be observed how these supporting functions enable primary and secondary functions, with a higher detailed listing. At the end of the tree, the detailed definition of supporting functions is found, which can serve as a guide to design the physical components. This function tree is also not exhaustive, but an approach towards a general overview of the different requirements and functions.

7.2.1 Function Analysis for Reference Project

The façade established as a reference project will be analysed according to Klein's (2013) façade function tree. This will serve as a guide to redesign the components in Chapter 8 Designing a Circular Window system, along with other important criteria.

Because the reference project is a relatively simple façade system, the functions that can be derived from it are simplified from the original three. There are three main primary functions ("create a durable construction", "provide a comfortable interior climate", and "support use of the building"). From these, the secondary functions, supporting functions, and detailed functions derive, giving information about the functions and requirements for each component. To understand these relationships in a more detailed way, another map was created where secondary/supporting functions are matched to every component of the façade. There are eleven main components that comprise the façade: external brickwork, cavity, insulation layer, internal blockwork, window aluminium frame, triple IGU (Insulating Glazing Unit), sun shading, lintel, metal clad flashing, window brackets, and the waterproof layer. These main eleven components were matched to the functions identified previously according to Klein (2013) façade function tree. Figure 7.5 illustrates the function tree for the reference project, and Figure 7.6 depicts the element - function analysis.

From the element - function analysis, it is clear the amount of functions the aluminium frame has to fulfill. The redesign of the circular façade should achieve this functions, along with circular and aesthetic requirements (further explained in Chapter 8).

7.2.2 Hierarchy Definition

To analyse in detail the functions of the RT 82 HI + aluminium frame component, the methodology for Hierarchical Range of Industrial Building Products developed by Eekhout (2008), explained in Section 3.1.2, is applied.

From this, the different elements from the frame component can be understood better. This breakdown of the hierarchy definition goes from building-system-subsystem-component-subcomponent-element-material. Figure 7.7 illustrates the analysis according to this methodology, focusing on the aluminium frames of the window system.

Façade Requirements

Outside

Context-Specific Conditions

· Solar radiation
· Temperature
· Humidity
· Precipitation
· Wind

· Surrounding noises
· Amount of gas and dust
· Mechanical loads
· Electromagnetic radiation

· Urban surroundings
· Local resources
· Socio-cultural context

Façade

Inside

· Comfortable temperature/humidity range
· Amount & quality of light
· Air exchange rate
· Comfortable air velocity
· Comfortable sound level

· Visual relationship with external surroundings
· Differentiation of private & public areas
· Mechanical damage protection
· Fire protection
· Limitation of toxic loads

Protective Functions

· Insulation/Attenuation
· Seals & barriers
· Fitters
· Storage
· Redirection
· Physical barriers

Regulatory Functions

· Controlling/regulating
· Responding / Changing

Façades w. Integral Services

· Integral air/water collection
· Solar walls
· Media transport distribution
· Heat recovery systems

Supplementary functions with a direct effect

· Thermal insulation
· Sunshading
· Measures influencing the microclimate (i.e. vegetation)

Supplementary building services

· External collectors
· PV/PVT
· Heatpipes
...etc

Supplementary functions with a direct effect

· Glare protection
· Privacy provision
· Redirection of daylight
·Storing/releasing energy for heating & cooling

Supplementary building services

· Convectors/radiators
· Artificial lighting
· Air conditioning (centralised/decentralised)

Figure 7.3 Functions of a façade. Image by author, derived from Herzog et al. (2004).

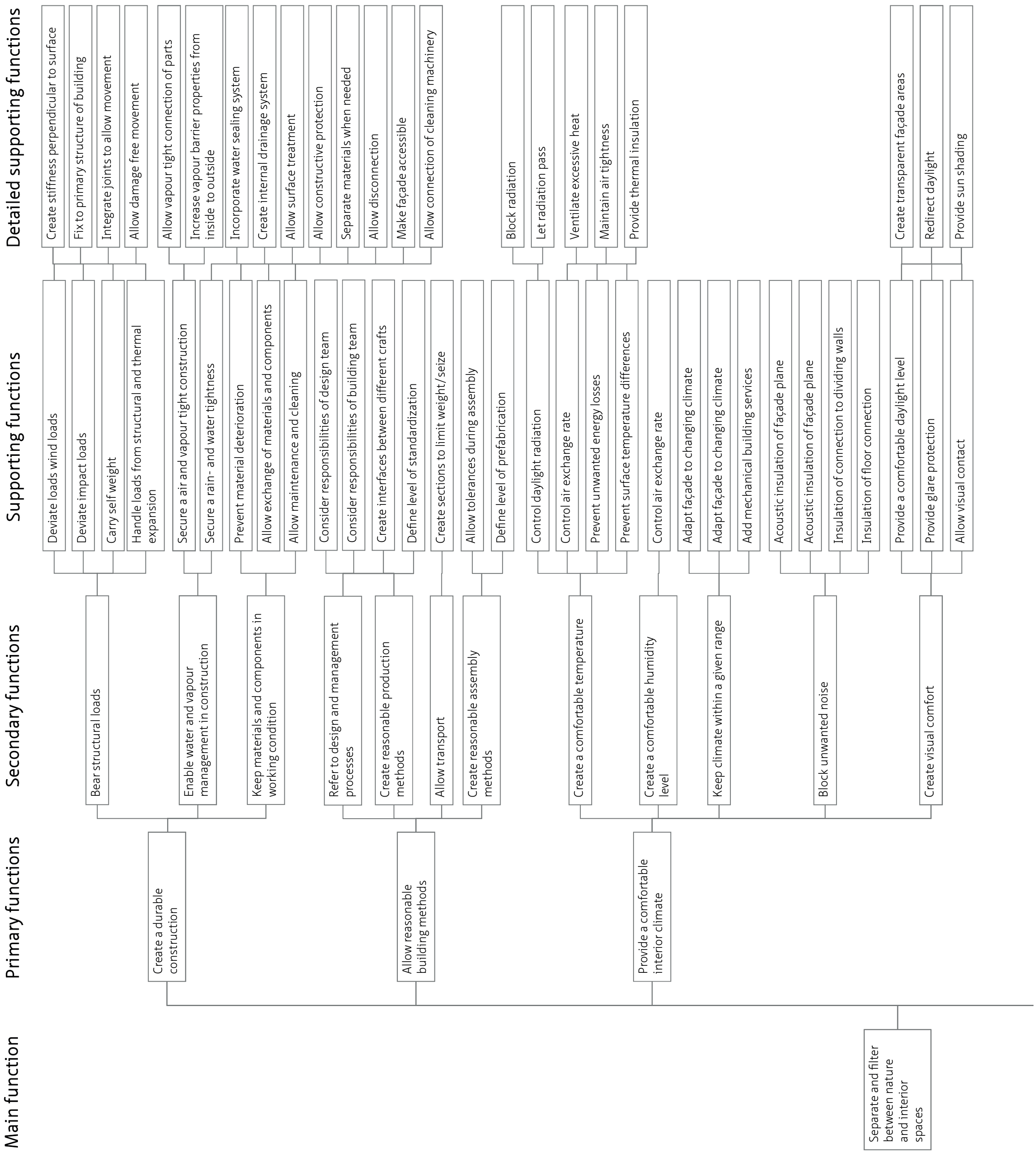
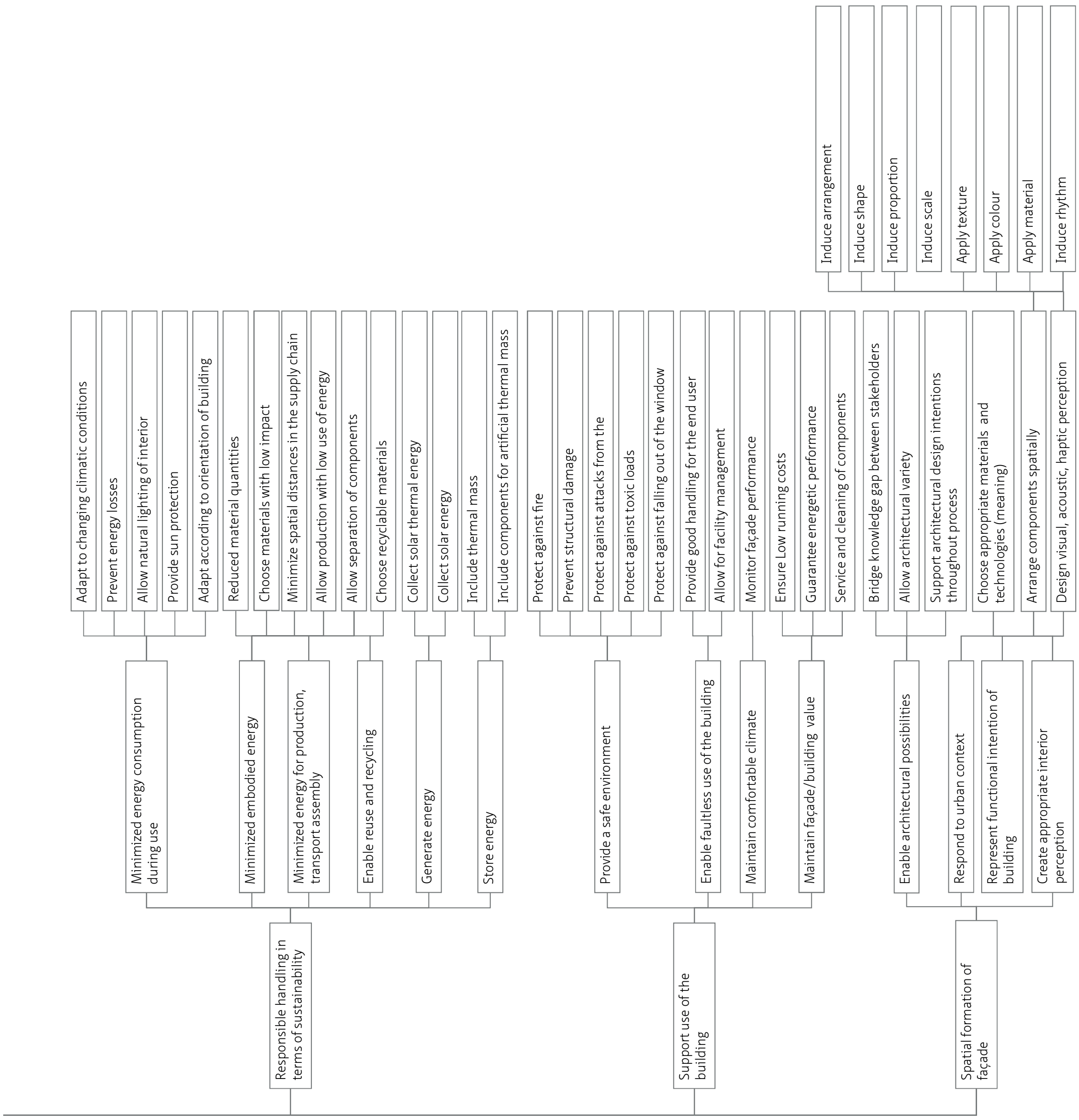


Figure 7.4 Façade function tree. Image by Klein (2013).



Responsible handling in terms of sustainability
Minimized energy consumption during use
Adapt to changing climatic conditions
Prevent energy losses
Allow natural lighting of interior
Provide sun protection
Adapt according to orientation of building
Minimized embodied energy
Reduced material quantities
Choose materials with low impact
Minimized energy for production, transport assembly
Minimize spatial distances in the supply chain
Allow production with low use of energy
Enable reuse and recycling
Allow separation of components
Choose recyclable materials
Generate energy
Collect solar thermal energy
Collect solar energy
Store energy
Include thermal mass
Include components for artificial thermal mass
Support use of the building
Provide a safe environment
Protect against fire
Prevent structural damage
Protect against attacks from the
Protect against toxic loads
Protect against falling out of the window
Enable faultless use of the building
Provide good handling for the end user
Allow for facility management
Maintain comfortable climate
Monitor façade performance
Maintain façade/building value
Ensure Low running costs
Guarantee energetic performance
Service and cleaning of components
Spatial formation of façade
Enable architectural possibilities
Bridge knowledge gap between stakeholders
Allow architectural variety
Support architectural design intentions throughout process
Respond to urban context
Represent functional intention of building
Choose appropriate materials and technologies (meaning)
Create appropriate interior perception
Arrange components spatially
Design visual, acoustic, haptic perception
Induce arrangement
Induce shape
Induce proportion
Induce scale
Apply texture
Apply colour
Apply material
Induce rhythm

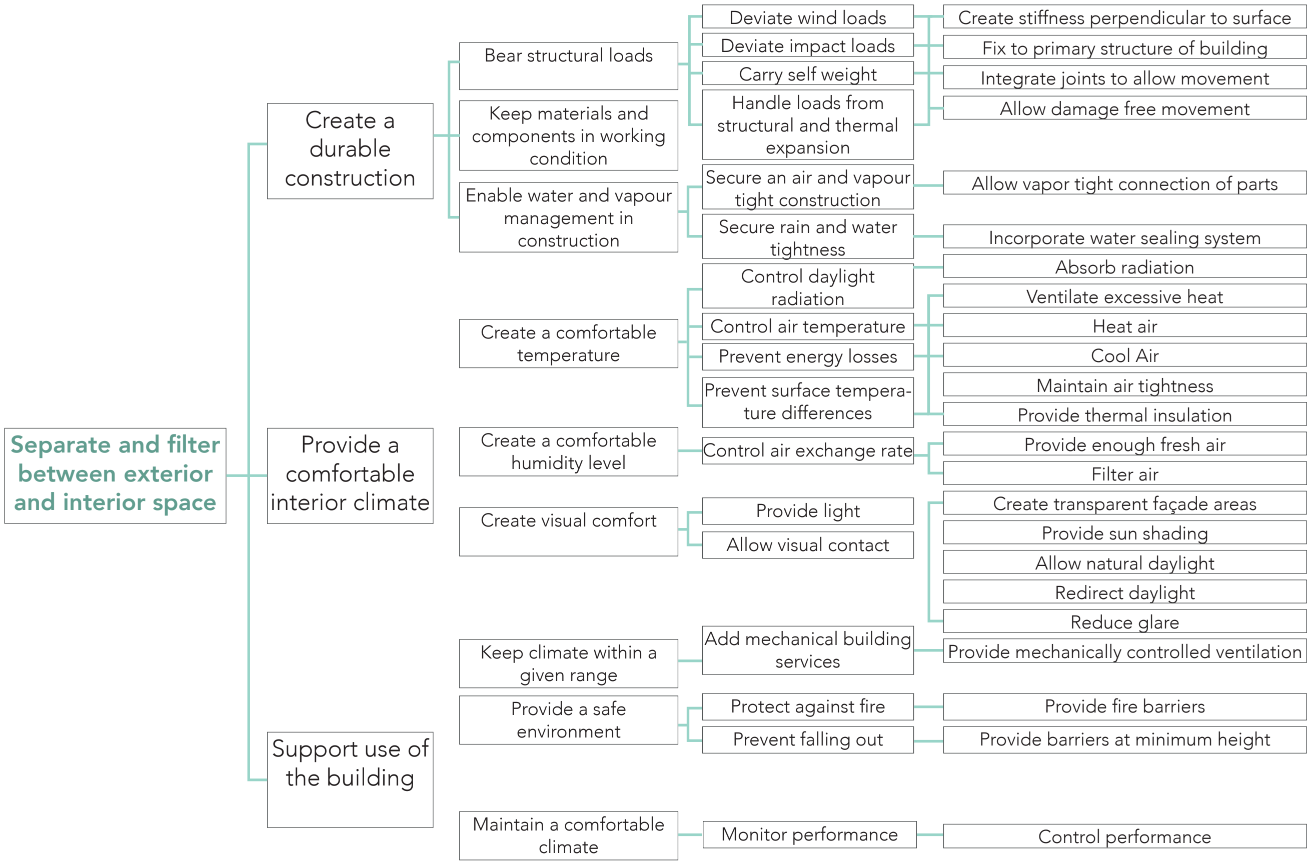


Figure 7.5 Façade function tree for reference project. Image by author, based on Klein (2013).

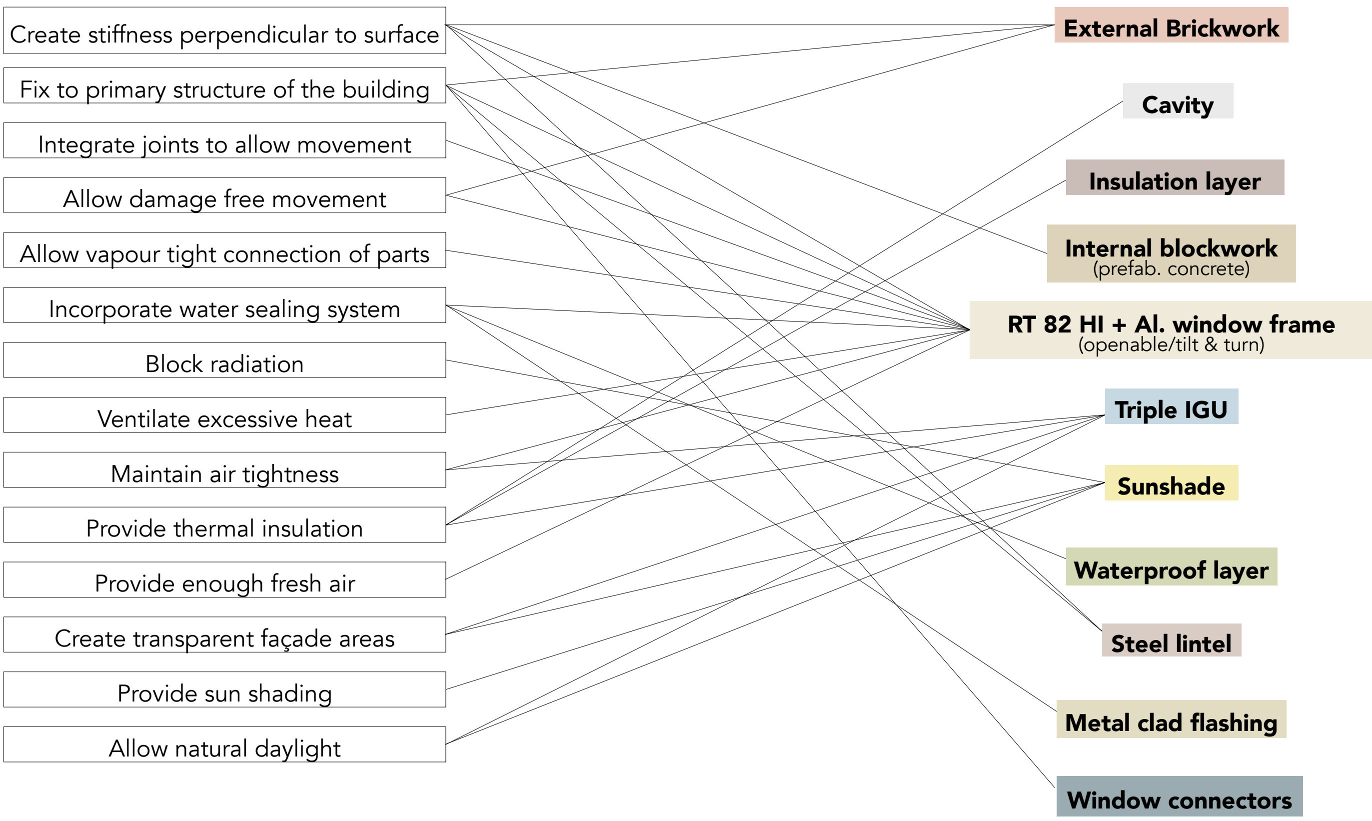


Figure 7.6 Function - element analysis. Image by author.

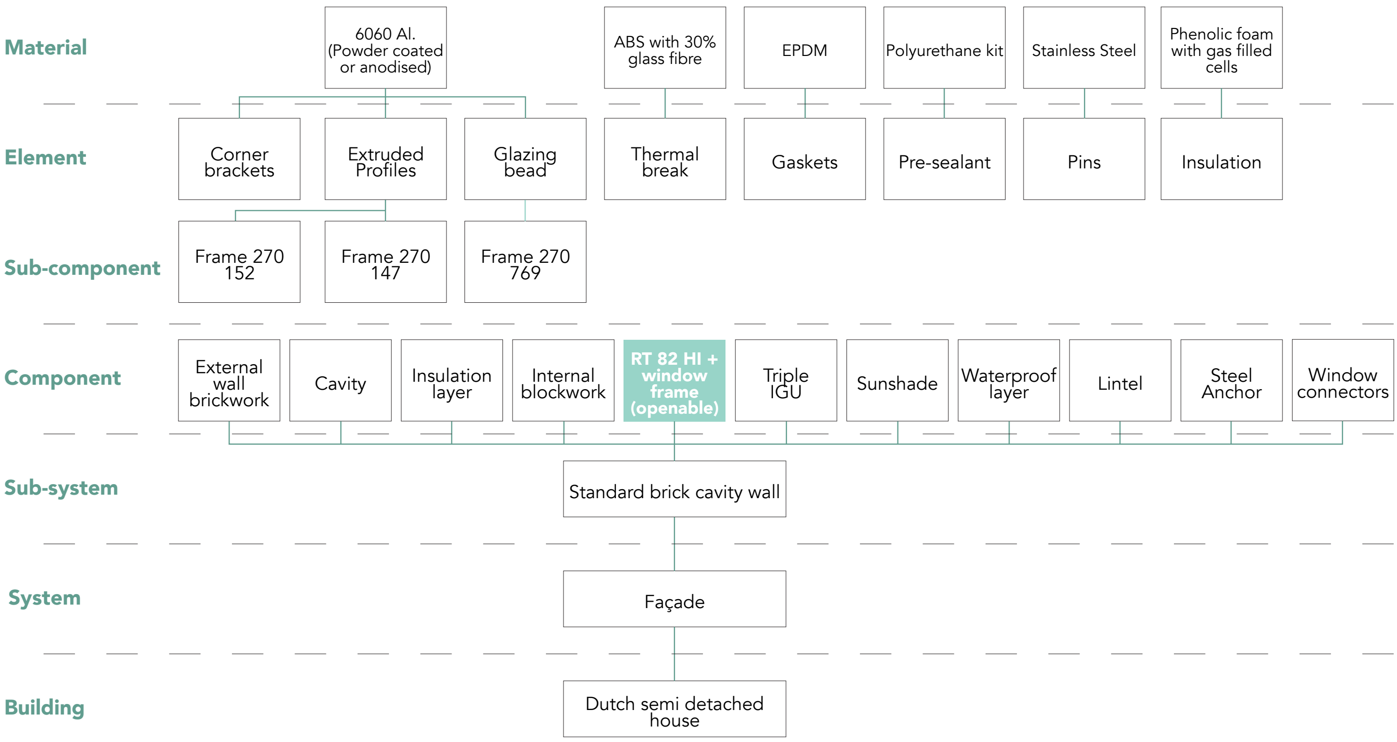


Figure 7.7 Hierarchy definition of the RT 82 HI +. Image by author.

7.3 Current End-of-life Scenarios for RT 82 HI +

After the reference project is established and analysed, the next step is to understand the different elements and their functions on the RT 82 HI +. While an initial analysis was elaborated on Section 6.8.1, a further analysis on circularity will be done according to the framework established in Chapter 2 and 3. Three main assessments will be done, one for each design guideline that was established as part of the methodology: Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Remanufacturing (DfRem). These assessments will serve as design criteria for the circular redesign of the RT 82 HI +.

However, before establishing each analysis, it is important to understand the current end-of-life scenarios of the elements. This information is the starting point for the further assessments. These are synthesised in Table 7.1.

Element	Material	Expected lifetime	Type of connection	Current EOL scenario
1. Extruded profiles	6060 Aluminium (Powder coated or anodised)	75 years	Pinned	Recycled
2. Glazing beads	6060 Aluminium (Powder coated or anodised)	75 years	Snapped	Recycled
3. Corner Brackets	Aluminium	30 - 50 years	Pinned/Pressed	Recycled
4. Thermal Break	ABS with 30% glass fibre	Unknown (approx. 40 years)	Rolled	Incinerated
5. Thermal insulation foam	Phenolic foam with gas filled cells	Unknown (approx. 40 years)	Fitted	Incinerated
6. Sleeve for thermal insulation	Acrylonitrile butadiene styrene (ABS)	Unknown (approx. 40 years)	Fitted	Recycled
7. Gaskets	EPDM	25 - 30 years	Pushed	Incinerated
8. Pre-sealant	Polyurethane kit	30 years	Glued	Incinerated
9. Pins	Stainless steel	30 - 50 years	Pinned	Recycled

Table 7.1 Current end-of-life scenarios for the RT 82 HI +.

7.4 Assessment on Design for Disassembly (DfD)

In conventional structures, design approaches are towards functional, technical and physical composition. Contrary to this, in the case of transformable structures, the approach is towards functional, technical, and physical decomposition. Such approach enables structures to become transformable.

7.4.1 Transformation Capacity Methodology

Durmisevic (2006) framed a transformation capacity methodology to analyse the disassembly potential of a building system. She states that for a structure to be transformable, all building products should be independent and their interface should be designed for exchangeability. In this framework, the independence of building products is determined by the functional design domain, at a material level. Exchangeability, on the other hand, is determined by technical and physical design domains. These determine a hierarchy of the design according to the type of assembly, and the physical integration. The assessment will be carried under the Transformation Capacity Scheme by Durmisevic (2006), depicted in Figure 7.8, will be shortly reviewed to realise the DfD assessment.

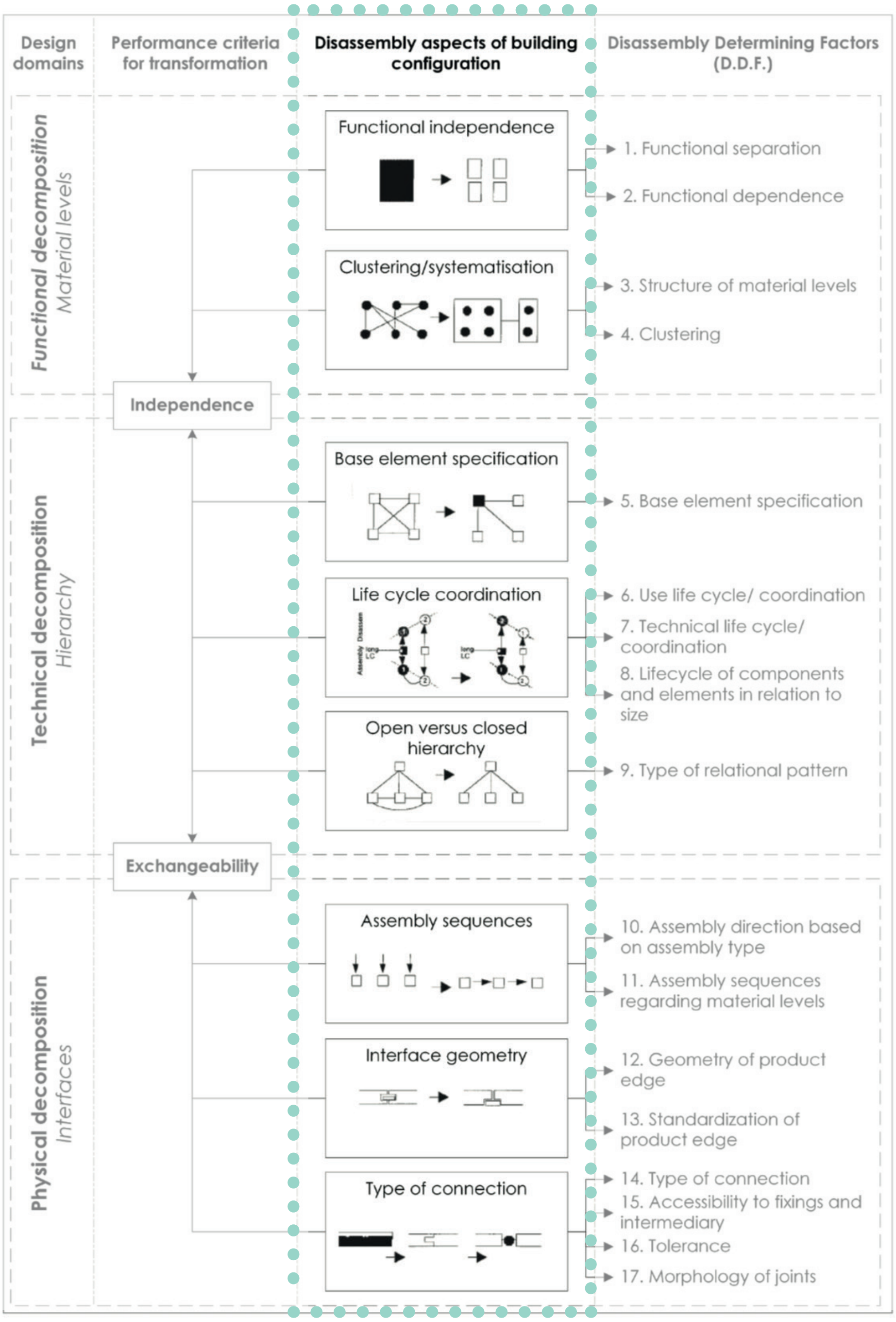


Figure 7.8 Transformatio Capacity Scheme. Image by Durmisevic (2006).

I. Functional decomposition

It refers to the functionality of the assembly, particularly, the decomposition of the functions. An important input of this domain is the specification of requirements. A transformable configuration will start with the design of a functional decomposition, and clustering/systematization.

(a) Functional independence: Refers to the dissociation of functions within a single configuration. The importance of this aspect relies on the possibility to disassemble an element that needs to be replaced (for instance, because it becomes obsolete).

(b) Clustering/Systematization: Elements are systemized in clusters. The premise derives from the fact that is there are as minimum building parts integrated into a single component, the physical connections needed on the site are much less.

II. Technical decomposition

This domain is centered in the composition of the different elements of the structure, and functional decomposition is an input. The technical decomposition is oriented towards the definition of technologies and methods that specify principle solutions for composition of structures.

(c) Base element specification: Different clusters form a configuration that might be coordinated through: use lifecycle/coordination, technical lifecycle/coordination, and life-cycle of components and elements in relation to size.

(d) Life cycle coordination: Materials are integrated and selected according to their life cycle. The sequence of assembly and disassembly. Materials with the longest life cycle are assembled first, and will have a more dependant role in a cluster, compared to elements with a shorter life cycle.

(e) Open/closed hierarchy: It refers to the number of relations and the relational pattern, and how these might affect the disassembly potential of structures. Clusters and base elements, if applied correctly, might be able to form open systems. In this case, materials are kept independent from each other. This disassembly aspect can be aided through a study of the type of relational pattern.

III. Physical decomposition

Because of a description of elements in a cluster, and their relationship, this domain fulfils the performance of the configuration. A strong link with manufacturing and construction of clusters, based on the previous technical and functional decomposition.

(f) Assembly sequence: The disassembling capacity is the key aspect of a transformable structure. The disassembly should be possible without destructing or damaging the elements, and without producing waste. The assembly sequence could create a dependence between different building components, for instance, if they are locked together. This aspect can be aided through the assembly direction based on the assembly type, and the assembly sequence at a material level.

(g) Interface geometry: Is associated with the type of connection, such as the geometry of the product edges. This characteristic determines its disassembly possibilities, if it is either with an open or an interpenetrating geometry. In the last case, this is less suitable for disassembly, because it only enables to do so in one direction, or by a partial destruction/demolition of the elements. The geometry of the product edge, along with the standardization of the product edge can enable further investigation of this aspect.

(h) Type of connection: It determines the degree of freedom among product levels. Connections can be classified in three different types: filled (based on chemical material), direct (dependent on the geometry of product edge), and indirect (an independent part is added as a connection). This aspect can be further researched with the aid of types of connection, accessibility to fixings and intermediary, tolerances, and the morphology of joints.

Each aspect previously mentioned will be scored in the following scale: 1-2-3-4-5-6 ; very unsatisfactory - unsatisfactory - slightly unsatisfactory - neutral - slightly satisfactory - very satisfactory.

7.4.2 Application of Transformation Capacity Methodology

The methodology described in Section 7.4.1 is applied to understand the disassembly potential of the RT 82 HI +. This assessment was aided both by the application of the previously explained methodology, but also by disassembling a physical prototype of the RT 72 provided by Kawneer (seen in Figure 7.9). The prototype has the exact same composition as the RT 82 HI +, except for the width of the thermal break. Each disassembly aspect of the disassembly of the prototype is explained as follows:

(a) Functional Independence: The configuration of the system presents a level of separation that is described as "integrated". This means that each element has different functions (as it was seen on the comparison matrix from Section 6.9), and other functions, are fulfilled by the combination of different elements. Score: 2/6

(b) Clustering/Systematization: The window system is composed by three different clusters: (1) aluminium baby profiles rolled into thermal break, (2) glazing beads, (3) thermal insulation. Each cluster serves a different function, but there is some small overlapping. Score: 4/6

Figure 7.9 View of the RT 72 prototype. Image by author.

(c) Base Element Specification: In the case of clusters (1) and (2) there are base elements that integrate the cluster, and connects it to the others. For (1) is aluminium baby profiles; (2) glazing beads. In the case of cluster (3) there is not a base element. Score: 4/6

(d) Life Cycle Coordination: The aluminium profiles, glazing beads and have the same service life (75 years). The EPDM gaskets and the pre-sealant, along with the corner brackets have a lower service life (30 years in the case of the first two, and up to 50 in the case of the last one). The EPDM gaskets and the pre-sealant are easily replaced. If the corner brackets are screwed, they can be fixed relatively easily. What is still a bit unclear is the service life of the thermal break and the insulation, as there is not exact information on the durability of these elements, but it can be approximated that they last 40 years. Score: 5/6.

(e) Open/Close Hierarchy: This is different for each cluster. In the case of (1) and (2), they are closed integral geometries. This can also be analysed through the (h) type of connection. Cluster (3) is open. The type of relational pattern can also give further information on this aspect. In the case of this window system, it has vertical and horizontal relationships. This makes the pattern dynamic. Score: 3/6

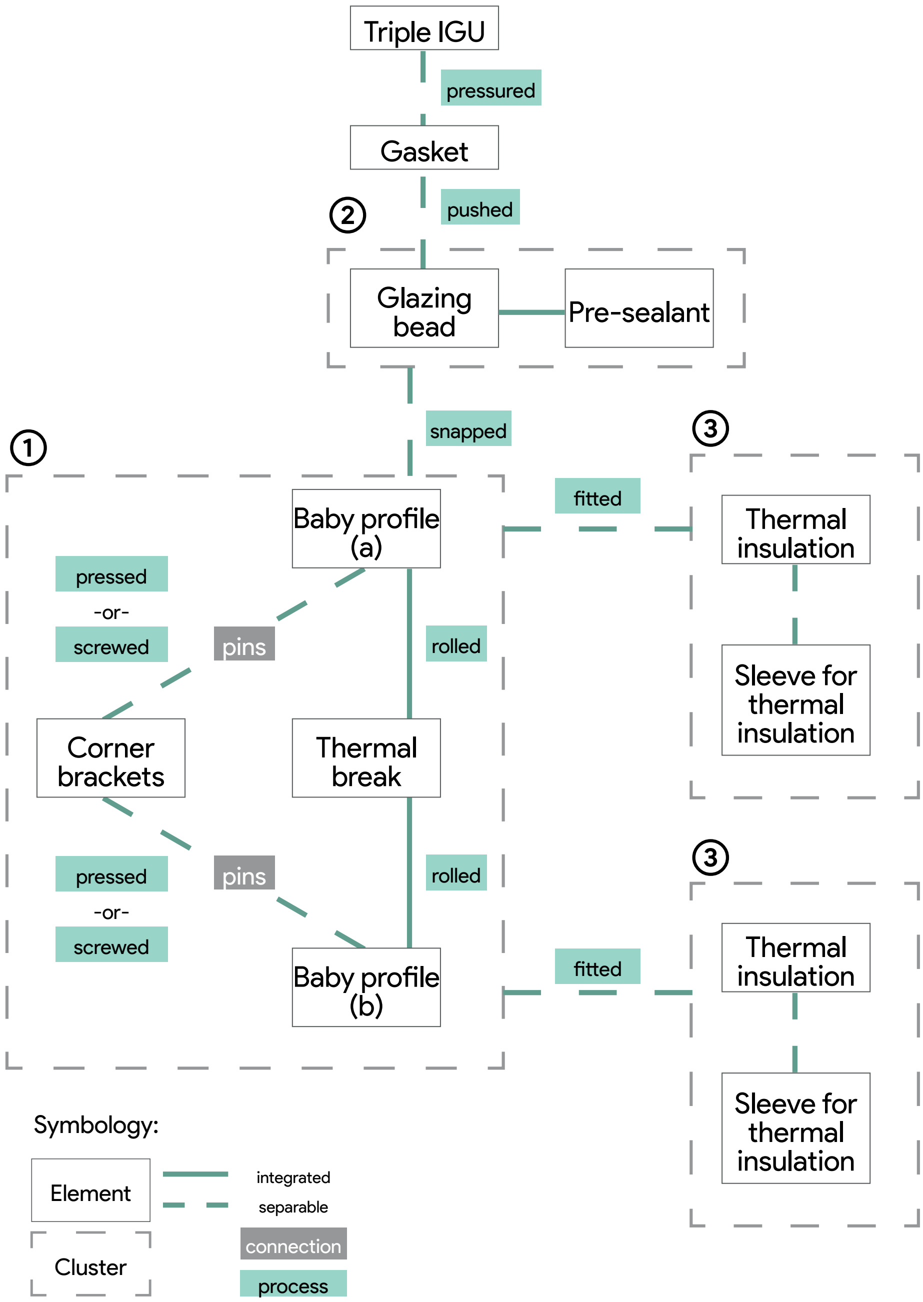


Figure 7.10 Relational patterns and clusters from the RT 82 HI +. Image by author.

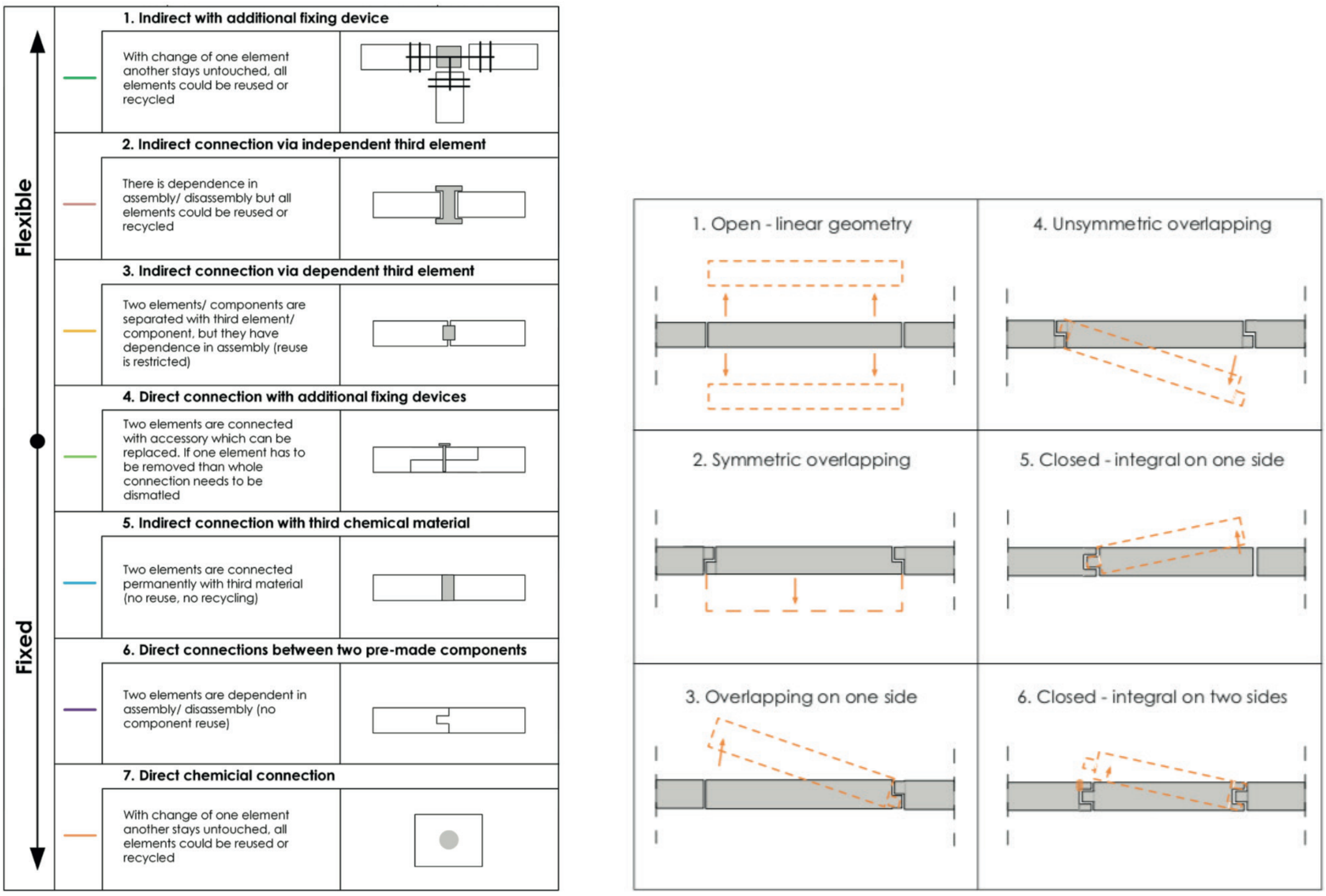


Figure 7.11 Left: Types of connections. Image by Beurskens and Bakx (2015). Right: Interface geometry. Image by Beurskens and Bakx (2015

(f) Assembly Sequence: The window system is manufactured through sequential assembly, a process with linear dependency along each element. Every element that is added is attached through the assembly of a new element, since replacing one element requires dismantling others that should be kept in place. This is not the best solution if the product is intended to be disassembled efficiently. Score: 3/6

(g) Interface Geometry: This aspect can be further investigated through the "geometry of product edges", as it can indicate the disassembly potential through the relationship of an open or interpenetrating geometry, where an open one is the most suitable for DfD, and closed the least suitable. In the case of this window system, closed geometries integral on both sides are predominant. Probably the best example is the connection between the baby aluminium profiles and the thermal break, which is closed - integral on two sides (Number 6 as seen on figure 7.6). Other types of edges that seem to be a little bit better than the closed ones are the glazing beads, which are overlapping on one side (Number 3 as seen on figure 7.6). On the other side, the best geometry of product edge might be the glazing and the insulation and its sleeve, which are fitted through an open linear geometry (Number 1 as seen on figure 7.6). Because most of the edges are closed, this is not an optimum solution for DfD. Score: 2/6.

