Design for Disassembly Guideline

Melissa Campos Soto
Msc Architecture, Urbanism and Building Sciences
Track Building Technology
Delft University of Technology
in cooperation with Aldowa

Colophon
Msc Graduation Thesis Report
Final Report - October 31, 2023 3:46 PM

Name: Melissa Campos Soto
Student number: 4532686

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: Marcel Bilow	Building Product Innovation, Façade Design
Second Mentor: Rebecca Hartwell	Structural Design & Mechanics
Company Supervisor: Rick van Horssen	Aldowa
Company Supervisor: Nondas Ntailianas	Aldowa

Acknowledgments

Collaborating with Aldowa on this thesis has been a very educational and professional experience. I am grateful for the inspiring and knowledgeable people I have met who helped me in this project.

I would like to thank first my TUDelft mentors Marcel and Rebecca for guiding me through the process and for their prompt responses to my inquiries. Since embarking on the Master's program in the Bucky lab course, Marcel has imparted to me the significance of iterative refinement through models and prototypes. This taught me to provide as many alternative as well as practical solutions as possible to make a more informed decision. I am also very grateful to Rebecca for providing feedback on my report to help me structure my research and make it clear for the reader.

A sincere thank you to my company supervisors Rick and Nondas who helped me throughout this whole process. Rick, in particular, taught me about the importance of a well thought research process to lead to clear solutions, while Nondas's critical insights have been essential in maintaining the course of my research and producing prototypes.

My appreciation extends to the entire team, always open and willing to address questions and offer valuable input to enhance the quality of my thesis. I want to express also my gratitude to the production team for their time and effort in the manufacturing of the prototypes.

I am happy to have shared this journey with my fellow students, particularly Juan, whose presence has not only added an element of fun but has also been open to help me throughout. Finally, I would like express my heartfelt gratitude to my family and Stef for their love and support during the entire Master.

Thank you all,

Melissa Campos Soto

Summary

Aldowa, a facade manufacturing company, aims to transition from a single-use aluminum product to a circular, Cradle to Cradle (C2C) certified, product. This certification comprises multiple levels, starting with Bronze and finishing with Platinum. Achieving the Platinum level signifies that the product is entirely circular, made of materials that can be continuously re-purposed or recycled without generating waste or harming the environment. Aluminium can be continuously recycled into new aluminium ingots without loss in quality. Furthermore, aluminium recycling uses only 5% of the energy used in the primary production. Nevertheless, reuse of aluminium components can provide higher environmental benefits therefore the consideration and practical realization of efficient disassembly methods is vital.

Aldowa's products need to fulfill Design for Disassembly (DfD) requirements to be eligible for a Cradle-to-Cradle (C2C) certification. Therefore, this master's thesis develops a DfD guideline to aid Aldowa in designing fully demountable products that also meet the certification requirements. The research comprises two main parts: literature review and practical investigation.

In the first part the concept of Cradle to Cradle is compared to other circular system theories. While it establishes a framework for evaluating product circularity, it is essential to clarify that the certification's focus does not quantify specific environmental impacts or measures disassembly.

Other existing environmental assessments are compared but they seem to not take into consideration the influence of design decisions on end-of-life scenarios. The Building Circularity Index (BCI) is adopted as a useful rating system to assess detachability. Aspects of other models such as the PAC Model and the Disassembly map are also incorporated in the DfD Guideline.

After selecting the criteria and methods to assess the disassembly potential a practical investigation at the company Aldowa was carried out. The user research, focused on identifying the primary stakeholders with significant influence in the design for disassembly process and find how and when the guideline can help them. The findings from this informed the development of a list of requirements that delineate the necessary content for the guideline and the key moments of its possible application.

Finally the guideline is validated with user testing and applied to design alternatives for the Cradle-to-Cradle case study. The practical application of the guideline for the case study provided a functional insight on how Aldowa can use this guideline to design fully demountable products.

In conclusion, criteria derived from existing disassembly models has been incorporated into Aldowa's DfD Guideline for evaluating the disassembly potential. The guideline has been tailor-made to integrate with Aldowa's project workflow, primarily benefiting the sales and engineering departments. The primary purpose of the newly developed guideline is to assist Aldowa in prolonging product life cycles through design-for-disassembly strategies and aligning with the Cradle-to-Cradle certification standards. It can be used before a project starts, during a budget agreement with clients, at the early engineering design stage and when re-designing a new connection for disassembly.

Table of Contents

Research Framework 8
1.1 Background 9
1.2 Problem statement 9
1.3 Objective 9
1.4 Focus and limitations 9
1.5 Research questions 10
1.6 Approach and methodology 10
1.7 Reading guide 11

Cradle to Cradle 12
2.1 Introduction of Cradle to Cradle 13
2.2 The Principles of Cradle to Cradle 13
2.3 Related System Theories 14
2.4 Cradle to Cradle in the Built Environemnt 16
2.5 Cradle to Cradle Certification 17
2.6 Limitations of the Cradle to Cradle Certification 21
2.7 Conclusions 21

Environmental Assessments 22
3.1 Positioning Cradle to Cradle Certification 23
3.2 Existing environmental assessments analysis 23
3.3 Dfd criteria in environmental assessments 25
3.4 Conclusions 29

Design for Disassembly 30
4.1 Background theory 31
4.2 Impact in the Built Environment 32
4.3 Barriers 35
4.4 Existing DfD frameworks 35
4.4.1 The Disassembly Map 36
4.4.2 The PAC Model 39
4.5 Robustness criteria 43
4.6 Criteria to assess Design for Disassembly 44
4.7 Conclusions 45

Cycling Pathways 46

5.1 Background Information 47
5.2 End-of-life 50
5.3 Re-use 51
5.4 Re-furbishment 51
5.5 Re-manufacturing 53
5.6 Recycle 55
5.7 Post-disassembly scenario 57
5.8 Conclusions 58

Company Analysis 59

6.1 Product and system breakdown 60
6.2 Life cycle of products 62
6.3 User research 66
6.4 User research results 67
6.5 Guideline requirements 68
6.6 Conclusions 69

The DfD Guideline 70

7.1 Introduction 71
7.2 Sales department 71
7.3 Engineering department 74
7.3.1 Disassembly Map Steps 76
7.3.2 Basic Structural Analysis 78
7.3.3 Re-design steps 83
7.4 Conclusions 85

Validating the guideline 86

8.1 User testing 87
8.1.1 Sales department 87
8.1.2 Engineering department 88
8.2 Redesign 93
8.3 Evaluating the guideline 107
8.4 Conclusions 108

Product development 109

9.1 Program of requirements 110
9.2 Improving design 113
9.2.1 Gaps and Tolerances 113
9.2.2 Strength 115
9.2.2.1 Clicking connection 117
9.2.2.2 Snap fit connection 123
9.3 Final product design 127

Conclusions 130

10.1 Revisiting the research question 131
10.2 Discussion, limitations and further research 134

Bibliography 136

Appendix 143

12.1 Building site visits 144
12.2 Dfd Guideline documents 146
12.3 Production drawings 151
12.4 Highrise structural analysis 154

01.

Research Framework

This chapter serves as an introduction to the research topic, providing necessary background information and outlining the problem that prompted the investigation. It states the objective(s), research question(s), and design question(s) that guide the study, while also identifying the specific focus and limitations. Furthermore, the approach and methodology are explained. Additionally, a reading guide is provided, offering an overview of the report's content.

List of Figures:

Fig. 1.1 Example of the approach for a search query
Fig. 1.2 Structure of report

1.1 Background

Aldowa is a façade cladding company that specializes in manufacturing and assembling aluminium facades. They are committed to providing a more sustainable service and implementing circular strategies in their production process. Their goal is to design cladding products that have a longer lifespan and achieve a cradle-to-cradle certification for their cassette panel system. The Cradle-to-Cradle certification consists on different levels, starting with Bronze, Silver, Gold and finalizing with the highest level of platinum. While Aldowa initially aims for the bronze level, they recognize the need for a comprehensive plan to reach higher certification levels. To achieve a circular cycle for the product, an integral plan and strategies have to be taken into consideration.

Circular product life-cycles require close consideration of the product's end-of-life phase. Upon reaching the end of its service life, each panel should undergo inspection and analysis to explore potential cycling pathways. These pathways may include reuse, repair, refurbishment, remanufacturing, repurposing, or recycling. A critical step in enabling these strategies and extending the product's service life is to be able to detach the facade product from the building and dismantle it into independent mono-material components.

1.2 Problem statement

Aldowa's existing facade product range typically has a single use life span where substantial energy and virgin materials are embedded and regarded as waste at the end of their service life. This results in waste that can be prevented. The facade products Aldowa sells are not fully designed to be dismantled, hindering their potential for reuse or other cycling pathways. In the hypothetical scenario where the panels are successfully detached and dismantled, other challenges arise. Firstly, determining the most suitable recovery scenario and adopting a new business model that facilitates product recovery and disassembly. Secondly, from a logistical standpoint, there is a need to establish control over the product data and create a production plan accordingly. In conclusion, Aldowa is uncertain about the ease of disassembling their panels and lacks an overview of what a post-disassembly scenario would entail.

1.3 Objective

The main objective of this thesis is to provide a **guideline** for Aldowa to assess the **disassembly potential** of its cladding products, focusing on the application of **design for disassembly strategies** to enhance the **product's life cycle**.

From this main objective the following sub-objectives derive:
- To identify the **barriers** facilitating the **disassembly** of Aldowa's products
- To understand the **impact** of the product **design**, **manufacturing**, and **assembly** on the product's **life cycle**
- To **apply** the newly developed **guideline** to product **case studies**, namely the Aldowa **cassette panel**

1.4 Focus and limitations

This research aims to focus on assessing the disassembly potential of Aldowa's products. Design improvements to enhance its ease of disassembly and promote material recovery at high environmental value will be proposed. The study will also provide a general overview of post-disassembly strategies for Aldowa to consider the possible recovery scenarios.

The case studies will primarily center around the cassette panel, which serves as the focal product for certification. Given its complexity in terms of connections and material usage, the cassette panel represents the most complex facade system within Aldowa, with other assembly systems deriving from it. Consequently, the research conducted on the cassette panel can serve as a foundation for future analyses of the other systems.

1.5 Research questions

The aim of this research is to provide a comprehensive guideline to asses the disassembly potential of Aldowa's cladding products, and to propose design alternatives that facilitate its disassembly and extend its service life. Therefore, the paper will answer the following research question:

How can the **disassembly potential** of Aldowa's cladding products be **assessed**, and what **design guideline** can be proposed to comply with the design for disassembly requirements of the **Cradle-to-Cradle certification**?

From which the following **literature research** sub-questions derive:

1. What is the scope and significance of the Cradle to Cradle certification, and what differentiates it from other environmental assessments?
2. What are the available guidelines for Design for Disassembly and can a new guideline be developed specific to Aldowa's products and design workflow, to promote higher material recovery?
3. What are the current end-of-life scenarios for aluminium products, and which could be the circular (re) life pathways?

Additionally, the following **practical research** sub-questions derive:

1. How does Aldowa's production process impact the disassembly potential of its products?
2. In what scenarios and for which stakeholders will the proposed guideline prove beneficial?
3. What are the feasible design alternatives that can be integrated into Aldowa's products to improve their disassembly potential and extend their lifespan?

1.6 Approach and methodology

Two different methodologies were used to realize the presented research. This was based on a (1) Literature Review and (2) Practical Case Studies. First, the literature review was conducted mainly about the following topics: Cradle to Cradle, Environmental Assessments, Design for Disassembly and Re life strategies. Google scholar and TUDelft repository were the main search engines for the literature review.

The following approach was used for different search queries where the literature was reviewed, analyzed and the main conclusions were stated.

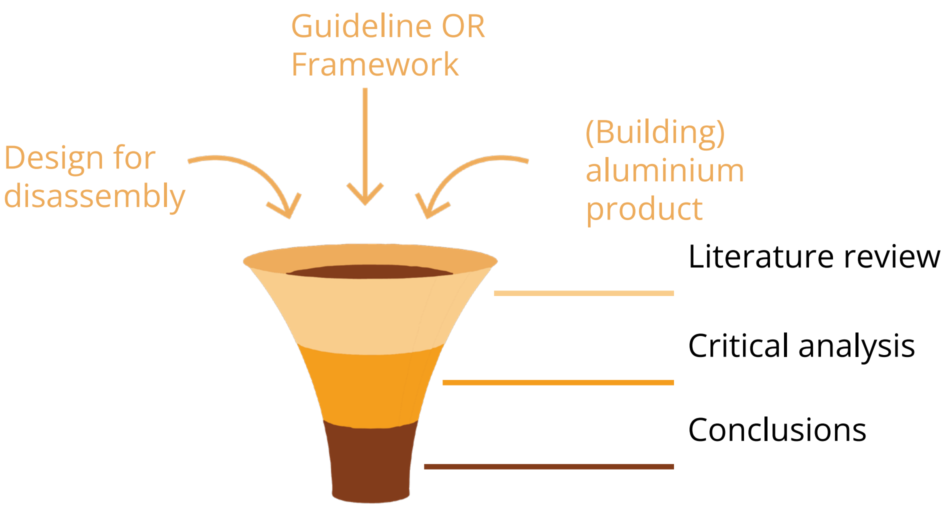


Figure 1.1 Example of the approach for a search query (Illustration by author)

1.7 Reading guide

This research paper is divided into several sections to provide a structured and comprehensive analysis. The paper begins with a literature review (Part I), which presents the findings and insights gathered from existing research and scholarly articles related to the topic. Following the literature review, the paper delves into the practical research about the company's production process (Part II). Part III presents the guideline, including the requirements specific for the company. Then the guideline is validated through user testing from which design alternatives derive. Finally, an evaluation of the design alternatives is conducted and the key findings of the design for disassembly guideline are concluded (Part IV).

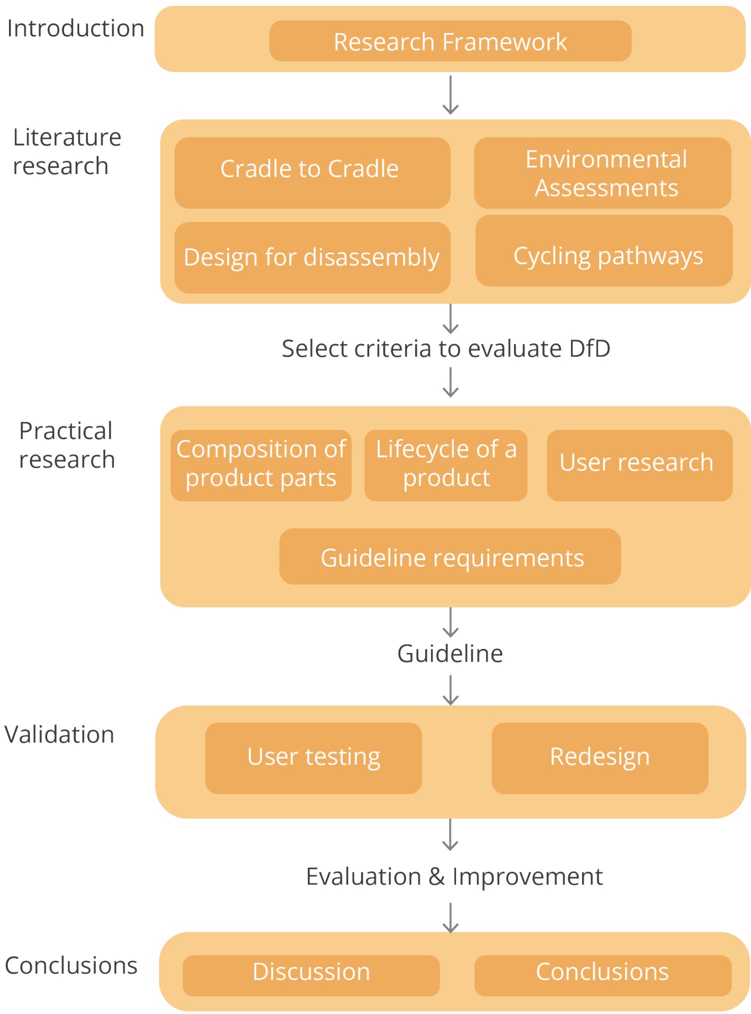


Figure 1.2 Structure of report (Illustration by author)

02.

Cradle to Cradle

This Chapter introduces the first part of the literature review: the concept of cradle to cradle. The core of this research was based on the framework proposed by McDonough and Braungart (2002) in the book: Remaking the Way We Make Things'. Section 2.1 introduces Cradle to Cradle. Section 2.2 and Section 2.3 explain the main principles of Cradle to Cradle and how it relates to other circular system theories. Section 2.4 explores the application of C2C in the Built Environment. Section 2.5 and Section 2.6 explain how the cradle to cradle certification works and its limitations.

Fig. 2.1 Cradle to Cradle principles
Fig. 2.2 Timeline of the eight systems theories
Fig. 2.3 The five categories of the Cradle to Cradle Certification

2.1 Introduction of Cradle to Cradle

The Dutch building industry is facing a significant environmental challenge, having accounted for half of the total waste generated in 2016. The sector has made commendable strides in sustainable practices, with 54% of all recycled materials used in construction coming from the building industry (Centraal Bureau voor de Statistiek, 2019). The direct reuse of building components aligns with the government's objective of achieving a circular economy by 2050. While reducing the operational energy use in buildings has been the primary focus for minimizing environmental impact, the significance of material use is also increasing. Responsible material use is a crucial enabler in reducing the net environmental impact of the built environment. Both, material reuse and recycling offer significant opportunities in reducing the production and transportation-related energy consumption of the built environment (van den Dobbelsteen, 2004).

The importance of efficient material use has led to the increasing adoption of the Cradle to Cradle (C2C) design framework in the Netherlands. Introduced in the book "Cradle to Cradle: Remaking the Way We Make Things" by McDonough and Braungart (2002), C2C aims to create products and systems that are environmentally sustainable and beneficial for the ecosystem and human health. The framework is based on principles that promote a closed-loop system, eliminating waste and continually reusing resources.

Despite some criticism about the practicality of implementing the C2C framework, it has been embraced also by international companies such as Herman Miller, Ford, Philips, and Nike (Van Dijk et al., 2014). Municipalities and regions in the Netherlands have also adopted C2C as a basis for their plans, though several difficulties they have encountered in applying the principles in practice according to Van Dijk et al. (2014).

2.2 The Principles of Cradle to Cradle

The C2C design framework is based on the principle of creating products and systems that are not only environmentally sustainable but also beneficial for the ecosystem and human health. The framework is based on a set of principles that aim to transform the industrial system from a linear economy, where products are made, used, and then discarded, into a closed-loop system where waste is eliminated, and resources are continually reused.

The three principles of Cradle to Cradle are the following:

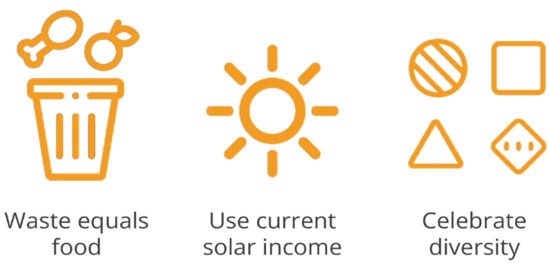


Figure 2.1 Cradle to Cradle principles (Illustration by author) (McDonough & Braungart, 2002)

In this framework based on these three principles waste doesn't exist because it provides the nutrients to other (technical or biological) metabolisms. Therefore, a product or process needs to be designed in a way to enable the "decomposability" of the product into single nutrients. (McDonough & Braungart, 2002)

2.3 Related System Theories

The concept of closing loops in human systems is inspired by the closed-loop systems found in nature, where all elements are interconnected and interdependent, and waste is minimized through the continuous use of nutrients. However, the industrial revolution introduced an open end-of-pipe system that generates waste, which is not compatible with nature's closed-loop systems (McDonough & Braungart, 2002) (Van Dijk et al., 2014). While the Cradle to Cradle (C2C) design principles are one approach to achieving closed-loop systems, other system theories also explore this idea. Figure 2.1 presents a timeline that illustrates the emergence of each system theory.

According to the literature review conducted by Van Dijk et al. (2014), the other system theories are synthesized as follows:

1. **Laws of ecology:** The Laws of Ecology were formulated by scientist and environmentalist Barry Commoner in the 1970s. The 4 laws describe the fundamental principles that govern the interactions between living organisms and their environment.
2. **Looped Economy:** aims for an economy that operates through spiral loops, with the goal of reducing material and energy flows as well as environmental degradation. This should be achieved without impeding economic growth or social and technological advancement.
3. **Regenerative design:** seeks to create systems that not only sustain themselves but also improve and regenerate the natural environment around them.
4. **Biomimicry:** seeks to emulate the strategies and systems found in nature to solve human problems and improve sustainability.
5. **Industrial ecology:** aims to create more sustainable industrial systems by modeling them after natural ecosystems, with a focus on minimizing waste and maximizing resource efficiency
6. **Circular economy**: There are several definitions of a circular economy, but according to the glossary of the Ellen MacArthur Foundation (2013), "it is a design-driven approach that is built upon three principles: eliminating waste and pollution, circulating products and materials at their highest value, and regenerating nature."
7. **Blue economy:** it is an approach to business design that utilizes available resources in a cascading system, where the byproducts of one product are re purposed to create new revenue streams.

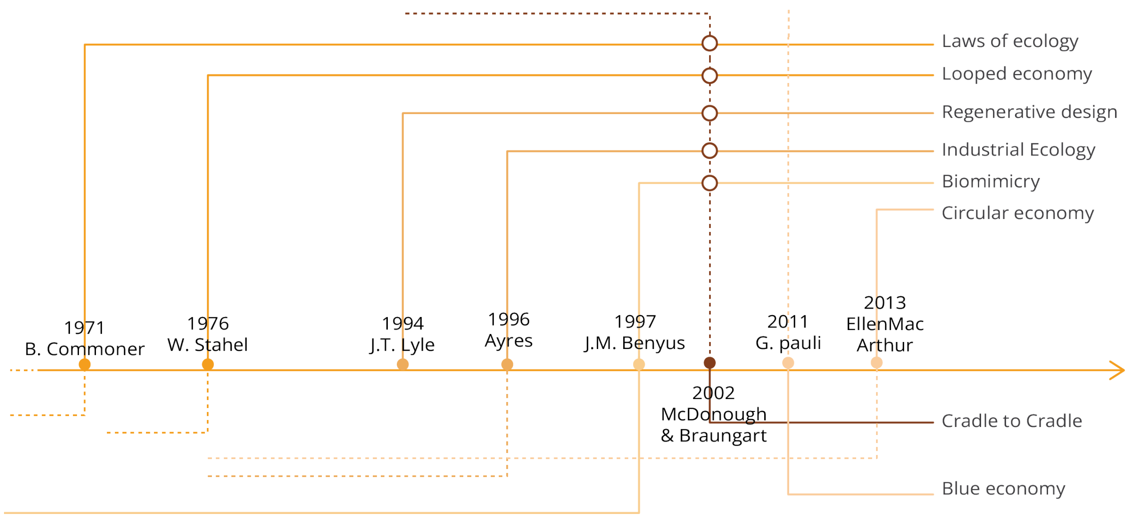


Figure 2.2 Timeline of the eight systems theories (Illustration by author) (Van Dijk et al., 2014) (EMF, 2013)

The following table provides insights on how each principle relates to the three C2C principles according to Dijk et al. (2014). The principles from the EMF (2013) have also been added to the table:

Table 2.1 Comparison of C2C Principles and other Systems' Theories Principles

Systems' Theories	Principles
Cradle to Cradle	Waste equals food Use current solar income Celebrate diversity All
Laws of ecology	Everything is connected to everything else Everything must go somewhere Nature knows best There is no such thing as a free lunch
Looped economy	Product design optimized for durability, adaptability, re manufacturing and recycling Re manufacturing that preserves the frame of a product after use, replacing only the worn-out parts Business models based around "product leasing" as opposed to "product selling", where ownership remains with the manufacturer over the entire product life cycle, thereby encouraging product durability and improved quality approaches to product design, manufacture and maintenance Extended product liability/stewardship/responsibility: encouraging manufacturers to guarantee low-pollution-use and easy-reuse products
Regenerative design	Letting nature do the work Considering nature as both model and context Aggregating, not isolating Seeking optimum levels for multiple functions, not the maximum or minimum for any one Matching technology to need Using information to replace power Providing multiple pathways Seeking common solutions to disparate problems Managing storage as key to sustainability Shaping form to guide flow Shaping form to manifest process Prioritising for sustainability
Biomimicry	Nature runs on sunlight Nature uses only the energy it needs Nature fits form to function Nature recycles everything Nature rewards cooperation Nature banks on diversity Nature demands local expertise Nature curbs excesses from within Nature taps the power of limits
Industrial ecology	Reduce, and eventually eliminate, inherently dissipative uses of non-biodegradable materials, especially toxic ones (like heavy metals) Design products for easier disassembly and reuse, and for reduced environmental impact, known as 'design for environment' (DFE) Develop much more efficient technologies for recycling waste materials, so as to eliminate the need to extract 'virgin' materials that only make the problems worse in time Dematerialisation Substitution of a scarce or hazardous material by another material Repair, re-use, remanufacturing and recycling Waste mining

Systems' Theories	Principles
Blue economy	○ Solutions are first and foremost based on physics ● Substitute something with Nothing- question any resource regarding its necessity of production ● Natural systems cascade nutrients, matter and energy – waste does not exist. Any by-product is the source for a new product. ● Nature evolved from a few species to a rich biodiversity. Wealth means diversity. Industrial standardization is the contrary. ● Nature provides room for entrepreneurs who do more with less. Nature is contrary to monopolization. ● Gravity is main source of energy, solar energy is the second renewable fuel. ● Water is the primary solvent (no complex, chemical, toxic catalysts). ○ In nature the constant is change. Innovations take place in every moment. ● Nature only works with what is locally available. Sustainable business evolves with respect not only for local resources, but also for culture and tradition. ● Nature responds to basic needs and then evolves from sufficiency to abundance. ● The present economic model relies on scarcity as a basis for production and consumption. ● Natural systems are non-linear. ● In Nature everything is biodegradable – it is just a matter of time. ● In natural systems everything is connected and evolving towards symbiosis. ● In Nature water, air, and soil are the commons, free and abundant. ● In Nature one process generates multiple benefits. ○ Natural systems share risks. Any risk is a motivator for innovations. ● Nature is efficient. So sustainable business maximizes use of available material and energy, which reduces the unit price for the consumer. ● Nature searches for the optimum for all involucrated elements. ○ In Nature negatives are converted into positives. Problems are opportunities. ○ Nature searches for economies of scope. One natural innovation carries various benefits for all.
Circular economy	● Eliminate waste and pollution ● Circulate products and materials at their highest value ● Regenerate nature

As it can be seen in Table 2.1 many of the principles of C2C can be found in other systems' theories since they also consider aspects of closed material cycles. Their main aim is material reduction, while C2C does not emphasize to minimize material use since in the system theories the materials are used again and again. However, it does recommend energy and material minimization for production processes. C2C in contrast with the other theories proposes to create a positive impact instead of reducing the negative impacts. Furthermore, van Dijk et al. (2014) highlights 5 principles considering nutrient reutilization that can be added to the C2C criteria. These are the following:

1. Managing storage
2. Business models based around product leasing
3. Waste mining
4. Cascade nutrients
5. Use of abundantly available materials

2.4 Cradle to Cradle in the Built Environemnt

In comparison with other environmental assessments that aim to reduce negative impact on the environment, Cradle to cradle aims for a positive impact. For example, instead of reducing toxic levels on materials, Cradle to Cradle does not allow using materials with toxic chemicals at all. In other words, C2C aims to go beyond reducing the negative impacts and provide, "comprehensive strategies for creating a wholly positive footprint on the planet (eco-effectiveness)," (MBDC, 2005).
Braungart and Mulhall (2010) attempted to create application tools for the C2C principles to be applied in the built environment. They used C2C principle criteria and translated it into implementation criteria. These tools can be used by designers to add extra value to the product.

Implementation of waste equals food criteria:
1. Find actively beneficial material qualities
2. Define product recycling
3. Define use pathways
4. Define use periods
5. Design for assembly, disassembly and reverse logistics
6. Practice materials pooling
7. Preferred ingredients lists (P-lists)

By advocating for the elimination of waste and the continuous reuse of materials, Cradle to Cradle has encouraged the development of innovative building materials and systems that minimize environmental impact. It has also encourage the adoption of sustainable building certifications, such as the Cradle to Cradle Certified™ program, which ensures that buildings or products meet rigorous standards for environmental and human health.

2.5 Cradle to Cradle Certification

To create a positive impact the C2C certified program has established 5 criteria to assess products for safety to human and environmental health, design for recyclability or compostability, and responsible manufacturing processes (MBDC, 2005). For a product to receive a Cradle to Cradle certification it has to meet the requirements of the five criteria categories. These categories cover the three basic principles and establish a road map towards a circular product.

Figure 2.3 The five categories of the Cradle to Cradle Certification

Each category will be described according to McDonough and Braungart (2002) and C2C® (2021):

1. Material Health: The materials used in products should be safe for human and environmental health. This principle requires the elimination of harmful substances in products and the use of materials that can be safely reused or biodegraded. The C2C framework encourages the use of renewable resources and the adoption of closed-loop production systems.

2. Material Reutilization: The C2C framework promotes the idea of using waste as a resource. Products should be designed to be easily disassembled and materials should be separated to facilitate their reuse or recycling. This principle requires the elimination of the concept of waste, and the adoption of a circular economy.

3. Renewable Energy: The C2C framework encourages the use of renewable energy sources to power production and manufacturing processes. The use of renewable energy sources such as solar, wind, and geothermal power is preferred over non-renewable sources such as fossil fuels.

4. Water Stewardship: The C2C framework emphasizes the importance of responsible water use. Products and systems should be designed to reduce water consumption, promote water reuse, and protect water quality.

5. Social Fairness: The C2C framework acknowledges the importance of social fairness in the production and distribution of products. The framework promotes the use of fair labor practices and the inclusion of all stakeholders in the decision-making process.

This research study will be focused on the category of product circularity. Defined as, "enabling a circular economy through product and process design," (C2C®, 2021). The certification is awarded in five levels: Basic, Bronze, Silver, Gold, and Platinum. Each level represents a higher degree of sustainability and circularity, with Platinum being the highest level of achievement. Figure 2.3 shows an overview of the different milestones for each level of product circularity.

5 // Product Circularity Requirements	Bronze	Silver	Gold	Platinum
5.1 Circularity education	X	X	X	X
5.2 Defining the Product's Technical and/or Biological Cycles	X	X	X	X
5.3 Preparing for Active Cycling	X	X	X	X
5.4 Increasing Demand: Incorporating Cycled and/or Renewable Content	X	X	X	X
5.5 Material Compatibility for Technical and/or Biological Cycles	X	X	X	X
5.6 Circularity Data and Cycling Instructions	X	X	X	X
5.7 Circular Design Opportunities and Innovation		X	X	X
5.8 Product Designed for Disassembly		X	X	X
5.9 Active Cycling			X	X

Table 2.2 Product circularity requirements per level from the user manual (Cradle to Cradle Products Innovation Institute, 2021)

The company is aiming first for a bronze level certification. The first steps have been taken and a person from EPA (Environmental Protection Agency) is guiding Aldowa through the process. The product that will be certified is a standard design of a cassette panel. The cassette panels Aldowa designs are actually unique and different from each other because they depend on the project and the client's demands. This means the design may vary from this standard one but this model will be the basis. The definition from the C2C® Product Standard Version (2021) will be used to explain what cycling pathway means and is used for their criteria.

Cycling pathway- A specific method, system, or other means of processing a material at the end of its use phase. Examples include: municipal recycling, home composting, aerobic biodegradation in wastewater (i.e., at municipal treatment plant), take-back and repair/remanufacture by the manufacturer.

Furthermore, the requirements for this category from the user guidance will be explained and the current state will be described:

1. Circularity education

This criteria applies for the bronze level where Aldowa has to participate in a circularity education initiative to share knowledge about the circularity strategies. For this criteria, Aldowa will collaborate with the study association of Building Technology, BouT in TUDelft, to accom-

2. Defining the Product's Technical/Biological Cycles

The products components are made of mostly metals and one component made out of plastic. These materials are defined for the technical cycle defined as a, "cycle by which a product's materials or parts are reprocessed for a new product use cycle via recycling, repair, refurbishment, remanufacturing, or reuse," (Cradle to Cradle Products Innovation Institute, 2021).

3. Preparing for Active Cycling

This criteria applies for bronze and silver level where Aldowa has to identified the, "barriers to material recovery and processing in order to actively cycle those materials for their next use," (Cradle to Cradle Products Innovation Institute, 2021).

4. Incorporating Cycled Content

Each level demands different percentages of recycled content in their products. The main material used is aluminium which can maintain its properties during the recycling process. The main suppliers of Aldowa's aluminium sheets are Roba and Speira. A documentation of how much recycled content is in their products is necessary. For the other materials it is unknown how much cycled content they have.

5. Material Compatibility

For the bronze level only 50% of the product's materials have to be compatible with a selected cycling pathway. In this case, it is aluminium which is compatible with the cycling pathway of recycling. A cycling pathway has not been identified for the other materials but is necessary to have a plan to execute for the next levels.

6. Circularity Data and Cycling Instructions

Information about the proper end of use of the product has to be publicly available at all levels. For the bronze level the C2C documentation (C2CPII Circularity Data Report form) for the bronze process is sufficient.

7. Circular Design Opportunities and Innovation

This criteria applies for silver, gold and platinum level, where the product is designed in a way that creates more end-of-use cycling opportunities. At this begin stage, the product's intended end of life scenario is recycling. For the next levels a plan for an innovation strategy, such as stated in the manual, is necessary. These are the strategies proposed by the manual:

- Designed to minimize material weight
- Design strategy to prolong use phase
- Design for Product as a Service
- Design for Modularity or upgradability
- Design for Maintenance, repair or refurbishment services
- Design for Manufacturer recovery or reuse
- Design for Product compatibility/ standardization
- Design for Re manufacturing
- Design for Industrial symbiosis
- Design for Extending resource value

8. Product Designed for Disassembly

This criteria applies for silver, gold and platinum level. The product has to be, "easily disassembled into discrete materials compatible for its intended cycling pathway(s)" (Cradle to Cradle Products Innovation Institute, 2021). There are two requirements for this criteria:

1. "Include a design feature that improves the ease of disassembly compared to a previous design product "(Cradle to Cradle Products Innovation Institute, 2021). The possible design features are:

- Uses fewer fasteners
- Decreased number of disassembly operations
- Elimination of destructive processes
- Minimized the tools needed to disassemble the product
- Use of detachable/resolvable fasteners
- Full accessibility to critical parts
- Increased automation of disassembly and/or improved other mechanisms for material separation that minimize loss of material

A new design feature with evidence that it improves the ease of disassembly is also accepted.

2. "If disassembly operations are conducted by an entity other than the applicant company, comprehensive disassembly instructions must be publicly available and accessible to the party(ies) involved in disassembly" (Cradle to Cradle Products Innovation Institute, 2021).

The instructions require the following information:
- A description of each step in the disassembly operation
- Identification of parts and components
- The type of connectors involved
- How to access components and parts
- Tools required for each step
- Accompanying audio or visual instructions or diagrams (e.g., disassembly precedence graph, disassembly tree, state diagram, hypergraph)

Implementing one of the innovation strategies mentioned before may count as fulfillment of this requirement for the Gold level.

9. Active Cycling

This criteria applies for gold and platinum level where, "the product's materials are actively being recovered and processed for their next use via the intended cycles and/or the product manufacturer is demonstrably invested in a program that will lead to higher product and material cycling rates and/or a higher quality of materials available for cycling" (Cradle to Cradle Products Innovation Institute, 2021).

2.6 Limitations of the Cradle to Cradle Certification

As environmental assessments and certifications continue to evolve, it is important to acknowledge that while Cradle to Cradle certification serves as a benchmark for attaining the Cradle to Cradle principles, it does not serve as a tool for quantitatively assessing environmental impacts, as noted by Minkov et al. (2018). The following limitations have been identified regarding this certification:

1. The indicators used are based only on material weight of **recycled/recyclable parts** or renewability/ non-renewability of input resources
    - **IR** Intrinsic recyclability
    - **RC** Recycled content
    - **MRS** Material reutilization score

    MRS = (2 IR + RC) /3*
2. Doesn't take into account EE (Embodied energy) or EC (Embodied carbon)
3. The packaging of a certified product is not taken into account in the case if it is not used by the consumer
4. It is not considered how many times a material can be recycled.
5. A product/material is defined as being recyclable, when it is recycled once.
6. Quality loses due to recycling are not reflected

(Cottafava & Ritzen, 2021b) (Bach et al., 2018) (Bakker et al., 2010) (Minkov et al., 2018b)

2.7 Conclusions

In comparison with other system theories, Cradle to Cradle aims to create a positive impact instead of minimizing the negative effects related to: material health, product circularity, clean air and climate protection, water and soil stewardship and social fairness. Nevertheless, it is based on principles from other system theories where closed loop systems are preferred rather than linear waste streams. Cradle to cradle is based on three principles: waste equals food, use current solar income and celebrate diversity. From this principles the Cradle to Cradle products innovation institute based their certification process and its 5 categories. Theproduct circularity category will be the focus of this research.

There are four different levels to achieve in the product circularity certification process which reflect the level of circularity of the product. While Aldowa is trying to achieve bronze level (the first level), plans and strategies for higher levels are necessary. Design for disassembly plays a crucial role in achieving higher levels of Cradle to Cradle certification since it is one of the requirements. It involves designing products with the intention of easy disassembly and component separation at the end of their useful life. By incorporating disassembly-oriented design strategies, products can be easily taken apart, allowing their individual components to be more easily repaired, refurbished, or upgraded, extending their service life. Design for disassembly also paves the way for future innovative strategies to take place.

In conclusion, the Cradle to Cradle certification serves as a valuable guideline for adhering to the principles of sustainability. However, it should be noted that the certification does not quantify the specific environmental impacts of a product. Instead, the certification requirements are flexible, allowing companies to provide evidence to demonstrate their fulfillment of the criteria.

It is important to recognize that the level of improvement achieved in a product's design is determined by the company. For instance, a product may fulfill the criteria by simply reducing the number of disassembly steps from 10 to 9. There is no distinction made if the product goes further and reduces the disassembly steps to 5. The criteria do not provide a disassembly rating; rather, they focus on whether the criteria are fulfilled or not.

03.

Environmental Assessments

This Chapter explains the second part of the literature review, an overview of the different environmental assessments. The first Section states the importance to locate the Cradle to Cradle Certification with respect to other existing environmental assessments. Section 3.2 is based on literature reviews of environmental assessments to understand their limitations. Furthermore, Section 3.3 discusses how design for disassembly is rated in an LCA and in the BCI. Finally, Section3.4 states the main findings.

List of Figures:

Fig. 3.1 1st Supplier LCA System boundaries
Fig. 3.2 2nd Supplier LCA System boundaries

3.1 Positioning Cradle to Cradle Certification

It is essential to position the Cradle to Cradle (C2C) certification guideline alongside other environmental assessment tools to conduct an integrated evaluation of the product life-cycle of Aldowa's cladding systems. This preliminary step is essential before delving into the DfD criteria, as it enables a comprehensive understanding of the product's environmental impact and sustainability performance. Integrating various environmental assessment tools provides additional insights and allows for a more holistic perspective on the product life-cycle of Aldowa's cladding systems. Therefore, this chapter emphasizes on positioning the C2C certification guideline within the broader context of environmental assessment tools. This approach identifies opportunities for improvement and provides a more comprehensive evaluation of the product life-cycle of Aldowa's cladding systems

3.2 Existing environmental assessments analysis

During the 1990s, the construction industry started to be aware of the environmental consequences of its activities. This called for new quantitative assessment methods that enabled the environmental performance of building products to be measured (Haapio & Viitaniemi, 2008). The first commercially available environmental assessment tool for buildings was the Building Research Establishment Environmental Assessment Method (BREEAM) established in 1990 in the UK. (Grace & Centre for Sustainable Construction, 2000). Since then many other tools became available and other organizations and research groups have contributed knowledge in their development.

To establish standardized requirements for the environmental assessments the International Organization for Standardization (ISO) has published technical specifications for the built environment. Furthermore, the European Committee for Standardization (CEN) develops standardized methods for the assessment of construction works and environmental product declarations (EPDs) of construction products (CEN, 2012). The product category rules (PCR) describe which stages of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle. It includes the rules for calculating Life Cycle Inventory and Life Cycle Assessment of which the EPD is based. It also has rules for reporting environmental and health information and under which conditions the product can be compared.

The environmental assessments can differ from one another due to the criteria used to assess a phase of the building's life cycle and the indicators used that correspond to this criteria. Identifying the limitations of the criteria and indicators used in each environmental assessment is necessary to select the ones that provide more significant information to the user. According to Happio & Vietaniemi (2008), the expected service life of a building and its components is assumed to be a fixed value. Nevertheless, some parts have shorter service lives where maintenance or refurbishments are necessary. Both maintenance and refurbishment have environmental impact which is most of the times not assessed in the environmental assessments (ibid.).

Several studies have identified the knowledge gaps in existing environmental assessments to bridge the distance between design decisions and the assessment of end of life scenarios to reclaim the embodied energy in product's materials.

Hartwell and Overend (2020) and O'Grady et al. (2021) both identify a lack of consideration for the end-of-life scenarios of building materials and components in existing environmental assessments, specially LCAs. Hartwell and Overend (2020) note that reclamation potential is not usually considered and LCAs do not make a comparison between different recovery strategies. O'Grady et al. (2021) highlights the absence of methods to quantify the potential reuse of building materials. To address this gap, both sources propose new methods to calculate the potential for disassembly, reuse or reclamation of materials.

In addition to proposing new quantitative methods, some researchers have developed qualitative models that focus on the early design stages that influence end-of-life scenarios. For example, Bakx et al. (2016) proposes a model to guide designers in the design and evaluation of a circular facade, with an emphasis on adaptability and modularity. While the model offers solutions for an adaptable and modular conceptual facade, it does not evaluate the end-of-life scenarios of the product's parts after disassembly.

Further research has evaluated the environmental potentials of circular building design based on two cases—one constructed primarily from upcycled materials and the other with principles of design for disassembly (DfD). Rasmussen et al. (2019) found that the up cycling strategy results in lower greenhouse gas emissions, especially from the production stage, while the DfD strategy does not realize an environmental advantage within the framework of the EN standards.

Hartwell et al. (2021) emphasizes the significance of material recovery to reclaim embodied energy and carbon. The effectiveness of recovery methods depends on how the design decisions influence the ability to reuse the facade systems. However, despite the benefits of these methods, they are not acknowledged by external regulation or certification schemes, and the supply chain does not incentivize improvements in the deconstruction stage. As a result, many materials cannot be adequately separated and are wrongly categorized as waste.

3.3 Dfd criteria in environmental assessments

This paper will focus on product-level assessments, specifically those relevant to Aldowa. While the company is primarily interested in the Cradle to Cradle assessment, they also recognize the importance of other established assessments such as LCA and are willing to consider new frameworks such as the Building Circularity Index (BCI). The paper will compare these assessments focusing on design for disassembly.

Life Cycle Assessment (LCA)

An LCA, or Life Cycle Assessment, is a systematic method used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle, from extraction of raw materials to final disposal. It provides a holistic perspective by considering various stages, such as production, transportation, use, and end-of-life stages (Rasmussen et al., 2019). LCA takes into account factors like resource consumption, energy use, emissions, waste generation, and potential environmental damage, allowing for informed decision-making and the identification of opportunities for environmental improvement (Minkov et al., 2018).

The following shortcomings based on research from Rasmussen et al. (2019) and Hartwell and Overend (2020) about this assessment have been identified:

1. The assessment is complex due to **lack of data** of used materials, their **origin** and **traceability**
2. It has no **differentiation** in **recovery strategies**
3. It does not **quantify** the link between **design** choices and **end of life** scenarios
4. The **DfD** (Design for Disassembly) strategy does **not** realize an **environmental advantage** within the **framework** of the EN standards

Environmental product declarations (EPDs) are used by manufacturers to report data about the environmental performance of their products. It presents the results of a life cycle assessment (LCA) study and other information. Two EPD's of Aldowa's aluminium sheet suppliers were analyzed to understand if the shortcomings listed above were present.

In Figure 3.1 the LCA considers reuse, recovery and recycling potential. On the other hand, the second LCA in Figure 3.2 states recycling as the only potential recovery scenario without considering other cycling pathways. There are no categories during the product or assembly stage that take into account the design of the product .

Product stage			Assembly stage		Use stage							End of life stage				Benefits & loads beyond system boundary
Raw materials	Transport	Manufacturing	Transport	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	x	MND	MND	MND	MND	MND	MND	MND	MND	MND	x	x	x	MNR

Figure 3.1 1st Supplier LCA System boundaries (X = included, MND = Module not declared, MNR = Module not relevant) (Assan Alüminyum, 2022)

	Product Stage		Construction Process Stage			Use Stage							End of Life Stage				Resource Recovery Stage
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Recycling potential
MODULES	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Modules declared	X	X	X	X	X	ND	ND	ND	ND	ND	ND	ND	X	X	X	X	X
Geography	GLO	GLO	TR	GLO	GLO	-	-	-	-	-	-	-	GLO	GLO	GLO	GLO	GLO
Specific data used	>99.5%			-	-	-	-	-	-	-	-	-	-	-	-	-	-
Variation – products	Not relevant			-	-	-	-	-	-	-	-	-	-	-	-	-	-
Variation – sites	<10%			-	-	-	-	-	-	-	-	-	-	-	-	-	-

X: Declared; ND: Not Declared

Figure 3.2 2nd Supplier LCA System boundaries (X = included, ND = Not declared) (Speira Karmøy Aluminium Rolled Products VERSA, 2022)

Building Circularity Index (BCI)

The BCI is a measuring instrument to determine the circular potential of a real estate object. The organization designed it together with the platform CB'23, which contributes to the circular construction sector in the Netherlands by focusing on:

1. Building and sharing knowledge
2. Identifying and scheduling obstacles
3. Drafting Dutch construction sector-wide agreements

The CB'23 has recently laid down guides rather than formal standards to work with the Dutch government towards a circular economy, specifically in the construction industry. The guides are divided into seven topics:

1. Framework with lexicon (Interpretation of circular construction)
2. Circular design and circular construction strategies and requirements
3. Measuring circularity
4. Information and data for product passports, data management and system requirements
5. Value creation and financing
6. Assurance (Legislation and regulations)
7. Supply chain transformation (Division of roles & interrelationships)

Consequently, the tool focuses of raw materials, material use as well as **detachability**. The score is expressed between 0% and 100%, where 0% is completely linear and 100% is completely circular. It consists of two Key Performance Indicators (KPIs): **material usage** and **detachability**. Both of these indicators make up the product circular index (PCI), which is also expressed between 0.00 (fully linear) - 1.00 (fully circular).

Material circularity index

To calculate the material use there is a differentiation among the following:

1. The origin of the material: new raw materials, recycled raw materials, biobased raw materials or reused
2. The future scenario: reuse, recycle, incinerate and landfill
3. The lifespan of the material: Measured by a utility factor based on the ratio between the technical life and the expected life based on the industrial average

MCI is calculated by the percentage addition of the origin of the materials, future scenario and the utility factor where 0 is fully linear and 1 fully circular.

Detachability index

This index takes into account that buildings are made up of different materials, products and elements connected to each together. The following criteria is used to measure the detachability of a product:

1. Connection type
2. Accessibility of the connection
3. Mold containment
4. Crossings

The BCI uses the following rating system to quantify the detachability of a connection:

Type of connection

Type of Connection	Description	Score
Dry connection	Dry	1,0
	Click	1,0
	Velcro strap	1,0
	Magnet	1,0
Connection with extra connective elements	Bolt and nut connection	0,8
	Ferry connection	0,8
	Corner	0,8
	Screw	0,8
	Connection with extra connective elements	0,8
Direct integral connection	Direct integral connection	0,6
	Spike connection	0,6
Soft and chemical compound	Kit connection	0,2
	Pur connection (Polyurethaan)	0,2
Hard chemical connection	Glue connection	0,1
	Poured connection	0,1
	Laser connection	0,1
	Cement connected	0,1
	Chemical anchors	0,1
	Hard chemical connection	0,1

Table 3.1 Rating system proposed by the BCI to rate the detachability of the ***type of connections*** *(BCI, 2023)*

Accessibility

Description	Score
Freely accessible without additional actions	1,0
Accessible with additional actions that do not cause damage	0,8
Accessible with additional actions with fully repairable damage	0,6
Accessible with extra actions with partially repairable damage (more than 20% of value)	0,4
Not accessible – irreparable damage to the product or surrounding products	0,0

Table 3.2 Rating system proposed by the BCI to rate the ***accessibility*** *of connections (BCI, 2023)*

Mold containment

Description	Score
Open, no obstacle to the (interim) removal of products or elements	1,0
Overlap, partial impediment to the (interim) removal of products or elements.	0,8
Closed, Completely obstructing the (interim) removal of products or elements	0,6

Table 3.3 Rating system proposed by the BCI to rate the mold containment of connections (BCI, 2023)

Crossings

Description	Score
No crossings - modular zoning of products or elements from different layers	1,0
Occasional crossings of products or elements from different layers.	0,4
Full integration of products or elements from different layers.	0,1

Table 3.4 Rating system proposed by the BCI to rate the effects of crossing connections (BCI, 2023)

The BCI uses this rating system for building products and if the Dutch government accepts this rating system as the norm, Aldowa's products will be assessed with this criteria. By considering and improving upon each category and rating score for detachability, Aldowa can enhance its products to meet and exceed the criteria outlined, thereby positioning itself favorably in the market.

3.4 Conclusions

The influence of design decisions on a product's end of life scenario is missing as a criteria in existing environmental assessments. Overall, a comprehensive and integrated approach to environmental assessments is needed to address the gaps in existing methods, including the consideration of end-of-life scenarios and the benefits of recovery methods based on design decisions.

In addition, the current LCA assessment lacks emphasis on design for disassembly principles, unlike the new assessment method known as the BCI (Building Circularity Index). The BCI offers a comprehensive rating system specifically designed to evaluate detachability. If the BCI rating system were to be adopted as the standard in the Netherlands, it would provide a valuable framework for assessing the detachability of cassette panels. By utilizing the BCI's rating system, Aldowa can ensure that its cassette panels meet the criteria outlined by the BCI, thereby enhancing their market competitiveness and compliance with building industry standards.

04.

Design for Disassembly

This chapter focuses on the third part of the literature review, which is design for disassembly (Dfd). The first section provides background information and discusses the principles of Dfd. In section 4.2, the impact of Dfd on the built environment is described. Section 4.3 examines the barriers and challenges associated with implementing design for disassembly. Furthermore, section 4.4 introduces and compares two different types of Dfd frameworks. Section 4.5 explains how the robustness criteria is derived, and section 4.6 lists a criteria to assess the disassembly potential of Aldowa's cladding products. Section 4.7 states the main conclusions.

List of Figures:

Fig. 4.1 Building layers of Brand (1994)
Fig. 4.2 Hierarchy of building products of Eekhout (1997)
Fig. 4.3 Hierarchy of material levels of Durmisevic (2006)
Fig. 4.4 Circular construction model
Fig. 4.5 Circular building design principles
Fig. 4.6 Disassembly Map of the redesigned vacuum cleaner
Fig. 4.7 Template for the Parent- Action-Child (PAC) model.
Fig. 4.8 Example of Type I and Type II Disassembly Failure.
Fig. 4.9 Assessing DEI (Design effort index) score depending on the disassembly failure.
Fig. 4.10: DEI (Design effort index) and CI (Circularity indicator) results.
Fig. 4.11 Robustness (0-1) vs time (years) graph

4.1 Background theory

The concept of "design for disassembly" emphasizes the importance of creating products and buildings that can be easily dismantled and their components reused or recycled at the end of their life cycle (Beurskens & Bakx, 2015). It aims to optimize the recovery and recycling of materials at the end of a product's lifecycle, reducing waste and promoting resource efficiency. This approach aligns with the principles of cradle to cradle and circular economy, which aim to maximize resource efficiency through a closed loop system where materials and resources used in products can be continuously recycled and reused, without generating waste or depleting natural resources (McDonough & Braungart, 2002).

Design for disassembly principles operate at different scales, ranging from the overall building down to the individual components of a product. To grasp the implementation of these principles, it is crucial to differentiate between building layers, building product levels, and material levels.

Brand (1994) introduced the concept of "building layers" as a framework for understanding the different levels of a building's composition and functionality. In his work, Brand emphasized the need to consider buildings as systems composed of various layers, each serving a specific purpose. Understanding and addressing each layer's specific requirements and interactions can lead to more efficient and sustainable building solutions. This approach recognizes the interconnectedness and interdependence of the various layers, highlighting the importance of considering the whole system rather than individual components in the design process.

Figure 4.1 shows how the building layers are divided into four main types: the site, structure, skin, and services. This paper will focus on the skin layer, which refers to the building envelope, including materials and systems that protect the interior from external elements.

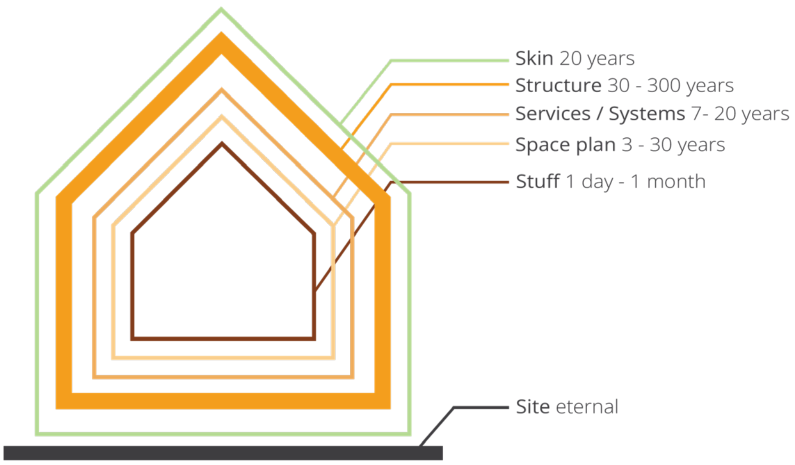


Figure 4.1 Building layers of Brand (1994) (Image adapted by author)

The hierarchy of building products proposed by Eekhout (1997) in Figure 4.2, provides a foundation for understanding the transformation from raw materials to complex building structures. Eekhout highlights the need to bridge the gap between architects, engineers, and other stakeholders involved in the building process. Eekhout's hierarchy of building products recognizes the importance of considering the entire lifecycle of a building, from raw materials to the final built structure. This aligns with the principles of Cradle to Cradle, which promotes a closed-loop system where materials and resources can be continuously recycled and reused, eliminating waste and minimizing environmental impact.

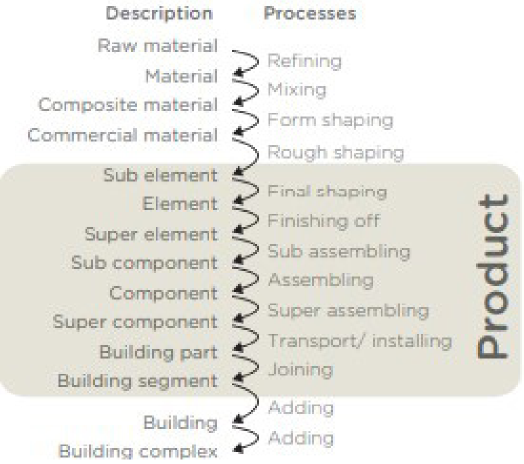


Figure 4.2 Hierarchy of building products of Eekhout (1997)

Durmisevic (2006) introduces the hierarchy of material levels seen in Figure 4.3, which considers both functional and technical/physical aspects of a building. This hierarchy aids designers in developing decomposable building structures and products. Durmisevic's hierarchy, along with Cradle to cradle, recognizes the importance of considering the different levels and interdependencies within a building/product to optimize its disassembly and potential for material recovery. By understanding the lifespan of components and their relationships within the overall structure, designers can plan for efficient disassembly and ensure that materials can be safely and effectively reintroduced into the biological or technical cycles.

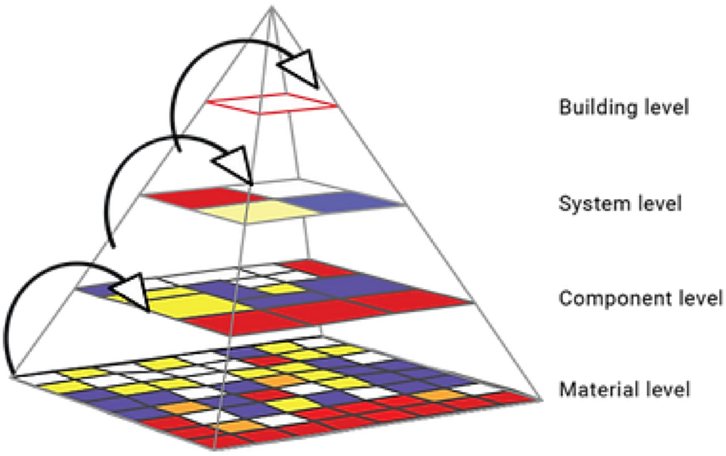


Figure 4.3 Hierarchy of material levels by Durmisevic (2006)

4.2 Impact in the Built Environment

The integration of "design for disassembly" (DfD) principles in the built environment can have significant positive impacts. Embracing DfD enables the recovery and reuse of materials, thereby reducing the need for new resources and promoting resource efficiency (Beurskens & Bakx, 2015). This approach contributes to waste reduction, lowering the environmental footprint of the construction industry, and fostering sustainability.

Moreover, DfD encourages collaboration and cooperation among diverse stakeholders involved in the building process, addressing the gaps highlighted by Eekhout (1997) and promoting a more integrated and holistic approach to building design. By considering disassembly and end-of-life scenarios from the outset, designers can effectively minimize or prevent up to 70% of the environmental impact associated with building products (Cottafava & Ritzen, 2021). This emphasis on design underscores the crucial link between the initial phases of a product's life cycle and its ultimate end-of-life fate.

Through the application of DfD principles, components with high embodied energy can be reclaimed during the disassembly process (Hartwell & Overend, 2020). If these components are not easily separable from their assemblies, they are often deemed as waste. However, by reclaiming and repurposing them, new end-of-life scenarios such as reuse, refurbishment, remanufacturing, and recycling become viable options. This transformative shift in the built environment opens doors to new business models as well, where products can be offered as services, such as in leasing models or trade-in programs practiced already in the automotive industry (Hu et al., 2023).