(h) Type of Connection: Cluster (1) is connected to cluster (2) through direct connections (based on the geometry of the product edge), Cluster (1) and (3) are connected through an indirect part (thermal insulation sleeve). However, inside the clusters the three different types of connection are found. Filled (based on chemical material) between the glazing bead and the pre-sealant, direct (thermal break knurled into the aluminium baby profiles), and indirect (EPDM gaskets to IGU and glazing beads), which is the optimal type of connection. The complexity of these types of connections makes the disassembly longer and more difficult. Score: 2/6

Figure 7.13 shows the results of the assessment. The total score is 54%.

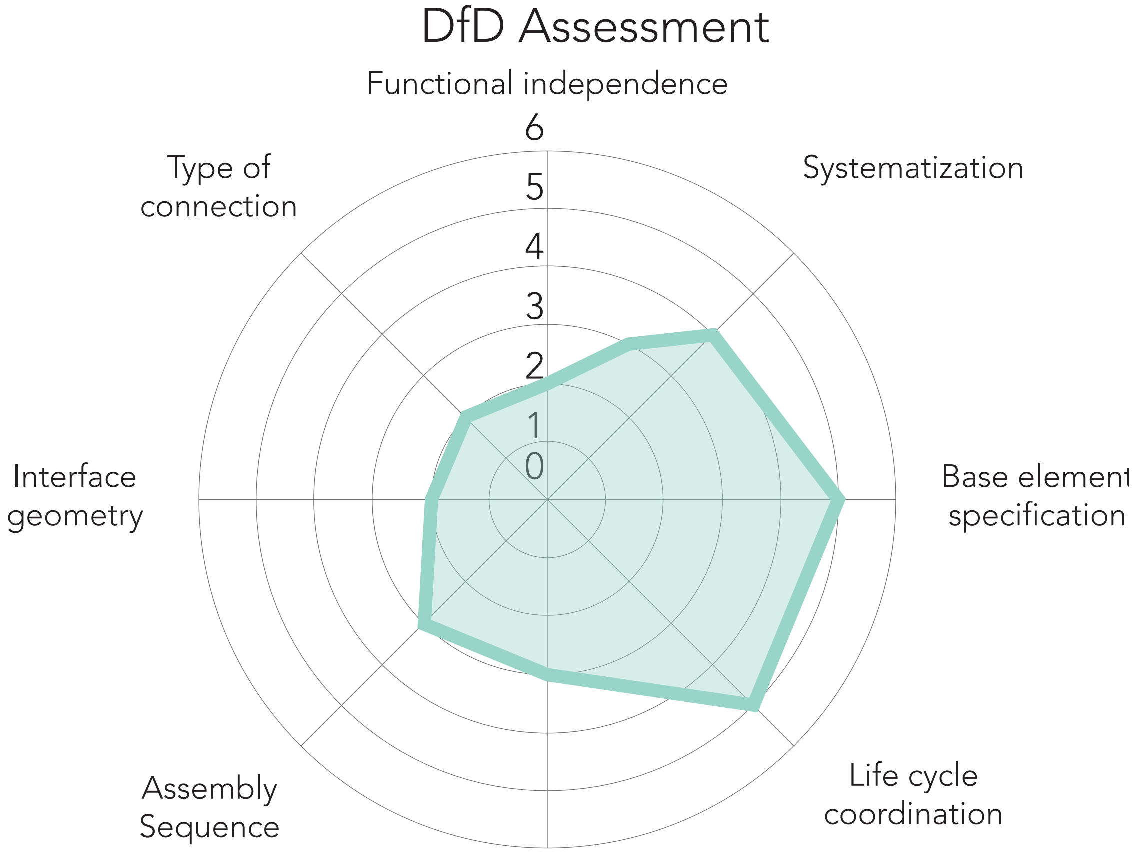


Figure 7.12 Results of the DfD assessment of the RT 82 HI +. Image by author.

7.4.3 Notes From the Disassembly of the Prototype

On the 31st of May, 2019, a prototype of the RT 72 (provided by Kawneer) was disassembled with the help of Dr.Ing. Marcel Bilow. As mentioned before, the element configuration of the RT 72 and RT 82 HI + are exactly the same, with the difference that the RT 72 has a thermal break that is 10 mm slimmer. In principle, the process of disassemblying the RT 72 and RT 82 HI + is the same.

The entire disassembly process was recorded on video, and a full transcript of it can be found in the Appendix. The following were some of the key remarks from the disassembly session:

00:14:50
[Talking about glued EPDM gaskets] Tany: But then if you want to make it more circular what do you do if you have to glue them?

00:14:56
Marcel: In principle you have to. I've seen lots companies who vulcanize them. Yes, they do this together like the tire. Yeah. If you have a puncture tire and then there are vulcanize that sort of glue. I do not think that is so harmful. It's more like material to material.

[Talking about corner brackets] Tany: So, if you would like to make it circular you can use the same elements but by riveting.

00:18:45
[Talking about the corner joint of a window] Marcel: And my experience is that all I know from experience that the quality of a window frame is determined by the closeness of the gaps.

00:20:34
[Talking about the most challenging parts] Marcel: Precisely, so therefore I think within circularity, that part, the corner brackets and how to assemble them is the most difficult part because these elements would never be as perfect as this. So that's a little bit tricky, I think.

7.4.4 Steps taken to disassemble the RT 72 Prototype

The following steps (depicted in Figure 7.14) were taken to disassemble the RT 72 prototype:

1. External gaskets are removed by hand by being pulled (if they are glued, heat might be needed)
2. The glazing beads are stressed by squeezing them at the bottom, then removed (they are snapped)
3. Removal of the glass. In practice, the glass is taken out with a suction cup.
4. Glass supports are taken out from the inside frame with the help of a small screwdriver, as they are snapped.
5. The moving part of the window is demounted by unscrewing the fixed points.
6. The insulation rubber foam is removed (depending on the type of glue, heat might be needed)
7. Inner gaskets are removed by hand by being pulled (if they are glued, heat might be needed).
8. The brackets for the T joint are removed by drilling out the riveted connection, and pushing the bottom frame with a hammer (if glue is applied to the bottom of the bracket, heat might be needed).
9. An attempt to remove the hardware was done by trying to snap out the handle, or removing the bolts from the inner mechanism. However, it was unsuccessful.
10. The corner bracket is removed by drilling out in the riveted connection. The bracket needed further force applied to it to be completely removed. In the case of this prototype, a part of the corner bracket was not completely removed from the inside of the frame.

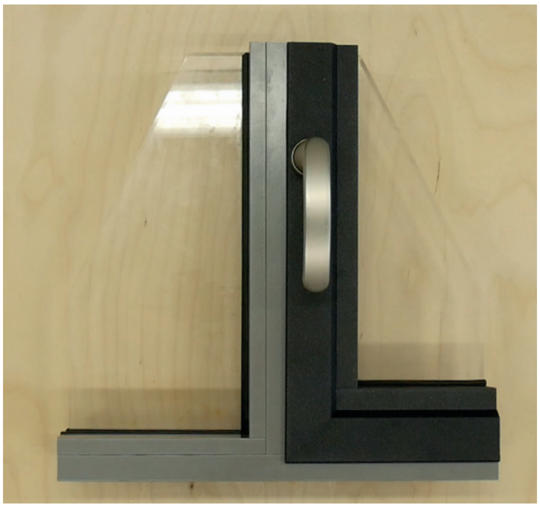


Figure 7.13 Initial set-up of the RT 72 prototype for disassembly.

7.4.5 Conclusions on DfD Assessment

According to the disassembly assessment, there is room for improvement the following aspects: "assembly sequence", "interface geometry", "type of connection", and "functional independence". It is clear that many of the different product edges, and the different types of connections have a great influence on the disassembly potential of the window system. Furthermore, the assembly sequence is highly related to the construction method, which is developed under a linear economy. Improvements on the different product edges towards open connections, along with connections that are indirect are some of the initial strategies that can be implemented to improve the design. With open geometries and indirect connections, it is expected to see an improvement in the sequence of assembly. On the other hand, "life-cycle coordination" and "base element specification" are aspects which score quite strong in the disassembly potential, mostly because of the selection of materials. This is to be kept into consideration during the design phase, as there are strong aspects from the product.

From disassemblying the prototype, it was also learned that the corner connection is one of the most critical parts of the design, as it is not designed to be taken appart. Further investigation on disassemblying the hardware should also be taken into consideration, as it was not possible to disassemble it from the prototype. Additionally, the type of tools required to disassemble the window can be optimized. This will probably be related to using as few tools as possible, and trying to standarize the type of connections as much as possible.

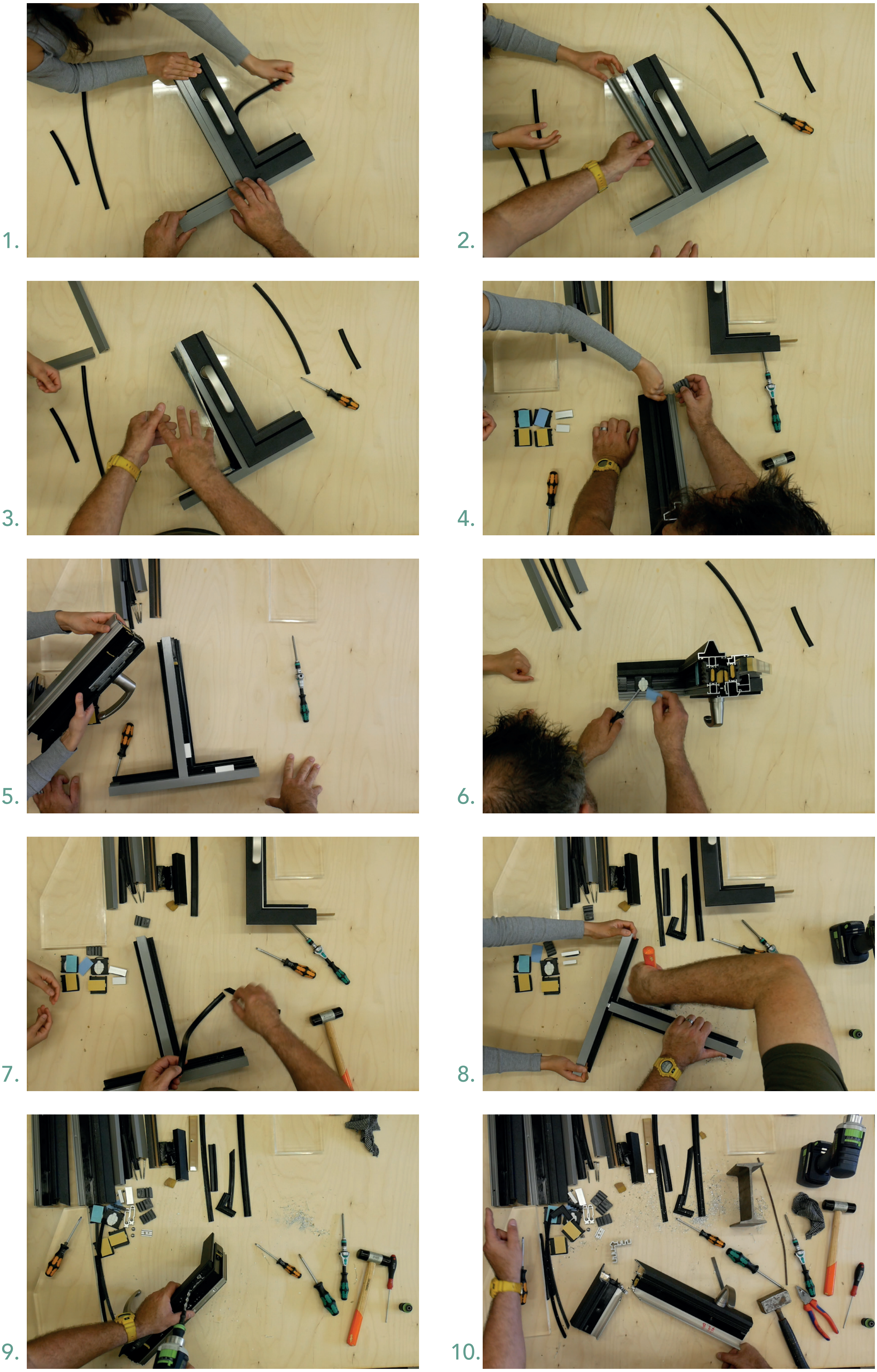


Figure 7.14 Disassembly process step by step for the RT 72 prototype. Images derived from the video footage by M. Bilow (2019).

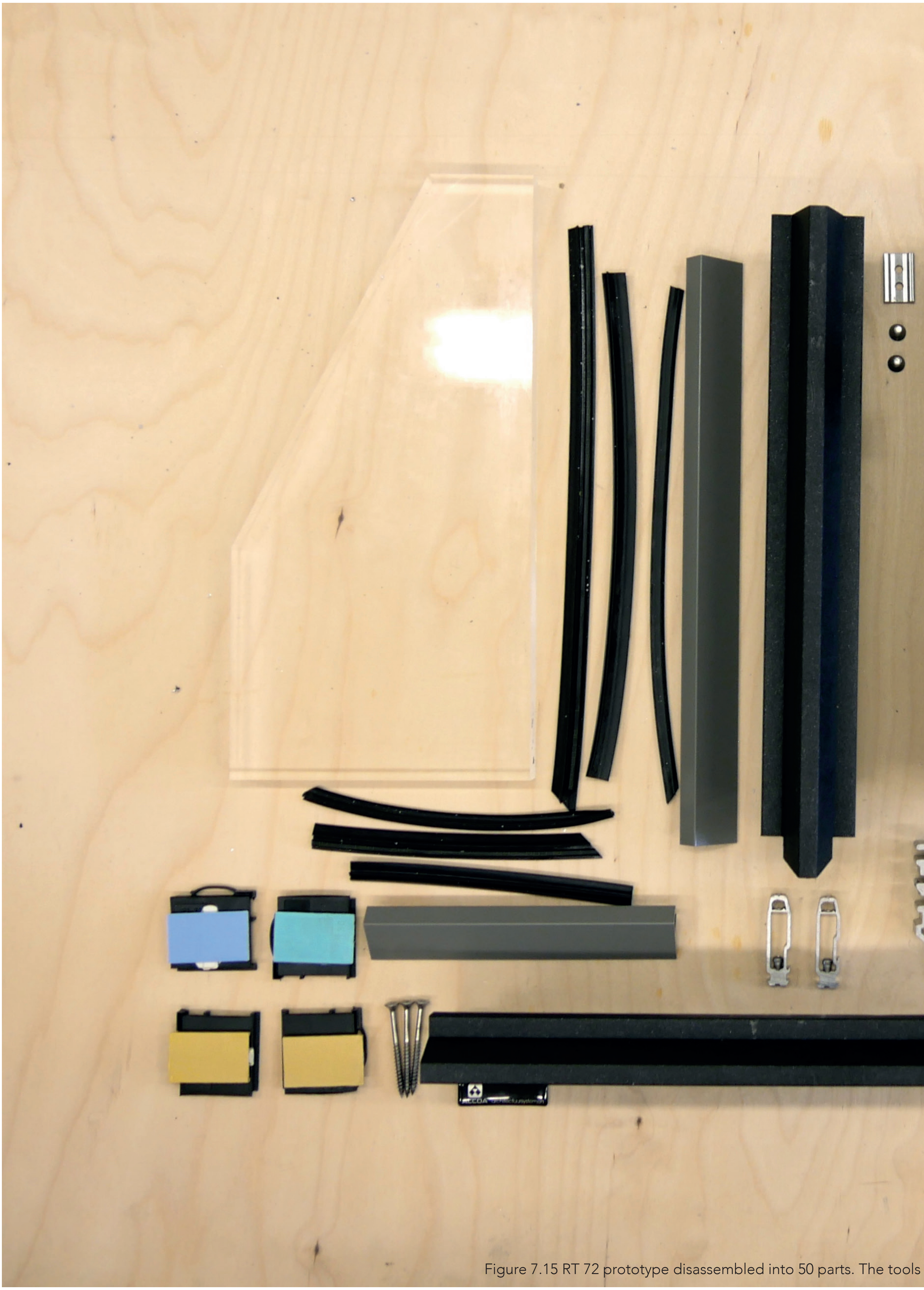


Figure 7.15 RT 72 prototype disassembled into 50 parts. The tools

used for the disassembly are shown on the right. Image by M. Bilow (2019).

7.5 Assessment on Design for Adaptability (DfA)

One of the cores found at the framework on circular economy by the Ellen MacArthur Foundation states that "insights from living systems (...) have proved to be adaptable and resilient" (EMF, 2013). Adaptable buildings, along with adaptable façades are concepts that are not new for the built environment. However, in the last decades, the continuous technological advancements, along with an increasing demand for buildings due to population growth have been some of the key factors for the demand of adaptable buildings

7.5.1 Methodology to Assess DfA

Section 3.7 explained the importance of DfA and its impact on the built environment. To assess DfA, Schmidt (2014) recognises six different adaptability strategies, and one more is added in the work developed by Beurskens and Bakx (2015), who also developed a clear methodology to assess DfA in a Circular Façade framework. The methodology is based on reviewing the six adaptability strategies by Schmidt (2014), while establishing a relationship between these and circular façades. The base for this analysis is explained in Chapter 3, where the different Circular building product levels specified for the skin were explained, along with other important concepts. The review of each adaptability strategy will provide feedback on adaptability design options, and could even investigate possible future scenarios of change.

I. Versatile: Buildings are able to change space and configuration of systems. In the façade framework, this adaptability strategy recalls the possibility to include changes in configuration at a sub-system, component, and element level. These reconfigurations might require different types of measures that are to be taken into account.
II. Refitable: At a building level, it implies that buildings should be able to adjust their performance. In the case of façades, it can be explained as "the replacement, addition, removal or upgrade of functions" (Beurskens and Bakx, 2015). This implies that a façade might be able to derive other functions: biodiversity, climate regulation, aesthetical functions, and addition of active technology.
III. Convertible: This strategy implies that buildings should be able to change their function. Analysing a change in building functions might derive other convertible possibilities for façades, such as change of façade requirements (for instance, an office building that is transformed into housing), which might be related to the capacity to change the window area of a façade.
IV. Scaleable: This strategy established that buildings should be able to change their size. This can be translated into three different transformation scenarios: increase the building size, decrease the building size, or the addition of an outside space. In the case of façades, these three different scenarios can derive on increasing or decreasing the façade area, the addition or removal of a storey, and the creation of balconies or loggias.
V. Movable: This strategy refers to the ability of buildings to change their location. This adaptability strategy is related to the capacity of moving the systems from a building. In the case of a façade, the possibility to relocate it.
VI. Reusable: The strategy implies that buildings should be able to change their use, or that their building products might be reused in other buildings. However, this strategy is different from the rest as it implies changes in other buildings, while the others are focused on the initial building. In the case of façades, it can be translated to the reuse of a full façade system, sub-systems, components or elements. It is suggested that to overcome different dimensions between different buildings, the Built Environment would need to switch to designing façade products according to a modular grid that will determine standard sized. The second option would be to design façade products that can be easily adjusted (for instance, through a sliding system). If they require to be shorter or longer, the product can adjust itself. There are certain limitations to this, like a maximum span, and this solution can also be seen as highly material intensive.

This methodology analyses different adaptability strategies for façades, which can be applied at a system, sub-system, component and element level. However, for the purpose of the presented research, the assessment is applied to a component and element level. Figure 7.16 illustrates the different adaptability strategies, with their adaptability options for façade. From the adaptability options for façade, the ones related to a component and element level are highlighted, as only these are taken into account for the assessment. Each strategy, and the adaptability options for façade will be analysed for the RT 82 HI + frame, and a score between 1-2-3-4-5-6; very unsatisfactory - unsatisfactory - slightly unsatisfactory - neutral - slightly satisfactory - very satisfactory.

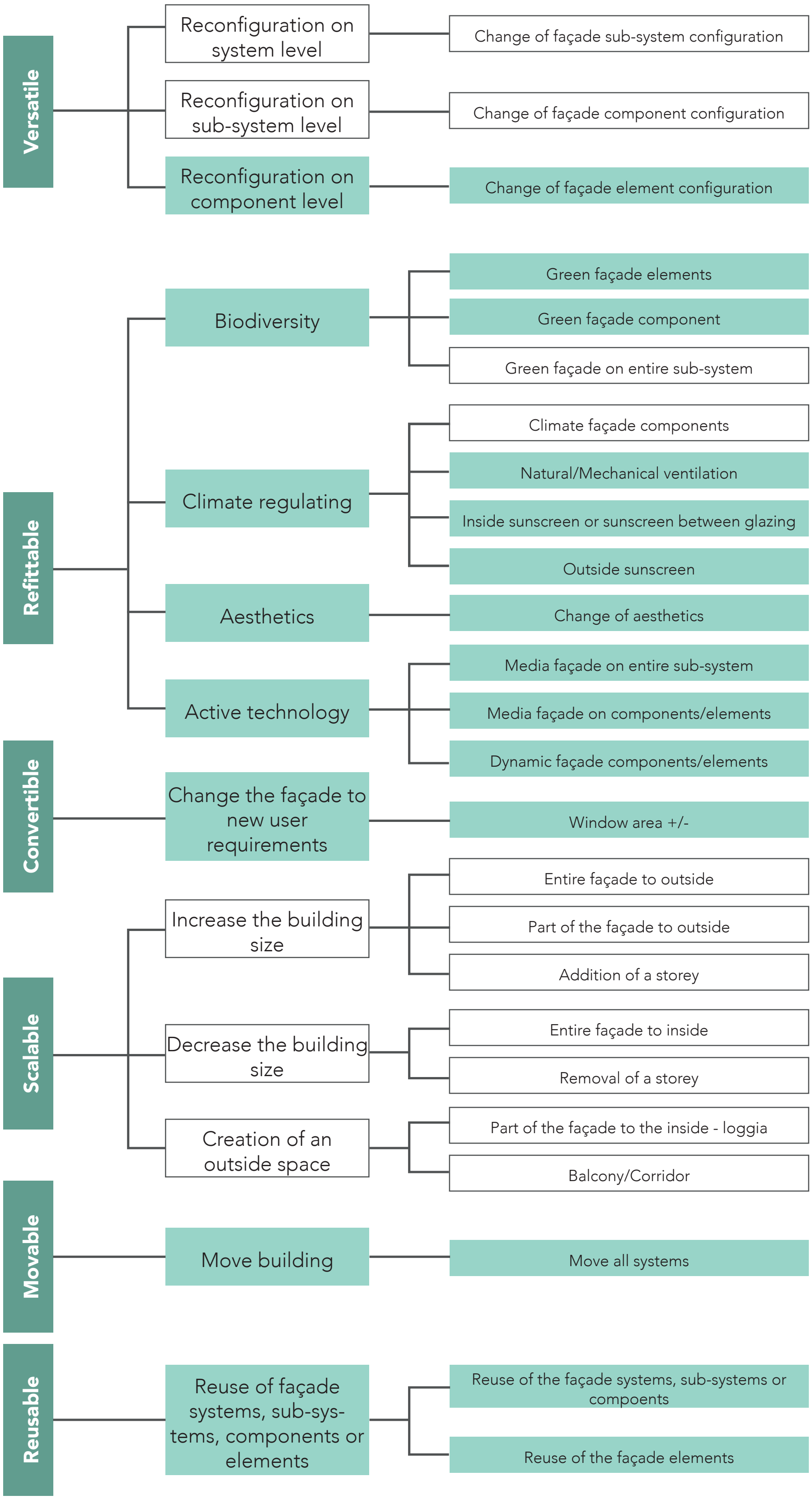


Figure 7.16 Adaptability strategies for façades. Image derived from Beurskens and Bakx (2015).

7.5.2 Application of Methodology for DfA

(a) Versatile:

i. Reconfiguration at a component level

- Change of façade element configuration: At the moment, it is only possible to change the glazing beads, but the configuration of the elements cannot be altered. Score: 3/6.

(b) Refitable:

i. Biodiversity

- Green façade elements: In the current system, it might be possible to add green façade elements (if taking as a reference project the Façade Leasing concept which uses the RT 72 frames with a foam green façade infill). Score: 5/6.
- Green façade components: In the current system, it might be possible to add green façade components (if taking as a reference project the Façade Leasing concept which uses the RT 72 frames with a foam green façade infill). Score: 5/6.

ii. Climate regulating:

- Climate façade components: The current system does not include them, but if they are included in a new infill that is adjusted to the frames of the building, it might be possible to add them. Score: 5/6.
- Natural/Mechanical ventilation: The system is able to provide natural ventilation because it incorporates moveable frames. Mechanical ventilation components can also be added if designed carefully and fitted into the frames. Score: 6/6
- Inside sunscreen or sunscreen between glazing: if the sunscreen if fitted inside the IGU, it is possible to integrate it. Score: 5/6.
- Outside sunscreen: The frames support outside sunscreen, and this a regular application. Score: 6/6.

iii. Aesthetics:

- Change of aesthetics: The system offers a variety of finishings and outer frames that can be selected before building the window. However, once the window is built, it is not easy to change this. Score: 2/6.

iv. Active Technology:

- Media façade on components/elements: Media components can be added as long as they can fit on the frame, like for example, outdoor LED display boards. Score: 4/6
- Solar Panel components/elements: As long as they are building integrated photovoltaics, and they can be fitted into the frame, they can be added. Score: 5/6.
- Dynamic façade components/elements: This might refer to dynamic sunscreen or other types of components/elements that might respond to climate conditions. The strengthening of the frame might be able to support them to certain extent, and probably additional hardware would need to fit inside. In theory, it should be possible, but because this is a 100% residential product, it has never been taken into action. Score: 4/6.

(c) Convertible:

i. Change the façade to new user requirements

- Change of window area: At the moment, this is not really possible. If the window area is to be decreased, the profiles should be cut and new connections can be done. On the contrary, if the window area is to be increased, a new frame should be manufactured. Score: 2/6.

(d) Moveable

i. Move building

- Move all systems: Currently, if the frame is to be relocated, in theory it should be possible as long as the new building requires the same measurements. The aluminium frame system does not present a problem with this adaptability strategy, but rather the connections of the construction. Score: 4/6.

(e) Reusable

I. Reuse of façade components or elements

Reuse of façade components: In a life span of 75 years, full frame component can be reused. Special care should be taken to the connection with these and the building. Score: 4/6.

Reuse of façade elements: Not all the elements are easy to dismantle to be reused in the future. At the moment, there can be direct reuse of the aluminium frame as elements, but the rest of the elements seems unclear if they can be reused. Further analysis on this is required. Score: 3/6.

Figure 7.17 synthesises the adaptability potential of the RT 82 HI + system, according to the previous methodology. The total score is 69.52%.

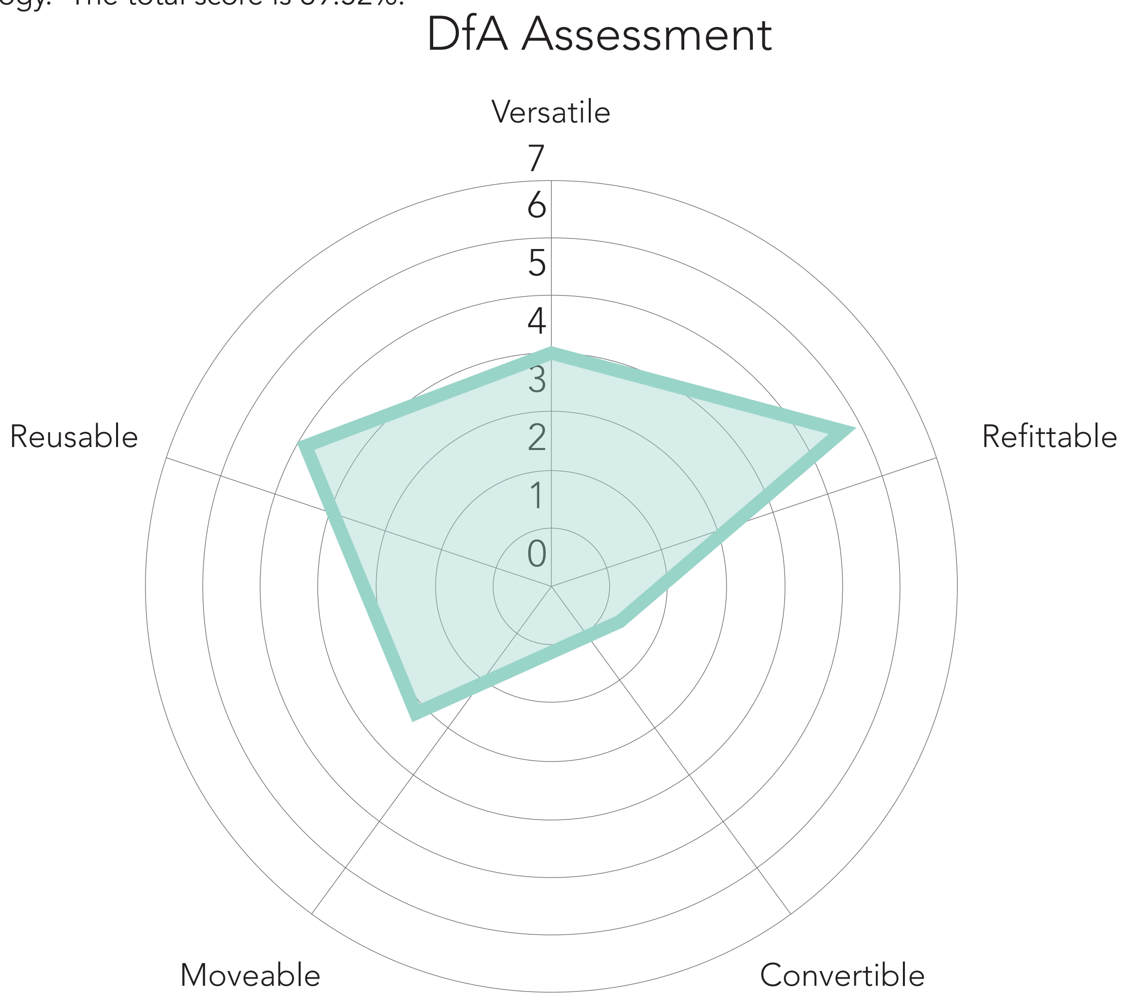


Figure 7.17 Results on the DfA assessment for the RT 82 HI +. Image by author.

7.5.3 Conclusions on DfA Assessment

The assessment shows that in the five different analysed strategies, the highest score is for the "Refittable" strategy, where biodiversity, climate regulating, aesthetics and active technology are evaluated. This is because the frames can adapt to different types of infill. However, in the case of "aesthetics", it scores very low, and there might be room for further improvement. The second highest score is for the "Reusable" strategy. However, in this case is by taking into account a direct reuse of the components. If the elements are to be directly reused, it becomes complex, as the disassembly of the elements is not completely easy, especially in the case of permanent connections with the aluminium profiles and thermal breaks. The next strategy with the highest score is "Moveable", referring to the capacity of moving the frames to another building. In principle, the window system can be moved, as long as the connection to the construction allow it. This has room for further improvement. The next adaptability strategy is "Versatile", which refers to the façade element configuration. The element configuration cannot be easily changed, however, it is still to be proven if this is a required quality for the redesign,

which will be further discussed afterwards. The last adaptability strategy, and the one with the lowest score, is the "Convertible". This one is directly related to the change of window area, which is not currently supported, and there might be room for improvement in the redesign.
In conclusion, there is room for improvement in the following aspects: Refittable > Aesthetics, Convertible > Window Area, Move Building > Move Façade Systems, and Reusable > Reuse of façade elements. In the case of Versatile > Change of Façade Element Configuration this shall be further analysed to understand if the configuration of the elements needs to reach such a high level of adaptability.

7.6 Assessment on Design for Remanufacturing (DfRem)

As it was thoroughly reviewed in Chapter 4, DfRem is a series of guidelines that prepare the product to be remanufactured. Different product properties are to be matched to the remanufacturing process, as it can be seen in the RemPro-matrix (Section 4.7.1) developed by Sundin (2004). However, before designing for remanufacturing, first it should be determined if a product is suitable for remanufacturing.

7.6.1 Methodology to Assess DfRem

The methodology used to assess the remanufacturing potential of a product was developed by Boorsma et al. (2018), and it has been implemented in different workshops with companies, as part of EU projects. It has proven to be simple, yet effective at demonstrating if a product is suitable for remanufacturing, as well as identifying points for improvement This methodology is also based in the eight-point criteria developed by Vogtländer et al. (2017), but with slight modifications, as follows:

I. The product is very durable
II. Functional considerations are decisive in discarding
III. The product is standardized and the parts are interchangeable
IV. The remaining value is high
V. The price to obtain the cores is affordable
VI. The product technology is stable
VII. The consumer is accepting remanufactured products
VIII. Access to spare parts is guaranteed for 5-10 years

A score to each criteria is given, from 1 - 2 - 3 - 4 - 5; strongly disagree - slightly disagree - undecided - slightly agree - strongly agree.

7.6.2 Application of Methodology for DfRem

I. The product is very durable: According to Kawneer, the RT 82 HI + window system has a service life of 75 years, as long as it receives proper maintenance. According to this, the product is very durable. Score: 5/5.
II. Functional considerations are decisive in discarding: The window system might be discarded if it stops performing properly. For instance, if the legislation on insulation becomes even more strict, it is not possible to upgrade the system, and at the moment, it might be completely replaced by a new window. Score: 4/5.
III. The product is standardized and the parts are interchangeable: The product is highly modular, as it is constructed almost like the 52/62/72 window series, but the width of the thermal break changes. However, while the parts of the product are standardized, they are not designed to be interchangeable. Score: 3/5.
IV. The remaining value is high: This is debatable, as at the moment it is unknown what is the depreciation rate of a window. However, it is true that the aluminium will retain its value, which is quite high. Score: 4/5.

V. The price to obtain the core is affordable: The price to obtain the aluminium frames might remain stable over the years. Score: 5/5.
VI. The product technology is stable: This window system has already one of the highest thermal insulation values of the market. This type of technology is not expected to change much, at least in the following 50 years. The acoustic insulation, air and water tightness are also really good, but in this case, the legislation could require slightly higher values. Score: 4/5.
VII. The consumer is accepting remanufactured products: This is not currently available in the market, however, according to Circularity Interview and Brainstorming Session (Section 5.4), there is a future in the market for remanufacturing products. M. Veerman even brought to the attention that Real Estate developers might be the most suitable potential client for remanufactured façades. Score: 3/5.
VIII. Access to spare parts is guaranteed for 5-10 years: This is guaranteed, especially because the parts have been manufactured under the same process and type of architecture for the past 10 years. It is not expected to change. Score: 5/5.
Figure 7.18 shows the results of the assessment. The total score is 82.5%.

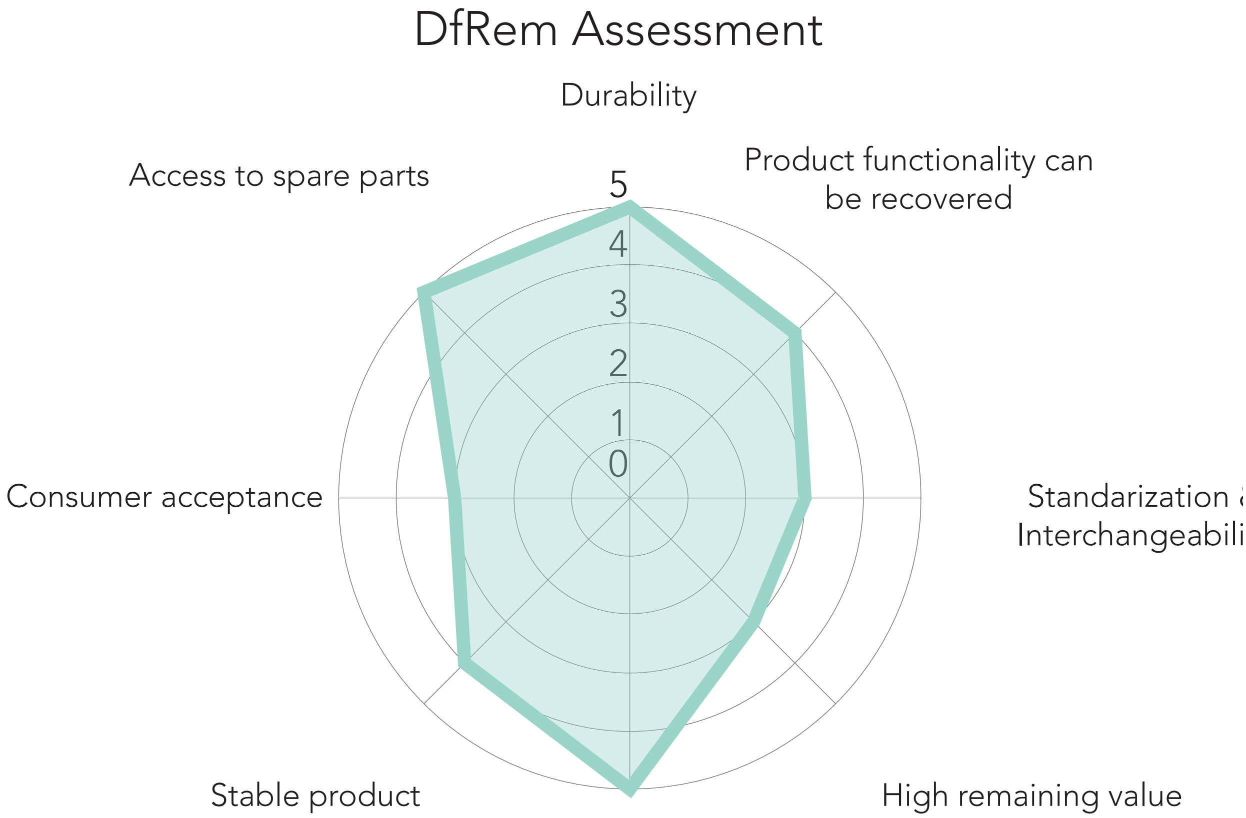


Figure 7.18 Results on the DfRem assessment for the RT 82 HI +. Image by author.

7.6.3 Conclusions of DfRem Assessment

The assessment shows that there is a very high potential for the product to be remanufactured. There seems to be a lot of potential in the "standardization and interchangeability" of parts, as at the moment they are not completely interchangeable because it is not easy to dismantle them. The "high remaining value" and "consumer acceptance" also seems unclear, since at the moment there is re-manufacturing in the market of façades. However, at it was stated before, many experts expect this to change over the years if the product is in good condition, and at an affordable price, cheaper than a new product. However, as it was thoroughly reviewed in Section 3, if remanufacturing business models are developed correctly, there can be high revenues while reducing the environmental impact, as well as creating new jobs. This will be further studied in Chapter 8 Designing a Circular Window System.

In addition, "Product functionality can be recovered" is a parameter that can be improved through the guidelines of DfRem, and DfD, since the dismantling of the elements can allow their upgrade. Additionally, the parameters of "Affordable cores", "Durability" and "Access to spare parts" seem to be the strongest aspects of the design. These are related to the product being manufactured through aluminium extrusion, and indirectly related to the stable product technology. In conclusion, the product has very strong aspects that make it highly suitable for remanufacturing. There are some areas for improvement, but these can be tackled through the implementation of the DfRem guidelines.

7.7 Conclusions on Chapter 7

In this Chapter, a reference project was established: a brick cavity wall façade of 3.00 m by 3.00 high with a window of 1.20 m by 1.20. This reference project established the base to elaborate a function analysis, mostly based on Klein (2013) Façade Function Tree. This function analysis provided input on the complex functions and requirements a façade must fulfill, which was later applied to the reference project. In the case of this façade system, there are three main primary functions to be fulfilled: "create a durable construction", "provide a comfortable interior climate", and "support use of the building." These functions were further analysed by the secondary functions, supporting functions, and the detailed supporting functions. After this function analysis, the RT 82 HI + was analysed according to the Hierarchical Range of Industrial Building Products developed by Eekhout (2008). This allowed to understand the different levels: from material, element, sub-component, component, sub-system, system and building.

After this initial function and product level analysis was elaborated, three different assessment methods were analysed and applied to the existing window system, RT 82 HI +. The assessments were based on the principles of Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Remanufacturing (DfR). To obtain quantitative results, each assessment integrated a scoring system, depending on the methodology. This allows to have a numerical result on each assessment, and compare it to the new designs in Chapter 8.

The assessment on DfD, based on Durmisevic (2006) Transformation Capacity methodology, gave input on the different types of connections, the interface of each geometry, the sequence of assembly of the product, the life cycle coordination, the base element specification, systematization, and last but not least, the functional independence of the elements. The results of this assessment show that there is a high potential for improvement in the different types of connections—from closed to open—and the geometry of the product's edges. These two design properties affect the sequence of assembly and the systematization, improving the disassembly potential of the product. The total score for the DfD assessment is 54%.