Beurskens and Bakx (2015) expanded upon the transformation capacity sheme of Durmisevic (2006) and integrated the principles of the circular economy, by the MacArthur Foundation's Butterfly diagram (2013). They established their framework of a circular construction model where central to their approach is the integration of the "design for disassembly" principle in building design as it can be seen in Figure 4.4. They emphasize that disassembly often serves as the initial step in various re-life options for building products, wherein non-destructive disassembly preserves the inherent value of the product, enabling its reuse. Nonetheless, they also acknowledge that recycling may necessitate a destructive disassembly process in certain cases. When applied to the built environment, Dfd facilitates the attainment of multiple lifecycles for building components and reduces waste generation.

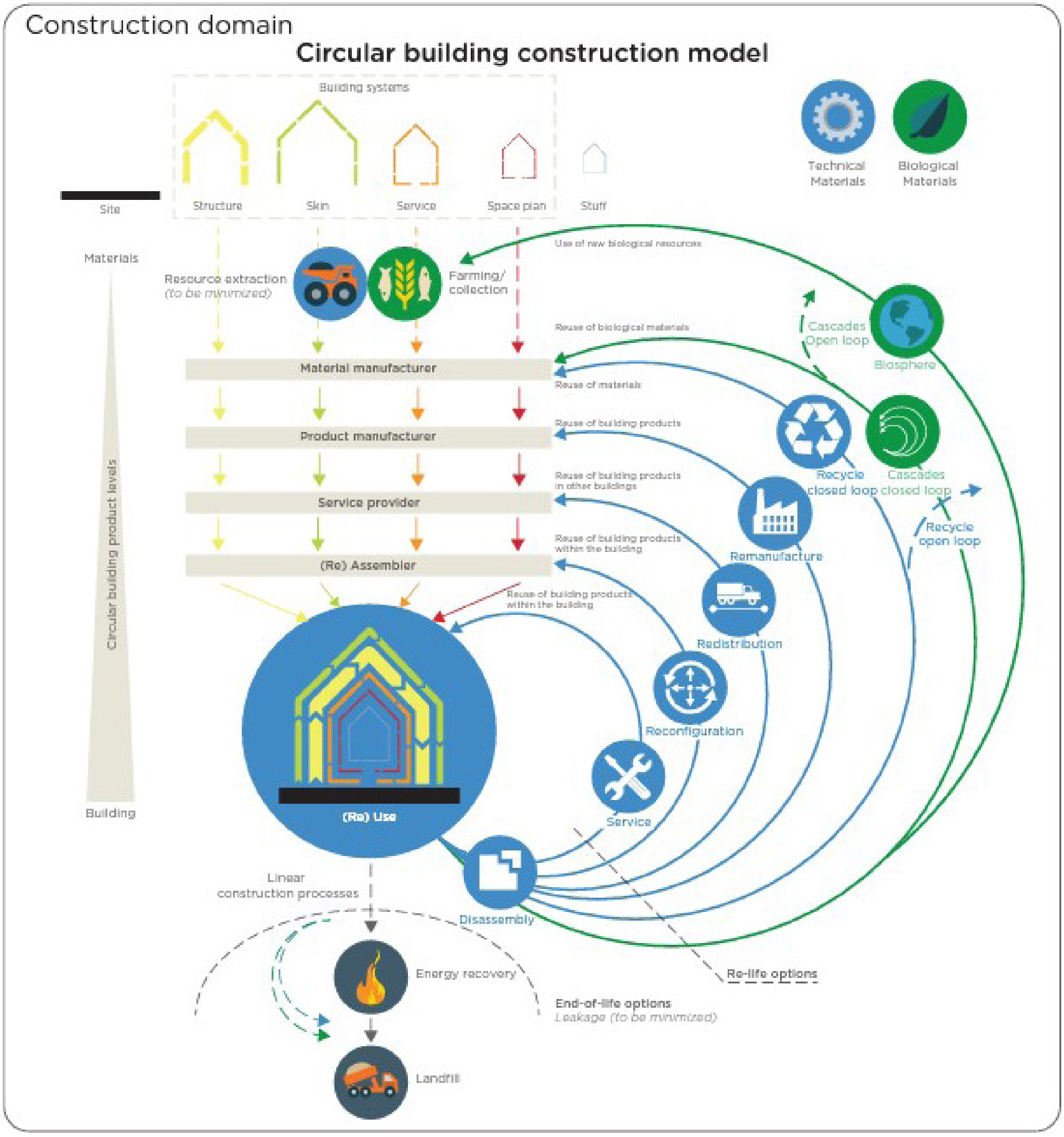


Figure 4.4 Circular construction model by Beurskens and Bakx (2015).

Furthermore, Beurskens and Bakx (2015) also developed a design framework with circular design principles, where the factors enabling disassembly can be found in Figure 4.5. Their Dfd guideline is based on the transformation scheme by Durmisevic (2006). It considers the functional, technical and physical decompositions that enable disassembly and transformation within the built environment. Nevertheless, it does not quantify how detachable a system is.

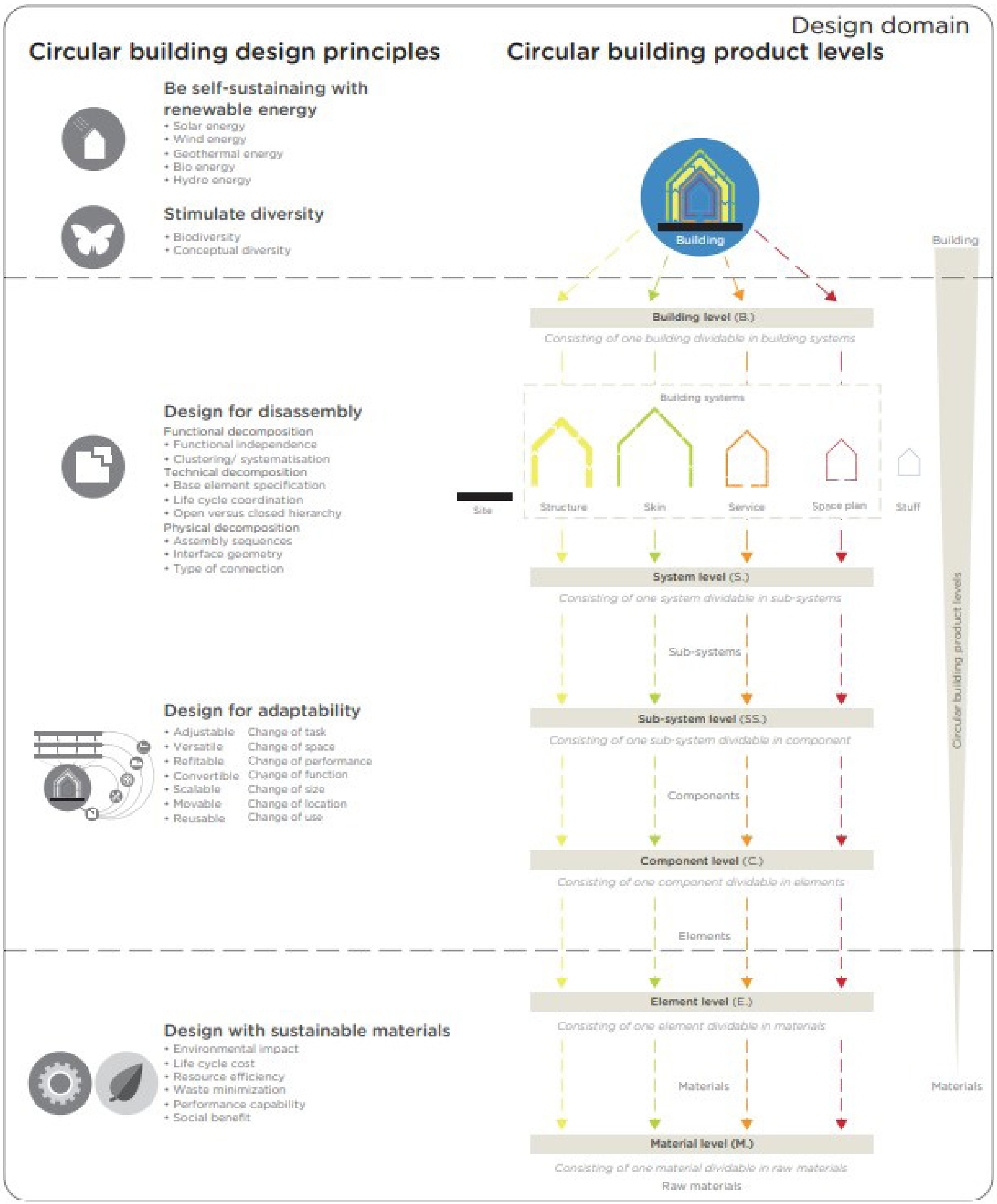


Figure 4.5 Circular building design principles by Beurskens and Bakx (2015).

4.3 Barriers

Implementing design for disassembly in the built environment faces several barriers that can hinder its widespread adoption. Some of the key barriers identified by Sumter et al. (2018), Hartwell et al. (2021), Hu et al.(2023), CB (2023) include:

1. **Lack of awareness:** Limited awareness and understanding of its principles can impede its integration into building design processes. Guidelines quantifying the disassembly potential can help designers, engineers and construction professionals implement Dfd principles.
2. **Fragmented responsibility:** The building industry is composed of numerous stakeholders, including architects, engineers, contractors, manufacturers, and suppliers. Coordinating their efforts and fostering collaboration can be challenging due to fragmented practices and a lack of standardized approaches for disassembly-oriented design.
3. **Traditional industry practices:** The prevailing focus on initial construction and functionality often overshadows considerations for end-of-life scenarios. Traditional design practices prioritize ease of construction and neglect the disassembly and recovery of materials, making it challenging to implement design for disassembly principles. New technologies can be implemented to facilitate its application.
4. **Economic factors:** Building for disassembly may require additional planning, materials, and labor, which can increase upfront costs. The economic viability of implementing design for disassembly needs to be carefully assessed and communicated to stakeholders to overcome financial barriers.
5. **Management and data Infrastructure:** Design for disassembly relies on accurate and accessible information about the composition, properties, and availability of building materials. Insufficient data and limited access to suitable disassembly-friendly materials can hinder effective implementation.
6. **Regulatory and legal constraints:** Existing regulations and building codes may not explicitly address design for disassembly, limiting the flexibility and feasibility of incorporating such principles into projects. The absence of specific guidelines or incentives can discourage designers and developers from prioritizing disassembly-oriented design.

4.4 Existing DfD frameworks

Most design for disassembly (DfD) frameworks operate under the assumption of ideal product conditions during disassembly, disregarding real-world factors such as product modifications made by assemblers, unrecorded changes in the digital model, natural material degradation over time, and potential damage to components during disassembly (Formentini & Ramanujan, 2023). Additionally, the significance of time in the disassembly process is often overlooked in traditional DfD frameworks (De Fazio et al., 2021). To address these gaps, two distinct design for disassembly frameworks have been analyzed: the Disassembly Map and the PAC Model. These frameworks consider the practical complexities of disassembly, accounting for modifications, product condition, and the value of time, thus bridging the divide between idealized assumptions and real-world disassembly scenarios with quantifiable measures.

In the subsequent analysis, each framework will be introduced individually, highlighting its steps, unique features and results. Furthermore, a comparative evaluation will be conducted to identify the respective strengths and limitations of these frameworks, enabling a comprehensive understanding of their opportunities for their application.

4.4.1 The Disassembly Map

The **aim** is to help designers to assess the ease of disassembly and repair of household products. The disassembly map focuses on design for disassembly to facilitate repair. It is a visualization tool to easily interpret parameters and attributes.

The following parameters are addressed:

1. Target components
1. Disassembly sequence
2. Type of tools and actions
3. Disassembly penalties
4. Disassembly time

The authors develop the map by combining literature and the analysis of seven different products. These are the summarized steps for creating a disassembly map:

1. **Step 1**: Identify the target components: These are based on their intended end-of-life strategy
   a. High failure/functional importance (EoL: repair operations)
   b. High embodied environmental impact (EoL: recycle)
   c. High economic value (EoL: refurbishment)
2. **Step 2:** Disassembly research protocol: Disassemble the product and repeat it three times. Take notes of weight and material composition
3. **Step 3:** Answer “user questions” at the end of each step to describe disassembly dependencies between components:
   a. Which next disassembly step is required to reach the target component?
   b. Is this disassembly operation absolutely necessary to reach the target component?
   c. Is there any other operation that could be carried out first?
   d. Is there any other operation that could be carried out in parallel with the one just completed?

Considerations

- Step is defined as an operation that finishes with the removal of a part, and or change of tool
- Grabbing and putting down a tool is not considered as a step
- A disassembly sequence is the number of steps required to reach/remove a target component.

De Fazio et al. (2021) emphasize that the factors that influence the disassembly time and difficulty are: the “type of disassembly motion” and the “intensity of the required force.” The author applies methods such as MOST, the eDiM method, and Kroll’s evaluation chart to determine these factors and time estimates.

The Disassembly Map also includes disassembly penalties, which refer to design features that should be avoided when considering disassembly, as they increase the time and difficulty of the process. There are four specific aspects that can have a negative impact on disassembly:

- **Product manipulation:** This penalty occurs when a product of small to medium size needs to be manipulated on a working surface in order to access certain fasteners. It can also involve walking around the product to reach a connector if the product is too heavy to move.
- **Low visibility/identifiability:** This penalty arises when hidden connectors are difficult to find or access, resulting in additional time required for disassembly.
- **Uncommon tool:** This penalty occurs when a disassembler does not have access to a specific tool required for disassembly. This can hinder product repairability and disassembly if the tool is not commonly available.
- **Non-reusable connector:** Connectors that cannot be reused do not directly impact disassembly time but pose a challenge for re-assembly since new connectors or spare components are needed.

These penalties highlight design features that should be minimized to facilitate efficient and easy disassembly.

Results

The map can be seen in Figure 4.6 and it **results** in the steps needed to dismantle the product and the time it will take to achieve this. This map includes the following attributes in the legend:

- Motion type
- Connectors
- Force intensity
- Type of tool
- Penalties
- Target components

Opportunities and limitations

The Disassembly Map is a valuable tool for visualizing the disassembly steps of a product and considering attributes such as motion type, connectors, force intensity, type of tool, penalties, and target components. It aids designers in evaluating the ease of disassembly for their products and serves as a qualitative framework for identifying areas of improvement.

However, the Disassembly Map does have some limitations. It is not suitable for use in the early stages of product design but can be used as an inspiration by analyzing previous or similar products. In other words, by analyzing an existing design and identifying its limitations, the new design can be improved based on the previous one. The distance between component circles in the map is determined by the number of disassembly operations, rather than the time required for each operation. Additionally, the method has primarily been tested on vacuum cleaners, which may introduce limitations when applied to different product types. Finally, the framework doesn’t take into consideration failures of fasteners or components that may hinder the disassembly process in a future scenario.

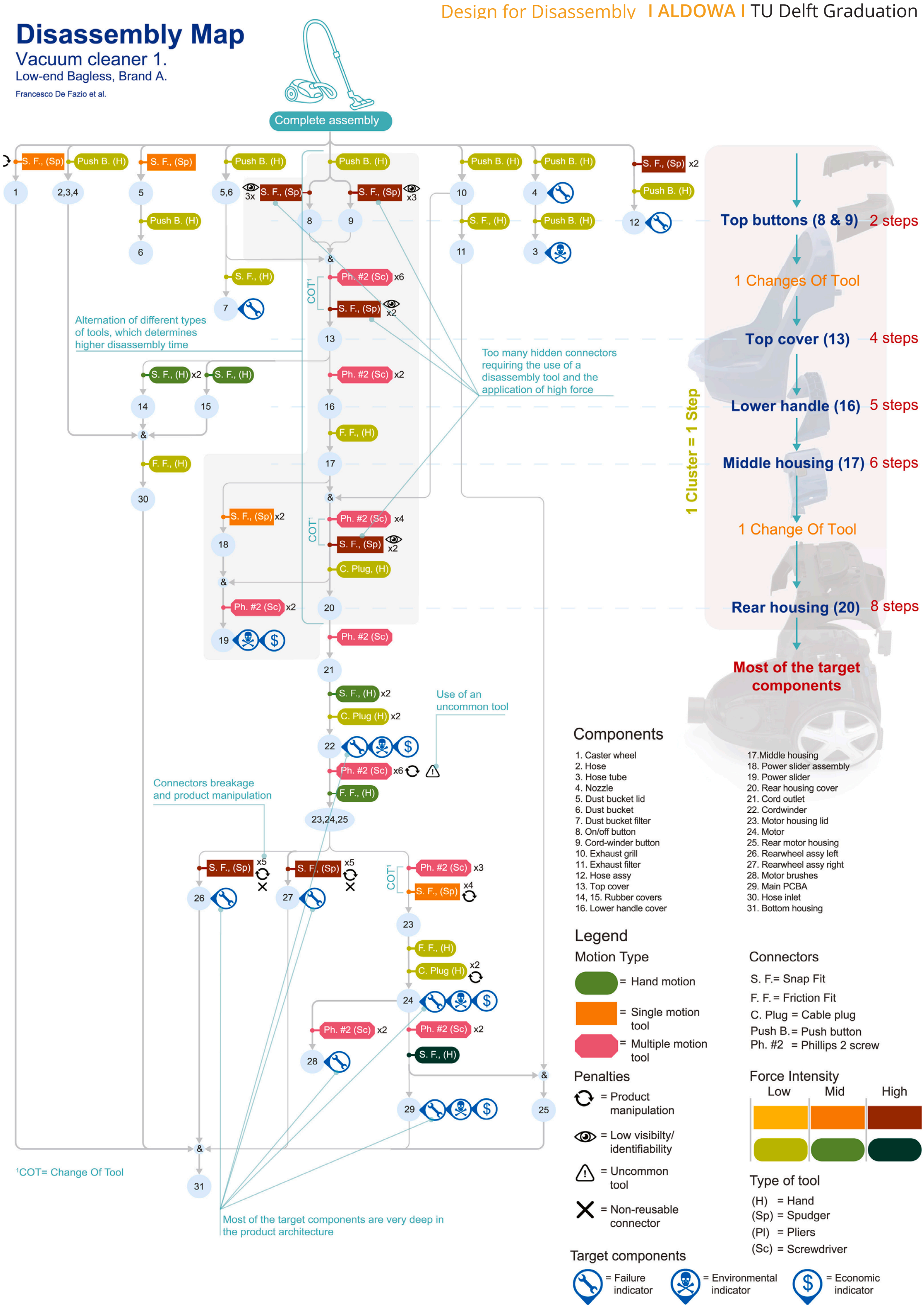


Figure 4.6 Disassembly Map of the redesigned vacuum cleaner. Image by De Fazio et al. (2021)

4.4.2 The PAC Model

The **aim** is to take into account the effects of a product's end-of-life status on the disassembly process, and hence, the potential for circularity of the product (Formentini & Ramanujan, 2023).
The following parameters are addressed:
1. Disassembly sequence
2. Type of tools and actions
3. Disassembly failure scenarios
4. Disassembly effort index (disassembly time)
5. Circularity index

Steps
1) Product data gathering: Classification (parents & children)
2) Description of relations among parts: Disassembly process and tools
3) Disassembly failure analysis (DF)
4) Scenario simulation

Step 1. & 2 :
In this framework they make a distinction between parts and assembly:
Assembly - It is a group of parts
Part - elementary item of an assembly and cannot be disassembled (Example: a screw)

From these definitions the PAC (Parent - action - child) models receives it name because a parent is an assembly or sub-assembly, an action is the physical act that changes a parent into a child and a child is the output of the disassembly process. This process can be seen in Figure 4.9.
The author defines the following rules to create the PAC model:
- A parent can only be subjected to one action.
- A parent subjected to an action can generate one or more children.
- A set of "Parent-Action-Child" elements create a PAC Unit, and represents a complete disassembly cell, in terms of disassembly action and items.
- Within a PAC Unit, children represent the final outcome. They cannot be subjected to any further disassembly action.
- When it is desired to further disassemble a child, the select child needs to be transformed into a parent and initiate a new PAC unit
- The transformation of child into a parent is performed by expressing the will to further disassembly the selected child.

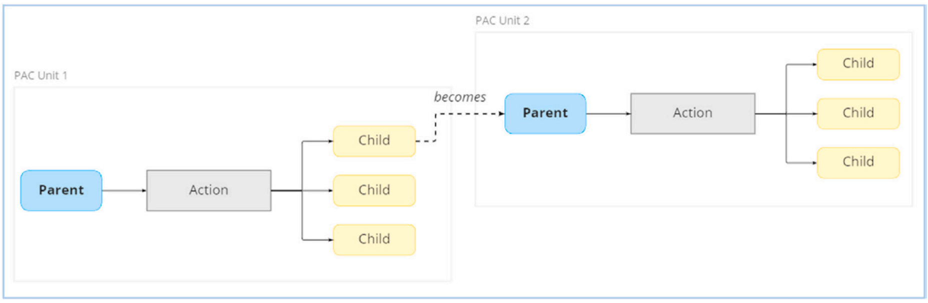


Figure 4.7 Template for the Parent- Action-Child (PAC) model. Image by Formentini and Ramanujan (2023).

The PAC model can simulate the disassembly of products by taking into account their status at the end of their life (EoL), which can be either perfect or actual. Perfect EoL refers to products that have no issues with disassembly or functionality, while actual EoL takes into account real-world issues like rusted screws, worn-out parts, and aesthetic imperfections. To accurately model disassembly at EoL, it's important to understand the product's real-world EoL status. However, this information may not be available during the design phase, so Disassembly Failure (DF) analysis is used to predict potential failures that could impact circularity or disassembly actions.

Step 3. Disassembly failure analysis

There are three types of Disassembly Failures (DFs) in the PAC model:

1. **Type I DFs**: are related to failures that occur during product use and alter the product's End-of-Life (EoL) status. These failures, such as rusted or missing screws, are always related to the children in the model.
   a. One child is affected (OCA)
   b. One child and preceding action are affected (OCPAA)
   c. A child, action, and multiple children affected (CAMCA)

2. **Type II DFs:** are obtained during disassembly actions that further damage the children, and are linked to actions in the model. For example, if a destructive disassembly action damages certain children.
   a. One child is affected (OCA)
   b. More than one child affected (MCA)

3. **Type III DFs:** affect the parent and one or more children at the same time. For example, if two plastic parts are fused together due to high temperature use, the parent from which they originate is damaged, and the original disassembly action is affected. Type III DFs are linked to parents in the model.
   a. Parent, action, and children affected (PACA)

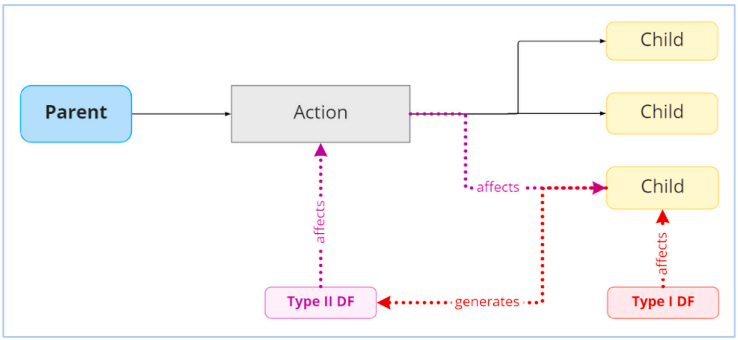


Figure 4.8 Example of Type I and Type II Disassembly Failure. Image by Formentini and Ramanujan (2023).

Step 4. Scenario simulation

After completing the DF analysis, the fourth step is to simulate scenarios and compute indices to assess product performance with respect to each identified DF (Design failure). Each DF generates a scenario with associated indices. The approach considers two indices:

1. **The Disassembly Effort Index (DEI)**, which represents the effort required to disassemble a component. The DEI is linked to actions in the PAC model and is measured in seconds. It represents the time taken to complete an action in a PAC unit or the time to disassemble a parent in a PAC unit via a corresponding action. DEI can be calculated using various methods, including direct experimental measurements or prior literature techniques like the MOST technique.

2. **The Circularity Index (CI),** which represents the circularity performance of the analyzed component. In the PAC model, the CI is linked to children because the end-of-life fate of materials in a PAC unit depends on the generated children. Different circular economy (CE) indicators from prior literature, such as mass percentage of virgin materials in a component or component realized lifetime, can be used to measure the CI. The selection of specific CE indicators depends on the analysis goals and available product data.

An example can be seen in Figure 4.9 where in case no disassembly failure occurs (Benchmark) the red box becomes a critical element demanding more disassembly effort. Where as if disassembly failure 1 occurs, the critical element will be the green box.

Action ID	Action	DEI	
		Benchmark	***DF1***
S1	Separate	1,08	1,08
U1	Unscrew	24,48	57,60
D1	Disconnect	12,96	12,96
UR1	Unscrew & Remove	17,28	17,28
U2	Unscrew	20,52	20,52
U3	Unscrew	19,44	19,44
R1	Remove	21,60	21,60
D2	Disconnect	19,44	19,44
U4	Unscrew	6,48	6,48
U5	Unscrew	15,84	15,84
R2	Remove	3,96	3,96
U6	Unscrew	30,24	30,24
R3	Remove	3,96	3,96
U7	Unscrew	12,96	12,96

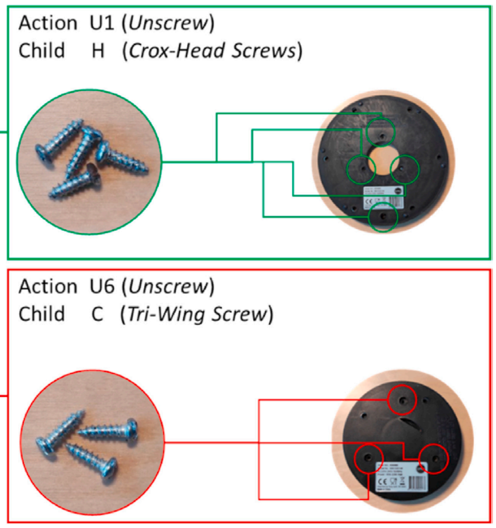


Figure 4.9 Assessing DEI (Design effort index) score depending on the disassembly failure. Image by Formentini and Ramanujan (2023).

Results

The final PAC model results in an excel sheet such as Figure 4.10 where a final score for Disassembly Effort (DEI) and Circularity Index (CI) is awarded. These values are influenced by the impacts of components EoL status on disassembly actions, and consequently the circularity potential of that component (child).

Child ID	Child	Circularity Index (CI)			
		Benchmark	DF1	DF2	DF3
H	Crox-Head Screws	1,00	0,91	1,00	0,00
I	Plastic cover kettle base	1,00	1,00	1,00	0,00
L	Metal ring kettle base	1,00	1,00	1,00	0,00
M	Crox-Head Screws electronic connection to heater	1,00	1,00	1,00	0,00
N	Rings for screws electronic connection to heater	1,00	1,00	1,00	0,00
O	Electronic component	1,00	1,00	1,00	0,00
P	Bolts	1,00	1,00	1,00	0,00
S	Metal Heating Part	1,00	1,00	1,00	0,00
Q	Crox-Head Screws connecting plastic part to metallic one	1,00	1,00	1,00	0,00
R	Plastic Heating Part	1,00	1,00	1,00	0,00
T	Plastic cover handle kettle	1,00	1,00	1,00	0,00
U	Kettle button	1,00	1,00	1,00	0,00
V	Cross-Head Screw for PCB card	1,00	1,00	1,00	0,00
Z	PCB card	1,00	1,00	1,00	0,00
AA	Led	1,00	1,00	1,00	0,00
BB	Cross-Head Screw Handle	1,00	1,00	1,00	0,00
CC	Handle	1,00	1,00	1,00	0,00
DD	Lid	1,00	1,00	1,00	0,00
EE	Probe Faston	1,00	1,00	1,00	0,00
FF	Probe	1,00	1,00	1,00	0,00
GG	Kettle body naked	1,00	1,00	1,00	0,00
C	Tri-Wing Screw	1,00	1,00	1,00	0,00
B	Base Part Cable cover	1,00	1,00	1,00	0,00
A	Top Part Cable cover	1,00	1,00	1,00	0,00
E	Plastic Cap	1,00	1,00	1,00	0,00
D	Small screws copper connections	1,00	1,00	1,00	0,00
F	Plastic structure connector	1,00	1,00	1,00	0,00
G	Cable	1,00	1,00	0,00	0,00

Action ID	Action	Disassembly Effort Index (DEI)			
		Benchmark	DF1	DF2	DF3
S1	Separate	1,08	1,08	1,08	0,0
U1	Unscrew	24,48	57,60	24,48	0,0
D1	Disconnect	12,96	12,96	12,96	0,0
UR1	Unscrew & Remove	17,28	17,28	17,28	0,0
U2	Unscrew	20,52	20,52	20,52	0,0
U3	Unscrew	19,44	19,44	19,44	0,0
R1	Remove	21,60	21,60	21,60	0,0
D2	Disconnect	19,44	19,44	19,44	0,0
U4	Unscrew	6,48	6,48	6,48	0,0
U5	Unscrew	15,84	15,84	15,84	0,0
R2	Remove	3,96	3,96	3,96	0,0
U6	Unscrew	30,24	30,24	30,24	0,0
R3	Remove	3,96	3,96	3,96	0,0
U7	Unscrew	12,96	12,96	0,00	0,0

Total Disassembly Effort (Total DEI)			
Benchmark	DF1	DF2	DF3
210 sec	243 sec	197 sec	0 sec

Total Circularity Index (Total CI)			
Benchmark	DF1	DF2	DF3
1,00	0,99	0,96	0,00

Figure 4.10: DEI (Design effort index) and CI (Circularity indicator) results. Image by Formentini and Ramanujan (2023).