The assessment on DfA was based on the methodology developed by Beurskens and Bakx (2015), based on Schmidt (2014), by analysing six different types of adaptability strategies applied to façade design: versatile, refitable, convertible, scaleable, moveable, and reusable. The results of the assessment show that the design of the system shows improvement potential on the aspects of "versatile", "moveable", and "convertible". The aspect of "refittable" scored already quite high, which is also one of the reasons the product overall has a high value. The total score for the DfA assessment is 69.52%.

The assessment on DfRem was realised under the methodology developed by Boorsma et al. (2018), based on Vogtländer et al. (2017), also previously applied in workshops with companies. The methodology is based on an eight point criteria, synthesised as follows: durability, product functionality can be recovered, standardization and interchangeability, high remaining value, affordable cores, stable product technology, consumer acceptance, and guaranteed access to spare parts (5-10 years). The assessment based on this eight-point criteria shows that there is room for improvement in "standardization and interchangeability", and "consumer acceptance". Compared to the assessments on DfD and DfA, the score was quite high, giving the total score for the DfRem assessment 82.5%.

The output from this Chapter is highly important for the design criteria of Chapter 8, as it determines which are the important aspects to be improved, and which ones should remain similar to the original system.

08.

Designing a Circular Window System

This Chapter discusses and proposed the design of a circular window system through proposing three different variants. Section 8.1 establishes the initial design requirements. Section 8.2 explains the different design concepts. Section 8.3 explains improvements in the different materials that are selected for the new variants, and Section 8.4 the improvements on hardware and other elements. Sections 8.5 - 8.7 analyse the different reuse, remanufacturing, and adaptability scenarios. Section 8.8 briefly explains the maintenance and warranty of a remanufactured window system, and Section 8.9 is an analysis on the thermal transmittance of the proposed variants.

List of Figures:

Fig. 8.1 Administrative and social building Karl Köhler by Wittfoht Architekten bda. Image by archello.com
Fig. 8.2 Overview of the different design requirements: functional, circular and aesthetical. Based on (Klein, 2013), (Beurskens & Bakx, 2015), (Henry, 2015), (Leising, 2017), (Cortés Vargas, 2019).
Fig. 8.3 Early sketch for Optimization of RT 82 HI + .
Fig. 8.4 Side view of the profile for Optimization for RT 82 HI +.
Fig. 8.5 DfD, DfA, and DfRem assessments for Optimization for RT 82 HI + compared to the original RT 82 HI +.
Fig. 8.6 GRP Window System XFrame. Image by Michael (2015).
Fig. 8.7 Early sketch for Hybrid System Variant A.
Fig. 8.8 Side view of the profile for Hybrid System Variant A.
Fig. 8.9 Isometric view of the Hybrid System Variant A.
Fig. 8.10 Exploded isometric view of the Hybrid System Variant A.
Fig. 8.11 DfD, DfA, and DfRem assessments for Hybrid System Variant A compared to the original RT 82 HI +.
8.12 Left: Aluminium/PVC frames. Image source: dalmen.com/ Right: Wooden/Aluminium frames. Image source: archiexpo.com/
8.13 Early sketch on Hybrid System Variant B. Image by author
Fig. 8.14 Side view of the profile for Hybrid System Variant B.
Fig. 8.15 Isometric view of the Hybrid System Variant B.
Fig. 8.16 Exploded isometric view of the Hybrid System Variant B.
Fig. 8.17 DfD, DfA, and DfRem assessments for Hybrid System Variant B compared to the original RT 82 HI +.
Fig. 8.18 Design concepts element's function matrix for the two proposed variants.
Fig. 8.20 Top: Section of the Hybrid System Variant A in the reference project, cavity brick façade. Bottom: Axonometric view.
Fig. 8.21 Top: Section of the Hybrid System Variant B in the reference project, cavity brick façade. Bottom: Axonometric view.
Fig. 8.22 Different WCP extruded profiles. Image by globalsources.com
Fig. 8.23 Example of a window handle and its ease of disassembly. Image by wodowo.es
Fig. 8.24 Hypothetical scenario of a sensor linked to a mobile app.
Fig. 8.25 Isometric view of the redesigned corner cleat.
Fig. 8.26 Key activities.
Fig. 8.27 Key resources.
Fig. 8.28 Vertical and horizontal details of the three proposed designs attached to a brick cavity façade system and construction.
Fig. 8.31 3D views of Hybrid System Variant A (left) and Hybrid System Variant B (right) in a brick cavity wall construction.
Fig. 8.30 Vertical details of the three proposed designs attached to a passive house façade system and construction.
Fig. 8.31 Vertical details of the three proposed designs attached to a residential storey floor longitudinal system and construction.
Fig. 8.32 Vertical details of the three proposed designs attached to a passive house façade system and construction.
Fig. 8.33 Convertible conceptual designs for the window systems.
Fig. 8.34 Top: Isometric view with exploded elements of Hybrid System Variant A. Bottom: Change of aesthetics through weatherboards for Hybrid System Variant A.
Fig. 8.35 Top: Isometric view with exploded elements of Hybrid System Variant B. Bottom: Change of aesthetics through weatherboards for Hybrid System Variant B.
Fig. 8.36 Refittable strategies for window and window sections according to DfA principles.
Fig. 8.37 Overview of the elements most likely to cause problems. Image derived from Vipat (2017).
Fig. 8.38 Thermal transmittance simulation for Hybrid System Variant A.
Fig. 8.39 Thermal transmittance simulation for Hybrid System Variant B.

Figure 8.1 Administrative and social building Karl Köhler by Wittfoht Architekten bda. Image by archello.com

8.1 Establishing Design Requirements

The conclusions from the literature review from Chapters 2-4, along with the analysis on the company (Chapter 5), Window Systems (Chapter 6), and the extensive analysis on the existing design (Chapter 7), have served as input to determine the different design requirements. According to the conclusions from the previous Chapters, along with the discussions held with the different stakeholders involved in façade engineering, a circular façade can be defined as follows:

> *"A system that is designed for disassembly and for adaptability, able to circulate hierarchically between the technical cycles of reuse, remanufacturing, and recycling. Is built with sustainable materials that reduce the demand for virgin feedstock input, prevents valuable material losses, and reduces or offsets carbon emissions. The façade system, sub-system, and components should function in the same way or better than a traditional linear façade, as the performance of it is more important than the product itself".*

This definition allows to set the initial base for the design requirements for the circular window system. These design requirements can also be divided into three different categories: functional, aesthetical, and circular. Concluded from the extensive analysis from previous Chapters, they have been synthesised in Figure 8.2.

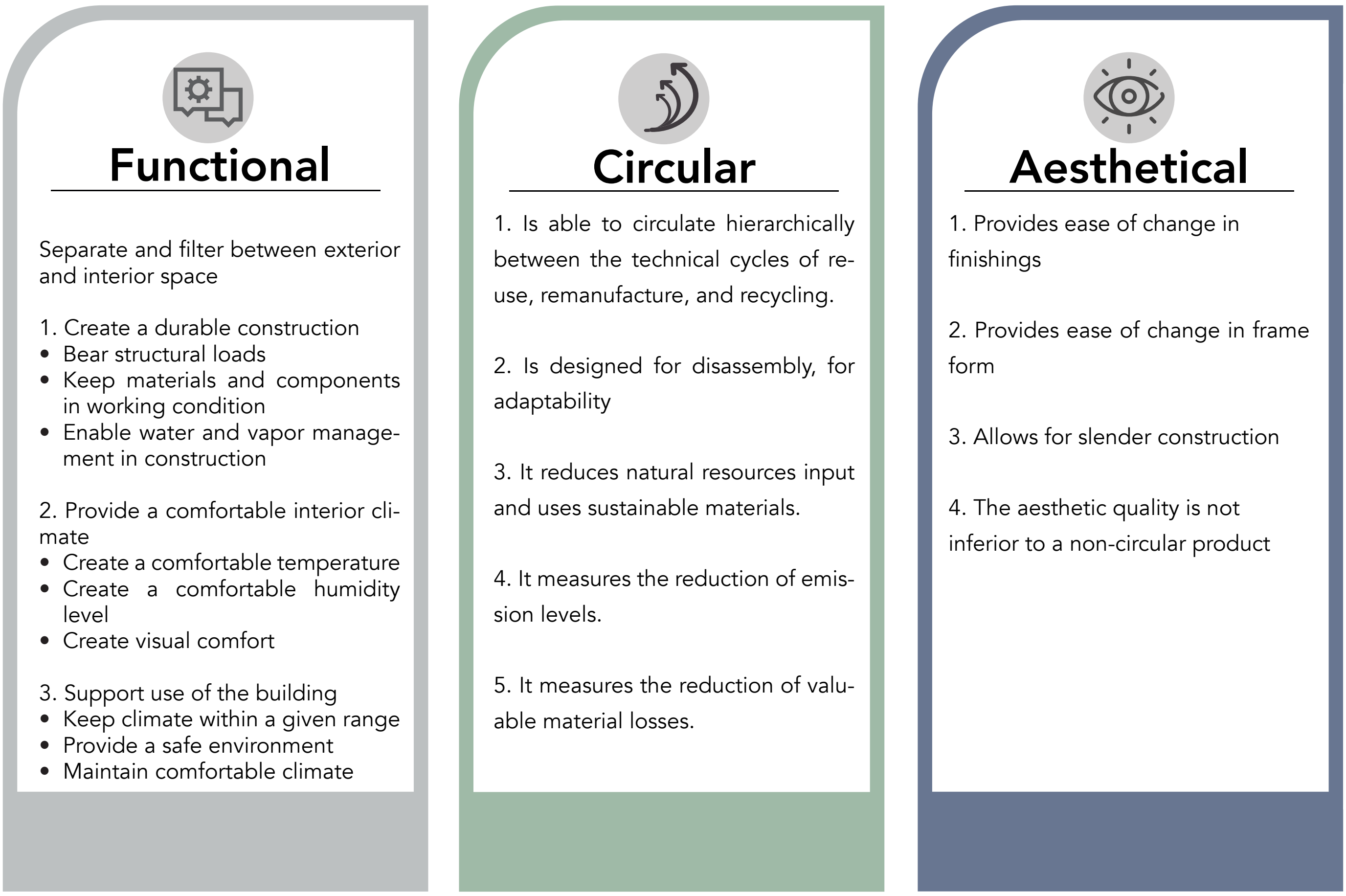


Figure 8.2 Overview of the different design requirements: functional, circular and aesthetical. Based on (Klein, 2013), (Beurskens & Bakx, 2015), (Henry, 2015), (Leising, 2017), (Cortés Vargas, 2019).

8.2 Design Concepts

Section 6.8 Comparison Method on Window Systems: Harris Profiles Matrix gave input about the different materials, along with their properties. The output from the matrix established that the best materials for a circular window system, according to the established criteria, were the hybrid variant of Aluminium/Window systems, and Aluminium.

However, in order to do a deeper exploration in the circularity of the material, and to explore new forms of wooden systems, it was decided to work with Wood Composite Polymer (WPC), instead of the regular wooden frames. This material has been recognised as one of the main examples of cyclability (Teuber et al., 2015; Carus et al. 2014). The composition and properties of this material will be explained in Section 8.3 Improvements through Material Selection.

(a) Problem statement: As it was shown in the DfD assessment, the geometry of the product edges, and the types of connections fell into the 'closed' category. This is not an optimal solution for DfD, as it makes the assembly sequence more complicated. The most predominant closed geometry/connection is the polyamide thermal break - aluminium profiles. Another problem is that because of the current type of architecture, the frame has a lot of different elements, which is translated into many different types of connections and assemblies. In the aspect of DfA, there seem to be limited options for aesthetics, crucial to one of the Design Questions from this research. It is not easy to change the finishing of the frames, or to change the form over time. The optimization of the existing design, along with the hybrid system variants aim to tackle this problem by giving different solutions for each aspect. They will be discussed in Section 8.2 Design Concepts.

8.2.1 Optimization of RT 82 HI +

(a) Objective: To optimize the existing RT 82 HI + through small changes that can lead towards a more circular design.

(b) Initial ideas and references: The DfD analysis showed that some of the parts have glue in it, and they require many different tools for disassembling it. The corner cleats (in the prototype) were riveted, and there was glue in the gaskets. The aluminium profiles are also permanently attached to the thermal break, as they are rolled in the factory. Neither of these are optimal solutions for circularity. The redesign will be based on giving suggestions on how this can be improved.

(c) Concept description: Through the different discussions with Wijnand van Manen, it was advised to have a removable thermal break. This works under the principle of having snap in connections where the thermal break is slidded in. If the thermal break needs to be removed, it will have to be stressed, and then slid outwards.

In the case of the gaskets, instead of gluing them, they can be vulcanized. This way the material is being joined through itself, without having another material, as stated by the principles of a circular economy.

Additionally, the corner cleats of the window can be joined through the use of a standard bolt. This allows for an easy disassembly, while still taking into account the precision required for manufacturing a window.

On the other hand, the AlcoaTherm insulation can have a different form. The current foam bars that are slid into the window systems have a small possibility of being reused. Having the same material, but in a different form might have a positive impact, for instance, in the form of beads, so that it can be easily removed and reused. The insulation and other material improvements are further discussed in Section 8.3 Improvements through Material Selection.

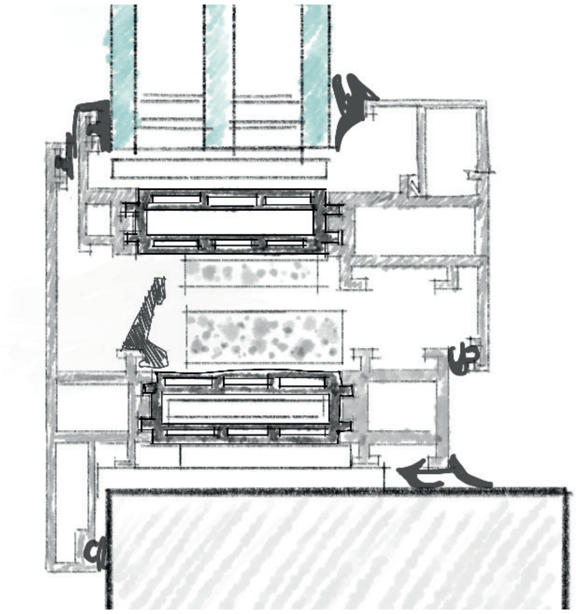


Figure 8.3 Early sketch for Optimization of RT 82 HI + .
Image by author.

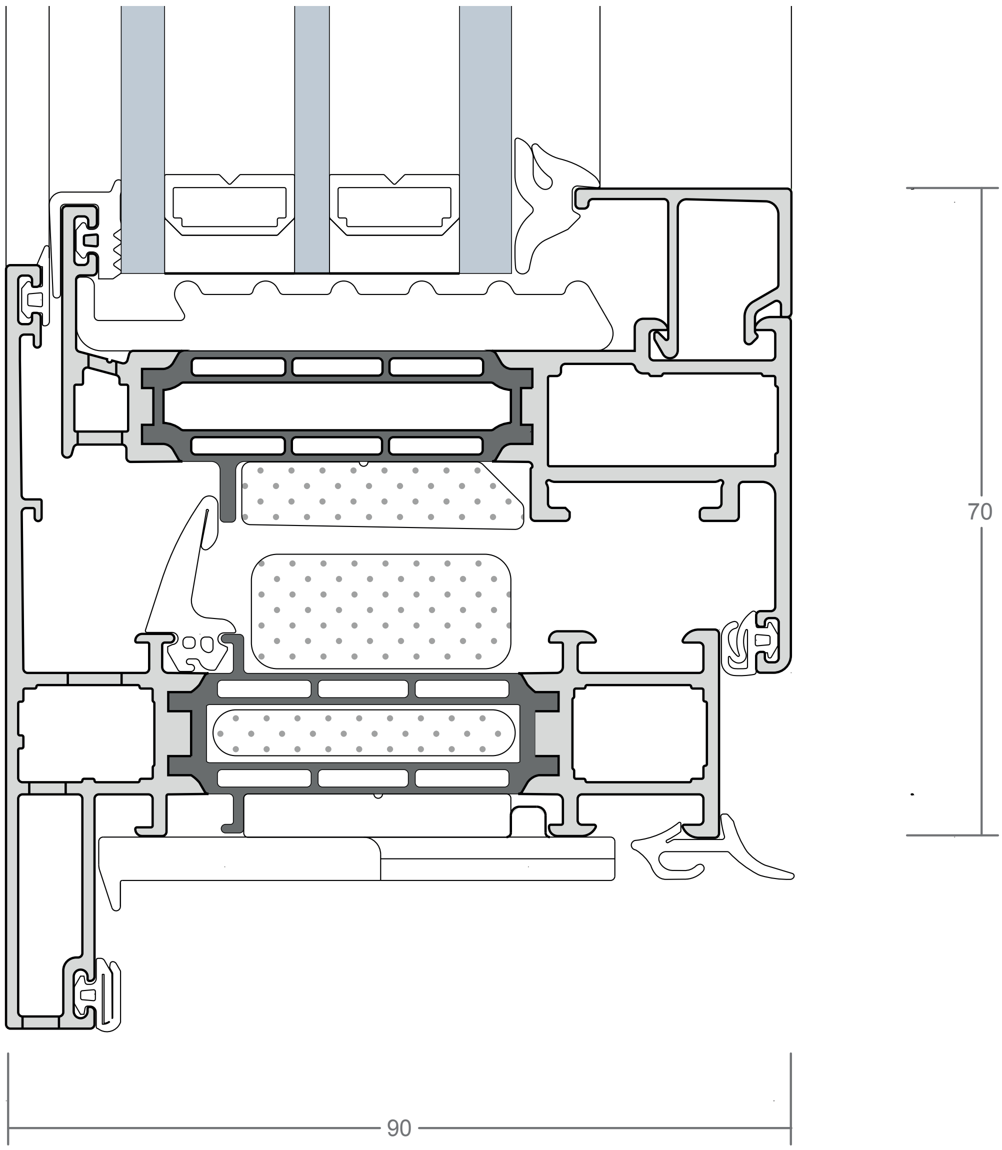


Figure 8.4 Side view of the profile for Optimization for RT 82 HI +. Image by author.

(d) Assessment: The only type of connection that is dramatically improved is the thermal break with the aluminium profiles. As this was changed to a permanent direct connection between two pre-made components to a non-permanent direct connection between two pre-made components. This is not a dramatic change in the DfD assessment, as it only changed the parameters of "interface geometry" and "type of connection". In the case of DfA, the improvement was mostly in "versatile", change of façade element configuration, and "convertible", change the façade to new user requirements. Even more, in the case of DfRem, the only improvement is seen in "standardization and interchangeability". The following graphs show the optimization's improvement against the original product.
The total scores are: DfD 60.41%, DfA 71%, DfRem 85%.

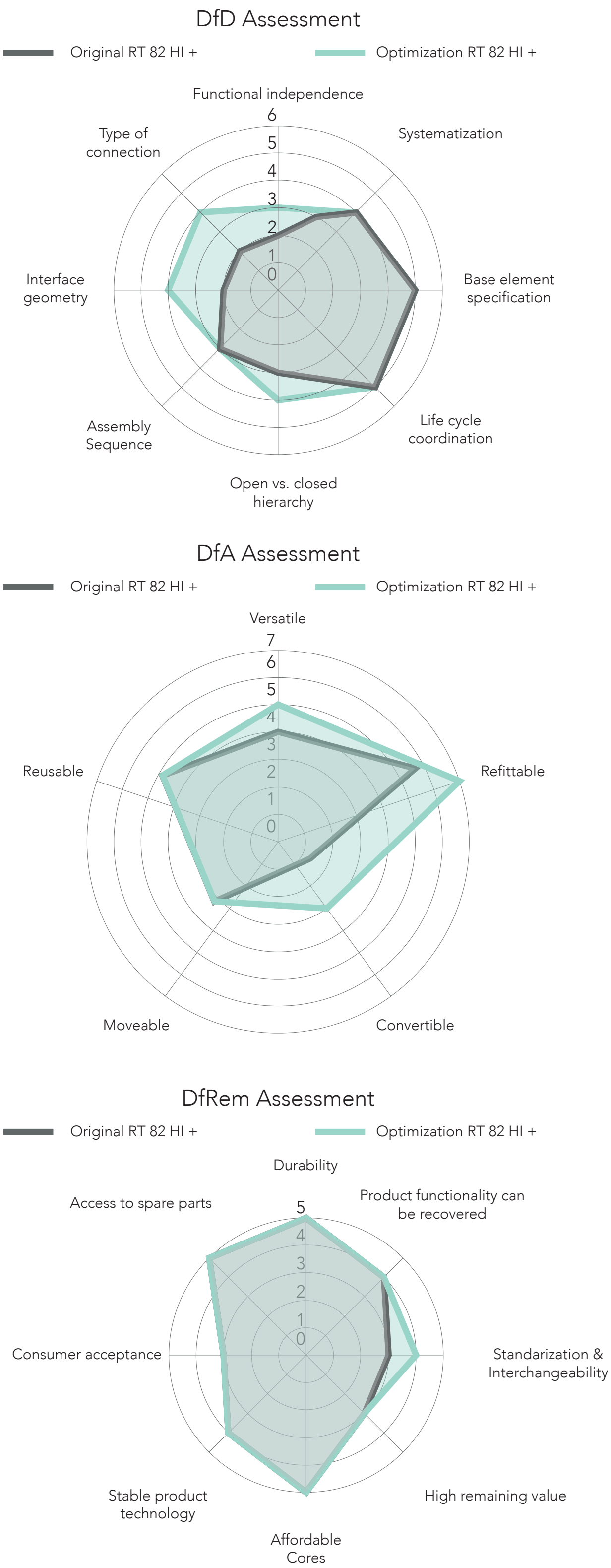


Figure 8.5 DfD, DfA, and DfRem assessments for Optimization for RT 82 HI + compared to the original RT 82 HI +. Image by author.

(e) Conclusions on Optimization of RT 82 HI +: While this optimization shows a small improvement in terms of DfD, DfA, and DfRem, it is constrained to the limitations of the product architecture of aluminium window systems. This product architecture is highly complex by nature, especially because of the thermal conductivity and low condensation resistance of the aluminium. This, along with many other factors, demand for the product architecture to have many different pieces that are connected to each other through integral closed geometries. This is the main reason the next two variants explore the use of a different material with higher insulating properties, that might deliver a new type of simplified product architecture.

8.2.1 Hybrid System Variant A

(a) Objective: An overall simplification of the architecture system of the frame. Exploration into the geometry of the product edges towards open connections, and possibilities for aesthetical adaptability.

(b) Initial ideas and references: Based on the analysis from Chapter 6. Window Systems, GRP window systems provide a different type of architecture that is much more simple, has less connections, and is easier to assemble. Even though the material scored low on Section 6.8, the type of architecture of this window system seem to be an example for this redesign. The question is, however, if the selected materials could be designed according to this type of architecture.

(c) Concept Description: By taking as a reference the XFrame, an asymmetrical window profile with three main extruded elements profiles. This simplification is important, as it replaces the original with five extruded profiles, which is assembled through closed geometries and connections. In this case, the bottom frame is made of aluminium, similar to the current manufacturing process. However, the main difference is that the polyamide thermal break is connected to the aluminium profile through mechanical fasteners. Bolts make less noise than pins, and are also more flexible, thus they are selected to connect the thermal break and the aluminium profile. The shape of the baby aluminium profiles adapts to accommodate four different bolts that are not in contact with each other, avoiding a thermal bridge. The aluminium frame also covers the upper frame, which is made of a different material. During the early design stages, it was thoroughly discussed which material would suit the upper frame, as another thermal break had to be avoided at all costs. After an extensive analysis and much more research on materials for window systems, it was selected to work with Wood Polymer Composites (WPC). This selection and how it improves the system will be further discussed in Section 8.3 Material Improvement.

Additionally to this, the lower aluminium frame has a protective outer profile that covers the WPC upper profile. This enhances the durability of the overall product, as well as providing a uniform view from the outside, since the frame has an asymmetrical nature. This outer profile also accommodates snapping connections to add a weatherboard, similar to the cover cap principle of a curtain wall. This can allow for different aesthetical finishings and even changing the form of the window. This type of connection is direct between two pre-made components due to the nature of the snap connections, but it does not require disassembly of another element.

Figure 8.6 GRP Window System XFrame. Image by Michael (2015).

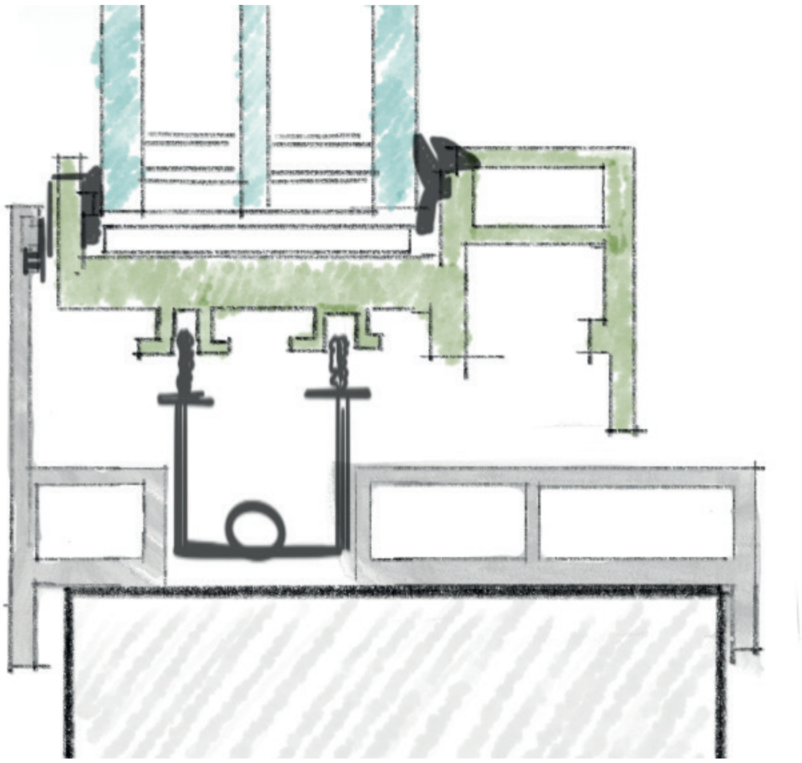


Figure 8.7 Early sketch for Hybrid System Variant A. Image by author.

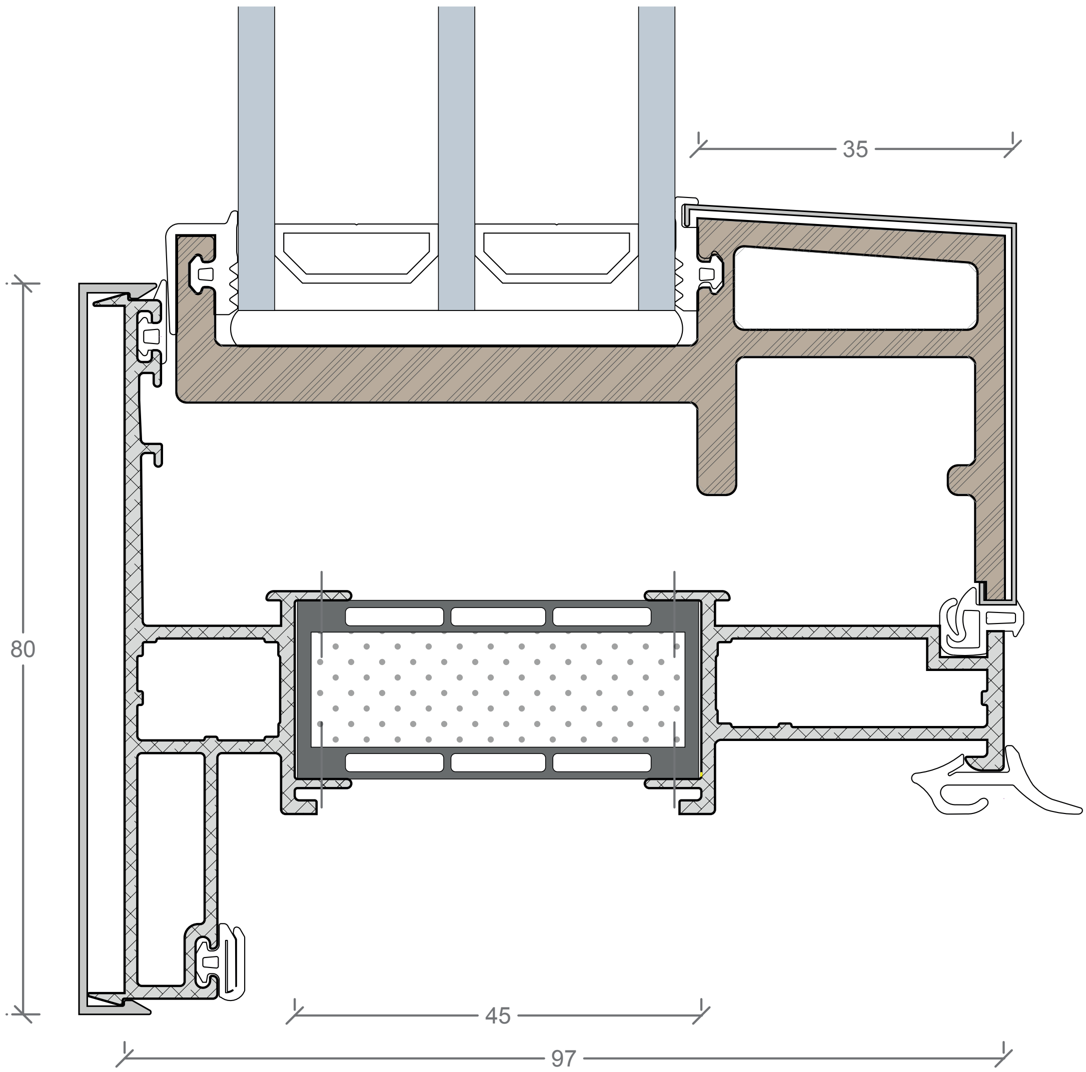


Figure 8.8 Side view of the profile for Hybrid System Variant A. Image by author.

Legend
(1) IGU
(2) WPC extruded profile
(3) Aluminium weatherboard
(4) Aluminium extruded profile
(5) Castor oil thermal break
(6) Insulation beads

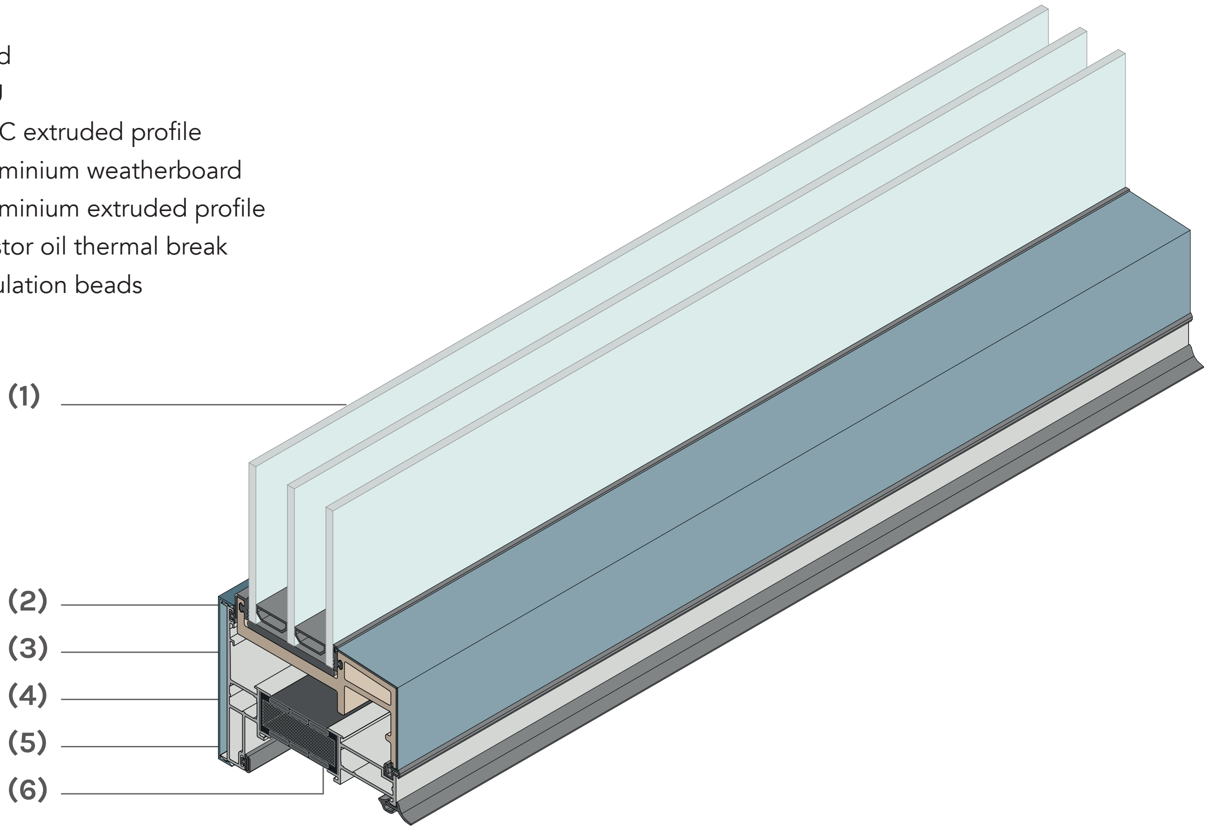


Figure 8.9 Isometric view of the Hybrid System Variant A. Image by author.

Legend
(1) IGU
(2) WPC extruded profile
(3) Aluminium weatherboard
(4) Aluminium extruded profile
(5) Castor oil thermal break
(6) Insulation beads

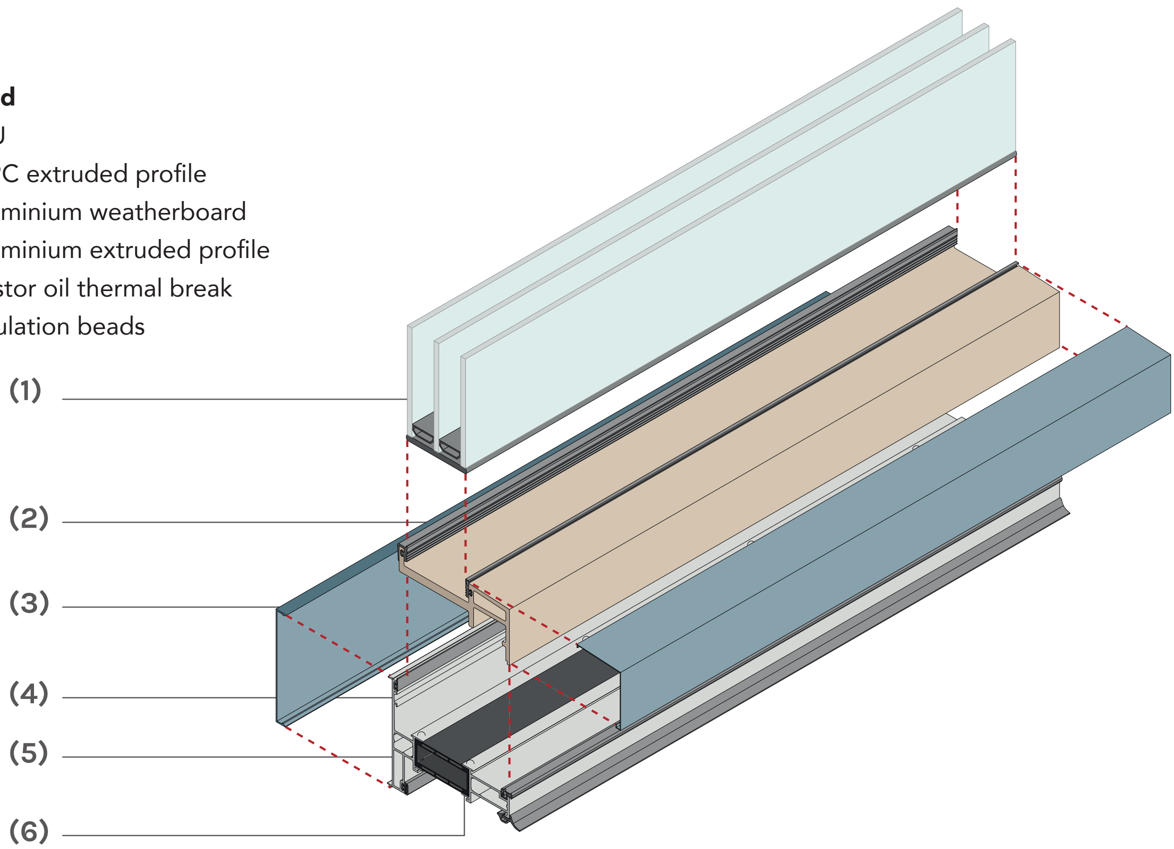


Figure 8.10 Exploded isometric view of the Hybrid System Variant A. Image by author.

(d) Assessment: According to the DfD principles, the type of connections in this new system fall into the more flexible spectrum from Durmisevic's (2006) hierarchy. The thermal break's connection improved from direct connection between two pre-made components to direct connection with additional fixing devices. The connection between the frames improved by being also direct connections between pre-made components by being indirect connections via independent third elements, as they are snapped through each other with gaskets that allow for movement.

In terms of DfA, this system can accommodate different "element configuration" ("Versatile"), as it allows to remove the thermal break. This can translate into the need to achieve a higher U-value if the future legislation requires it. In the strategy of "Refitable", the system shows different possibilities

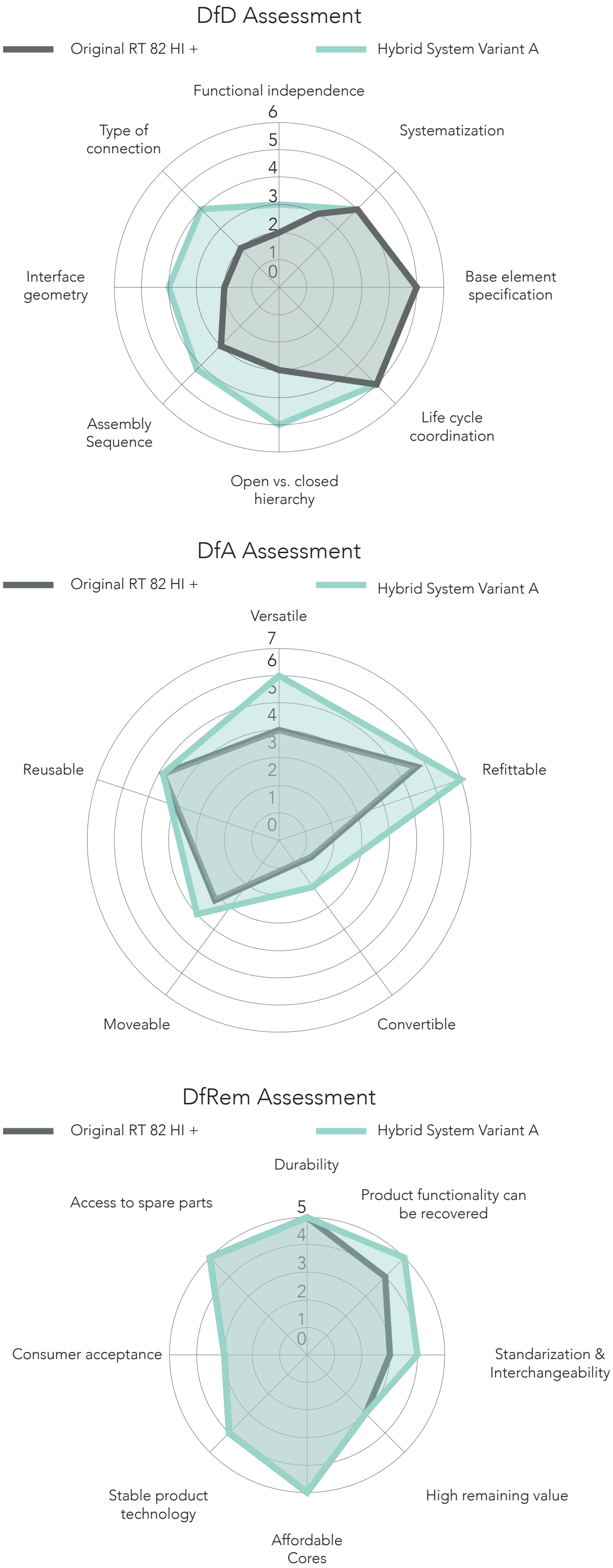


Figure 8.11 DfD, DfA, and DfRem assessments for Hybrid System Variant A compared to the original RT 82 HI +. Image by author.

for "aesthetics". This comes from the cover caps that accommodate different types of finishing and forms, which can adapt in case the window is to be directly reused.

In terms of DfRem, the aspect of "functional considerations are decisive in discarding" was improved through the possibility of removing other components to be updated (i.e. thermal break). The "interchangeability" was also improved by following the DfD guidelines, through the improvement of closed to open connections and geometries. This allows to interchange the parts easily, wereas they are the upper profile, or the baby aluminium profiles mechanically fastened to the thermal break. The "customer acceptance" still remains unclear, and this is an aspect that cannot be directly addressed through design. This aspect remains the same.

Figure 8.11 show the overall improvement (green) compared to the original (grey) design in all three aspects.

The total scores are: DfD 70.83%, DfA 78%, DfRem 90%.

(e) Conclusions on Hybrid System Variant A: This system variant provides a significant improvement in the aspects of DfD, DfA, and DfRem because it dramatically simplifies the elements. This simplification translates to easier connections, open geometries, interchangeability, and possibilities for upgrading or change or aesthetics.

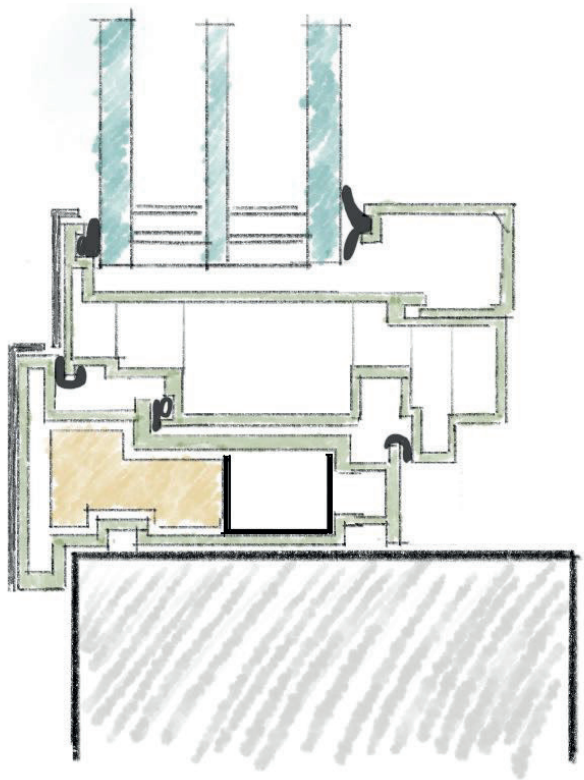
8.2.2 Hybrid System Variant B

(a) Objective: This variant aims to explore an even more radical simplification of the number of elements and connections. This dramatic simplification will have an impact on the the product edges through the use of a different material (wood polymer composites) as an alternative to the permanent joining methods of aluminium extrusion. This simplification also tackles the different geometry edges and the types of connections, aiming for these to become "open", contrary to the current "closed" ones. The system should also allow the integration of different forms and finishings in the case of aesthetic qualities.

(b) Initial ideas and references: This concept derives from the studied systems in Chapter 6, where it was proven that the combination of two different materials will enhance dramatically the performance of a window system. However, in this case, the combination is between WPC and Aluminium. The WPC is the core of the system, and it has higher thermal properties, and it provides a simplification of geometry between the connections. The proposed geometry is even more simplified than in Variant A, as in this case only two extruded profiles are required.

(c) Concept Description: Two extruded WPC frames are snapped to each other (through the use of


8.12 Left: Aluminium/PVC frames. Image source: dalmen.com/ Right: Wooden/Aluminium frames. Image source: archiexpo.com/



8.13 Early sketch on Hybrid System Variant B. Image by author

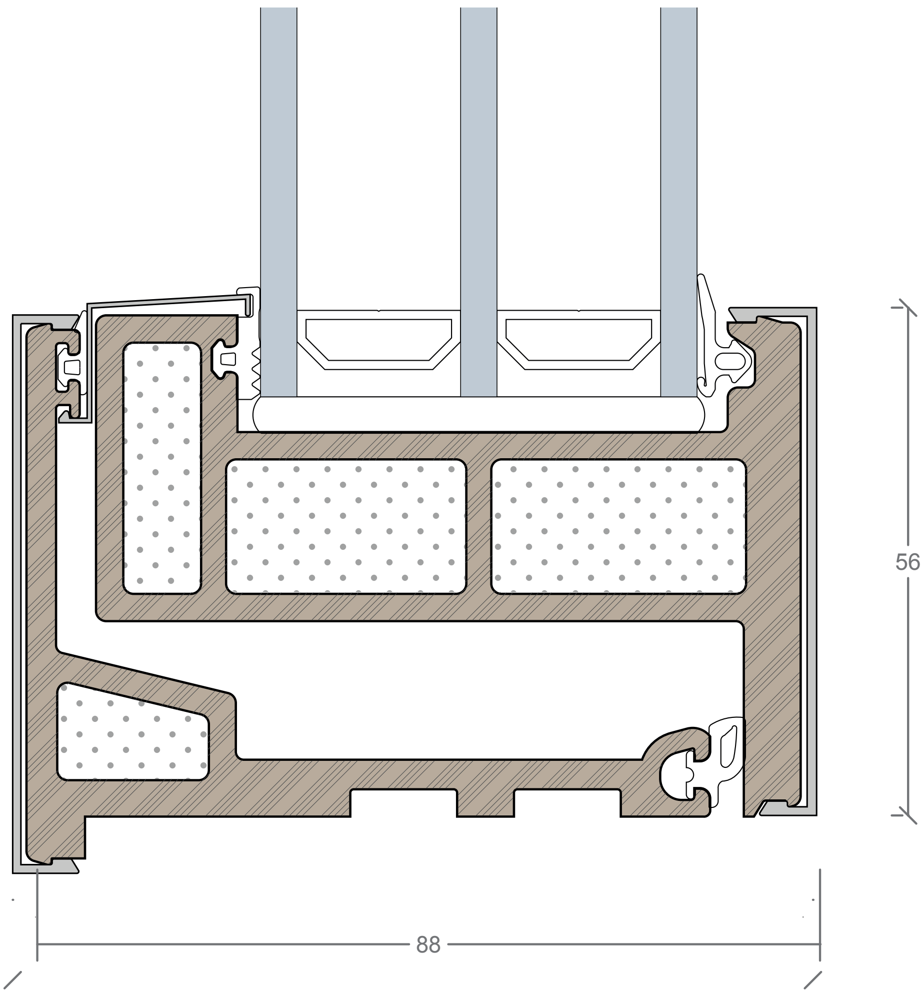


Figure 8.14 Side view of the profile for Hybrid System Variant B. Image by author.

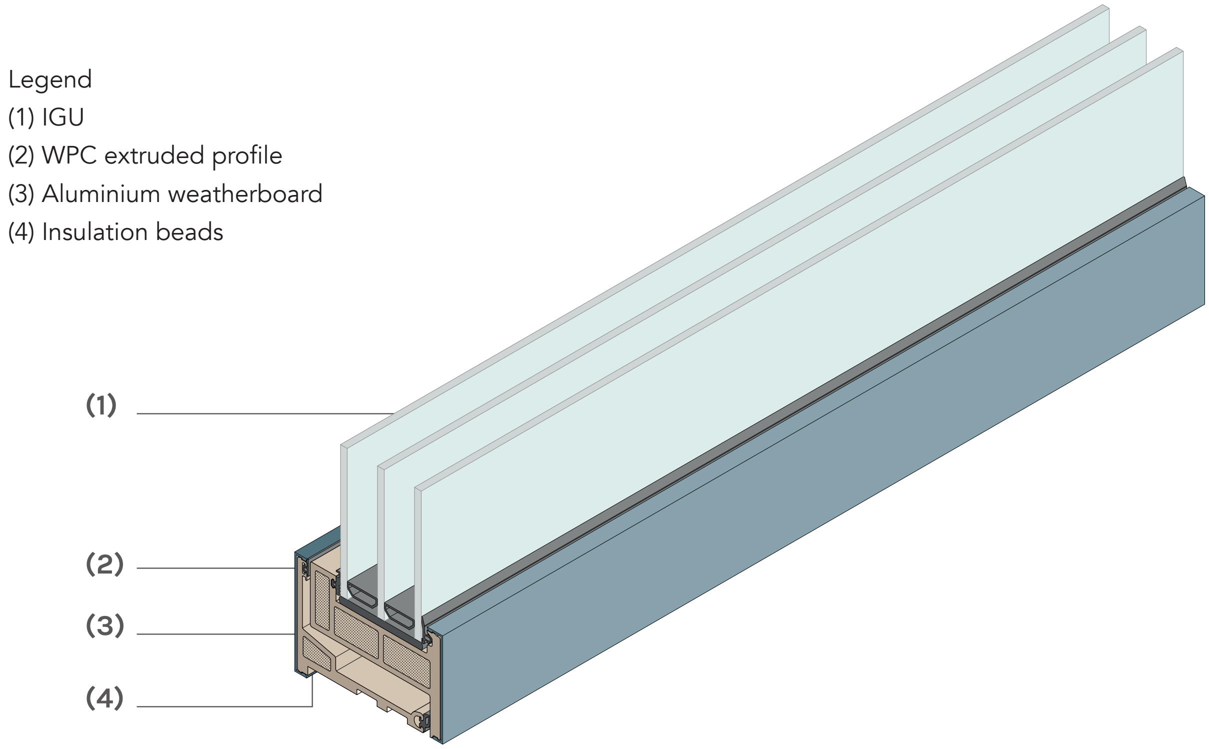


Figure 8.15 Isometric view of the Hybrid System Variant B. Image by author.

Legend
(1) IGU
(2) WPC extruded profile
(3) Aluminium weatherboard
(4) Insulation beads

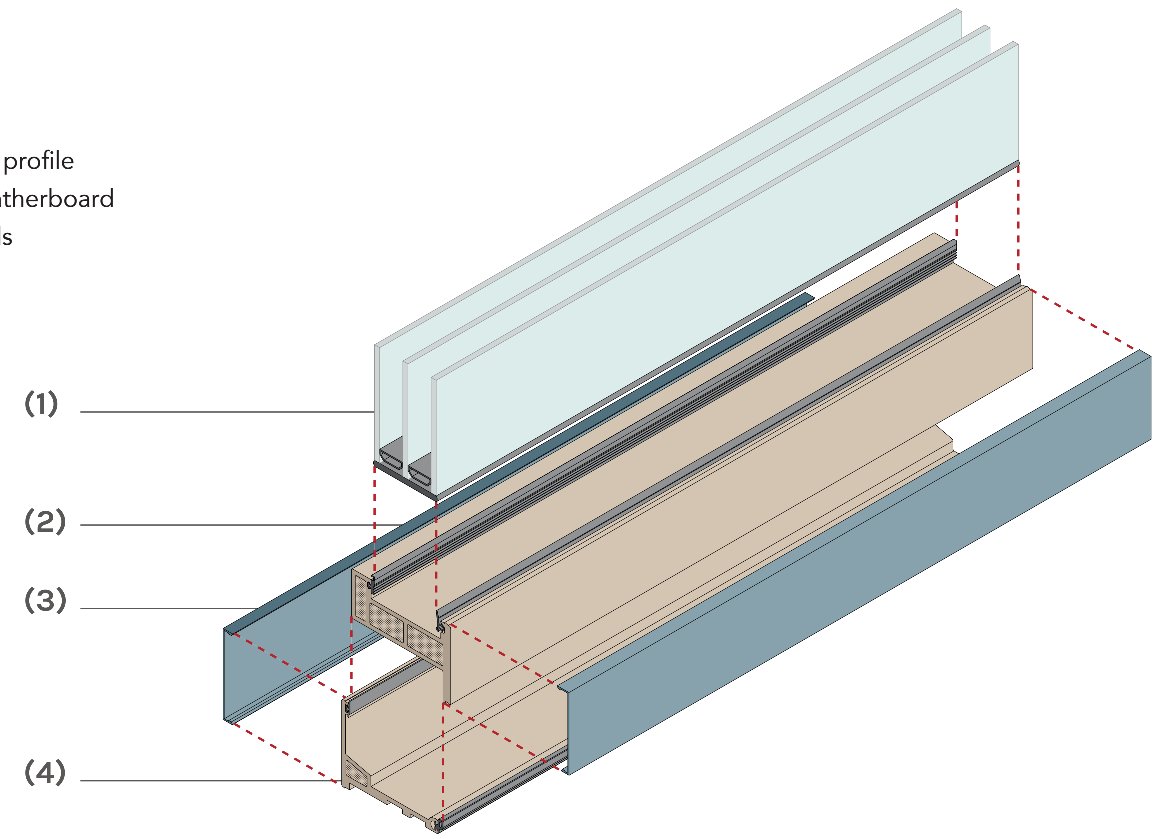


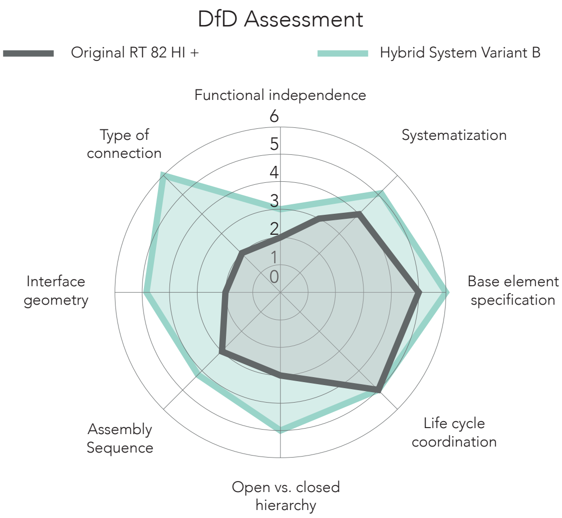
Figure 8.16 Exploded isometric view of the Hybrid System Variant B. Image by author.

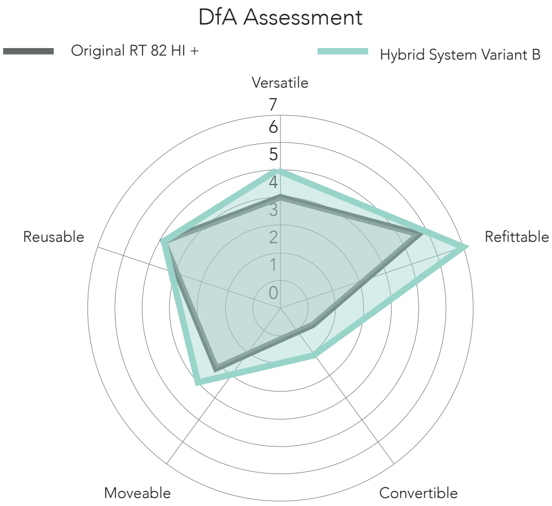
gaskets) and covered with an aluminium weatherboard. This weatherboard protects the WPC frames to make the material last longer, and to enhance its appearance. The aluminium weatherboard element also serves aesthetical adaptability functions, as it can be interchangeable to give a different finishing, or to provide a different form. The weather board is applied both to the inside and to the outside, similar to the examples studied of wooden/aluminium frames or aluminium/pvc frames.

Because of the nature of this system, highly based on WPC, there is not thermal break, simplifying dramatically the number of elements and connections. The thermal performance of this system can be increased by filling the inner chambers with insulation. Because of the overall objective of simplifying the architecture and overall geometries, this system has only two main structural pieces, which are the extruded WPC frames.

(d) Assessment: According to DfD principles, there is an improvement in "open/closed hierarchy", "assembly sequence", "interface geometry" and "type of connection". However, because of the simplification of elements, the "functional independence" did not saw an improvement. This is because the less elements are present in a window system, the more functions each element fulfills. Nevertheless, the principle of this system about attaching and detaching elements, and adding elements in between might improve the "functional independence" as it is further detailed.
In the case of DfA, there seems to be improvement in "refitable", "change of aesthetics". This is because of the aesthetic functions the weatherboard is able to provide. Additionally, the simple addition and subtraction of elements improves the "versatile" strategy, "change of façade element configuration". It is still to be investigated the "reusable" potential of this design variant.
In terms of DfRem, there was improvement in "standardization and interchangeability" related to the improvement of open geometries and connections. Other improvements are shown in "product functionality can be recovered" as the system allows an easier disassembly and exchange of parts. However, in terms of "high remaining value", it is still to be discussed if a WPC profile has a higher value than an aluminium profile. This will be further analysed. Figure 8.17 shows the graphs with the results of the three different assessments.
The total scores are: DfD 68.75%, DfA 73%, DfRem 87.5%.

(d) Conclusions on Hybrid System Variant B: Overall, this system shows a simplified architecture for a window system that combines the strengths of two different materials. WPC are able to provide higher thermal insulation, a simplified form, and easier connections. The aluminium weatherboard protects the system and provides the possibility of different finishings. It can also accommodate different element configurations, for instance, by upgrading the thermal insulation and placing it between the weatherboard and the WPC profile. However, further analysis on this new material should be done, as it provides different properties that must be further examined. The improvement relies highly on the simplification of the product architecture, but this also has its possible drawbacks. For instance, the "functional independence" is reduced because an element has to fulfill more functions. This is not necessarily negative in the case of a window system, as long as it can be proven that it can remain flexible. This should also be further investigated.





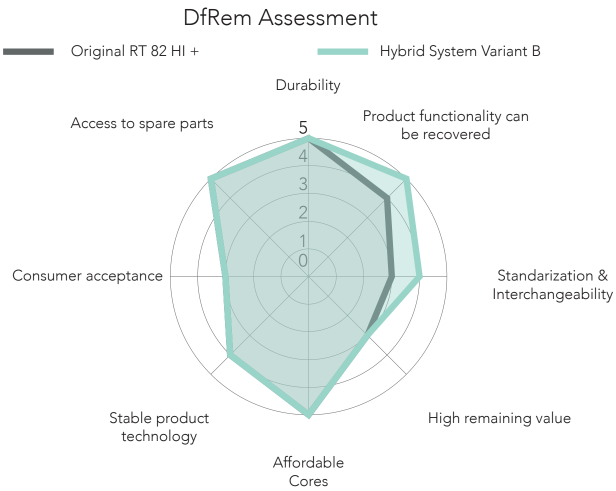


Figure 8.17 DfD, DfA, and DfRem assessments for Hybrid System Variant B compared to the original RT 82 HI +. Image by author.

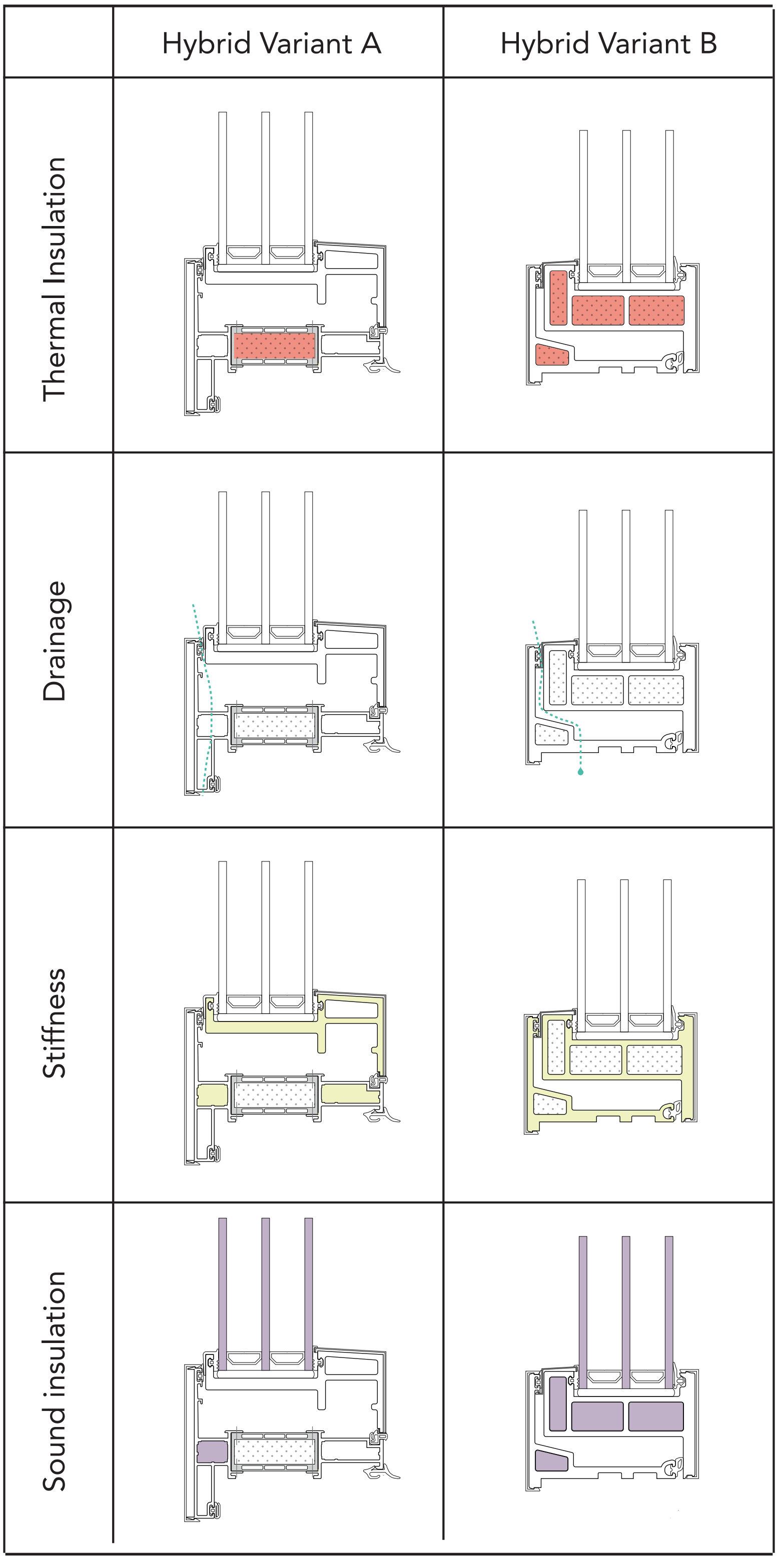


Figure 8.18 Design concepts element's function matrix for the two proposed variants. Image by author.

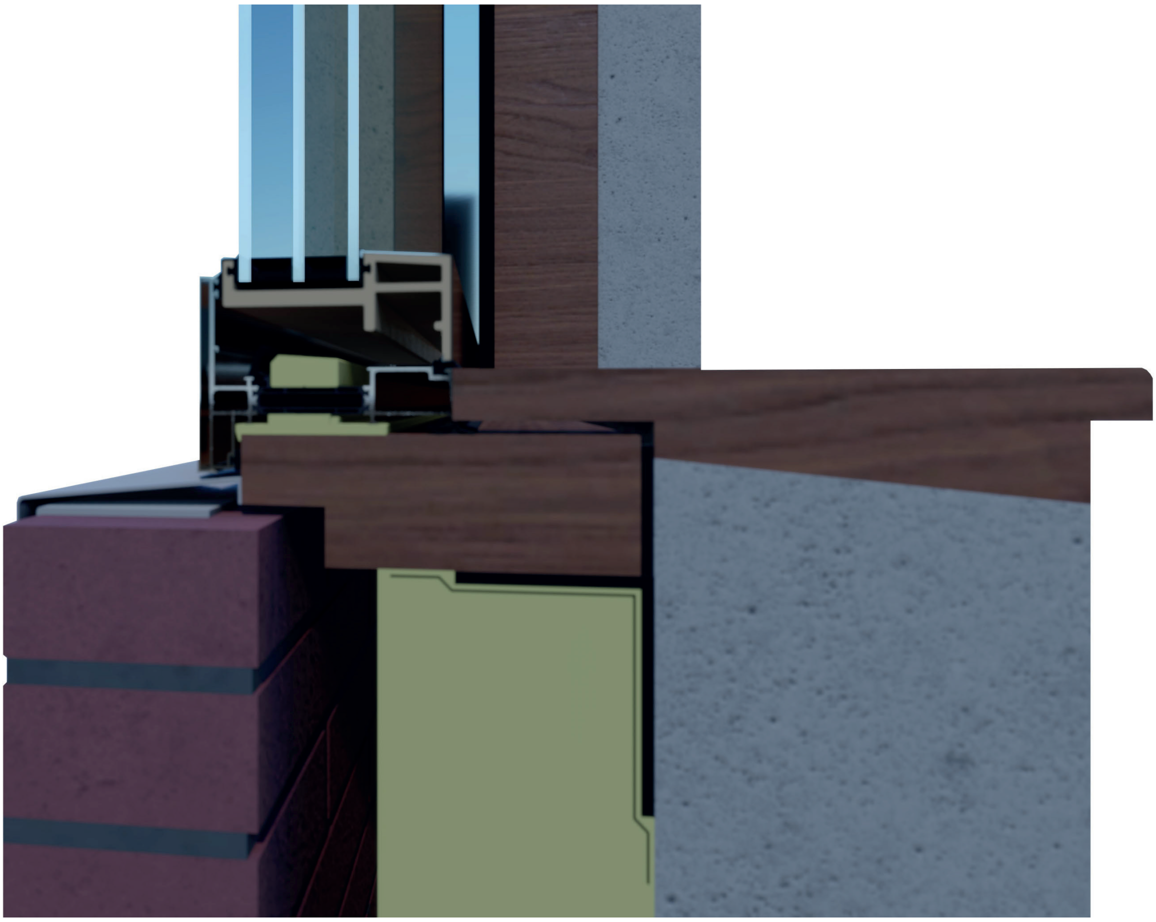


Figure 8.20 Top: Section of the Hybrid System Variant A in the reference project, cavity brick façade. Bottom: Axonometric view. Image by author.

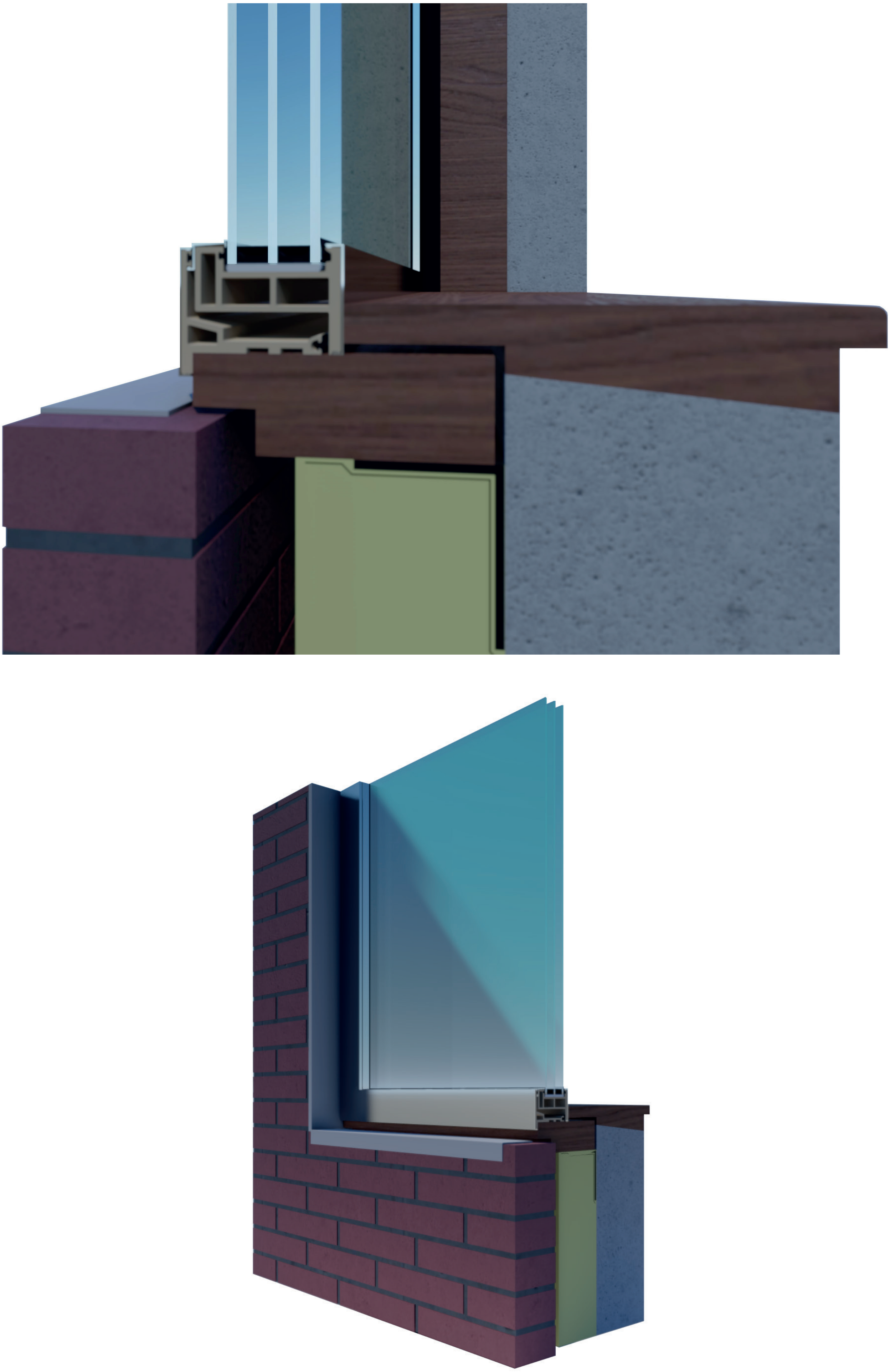


Figure 8.21 Top: Section of the Hybrid System Variant B in the reference project, cavity brick façade. Bottom: Axonometric view. Image by author.

8.3 Improvements through Material Selection

This Section will discuss the different improvements in the system through changes in materials. The Section discusses and analyses three different materials: Wood Composite Polymers (WCP), Bio-obased Polymer, and Phenolic Glass Foam. The changes in this materials were done by thinking in the cyclability, and their properties.

8.3.1 Wood Composite Polymers

(a) Composition and Properties: The material selected for the hybrid systems are Wood Composite Polymers (WCP) profiles. This material has a general composition consisting of wood, thermoplastic polymers, and some additives. The ratio of each material can vary, some WPC can have up to 80% of wood fibers (Teuber et al., 2015). On the other hand, the thermoplastic matrix materials that are commonly used for WPC are either polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP). These combination of different materials results in a composite with enhanced qualities. For instance, wood is a hydrophilic material by nature, which makes it vulnerable to decay if not maintained properly. However, while combining it with a polymer matrix, its resistance to water increases significantly. Wood also has high thermal insulating properties and stiffness, which are able to stabilize the performance of the polymer. This composite benefits from the strenghts of two main materials, making it a long lasting material that requires low maintenance, and with high thermal insulation. However, there have been studies that show that the material might not perform well under constant exposure to UV rays (Teuber at al. 2015). Yet, some of the main suppliers of WPC have added other materials to the mix that can enhance the resistance to UV, or it has been protected with aluminium weatherboards.

(b) Applications: At the moment, this material is used in the automotive industry (door panels and dashboards), but also in the building industry as decking and window frames. Carus et al. (2014) predict that the EU market for WCP will grow 10% per year.

(c) Manufacturing Process: According to Teuber et al. (2015), the common manufacturing processes for WPC are extrusion, injection moulding, compression moulding and thermoforming.

(d) Cyclability: Because of its hybrid composition, WPCs provide flexible and high performance properties, but more importantly, because it is a material mostly made from other scrap material. As it was stated in Chapter 2, one of the main principles of a Circular Economy is "waste equals food". The creation of a high durable material with high thermal and mechanical properties by using recycled materials seems to be one of the best examples of cascading. This is an opportunity to improve the cascading of both wood and PVC, PE and PP, which are thoroughly used in the construction industry. WPC can also be recycled, even up to 7 times before showing any loss of mechanical or thermal properties. And even so, if the polymers added to the WPC are biodegradable, a fully biodegradable composite can be achieved. In conclusion, the selection of this material is the perfect example of cascading in a circular economy, as it shows an efficient use of resources that cycle longer through the different loops.

8.3.3 Bio-based Polymer

Inspired by the Window AWS 90.SI+ Green by Schüco (analysed on Chapter 6), it was decided to search for alternatives to replace the thermal break, which is currently incinerated. This is a critical point for Hybrid System Variant A, because it still carries the polyamide strip, which serves as a thermal break. Even though the strip can now be removed, it is desirable to change its end-of-life scenario. But due to the nature of aluminium which has high thermal conductivity, a thermal break is mandatory.
However, there have been recent developments in the industry where bio-based polymers have started to substitute non biodegradable materials. Polyamide is not the exception, and neither is the case of the construction business. PCs and mobile phones which also use a variant of the polyamide, have been replaced by bio-based polymers. To obtain a product with a similar low thermal conductivity,

there have been recent developments in bio-based polymers derived from castor oil. This product means that when the thermal break strip reaches its end-of-service, its (re)life options are much more environmentally friendly.

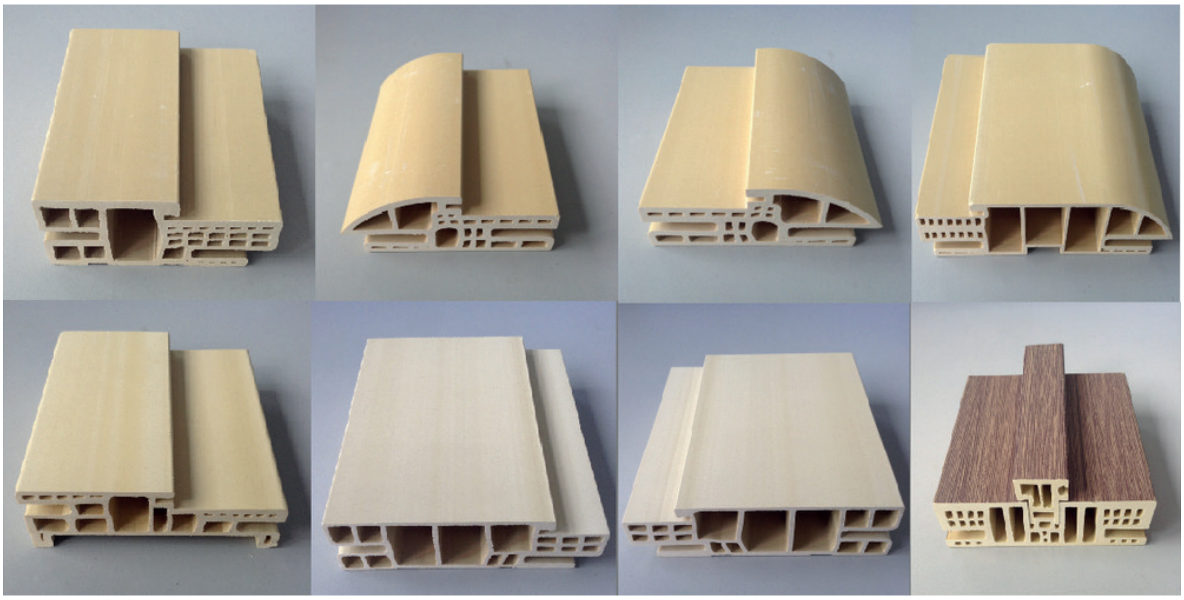


Figure 8.22 Different WCP extruded profiles. Image by globalsources.com

8.3.4 Phenolic Glass Foam

The current insulating material is a phenolic glass foam, derived from an existing commercial product called Kooltherm, manufactured by Kingspan. This insulation material is made from three main raw materials: Polyol, MDI, and a blowing agent. This produces a phenolic glass foam insulation that due to the closed cells, it has a thermal conductivity (λ) of 0.021. This is an extremely low value, and is one of the reasons the RT 82 HI + reached the passive house certificate. However, this material presents the disadvantage that it is derived from oil. In terms of circularity, it seems to have limited (re) life options. According to Frank Schotman (2019), Sales Manager of the company, the scrap material from the manufacturing process is being sold to other companies to insulate concrete slabs. Aside from this, the product is incinerated once it reaches its end-of-life. Similarly, it is unknown how long the product can last. Dennis Bol (2019), product manager, established that the company guarantees a service life of 25 years. However, they have seen cases of projects with insulation already 40 years old. It is predicted that the product can last more or less this period of time.

When it comes to the redesign of the circular window, it was discussed in the brainstorming session held with the company on the 7th of May, 2019, that the insulation can probably have a different form. The author suggested to have beads instead of the foam bars that are currently used. If the insulation sleeve is filled with beads, the product can be easily taken out. It is unknown if this suggests is feasible, as the insulation itself works by having 95% of closed cells. If it changes to a form of bead, the surface area is larger, and therefore, a larger amount of open cells is present. This can have a negative effect on the thermal conductivity of the material. This subject might not be further investigated as it is out of the research scope, and it should rather be seen as part of the limitations of the presented research.

8.4 Improvements on Hardware and Other Elements

During the steps taken to disassemble the RT 72 prototype (Section 7.4..4), it was not possible to disassemble the handle of the window. This was mostly because it was unclear how to disassemble the element. Even though the handle was stressed, pushed, and rotated, it was not possible to dismantle it. It was also not visible any type of joint with the window frame, neither bolts or screws.

8.4.1 Handle Connection to Frame

However, one of the main problems with window hardware might be the vast types that exist. In this case, standardization, one of the key principles of DfRem and DfD might play a key role. However, the type of standardization does not refer to the aesthetic qualities of the handle. It rather refers to the type of connection that is used to join the handle with the window frame. If this connection is standardized, then it can have a positive impact in the assembly, disassembly, and thus, reuse and remanufacturing processes. The standardization of this type of connection can be done through following either of these principles:

I. The handle is snapped into the frame through snap-fit connections. This might be critical because the handle might be made of a different material than the window frame. The tolerances for each material should be taken into account.
II. The handle is bolted, and the bolts are hidden under a plate that is snapped (only if required by aesthetic reasons). The bolts used are standardized, and thus, can be taken out with traditional disassembling tools (as seen in Figure 8.23).

In both cases, it should be clear how to disassemble the window handle, as time and speed are two of the crucial factors when it comes to disassembling a product.

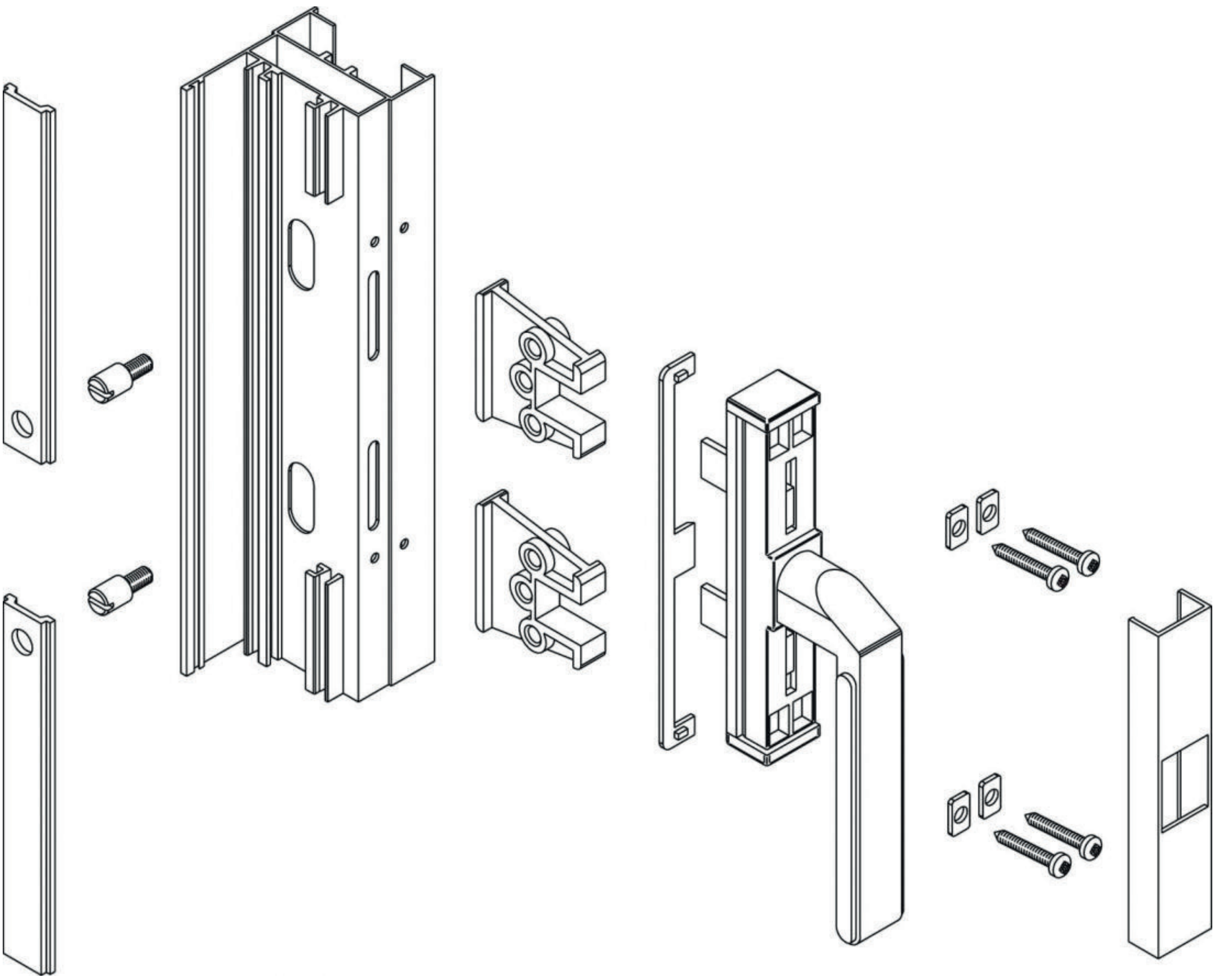


Figure 8.23 Example of a window handle and its ease of disassembly. Image by wodowo.es

8.4.2 Addition of a Sensor

As it was discussed in Section 5.4 Circularity Interview and Brainstorming Session, predictive maintenance is one of the key strategies in circular façades. This will ensure that the performance of the façade is maintained. In the case of hardware, especially in hinges, it is important to know when these are close to their end of their service life. If the window hinge is replaced shortly before it reaches its end of service, the window will be kept longer in use. At the moment, the expected service life of window hardware is measured in uses: 15,000. This can be translated to 20 - 25 years, which is lower than the service life of a window. If a window is expected to live 75 - 100 years, then the hardware will be replaced approximately four times.

However, it would be useful that the window can indicate the status of the hardware, especially if the window already entered a new (re) life option. This can be similar to receiving a laptop and running a battery diagnosis. The addition of a sensor on the hardware indicating the number of uses of

Figure 8.24 Hypothetical scenario of a sensor linked to a mobile app. Image by author.

the hardware component can serve as an important tool towards predictive maintenance, but also to guide in the path towards remanufacturing. Thus, a sensor is installed in the inner part of the frame (so it is hidden), and it will measure the number of uses according to the opening and closing movements of the window. Even more, the sensor could be connected to a mobile app where it can indicate the "health" status of the window's hardware. When the hardware is close to its end-of-service, it will notify the user through the mobile application. This is the moment when the user can call the remanufacturing administration centre to replace the hardware, as depicted in Figure 8.24. At this moment, it might be possible the the hardware does not require a replacement, but rather an upgrade. This is because we take into account that technology progresses incredibly fast, and the window will change its requirements through time.