Opportunities and limitations

The PAC (Product-Assembly-Component) model presents various **opportunities** for improving the design for disassembly (DfD) process. One notable opportunity is the **consideration of end-of-life (EoL) product status** and its **impact on disassembly actions**. By factoring in the condition of components and their expected lifespan, the PAC model allows for more accurate evaluation of the circularity potential of a product. This enables designers to make informed decisions regarding the reuse, recycling, or disposal of specific components based on their EoL status. Additionally, the PAC model **introduces indicators** such as the disassembly effort index (DEI) and circularity index (CI), which provide quantitative measures to assess the efficiency and circularity of disassembly operations. These indicators facilitate the identification of opportunities for improvement and support decision-making for more sustainable and circular product design.

However, the PAC Model does have some **limitations**. Assumptions and simplifications were made, such as **calculating disassembly time** using the MOST approach. Time to disassemble a panel in the building site can be different due to practical issues. Therefore a time estimate to disassemble a product would not be very relevant in a real building site scenario if the margin error is too big. Nevertheless, the amount and type of steps necessary to disassemble the panel could give more insights to the assemblers/disassemblers about how much time they need to disassemble it. Furthermore, the disassembly **failure scenarios** are also **difficult to anticipate** in a long period time when external conditions may affect the panels.

4.5 Robustness criteria

It is important to consider the risk for damage during the disassembly process, as highlighted by the PAC Model (Formentini & Ramanujan, 2023). The disassembly procedure might not always occur under ideal circumstances, and when confronted with damage, it can impact the post disassembly scenario. When repair remains a viable option, the potential of engaging in remanufacturing, refurbishing, or reuse becomes more likely. Robustness criteria have been created for specific products such as the one proposed by De Fazio and Maartens (2021), for the company Phillips.

In this case, the robustness scoring indicates the risk of damage when carrying out the disassembly process. The part might already have a failure or damage before disassembly, or there's a potential for damage during the disassembly itself. If the risk of damage is too high then the part cannot be repaired and later reassembled to work as intended. For example, fasteners such as screws receive a 0 rating because they have a high risk of damage if reassembled according to safety standards.

The scoring is derived from a logarithmic formula that plots the durability of a component (y-axis) against time (x-axis). See Figure 4.11. Aldowa provides a 15-year guarantee for their aluminium products and recommends cleaning the product at least once annually. Following this legal and aesthetic service life of 15-years, it's advisable to inspect the product for any required repair procedures or replacements. Notably, the aluminium material itself has a longer technical service life, extending to around 60 years (International Aluminium Institute, 2014). This leads to the utilization of the subsequent graph to capture robustness values:

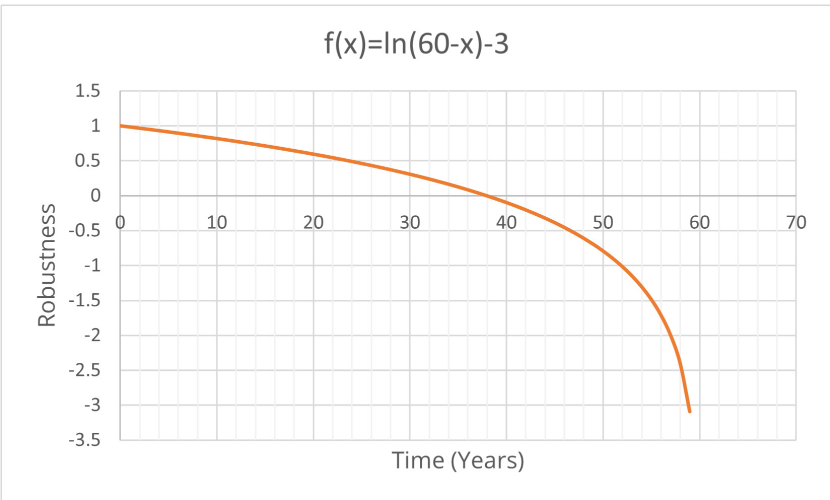


Figure 4.11 Robustness (0-1) vs time (years) graph (Made by author)

Where y represents the robustness score and x the time elapsed since assembly, measured in years, when the product undergoes disassembly. The number 60 is the lifespan of 4 legal service lives of the product and the number 3 allows the result to be in a range between 0-1. This formula can be modified depending on the service life span that the company wants to address. Reliability testing is recommended for future research to ascertain a part's reusability and its capacity to regain intended functionality post-reassembly. Also an FMEA (Failure modes and effects analysis) can be executed to indicate which risks of damage could occur during the disassembly process and how they affect the ability to be reassembled to work as intended.

The following robustness scoring is proposed with f(x=0) =1.0, f(x=10) = 0.9, f(x=15) = 0.8 and f(x=30)= 0.4, f(x=39) = 0.

Robustness

Description	Score
No risk of damage at the end of its service life: The part remains robust and reliable, capable of fulfilling its intended purpose again.	1,0
Low risk of damage at the end of its service life	0,9
Repairable Risk of Damage: presence of a potential risk of damage during disassembly, but this damage is repairable and the part can be reassembled.	0,8
Moderately Vulnerable: There is a notable risk of damage during the disassembly process, and repair might be more challenging. Evaluation and consideration are necessary to determine if repair and reassembly are viable options.	0,4
High risk and reassembly not possible: Attempting to repair and reassemble the part is unlikely	0,0

Table 5.2 Robustness scoring

4.6 Criteria to assess Design for Disassembly

Based on the previous literature and the Cradle to Cradle requirements for DfD from chapter 1, the following criteria to assess the disassembly potential of Aldowa's products can be implemented:

Cradle to Cradle Requirements

It includes the requirements of C2C 5.8 Product Designed for Disassembly:

- Amount of fasteners
- Amount of operations
- Amount of destructive processes
- Amount of tools needed to disassemble the product

BCI - Detachability score

- Type of connection
- Accessibility
- Interdependence: Mold containment and crossings

Disassembly Map & PAC Model

- Disassembly sequence
- Identification of assemblies and parts
- Disassembly penalties
- Disassembly risk of failure: robustness scoring

Disassembly time has not been included. Both the disassembly Map and the PAC model use the MOST (Maynard operation sequence technique) to determine the disassembly time. Its values are typically proprietary and provided by organizations that offer training and certification. These organizations often provide manuals, software, and training materials that include the standardized values for basic motions and work factors. (Accenture's Maynard Assets, 2023) If the company Aldowa would like to know the disassembly time, it could be incorporated in the disassembly guideline by using these standard times.

4.7 Conclusions

Design for disassembly can be applied at various scales, ranging from entire buildings to individual product components. Brand (1994), Eekhout (1997), and Durmisevic (2006) present different hierarchical approaches to optimize disassembly by understanding interdependencies. This approach in the built environment helps reduce waste by separating and reclaiming components, while also enabling new business models based on product-as-a-service.

Implementing design for disassembly in the built environment faces several barriers, including limited awareness, fragmented stakeholder responsibilities, resistance to change traditional industry practices, economic considerations, management and data infrastructure challenges, and regulatory/legal constraints.

Beurskens and Bakx (2015) emphasize the significance of design for disassembly in their circular building construction model. They provide a guideline based on Durmisevic (2006), which considers functional, technical, and physical decompositions to facilitate disassembly.

While most design for disassembly frameworks assume ideal product conditions during disassembly, the PAC Model attempts to account for real-life scenarios. The PAC model and the Disassembly Map compute disassembly sequences that identify parts, actions, and tools, and incorporate time measurements. The Disassembly Map considers target components and disassembly penalties, while the PAC Model incorporates disassembly failure scenarios and a circularity index.

A robustness scoring was proposed to identify the risk of damage when carrying out the disassembly process. This will offer more insights about which is the most appropriate cycling pathway for a post disassembly scenario.

Based on the research from this and previous chapters, several criteria are selected to assess the disassembly potential of a product.

05.

Cycling Pathways

In Section 5.1 the material of aluminium will be discussed, covering its origin, properties, durability, applications and coating methods. Section 5.2 discusses the current end-of-life scenarios of aluminium products. Consequently, Sections 5.3, 5.4 5.5 and 5.6 analyze the opportunities and challenges of the following cycling pathways: reuse, refurbish, remanufacture and recycling. Furthermore, Section 5.7 takes into account the previous findings and proposes a post-disassembly plan. Finally, Section 5.8 concludes the key findings.

List of Figures:

Fig. 5.1 Aluminium primary process
Fig. 5.2 Factors affecting service life
Fig. 5.3 Coating methods
Fig. 5.4 R-strategies
Fig. 5.5 Recycling scenario with Roba
Fig. 5.6 Cycling plan of a circular cassette panel

5.1 Background Information

If panel disassembly is feasible, it is essential to formulate a comprehensive post-disassembly strategy. This strategy should consider the logistics involved and map the potential cycling pathways. Prior to exploring post-disassembly scenarios, it is essential to gain a thorough understanding of the material production process, properties, durability, and coating methods. This section primarily focuses on aluminum as it constitutes the majority of the components in the cassette panel.

Production process

Aluminium is the third most abundant element in the Earth's crust but requires significant energy for extraction and processing (European Aluminium, 2020). It is mined as bauxite ore and then processed into aluminium, a lightweight and versatile metal widely used in various industries. It is known for its excellent strength-to-weight ratio, corrosion resistance, and electrical conductivity. Due to its favuorable properties, it is utilized in applications ranging from construction and transportation to packaging and electronics (ibid).

The production of aluminium products for consumers involves a significant amount of embodied energy. This is primarily attributed to the energy-intensive process that transforms bauxite, the main raw material, into alumina. Bauxite typically contains 20-30% aluminium content, and it undergoes a refining process known as the Bayer process to produce alumina. Subsequently, aluminium is obtained through molten electrolysis, a process that demands substantial electricity (Hydro, 2023). Approximately 2 kg of alumina can be derived from 4 kg of bauxite, resulting in the production of 1 kg of aluminium (ibid.). The embodied energy of aluminium amounts to approximately 186 - 205 MJ of primary energy per kilogram of aluminium extracted and processed (Granta EduPack, 2022).

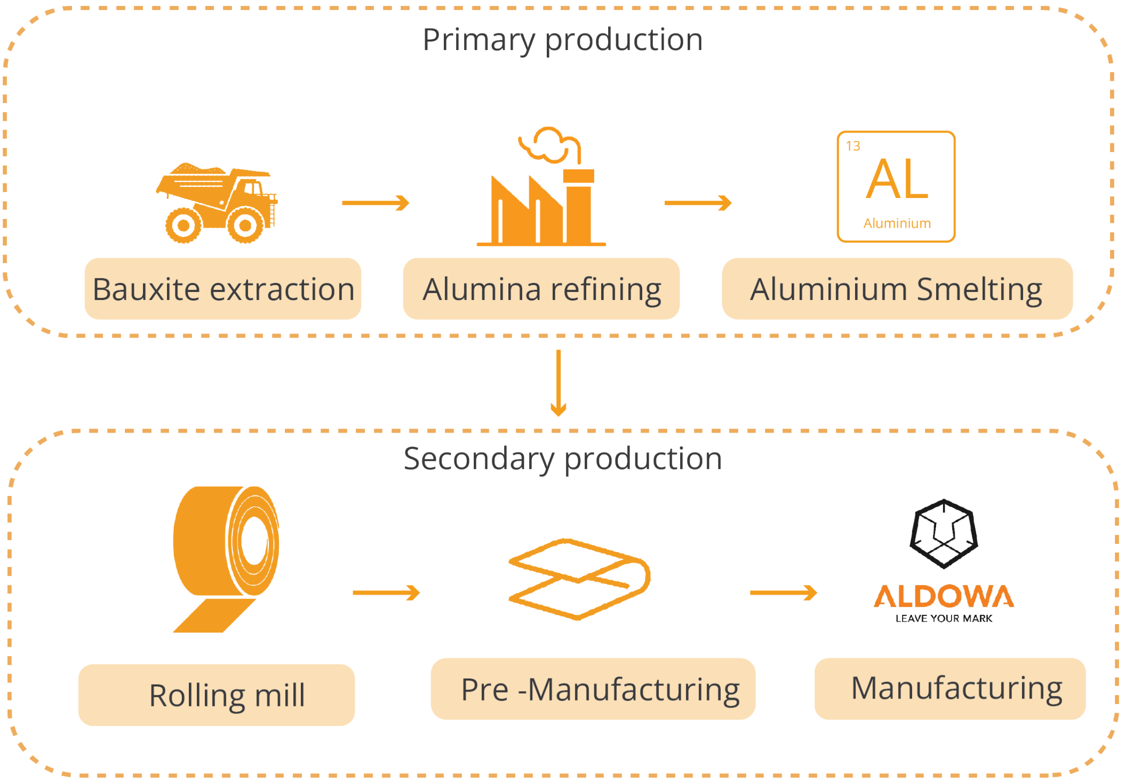


Figure 5.1 Aluminium primary process (Image by author)

Application & Durability

Aluminium lightweight nature and good strength-to-weight ratio, makes it an ideal choice for transportation industries, such as aerospace, automotive,marine and the built environment. Aluminium is extensively used in construction for doors, windows, facades, and structural components due to its corrosion resistance and durability (European Aluminium, 2020) (Hydro, 2023).

According to the International Aluminium Institute (2014), aluminium demonstrates a remarkable longevity. In their comprehensive analysis of 50 aluminium structures constructed between 1895 and 1986, it was concluded that aluminium components exposed to weather conditions, including sun and rain, can have a life expectancy exceeding 80 years. Their study also highlighted the durability of polyester powder coatings, as evidenced by a coating that remained in service for 42 years without requiring reapplication, despite its original 10-year guarantee in 1973. It is important to note that environmental factors, particularly in coastal areas, and low maintenance cleaning may potentially limit these life expectancies.

The material aluminium may have a long life expectancy but its service life may vary depending on the time it remains in productive use before being replaced or disregarded. Hartwell and Overend (2020) distinguish four factors affecting the service life of a component: design/functional, technical, aesthetic, and economic. Cooper (2014) also takes into account these factors and includes the legal lifespan of a component for example in a service business model. All these factors can be seen in Figure 5.2. Hartwell and Overend (2020) argue that service life and the method of disassembly of the different components has to be considered when comparing the most appropriate end-of-service scenario.

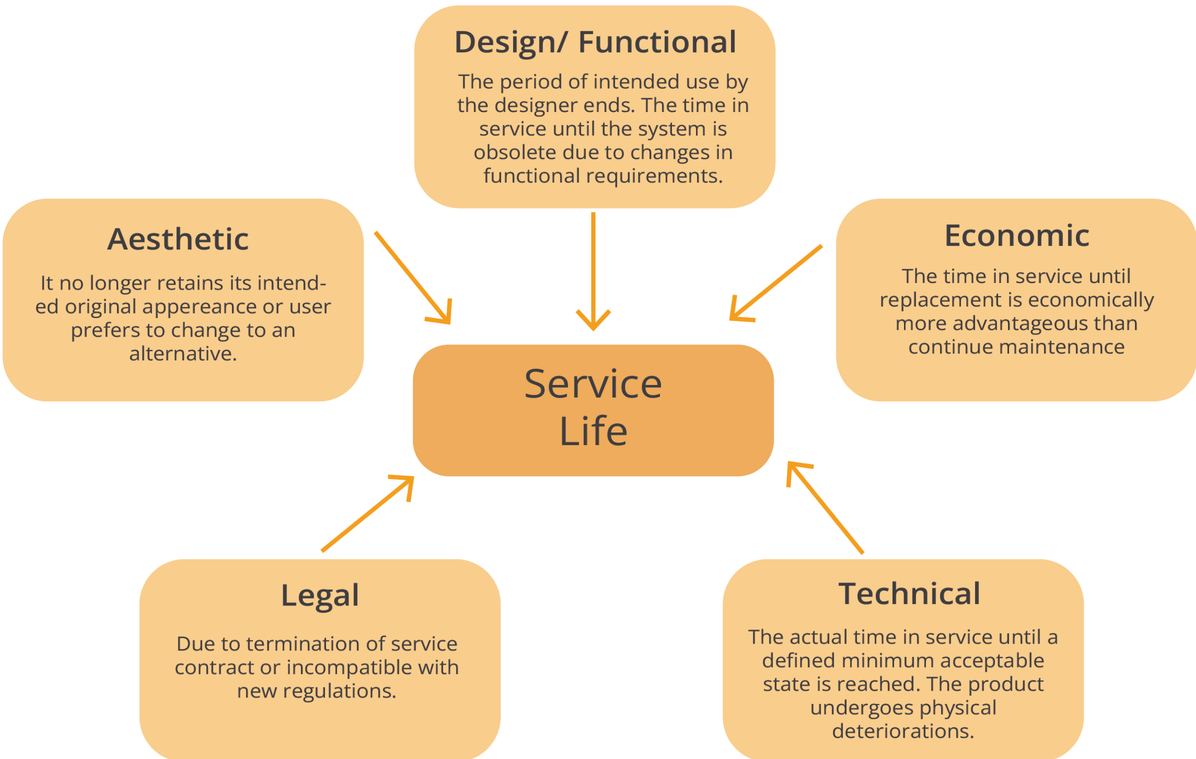


Figure 5.2 Factors affecting service life . Image adapted from Hartwell and Overend (2020) and Cooper (2014)

Coating process

Understanding the coating process of aluminium products is crucial for determining end-of-life strategies such as reuse, refurbishment, remanufacturing, or recycling. The coating acts as a protective layer, enhancing durability and corrosion resistance. By assessing the coating type, condition, and compatibility, decisions can be made regarding the feasibility of different options. Intact coatings may allow for reuse or refurbishment, prolonging the product's life, while worn or incompatible coatings may indicate the need for remanufacturing or recycling. Additionally, the coating process can impact recyclability, with certain coatings introducing complexities or contaminants.

Powder coating and anodization are the two primary coating processes used for Aldowa's aluminum products. In order to provide a comprehensive understanding of each process information presented by Evans and Guest in 2002 and the International Aluminium Institute in 2014 will be synthesized:

Anodization- Aluminium anodizing is a process that enhances the surface of aluminium by creating a protective oxide layer. The process as shown in Figure # involves immersing the aluminium in an electrolytic bath and passing an electric current through it. This causes oxidation to occur on the surface of the aluminium, forming a layer of aluminium oxide. The thickness of this oxide layer can be controlled to achieve desired properties. Anodizing provides several benefits, including increased corrosion resistance, improved durability, and the ability to apply various colors and finishes to the aluminium surface.

Powder coating - Aluminium powder coating is a process used to apply a protective and decorative coating to aluminium surfaces. It involves three main steps: preparation, application, and curing. Firstly, the aluminium surface is cleaned and treated to ensure proper adhesion. Then, charged dry aluminium powder particles are sprayed onto the prepared surface, creating a uniform coating. The thickness of the coating can be adjusted for desired protection and appearance. Lastly, the coated aluminium is heated in an oven, causing the powder to melt and form a durable coating. This curing process enhances adhesion and resistance to scratches, chemicals, and UV rays.

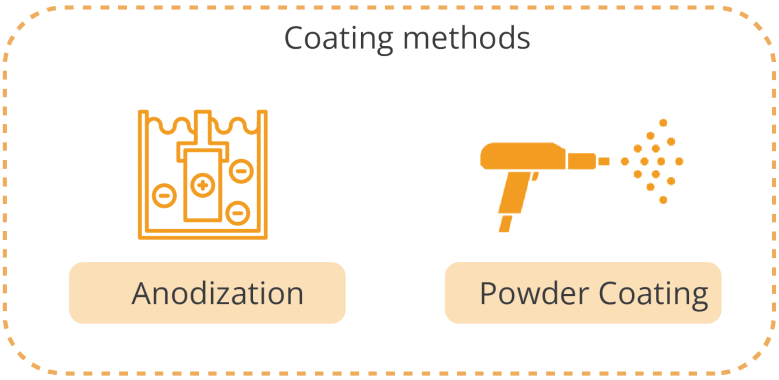


Figure 5.3 Coating methods (Image by author)

De-Coating process

Coatings play a vital role in extending the service life of aluminium products. However, when it comes to the end of a product's lifespan, the presence of the coating can present challenges for reuse, refurbishment, remanufacturing, or recycling. For instance, the client may desire a different color for a panel, or the panel itself may need to be decoated to serve a new purpose. Recycling coated scrap metals also leads to more impurities, making a prior decoating process crucial for achieving a higher metal yield. Several methods exist for recycling coated products, including pyrolysis, twin chamber furnaces, bed type ovens, and rotary kilns (Evans & Guest, 2002).

However, these processes involve direct re-melting of coated scrap, leading to significant contamination and gas emissions. According to Evans and Guest (2002), "all products exhausting from the decoating process, with the possible exception of water vapor, are harmful to the environment." Kvithyld et al. (2008) explored the opportunities offered by thermal decoating processes without oxidizing the metal. However, achieving the right balance between insufficient, optimal, and excessive decoating, which may result in oxidation, presents a time frame challenge. Further advancements in decoating processes and their practical implementations are necessary.
During a visit to Coating, a powder coating factory near Aldowa, it was clarified that they **do not** undertake **decoating procedures**, but they are capable of recoating products. However, they cannot ensure an identical finish to the initial recoated product. They further mentioned that **recoating** can be carried out a maximum of **three times**, otherwise excessive accumulation of powder on the edges hinders proper coverage of the product.

5.2 End-of-life

In the end-of-life scenario of Aldowa's cassette panels, the panels are not reclaimed because they belong to the building owner. Their end of life scenario is therefore unknown. The assumption is that when a building comes to its end of life a demolition or dismantling company takes apart the building and the panels. The product then ends up according to the end-of-life scenarios for aluminium scrap recorded in 2019 in Europe, as outlined by European Aluminium (2020), are 50% used in Europe, 30% exported legal or illegally (mainly to Asia), 20% ending up in a landfill or collected and recycled without proper registration (ibid). This situation highlights the fact that half of end-of-life aluminium scrap is not reclaimed, resulting in a loss of high value for the European economy and companies such as Aldowa.

To address this issue, the highlighted R-strategies from Figure 5.4 will be investigated to extend the service life of the panels and ensure a proper recycling end of life. By maximizing the environmental and economic advantages associated with aluminium while minimizing waste and losses in end-of-life management, a more sustainable system can be created. Therefore, this sub-chapter focuses on the following potential cycling pathways: reuse, refurbish, remanufacture and recycle. This will provide the necessary knowledge for informed decision-making for a post-disassembly scenario of Aldowa's products.

While there is limited literature on aluminium cassette panels like those produced by Aldowa, case studies on other aluminium products, such as automobiles, were examined to gain insights into the cycling opportunities for aluminium components.

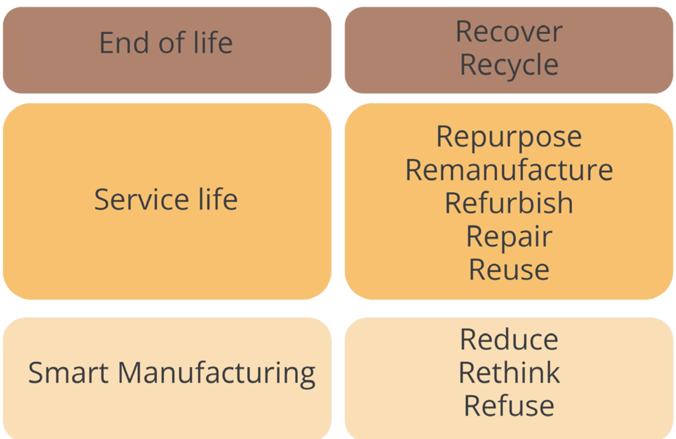


Figure 5.4 R-strategies.
Image adapted by author based on CircularX: Circular Economy - an Introduction. TU Delft online course

5.3 Re-use

Applications
The reuse of components is a known practice, although the amount of metal that is actually reused and documented tends to be small (Cooper, 2014). However, there is one notable example of extensive industry-wide component reuse in Asia, specifically in the ship dismantling sector, where a significant portion of the world's discarded ships are broken down. Studies conducted by Tilwankar et al. (2008) on the Indian steel industry and Asolekar (2006) on ship-breaking waste indicate that up to 95% of the steel recovered from vessels in India is repurposed as re-rollable ferrous material.

Opportunities
In his PhD thesis, Cooper (2014) focuses on the potential for reuse of steel and aluminium components without melting them. The results of the study suggest that up to 30% of steel and aluminium currently used in various products could be effectively reused. To facilitate future reuse efforts, Cooper provides valuable recommendations for redesigning these components such as design for disassembly, standardization, product identification and a need for a reuse assessment protocol.

Challenges
Despite its benefits, Cooper (2014) also highlights the following barriers to the implementation of the Re-use strategy:
1. Non-destructive disassembly of products:
2. Unknown properties of reclaimed parts need to go through mechanical testing
3. Obsolescence of reclaimed parts and incompatibility
4. The reuse of components in other Aldowa projects is limited mostly by aesthetic factors such as irregular dimensions, varying depths, shape and color which pose challenges for their incorporation into new designs.

Conclusions
Reuse is a compatible cycling pathway for the **back structure** of the cassette panel because these components are not coated and since they are placed at the back of the panel they do not have to meet aesthetic requirements. A material **passport** (Cooper, 2014) could help Aldowa control the service status of the product's parts. When the panels are disassembled from the building **mechanical tests** need to be carried out from a sample of the whole amount of components that will be reused. Platform **CB'23** is a platform working towards reuse building components regulations and guidelines to provide quality assessments for this types of reuse (CB, 2023). Their guidelines can be useful for future **reuse assessments**.

5.4 Re-furbishment

C2C definition
"The process of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure, and making cosmetic changes to update the appearance of a product, such as cleaning, changing fabric, painting, or refinishing" (C2C®, 2021).

Applications
According to Hu et al. (2023) the electronics industry is leading in refurbishment product programs and the automobile industry is starting to integrate it in their business models. Toyota started its "trade in and refurbishment program" where they take back used cars and restore them to better conditions for their new mobility sub-brand called Kinto. They will perform refurbishment three times on their product before recycling it. This will allow to extend the vehicle's life cycle. In their study, the authors create a framework to identify when a manufac-

turer should offer trade-in and refurbishment programs to increase its profits.

A **trade in program** consists on a model where consumers dispose their used product in exchange for cash, a new one or refurbished product. This model is practiced already by automobile companies (Toyota, Tesla, BMW and Subaru), electronic companies (Apple, Best Buy, Amazon, Target, AT&T and Verizon) and clothing companies (H&M, The North Face, Levi's, Patagonia).

A Dutch design-driven manufacturer of baby strollers also implemented a **lease and refurbishment pilot project**. The strollers would undergo two consecutive lease cycles and be refurbished after each cycle. Once the second lease cycle is completed, the strollers would be refurbished, certified, and sold on the second-hand market as Bugaboo Refurbished, while the leasing contract would automatically end after a period of six months to three years (Sumter et al., 2018) .

Opportunities

Refurbishment opens the door to a different business model where **maintenance, leasing contracts** or **second hand** products are available. Both Hu et al. (2023) and Sumter et al. (2018) agree that **design for durability** and **design for disassembly** are key design strategies to facilitate refurbishment. Hu et al. (2023) argues that manufacturers can always increase their profit by improving the quality of their new products and reducing the quality depreciation rate. In other words, producing **durable** products.
The authors propose two types of business models for refurbished products (Hu et al.,2023) :

1. **A leasing model**: The consumers will use the product at a lower price than the new product's sales price. Since the company owns the product it is incentivised to design it more durable.
2. **Second hand model**: The consumers use the product at a lower price and the company does not own the product after use.

Challenges

The case studies conducted by Hu et al. (2023) and Sumter et al. (2018) have highlighted three category challenges:

1. Functional Challenge: There is a need to establish a consensus on the frequency of maintenance offered within a specific time period. While maintenance can extend the product's lifespan, it also entails additional costs. Manufacturers must have a clear understanding of different failure modes and corresponding maintenance procedures. It requires finding a balance between improving the **repairability** of individual parts and maximizing the overall **durability** of the product. This decision impacts the selection of materials and connecting mechanisms.

2. Management Challenge:

a. Post-lease periods involve managing an **inventory** of both **old** and **new parts**. Adequate control and documentation are necessary for each part, along with suitable storage arrangements before their next use.
b. It is crucial to establish a model that can categorize parts based on their quality and **expected lifetime**. Different parts may have varying requirements, such as lasting for three use cycles, degrading during one use cycle, requiring replacement after each use cycle, or being designated for one-time use.

3. Financial and Legal Structures: Refurbished products, whether leased or second-hand, require different **contract agreements** compared to new products. The provision of personnel for maintenance, status control, and other related tasks is also essential.

Conclusions
Refurbishment is a compatible cycling pathway for Aldowa's cladding products because they can be kept in use for a longer period of time, reducing the need for new production and resource consumption. This R-strategy creates economic opportunities and new markets where manufacturers can offer **value-added services**, **extend the lifespan** of their products and fulfill the growing demand for **sustainable and affordable alternatives**. Several functional, management, legal and financial challenges mentioned above need to be addressed to achieve this.

5.5 Re-manufacturing

C2C definition
"The process of disassembly and recovery at the subassembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a **new one**. This process includes **quality assurance** and potential enhancements or changes to the components." (C2C®, 2021).

Remanufacturing, unlike refurbishment, focuses on restoring used products to their original performance, ensuring the same quality as new equivalents. Ijomah and Chiodo (2010) argue that achieving this superior quality and performance requires more work. The remanufacturing process begins with product disassembly, such as removing a façade system from a building. Then, it is transported back to the manufacturing facility and further disassembled into parts.

Applications
The automotive sector accounts for two-thirds of the re-manufacturing business volume (Steinhilper & Weiland, 2015). Additionally, other industries, such as aerospace, medicine, and industrial equipment, are increasingly adopting re-manufacturing strategies (ibid). Steinhilper and Weiland (2015) suggest that the longer the product's service life, the more suitable it is for re-manufacturing.

Opportunities
Remanufacturing offers various opportunities for manufacturers to stay competitive, reduce waste, conserve resources, save energy, cut costs, and contribute to pollution reduction (Ijomah & Chiodo, 2010) (Steinhilper & Weiland, 2015) (Boorsma et al., 2019). These opportunities are individually explained further:

1. **Competitive advantage:** Remanufacturing can provide a competitive edge because it allows manufacturers to offer profitable and sustainable solutions, differentiate themselves in the market, and meet the growing demand for environmentally conscious products.
2. **Waste reduction and resource conservation:** Remanufacturing plays a central role in waste management, material recovery, and environmentally conscious manufacturing. It limits waste generation and reduces energy and resource consumption compared to conventional manufacturing.
3. **Energy savings:** Remanufactured products require significantly less energy to produce compared to new equivalents. Studies from Ijomah & Chiodo (2010) indicate that remanufactured products can achieve energy savings of 50-80% compared to conventional manufacturing processes. By reducing energy consumption, remanufacturing contributes to lowering CO_2 emissions and mitigating environmental impacts.

Challenges

Re-manufacturing presents significant opportunities for manufacturers to embrace circular practices and benefit at the same time. However, its adoption remains limited in the building industry (Boorsma et al., 2019). Through the studies conducted by Boorsma et al. (2019) and Ijomah and Chiodo (2010), the following challenges have been identified:

1. **Challenges in product disassembly:** Products are nor designed to be disassembled which makes cleaning and repairing almost impossible.
2. **Reverse logistics and collection systems:** Retrieving used products or components from customers can be complex. Mostly because building products are part of a large supply chain of an entire building which includes many stakeholders.
3. **Lack of consumer awareness & willingness to buy:** Customers are less willingly to buy a remanufactured product if the price is similar or more to the new alternative.
4. **Economics (production costs and prices):** In the study of remanufactured electrical and electronic products, Ijomah and Chiodo (2010) argue that remanufactured products must be at least 25% cheaper than new alternatives to win customers. Low production costs can allow lowering the selling price
5. **Period of ownership:** The service life of Aldowa's aluminium panels is relatively long compared with the period of ownership of a building. As the owner changes those responsible for maintenance might not know the original manufacturer of the building product. The user therefore, contacts a general repair or demolishing company instead of the original manufacturer.
6. **Regulatory and legal considerations:** Compliance with regulations related to product warranties, labeling, and safety can pose challenges for remanufacturers.

Conclusions

Implementing remanufacturing as a cycling pathway at the end of service of Aldowa's cassette panel requires a lot of planning in logistics, production process, design and a new business strategy. There is a whole study about re-manufacturing with specific guidelines on how to adopt it in an existing manufacturing process.

Boorsma et al. (2019) compiles a list of 46 design for re-manufacturing guidelines from their literature research . Furthermore, in the second paper, Boorsma et al. (2018) argues that the main barrier for its practice is operational. Therefore, Boorsma et al. (2018) created a **step by step workshop** to help a **manufacturing company become a re-manufacturing company** as well and overcome these operational barriers. Aldowa could use this guideline for a further study on how to implement remanufacturing in their production and business model.

5.6 Recycle

C2C definition
"The process by which a material, after serving its intended function, is processed into a new material via mechanical or chemical transformation and then added to a new material formation in a different context."
(C2C®, 2021).

Applications
The recycling of end-of-life aluminium is already significant, with high recycling rates in sectors such as automotive and building. However, due to the long lifespan of aluminium products and the growing demand for aluminium, the availability of post-consumer scrap is limited. The amount of aluminium reaching its end-of-life creates a potential pool of scrap that can be reintroduced into the circular economy (European Aluminium, 2020).

The European Aluminium (2020) differentiates two types of metal scraps:

1. **Pre-consumer scrap:** is the material leftovers generated during the manufacturing or production process before they reach the consumer. It is defined by the European Aluminium organization (2020) as the scraps, "generated during the transformation of semi-finished products into finished products."
2. **Post-consumer scrap:** are discarded metal materials from used products. They are collected for recycling and transformed into raw materials for manufacturing new metal products, reducing the need for virgin metals.

Opportunities
Forecasts suggest that the amount of post-consumer aluminium available for recycling will more than double by 2030, reaching 8.6 million tonnes by 2050 (European Aluminium, 2020). By mid-century, it is estimated that 50% of aluminium needs, could be supplied through post-consumer recycling. The recycling process for aluminium requires significantly less energy compared to primary production, resulting in reduced greenhouse gas emissions (Hydro, 2023).

For the Bronze level, Aldowa aims to **recycle** its products as **recovery strategy**. Most of the materials are made of aluminium so a meeting was arranged with Lars, the representative from Roba, one of Aldowa's primary suppliers of aluminum, to explore the potential for establishing this recovery scenario. Lars elaborated on a potential future scenario involving Roba's two divisions: aluminum sheet providers and their scrap melting facility. The proposed process entails the collection and examination of Aldowa's metal scraps, both pre- and post-consumer, at the melting facility to assess their alloy qualities. In the case of post-consumer scrap, such as the dismantled cassette panel, it must be completely disassembled into separate components based on their alloy type. Strict measures are in place to prevent metallic contamination, as contaminated components would be subject to downcycling.

Once the scraps are melted, Roba sells the resulting aluminum grades to third-party entities who process them into coils, which are then sold back to Roba. Roba utilizes these coils to create aluminum sheets, which are subsequently sold to Aldowa. A visual representation of this recycling scenario can be found in Figure 5.5.

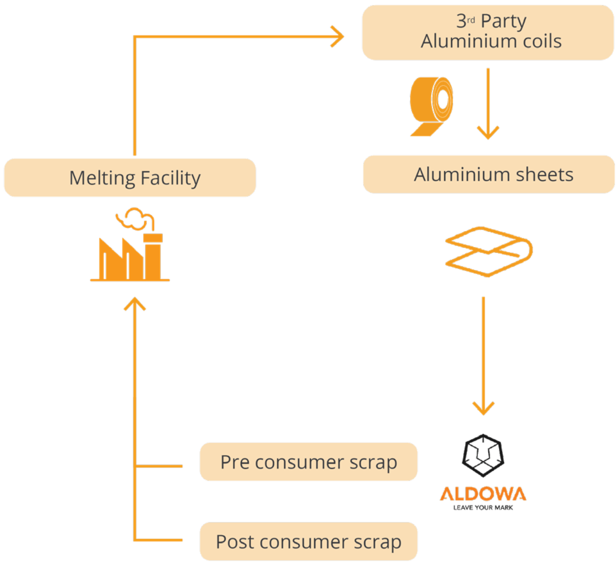


Figure 5.5 Possible recycling scenario with Roba (Illustration by author)

Challenges

Even though aluminium can be theoretically recycled infinite times, inefficiencies in separation of metals and recycling processes result in impurities in secondary metals. Therefore, addition of virgin metals to meet purity requirements is still in practice (Soo et al., 2018). In their study on end-of-life vehicles, Soo et al. (2018) analyzed the impact of different joining techniques on the presence of impurities in aluminium recycling streams. They found that mechanical fasteners, primarily made of steel, were a major contributor to the presence of iron (Fe) impurities in the recycled aluminium stream. Therefore, a proper disassembly and separation of alloy components is necessary as well as planning the logistics for the recollection of the panels after consumer use.

The following list of challenges have been identified by putting together the conclusions from International Aluminium Institute (2015), European Aluminium (2020), Soo et al. (2018), Wallace (2011), and interviews with Roba metals and Hydro.

1. **Impurities:** Aluminium recycling faces challenges due to the presence of impurities and contamination from other materials and alloys.
2. **Sorting Complexity:** Manufacturers need to improve the sorting of different alloys and grades of aluminium in both pre and post-consumer scrap to ensure effective recycling.
3. **Energy Intensive:** The recycling process for aluminium is energy-intensive, requiring innovative energy processes and advanced sorting technologies like Eddy Current or Robotics.
4. **Collection and Transportation:** With the increasing volume of end-of-life aluminium, efficient methods for collecting and transporting aluminium scrap to recycling facilities need to be developed.
5. **End-of-Life Product Design:** Product designs should consider recycling possibilities and prioritize easier disassembly to facilitate the collection of components for recycling.

Conclusion

Recycling is a common practice for pre and post consumer aluminium products. Measures have to be taken to separate the different alloys, specially coated components, to prevent down cycling. Aldowa's main recovery scenario is recycling the aluminium parts of its products. Discussions with Roba are taking place to plan a future collaboration.

5.7 Post-disassembly scenario

Criteria per cycling pathway

The cycling pathways previously explained will be compared to understand which strategies need to be implemented to conduct the corresponding cycling pathway after disassembly Aldowa's products.

Strategies	Reuse	Refurbish	Remanufacture	Recycle
Design for disassembly	√	√	√	√
Design for repairability		√	√	
Design for durability	√	√	√	
Design for remanufacture			√	
Standardized connections	√	√	√	
Modular connections	√	√	√	
Product passport	√	√	√	√
Identify core materials	√	√	√	√
Identify failure modes	√	√	√	
EoS Inspection tests	√	√	√	
Find storage possibilities	√	√	√	
Select a suitable business model	√	√	√	
Partnership with recycling facilities				√

Table 5.1 Strategies for each cycling pathway

Currently, Aldowa's cladding products lack modular or standardized connections. This is primarily due to the customizability required for each project, as engineers have the flexibility to design a back structure that best suits the specific project's needs. Furthermore, the proximity of the factory allows for the production of customized brackets and other components. However, incorporating standard or modular connections into the design can result in a more adaptable structure that is well-suited for future post-disassembly scenarios.

5.8 Conclusions

Aluminium is widely used in the built environment due to its lightweight and good strength-to-weight ratio. Nevertheless, its primary production requires a lot of energy which can be reclaimed at the end of its service life. Most of aluminium product's end of life scenarios are currently in a landfill or a recycling facility, largely due to inadequate alloy separation leading to downcycling.

To extend its service life, various cycling pathways were analyzed. The opportunities and challenges of case studies implementing those cycling pathways were assessed. The initial crucial step to enable reuse, refurbishment, or remanufacturing is designing for disassembly. The following list outlines the strategies essential for all these cycling pathways:

1. Design for disassembly
2. Design for repairability
3. Design for durability
4. Standard and modular connections
5. Product passport
6. Identification of core materials
7. Identification of failure modes
8. EoS inspection tests
9. Storage possibilities
10. Adoption of a suitable business model

06.

Company Analysis

Section 6.1 introduces the company's products. Section 6.2 illustrates the current lifecycle of a product, detailing its manufacturing, production, and assembly processes. Section 6.3 identifies key stakeholders influencing design for disassembly, while user research findings are outlined in Section 6.4. The subsequent sections outline guideline requisites for each stakeholder (Section 6.5) and summarize key conclusions in Section 6.6.

List of Figures:

Fig. 6.1 Aldowa's facade products
Fig. 6.2 Parts to be certified
Fig. 6.3 Fasteners to be certified
Fig. 6.4 Current Life cycle of a Cassette Panel
Fig. 6.5 Left: Metal scrap from punching. Right: Illustration
Fig. 6.6 Top Left: Sizes of dies. Top Right: Bending machine. Down middle: Bending process
Fig. 6.7 Metal pallet
Fig. 6.8 Filler plates
Fig. 6.9 Pallet list document
Fig. 6.10 Sticker identification
Fig. 6.11 Cycling plan of a circular cassette panel
Fig. 6.12 Aldowa's workflow of a project

6.1 Product and system breakdown

Aldowa is a leading facade company specializing in the manufacturing, production, and assembly of high-quality facade systems. They offer a range of products, including roof caps, water sills for windows, cassette panels, box panels as depicted in Figures 6.1. Aldowa can attach these panels to various structural materials, including concrete, timber, steel, and curtain walls.
While Aldowa's facade elements demonstrate high design and functionality, it's important to note that they are not water resistant. In most cases, the responsibility for incorporating insulation materials lies with other involved parties.

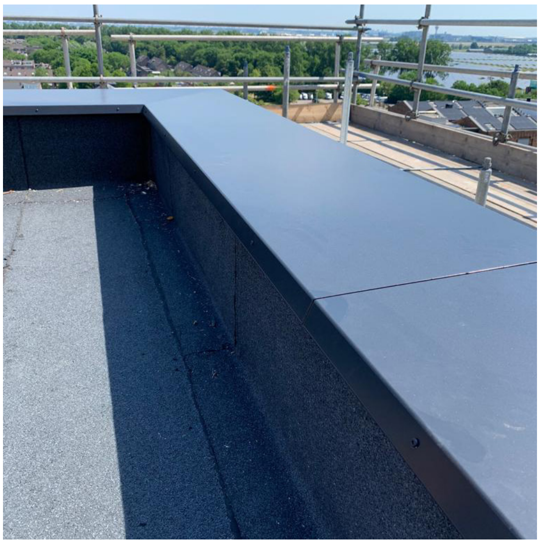


Figure 6.1a Aldowa's facade products: Roof cap. (Picture taken by author)

Figure 6.1b Aldowa's facade products: Window water sill (Picture taken by author)

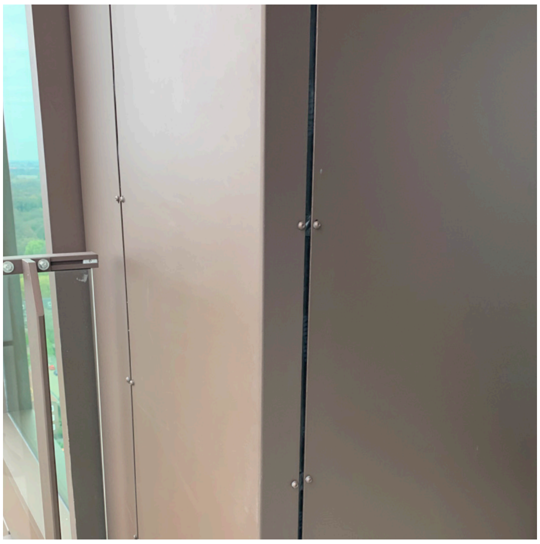


Figure 6.1c Aldowa's facade products: Box panel with exposed screws. (Picture taken by author)

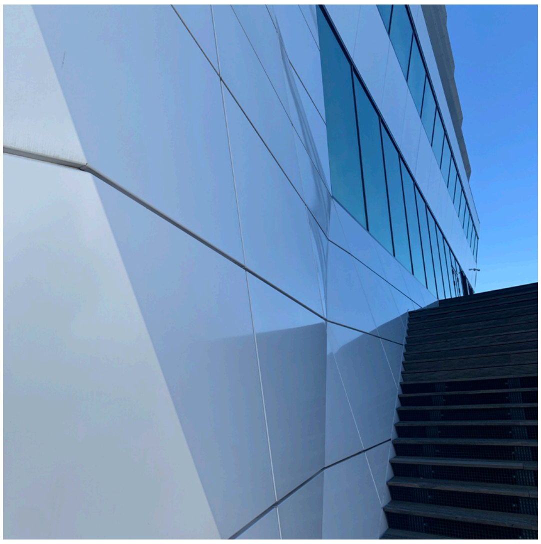


Figure 6.1d Aldowa's facade products: Cassette panels with hidden screws (Picture taken by author)

The products used mainly in a project are roof caps, water sills and a type of panel (cassette or box panel). For the Cradle to Cradle certification they want to certify the cassette panel along with the roof caps and the water filtration panels. See Figure 6.2 to see the parts and Figure 6.3 to see the fastening elements.

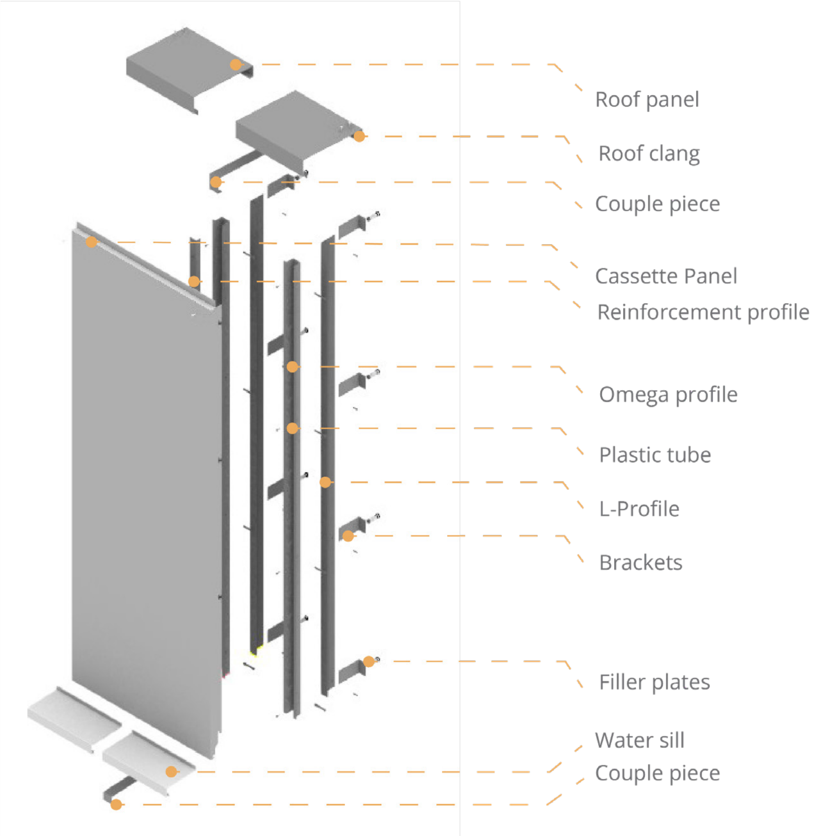


Figure 6.2 Parts to be certified (Illustration made by author)

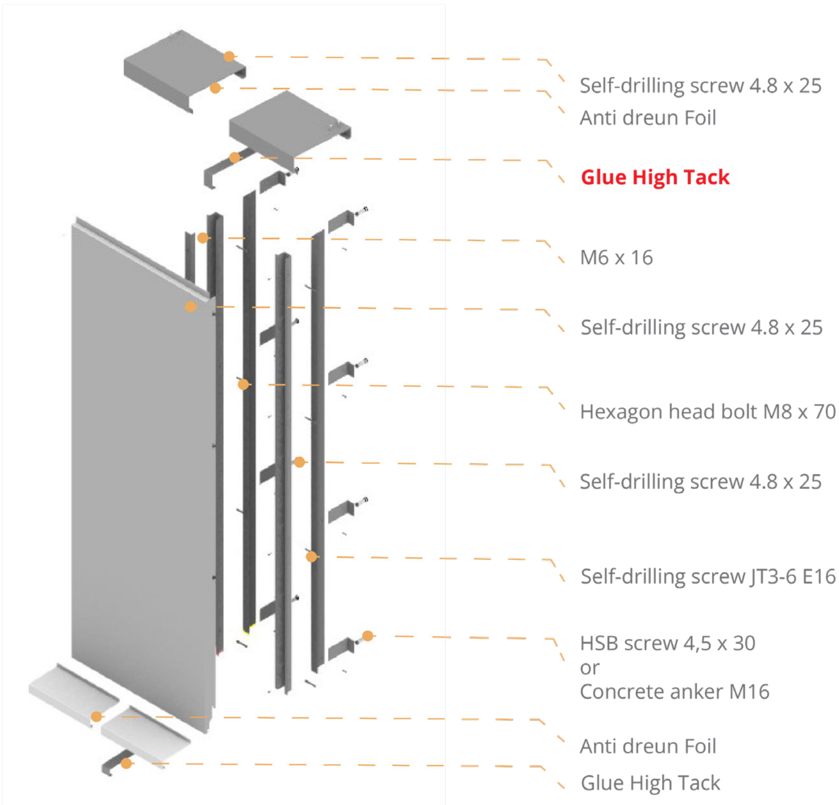


Figure 6.3 Fasteners to be certified (Illustration made by author)

Figures 6.2 and 6.3 show the list of the certified parts/fasteners and their corresponding materials. The material that needs to be replaced is the “Glue High Tack” that is used to connect the couple pieces with the roof caps or the water filtration panels. It contains chemicals listed in the RSL (Restricted substances list) so an alternative needs to be found.

6.2 Life cycle of products

It is important to understand the existing product life-cycle and map the stakeholders involved in product specification. A typical life cycle of a cassette panel is pictured in Figure 6.1. The manufacturing, production and assembly process are furthered explained in the following paragraphs.

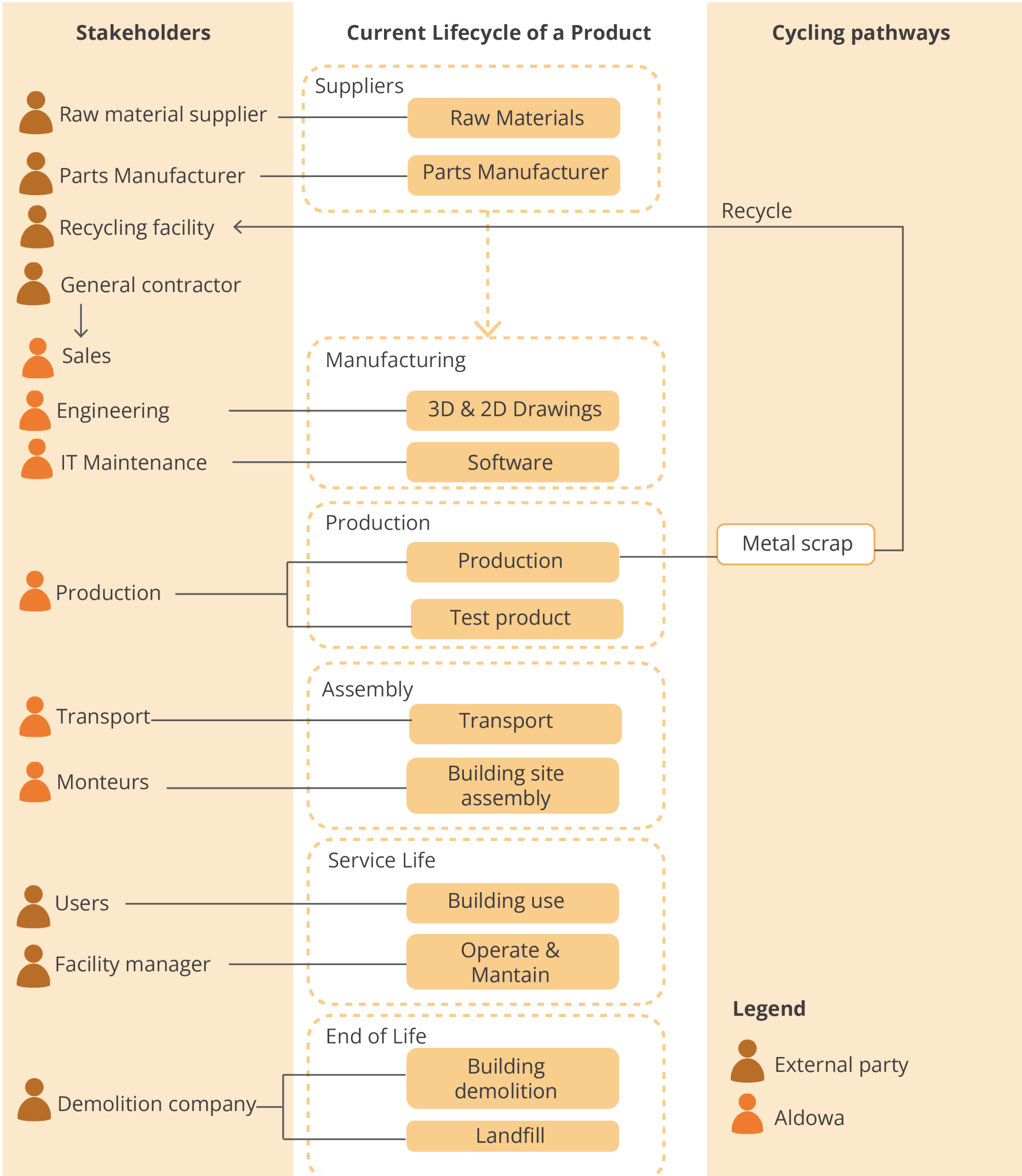


Figure 6.4 Current Life cycle of a Cassette Panel (Illustration by author)

1. Manufacturing process

The manufacturing process starts when a client accepts the offer calculated by the sales department and the drawings and agreements are sent to the engineer. The engineering department plays a crucial role in ensuring that the project aligns with the customer's or architect's expectations. The engineer creates technical drawings that serve as the foundation for the design process using advanced software such as Solid Works or Catia.

Throughout the progression of the project, the drawings undergo continual refinement, gradually gaining more details and controlled by the Project Manager. Collaboration between the engineering and production departments is integral, with frequent exchanges to test the feasibility of designs and determine manufacturing possibilities.

2. Production

Production starts after the engineer sends the production drawings. The timing and sequence of production are determined by the priority assigned to each product and the quantity of parts required. To fabricate these components, Aldowa orders aluminum or steel sheets that are then subjected to various manufacturing techniques, including punching, bending, and rolling, depending on the specific design specifications. This is achieved through the utilization of hydraulic or electrical machinery, equipped with a range of specialized tools for creating different cuts and diverse bending angles.

It is worth noting that the leftover scrap metal resulting from the punching process, as depicted in Figure 6.2, is sent to Metallimex, a metal recycling facility near Aldowa. In terms of bending, Aldowa employs a die, as illustrated in Figure 6.3, to achieve the desired shape. During the bending process, specific optimization rules are followed to account for any material length loss that may occur. This ensures accurate planning and efficient utilization of materials throughout the production phase.

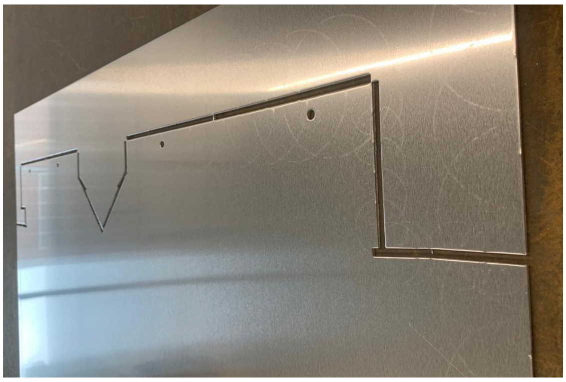


Figure 6.5a Metal scrap: from punching.
(Picture made by author)

Figure 6.5b Metal scrap: Illustration
(Illustration made by author)

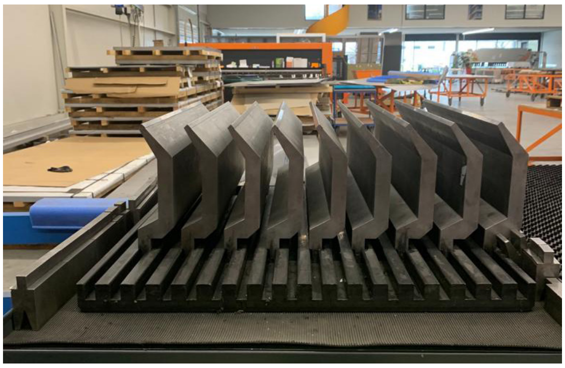


Figure 6.6a Punching equipment: Sizes of dies
(Picture made by author)

Figure 6.6b Punching equipment: Bending machine.
(Picture made by author)

Figure 6.6c Punching equipment: Bending process
(Illustration made by author)

3. Assembly

The following information was gathered from visits to various building sites. More information about these visits is recorded in the appendix.

Once the production process is complete, each part is assigned a unique identification number with a corresponding sticker. These labeled parts are then carefully stacked on metal or wooden pallets. Each pallet is accompanied by a pallet list document, which outlines the order and sub-order numbers along with the quantity of products included. To ensure secure transportation, the products are wrapped with plastic foil before being dispatched to the designated building site.

Upon arrival at the site, the assemblers refer to the pallet information, assembly drawings, and the 3D model via Ipads to start the assembly process. The specific assembly method employed varies depending on the project’s requirements and may involve the use of scaffolding, construction lifts, cranes, mast towers, or other suitable equipment. A minimum of two assemblers work in collaboration to complete the task efficiently.

Since the cladding elements are typically installed towards the final stages of the building process, the assembly team must coordinate with other involved parties responsible for assembling their respective building components. This interdependency can introduce greater tolerances than initially anticipated and occasionally lead to unexpected errors during the assembly stage. Mainly plastic filler plates are used to overcome the tolerances.

Figure 6.7 Metal pallet (Picture taken by author)

Figure 6.8 Filler plates (Picture taken by author)

Figure 6.9 Pallet list document (Picture taken by author)

Figure 6.10 Sticker identification (Picture taken by author)

Post-disassembly plan

By taking into account the criteria for each cycling pathway from the Chapter 5 and the company analysis of this Chapter 6, a future cycling plan for a circular facade product has been mapped out in Figure 6.11.