8.4.3 Redesign of Corner Cleats

In Section 7.4.3 and 7.4.4, it was mentioned that the corner cleats were riveted. This is not the best solution according to circular principles. Connections should be easily assembled and disassembled. Rivets might be easy to install, and with the right size of a drill, relatively easy to take out (they have to be drilled out). However, during the drilling process, the aluminium frames as well as the corner brackets can be damaged, even destroyed if not done carefully. The redesign of the corner cleats is oriented towards the use of standardized connections, easy of assembly and disassembly, while keeping the elements in optimum conditions.

This was achieved by replacing the rivets with screws. The selected screw type was 2 x .25 panhead that can be easily dismantled with a Phillips or Torx screwdriver. The screwed connection of the windows also allows for the same precision as rivets provide, which is one of the most critical points in terms of window quality. Screws can also keep the window frames strong, but while allowing the flexibility of dismantling.

The corner cleat is made of extruded aluminium, manufactured in lengths of 6.00 m, and then cut into 250 mm thick pieces. Each piece will then join the two window frames through the screwed connection, two on each side, four for each corner cleat. Figure 8.25 shows an axonometric view of the redesign.

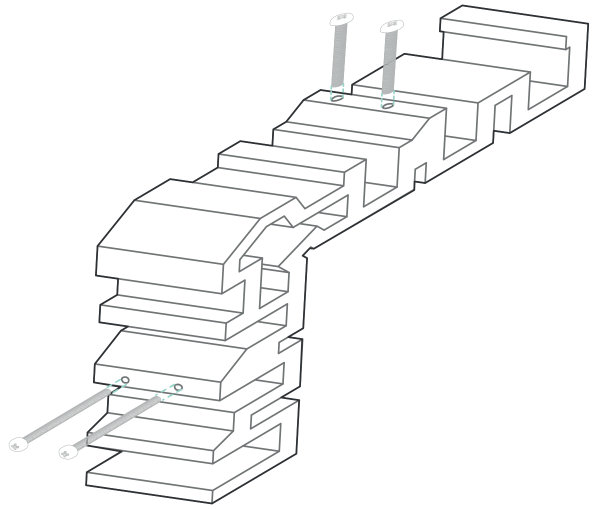


Figure 8.25 Isometric view of the redesigned corner cleat.

8.5 Remanufacturing Scenarios: Creating Value through New Designs

One of the important parts of the presented research is to understand the economical benefit of product life extension, especially remanufacturing, for window systems. Similar to the analysis carried on Section 5.2 Current Business Model, a hypothetical scenario based on the circular business models reviewed on Section 2.6, and the extensive background on Chapter 4 Remanufacturing, was developed. As before, it will be based on the Business Model Canvas, for it to be compared with the original (Section 5.2).

I. Value proposition:

(a) Product: (a) Built Environment: Circular expertise, linking CBE with product, high performance reliability, high performance and innovative solutions. (b) Private Sector: Linking CBE with product, avoid distraction of non-core activity, circular expertise. (c) Public Sector: linking CBE with society (students, citizens), rate costs.

(b) Customer Segments: Three main groups: (a) Built Environment (Architectural consultants, construction companies, façade manufacturers, service and maintenance companies), (b) Private Sector (Financial services, banks, CE 100 partners, Not for profit/NGO), Housing associations (DWUO), (c) Public Sector (Central government, Universities, Hospitals, Schools, Gemeente, other CE Cities)

(c) Customer Relationships: Long-term relationships: installation, inspection of installed windows, service and maintenance.

II. Value creation and delivery:

(d) Key Activities: This process becomes highly critical, as the product is manufactured, but it should be easily retrieved to come back to the original manufacturing company. Figure 8. Illustrates the entire process, and highlights the process of remanufacturing with the dashed box.

(e) Key Resources: According to the "key activities", there are three main resources required to fulfill the entire process: a remanufacturing administration centre, logistics and sales. Figure illustrates this and matches the color relationship with figure.

(f) Distribution channels: trade fairs, office fairs (OE), advertisement, e-commerce, learning events,

workshops
(g) Key Partners: Architects, façade manufacturers, logistics, service & maintenance companies, communication sales, investors and stakeholders, education, Universities.

III. Value Capture
(h) Cost Structure: New remanufacturing facility, trained & skilled people on remanufacturing (from product design to process and logistics), packaging, new parts, retrieving the cores.
(i) Revenue Streams: Logistics and service and maintenance companies might pay Kawneer (i.e. finders fee), OE sales or leasing, research funding, government investment on circularity.

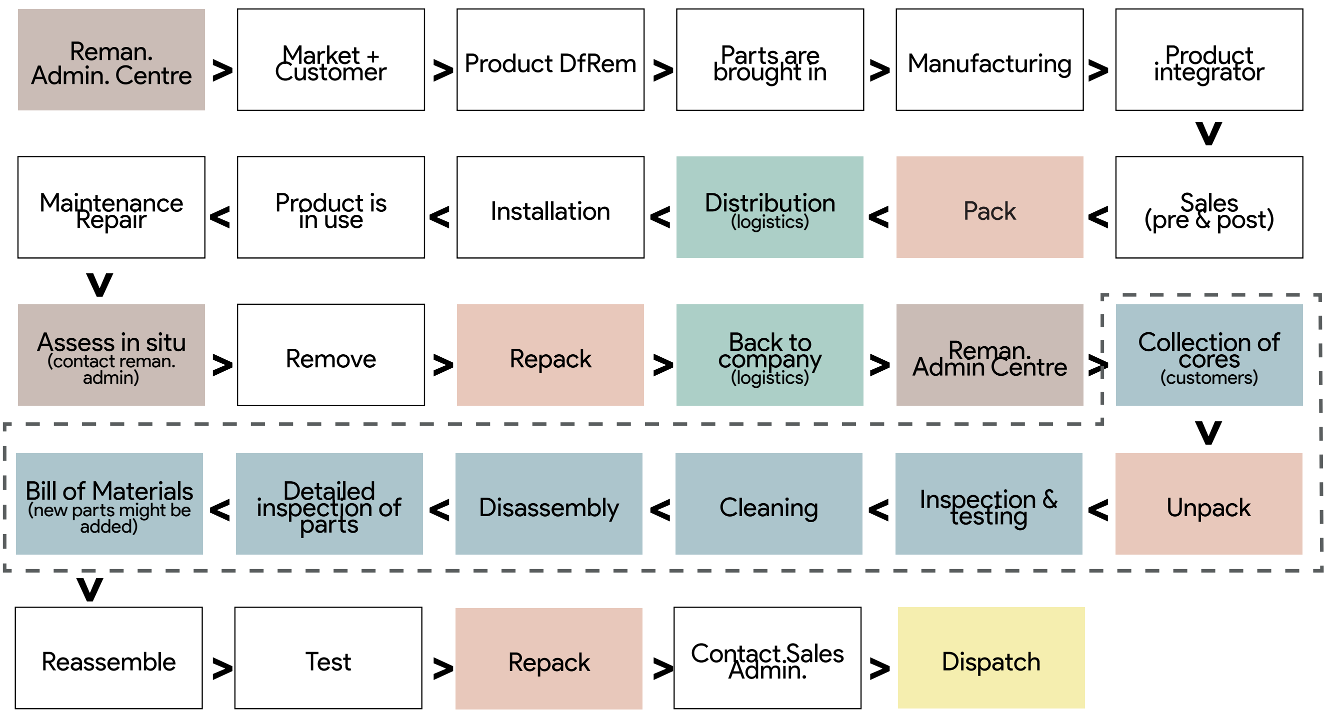


Figure 8.26 Key activities. Image by author.

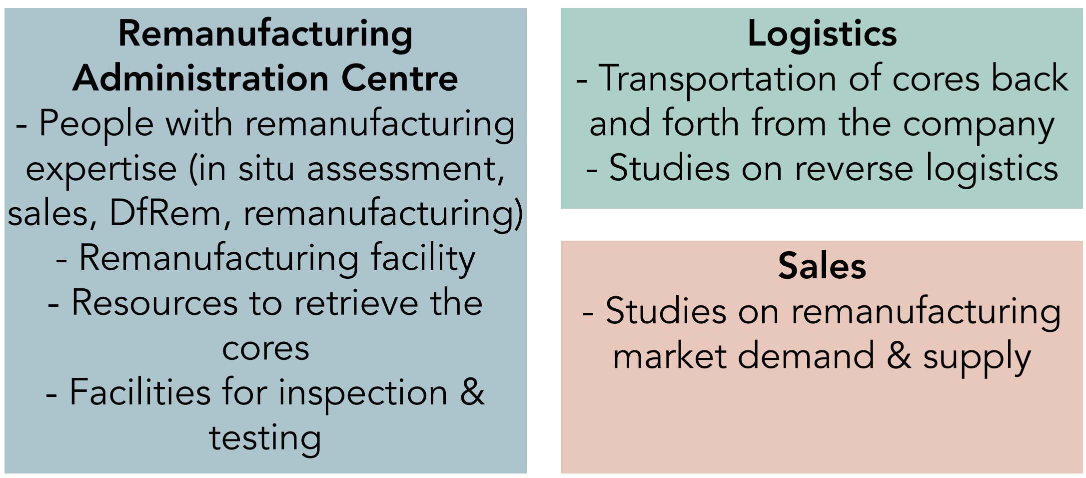


Figure 8.27 Key resources. Image by author.

8.6 Reuse Scenarios: Attachment to Other Types of Construction

Additional to the remanufacturing scenarios, it is important to analyse the possible direct reuse scenarios of the three different proposed designs. This implies that the window is directly applied to other types of construction. The importance of this aspect is not only to the design of the window itself, but on the way this is attached to other types of construction. For this purpose, four different types of façades were analysed. The first one is a brick cavity façade, which is the same construction as the reference project. The second one is a passive house construction (SReferentiedetail 201.0.7.01.PH), the third one is a residential storey floor longitudinal façade with top and bottom frames (376.0.3.01), and the last one is a non-residential building with a metal sheet cladding with a steel support structure (S.04.01.206.2). Each type of construction and the attachment of the window will be shortly reviewed to understand how the window can be reused in either of these scenarios.

8.6.1 Brick Cavity Façade System and Construction

The brick cavity façade typology has already been thoroughly analysed in Chapter 7 according to the façade function tree. In this case, the relevance relies on the connection between the window and the construction. If a window is to be installed in a brick cavity wall, it will be attached through a wooden beam. This wooden beam is supported by a steel anchor, attached to the prefabricated concrete inner wall. The outer brick wall of the construction has a small metallic apron. A backing rod or sealant in between the brick wall and the apron prevents air leakage. This exterior seal should come in a dry form, so it does not interfere when the window is removed from the construction.

Additionally, when the window has to be removed from the construction, the IGU will be taken out through a suction cup, a saw will have to cut the bolted connection between the wooden frame and the window frame, and then the window can be dismantled. This process is relatively easy, but the effectivity of it lies in precision and carefulness. Figure 8.28 illustrates the vertical and horizontal details of the three proposed designs: Optimization for RT 82 HI +, Hybrid System Variant A, and Hybrid System Variant B.

8.6.2 Passive House Façade System and Construction

This façade system and construction has similar principles to the brick cavity façade . However, in this case, there is a much thicker layer of insulation, sealed by a decorative plaster. The inner wall construction is a calcium silicate block. The window rests in a wooden beam, similar to the brick cavity façade. The wooden beam rests in an extra layer of insulation that is also sealed, supported by a steel anchor. A sealant under the window apron prevents air leakage.

If the window is to be dismantled from this type of construction, the same procedure mentioned in Section 8.6.1 should be followed. The IGU is taken out through a suction cup, and the connection between the wood and the window is carefully cut with a saw. Figure 8.30 illustrates the vertical details of the three proposed designs attached to this type of construction.

8.6.3 Residential Storey Floor Longitudinal Façade System and Construction

This façade system and construction is based on three main layers, from the inside to the outside: a calcium silicate block, rockwool insulation layer, and an outer sheet metal for cladding. The window lies in the mid layer, where the rockwool insulation is placed. A steel anchor holds a first beam of wood, where a layer of laminated wood is placed on top. The window is attached to this layer of laminated wood, and it also clips in the upper part of the cladding with a gasket.

For a window to be detached from this type of construction, the cladding would need to be detached first. Afterwards, the connection to the laminated wood and the window is removed, and the window can be detached easily. This standard detail specifies glue in between the wooden layers. During the redraw for this research, the author removed this solution and replaced it with screws, following the principles of DfD. Figure 8.31 depicts the vertical details for this façade system.

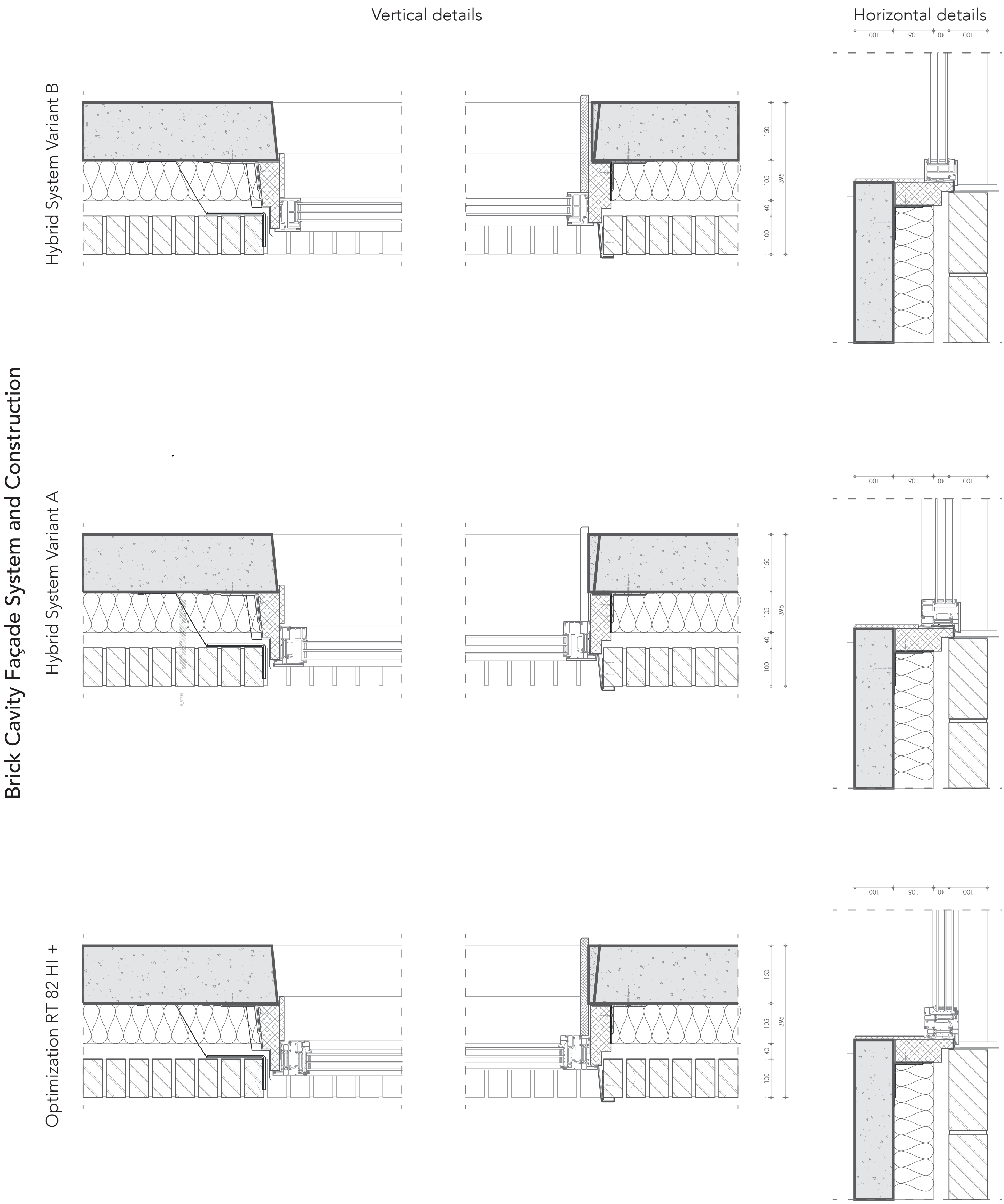
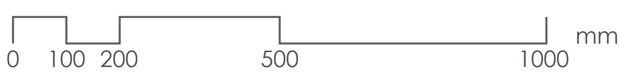


Figure 8.28 Vertical and horizontal details of the three proposed designs attached to a brick cavity façade system and construction. Image by author.



Brick Cavity Façade System and Construction

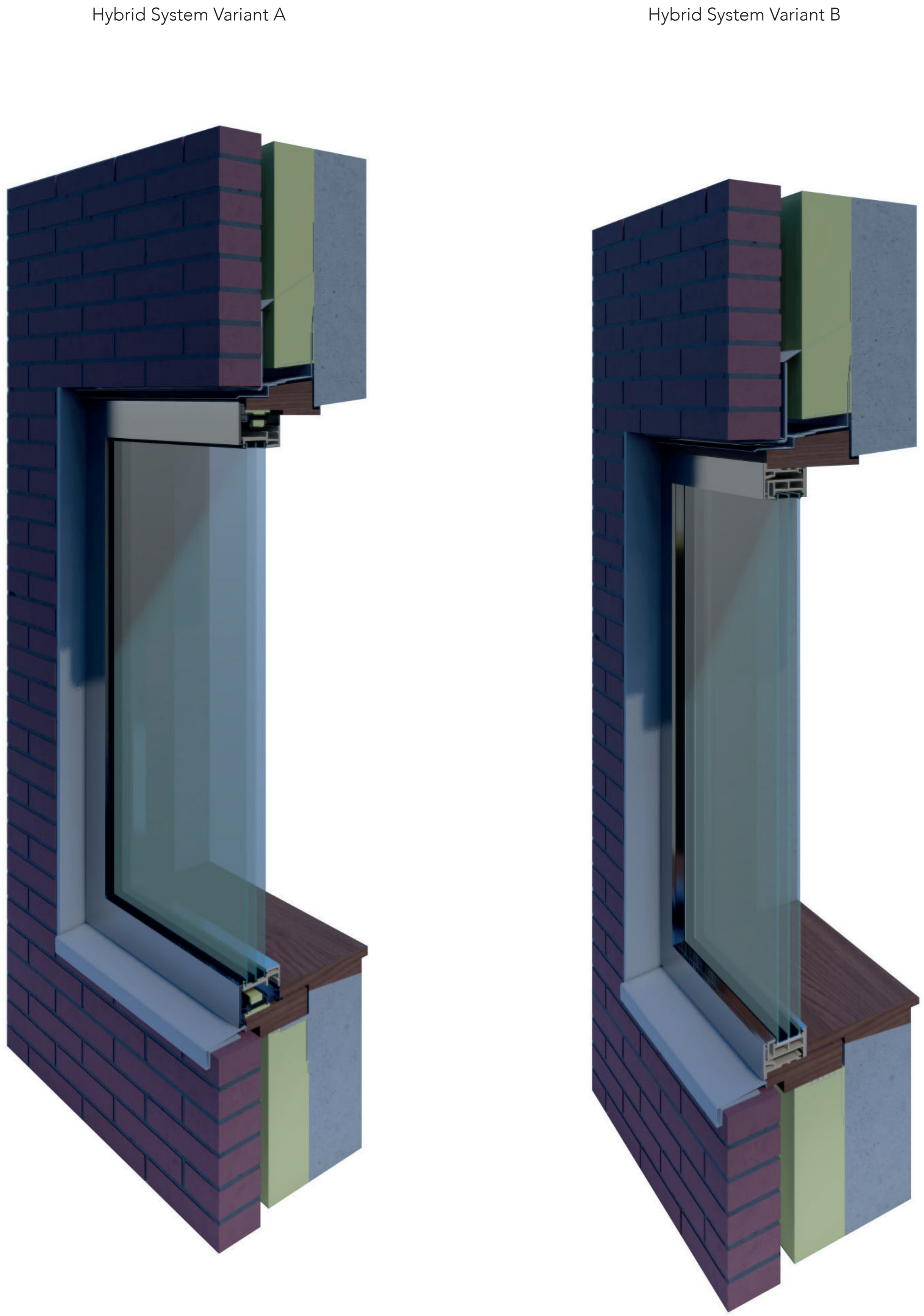


Figure 8.31 3D views of Hybrid System Variant A (left) and Hybrid System Variant B (right) in a brick cavity wall construction. Image by author.

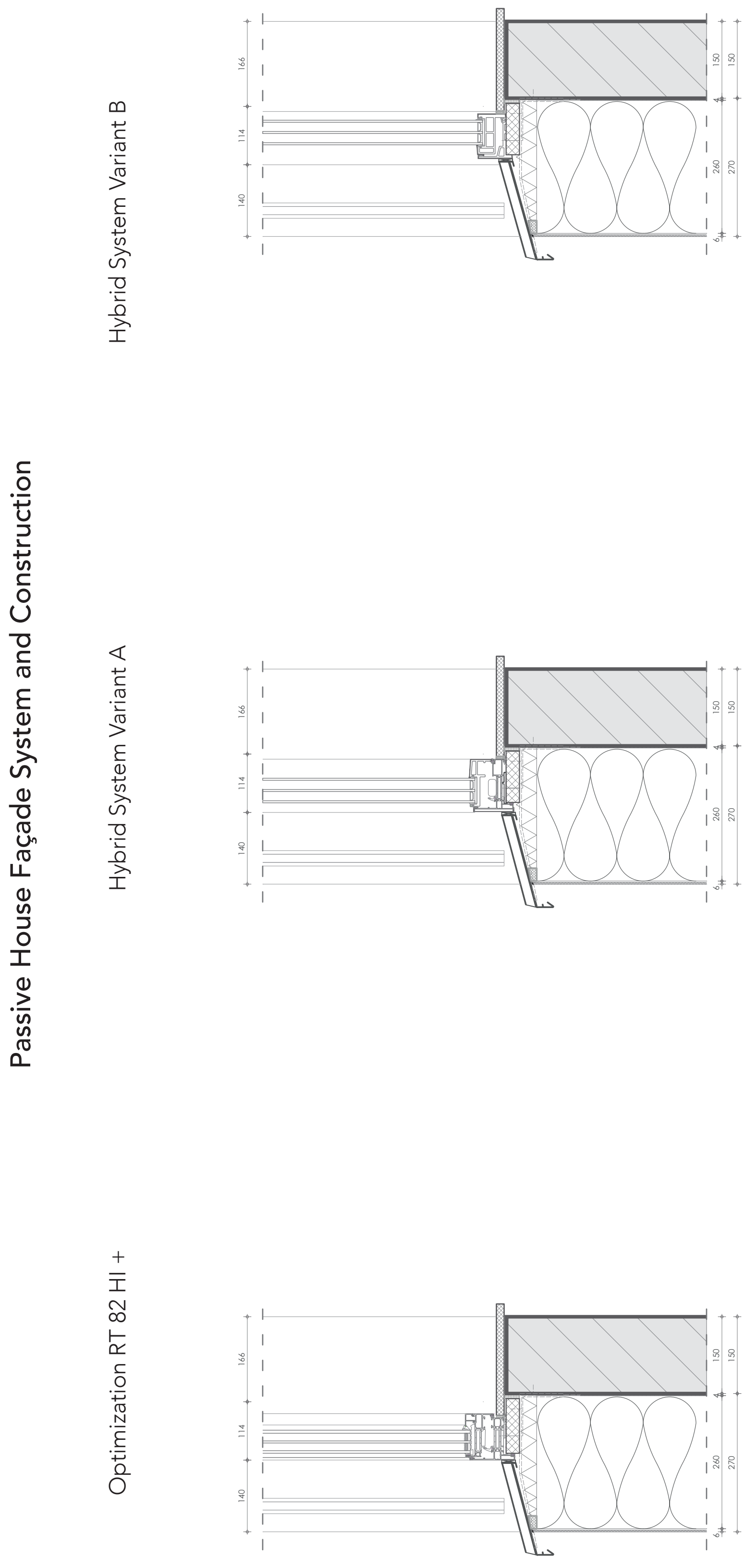
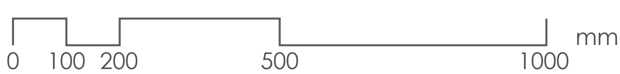


Figure 8.30 Vertical details of the three proposed designs attached to a passive house façade system and constrution. Image by author.



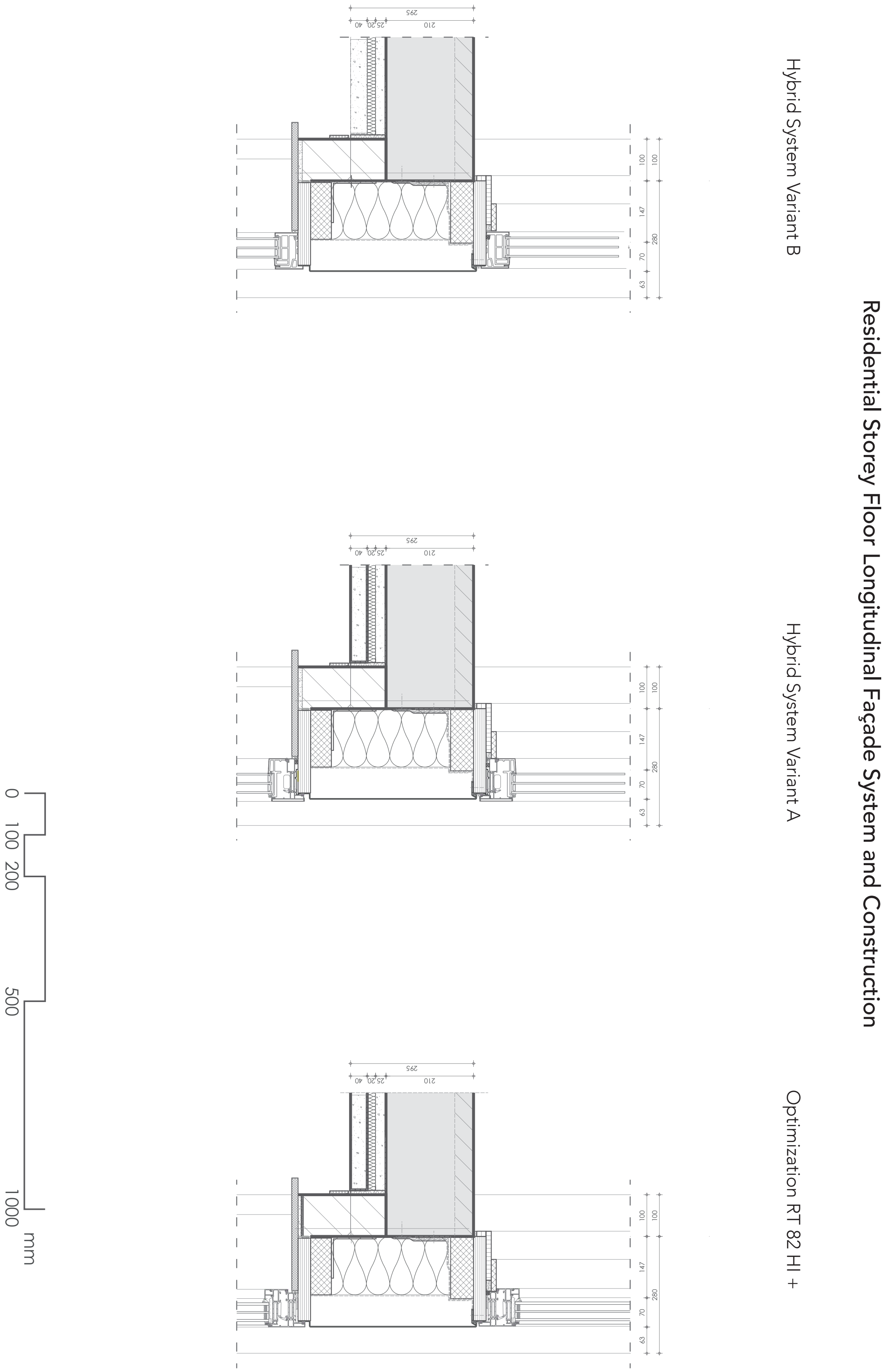


Figure 8.31 Vertical details of the three proposed designs attached to a residential storey floor longitudinal system and construction. Image by author.

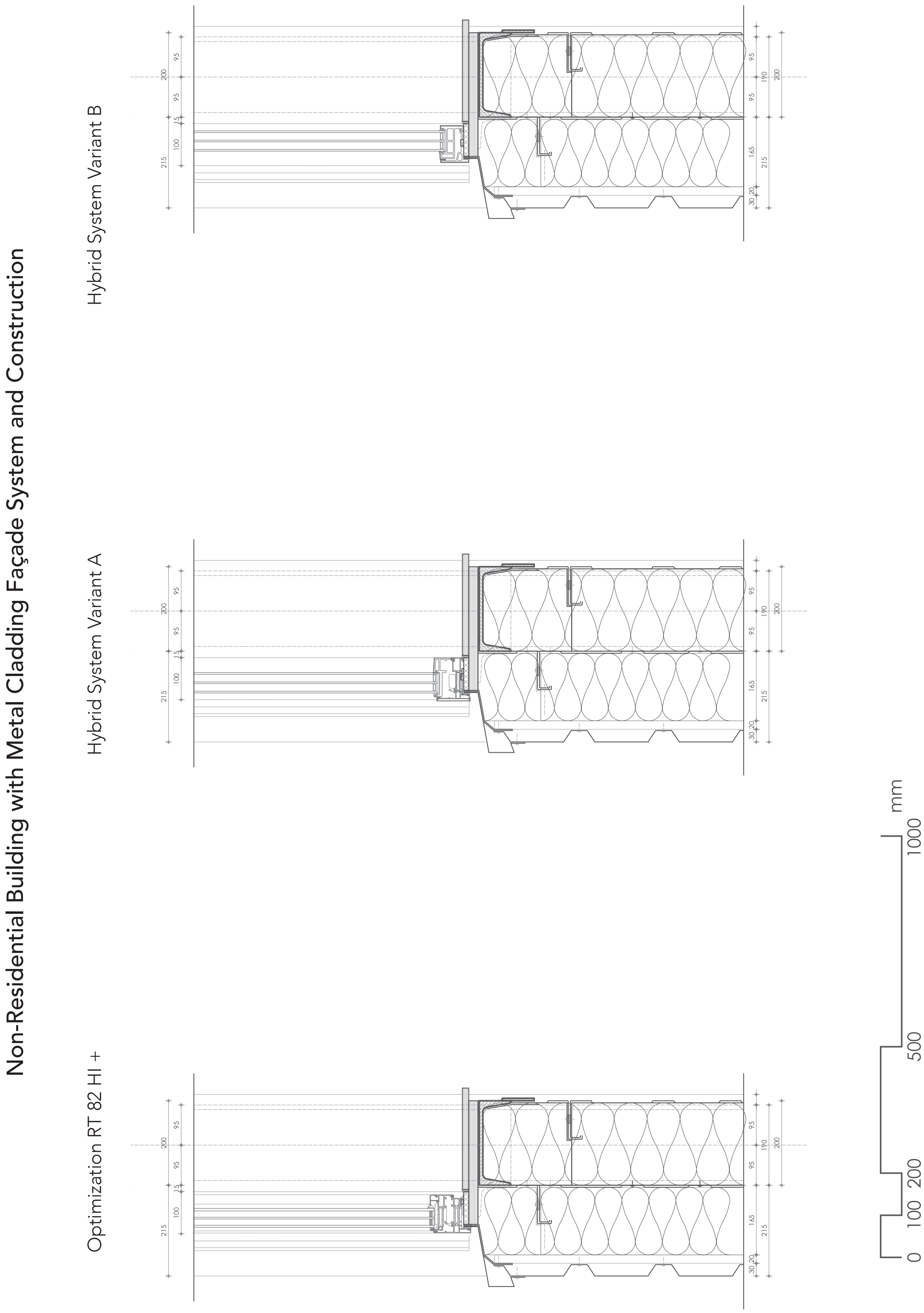


Figure 8.32 Vertical details of the three proposed designs attached to a passive house façade system and construction. Image by author.

8.6.4 Non-Residential Building with Metal Cladding Façade System and Construction

This façade system and construction consists of a double layer of mineral wood with a steel support structure. The façade is cladded on the outside with a folded metal sheet. A 22 mm laminated wood layer sits along both insulation layers, and at the end of it, the window frame rests by sitting in a sealant that ensures air tightness. A window apron sits in between the frame and the cladding.
If a window is to be disassembled from this façade system, first the apron would need to be removed. Contrary to the case of the residential storey floor longitudinal façade, this system does not require to remove the cladding to dismantle the window. It will be required to carefully detach the window by cutting out the connection, similar to the other cases. However, because in this façade system the window is sitting on a seal, the dismantling is even easier. Figure 8.32 depicts the vertical details for this façade system.

8.6.5 Conclusions on Reuse Scenarios

The direct reuse of the three proposed designs is the most effective way to enable a (re)life option for the window system. However, this will depend upon the type of construction the window was attached to during its previous service life. The disassembly of the window from the façade system and construction should be done carefully to keep the components and elements in optimum conditions. The required steps for the disassembly will vary depending on the type of construction the system is fixed into. Four different façade systems and constructions were reviewed to understand the different steps and requirements: brick cavity, passive house, residential storey floor longitudinal, and non-residential building with metal cladding. These four systems were redrawn according to standard details, with slight modifications to follow circular principles. The main focus, however, was towards the window connection to the construction, as this is the critical point within the scope of the presented research.

8.7 Adaptability Scenarios: Overcoming the Fear of Change

As it was discussed in Chapter 3, a Circular Built Environment understands that buildings are dynamic systems under constant change. Also reviewed on this Chapter, Design for Adaptability (Section 3.7) highlighted the importance of adaptable buildings and components. In Section 7.4 the methodology from Schmidt (2014) was applied to the existing design. While some of the principles of DfA have already been taken into account in the three proposed designs, the concepts of "refittable" and "convertible" are further developed conceptually.

8.7.1 Refittable - Addition of New Functions

The aspect of "refittable" will be tackled through the understanding of different types of infills that can add new functions to an existing façade. This allows the upgrade to new requirements, or the possibility to fulfill new functions. This conceptual aspect focused on the demand for "climate components", "biodiversity", and "active technology". These three requirements are fulfilled through the understanding of the window as a fixed frame, with a flexible infill that can be easily exchanged. Additionally, the window itself can also serve as a modular system with internal divisions (similar to a curtain wall), which are fitted in between the gaskets. The type of connection between the glass and the frame is optimum, as it is indirect with additional fixing device, the gaskets. Figure 8.36 illustrates the three different possibilities: a BIPV panel (climate components), a green façade panel (biodiversity), and a media façade (active technology). These three types of panels are just conceptual examples, as actually the possibilities are actually broader than this. As long as the frames are able to carry the load of the panel, and the cross section of the panel is compatible with the frame, the type of infill can be easily replaced, adding new functions, aesthetic qualities, and with the possibility to overcome change.

8.7.2 Refittable - Change of Aesthetics

As it was explained in Section 8.2, Hybrid System Variant A and Hybrid System Variant B both have a weatherboard system that aside from protecting the inner frame, provide the possibility to change the aesthetics. At the moment, the current system does not allow for an easy change of finishings. Because the weatherboard system has snap-in connections, it can be easily clicked in and out. When a window is to have a different (re) life option, this ease of change of aesthetics can give the window a new identity. Additionally, it can easily help in the case of renovations, or just a general upgrade of the window. Figures 8.34 and 8.35 depicts the possibility on change of aesthetics through the weatherboards.

8.7.3 Convertible - Change of Window Area (+/-)

One of the key problems when it comes to reusing a window is that there is not enough standardization to fit windows into different types of construction. The windows of a project are usually custom-made for the specific building, thus if they are to be reused somewhere else, they shall have the same measurements.

There are two strategies from DfA that can be applied there: an "adaptable circular façade", or a "modular circular façade" (Beurskens and Bakx, 2015). The adaptable circular façade has components with built-in elements that allow easy modification and adjustability to further changes. This means that the dimensions, connections, and load bearing capacity are overdimensioned. On the other side, the modular circular façade aims for modular coordination and standardization of connections. These

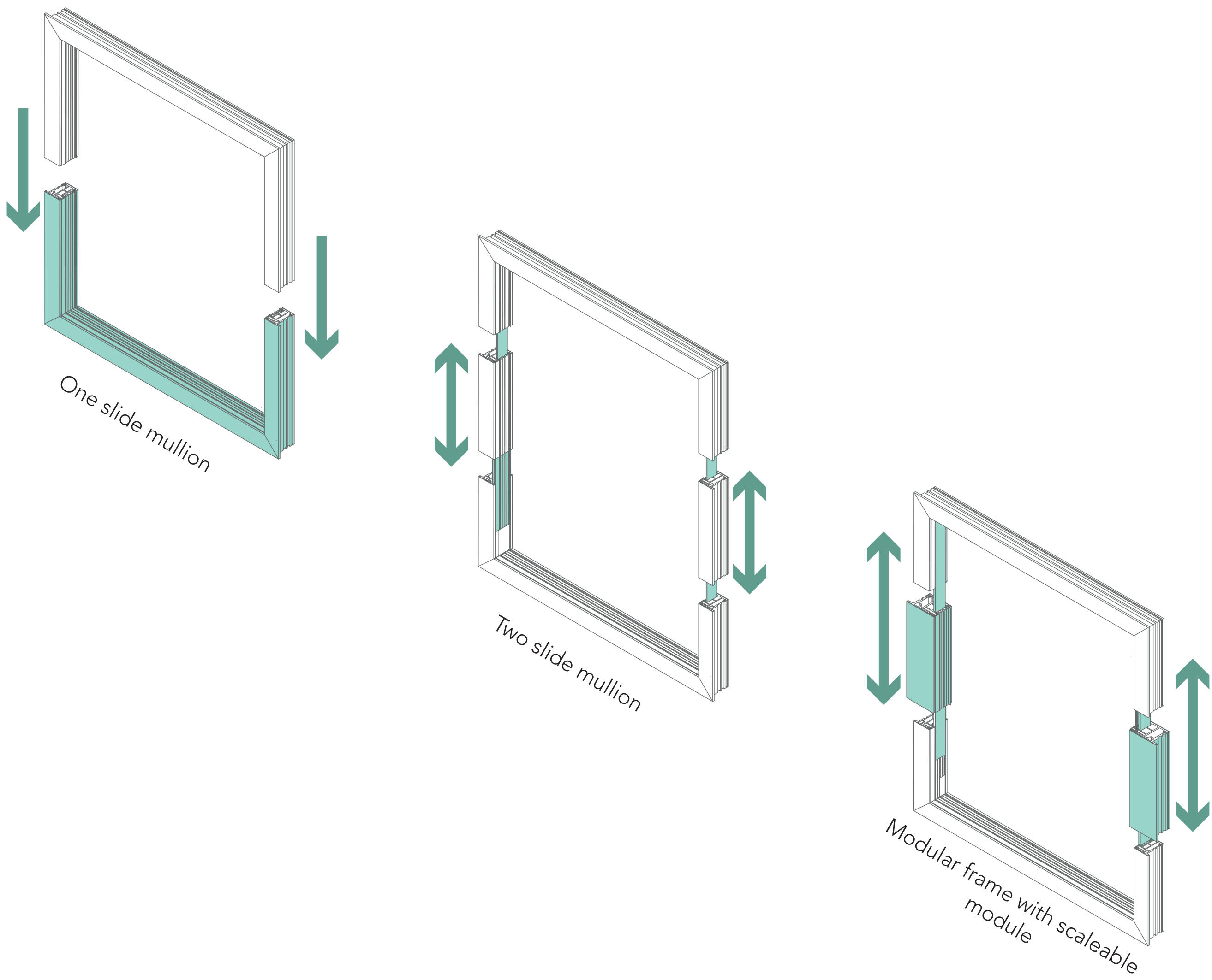
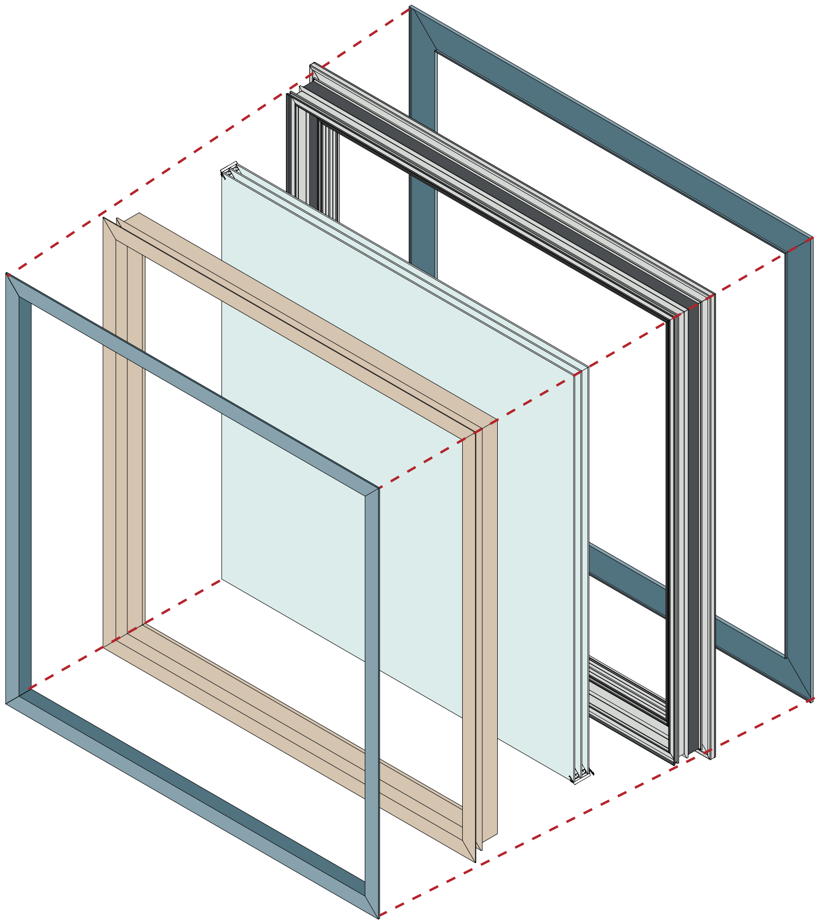


Figure 8.33 Convertible conceptual designs for the window systems.