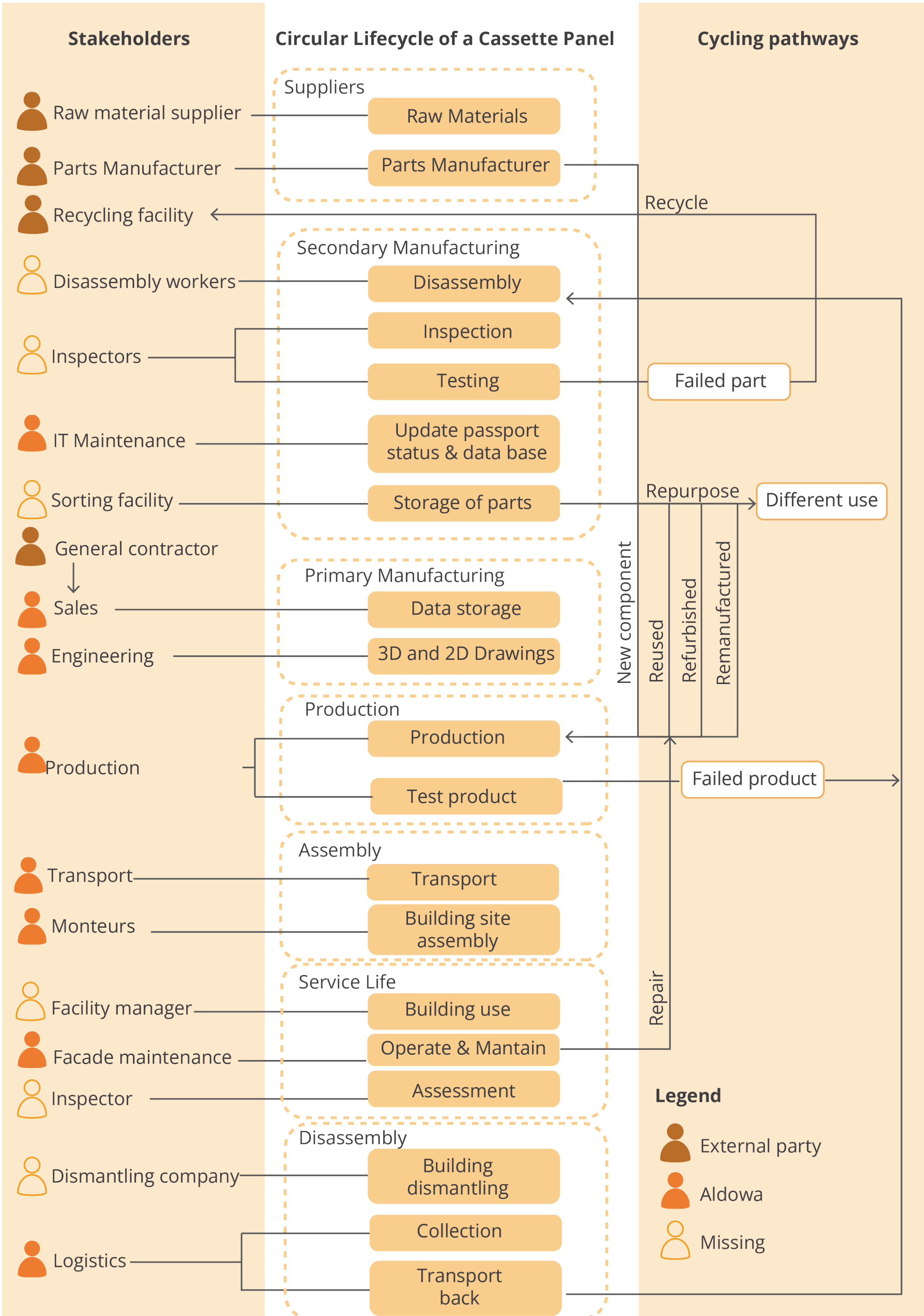
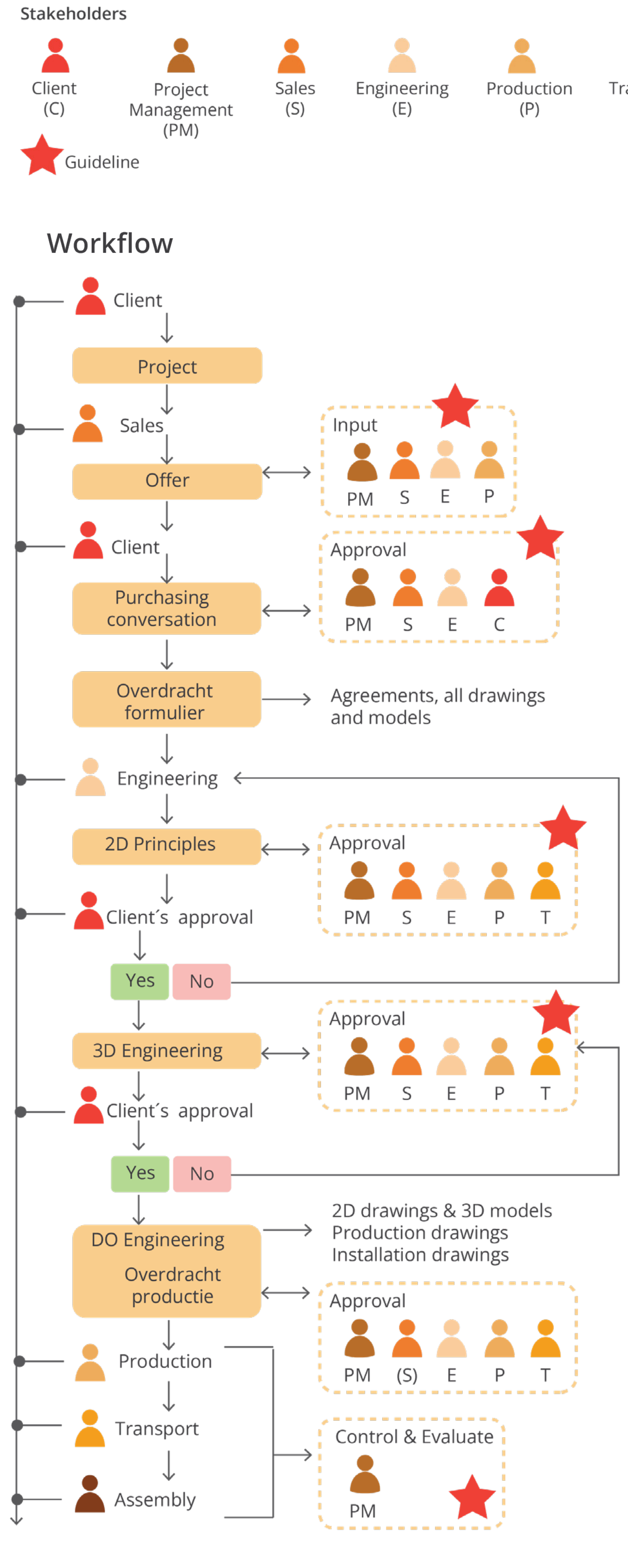


Figure 6.11 Cycling plan of a circular cassette panel (Image by author)

6.3 User research

To identify the barriers facilitating the disassembly process it is important to understand who are the stakeholders involved in design for disassembly and what information do they need. User research was conducted to provide insights into what the new DfD guideline should include, how it can be most impactful and what visualizations are necessary for the corresponding stakeholders. A typical internal workflow of a project has been mapped out by interviewing the potential users and the key moments to implement the DfD guideline have been identified in Figure 6.12:



1. The client places a potential project in the online platform 12Build and sends it to a list of possible contractors who he or she would like to work with.

2. The sales department receives the project specifications and analyses if it is in the scope of Aldowa. The drawings detail level ranges from sketches to already detailed 2D drawings. Then, with the input of other stakeholders an offer is made and sent to the client.

3. During the purchasing conversation the budget is established with the approval of all the stakeholders.

4. After everybody agrees, the sales department writes an “overdrachts formulier” (transfer form) with the agreements for materials, engineering, production and assembly.
This is a key moment because the type of materials and connections are determined in this stage.

5. The engineer receives the transfer form together with all the agreements and available drawings of the project. They create more detailed 2D drawings and ask for approval. Sometimes, they ask for approval of an external constructor to carry out a structural analysis.

6. After approval the engineer starts with the 3D drawings and sends them again to the client.

7. After approval the definitive drawings are created, approved and sent to production. While it is being produced the engineer makes the installation drawings.

8. The production department receives the orders and starts production.

9. Depending on the size, shape, location, etc, the logistics department arranges the transport of the products to the coating place or directly to the building site.

10. The constructors receive the pallet(s) with identification numbers, 2D drawings and a 3D model in an ipad to start the assembly.

Figure 6.12 Aldowa’s workflow of a project (Illustration made by author)

6.4 User research results

Sales Department

The sales department of Aldowa establishes the boundary conditions of the design and fills in an excel sheet for the budget. Along with the client and other stakeholders they agree on the types of materials and connections that will be used. Not all materials are within the cradle to cradle certification and only demountable connections facilitate disassembly. Therefore, the guideline should **help the sales department identify which materials are within the certification scope and which types of connections are more desirable.** In this way, they can already create a budget offer that aligns with the Cradle to Cradle requirements. It is also necessary that the sales department understands what a Cradle to Cradle product means and the importance of choosing demountable connections to answer any questions the client may have.

Engineering department

The engineer has to design the 2D and 3D drawings according to the agreements established by the sales department. They can be encountered with two scenarios: an existing design/ drawing which they have to improve or a vague design/ idea which they have to engineer from 0. The guideline should **help them improve the disassembly of an existing design or design a new product for disassembly**.
In most cases if they want to reduce or know the minimum amount of connections for a panel they ask an external structural engineer. There are also rules of thumb from which they can base their designs but they are very general. Therefore, the guideline should **help them calculate in an easy way what is the minimum amount of connections necessary for a structural safe product.**

Project Leaders

Project leaders have the responsibility for overseeing the entire project development lifecycle. In a Cradle to Cradle project, their role encompasses the verification of compliance with product certification requisites. This entails unique selection of materials and connections to ensure alignment with C2C standards. The guideline will **serve as a roadmap for delineating tasks to be executed by other stakeholders, and check if they are fulfilled**.

Production, transport & assembly

The engineers must engage in communication with these departments to ascertain the feasibility of production, transportation, and assembly for their designs. Specifically,the transport and assembly departments were consulted to envision a reverse logistics framework for a potential disassembly scenario. Unfortunately, they lacked knowledge of it so further research is necessary to carry out the reverse logistics of a post-disassembly scenario.

In the present context, the guideline should **serve the purpose of outlining when in the design process the engineers should validate their designs with these departments**. Furthermore, the guideline should include recommendations that these departments could implement to facilitate the disassembly process.

6.5 Guideline requirements

Based on the company analysis and user research, the following guideline requirements are proposed:

What is the goal of the guideline?

To provide a comprehensive manual that enables Aldowa to engineer fully demountable facade products.

Characteristics of the guideline:
- Easy to follow and implement
- Helpful

What is the result?

The steps that need to be taken from the first phase of the design-manufacturing process until the assembly of the facade products. Research recommendations for a post-disassembly scenario.

What should the guideline include and for who is it relevant?

The guideline for the _____ department should ____ .

Sales department

- Present a brochure about our C2C products that includes:
  - Exploded image of the main product's parts
  - Aldowa's cradle to cradle vision
  - Information about the certified product
  - What is Cradle to Cradle
  - How does the certification work
- Answer frequently asked questions about:
  - Cradle to Cradle
  - Design for disassembly
- Present an Excel file that calculates
  - If the design aligns with the C2C bill of materials
  - If the connections are detachable (BCI index)
- Advice on:
  - Which disassembly companies to contact
  - Which material 2nd hand data bases/ markets to contact
  - Further research topics to investigate

Engineering department

- Help engineers [insert scenario].
- Ensure that their design aligns with the requirements of Design for Disassembly of the Cradle to Cradle manual

Scenario 1: Improve the disassembly of an existing design
Scenario 2: Design a new product for disassembly

Project leaders department

- Let project leaders know which Cradle to Cradle Design for disassembly checklist needs to be completed or agreed upon during a project workflow

Production & Transport department

- Give advice to engineers on when to reach out to the Production/Transport department for their approval of the design and ask them:
  - If it can be produced?
  - If it can be transported?
- Advice on:
  - Punching the identification number on the parts instead of using a sticker
  - Further research about transport optimization to reduce transport emissions
  - Further research about replacing plastic foil of the pallets for transportation

Monteurs

- Advice on
  - Make the drawings accessible in a database, both 2D drawings and 3D models for the disassembly phase
  - Allow builders to be able to make or indicate changes in the building site that get recorded in the 2D & 3D drawings

6.6 Conclusions

Aldowa's product line primarily comprises four distinct products, each featuring various material types and dimensions. The company's goal is to obtain certification for a cassette panel accompanied by a roof cap and a water filtration panel. To achieve certification, all constituent parts' and fasteners' materials **cannot** be listed in the Restricted Substances List (RSL). However, a single fastener is made out of a material that falls within the RSL; thus, an alternative material must be identified.

In order to delineate a general life cycle of a cassette panel, practical investigations were conducted within the company, involving interviews and on-site visits. Aldowa's primary role within this life cycle encompasses manufacturing, production, and assembly. While Aldowa plays a key part, other absent stakeholders crucial for realizing a fully circular Cradle to Cradle (C2C) facade product life cycle have been identified.

The user research undertaken focused on identifying the primary stakeholders with significant influence in the design for disassembly process. The result is a compiled list of requirements that delineate the necessary content for the guideline. This will facilitate Aldowa design fully demountable and certified facade products. It's important to note that these requirements are customized to fulfill the needs of each stakeholder involved in the design for disassembly process.

07.

The DfD Guideline

Section 7.1 lists the different documents of the DfD guideline. Section 7.2 focuses on the sales department guideline and explains when and how it can be used. Section 7.3 is divided into three sub-sections focused on the guideline for the engineering department. Sub-section 7.3.1 outlines the steps to make a Disassembly Map. Sub-section 7.3.2 states the method and parameters used for a structural analysis of a parametric model of a cassette panel. Sub-section 7.3.3 outlines the steps to re-design with the help of a design for disassembly road map. Section 7.4 concludes with a summary of the guideline.

List of Figures:

Fig. 7.1 Users and application moments of the DfD Guideline
Fig. 7.2 Aldowa's Cradle to Cradle products flyer
Fig. 7.3 Aldowa's standard budget calculation sheet
Fig. 7.4 C2C check: Bill of Materials
Fig. 7.5 C2C check: Type of Connections
Fig. 7.6 Steps to make a Disassembly Map
Fig. 7.7 Grasshopper model flow chart
Fig. 7.8 Aluminium material properties Karamba
Fig. 7.9 Wind pressure coefficients
Fig. 7.10 Wind regions and peak velocity pressures
Fig. 7.11 Maximum deflection
Fig. 7.12 Parametric model of the cassette panel showing the sliders and the shape of the bed hooks for support points.
Fig. 7.13 Steps to re-design for disassembly

7.1 Introduction

The design for disassembly guideline consists on different documents that can be used by its respective users. See Figure 7.1. It consists on five main files: The Cradle to Cradle products flyer (PDF file), C2C_Check_Bill_of_Materials (Excel file), the structural analysis calculation (Grasshopper file), the guideline: How to make a Disassembly map (PDF file), and the guideline: Redesign process (PDF file). The complete PDF documents can be found in the appendix. The following sub-sections will explain who are the users, when can they use it and what does it include.

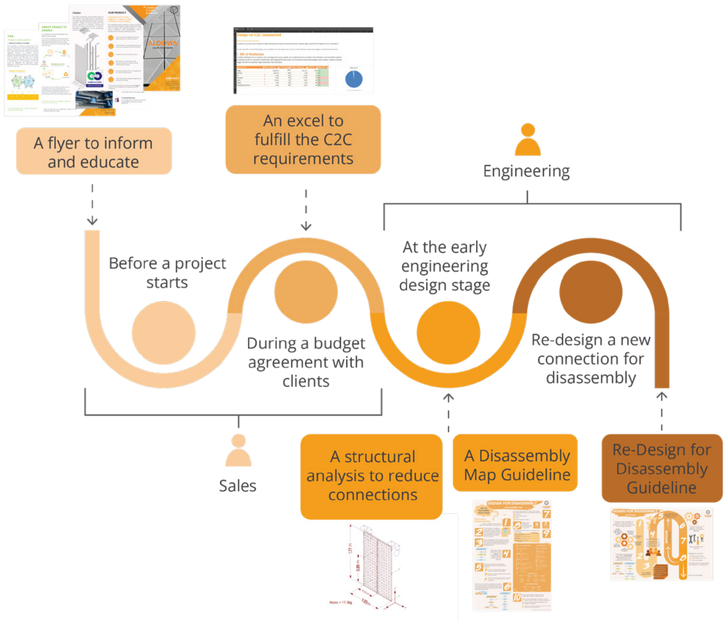


Figure 7.1 Users and application moments of the DfD Guideline (Illustration made by the author)

7.2 Sales department

The Cradle to Cradle products flyer can be used **before a project starts** to inform the client about Aldowa's certified products. It highlights the certified product's key attributes, emphasizing the significance of design for disassembly, which promotes efficient recycling and other R-strategies. The flyer outlines how products undergo assessments for different criteria such as material health and product circularity. Clients can also learn about Cradle to Cradle's core principles and frequently asked questions are addressed. Importantly, the flyer also serves as an internal tool, informing the sales department about the certified product, enabling them to better communicate its value to customers.


ABOUT CRADLE TO CRADLE

A concept by Michael Braungart and William McDonough

This visionary approach prioritizes positive impacts by prohibiting the use of toxic materials and engineering products that undergo continuous recycling or repurposing throughout their life cycle.

Our products can be deconstructed into raw materials at the end of their lifecycle, transforming our cladding systems into valuable resources for creating new products, thus eliminating waste and enabling potential reuse.

For more information on Cradle to Cradle visit: https://c2ccertified.org/

"It is necessary to rethink how we design our products and integrate sustainable practices from the beginning to the end of the production process. By adopting this approach, we can construct products that possess long-term value and meet the demands of a sustainable future."

CRITERIA FOR CERTIFICATION

To attain Cradle to Cradle Certified® Product Standard certification, products must undergo evaluation against five extensive criteria, each carrying equal weight. Among these requirements is the design for disassembly, which Aldowa incorporates into their C2C products.

1. **Material Health**
Ensuring the use of environmentally safe and healthy materials. No certification is granted if a material is listed in the restricted substances list.

2. **Product circularity**
Engineering products to extend their service life and ensure recycling at the end of their life cycle.

3. **Climate protection**
Striving to utilize renewable energy sources and implementing carbon management practices to minimize the product's carbon footprint.

4. **Water & Soil Stewardship**
Employing conscious water management strategies to conserve and handle water & soil responsibly.

5. **Social fairness**
Promoting ethical practices and social responsibility, ensuring fair labor practices.

FAQ

Frequently asked questions

1. What is Cradle to Cradle?

The foundation of Cradle to Cradle stems from the book authored by Michael Braungart and William McDonough. Their approach, distinct from other system theories aimed at minimizing negative impacts, is centered around generating a positive impact. This is achieved through a twofold strategy: firstly, by NOT using toxic materials, and secondly, by creating products that can undergo continuous recycling or repurposing at the conclusion of their life cycle. By adopting this approach, waste generation is eliminated, and the environment remains unharmed.

For more information on Cradle to Cradle visit: https://c2ccertified.org/

2. What does a Cradle-to-cradle Certification mean?

The Cradle to Cradle Products Innovation Institute (C2CPII), located in San Francisco, has developed an evaluation system aimed at creating, assessing, and certifying products that meet the C2C requirements. In response to the increasing demand for building certifications like LEED, BREEAM, and DGNB in recent years, there has been a corresponding rise in the need for sustainable materials and products.

C2C certification serves as an independent confirmation of a product's quality, encompassing various aspects. It verifies compliance with harmful emissions throughout installation, usage, and dismantling processes. Moreover, the certificate holds weight as evidence of sustainability, making it valuable for use in tender specifications that prioritize eco-friendly solutions.

3. Why do the products need to be demountable?

Design for disassembly means that the product is designed in such a way that the product can be demounted from the building and dismantled into assemblies and further into parts in a non-destructive way. After the disassembly process the parts can be recovered, sorted and inspected to apply an R-strategy (Reuse, refurbish, repair, remanufacture or repurpose) to extend its service life.

4. How does the certification work?

To achieve the certification, Aldowa must demonstrate strict adherence to all the certification standards, documenting and providing corresponding certificates and measurements as evidence. The certification body conducts a conformity check based on the submitted documents. Only upon meeting all the requirements, Aldowa is granted the certificate. It's worth noting that the certification needs to be renewed every two years.

If any materials are found to be in the RSL (Restricted substances list), Aldowa must replace them with other material alternatives. This process ensures that the company's facade products meet the highest environmental and sustainability standards. Due to the strict analysis of the composition of materials, which extends deep into the supply chain, Aldowa involves suppliers and subcontractors in the process. To protect sensitive information, such as production processes, suppliers may use non-disclosure agreements (NDAs) to safeguard their business secrets.

5. What is the difference between general recycling and Cradle to cradle recycling?

Recycling, especially aluminium recycling, faces challenges due to impurities, leading to "downcycling" where materials lose their technical quality. Cradle to Cradle recycling aims for consistent, high-quality circulation by proper disassembly, separating materials to prevent contamination and preserve their value from manufacturing and finishing processes.

CONTACT

Spaarnestraat 49
3044 CM Rotterdam
+31 (0)10 - 208 37 88
info@aldowa.nl

Figure 7.2 Aldowa's Cradle to Cradle products flyer (Flyer made by author)

C2C Check Excel Sheet

The second part of the guideline for the sales department is an automatic excel calculation **during a project agreement with clients**. They already use an extensive excel file to calculate the budget of a project. See Figure 7.3. In this excel file they have to calculate the amount of materials and type of connections that will be used, among other factors affecting the budget. Another excel sheet has been added named "C2C Check" which automatically calculates the following:

1. If the materials are within the certified list of materials and in accordance with its respective quantities (See Figure 7.4)
2. It presents a detachability score only based on the average type of connections. (See Figure 7.5) The scores are based on the BCI index where the desired final score has to be above 0.5.

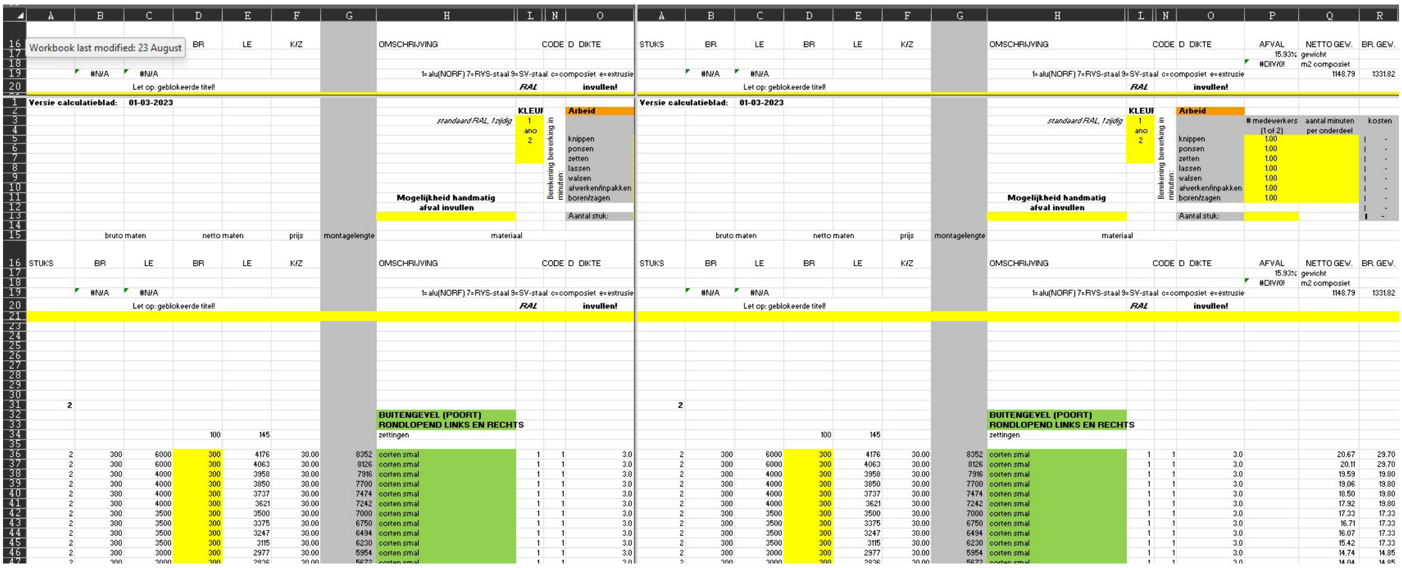
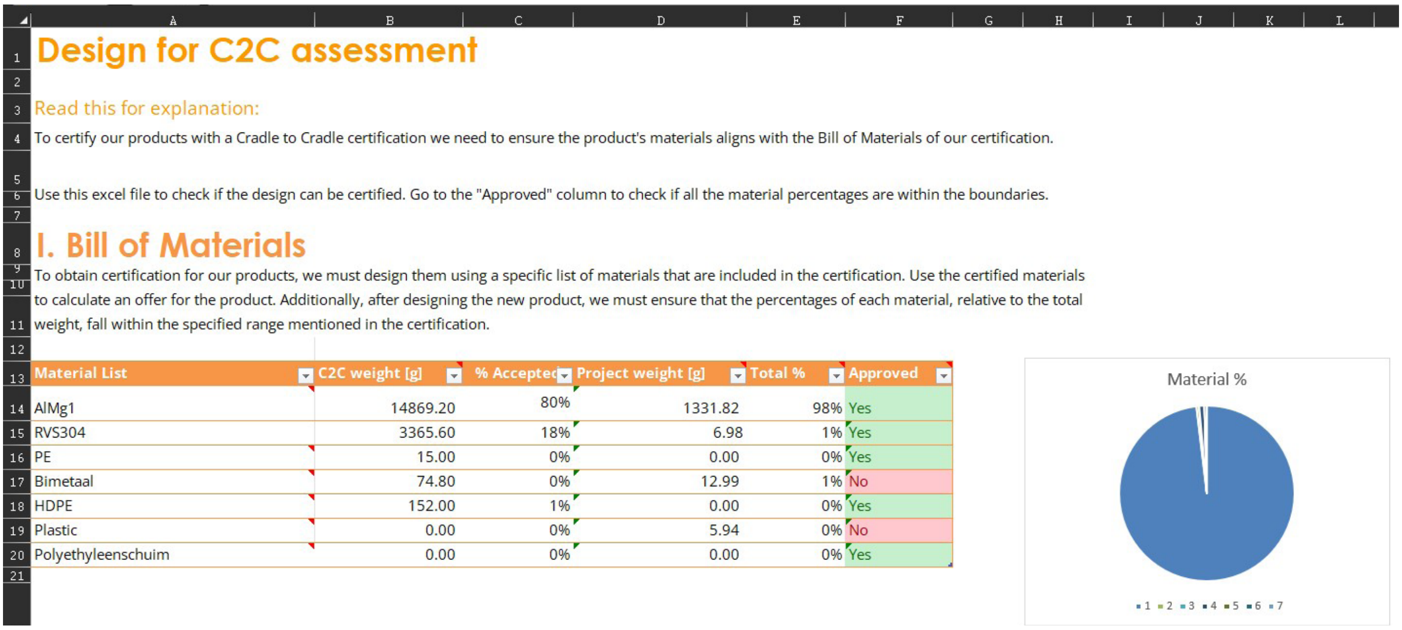


Figure 7.3 Aldowa's standard budget calculation sheet (Excel sheet made by Aldowa)



Design for C2C assessment

Read this for explanation:

To certify our products with a Cradle to Cradle certification we need to ensure the product's materials aligns with the Bill of Materials of our certification.

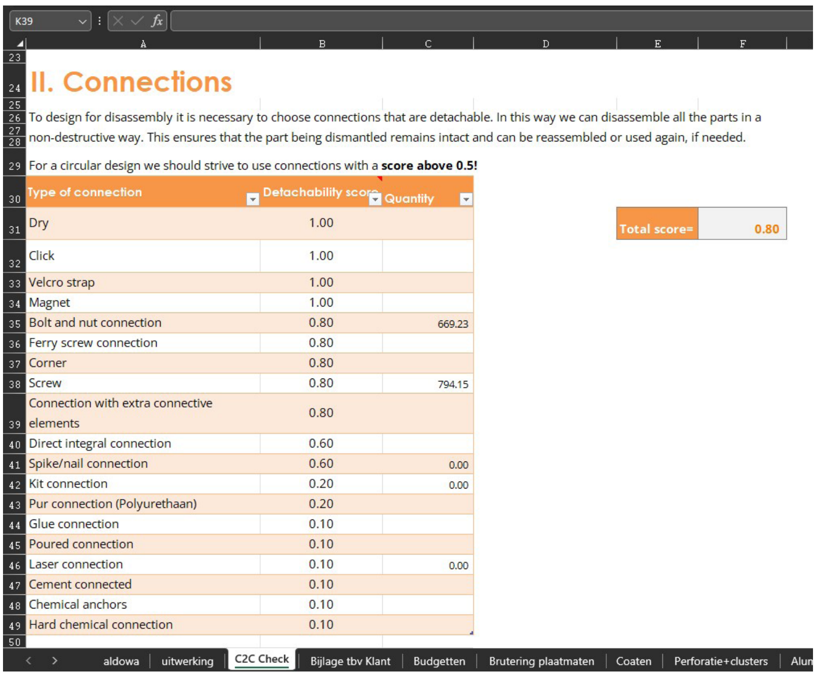
Use this excel file to check if the design can be certified. Go to the "Approved" column to check if all the material percentages are within the boundaries.

I. Bill of Materials

To obtain certification for our products, we must design them using a specific list of materials that are included in the certification. Use the certified materials to calculate an offer for the product. Additionally, after designing the new product, we must ensure that the percentages of each material, relative to the total weight, fall within the specified range mentioned in the certification.

Material List	C2C weight [g]	% Accepted	Project weight [g]	Total %	Approved
AlMg1	14869.20	80%	1331.82	98%	Yes
RVS304	3365.60	18%	6.98	1%	Yes
PE	15.00	0%	0.00	0%	Yes
Bimetaal	74.80	0%	12.99	1%	No
HDPE	152.00	1%	0.00	0%	Yes
Plastic	0.00	0%	5.94	0%	No
Polyethyleenschuim	0.00	0%	0.00	0%	Yes

Figure 7.4 C2C check: Bill of Materials (Excel sheet made by author)



II. Connections

To design for disassembly it is necessary to choose connections that are detachable. In this way we can disassemble all the parts in a non-destructive way. This ensures that the part being dismantled remains intact and can be reassembled or used again, if needed.

For a circular design we should strive to use connections with a **score above 0.5!**

Type of connection	Detachability score	Quantity
Dry	1.00	
Click	1.00	
Velcro strap	1.00	
Magnet	1.00	
Bolt and nut connection	0.80	669.23
Ferry screw connection	0.80	
Corner	0.80	
Screw	0.80	794.15
Connection with extra connective elements	0.80	
Direct integral connection	0.60	
Spike/nail connection	0.60	0.00
Kit connection	0.20	0.00
Pur connection (Polyurethaan)	0.20	
Glue connection	0.10	
Poured connection	0.10	
Laser connection	0.10	0.00
Cement connected	0.10	
Chemical anchors	0.10	
Hard chemical connection	0.10	

Total score= 0.80

Figure 7.5 C2C check: Type of Connections (Excel sheet made by author)

Further advice

Based on the literature and practical research, several valuable insights have emerged that could benefit Aldowa in its future endeavors.

I. Supporting supply chain for take-back infrastructure

Reverse logistics processes following the detachment of a product from a building have to be further investigated. Aldowa currently collaborates with an external construction and assembly company, which could also offer disassembly services. Other notable disassembly companies have been identified that are actively engaged in building dismantling and could give insights into reverse logistics, including:

- New Horizon
- De Heren van Demonteren

For future scenarios where Aldowa aims to repurpose their products, they can explore the following second-hand databases to find clients:

- DuSpot
- Insert.nl
- Oogstkaart
- Material Scout

II. Traceability

To enhance the identification of parts and materials, it is suggested that codes be punched into components instead of using adhesive stickers. This method offers increased durability, aiding in better part identification and reducing material consumption. However, it's necessary to conduct a comparison to determine whether the energy expenditure associated with punching outweighs the material savings.

III. Material substitution for packaging

Exploration of alternative materials to replace plastic foil in transport packaging needs to be investigated. The following packaging materials could be tested:

- Truck tarps
- FIBC (Flexible intermediate bulk container) Big bags (Bouwzakken) from the company LC Packaging where they use a reuse system

7.3 Engineering department

After a budget agreement is established with the client, all the drawings are sent to the engineer. The detail of the drawings could range from sketches to worked out connection details. In any case, the engineers can use the guideline in this **early engineering design stage** when preparing the more elaborated 2D drawings.

The method proposed to assess the disassembly potential of a design is by creating a Disassembly Map. A disassembly map is a flow chart showing the disassembly steps needed to disassemble all the parts. One way to do this is easily with the website Miro.com. but they can also draw it on paper or use any other visual tool. An overview of the steps to create a Disassembly Map is shown in Figure 7.6. Each step is explained afterwards.

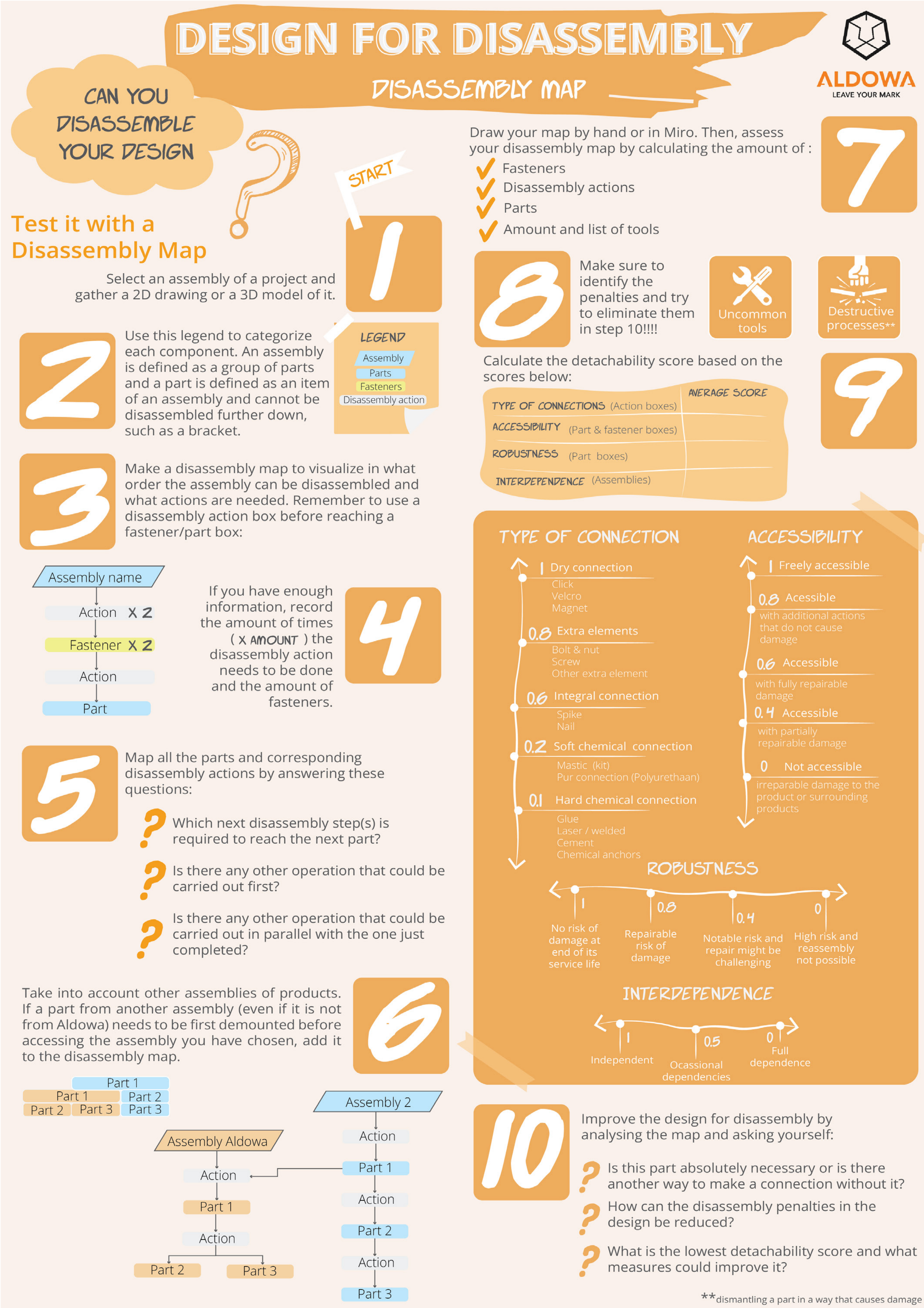
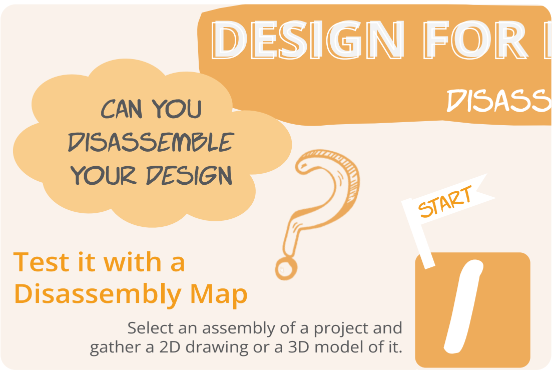


Figure 7.6 Steps to make a Disassembly Map (Illustration made by author)

7.3.1 Disassembly Map Steps

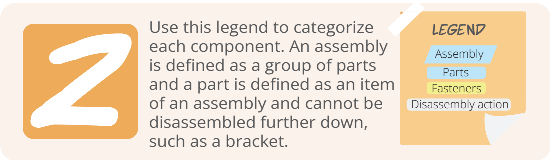


Step 1

To start they need to choose an assembly of a project. A project is composed of multiple assemblies in different locations in a building. Each assembly can be further broken down into parts made of various materials. Therefore, the following decomposition structure will be employed for categorizing assemblies and parts:

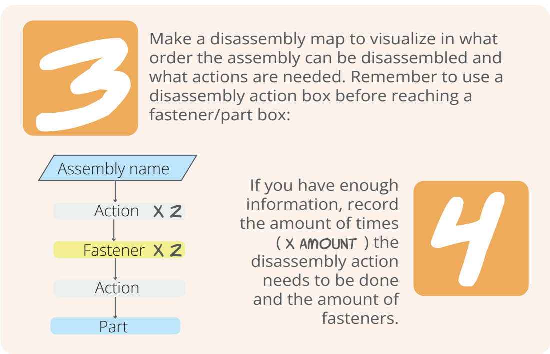
Project > Assembly > Parts > Materials

An assembly is defined as a group of parts and a part is defined as an elementary item of an assembly and cannot be disassembled further down, such as a screw.



Step 2

From this decomposition, based on the PAC model (Formentini & Ramanujan, 2023), the engineers can use this legend.

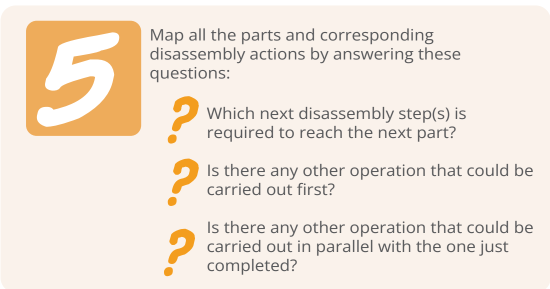


Step 3

This step explains how to begin the map, where the name of the assembly is followed by a disassembly action box. A disassembly action box has to be placed before reaching a fastener/part box. Disassembly actions can be: unscrew, take apart, disjoin, unhook, separate, remove, unbolt, unclip, cut, split, divide, dissolve, etc.

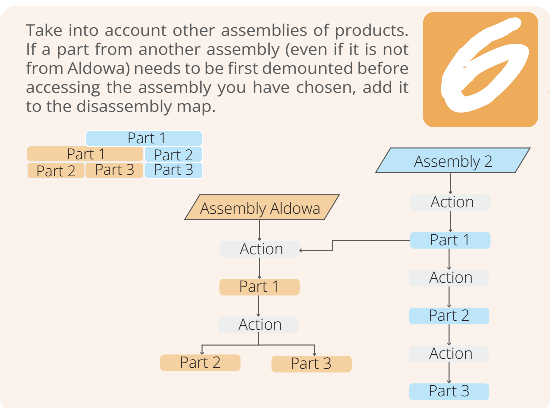
Step 4

If the engineer already has enough information over the assembly they can record the amount of times these disassembly actions take place according to the amount of fasteners that have to be dismantled.



Step 5

The engineer can start constructing its disassembly map by answering these questions.

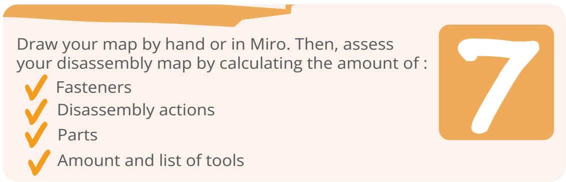


Step 6

This step explains the interdependence between assemblies. Assemblies from 3rd parties could also interfere with Aldowa's assembly. This is important to take into consideration because it can affect the accessibility of an assembly.

Step 7

The first assessment starts in this step by calculating the amount of fasteners, disassembly action boxes, part boxes and list of tools.



Step 8

The two penalties from which engineers have to be aware are using uncommon tools and if any destructive processes take place. A destructive process is dismantling a part in a way that causes damage.

Step 9

This step shows what is being assessed to calculate the detachability score: type of connections, accessibility, robustness and interdependence.

Type of connection:

It categorizes the type of connection between two parts. The action boxes are given a type of connection score. This is because the type of connection highest score is a dry connection which would mean that between two part boxes there is not a fastener box. These two parts would be connected by a disassembly action such as: unclick, separate, disjoin, slide, unhook, etc. That is why the type of connection is used to score disassembly action boxes rather than the fastener boxes.

Accessibility:

It indicates how accessible a part or fastener is when performing a disassembly process. It also addresses the risk of damage during/after the disassembly process. Accessibility scores are applied to both parts and fastener boxes.

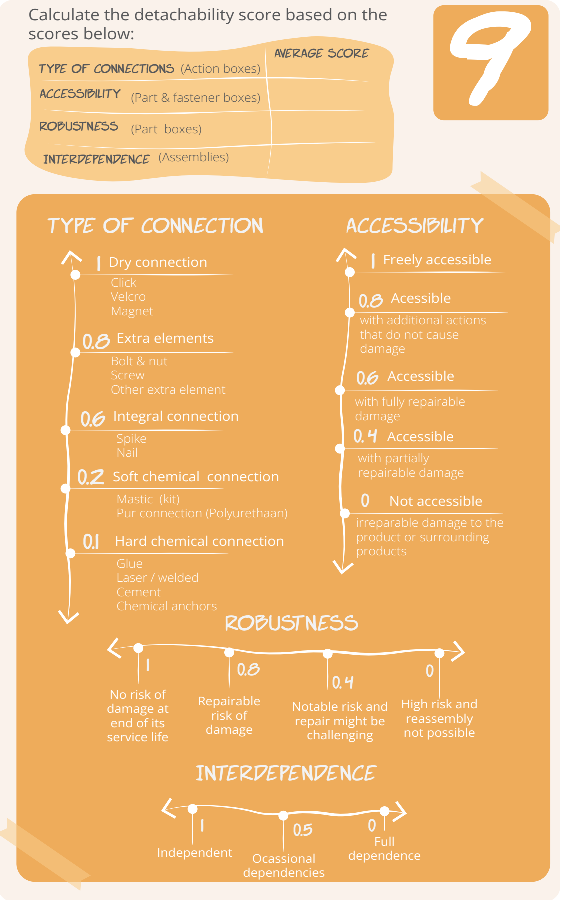
Robustness:

It indicates the risk of damage the part might already have before disassembly takes place. If the risk of damage is too high it may complicate the disassembly process. The robustness score is only applied to parts because even if fasteners are in good state, Aldowa is not allowed to reuse them due to safety regulations.

Interdependence

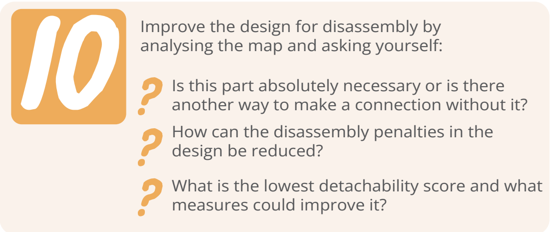
It indicates how the disassembly of assembly A is directly dependent on the disassembly of assembly B.

The final score is an average score per category.



Step 10

This step helps the engineer improve the disassembly by analyzing the map, identifying the penalties and lowest scores.



7.3.2 Basic Structural Analysis

Some of the requirements for Cradle-to-Cradle design for disassembly is that Aldowa needs to reduce fasteners, reduce disassembly steps, and increase automation of disassembly. To achieve this, the engineers would need to know the minimum amount of fasteners necessary to still have a safe structure. Therefore, a basic structural analysis can be useful to refine their designs, ensuring they can withstand expected loads. By analyzing the minimum amount of reinforcement and supports needed, like bed hooks in cassette panels, engineers establish a baseline for structural integrity. Optimizing the number of connections or materials in a design can significantly impact its suitability for disassembly.

To automate this process a grasshopper script has been created where a parametric model of a cassette panel undergoes a structural analysis. The input are the panel dimensions as well as the wind load depending on the position of the panel. The output is the maximum deflection and stresses under a certain load. From this output more fasteners (bedhooks or reinforcement) can be added until the design is under the maximum deflection and stresses allowed. In this way, the engineer knows the minimum amount of fasteners for a safe product.

An overview of the model set up can be seen in Figure 7.7. The set up of this model is further explained:

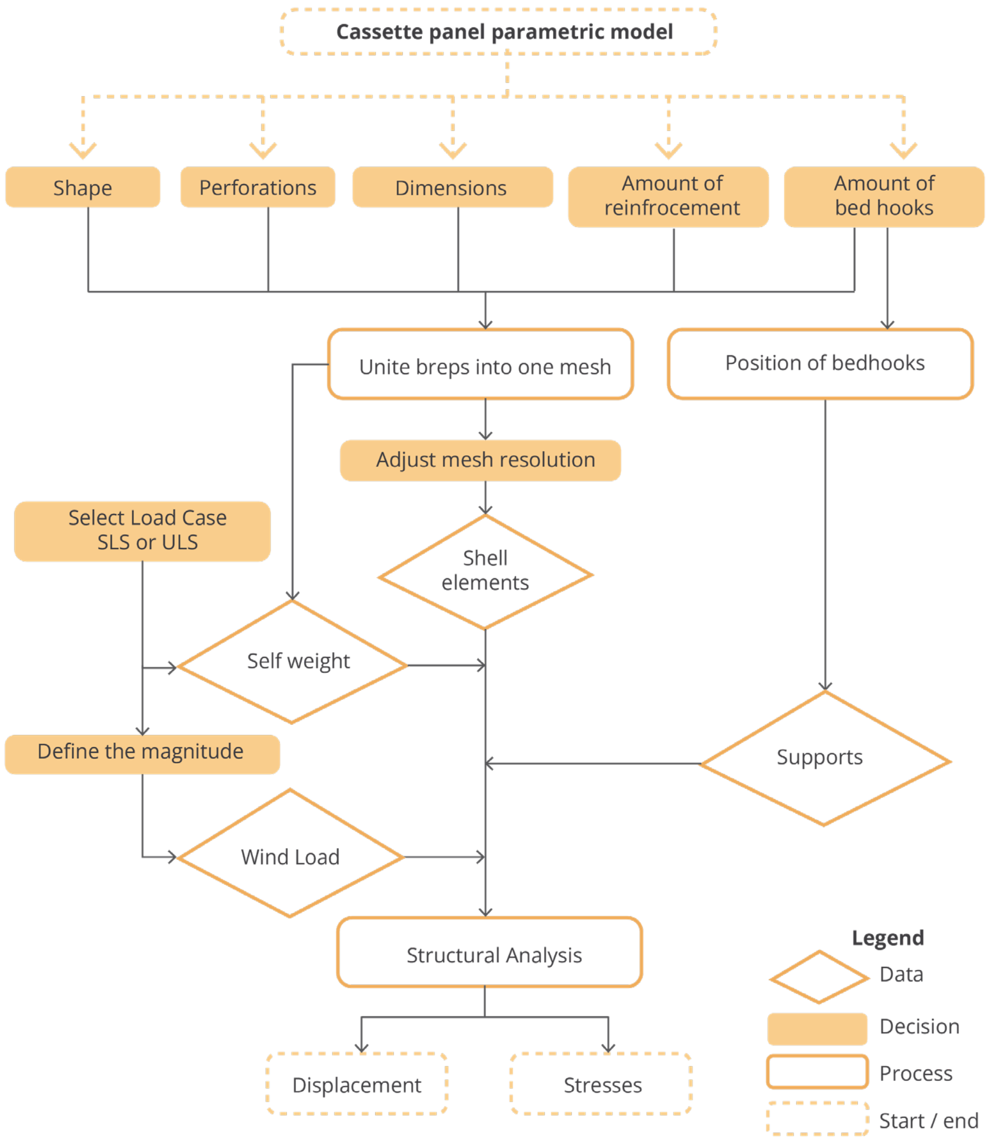


Figure 7.7 Grasshopper model flow chart: Depicting process sequence and data flow for displacement and stress results (Illustration made by author)

Code Frame
The following building codes are followed:
1. NEN-EN 1990 : Eurocode 0 : Grondslagen van het constructief ontwerp
2. NEN-EN 1991-1 : Eurocode 1 : Belastingen op constructies
3. NEN-EN 1999 : Eurocode 9 : Ontwerp en berekening van aluminiumconstructies

Design Loads
Accelerations

Only gravity (9.81m/s^2)

Wind load
Suction or pressure as failure mechanism of the panel(s). The magnitude of the wind load is calculated in page 80.

Snow
Not applicable

Other loads
Thermal expansion: Not taken into consideration

Material properties
The Karamba plugin is used and it offers a range of material selection. In this case the material chosen is AlMg1 (Aluminium) which has the following properties:

Elastic modulus = 7000 kN/cm^2

Tensile strength = 11 kN/cm^2

Compressive strength= -11 kN/cm^2

The thickness of the material can be adapted but a 3mm sheet thickness is used.

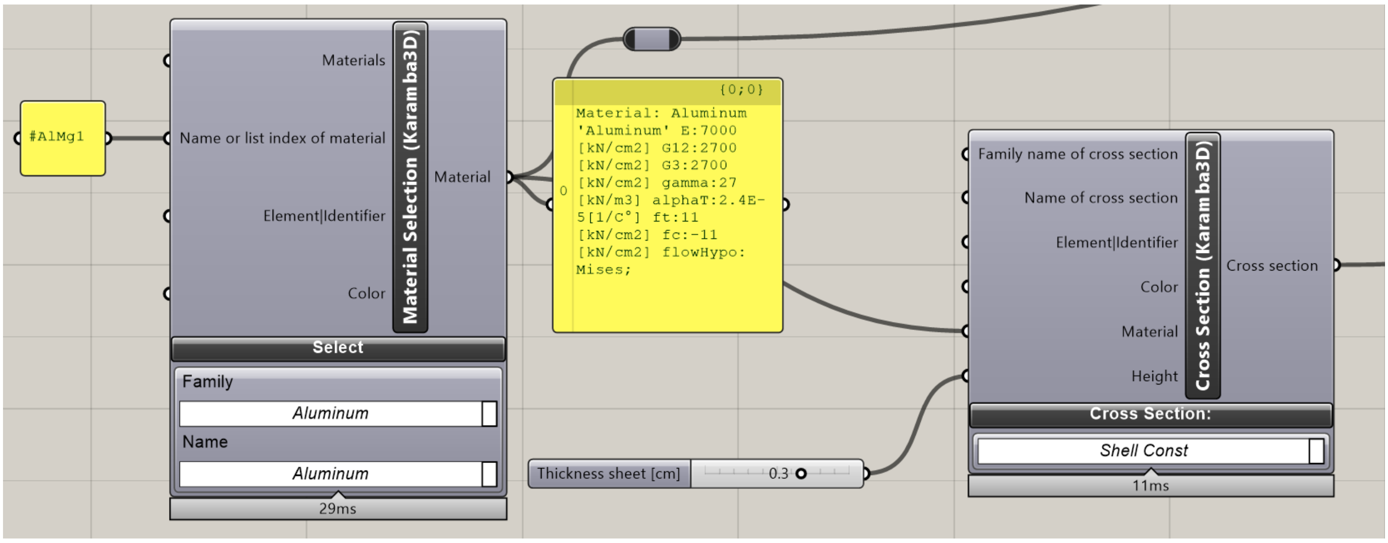


Figure 7.8 Aluminium material properties Karamba. (Screenshot made by author)

Defining the wind Load

The following formula, according to NEN-EN 1991, is used to calculate the wind load (W_e):

$$W_e = C_sC_d * C_{pe} * q_p(z_e) \ [kN/m^2]$$

Where:

C_sC_d = 1 [-]
This factor can be taken as 1 for regular low rise buildings (NEN, 2020)
C_{pe} = is the pressure coefficient for the external pressure [-]

$q_p(z_e)$ = is the peak velocity pressure based on the reference height z_e [kN/m²]

The highest pressure coefficient (C_{pe} = -1.4) is considered on the corners of a facade. In the model this coefficient can be lowered to analyze panels in the middle of a facade.

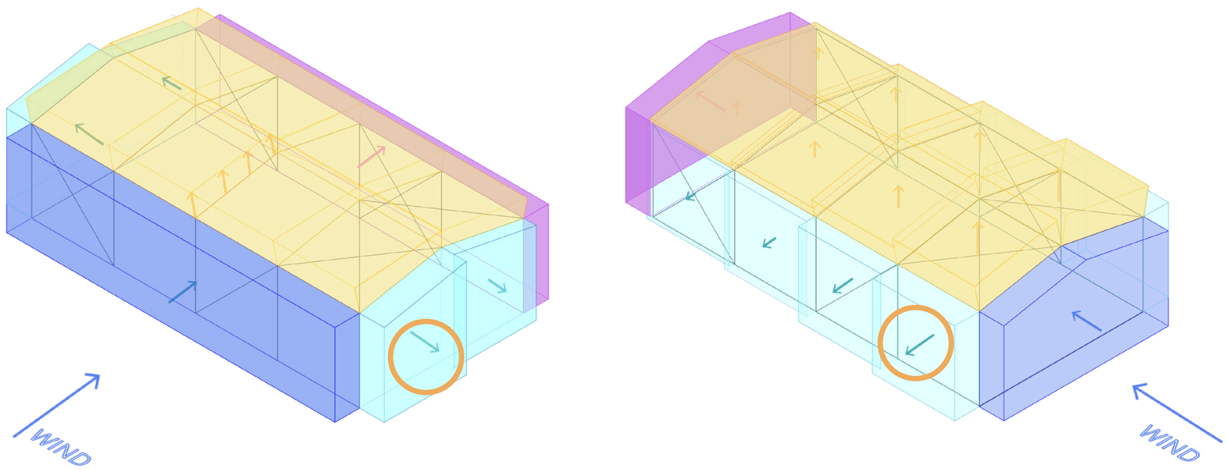
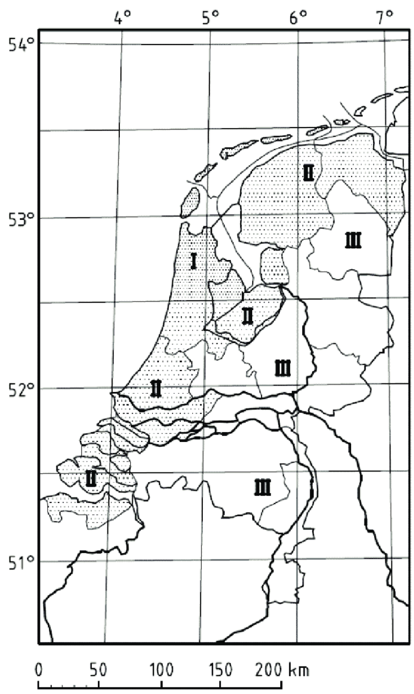


Figure 7.9 Wind pressure coefficients (Illustration made by author)

The peak velocity pressure is based on the NEN-EN 1991. This value depends on the region in the Netherlands where the building is located, area (coastal, urban or rural), and the reference height the panel is located in the building.



peak velocity pressure

z_e [m]	Area I Coastal	$q_p(z_e)$ [kN/m²] Rural	Urban	Area II Coastal	Rural	Urban	Area III Rural	Urban
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0.49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13
80	2,30	1,86	1,66	1,92	1,55	1,39	1,28	1,15
85	2,32	1,88	1,69	1,94	1,58	1,42	1,30	1,17
90	2,34	1,91	1,72	1,96	1,60	1,44	1,32	1,18
95	2,36	1,93	1,74	1,98	1,62	1,46	1,33	1,20
100	2,38	1,96	1,77	1,99	1,64	1,48	1,35	1,22
110	2,42	2,00	1,81	2,03	1,68	1,52	1,38	1,25
120	2,45	2,04	1,85	2,05	1,71	1,55	1,41	1,28
130	2,48	2,08	1,89	2,08	1,74	1,59	1,44	1,31
140	2,51	2,12	1,93	2,10	1,77	1,62	1,46	1,33
150	2,54	2,15	1,96	2,13	1,80	1,65	1,48	1,35
160	2,56	2,18	2,00	2,15	1,83	1,67	1,50	1,38
170	2,59	2,21	2,03	2,17	1,85	1,70	1,52	1,40
180	2,61	2,24	2,06	2,19	1,88	1,72	1,54	1,42
190	2,63	2,27	2,08	2,20	1,90	1,75	1,56	1,44
200	2,65	2,29	2,11	2,22	1,92	1,77	1,58	1.46

Figure 7.10 Wind regions and peak velocity pressures (Images from the Nederlands Normalisatie Instituut (1991))

Load combinations
Aldowa produces mostly panels for buildings of consequence class 2 or 3 (CC2 & CC3). For a building or a panel analyzed at a height higher than 70m the following load combination factors are applied from the consequence class 3 as described in the NEN-EN 1990:

SLS= 1 * G + 1 * Q
ULS = 1.3*G + 1.65*Q
(NEN, 2019)

Where the following acronyms mean:
ULS- Ultimate limit state
SLS- Serviceability limit state
G - Permanent loads
Q - Variable loads

Acceptance criteria deflection
The maximum deflection is calculated at the SLS state.
The maximum deflection (Wmax) may not be higher than 1/200 x the length/height of the panel.

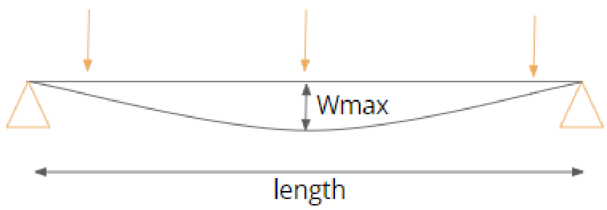


Figure 7.11 Maximum deflection (Illustration made by author)

Acceptance criteria stresses
The maximum stress is calculated at the ULS state. According to NEN-EN 1999 the material factor for aluminium is of 1.1.