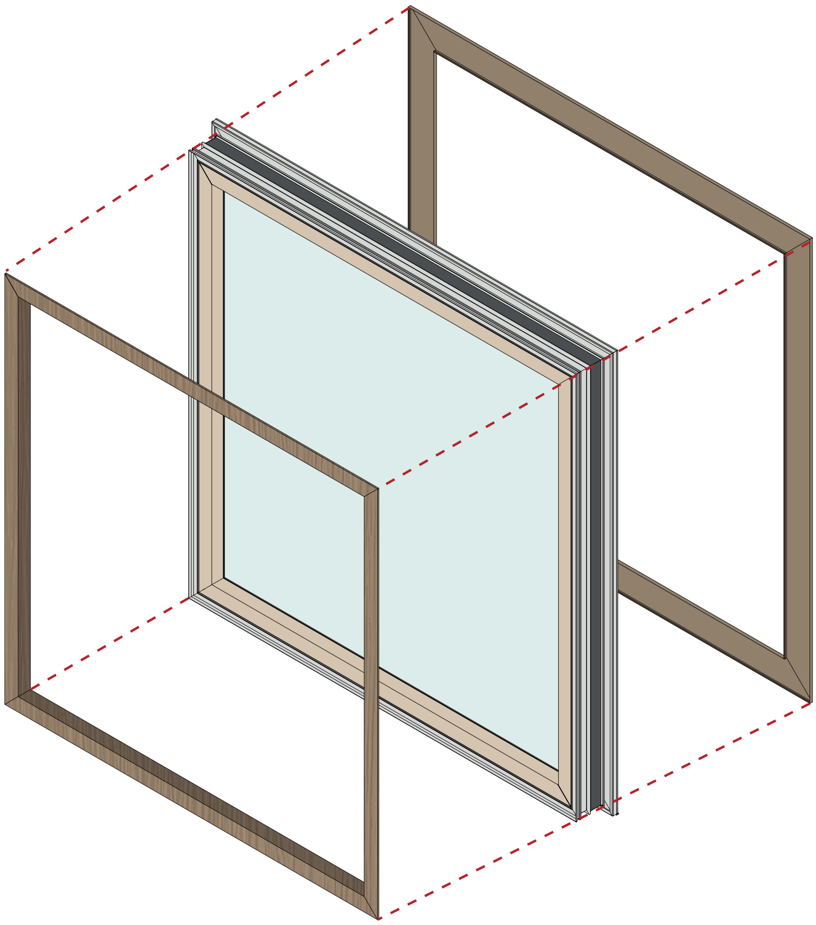


Figure 8.34 Top: Isometric view with exploded elements of Hybrid System Variant A. Bottom: Change of aesthetics through weatherboards for Hybrid System Variant A. Image by author.

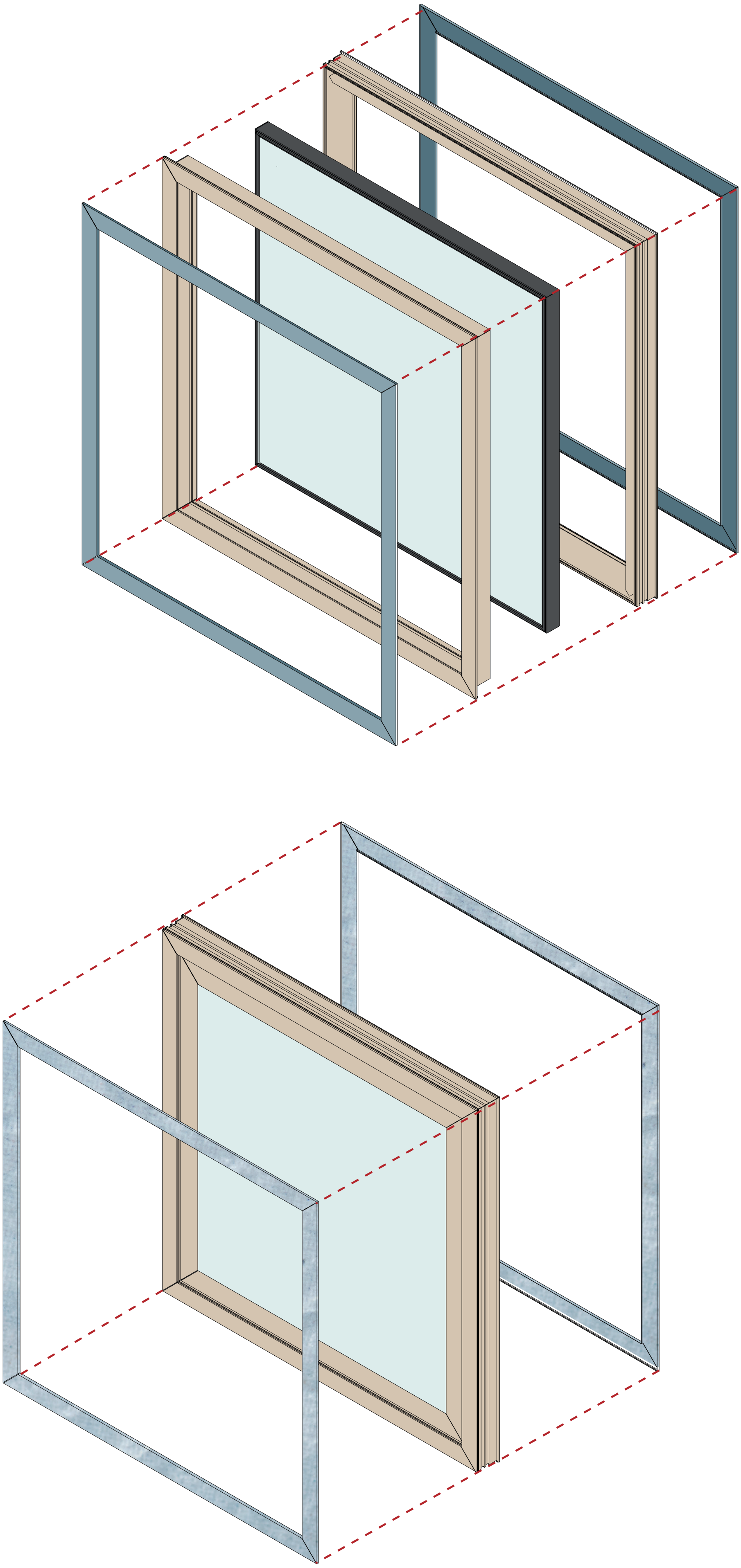


Figure 8.35 Top: Isometric view with exploded elements of Hybrid System Variant B. Bottom: Change of aesthetics through weatherboards for Hybrid System Variant B. Image by author.

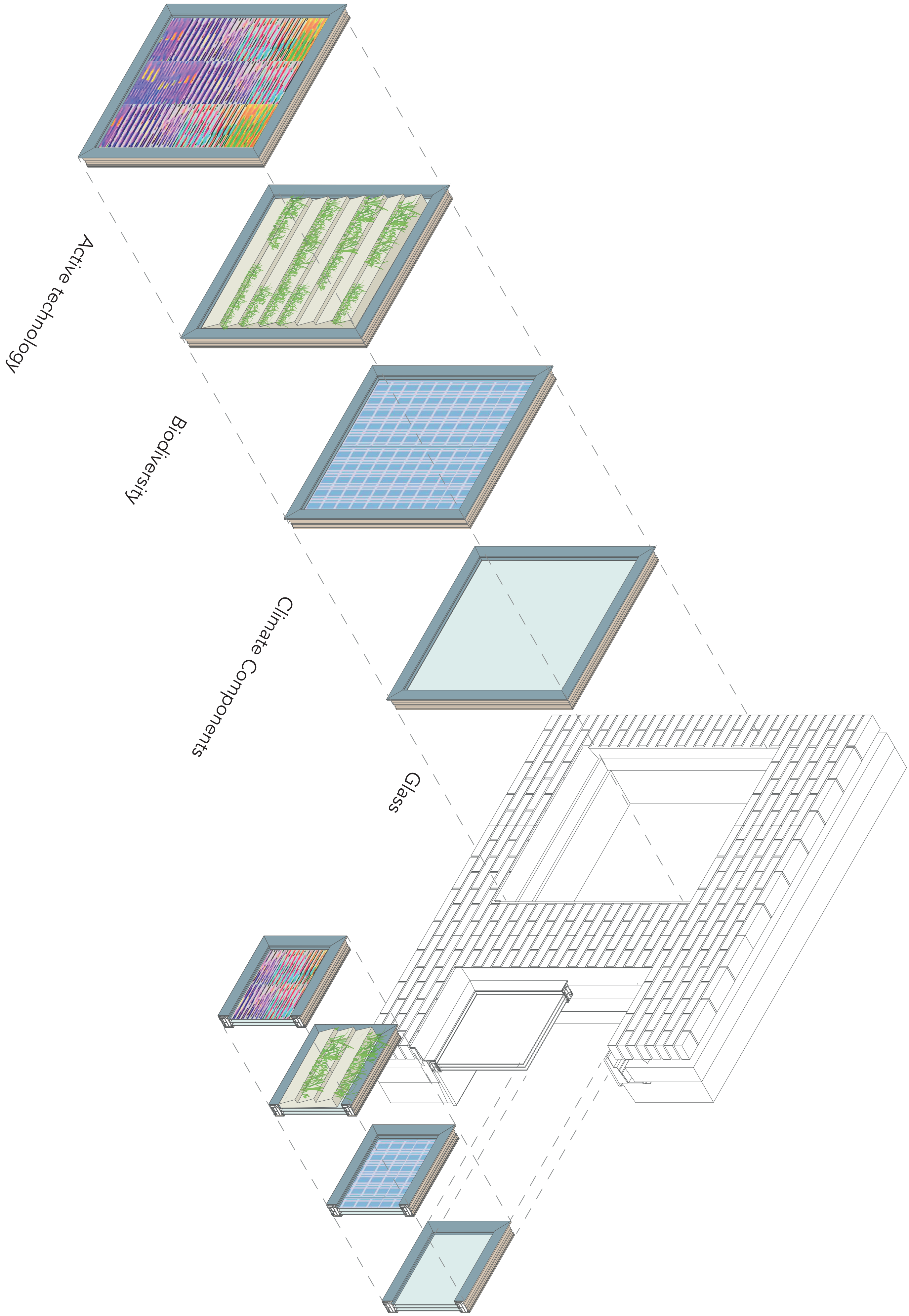


Figure 8.36 Refittable strategies for window and window sections according to DfA principles. Image by author.

two key points allow the façade to be easily adjusted to certain pre-designed solutions from an overall modular system. Figure 8.33 is a conceptual representation of three of these strategies applied to the hybrid system.

8.8 Maintenance and Warranty

Maintenance is one of the key principles in a circular economy to keep products for as long as possible in optimum conditions. It is not surprising that this strategy is also a part of a business model, as reviewed in Section 8.5.

8.8.1 Types of Maintenance

As it was stated in Section 8.5, service and maintenance is one of the new sources of value creation for companies. According to Yeh, Kao, and Chang (2009), maintenance can be broadly divided into three different types:

I. Corrective Maintenance: It is carried out after the product has failed.
II. Preventive Maintenance: Maintenance is performed for regular intervals to avoid product's failure.
III. Predictive Maintenance: The health and current status of the product is constantly monitored through equipment. Maintenance is performed by the system/machine itself. This type of maintenance is also considered as a scheduled service that reduces high maintenance cost.

As stated in Section 5.4, predictive maintenance is more cost-efficient than corrective maintenance. Even so, M. Veerman (2018), circular façade specialist for Alkondor Hengelo B.V., stated that corrective maintenance was "a linear way of thinking". This is also one of the main reasons in Section 8.4.2 it was discussed the addition of a sensor to the window. This is a small example of predictive maintenance, which also translated into business models, is a source of value creation.

8.8.2 Durability

The façade is a complex system with different components that might have different service lives.

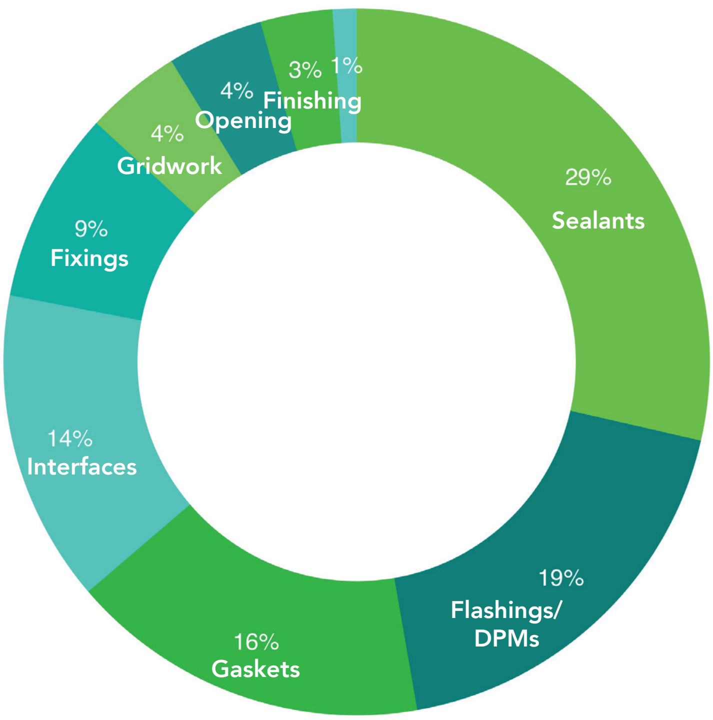


Figure 8.37 Overview of the elements most likely to cause problems. Image derived from Vipat (2017).

However, one of the key strategies to extend their product is through maintenance. How and under which principles is the maintenance performed, as reviewed in Section 8.8.1 is one of the critical aspects. Additionally, it is important to understand what are the critical points of the design.

According to Vipat (2017), the three main elements that are most likely to cause maintenance problems are: sealants (29%), flashings (19%), and gaskets (16%). This data can already give input for the three design proposals, and how these are attached to the construction. Special care should be given to the elements that might present problems, as they can affect the durability of the window system.

8.8.3 Warranty

As it was stated in Chapter 5, a remanufactured product will receive a warranty and a serial number after the remanufacturing process. This is one of the key aspects in terms of market demand. The quality of a remanufactured product seems to be uncertain for many consumers. A warranty that can assure the same, or an even higher performance than the original product, along with predictive maintenance is one of the key strategies to increase the reliability of remanufactured products. This is a complex topic that is situated outside of the scope of this research. However, it is important to understand that if any of the three designed variants (Optimization for RT 82 HI +, are remanufactured, they will require a warranty scheme with predictive maintenance. This shall be a part of the proposed business model, and should incorporate many of the stakeholders in the supply chain.

8.9 Analysis of Thermal Transmittance

The thermal transmittance of Hybrid System Variant A and Hybrid System Variant B was analysed through a thermal bridge simulation. The Optimization on RT 82 HI + was discarded from this analysis, as the overall geometry of the window is not particularly different from the existing window, and the changes done in this redesign concept do not really have an impact in thermal transmittance.

8.9.1 Simulation Set-Up and Parameters

The simulation was carried out with a simplified vertical section of Hybrid System Variant A, and Hybrid System Variant B (in separate files, as each variant has its own simulation). This Rhinoceros model was then linked to a Grasshopper script that applied Ladybug, Honeybee, and THERM plug-ins. The parameters for the boundaries were as follows:

- Tout = 0 °C
- Tin = 22°C
- Film coefficient inside = 7.8 W/m2-K
- Emissivity = 0.9
- Mesh = 8 (maximum size)

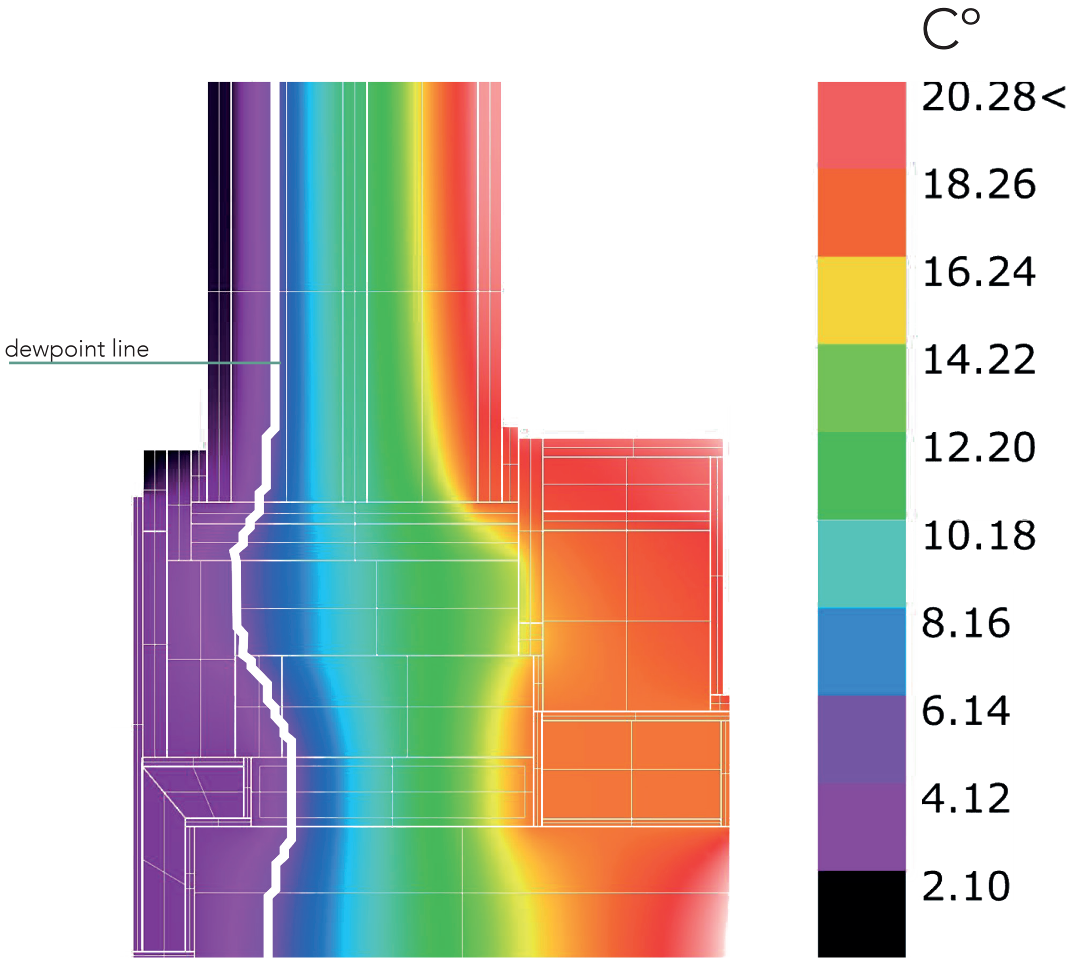
Furthermore, the thermal conductivity of the materials was assigned according to the material's database from THERM. The materials retrieved from this database were:

- Aluminium (anodized)
- Glass (plate or float)
- EPDM
- WPM
- Air
- Foam glass

To simulate and take into account the coatings of the glass, the resistance of the cavity of the triple glazing was calculated as if it was filled with argon gas. The thermal conductivity was λ = 0.016 W/mK.

8.9.2 Results for Hybrid System Variant A

Hybrid System Variant A presented a relatively uniform result in the colour bands of the analysis, and a dew point line that tends to verticality, meaning that there will not be problems with condensation in the window. The outer surface of the glass and the frame is around 20 ° C degrees, close to the interior temperature of 22 ° C. This means that there is no thermal bridge. The results of the thermal simulation also indicate an approximate U-value of 1.2 W/m2K. Further investigation is still to be prov-



en in this. It will be further explained in Section 8.9.4 Limitations of Thermal Transmittance Simulation.

8.9.3 Results for Hybrid System Variant B

The results for Hybrid System Variant B show a less uniform distribution of temperatures if compared to Hybrid System Variant A. This is probably related to the difference in material, as Hybrid System Variant B is highly composed of WPC. However, the results of this thermal analysis seem to be cryptic because the inner surface of the glass is approximately 14 °C.
Therefore, hand calculations were performed to determine if this was a critical thermal break. The following formula indicates is used to calculate if a thermal bridge is critical.

The temperature factor (f) is understood as the temperature difference between the inside surface temperature and the outside air temperature (Tio - Te) divided by the temperature difference between the inside and the outside air (Ti - Te), as seen in Equation 1.

$$f = (Tio - Te) / (Ti - Te) \qquad (E1)$$

There is a minimum requirement for the temperature factor to prevent damage to the structure from condensation. In the case of the Netherlands this is:

$$f \geq 0.65$$

Therefore, according to the results from the thermal transmittance simulation and the boundary conditions the temperature factor for Hybrid System Variant B is calculated as follows=

$$f = (14 - 0) / (22 - 0) = 0.64$$

This means that the temperature factor is at the edge of having an acceptable performance. The thermal transmittance should be slightly higher. However, the thermal bridge is not critical.
The results of the thermal simulation also indicate an approximate U-value of 1.09 W/m2K.

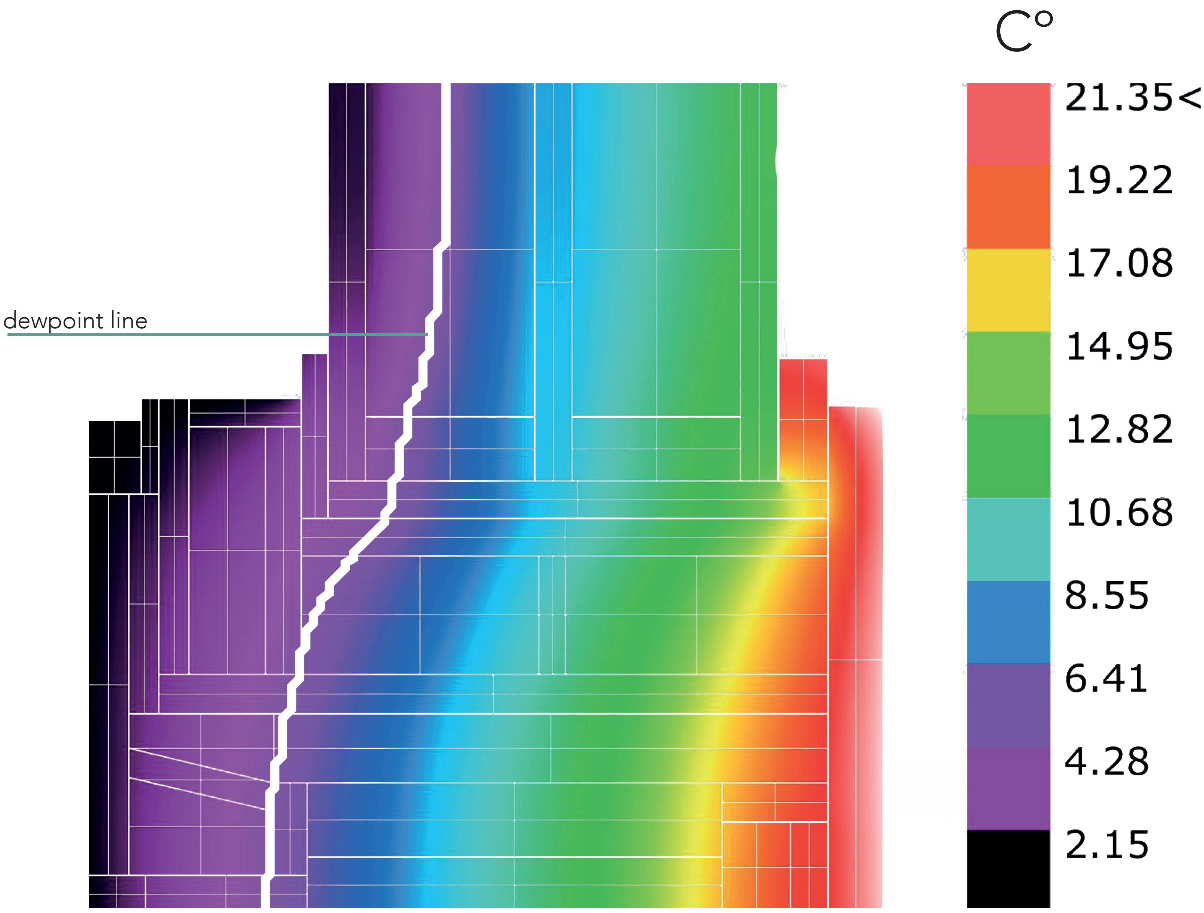


Figure 8.39 Thermal transmittance simulation for Hybrid System Variant B. Image by author.

8.9.4 Limitations of Thermal Transmittance Simulation

The thermal transmittance simulation had to mostly rely on the material library provided by the THERM plug-in. It was not possible to input the AlcoaTherm insulation because the lambda value of the material was not enough to run the simulation. This information was not available, and therefore, the AlcoaTherm insulation was replaced by foam glass, which might have a similar thermal conductivity. Still, the U-values seem to be cryptic because they do not take into account the value of the insulation.

Additionally, the thermal simulation calculated the U-value of the entire window. The previous analyses were done only by taking into account the U-value of the frame. This is cryptic because it is not really possible to compare them. A frame can be highly insulating, but if the glass has a poor thermal performance, then the overall U-value of the window can increase dramatically.

8.10 Conclusions on Chapter 8

This Chapter established the initial design requirements for a circular window system. Then, three design concepts were explained by taking into account the design objective, initial ideas and references, the concept description, and three assessments (DfD, DfA, and DfRem). Additionally, it was explained the improvements through material selection by changing the polyamide thermal break to a bio-based polymer, the change in the form of the phenolic glass foam (from solid to beads), and more importantly, the introduction of Wood Polymer Composites (WPC) as the main material for the window frames of Hybrid System Variant A and Hybrid System Variant B.

Furthermore, the different scenarios towards remanufacturing, linked to a possible circular business model were analysed. The most important outcome of this analysis was the understanding of the new sources of value creation: service and maintenance. Additionally to remanufacturing scenarios, reuse scenarios were established by analysing four different types of façade systems and construction. These were: brick cavity wall (reference project, as stated in Chapter 7), passive house, residential storey floor longitudinal façade, and a non-residential building with metal cladding. The analysis was focused on the required steps to dismantle a window, and the attachment of the window to each construction. Additionally to the analysis of these possible scenarios, maintenance and warranty were briefly researched to understand their importance in product life-extension strategies. On the other side, a thermal transmittance analysis was done for Hybrid System Variant A and Hybrid System Variant B. The results of the simulation are discussed, along with the limitations in the set-up and parameters.

09.

Conclusions

This Chapter analyses the last part: closing the loop in a circular economy. Furthermore, it answers the research questions, the design questions, it discusses the limitations of the presented research, and it gives recommendations for further research. The last part is a reflection of the graduation topic, and its environmental and societal impact.

List of Figures:

Fig. 9.0 View of the Seagram Building by Mies van der Rohe. Image by plataformaarquitectura.cl
Fig. 9.1 How the loop is closed according to the proposed designs in Chapter 8. Image by author.
Fig. 9.2 RemPro-matrix based on Sundin (2004). Image by author.
Fig. 9.3 Diagram of the current life cycle of products from Kawneer. Image by author.
Table 9.4 Circular scenarios for the proposed redesigns.

Figure 9.0 View of the Seagram Building by Mies van der Rohe. Image by plataformaarquitectura.cl

9.1 Closing the Loop

Throughout the entire research, it was highly stressed the importance of closed loops, of having products circling longer throughout the inner circles, and even more, to enable (re) life options that can allow the shift from a linear model to a circular one. After the extensive literature review, the empirical research (with interviews and physical analysis of a prototype), and a long design process, it is important to ask: is the loop closed?

As it was thoroughly reviewed in Chapter 5, remanufacturing is an industrial process that by nature, is a truly closed loop. It deliberately recaptures and retains the value-added component of a product, giving it a new (re) life option which should be better than the one before. After the product is remanufactured, it receives a serial number, and a warranty coverage, equal or better than a new manufactured product. Remanufacturing is also commonly confused with refurbishing, which is a different process. Refurbishing means repairing a product to bring it back to an acceptable performance, whereas remanufacturing is a rebirth of the product. Remanufacturing, along with the other product life extension strategies, is also able to retain labour, energy and manufacturing processes that are integrated into the product since the original manufacturing. As stated before, the ratio of total energy required to manufacture a new product, against a remanufactured one, is approximately 6:1. Another important key aspect of remanufacturing is that is allows products to overcome obsolescence. Since the product is constantly upgraded, it does not become obsolete, which is one of the main reasons consumers dispose of many products in a linear economy. Thus remanufacturing does not only enables other (re)life options, but it is the only one from the product life extension strategies that allows

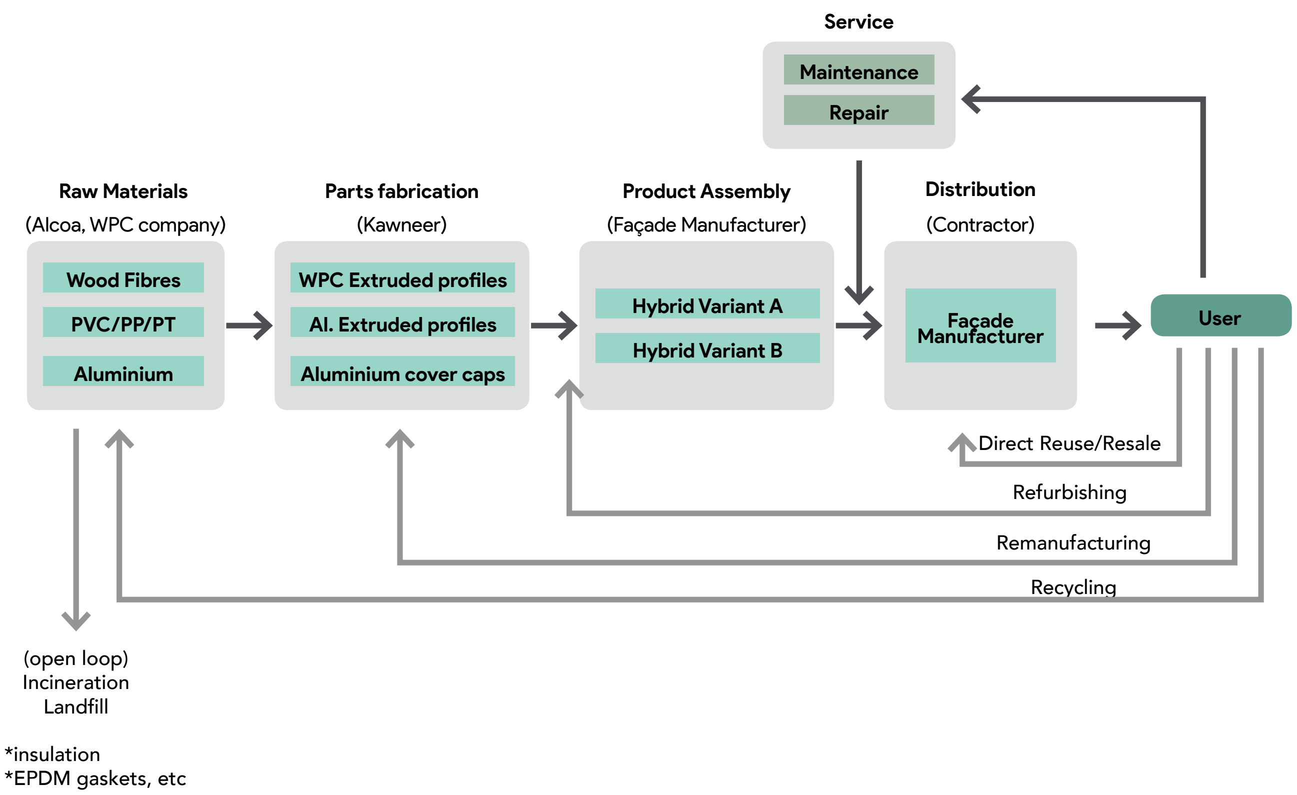


Figure 9.1 How the loop is closed according to the proposed designs in Chapter 8. Image by author.

an incremental upgrade.

Remanufacturing has also been widely applied in the automotive sector. There are actually limited examples, or none at all, of remanufactured building products. However, this does not mean that there is not potential for remanufacturing in the built environment. The shift towards product life-extension strategies will require the building industry to reconsider many of its processes and current practices. Even more, one of the main problems with remanufacturing is the low perception it has from clients. They usually do not trust a remanufactured product. Would someone buy a remanufactured façade? Would an Architect design a building taking into account materials that exist in a bank, which are ready to be claimed back? Will the windows designed in Chapter 8 be able to have different (re) life options for 100 years?

The research showed that there is potential for remanufacturing in the built environment, especially because circularity has become a norm, particularly in the Netherlands. This implies that the building industry will need to shift towards remanufacturing practices, along with other product life extension strategies.

Window systems are usually manufactured in mass production, with an intense market demand, and then disposal, forcing a constant consumption. Closing the loop implies keeping the products longer in use and designing them to enable other (re)life options. Design for Remanufacturing is then, a key strategy in a circular built environment.

9.2 Answers to the Research Questions

The main research question from this thesis was:

RQ - How can Kawneer's façade window systems be improved in terms of circular performance, as a long-term sustainable strategy?

However, in order to answer such a broad question, sub-research questions derived. The following will be answered in order to give a full detailed
From which, the following sub-research questions derive:

SRQ1 - What are the economic and environmental benefits of implementing product-life-extension strategies in window façade systems, such as repair, reuse, and especially remanufacturing?
As it was thoroughly explained in Chapter 2 and Chapter 3, the loops of the Circular Economy diagram have a hierarchical value. This means that the tighter the loop (referring to the butterfly diagram), the higher is the retained value. This is not only related to the direct value of a product, but also to the embodied energy and labour in it. As the loops grow wider, the value of the product or material decreases. That is the reason "recycling" is the last loop in the diagram, because it destroys the embodied energy and labour on it.

However, in the case of the construction sector, which is highly material intensive, implementing a circular economy will decrease the environmental impact. This is highly critical, especially because by 2050, the Netherlands should run completely under a Circular Economy. This will translate towards a reduction in resource consumption by 50%. What is more, the carbon emissions and other important environmental burden related to raw material extraction will be reduced, as products and materials are kept longer in use.

The economical benefits of a circular economy are also found at the core of the butterfly diagram. As it was explained in Chapter 2, they are referred to as "Sources of value creation". These are classified into four different principles. The first one is "the power of the inner circle", which as explained before it states that the tighter the loop, the higher the retained value. This means that the product's original purpose is perpetuated, translating into labour, energy, capita and other externalities (releasing toxic substances, for example) are kept minimum. The second source of value creation is "the power of circling longer". This states that keeping products, component, and materials longer in use will enable the creation of more consecutive cycles. Long lasting designs with service and maintenance integrated into their service life are only one of the many examples of this. The third source of value creation is the power of cascaded use. This one is related towards the stimulation of discarded materials from a chain, by integrating them into new products. This reduced the material demand and promotes growth between industries. The last but not least source of value creation is the power of pure circles. This implies that the product is built of non-toxic and easily separable materials, implying that the material would be able to circulate without contaminants between the circles. The quality of the technical and biological nutrients is then preserved.

Remanufacturing, in particular, provides different economical and environmental benefits. For instance, in the case of the consumer, it will offer a product with a lower price (usually between 60-80% of the original price), with purchased flexibility, and available for a longer period of time, than those products from a linear economy. In the case of the remanufacturing companies, it will create skilled local jobs, higher profit margins, new manufacturing techniques, and better customer relationships. Last but not least, in terms of sustainability, remanufacturing will reduce raw material consumption, energy consumption, reduction of CO_2 emissions, and a reduction in the material that is sent to landfill

SRQ2 - What are the available guidelines for DfRem (Design for Remanufacturing) and which are the circular business models that support it?

The logistics and business strategies behind remanufacturing were thoroughly discussed in Chapter 4, while the Circular Business Models were analysed in Chapter 2. Three business models were reviewed in Chapter 2. The first one was the "Access and Performance Model", which is also known as "Product Service System". This business model is based on delivering a service rather than owning a product. The second circular business model reviewed was "Extending product value". This business model is known for recovering products at their end-of-service to bring them back to life, usually, through remanufacturing. The third and last circular business model reviewed was "Classic long-life model and encourage sufficiency". This is related towards creating a highly durable product with high levels of service. There are usually long extended warranty periods where costs are absorbed by the manufacturer. These solutions aim to reduce resource consumption through a non-consumerist approach.

All of these three models are directly or indirectly related to remanufacturing. In the case of "Access and performance model" and "Extending product value", remanufacturing is implied as it is one of the three life extension strategies. In the case of the third business model "Classic long-life model and encourage sufficiency", remanufacturing might come indirectly in the chain if the manufacturer decides to add it. While this business model can support remanufacturing, contrary to the other two, it is not completely required for the business model to work.

These circular business models might be supported by other economic theories of remanufacturing. For instance, the type of remanufacturing companies (Section 4.4), which can be either the original equipment manufacturer, a contracted remanufacturer or an independent remanufacturer. Additionally, to support the business model, a company might require to have a stable demand and supply of the cores. The analysis on sources to retrieve the cores (Section 4.5) might help to balance this. There are main seven sources to retrieve cores: ownership-based, service contract, direct-order, deposit-based, credit-bases, buy-back and voluntary-based. The three previously described circular business models can be linked to one of more of these seven sources. Therefore, there is a close relationship between these seven sources, the type of remanufacturing companies, and the circular business models. This also allows the understanding that a company known as the original manufacturer of a product, does not need to do the remanufacturing itself to be involved. If the business model supports, for instance, service contracts, the original manufacturer is involved by giving expertise and supervision.

In conclusion, because remanufacturing is an important loop of the circular economy, most circular business models include it, especially as a "product-life extension" strategy. From the three business models reviewed, there is a lot of potential on the "access and performance model" and the "extending product value", as this ones involve remanufacturing directly. The "classic long-life model and

Product Property \ Remanufacturing Step	Inspection	Cleaning	Disassembly	Storage	Reprocess	Reassembly	Testing
Ease of Identification	x		x	x			
Ease of Verification	x						
Ease of Access	x	x	x		x		x
Ease of Handling			x	x	x	x	
Ease of Separation			x		x		
Ease of Securing						x	
Ease of Alignment						x	
Ease of Stacking				x			
Wear Resistance		x	x		x	x	

Figure 9.2 RemPro-matrix based on Sundin (2004). Image by author.

encourage sufficiency" model might not necessarily involve remanufacturing, although there are some cases of companies that do it.

On the other hand, Design for Remanufacturing (DfRem) is a tool for designers to understand the most important product properties needed throughout the manufacturing process. These properties are directly related towards the different steps of the process. A set of different guidelines synthesised from the literature results is provided (from Section 4.7). A detail on this is found on Appendix as High level remanufacturing guidelines:

- Selection of highly durable materials (at least able to survive one remanufacturing process)
- Material selection should not prevent upgrading or rebuilding the product
- Limit the number of different materials

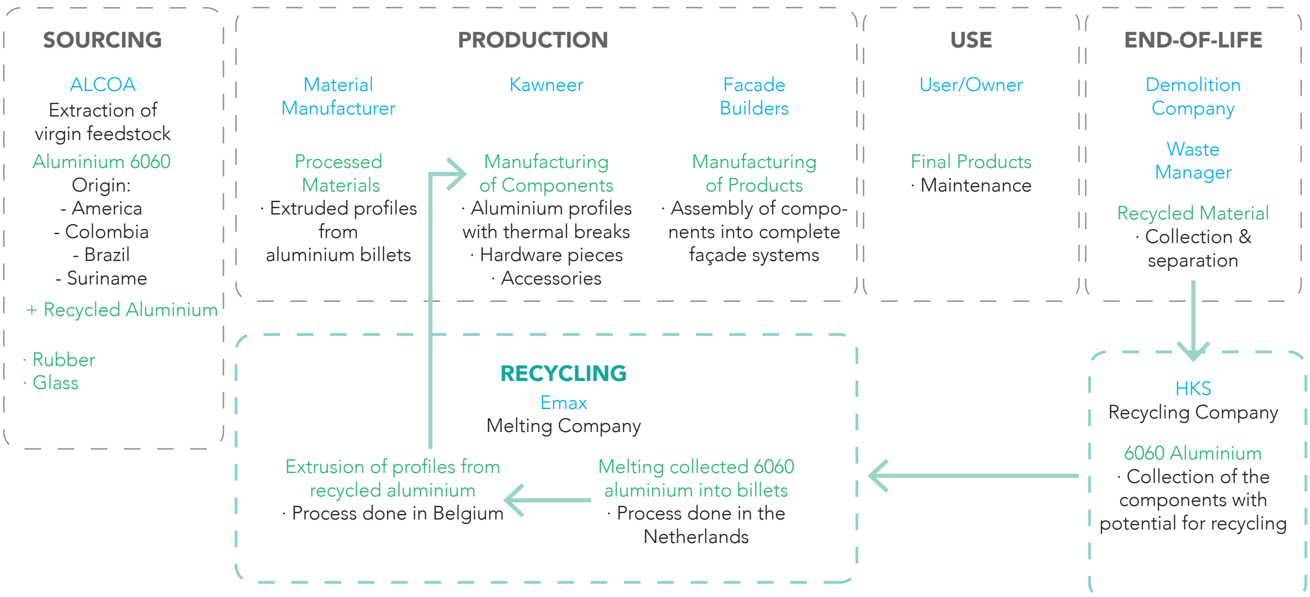


Figure 9.3 Diagram of the current life cycle of products from Kawneer. Image by author.

Element	Material	Expected lifetime	Type of connection	Current EOL scenario
1. Extruded profiles	6060 Aluminium (Powder coated or anodised)	75 years	Pinned	Recycled
2. Glazing beads	6060 Aluminium (Powder coated or anodised)	75 years	Snapped	Recycled
3. Corner Brackets	Aluminium	30 - 50 years	Pinned/Pressed	Recycled
4. Thermal Break	ABS with 30% glass fibre	Unknown (approx. 40 years)	Rolled	Incinerated
5. Thermal insulation foam	Phenolic foam with gas filled cells	Unknown (approx. 40 years)	Fitted	Incinerated
6. Sleeve for thermal insulation	Acrylonitrile butadiene styrene (ABS)	Unknown (approx. 40 years)	Fitted	Recycled
7. Gaskets	EPDM	25 - 30 years	Pushed	Incinerated
8. Pre-sealant	Polyurethane kit	30 years	Glued	Incinerated
9. Pins	Stainless steel	30 - 50 years	Pinned	Recycled

Table 9.1 Elements from the RT 82 HI + and their expected lifetime.

- Identify components that require similar assembly/disassembly tools and techniques
- Disassemble should not damage the components
- Reduce complexity of reassembly (i.e. standardization of fasteners)
- Modular and interchangeable elements
- Identification of products that require similar cleaning procedures
- Incorporate a fault tracking device
- The product is designed to recover its functionality
- Selection of materials that can survive cleaning processes (i.e. the material melting point of the selected material is higher than clean process temperature)

Additionally to this set of guidelines, it is important to keep in mind the RemPro-matrix by Sundin (2004) which relates the product properties to the different remanufacturing steps. This is an essential tool for designers, as they would be able to understand the hierarchy of the different product properties.

SRQ3 - What are the current end-of-life scenarios for the existing façade elements of the RT 82 HI + system and which could be the circular (re) life options?

Section 7.3 from Chapter 7. Analysis of Existing Design explained the current EOL scenarios from the different elements. At the moment, the aluminium parts are recycled. These aluminium elements are able to serve for 75 years, but at the moment they are mostly being recycled at a third of their service life. The thermal insulation components (phenolic foam insulation with glass filled cells and ABS with 30% glass fibre sleeve) are incinerated. Another problem with this element is that it is unknown the exact service life of the product. A meeting with the company is scheduled at the end of May, where this shall be discussed.

Figure 9.2 is a map of the current end-of-life scenarios at a large scale, in the context of Kawneer as a system supplier, as it was discussed in Section 5.3. Table 9.1 summarizes the different end-of-life scenarios of the elements from the RT 82 HI + system, as discussed in Section 7.3.

However, in the case of different (re) life options, there are two main options in this case. The first one is that the system can be directly reused in another building. The second one is a breakdown of the elements to reuse them individually in other window systems. This is a tricky question, because it shall rather be questioning how can the redesign enable other (re) life options. This shall be further analysed once the design is completed. Figure 9.3 is a schematic diagram of the possible (re)life options.

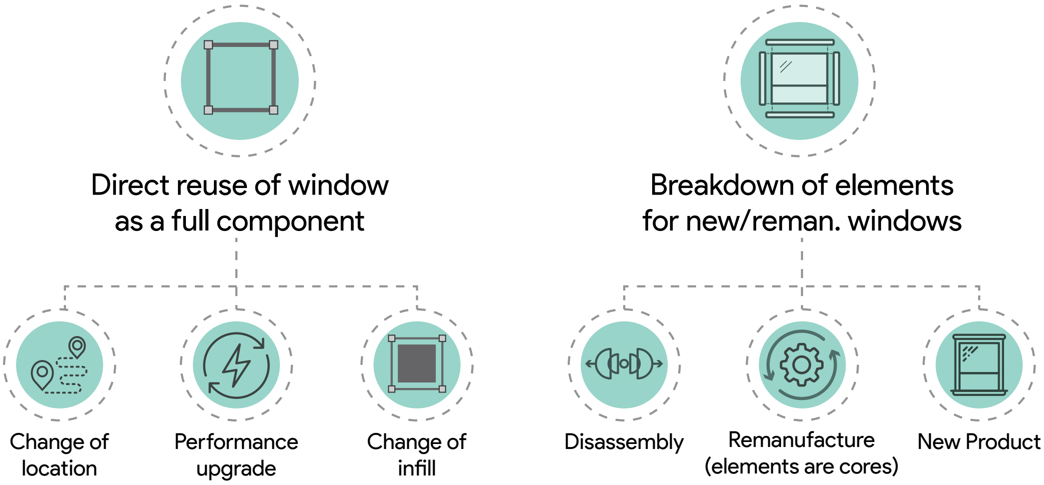


Figure 9.4 Circular scenarios for the proposed redesigns.

SRQ4 - What is the contribution of improving window façade systems by applying circular economy principles to the built environment at a larger scale?

The principles of Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Remanufacturing (DfRem) were at the core of the presented research. In Section 3.1.5, the impact of DfD and DfA in the built environment was analysed. In the case of DfD, it was described by Beurskens and Baxk (2015) as "the concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guarantee of the possibility, of all circular building product levels to undergo different (re)life options in a hierarchical way, achieved by implementation of disassembly determining factors in building design". This means that DfD will have an increase on resource efficiency and economic performance. More importantly, an easy dismantling of components allows the products/materials to have different (re)life options, and close the loop.

In the case of DfA, it will provide products, systems and buildings to overcome obsoletion. This is crucial, because in the current linear economy, many of the products or even buildings are discarded because they become obsolete. If a product or building demands constant replace, it stimulates the linear flow. DfA is one of the most effective design tools that gives seven adaptability strategies that might prevent the product or building to become obsolete. These strategies (Adjustable, versatile, refitable, convertible, scalable, movable, reusable) can have a huge impact in the built environment, because they will allow products to be easily transformed, and be able to deal with obsolescence.

DfRem is a little bit similar to the previous two scenarios, because it actually shares many of its guidelines with DfD and DfA. However, remanufacturing building products, and especially window systems will also have large impacts at a larger scale. Besides the already discussed environmental and economical benefits (SRQ1), remanufacturing building products will shift the current types of architecture and building methods. This means that materials, products, and buildings will have a longer service life, and they would be designed according to such. However, the industry around it should also be able to stimulate this. There needs to be a market for remanufactured building products, otherwise, designing for remanufacturing does not makes sense. The same applies for design for disassembly and adaptability. Components, systems and buildings needs to be claimed back once they reach their end-of-service, otherwise the effort that was put into these three design strategies does not make sense.

9.3 Answers to the Design Questions

The main design question for the presented research was:

DQ - How can façade components of the RT 82 HI + aluminium window system be redesigned for scenarios of remanufacturing and circularity?

From which, the following sub-design questions derive:

SDQ1 - Which are the components and connections that can be redesigned for remanufacturing in a circular economy?

The most critical aspect that was shown during the DfD, DfA, and DfRem analysis was the geometry of the product edges and the types of connections. As it was shown in Chapter 3 and Chapter 7, there is a hierarchy on the different types of connections, and different guidelines that follow a certain order. Open connections, and open geometries are highly desirable. However, in the case of the existing RT 82 HI +, there is a high complexity due to the architecture of the product, along with mostly closed geometries and connections. For instance, the thermal break and the baby aluminium profiles have a permanent closed integral connection. This was the reason the Optimization for RT 82 HI + had a removable thermal break, and Hybrid System Variant A had a thermal break that was mechanically fastened. Even more, this was also the reason Hybrid System Variant B did not had a thermal break at all, because this would simplify the overall architecture of the product.

Additional to this is the attachment to the construction. Having a fully circular window system does not make sense if its attachment to the rest of the façade system is not designed under circular principles. This issue was investigated in four different types of façades: brick cavity wall, passive house, residential storey floor longitudinal, and non-residential with metal steel cladding. Each type of construction had different specifications, and therefore, there is not a single answer.

SDQ2 - What is the impact of DfRem strategies on production processes for façade components?
As it was stated in Section 8.3, there were modifications on the materials used, in comparison to the original system. In the case of hybrid variant A, the bottom aluminium profile will be manufactured as it is now. The difference lies in the connection with the thermal break, which was changed from a permanent rolled connection, to a mechanically fastened connection. This might require a more labour intensive process, but in principle, it can also be automatized. The second biggest change is that the

WCP profiles are replacing many of the aluminium parts. This WCP profiles are extruded, but they need a different raw material.

In the case of the thermal break, it was proposed to change from polyamide to a bio-based polymer. Several studies have shown that derivatives from castor oil have served to make biodegradable thermal breaks. Further analysis on the production process of this material is required.
In the case of the insulation, it is currently an oil-based product which is manufactured by injecting a mix of three materials (polyol, MDI and a blowing agent) in a mould that is later on cooled for several days. It was suggested that the form of the material can be in the form of beads, to allow the insulation to be relocated or reused as an individual elements. This would change the current production process of the insulation. However, there seems to be limited information on how this new improvement would be carried on detailed. This is part of the limitations of the presented research, which are further discussed.

SDQ3 - What is the impact of DfRem strategies on the aesthetics of façade components?

The guidelines on DfRem demand a product that is easy to dismantle, clean, reassemble, and with functional independence that allows certain parts to be replaced. However, in the case of the proposed designers, DfD and DfA strategies were also incorporated. These required, for instance, the ability of the window system to change to a different appearance. The strategy for both hybrid variant A and hybrid variant B was to have snap connections that allowed caps to give a different appearance to the window system This is similar to the case of pressure caps (or weathestrips in the case of hybrid variant B) in curtain wall systems, which are easily removed and have an aesthetical function. From a material point of view, this can be seen as highly material intensive, because the window does not necessarily require this element. However, without the addition of this element, the window does not have flexibility in the case of aesthetics, making it less adaptable and prone to reuse.

Another thing is that the connection between the core of the profile to the pressure caps should allow easy dismantling, and should not add a significant load for the structural part of the window. They should be as lightweight as possible, durable, and easy to handle. Therefore, aluminium for the elements that carry cover functions. This is also giving the window system a higher functional independence, because the elements by themselves, have less functions, making them easier to transform.

9.4 Limitations

One of the main limitations of the presented research was time, and therefore, the redesign of the window system was limited mostly to the frames. Other sub-components, such as insulating glass units, were not directly addressed. The research, and therefore, the redesign was directed towards the frames of window systems. Other of the main limitations, established through the methodology, was that the frame was redesigned in terms of Design for Disassembly (DfD), Design for Adaptability (DfA), and Design for Remanufacturing (DfRem). This limitation was later on reviewed on the Section 3.1.5 Circular Building Design Principles, and even revisited on Section 8.1 Establishing Design Requirements, where it is stated that a circular façade is "designed for disassembly and for adaptability, able to circulate hierarchically between the technical cycles of reuse, remanufacturing and recycling." This definition, along with the initial research framework, limited the redesign, and the assessments towards these three main concepts.

Additionally to this, the (re) life options that were evaluated were mostly focused on remanufacturing. Other product life-extension strategies, such as refurbishing, or repairing, in this thesis are only reviewed slightly, while remanufacturing was extensively analysed.

During the literature review, the state-of-the-art on window systems was done according to the available data from providers. Some of the windows have hidden vents, others might have a fixed framr. This was because not all of the companies were able to provide the same data on a specific type of window, and thus the author adapted to it. However, a fair comparison would be between the exact same type of window system.

Another limitation was that the revision of materials was mostly limited to the possibilities in the window frames. There was not such an extensive exploration of materials for other elements of the window system, such as the insulation, or EPDM gaskets. These materials could be further improved, or other ideas could have been suggested (such as the case of the thermal break).

The assessments on the three different designs were also limited. They were assessed according to the methodology, but to fully understand if the designed proposals are able to work, a full working prototype is required. This was shown, for instance, during the thermal simulation. The thermal transmittance was tested, however, the software used to do so was limited (along with the input data). A more sophisticated software with the possibility of entering data on the materials would give better and more accurate results. But a physical prototype would give also very accurate data.

Another important limitation of this research was the main focus towards materials and components. Buildings are complicated systems, and analysing beyond materials and components will probably give different results in terms of circularity, especially if this is applied to an even bigger boundary such as regions or cities.

This thesis also did not reviewed throughly the aspects of warranty and leasing. These are two key important aspects in remanufacturing, especially when it comes to business models. Analysing them will give other possibilities to consumers, and even so, to product design.

9.5 Recommendations for Further Research

The presented research was limited to a component level, window system. In the case of circular façades, there is definitely room for studying DfRem at a system level. If this is to be applied to other components of a façade, or even the window system itself (for instance the IGU), the research outcomes will be different to the ones presented here, and could lead to different redesigns.

Additionally to this, the importance of a "materials passport", and BIM will have strong impacts in the built environment. Further research on this will provide tools for designers to shift towards circular design by documenting the way things are built and manufactured. There seem to be endless possibilities towards circular design, and the different levels, system, subsystem, component, sub-component, and elements, have all different areas of opportunity.

Furthermore, it should be throughly analysed the warranties and leasing of remanufactured products. These two key strategies can improve significantly the market perception towards remanufacturing products, which is also one of the main barriers for remanufacturing. Additional to this aspect would be the development of a model that can predict the remaning value of a product before being remanufactured and then after. This can also serve as a strong incentive to the building industry.

A full study on the thermal transmittance of the two proposed hybrid variants should be done. This analysis should be carried on through a specialized software that is able to input more accurate data, and to give a separate answer to the Uf (frame), Ug (glass), and thus, Uw (window). Calculating each of these U-values will allow a fair comparison between the proposed designs and the existing products.

More importantly, a physical prototype of the proposed designs should be manufactured for it to be tested. This is because at the moment, it is not possible to test all of the aspects of the proposed design. The prototype should be assembled and disassembled many times, in different scenarios, to ensure that it is able to have other (re) life options. More importantly, that it is strong enough to undergo the entire process of dismantling, cleaning, inspection, replacements of parts, reassembly, and re-location.

Additional to this would be further studies in reverse logistics. This is a highly complex topic that involves a lot of different stakeholders with different interests. However, without this, it is not possible to establish a circular business models. Further cooperation between the different stakeholders from each area is required.

9.6 Reflection

9.6.1 Graduation process

1. How is your graduation topic positioned in the studio:

The Built Environment, being a high material intensive sector, is one of the five key sectors that need to transition to circularity by 2050, as required by the Dutch government. The supply of crucial raw materials is limited, and additionally, energy consumption and carbon emissions have increased dramatically. The Circular Built Environment Studio aims to tackle these problems through the application of CE principles. Waste prevention, eco design, reuse, and remanufacturing imply not only positive environmental impacts, but also in the economy.

Remanufacturing is considered a highly important process in the manufacturing industry that uses resources efficiently. Additionally, it follows the Ellen MacArthur Foundation key principles of a circular economy (2013): "think in systems", "design out of waste", "think in cascades".

2. How did the research approach work out (and why or why not) and did it lead to the results you aimed for?

The results of the literature review were divided into five different parts: circular economy, circular built environment, remanufacturing, window systems, and the case study of the RT 82 HI +.

Strengths: The results are after reviewing some of the most important authors, by interviewing stakeholder, and by understanding the latest discussions on circularity. Weaknesses: Because of the time of the graduation project, the research was limited to a component level. Many other façade systems were excluded.

Opportunities: Further studies on reverse logistics, remanufacturing business models, warranties, serial numbers.

3. How are research and design related

To start designing, I first had to do an extensive research on different topics, from general to more detailed: circularity, circular built environment, circular façades, components, elements. After gathering so much information, and making connections between different authors, I was able to start defining the requirements for a circular façade. This initial foundation served as the starting point for design considerations and criteria.

9.6.2 Societal impact

1. To what extent are the results applicable in practice?

There are already some few examples of circular façade systems in the Netherlands. The design is still quite conceptual, it was intended to also analyse remanufacturing business models, understanding case studies, and through interviews with stakeholders involved in circularity, to make it closer to practice.

2. Does the project contribute to sustainable development?

One of the most important problems of sustainable development is the highly demanding material construction industry. This industry follows a linear model: 'take-toss-dispose'. The project aims to tackle this problem through the application of the CE principles in façade construction. Façades can make up to 20-30% of the embodied energy of a building. If the embodied energy, and the material value is retained, there can be an alternative to demolition, and thus is a way of tackling the scarcity of resources.

3. What is the socio-cultural and ethical impact?

The 'make-take-toss' system from a linear economy has caused several important impacts in society. Shifting to a circular economy implies a more responsible use of resources, and understanding the value on them. However, the transition to it seems to be highly complex, as it needs a lot of research, money, and efforts which will be seen in a long-term. According to some researchers, developing countries might have a harder time transitioning.

4. How does the project affect architecture / the built environment?

There seem to be a lot of risks on transitioning to a CBE. The whole supply chain should be identified to understand the different barriers and opportunities. For example, a contractor might understand the benefits of CE, but it might also see a lot of risks. In a CBE, buildings and infrastructure are designed for a whole life cycle, and not only for an end use. Different technological tools such as BIM should enable material passports, and document the service life of the building components. Design for disassembly and design for adaptability are two of the key tools for transitioning. This would enable the design of buildings that are not just structures that provide shelters, but are also able to adapt and change, through refurbishment, expansion or disassembly.

Bibliography

Books:

Brand, S. (1994). How buildings learn. New York: Viking.
Knaack, U., Auer, T., Klein, T., and Bilow, M. (2007). Facades: Principles of Construction (2nd ed.). Basel: Birkhhäuser.
McDonough, W., and Braungart, M. (2002). Cradle to Cradle. New York: North Point Press.

Conference Proceedings:

Eekhout, M. (2006). The Management of Complex Design & Engineering Processes. In: Adaptables 2006, International Conference on Adaptable Building Structures. TU/e, Eindhoven. [online] Available at: https://www.irbnet.de/ daten/iconda/CIB10949.pdf [Accessed 28 Dec. 2018].
Geldermans, B. (2016). Design for change and circularity – accommodating circular material & product flows in construction. SBE16 Tallinn and Helsinki Conference. 5-7 October 2016.
Lindkvist, L & Sundin, E. (2016). A stepwise method towards products adapted for remanufacturing. International Design Conference. Dubrovnik Croatia. May 16-19, 2016.

Journals and Reports:

Korhonen , J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. Ecological Economics (143), 37-46.
Bakker et al. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production (69), 10-16.
Barker, S. & King, A. (2006). The development of a Remanufacturing Design Platform Model (RDPM): applying design platform principles to extend remanufacturing practice into new industrial sectors. Proceedings of LCE. 399-404.
Bocken et al. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering (33), 308-320.
Butzer, S, & Schötz, S. (2016). Map of Remanufacturing Processes Landscape. European Remanufacturing Network (ERN).
Carus, M., Gahle, C., Korte, H., 2008. Market and future trends for wood-polymer
composites in Europe: the example of Germany. In: Oksman Niska, K., Sain, M. (Eds.), Wood-polymer Composites. Woodhead Publishing Limited, Cambridge, pp. 300-330.
Hatcher et al. (2011). Design for remanufacture: a literature review and future research needs. Journal of cleaner production (19), 2004-2014.
Ijomah et al. (2007). Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. International Journal of Production Research (45), 4513-4536.
Östilin, J et al. (2008). Importance of closed-loop supply chain relationships for product remanufacturing. International Journal of Production Economics, (115), 2, 336-348.
K, Guldager-Jensen et Sommer, J. (2016). Building a Circular Future. Danish Environmental Agency.
Teuber at al. (2015). Wood polymer composites and their contribution to cascading utilisation. Journal of Cleaner Production. 9-15.
Vogtländer, J et al. (2017). Combined analyses of costs, market value and eco-costs in circular business models eco-efficient value creation in remanufacturing. Journal of Remanufacturing, 7(1), 1-17.

Academic Reports, Master and Ph.D. Thesis:

Beurskens, P. and Bakx, R. (2015). Built-to-rebuild. Master thesis. Eindhoven University of Technology.
Boorsma, N. (2016). A Design Tool for Refurbishment: Generating Industry Specific Design Rules. Master Thesis. Delft University of Technology.
Durmisevic, E. (2006). Transformable building structures. Ph.D. Thesis. Delft University of Technology.
den Hollander, M. (2018). Design for Managing Obsolescence

A Design Methodology for Preserving Product Integrity in a Circular Economy. Ph.D. thesis. Delft University of Technology.
Henry, Q. (2018). Circular Façade Refurbishment. Master thesis. Delft University of Technology.
Leising, R. (2017). Steel Curtain Walls for Reuse. Master thesis. Delft University of Technology.
Kim, M. (2013). Efficiency and feasibility of the disassembly process for curtain wall systems. Master thesis. Delft University of Technology.
Klein, T. (2013). Integral Façade Construction. Ph.D. thesis. Delft University of Technology.
Michael, C. (2016). Design for disassembly for façade components in the circular economy. Master thesis. Delft University of Technology.
Sundin, E. (2004). Product and Process Design for Successful Remanufacturing. Ph.D. thesis. Linköpings Universitet.
Vipat, A. (2017). Design for Modularity & Flexibility of Facade Components. Master thesis. Delft University of Technology.

Other:

CircularX: Circular Economy - an Introduction. (TU Delft online course). (www.edx.org/course/circular-economy-in-troduction-delftx-circularx). Accessed on December 12, 2018.

Appendix

A) High-level remanufacturing guidelines

For further guidance, please refer to Chapter 5

Source: Ijomah et al. (2007).

Process activities	Product/design characteristics		
	Material	Assembly technique	Product structure (dimension, internal arrangement, ext. features)
Assemble product	• Limit the number of different materials.	• Identify components requiring similar assembly tools and techniques. • Choose assembly methods that do not prohibit disassembly without damage to reusable components. • Use assembly methods that facilitate easy disassembly without damage to reusable components. • Apply design for assembly methods that do not prevent disassembly without damage to components. • Reduce complexity of reassembly e.g. standardize fasteners.	• Clearly identify component load limits, tolerances and adjustments. • Reduce structural complexity. • Identify components assembly sequence. • Reduce redundant parts. • Standardize parts. • Structure for ease of access to short life and prone to break down parts. • Use modular structure so that obsolescence occurs with components rather than with entire product.

Process activities	Product/design characteristics		
	Material	Assembly technique	Product structure (dimension, internal arrangement, ext. features)
	• Identify components requiring similar cleaning procedures and cleaning agents.		• Arrange components so that all can be accessed for effective cleaning. • Ensure product surfaces are smooth and wear resistant.
Remanufacture components (including test components)	• Use materials that are at least durable enough to survive the refurbishment process.	• Use assembly methods that would allow disassembly at least to the point that internal components and subsystems requiring work can be accessed.	• Reduce/eliminate redundant parts.
	• Use materials that do not prevent upgrade and rebuilding of the product.	• Use assembly methods that do not prevent upgrade of product.	• Structure to facilitate ease of upgrade of product.
	• Identify component material.	• Use joining methods that allow disassembly at least to the point that internal components and subsystems requiring it can be accessed for testing before and after refurbishment.	• Arrange components for ease of access to parts prone to damage.
		• Incorporate fault tracking device.	• Standardize parts.
			• Structure for ease in determining component condition. • Structure so testing is sequential, mirroring reassembly order. • Minimize the disassembly level required to effectively test components. • Standardize test procedures.

Process activities	Product/design characteristics		
	Material	Assembly technique	Product structure (dimension, internal arrangement, ext. features)
Disassemble product	• For components destined for reuse ensure that their materials are sufficiently durable to survive disassembly. • Ensure that fasteners' material are similar or compatible to that of base material thus limiting opportunity of damage to parts during disassembly.	• Use assembly methods that allow disassembly without damage to components.	• Arrange components for ease of disassembly. • Reduce the total number of parts. • Reduce complexity of disassembly, for example by standardizing fasteners. • Use modular components thus reducing complexity of disassembly because types of assembly techniques are reduced. • Arrange components so that separation joints are easily accessible and easily identifiable. • Minimize the number of joints. • Reduce/eliminate redundant parts. • Simplify and standardize component fits.
Clean components	• Use material that would survive cleaning process e.g. ensure that material melting point is higher than clean process temperature. • Limit the number of material types per part.	• Use assembly methods that allow disassembly at least to the point that internal components can be accessed for cleaning.	• Ensure that all parts to be cleaned are easily accessed. • Reduce/eliminate redundant parts.

B) Brainstorming Session & Interview on Circular Façades

Present: Andre Smit, Martijn Veerman, Wijnan van Manen, Tania Cecilia Cortés Vargas Date and location: 27th of February, 2019. Kawneer offices. Harderwijk, Netherlands.

A: What is your assumption on the residual value of the façade after 15 year?
M: We don't know. We estimated 10%. We have not idea if it is ok or not ok, if we make profit out of it or not, but we have to start somewhere. That is the challenge/risk you take. But the client is asking what will be the consequence on the rest value if we take triple glazing or double glazing? They say ok, if you take triple glazing the rest value is higher. Can you give a calculation? No, [laughs] I have no calculation, and no idea what the [façade] market will be after 15 years. But just a feeling. But then it's hard to take risks, which no one wants to take. It's not hard value.
W: It is not possible to give it value to it at this time. Now, the differences between single glazing, double glazing, and triple glazing in the year of 2019. What you can give back to the guys then and also what you can give back for the aluminium at this time. What we see that economic level is going to rise then they will have an indication of in 15 years, it will be quite the same? Or lower? Or higher? But just give figures, what would be in 15 years? That is impossible M: For instance, we have the best façade you can imagine. With the lowest U value, the best sound insulation. The best attributes. It is very expensive. After 15 years you should assume it will have a high rest value. But do Architects want a façade 15 years old?
W: Also think about the knowledge of 15 years ago. When we look now 15 years back.
T: It was very different. The technology and the construction was very different.
W: And it's not even that much time. 15 years ago we had for example the 62
A: I think the issue is that in the next: how can we design to be able to upgrade the 62 afterwards to the 82 or 92, or whatever you name it, that you will need at the end. At that time we did not designed for disassembly. And if you look at the AA 100, it is very good for dismantling, and reusing it again. If you look at a curtain wall from 30 years ago, and you want to upgrade it to the new standards, what would you need?
W: Different thermal break, another type of glass: double glazing, triple glazing. And maybe another cover plate. And then you have another colour. And then it might be ready.
M: But what about the colours? The mullions and transoms. You designed them on a glazing package, at a specific place in Holland or whatever, so it is already specified for a location. If you take the façade out of the building and then it is placed somewhere in Germany, or if we take it to the coast, Scheveningen beach, it will need to be treated. You cannot really make everything the same, do you? It's really complicated to look for a solution. But I think that it is the future, so we have to go there anyway. I have a façade, I still do not know what the system supplier was, for the Tropicana Swimming Paradise in Rotterdam, close to the MAAS. It's a 30 year old curtain wall system. But the systems are not possible to get anymore. And they want a new glass packet. So we need new gaskets, glass, etc. And we said ok we have to make the construction bigger, the curtain wall sections bigger. This is impossible. It costs too much money, it is cheaper to replace it for a new one.

W: Yes, also because all the standards are also changing in this years. Everything has to be stronger for wind loads, for water tightness, everything has changed ever since. And also when you talk about aluminium. The paint has also changed, the gloss.
M: Yes! And the question is: can we change in 20 years the colour with a new very high value coating? My opinion is to get everything back to the painter. And do everything again in the oven and then you have a very good quality coating. If you do it on the building site, the spraying, then you get very high value, but the lifecycle would be 7 years, and then you have to do it again and again, and again. Same as painting wood.
A: I believe that you should be able to deliver some components back, and that you should be able to give the same guarantee to the product. Otherwise I don't think anyone will accept a depreciated product.

W: Or you have to change a little bit. You screw things. When we are talking about a window for example, you screw connections on it and you click on the outside a new surface: another colours, etc. On the inside, nothing changes. And then the colour will still be acceptable, but on the outside, with the rain, the snow, the sound, etc. I think it is also important to mention that for the next generation you should be able to click out a window, or only a vent, and put it somewhere else in the same building again. For example, you have that building [points at a picture]. And in that building there will be offices on the first, floor, and students living in the third floor, others living somewhere else. And all people have different wishes. Some of them want a vent that can be opened quite simple. But the others dont need that because they have conditioned their living rooms, so there must be a way that you can quite simple get a vent out of it, put it three storeys higher, or put it on the first floor. But that will be a total change of thinking because when we. At this time, we will see more and more electric driven hardware in the following years. The problem is that we have to make big holes in the transom or mullions when you install it reverse, that you put in the vent, the big hole for the driver. For example what we did at rotom. You do it reverse in the vent part and then you can quite simple take it out and put it in somewhere else without holes in the transoms or mullions.
M: (talking about a presentation) This is the most important scheme where we take our responsibility for the products we make. And the loops are very important, but for example recycling is the very last loop, it's the last stage, and it should be after 50 or 75 years theoretically. We go from product selling to far right, to product systems where we deliver comfort, but a façade itself is very difficult to describe because it you deliver comfort, you also imply the climate installation, and we also need the indoor rooms, and we need everything. So this is a very integrated solution. We are thinking now together with an insulation company to do that, together to deliver comfort. That is possible. If you look to performances, we have the comfort, and we can split it into four main comfort parameters: thermal, acoustics, ventilation, and light quality. You can split it more and more into technical parts that you can measure. If you look at the façade that we deliver, it is actually the building user who gets the comfort and the façade is expecting this. To get clean air inside the building, etc. This is all facilitated by the façade, it gives the output. This is a smart project. The façade is operated in this system. The building user gets the comfort in the beginning with the agreement. We also do the maintenance. Nowadays we see maintenance as 'corrective maintenance', which means that

we do something when it's too late. But if you do that, and you calculate the cost in 15 years, it is way too expensive. There is a linear way of thinking if you do it like this. It is very expensive to come everytime back when the product is not working anymore. For instance, in Delft we have 372 elements, and every element has three engines to control the windows, one motor for the sun screen, an adaptor for the windows, and ventilation boxes. That is a lot, and if you calculate what the cost is in 15 to fix all the issues, it will cost you way too much more money. So this pushed us to move forward to 'predictive maintenance'. That we measure when it is starting to fail a window, when is it not functioning correctly. You want to measure the wattage, and if that exceeds the specifications, then you know there is something wrong. And then you can do only the windows were you measure something like that. And then you specialize in a few windows. Then step 2, which is the 'preventive maintenance', will lower the cost. Another aspect that I saw in the time that I have been busy with this: for instance the adaptor for a window, electric components, can be that after 50 years, the product is not working anymore. In the product, there are consistors with moisture in it and that can be tried out. It is a very small part in the adaptor. What they do is that they get the old one out, put it in the bin and place a new one. That is very expensive. Actually, in 20 years we replace everything two times. It is expensive but also not really sustainable because it is only the little parts. They have not engineered it to easily take it out.
W: Plug in, plug out !
M: I am the first one to ask this to the suppliers of the systems. They are now asking 'why?' because they have always done it like this and it is more difficult. These are electronic components, but we have the same problem with the sun screens, the windows, the handles and hinges. It is not always that everything is designed for disassembly. The critical points, are the only ones that you actually have to switch.

W: It is the same with hardware in windows. We have locking points. It does not matter if it is more than thirty thousand times for example. But just the corners, for instance, the spring or whatever, that will be broken after 15 thousand times. When you put a sensor in it that measures how many times it will be opened and closed, then you know exactly 'hey that is 15 thousand times. So at 14 and a half we have to remove the corner pieces, replace them; or refurbish because you do not have to make a total new unit. But just replace a spring in it or whatever. Then you put it in the store as a refurbished material, and you can use it again.
M: That is also the way we think about our façade elements. We look for the critical points to find a solution on where we have to remove the critical points, and not the entire system. The challenges for kawneer, is do we have after 15 years still this critical point? At that part. Because after 15 years everything changes, and architects want different things. Maybe in the future we buy a 3d printer and print out the spare parts. There's a trigger to say ok, as a service model, it is interesting to implement this business models, but if you still do the calculations regarding the first part, then it is too expensive and it is not interesting financially.

T: It is too expensive to...?
M: To replace every single complete part.
T: But right now the problem is that is more expensive to remanufacture than to replace the units completely, right?
M: Right. Almost no party will take the risk either, also not the solar screens provider, or fabricator. The supplier of the hardware components. No one wants to take this risk. Their argument is that they take other responsabilities, which are not that risky. It is quite easy to make money this way. This is linear thinking, not circular thinking. So the thing is, the critical points in the facade we deliver, or that kawneer is delivering, that is a good question. Here the replacement, reuse, of façades (point at the loops in a CE diagram). The first one is 'disassembly on element level'. I believe this is the most highest value. If we also replace glass panels, or all the screens, or any other type of panel. Then it is also very important because you can upgrade the systems. Maybe replace some of the transoms and mullions, but to disconnect all the corner joints. I don't really believe that is the correct way of disassembling façades. That will be very difficult because it requires a lot of labour time, because it is already number 1, and product number 1 you can also upgrade it already. What is the need for investing in research or development if you just can disconnect the corners, for instance. If it is very simple, just do it. But it is not very simple, because there are a lot of performances we still need to take into account.
A: The only thing is first of is the ideal world. For example, wooden doors. Where you have fixed sizes , everybody knows how to find a second hand wooden door, or panel door, it has standard measurements. But that is not the way designers think today in the façade world. We need some modularity, at least in the Netherlands. Maybe in the US is not the case, they more or less have this modularity. They have fixed dimensions and are able to take windows out, and sell it again because they are based upon modular dimensions. But that is I think the first step. So you need to have an agreement with the designers to have some volume to put this first product back into a new project.
M: The designers like this, projects in Amsterdam, where we are now busy with an 18 hunderd square meter façade, not yet 10 years old. It is quite young. And I have now 4 interested parties in this curtain wall system. It is with panels in between. So there are architects interested in this new way of working. If we add the circular dimensions, which are in 30 centimers, 60 centimers, 120, and so on, I just want to make a grid of it. Eh, maybe the reuse options are getting bigger. If you think it like that.
T: So do you think Architects will change the way they design buildings, according to this (circularity)?

M: Yeah, yeah. Architects like inbo, next architects, but also project developers are also interested in this reused façades. So the market is changing. It is just now like this, but my feeling is that this will definately be the future.
T: So you think there will be a market for reused-remanufactured façades in the future?
00:29

M: Also the standards from the government, from the environmental topics, are also getting stricter and stricter. So that is also something that makes it. I think in 15 years it will not be possible to build a building with only new materials. Definitely we will have to use together with the environmental standards to use second hand products.
W: But I think, you are right. Architects want to change the world, but these are the headlines, but the other companies who are delivering all the materials are they also wanted to change everything?
M: In Holland? You mean?
T: Maybe also real estate owners, you think?
W: Yeah, but also the contractors?
M: Well the questions are not really coming from them but they also have seen that is changing. They are also interested in this topic.
W: What we see at this moment is that there are a lot of companies that are, what you said, interested. But do they really want to start a project on this way? That is a different question I think.
M: Yes! Architects are difficult, for example, because what is an architect now in the building process? He is more of an advisor, especially for an aesthetical part of a building. They don't take responsibility on how is made.
W: Yes! And when we want to make a building. You go first to an architect for design and looking for the possibilities. Maybe in the future they have to take the lead of the project, because you are saying "I want to have this, and I want to have that", and they give advice at your wishes, and when they are coming by a contractor, they are going to change everything. When an architect has the lead from the project, from the beginning to the end, then it will help.
M: Yeah, definitely. But some architects have some times an opinion in the rest of the process. Sometimes architects do say that they want to take the responsibility back. I think we have to start there. To show that it is possible, and what is not possible.

W: But also find an architect that wants to take the lead.
T: Yes, because you are giving them constraints, since the very beginning, right? I mean you are telling them 'now you need to design under this constraints', are they willing to do so?
M: You mean, we give them the dimensions?
T: Yes, for example, or maybe that the finishings are going to be something completely different, maybe coatings are not really an option. And this is, I mean I think that maybe they are scared of losing that freedom in the design part...
M: Yes that is true, but also on the other side they want to score with the most sustainable building. So it is also a branding for them. Just to make the most beautiful building out of reused components. Maybe it is a trend. But also because the standards, the laws are changing.
W: Not only the architect want to be in this trend, but also all companies, alkondor, Kawneer.
T: Do you think that we, for example, if we say, we have this window, and we will use it for the next 60-100 years. Do you think that it will block innovation in a way? So for example, what we were saying before that technology has been changing so quickly, and now we are constrained to reusing this product. Then do you think that is going to block innovation, if we are constrained to use the same products over and over again?
M: I think we have to think how we are going to make the products in a circular way. For instance, I can show a project.
T: Because for example, the façade for the CITG, it will be dismantled in 15 years. So then the complete elements will be reused. But we cannot know if the regulations in 15 years will be the same. Or if maybe we have different insulation materials. I do not know, I think it is hard to predict those scenarios.
M: Yes, but if we make it possible, then those changes can still go on, and be there. This is going a step further. The systems we deliver are already good to disassemble, so we can just engineer further, and make it better each time. Then you can replace things between the frames, that is also how we made this concept: this is an elements facade. The frames are always the same, but the infill, that will change. In the high rise buildings, or commercial buildings, or a hotel that is a five years residence. After an-

other five years, an office. It changes really fast, the market is also changing, and now we have too less residencies, and we want to keep transforming. We made this mock up (pointing at a presentation) with a part of an office and a residence part. The insulation is now in this elements, but the frame of the elements, are also insulated. That is not really needed because behind it is the insulation line. But you can also replace this panels for insulated panels, and then you have a facade for an office with an outside space. Maybe you insulate this first part, the balcony size, you connect it to the

structure, and then you make sure the element facade can be replaced individually. This is a concept we made that is already finished. Also this one is a step further regarding the delivery of comfort, automatically openable windows. Kind of what we did in Delft. Here we went a step further, because here are elements that do not have to do with the façade. We made it, we showed it, and we also made sensors in frames. This detects air quality and stuff, they are based in wireless long race gateway. That one is controlling the windows and the sunshading. Very nice. We tried to think about circular flexible concepts, not to replace the whole element but just the infill itself.
W: Do you think that in the future also the mullions and the transom must be changed?
For example, you are starting a family, maybe first on your own, then you get a partner, and after that time, you're going to get kids, and after 25 years the kids leave the home, and in that time you have different wishes, you want to have more sleeping rooms, or other things. It will be nice that you can change your facade. Then you screw out the mullions, and you put them one meter further away, and the other one. When everything can be dismantled, with screws, then it is quite simple to change everything.
M: But then in high-rise buildings, how big is the chance that you have to remove, or completely change it? I think on the housing scale, residential scale, of ground based building homes, yes. Of course. That we want to place an extra part on it, or just take it away. But for high-rise buildings it is so expensive to change completely facade elements.
W: But it can be quite simple. Click-out or screw in, to the inside, because when you are changing something in your house. You are thinking this could be the best way for the coming years. But after there will be much more times that you think after 1 year "Oh I could have done it better, or rather have done that!" Because you are living in your apartment or house, and then you are working with it, and you see, that at that time, you could change this or that. When you have a facade that is totally modular, then you can change everything in your own way.
Then your window can be this. Changing in other ways.
M: I completely agree. I see that it is very interesting that we can do it. But in the large scale, like in that building (points at a poster in the office), imagine a window frame in a building like that, which we specialized to do the building. What do we want to change then, for instance? After 10 years.
T: I think the IGU are usually a problem after some time. Either you pay more for your heating or you change the insulating units.
M: Not really an aesthetical part, it's rather technical.
00:45

A: No, you said that at the TU Delft, they wanted to have those windows for 15 years. I think that is a different segment. In residential cases, the window stays for 50 years. I don't see the need to change it in a commercial or other way. So more or less 50 years. A new owner or user will demand new windows, maybe at that moment. But it is a different product because if you look at 50 years, which is how long you can keep a window, in your building, for example, in a high rise, you will hardly change the facade, but you want to be able to upgrade the performance of the facade. Maybe if you want a railway in front of it, or a higher thermal/acoustic performance, or if you want to exchange the glass or the infill, etc. That will happen in that type of buildings. But if you look at those windows ydd(points at picture of a high rise) maybe this window could be the same as this window. Same dimensions. And then in 50 years this one will be in the market, and how can you put it into this building? And then you come to the fact of 'ok, this one, the owner wanted it to have fixed elements, and now it is going to be a residential, or it is going to be like that. It will change in 50 years. If you want to have exchangeability between buildings, you need to have flexibility into the frame, I believe. But then if you talk about high rise residential, I don't think you want to change it, if you are in the segment of low rise residential, I really believe in the modular building, that can be bigger or smaller, and that is able to change. And you want to have also a change.

M: For example, an architect saw the flexibility inside this building. He said, the outside is transparent, but it can also not be transparent if you put a panel in the outside, before the glass. Still also with the sun shading directly. Inside, the flexibility is that you can change the apartment from smaller to bigger by connecting two apartments. And also more floors connected to each other. For apartments, it is also about the floor flexibility, and in commercial buildings, make it is more interesting to see the outside. There is a project in the one we are working now, and we have the same question after 9 years. A new investor bought the building and he said "well I have a new vision about the building, so I want to change it". Not everything but a part of it will be disassembled. This is because of the asthetical part. This is a reality. Normally we demolish it, and we put it in a landfill. Now we see that there is still a high value on this facade, a u-value of 1,2. So we have to do something about it. I just asked what we can do, maybe for the internal walls.

T: How often do you think buildings need to be transformed? Because we have been talking about constant change due to thermal performance, or because a new owner, so we are talking about service spans that are not the same as life spans. Why would you toss a facade after 9 years if the lifetime is much longer than that. In the case of residential buildings. How often do you think they need to be transformed? The exterior? Or elements inside that can affect the façade.

00:51

A: I will make a breakdown. This is the residential stock today. We have 7.5 million family houses. And there is 70% is multi family, mainly, built in the 60s, 70s. 30% is single family, low rise. If you look today how the new buildings, maybe it might sound a little bit strange to you

Martijn, but if you look at new residential, 70% is being built low-rise. 30% is multi family, so it is the other way around in this case. We will transform into a 50-50%. What you see now is that 70% of this stock is private owned. So, when you look at low-rise, private owned, you can imagine that you want to have the possibility to add new things on it. For example, today I am having a meeting with my architect to see how we can make my house bigger, because my children are getting bigger. And it is very frustrating. This is normal. But it is normal that for a period of 10 years is ok. However, if you see in this private owned part, there is the opportunity for flexibility. More or less, during their life-span, which is 100 years, at least 3 times (it's a guess), someone wants to change it. For example, a skylight (koukook).

00:54

But things like this you know, you want to have this, take it out, make it bigger, or maybe you still have to make an extension, so these are the things that will be added on during the span time of a building. And this is where it might be useful to have flexibility in the windows for example. So this is the window of the bedroom, and I would rather have it like this, so I can open both sides, and maybe a little bit smaller. Probably my contractor will say "well this has to be a new window", and I just said "well, why don't you just cut this, off, take this and that out, and make a new vent over here". But this is done in wood, which is more or less more flexible. But if you have high-rise residential there is hardly any need for changing the functionality or the aesthetics of the window itself. Now you see the influence of the thermal performance of the façade, and maybe they have to change the windows. But it is rarely about the aesthetics or the whole functionality. For example, back then we had sliders, they were very popular, and now everybody is trying to put tilt and turn windows instead, but it is more in a commercial way, or new insides being better with airtightness. It is not because you want to change the aesthetics of it. That is a big difference. If you have this low rise residential not private owned, which is the other 30%, hardly you need to change this. Aesthetically there is not really a demand, if there is a transformation it will be to update the facade to be according to regulations, I think.

T: In 100 years, just to have the figure clear, you would say that a façade will go on for three transfor-

mations (at least)?
A: Three times sounds even low. Maybe even five. Then automatically, the window would be taken out.
T: My thesis is focused on Remanufacturing. I remember both of you attended the workshop at the end of January. So, first, do you think that there is a market for remanufactured façades?
M: You mean at an element level or as needed spare parts of the façade? T: For example, a window

M: Remanufacturing of this element, after 15 years, we get this element back. Then we need to do something with it, definitely. It will have a new owner. But what? Maybe a new colour, or a different panel. Maybe they want also this in glass. Or maybe they want to add a different ventilation system. Yes. Refurbishment / Upgrading are necessary. I believe that on the CITG building, which is a clear example, because in 15 years it will have to find a new owner. They want to do something different. It will probably be remanufactured.
T: Why do you think we don't do it nowadays? Why do you think reusing and remanufacturing is not a thing in façades yet?
M: You mean why no? Why is not interesting?
T: Yes because I was looking in general, the amount of products that are remanufacturing is 1,2 % of the total market. In the US is a lot more in comparison, but it is only 2,9%. Which means that a lot of companies and even the customers think that a remanufactured product performs as well as a new one. So do you think that can change in the future? That people can accept a remanufactured façade? Or that an architect agrees on working with a remanufactured façade?
M: That is very difficult to say. It has to do a lot with the demand of the market.
T: Exactly. Because if there is no demand in the market to claim back the components, why would you invest on product development for it?
M: It is the same that I said with the windows, there is no market. No one has ever even asked if they can engineer a more sustainable façade. No. Noone asked for it. I was the first one who is asking: either we do it differently because in the future, it will become more and more expensive. And we are losing a lot of our materials.
A: I think that architects will try to push this, if it can be as flexible as possible. It is best to be the first one, upgraded, and be as new in the market, right? But I think that architects will see that as a limitation of their creativity. I think there will be, from an architectural point, a need to be flexible in that one. Then the question is: how flexible can you be? So you really have to break down this complete element and understand: what do I want to reuse, or what do I want to refurbish? Something like that. So I basically don't think they have problems using 'second-hand' elements if it fits their needs. I don't think they will like to compromise the design.
M: But then an important point is who is our potential hand for the second-use façade? Maybe it is not an architect, but it is a real-estate owner.
A: Fully agree. But then it is about what do you offer, and the type of solutions. If you say I have this one, I can have a complete business model on how I manufacture and take back the elements, I think it sounds better. It says that you can put more on it. In the other hand, the limitation will be that you have to take it as it is. But basically the investor will say "this is nice",

but then someone will pop up and say "I can do the same, but I am flexible". You don't have limitations in design then.
M: That is true, of course. I do not know about how this will develop. What I hear, together with New Horizons, we work together in this, is that the new façade, or the new real-estate owners, if they want to make a building, they have to make sustainable buildings. Otherwise they have problems getting the permits. So they say, 'we have this label' whatever, I want a sustainable building, BREAM, whatever, so if we come up with a façade that is 15 years old...What the façade building will say to the architect is 'just make something nice with it'. But then I already thought. If we finish the building in Delft, we go to some architecture studio that is famous, and I say, after 15 years, be creative and think about how we can reuse it. We do everything with BIM, so everything is digitally documented. They just have to

gather the data and do something out of it. What will it take?
W: Then it is important how flexible the system is. That maybe the transom could be made longer, or shorter. When you screw out everything. Also the corner angles, you screw them and unscrew them, and you might make them a little bit longer.
A: Sorry, but on the other hand you throw away money. If you do that, you throw away money. And this is also one of the principles of the circular economy: to keep the value as it is. So first, you want to keep the materials of course, but then someone from alkondor took effort in making that corner connection. And if you take the material to make a new one, then you throw away the effort put into creating this existing corner connection. So it is money that you throw away in the end. That is why it is really interesting that if you are able to use the first option of the complete window. That is the way we throw away the least.
W: But then it is still important that you can update the thermal value, the noise reduction. A: Exactly, but that is because you want to upgrade it. That is actually, remanufacturing
W: That you can still use this. For example, the RT-62. That you can upgrade it instead of a thermal value of 2,0 to 1,0. It will be a hard job, but.
M: Definitely, but this is a way of engineering.
A: It is interesting if you talk to architects because then you can create a market.
M: Oh no, it is definitely not coming from the architects, because they do not have a driver for giving up their creativity or their freedom of design.
W: So then it is important to be as flexible as possible, easy to upgrade the system, but also the value of this element. Everything is about the money. And when it is the price in this 15-30 years or 45 years, when the price is totally less than on the way as we work in this time, then it is

easier to sell it. Because the materials are not son expensive, but the working hours of the people, these are expensive.
M: That is the most important problem. Labour cost is the most expensive part in making products, making façades.
W: In the total 30 years, for example. Exploitation, for instance, is 5 times more than the cost of the building.
M: But also, if you look at the production, then the other products are something else. What do we pay? Per kilo?
A: I put 35% of your standard window, so 35% of the total cost is from our window. If you have to buy the glass...
M: So we get a product from you, the profile, and accessories. But that is not only the material, there is already engineering in it. Like you have a very nice building, and Wijnand and the other engineers that are very talented are also very expensive (laughs).
A: We have this cost breakdown. So 35% of the cost of the window is ours. Glass I do not know anymore to be honest. Then you have 8% of fixing materials, like screws and sealants, etc. And this is fabrication and we need to add the same amount for installation. And then after this you break down the material.
M: And then you understand the value of the glass, and the value of the materials, and you see that the labour cost is the highest. You see the chain in a circular economy, it means that you have to shorten the chain. To get more value in the products, and less waste in the process. Or the precise chain.
W: Then I am coming back to the role of an architect. What we see: we have suppliers, for example, for the hardware, etc. These are all technical driven companies. Kawneer, it tries to be innovative, but still a technical driven company. alkondor, tries to be innovative, still, technical driven company. Contractor, collects everything, but still technical driven. Then, you get the building owner, who is not merely a technical driven person. And then for this, the role of the architect is very important because when every company makes their own product on technical driven knowledge, they put it over the wall, and then the user has a product. But there is the choice, or the knowledge, like what it is done by Ikea. They can make it by themselves. And they can make the choice of this handle, or that handle, or

anything. They can make a choice of their own way. However, in this moment, to get a façade in this way, or whatever, like technical driven person. Maybe we have to change our minds. To look more to the user, and not only to the technical ideas. This and that could be possible if we look at it. Is it always the right way? That is a big question.

M: That was my question too when I started in this. If the main contractor, my client, belongs in this tail, and they just make this building, and they make money out of the cost of the façade and what you sell. This is their business model. So if I want to sell sustainable façades, it gets complicated. My sustainability solutions are there, but they said thank you, but my task is to make a cheap building, not an expensive building, because their scope is when the building is delivered, or finished. So the sale ends there. I think if you go more to integrated solutions where you say we have a facade builder, responsible for the airflow of the building. Installation, structure, and the infill of the building. These four you need, then you have the building. These are the main suppliers. In the car industry, you also have main suppliers: the dashboards, the interiors. The structure, the wheel,s these mains suppliers have a cooperation chain, they deliver parts. They have direct contracts. For instance, BMW is the main supplier/assembler of these aspects and they have made this chain very optimal and they have direct contracts with this suppliers. In the building industry, you can also see this same. I presented it to the main suppliers, and in the future, we will probably act like this. What is their role? To coordinate everything, not only for the building phase but also for the exploitation phase where you enlarge the scope and that fits very good with our scope which we are busy with. Together we can have a good model because the real estate owner wants one person who you call when something is wrong. Not 30 or 10, just 1. That one goes to the main supplier and goes deeper into the chain. That is a good model for the future, I think, where we can implement sustainable aspects. And then you are not only selling products but also a service where you take it back, and exchange it or whatever.
1:20
T: Do you think scheme works the better if it is always leased? OR do you think it can also work if it is not leased, like a product service?
M: It can work both ways. To do this you're just saying that you guarantee on the performance, whatever the life span is, 15 years. That is the part. PSS is not always owned by the producer. Because you only need an incentive to do it better. So we are now busy with the contractor for Delft, very expensive, Delft also said ok this is research, so we pay something more, and if I do smarter maintenance I make more money. That is a drive which comes from the performance indicator. If you are also the owner, and you are financing. Then the incentive is bigger because you also have a bigger incentive, you make your money with services, not with selling.
T: With that you keep the product longer in use, which is the first loop of the CE
I have one more question, which might seem a little bit too simple. In my literature study I found a gap, where I did not see a universal definition of a circular façade. I understand this might be because it is a very new concept, and it is not understood as exactly the same. I am trying to construct a definition on this with people involved in it, and based on literature. So I want to ask you. What is a circular façade?

M: I will try to translate it. A circular façade is a service which is delivered as a sub-solution of building as a service, in which it is more about the function and the performance of it, than the product itself. A circular façade is delivered to the large cycle of the building, or the function of the building, and it follows a series of loops in a chain where it always comes back, not as waste, but as raw material. It is a very long definition, maybe you can shorten it.
T: This is quite complete. This includes more scenarios than recycling. This is one of the first times I hear about upgrading or reman.
M: Do you have a definition already, for a circular façade from Kawneer?
A: A dutch façade, basically has all the ingredients of the Calvinistic thought. It is designed carefully, along with the building products in it. It should be cheap, conscientiously used, constantly maintained, and not damaged; so it can live for as long as possible. If the façade is no longer in use, it should be

given to a new user. It should be reused for as long as possible. That is also the success of this CE in the Netherlands. If it is also a service, then it should be very important to understand it completely.
M: The service that you say it is very important, there is a lot of responsibility. Because we always make products, make products, and we don't feel connected to them after we sell them. If the product fails, usually, the guarantee is out of it, or it might not cover it. The building owner has actually no guarantees at the end. He takes full responsibility. If we swtich to a service, then we have to do something different, thinking before but mostly afterwards. That is only if we deliver a service, if we have a life cycle of products. The possibility to get resources back, keeping ownership, or performance based, etc. Pay per use, pay per service, pay for comfort, pay for mobility.
W: Do we need a bank? M: You are the bank !
W: (laughs) But the project from Delft, you use a bank for the money. Once you got all your responsibility, all your service by your own. You say, customer, lend it, you pay every month, every year. You give me money. I take care that everything is working ok. Where there isn't possibility for an update, you can make a choice to pay a little bit more, or you stay at this time. Then the product will be, in this 30 years, cheaper. Everything working ok. Everything after 30 years I will take back, and you pay only every month to give me money. The risk is when you lease it, or when you lend it. Because it's similar to leasing a car, because the owner of the car will be the bank. Everybody wants to make out of it, but when you say 'ok, I don't want to use the contractor, or I do not want to use the bank, you still have the responsibility to take care that everything is ok. You are directly getting money from your customer. You have to take care that everything is ok.

A: Yes, I think you are right, I think at some point you can do it without a bank. But today you need the money to pay your employees. You need a bank for the solvability.
M: But who is paying the labour costs?
W: And the first project! The very first project, not a big project, but a small project, then next year you start with 2 or 3 projects, and the year after 6 projects, etc, etc. That will be giving you much more customers.
A: But to pay the bills today, you have to get some money. You need a certain stock of rented façades before you get some income out of it to cover your cost. If you calculate it now, you would lose money. For example, if you count our stock, we always count how many days it has been there in relation to how much we sell a year, and everyone wants to keep their stock as short as possible, because stock is money. That is, actually, what you are doing with this façade is stock, a continuous stock.
M: What I think talking about this, the same model Andre designed, we have 50% materials, and the rest is labour cost. 30% for instance is aluminium, then we have 50% glass, and 5% others. The rest is engineering, production, etc. The business model, what I am thinking about, what if we, the price, is 30%. So you are not sending you an invoice. Then I pay 30 eur per m2, because this one has to be paid by the building owner. You, from Kawneer, gets paid monthly. Then this is hybrid model, very interesting. The monthly costs continue. That is a new kind of business model with a lot of flexibility on it. We also want to do a foundation where we look for investors that want to invest in façade projects. How big the company is with all the projects that are in, then the lower the risk, that is how they do it in the real estate. This is also a possibility, you are not sending us an invoice, but we connect you directly to the façade building owner, they pay for the materials monthly fees. That is also possible
W: Then you create a kind of consortium.
M: We do the maintenance, you do the intellectual-engineering changes in the system if the façade after 15 years needs to be replaced. The labouring, delivering, etc. After 50 years maybe it is recycled in the project. Then we have a big scale, something like that.
W: But also the parts we have to renew or whatever, what we talked about, the hardware, when we have a corner of a corner drive. Then normally, the corner drive will be broken in 15,000 times. You have a sensor of it. We measure it. It will get heavier to open it. In its own way of using. There is something wrong, we know we have to replace the corner drive, or you wait up to to 15 thousand times, or refurbish the corner drive. This part is delivered by kawneer.

M: You deliver the part. We have to install it. Because now our business model, the value in the chain we deliver is engineering, production, installation, maintenance. These four components. It is mostly a labour cost. The machinery for example, is part of it. We can also think about the

machines that are leased, it is possible. That is the next step. We make sure everything is in place, it will be maintained, monitored, and the system supplier will deliver the parts, repair, remanufacture, which is also part of the business. The automatic engine will come back to the place and we will re-manufacture it, and use it as a spare part for the façade. That will be the new loop between us and the life cycle. You play a role as a product supplier, since the beginning. There are smarter solutions.
W: Not only installing and another company doing the services, because then the risk is that you make good, but then the company has problems with the service.
M: We have the engineering. We produced it ourselves. We have it in the stock. We know everything about the façade. Every corner, every screw everything.
T: And in a way it is also feedback for the company because you know if something breaks, you know where it went wrong, and every project learns from each other, so you can apply that knowledge.
W: And because you are several times a year coming to the building site, and your customers say “Ah, I want to have a skylight!”. Then you are already with your user, and he says, well I will ask Alkondor, because they already know everything to make this.
M: It is true. This things have a real expectation of the company.
W: But then it’s really important that you are also taking the services.
M: We do the services on the process, the monitoring, the feedback loops, but we deliver the elements, components, which we have to replace, and repair, and if the one that is coming out, then we send it to you back for reman. And we get it back and use it as spare parts, and together we find a 15 years life or more in the future. Every changes in that level can be calculating. So then it is something like that. There is a hybrid model. If you do 40% of the total amount of a façade, then the back is doing the rest. What do we decide from now? Are you taking notes?
T: Yes! I am doing a transcript.
A: Then it is good that we keep a track of what Tania is doing with her project and have information on how this is used.
T: I will let you know because I have to deliver a scientific paper on the 29th of March and I am building a scientific framework where the circular façade definition will come. I will send it to you before submitting it so you can agree on what is being written there.
A: Thanks a lot !

C) Disassembly of the RT 72 Prototype

This was carried into two different videos.

Present: Marcel Bilow, Tania Cecilia Cortés Vargas.

First part of disassembling the RT 72 prototype

00:00:00

Marcel: Push the button and here we go, so you can see everything is sharp. Okay great. So how do we start. In principle we have to start taking apart. That would be the first thing. Do you want to do it by yourself or just we do it together? Yeah you can just pull it off it's fine. So, this would be actually the first you do. Yeah, I think so I'm taking the gaskets out.

00:00:31

Tany: Yeah and there is another one.

00:00:37

Marcel: Now we just leave it like that because it is only it's only done from one side to the other. So, and then you have to take the corner clips. Which should. How are they attached with pressure? Normally you just put it back like that. OK. This is in the club. OK. Here. Now this is actually how they go in like, here and you're it's like a snap, you can see it here. OK. Have a look. Does this lead the little tiny edge and then it's done? And then it's done OK. And then you take this is in principle the entire frame and then you take the glass with a suction cup out in this direction and take it apart. OK. Here you can see this is actually a strip that runs all the way around to fill the gap. That's for installation in order to insulate the cavity a little bit more. And these are the glass holding brackets. You have this element which should come in this is real. This is real. You normally should take this. Oh, they've put it together with a double piece of tape which is usually not done it's loosely on there. OK. So, you actually have this element which is now look put together with some tape that is not done usually. OK. I think that's just for the purpose of this prototype. And then you can take this thing out. And this is a glass supporting block. This is in principle the pieces where the glass is inserting glass in and you're standing on top. You're not able to rest it on the plastic or on the metal. Otherwise it would crack. And in this case, there are normally two of them at the edges, kind of like third into or something like that where it is supposed to stand. So that's the support structure and this will actually hold all the forces on the glass. If you have a 500 kilogram insert the glass unit it would be supporting on two of these and its plastic. We have the same here...

00:02:55

Tany: And, Marcel, this sits on top of this right because this runs across?

00:03:01

Marcel: Yeah. No, this is actually this only comes in between. They will just fill the gaps with that. This can't be insulated, so this is snapped in here.

00:03:20

Marcel: This is a snap here, this little spring. And this comes this usually is endless from a roll. And it fits in between here so in principle they just made a little that look inside that it looks fully filled to save material for the mockup here. Usually it runs through here and then again. And so that said here we do the same here. And these little glass, little plastic sheets they are prints principle the spaces I can show you another one. Between the glasses. Precisely. This in principle the spacers. This is blue. This has two millimeters also. This is also blue. It's color. They have a color code. And weirdly enough all these three colors say blue which is some sort of two millimeters. The red ones are three, the yellow ones are four millimeters. And you have to stack a couple of these elements in order to close the gap that you always have the right spacing. That' because the tolerances of the frame are differently than the tolerance to the glass. The glass has sometimes plus minus one or two millimeters depending on the size. So, they always have enough space. So, in principle if you have it in here you have to fill up the gap as much as possible. That's the contact area to the glass and then they also have a wooden wedge in which they squeeze this a little bit. OK you have to make sure because the glass is so stiff that you will not be able to. move that you can't squeeze the glass before you would move the frame so therefore you have to make sure that the windows still work perfectly. And that's why you have to

adjust this because you squeeze it against it. So, we take this out also.
00:05:18
Tany: So, this is what I took. Sorry.
00:05:22
Marcel: You can also take this approach and you can already see screws.
00:05:31
Marcel: So that is in principle here. The principle is the same order no business in here. You take this out.
00:05:41
Tany: How do you take it out so easily, where do you squeeze it?
00:05:44
Marcel: Give it a try. Just squeeze it at the very bottom. But let's just make sure you don't go into because then it will hurt you.
00:05:58
Tany: It need to go up that way. Oh great.
00:06:00
Marcel: So, in that it's the same here. You leave this out of the window section. Precisely. It's the same here. Yeah, they have a yellow one. You see that's a little bit thicker.
00:06:13
Tany: Yeah. Also, this.
00:06:19
Marcel: So, and then we can see here we have this one, its screwed. This is good. And I think this is a T somewhat, 25.
00:06:44
Marcel: Yeah.
00:06:46
Marcel: It's a Torch 25 but this will not be a standard screw. This is just for the mockup. This is not part of the facade. This is, well they just screw together the window frames, the moving parts, and the frame itself.
00:07:18
Tany: Yeah because otherwise you wouldn't be... you would be able to open it right.
00:07:22
Marcel: That's the lesson there. Precisely. Usually that's the opening frame. Into the base frame but they screwed the wing into the moving parts. So, this has to be a little bit let's say taking into consideration these elements are not standard. Here's the other one. So, this part. And then we should be able to take this like the other one. Here we go. So, this is in principle the window itself. That's the moving part of the window. Yeah. And here you can see that this would usually rotate out of that and they place this aluminum blocks in here just to show just to show... it just to position it in here. OK. We can take this first.
00:08:38
Tany: So, this one it has a little bracket, it's glued.
00:08:45
Marcel: Now we have to take a hammer in this case
00:08:54
Marcel: But it has a bracket right. I don't know. Is that a bracket?
00:08:58
Marcel: Yeah. But this is the bracket from this corner connection. OK. I would actually think that this is. This was just jammed in.
00:09:12
Tany: With the purpose of holding the window still?
00:09:14

Marcel: Precisely. And here's a little dab of glue. So, I think you can also easily... here. It was a little bit of glue. But this is just this to build this prototype. Yeah. So, I would say right and back here we are back in modern business for a façade. So, we have. The ceiling here. Yes. And as you can see this is double piece of tape, which for a circular approach that would be difficult because you have to have some sort of you would not be able to take this entirely off. No residues, no one here. So, we have to take would be actually running all alongside. This is in order to create a higher insulation value. You would see in the simpler and the less performing windows there won't be anything. And these elements are just placed in order to fill the gaps and increase the insulation value of the frame. So, they have the same here. This is in principle the same insulation, it's a little bit like a tube. It's the same problem. It's a tube. Some sort of shrink, which also comes in a long road and it's filled with a high-density foam. And this stuff is nasty.
00:10:44
Tany: Yes. This one is terrible. It's a little bit a little a little bit actually is I think it doesn't think that has to be any. This is not the real one. The real one is not like foam.
00:10:53
Marcel: Okay. But I think this is the real one.
00:10:57
Tany: Maybe not any one will actually build something like that. Yeah maybe that's because of that. I think that's the real one. But it's very in very bad conditions.
00:11:08
Marcel: I don't know. Does it also dehumidifier or is it just to insulate?
00:11:11
Tany: No, it's just to insulate
00:11:13
Marcel: OK. As far as I'm concerned this is also as you can see deep down was double piece of tape. So therefore, that might also be a problem out. If you take it out because here, they actually here they fill the gaps and they also have one in here. Yeah, I think that's the real deal.
00:11:35
Tany: You see it has three.
00:11:37
Marcel: Yeah. Yeah precisely. And that is there the rubber foam. Is this the glass brick. The glass block I would say the resting point was that the fault yeah, the glass supports this is a foam.
00:11:49
Marcel: So, this is this guy?
00:11:51
Marcel: Precisely. No this is the No. This is it looks like that, but this is actually this guy, it looks like that, but this should be actually the glass supporters. That's the glass support. And that's just a few. This is it's weird because it looks like it actually is like that but this block as they mentioned is the glass support but according where you cut you either see that or it is one.
00:12:16
Marcel: So therefore, I think they made maybe a little booboo. Yeah. So, in here also we have to take this apart. This is very brittle.
00:12:24
Tany: Yeah. I don't think you can I talk to the company that makes this insulation. They don't really think that there's is going to be able to become circular.
00:12:36
Tany: Yeah. This is really it's really messy.
00:12:39
Marcel: The foam reminds me of the foam that you usually don't take it here because you get the picture. So, picture lines. I mean. Is this also there. Yeah see you know. So, in principle this stuff is the pottery or the botanist who also have this form to put flowers in to make a nice book. So nasty stuff.

And then we have another sealing named. Here's a gasket. There should be this other gasket that are actually for the outer gasket. And in this case, you know you are lucky because they didn't glue this together here.
00:13:28
Tany: In practice, they are glued?
00:13:30
Marcel: In practice they are often glued. So, we take this out here. In practice I used to do that. They cut them with a scissor to the meter and then they put this together with super glue. And usually they are glued together not always.
00:13:55
Marcel: But we did always because then you make sure that these loose edges would never come loose. And you also have to push them in, so in principle if you have to have a meter you cut the length of a meter and one centimeter more to compress it, so you squeeze it in.
00:14:12
Tany: And these ones with time they shrink right.
00:14:14
Marcel: They shrink a little bit therefore you always make them a little bit longer a percent or two. And they put them here. Hear for instance you can also see. These are the ones on the marker for the outer layer. And these are in here the heaven corner cleat. So, they have this element just straight cut. And here's an overlap. And this would be also normally glued. So, you have to put a dab of superglue in here and then squeeze them tight in place here. And that would be actually not coming apart that easily.
00:14:50
Tany: But then if you want to make it more circular what do you do if you have to glue them?
00:14:56
Marcel: In principle you have to you can also I've seen lots companies who vulcanize them so that glue this together with some sort of rubber glue, this is EPDM. Yes, they do this together like the tire. Yeah. If you have a puncture tire and then there are vulcanize that sort of glue. I do not think that is so harmful. It's more like material to material. It's all the same material. Yes. I'd say the super glue is a different one, but I do not think that this is really a problem because in like percentage of the entire rubber the glue is so less. I think they may be able to filter it out or I don't know.
00:15:33
Marcel: But usually they are glued with a different kind of glue, But I've just seen them vulcanized
00:15:39
Marcel: And when we had in the company, I worked a hundred fifty thousand of the same windows, if the made a residential apartment with many, many, many, many of the same windows. Then we asked them to get them regularized so you actually got square frames, we put in it. It's time efficient thing. So, it's easier to install because you don't have to cut them anymore because they're all the same. But then you have to they let it go somewhere else. So, you have to preorder them, and you do not order preorder five of them.
00:16:13
Tany: Yeah you need a large batch.
00:16:13
Marcel: Precisely. And then you see this edge should be also just squeezed in. OK. That's the same that connects this to this element. Yeah. And this is the one. This is the element that goes into the win. These are longer ones that are very floppy is very soft. Because the window will actually fall into that and this edge here that will fall against that element.
00:16:49
Marcel: So that's it. And that's it right now. Here. This one over there. Take him out. This is the fixed element, and this was on a miter due to the fact that they had this here. So, and then. They usually have. Here you can see the rivets they put into this connector here and there's a connector here. And

you can't see anything from here, but I know from practice that they have riveted this. But you do not see any connection, so they put the connector in here first and then this on top. So, we have to drill this open.
00:17:37
Tany: This is not the best right. So, it should be bolted.
00:17:42
Marcel: Am... you can do whatever you like. This is a principle rivetted. Yes, for the sake of this. If you do this like but that's how you make these elements. There are also options where you can where you can actually where you can. Move a little bit of. They are screwed together or bolted. Makes it easier to get parts through this to disassemble. This is riveted, with some sort of smothering nail gun. Let's see if I could do it, these are usually out of aluminum so easier to take out some.
00:18:45
Marcel: They were just taken off the shims. These are aluminum they're not that sturdy let's say. But powerful enough to hold everything.
00:19:01
Marcel: One, two...Well so then you should be able to take this apart.
00:19:39
Marcel: You're lucky because they're not glued. Just pull this. Now pull it on both sides so, so you can see they didn't have applied any glue. Which could be done some sometimes. OK. So therefore, we can also see them the corner later. What happened there. But here this element is then fixed. So, if you have to open that hole three or four
00:20:15
Tany: This is the one that you just took out right, Marcel?
00:20:17
Marcel: This is the one I just took out from this direction. But now there's a little bit of aluminum in here. Well this is still the rivet. And so, the rivet that is in here so therefore we have to take it out here. That's the remaining part of the rivet.
00:20:37
Tany: It's destroyed.
00:20:38
Marcel: Of course, I drifted out. Yeah. So, this is the remaining part of the rivet.
00:20:42
Marcel: So, he can see that this is where they forced the rivet in. And what we're building that. They know exactly that the distance of that. So, this is actually put in the machine that.... Makes process so stamps the hole out there will not even be drilled. Most likely this machine that just, to the edge that which then made that in order to make this pulling a little bit. So, this is a little bit if you if you put him into it you would see that the holes don't align perfectly. Yeah, the little bit short. And then if you inject the rivet you would see that the element is squeezing the parts together to have a perfect closed fit. Yeah. That's why I would say every now and then put glue in it to make the gap disappear a little bit even more. In this case you would use black glue. And then you don't see it anymore. So, in here we have taken the rivets out and then this is a screw. And then this can be either removed entirely to the way that they go.
00:21:52
Marcel: Here.
00:21:55
Marcel: This has to be taken that should be allowed to take in an old way. Yes. So, in this case the have that slide from the sides would have to make sure that you put them in before you do the corner. So, they're taking. And this are actually screwed in with the powerful tools. Because this would puncture into the aluminum.
00:22:18
Tany: So, this hole is not there until you put the bracket.

00:22:21
Tany: Most likely. This is one. This is a system I don't know because it's not from Shueco. I used to build for Shueco, and they had a different system. I think that would not be produced but they're just punched into it. So, but this is actually kind of like taking apart. And now you are back to the outer to the frame itself. These are rolled into and this element here in principle is attached to one of the sites. Have you seen how they made them?
00:23:00
Tany: Yeah. They are like they have this machine and then they put the profiles, and they are rolled in.
00:23:04
Marcel: Precisely, they stack them on top of each other and then you have the two insulating sticks in there and then a little feeder fits them in. And then they take the entire package and rolling through a big set of roots. And this element is already attached to one of them. This one, the insulation. That already come pre insulated on that thing. So, you have two of the loose strips. One has already this and then you don't apply this. This already comes to the factory pre-assembled. So that is to this part. You can take it apart right now. There would be corners which would be most likely glued riveted or suppressed into each other. We would see how they did it over here. OK. This is how far it can go without cutting or destroying anything. Here we have the same. It's the same elements. Then it's also the same but in principle is that it is the same system but just with a symmetrical while this is all symmetrical for the other Yeah.
00:24:14
Marcel: It's at the bottom part
00:24:17
Marcel: Precisely the bottom part. And then we can continue to look at the other side. Three more minutes to go. So, this would be then the window frame itself. That. Would be. Just take the middle of a rebate. If you don't scratch anything. So, he has the same a little bit of the of the gaskets here that cut to a motor and also in this case they didn't glued together
00:25:07
Tany: But in principle they would?
00:25:09
Marcel: Yeah in principle they would. It's a little bit up to the standards that say I think as far as I know due to the ease all of our rules have to be glued. But I think only to each other and not to the frame. So that they can still move it doesn't come loose when they're on the tension. I do not know exactly. I noticed that we changed over the years because of the company's doesn't do it. I actually can't tell you if we always did the right thing. It's also a habit. So, gaskets are out here so last gaskets inside. And then we have the element of the handle itself the hardware. That's I would just stop it here.

Second part of disassembling the RT 72 prototype
00:00:01
Marcel: Here we go. So, in here we have the handle itself which is incomplete. Usually this strip I will show you later will run the entire length of the frame. That is what does the around the corner mechanism for locking here and there but it runs all out of here.
00:00:23
Tany: Yeah it goes 90 degrees precisely.
00:00:25
Marcel: There is a special element in here that has a very thin measuring tape like structure I can show you on the measuring tape. It looks the principle the same without the yellow numbers. So, it's the same principle here that we run across here. It's the same principle. But in silver and not in yellow. But it's a bit of a strip and this is a core element that we place in here. It's fixed element that has internally this thing that makes the direction around the corner.
00:00:57
Marcel: So, in this push rods they will have a whole puncture that will engage here. And then it moves

around the corner and then the profile starts again. That's the reason why this is square.
00:01:12
Tany: This is where the motion of colliding it sliding in here. Yeah. There. Yeah exactly.
00:01:17
Marcel: So that is actually the push rods are coming in lengths of six meters and you have to cut them according to size. We will now take this apart. This is the big screwdriver Phillips three. You can already see. This... This should yours. You can only take it out. So, this is what you. This is what I want. And this cannot be already taken out here. And you see I can't take this out because it's around the corner, but you see this is a thread. And this is a hole but there's a little pin on this. We can see... I'm wondering how this works because it has to be attached from the outside. That's usually there is. I haven't seen that. Most likely to have a little screw somewhere here. Yeah. And you had you untied the little said screw. Can be that this is just pushed on. OK.
00:02:45
Tany: So, with a little force we can take it out. But we have to take it out you stress. That somehow. Maybe you take out this part.
00:03:09
Marcel: No because it's attached. So that's what I'm wondering. I do not know this system. But any information about how this was done?
00:03:24
Tany: No, not about the hardware. I think we can leave it Marcel...
00:03:36
Marcel: The question is. That would be more parts to taken apart. Yeah. Because there's also the this is the entire system here.
00:03:42
Tany: But it's coming out. It's becoming loose.
00:03:45
Marcel: Yeah. But we can't take it. You can't get it out now. So, there should be somehow maybe it's a snap mechanism, but you have to just pull hard. Yeah. Could also be that it only puts this direction or in this direction. Yeah most likely back then. But I used to work on that. There is a screw in here you can loosen and then and then continue. It's like a door. Yeah. I could call a friend of mine who knows exactly how it is. You leave it like that but here I'd like to take this apart if you like or, leave it like that because this is where the part is not circular anymore.
00:04:22
Tany: That's the corner
00:04:23
Marcel: Yes, the corner because you can see these are pressed into. So, there's a corner key element in here. Most likely with glue. I don't see any glue here. But you usually squeeze out after you puncture that. But I think there's no glue in here. But they have a very good corner here. So therefore, very nice press. So, in principle you have two elements one in here, one in here that fills these and these chambers. This is an aluminum cut one and this is a forged or casted aluminum part. And then they squeeze it into a press which hold from here.
00:05:05
Marcel: Against here and then they squeeze with two sharp edges in here and they hit a little dent in the elements. I can take apart. We have to drill this open yeah. To remove the material then we can take it apart. I think. This is what you would see that this would be which is destroy the aluminum.
00:06:11
Marcel: This is the messy part. You can also see that it's not really easy to take apart. It's not meant to be taken apart. That might be it. So, let's see. There's still a burr in there so the material is a little bit bent over. But then we have to use brute force and hoping they didn't glue it. But here you can see it's already loose. So, there was still a little gasket here.
00:07:20

Tany: So now we should be able to take this. It's destroyed, you had to destroy the connection?
00:07:50
Marcel: Precisely. This is dented into.
00:07:52
Tany: I can see the little hook that objection and you're very lucky because it's not glued. Otherwise we had to heat up the entire system and then. So, you can only see we'll pass to the limit. But it's still a little bit.
00:08:23
Tany: There is no way to cut lose.
00:08:33
Marcel: So that's what you can see here. This little piece of plastic, I think is also EPDM. Precisely. This is in here to cover any leakages from behind these elements in here. Maybe you need to give us a little bit so you can see here. That came in. You know that this little edge here you can see that edge. This is the chamber where the aluminum profile was bent into. So, they squeeze it in here. So, this is actually the official corner of the edge of the profile. And then they squeeze the material in here. And you took the angle it pushes them together. And then we should be able to also take this apart here.
00:09:47
Tany: This is when this is not circular because you can only put it in. You cannot take it out.
00:09:53
Marcel: Exactly. There are other techniques which also uses rivets, that is very important.
00:10:00
Tany: But isn't it better to bolt it?
00:10:00
Tany: No, you cannot bolt it. You're not allowed to have the little piece poking out. Most likely entirely is hidden.
00:10:11
Tany: But the rivets. You can easily take them out. Like you did here?
00:10:16
Marcel: Yeah, I know for instance this standard window frames which would be something like two by two meter maximum. So, a person is still able to hold it. He stands in the frame runs to this machine and presses the cap there the motors of the edges into like they did here at a certain point for instance with this element they might be sometimes three, four, five meters white. Where they have six window frames in it. And you won't be able to handle this anymore on the work floor. So, they also put the same rivets there put it in here for the T junction or at the edges. OK. And then you can easily like that drill it out. Yes. I used a drill as big as the rivet. You can also use a drill bit that's a little bit smaller than the rivet itself that you do not harm or damage the product itself. Yeah. And then you could insert another rivet and disassemble and assemble it again.
00:11:14
Tany: You can use the same hole, right?
00:11:16
Marcel: Precisely right side precisely. I made it a little bit quicker. Not for sure. Yeah. But you can actually do this in order to take it really apart. OK. I would try to remove it off the table here. I would try to force it out. Yeah. Here we go. That's too thick. Does that fit in? Yes. And it's something that fits in here is one of two. Has to be somehow maybe a screwdriver. It's very small for that long and there's other too small or too short. Let me see if I can find a piece. Let's see if it works. It's things you should be. Should be fine.
00:13:14
Tany: It's quite strong. Yeah. Because it's squeezed in here?
00:13:18
Marcel: Well that's weird. It's fitting this part. OK. Now this is also bent. Weird. It's very hard. To try to do a little bit more here. Seems to be very, very tight. But you can see how difficult it is to take it out.

We can actually cut open more even here have a blade of the medium in the table so we can cut the entire group out here. If you would you need to take it out now.
00:15:04
Tany: No, it's fine because it's going to be smaller than this one.
00:15:10
Marcel: Precisely. And this is why this is also a casted element. No, it's extruded they it out in here. There's this also this is in principle the elements. Yeah. No, it's not the same. It's a smaller one. You can see this is a bigger. And this is a smaller. Sorry. Yeah. So, it's but it's the same principle. But they come as extrusion profiles in lengths of six meter and you cut them to sizes as they do this. And I know some corner clips are also casted from aluminum. OK. That they're actually. Really kind of like a casted. This is just a long profile Al profile. They cut to size.
00:15:47
Tany: Why did do you need these little strips there. Because of the friction?
00:15:51
Marcel: The strips here they are not actually needed. It's part of this. This here is in here. That is for gripping to the glue. So, in principle you put this into a neat little file. This is just the burst we made by drilling usually there's no holding down no. Yes. So, in this case it should be, and this is also very rough. Because we drilled.
00:16:47
Marcel: It because it is more so this fits in perfectly. So therefore, you see that these elements in here they will actually provide a little rough surface for the glue to be add to them. Yeah. That could also be that if they squeezed together that they have a little bit grip once against the aluminum but usually it's for glue. It's practically a possibility here. Luckily, it's not glued. Otherwise it is a two-component glue. So, it's a mess, which sets up after half an hour and then you have to heat treat the type thing with the hot air gun and then submission more of each other.
00:17:23
Tany: So, if you would like to make it circular you can use the same elements but by riveting.
00:17:29
Marcel: Yeah. This element will look different. It's not that element. I can maybe show it on the Shueco catalogue how they look like because it is then a cast element of aluminum with holes in it already for the rivets, with the right hand side that it's in principle what they do is they have two parts, left and right side with a little plastic inside most likely or just metal on metal pieces and they...they attach it here. And then they're riveted from here. But then you add the seal of machinery or in this case. Sorry my fault they're really good because they have the two parts together with the hole that shared both of the elements put in here rivets here and then you first with the rivet the elements out of each other and squeeze it against the channel. Yeah. And then you can take it apart you can also do this with the you can also do this with a set screw like they do in here. A little scoop. Craftsman possible because then you can easily take it out of each other. But the question is in my case will you be able to make the corners that's that tight?
00:18:45
Marcel: And my experience is that all I know from experience that the quality of a window frame is determined by the closeness of the gaps. This is where you start first looking. And within these elements you not only have the problem of where to begin. Yeah. Like this very difficult surface in principle that is the biggest challenge that is even with the system we have now under development for the last 25 years. I used to build windows like that for four decades with my friend, & that the flatness of the gap, the angle position, and the rotation is very critical because that is also influenced by if you press these elements together, you can see they vary in thickness. So therefore, you have to make sure that they are very precisely roads to the exact thickness. Otherwise if this comes from a batch from about an hour ago or two days ago it might not be as perfect as this might be when you actually try, with a hammer to smash down this edge and on the other side that's hanging over your head to put it again and then you figure out what never works because this is eighty point two millimeters and this is seventy

nine point nine millimeters. So therefore, and then, because of these huge presses, I think they have a couple of tongs pressing power to squeeze this in. They're able to maintain this very nicely. Yeah. You have to do it by hand and then squeeze them screw them down. That is really difficult to achieve a high performing position and then the quality edge.
00:20:32
Tany: And then the uniformity of your sample is different.
00:20:34
Marcel: Precisely, so therefore I think within circularity, that part, the corner brackets and how to assemble them is the most difficult part because these elements would never be as perfect as this. So that's a little bit tricky, I think. But I think we are at the end of taking everything apart. Yeah.
00:20:55
Tany: Exactly. Should I stop the video here.

2nd of July, 2019

Delft, The Netherlands