Material Yield stress = 110 MPa
Material factor = 1.1

The maximum stress may not be higher than 110/1.1 = 100 MPa

ϑmax <= 100 MPa

The maximum stresses are assumed to be near the supports. In this case, where the bedhook shape is cut from the aluminium plate.

Model setup

The cassette panel system was modeled. Where the following parameters can be changed:

- Height
- Length
- Width
- Amount of bedhooks
- Amount of reinforcement

The reinforcement is modeled as an aluminium plate perpendicular to the panel.
The support points are placed at the top of the bedhooks where each support has translational and rotational degrees of freedom. The model has initially 4 main supports at each corner and more can be added. The circles and arrows shown in each support indicate the restricted degrees of freedom.

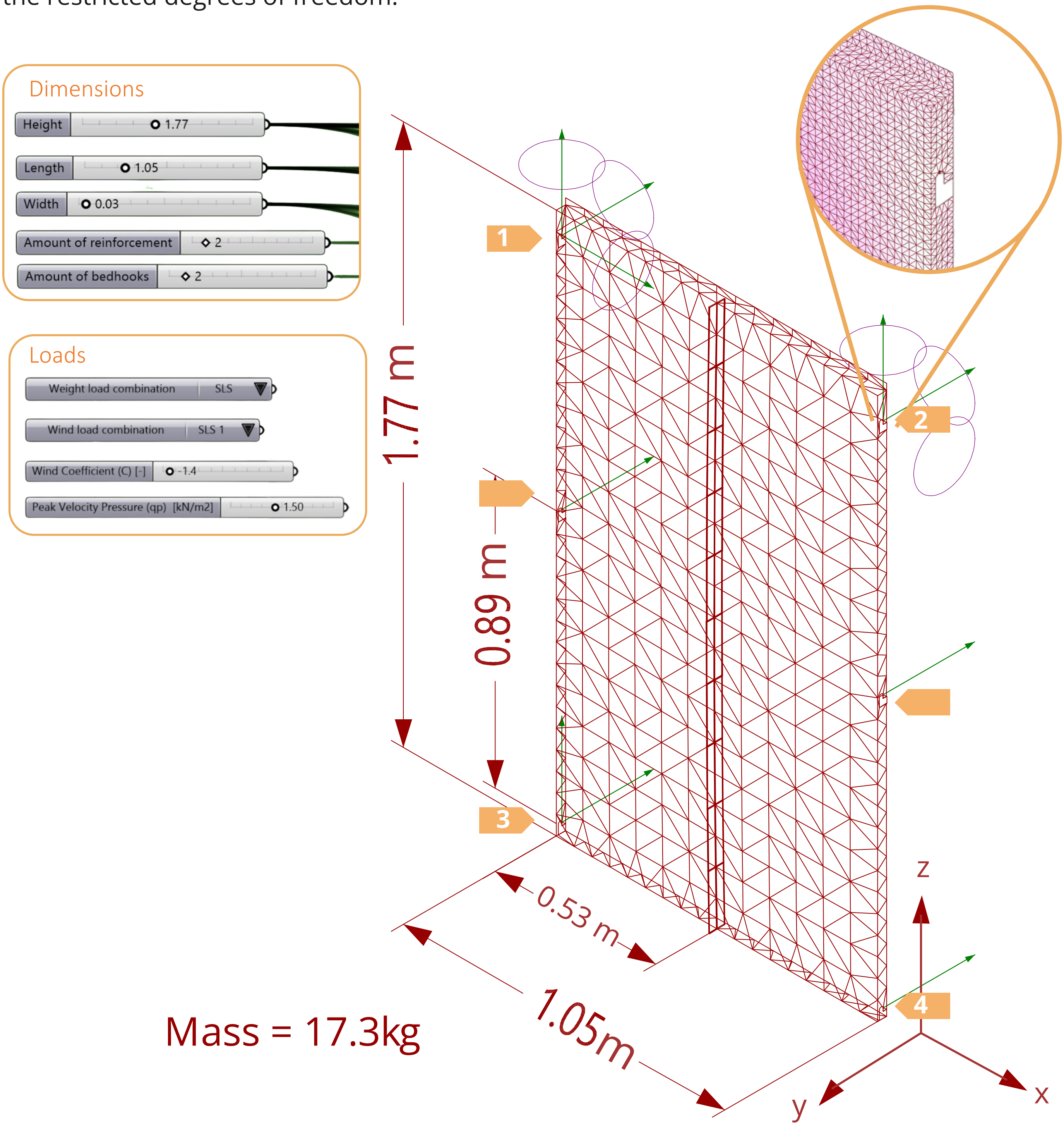


Figure 7.12 Parametric model of the cassette panel showing the sliders and the shape of the bed hooks for support points.
(Illustration made by author)

7.3.3 Re-design steps

In certain scenarios, once the barriers to disassembly have been identified, it may become evident the need for an entirely new type of connection design. In such instances, a re-design road map is formulated by consulting with engineers on their approach to devising a new design. This road map takes into account design for disassembly as a basis to start (re) designing.

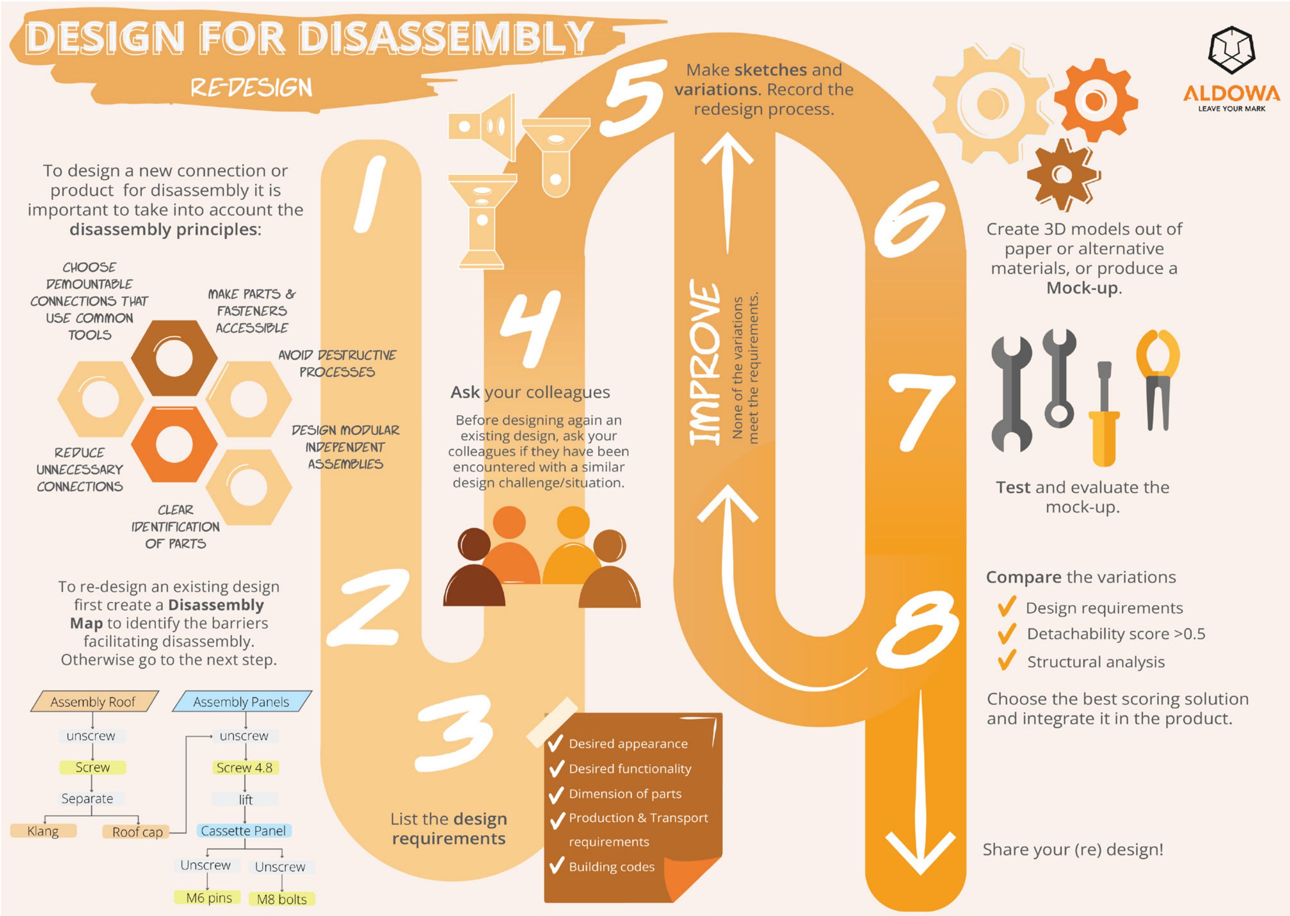


Figure 7.13 Steps to re-design for disassembly (Illustration made by author)

Step 1

To design a new connection for disassembly it is important to take into account the disassembly principles:

- Reduce unnecessary connections
- Choose demountable connections that use common tools
- Make parts and fasteners accessible
- Avoid destructive processes
- Design modular independent assemblies
- Clear identification of parts

Step 2

To re-design an existing design first create a Disassembly Map to identify the barriers facilitating disassembly. If the engineer is designing from 0, they can skip this step. The Disassembly Map evaluation will appear again in step 6.

Step 3

List the design requirements the new design has to fulfill:

1. Material selection
2. Desired appearance

3. Desired functionality
4. Dimension of parts
5. Production and transport requirements
6. Compliance and regulations (Building codes)

Step 4

To avoid miscommunication inside the company and designing again an existing design, it is important to ask other colleagues if they have been encountered with a similar design challenge/situation. This can be useful to get feedback, inspiration or a solution to the problem.

Also, it is important to hear the feedback not only from engineers but from other parties such as the production and logistics departments, as well as the constructors. This can reveal limitations about what can be produced, transported and assembled.

Step 5

During the design process it is important to record and produce as many sketches and variations as possible. This allows engineers to generate a range of ideas and communicate it visually. Variations help to evaluate different approaches and select the most efficient design solutions.

Step 6

The engineer can start creating a 3D model out of different materials such as paper, cardboard or produce a mock up. Prototypes help visualize an idea better and refine a design before moving forward with production.

Step 7

After producing the Mock-ups the engineer can evaluate and test them. Engineers can then identify potential flaws, usability issues or design problems in the early development process.

Step 8

Afterwards, the engineers can compare them. The first comparison is to check if the variation fulfills all the design requirements. In addition, the designs can be compared by:

1. Fulfillment of the design requirements
2. Detachability score > 0.5
3. Carrying out a structural analysis

If the variation meets all the requirements and demonstrates favorable results it can be integrated in the final product. Otherwise, the engineer has to go back to step 5. It is important at the end of the design process to communicate and share the re-design with other colleagues.

7.4 Conclusions

In conclusion, the Design for Disassembly guideline serves as a tool aimed at benefiting both the sales department and engineering teams. It is designed to be utilized at various stages of a project, from the project's initiation and during client agreements, to the early engineering design phase. For the sales department, it assists in communicating the significance of Design for Disassembly and Cradle-to-Cradle product concepts to clients, fostering informed decision-making. Additionally, it aids in budget calculations by ensuring that certification material and connection requirements align with the agreed budget.

For the engineers, the guideline offers a systematic approach to implementing Design for Disassembly principles. It provides methods such as the disassembly map for identifying disassembly barriers and basic structural analysis for optimizing amount of connections. When faced with the need for a new design, the guideline offers a re-design roadmap that integrates Design for Disassembly considerations. In essence, this guideline prioritizes ease of disassembly, and aims to contribute to a more circular and conscious approach to design.

08.

Validating the guideline

In this section, the proposed DfD Guideline from section 7 undergoes user testing in Section 8.1, involving both the Sales department (as described in sub-section 8.1.1) and the Engineering department (as detailed in sub-section 8.1.2). Section 8.2 demonstrates the application of the guideline within the context of the Cradle to Cradle case study. Section 8.3 is dedicated to the evaluation of the guideline's performance, and the findings and conclusions are presented in Section 8.4.

List of Figures:

Fig. 8.1 C2C Check results from the budget calculation
Fig. 8.2 Disassembly Maps from testing the guideline
Fig. 8.3 SLS simulation. Iteration1
Fig. 8.4 SLS simulation. Iteration 2
Fig. 8.5 ULS simulation
Fig. 8.6 Approaches to reduce deformation of Panel A
Fig. 8.7 2D Drawing of the project Logistiek & Mileu
Fig. 8.8 Disassembly Map of the 2D Drawing of the project Logistiek & Mileu
Fig. 8.9 Alternative 1: Click system
Fig.8.10 Alternative 2: Screw at the back
Fig.8.11 Click&Go system without screws
Fig.8.12 Alternative 3: Laser welded couple piece
Fig.8.13 Alternative 1: Slide connection
Fig. 8.14 Alternative 2: Compliant mechanism
Fig. 8.15 Alternative 3: Snap-fit mechanism
Fig. 8.16 Slide connection model
Fig. 8.17 Compliant mechanism model
Fig. 8.18 Snap fit connection model
Fig. 8.19 Test of the compliant and snap-fit system cuts
Fig. 8.20 Slider connection motion. Back view.
Fig. 8.21 Precision error in the prototype
Fig. 8.22 Compliant mechanism test plate with plastic foil
Fig. 8.23 Compliant mechanism motion
Fig 8.24 Snap fit test plates.
Fig 8.25 Snap fit motion
Fig 8.26 Welded couple piece to a water panel.
Fig. 8.27 Disassembly maps of couple pieces alternative connections
Fig. 8.28 Initial comparison of the disassembly maps of the couple pieces alternative connections
Fig. 8.29 Detachability criteria scores of couple pieces connection
Fig. 8.30 Final detachability scores of couple pieces connection
Fig. 8.31 Disassembly maps of cassette panel alternative connections
Fig. 8.32 Initial comparison of the disassembly maps of the cassette panel alternative connections
Fig. 8.33 Detachability criteria scores of cassette panels
Fig. 8.34 Final detachability scores of cassette panels

8.1 User testing

The guideline was tested by the following users:

8.1.1 Sales department

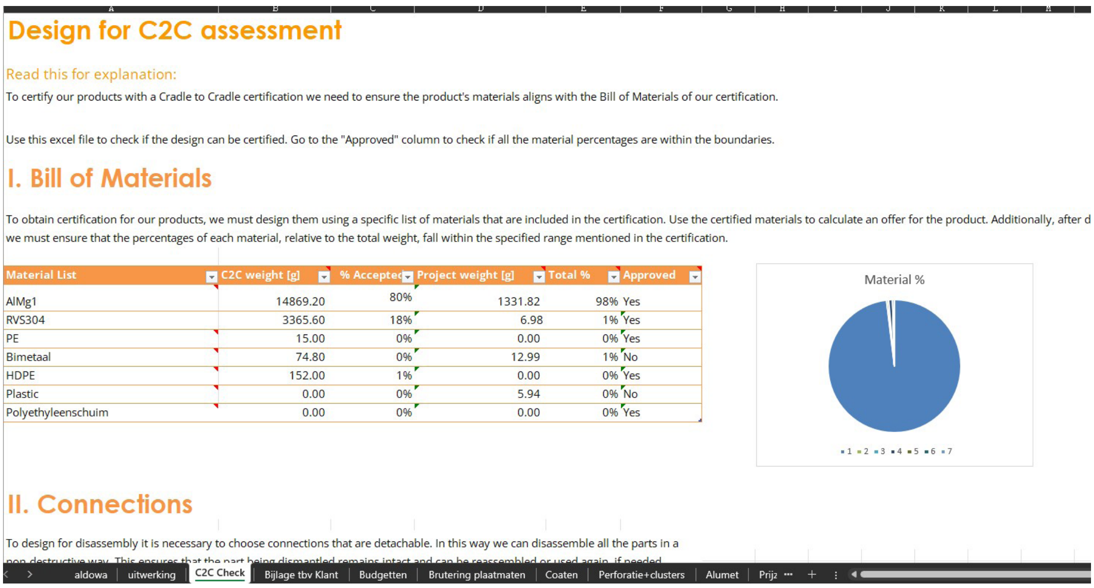
Goal: Test if the excel calculation for the sales department runs smoothly when they calculate a project budget

Experiment: The case study to test the guideline was the project called *Mileu & Logistiek*, which uses cassette panels as well as roof caps. A sales person will fill in the standard calculation for the budget and in the sheet “C2C Check” the results will show if the project aligns with the C2C material requirements.

Document used:

- C2C_Check_Bill_of_Materials excel file

Result: After various tests and improvements the calculation of the Bill of Materials runs automatically. This means that after calculating the budget for a project they can also check if the material quantity percentages align with the ones of the certificate and the average type of connections score (Detachability index) is calculated automatically.



Design for C2C assessment

Read this for explanation:

To certify our products with a Cradle to Cradle certification we need to ensure the product's materials aligns with the Bill of Materials of our certification.

Use this excel file to check if the design can be certified. Go to the "Approved" column to check if all the material percentages are within the boundaries.

I. Bill of Materials

To obtain certification for our products, we must design them using a specific list of materials that are included in the certification. Use the certified materials to calculate an offer for the product. Additionally, after d
we must ensure that the percentages of each material, relative to the total weight, fall within the specified range mentioned in the certification.

Material List	C2C weight [g]	% Accepted	Project weight [g]	Total %	Approved
AlMg1	14869.20	80%	1331.82	98%	Yes
RVS304	3365.60	18%	6.98	1%	Yes
PE	15.00	0%	0.00	0%	Yes
Bimetaal	74.80	0%	12.99	1%	No
HDPE	152.00	1%	0.00	0%	Yes
Plastic	0.00	0%	5.94	0%	No
Polyethyleenschuim	0.00	0%	0.00	0%	Yes

II. Connections

To design for disassembly it is necessary to choose connections that are detachable. In this way we can disassemble all the parts in a

Figure 8.1 C2C Check results from the budget calculation (Excel filled in by Aldowa)

Opportunities:

1. The assessment can be used in the early design stages: when establishing the design boundary conditions
2. It is an easy way to check if the C2C material requirements are met and the connections used are demountable

Improvements:

1. The list of materials is not completed because there are some materials whose chemicals still need to be checked in the RSL list and further certified
2. The list of materials can be modified if there are any changes in the certificate. This will mean other cells need to be referenced from the main budget calculation sheet.

8.1.2 Engineering department

A. Disassembly Map

Goal: Test if the guideline to make a disassembly map is self-explanatory

Experiment: Three engineers were tasked with creating a disassembly map to assess the disassembly potential of an assembly within their project. They were provided with the DfD Guideline in a word file and selected an assembly for evaluation. They could not ask for external assistance, as the guideline was intended to be sufficient to help them with the necessary information on how to perform the assessment.

Documents used:

- DfD Guideline word file

Results: The disassembly maps of the three engineers can be found in the Figure 8.2. According to the engineers' feedback, the guideline proved easy to comprehend and raised their awareness about designing for disassembly.

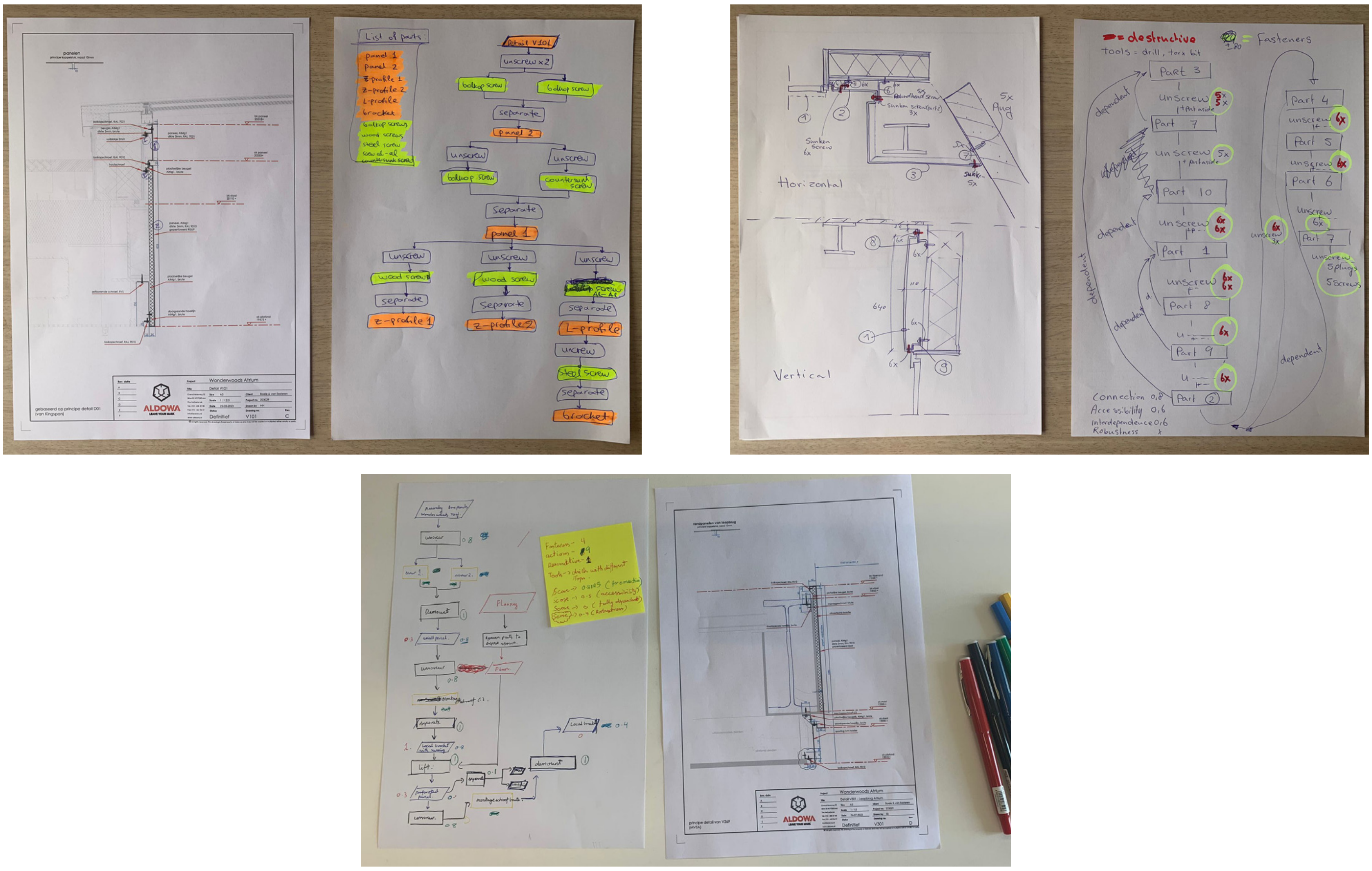


Figure 8.2 Disassembly Maps from testing the guideline (Drawings by Aldowa)

Opportunities of the Disassembly Map:

1. The assessment can be used in the early design stages: when an engineer receives the drawings from the sales department
2. It is a quick an easy way to assess the disassembly potential of an assembly
3. The disassembly barriers can be detected easier in a visual map
4. An initial disassembly score can be set as a base to improve or compare the re-design

Improvements:

1. Time is not reflected in the detachability score
2. The detachability score is not an ultimate value to determine the disassembly potential but it offers an estimation over its feasibility
3. There is a degree of subjectivity when assessing an assembly

B. Structural Optimization

Goal: Test if the structural analysis provides insightful and reliable results to reduce the amount of connections in a cassette panel

Experiment: The company Highrise BV carried out an FEA analysis for the project 223019-Berghaus Plaza in Amsterdam for two cassette panels of different dimensions (Hogewoning, 2023). The same variables of dimensions, loads and amount of connections are replicated in the model to test if it produces the same results. The report can be found in the appendix and it lacks information about the mesh size and the fixation method of the connections. The variables for each panel and the resulting deformation and stresses can be seen in Table 8.1.

Documents used:

- 23019 Analysis Facade Panels project 221031 (Hogewoning, 2023)
- Structual_analysis grasshopper file

Cassette Panels FEA case studies

Variables	Panel A	Panel B
Height (mm)	1775	1775
Length (mm)	1054	527
Thickness (mm)	3	3
Maximum suction pressure (Pa)	488	1152
Other loads	self weight	self weight
Amount of bedhooks per side	2	2
Amount of reinforcement	0	0

Table 8.1 FEA variables of two cassette panels (Hogewoning, 2023)

Mesh size and connections

The smallest mesh size reached in grasshopper was of 0.008m. Initial results were obtained by fixing the supports as stated in Table 8.2.

Degrees of freedom iteration 1

Degree of freedom	Axis	Top left	Top right	Bottom left	Bottom right	Other
		1	2	3	4	...
TRANSLATIONAL	X - axis	Fixed	Free	Fixed	Free	Free
	Y - axis	Fixed	Fixed	Fixed	Fixed	Fixed
	Z - axis	Fixed	Fixed	Free	Free	Free
ROTATIONAL	X - axis	Fixed	Fixed	Free	Free	Free
	Y - axis	Fixed	Fixed	Free	Free	Free
	Z - axis	Fixed	Fixed	Free	Free	Free

Table 8.2 Degrees of freedom of supports: Iteration 1.
(Screenshots made by the author)

Results displacement iteration 1: The deformation was calculated with the SLS load case and the stresses with the ULS load case. The mesh resolution is of 8mm. The results compared with Highrise had an error of + 0.5 cm (Panel A) and of +0.8 cm (Panel B).

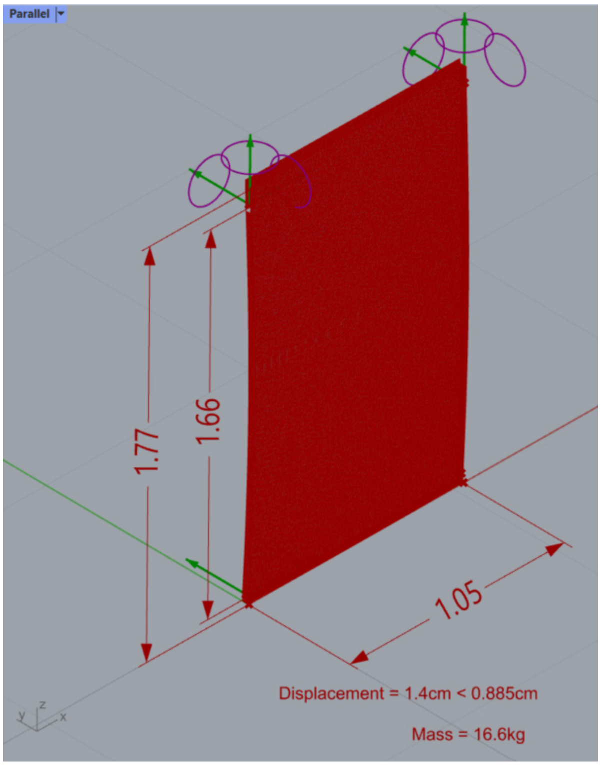


Figure 8.3a SLS simulation: Panel A. Dimensions in m. Displacement = 1.4cm (Screenshots made by the author)

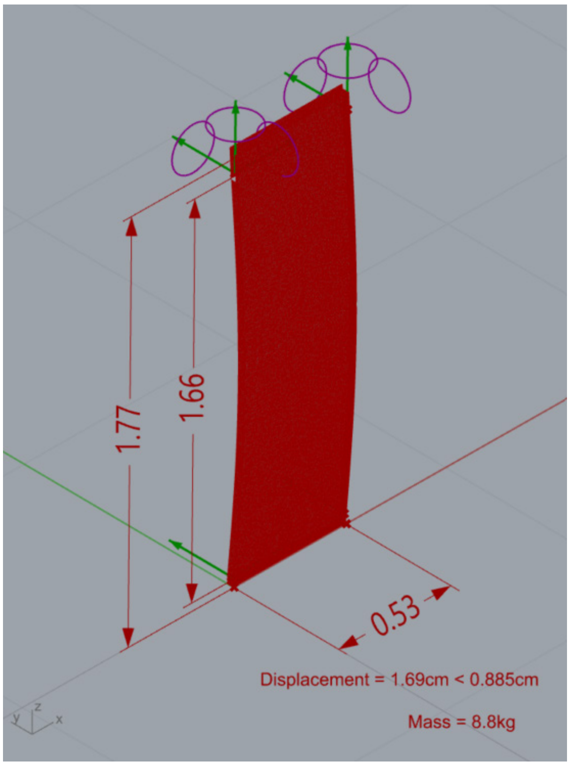


Figure 8.3b SLS simulation: Panel B. Dimensions in m. Displacement = 1.7 cm (Screenshots made by the author)

The fixation of supports 3 and 4 were changed in order to reach a value closer to the displacement calculated by Highrise. This new configuration can be seen in Table 8.3.

Degrees of freedom iteration 2

Degree of freedom	Axis	Top left	Top right	Bottom left	Bottom right	Other
		1	2	3	4	...
TRANSLATIONAL	X - axis	Fixed	Free	Free	Free	Free
	Y - axis	Fixed	Fixed	Fixed	Fixed	Fixed
	Z - axis	Fixed	Fixed	Fixed	Fixed	Free
ROTATIONAL	X - axis	Fixed	Fixed	Free	Free	Free
	Y - axis	Fixed	Fixed	Free	Free	Free
	Z - axis	Fixed	Fixed	Free	Free	Free

Table 8.3 Degrees of freedom of supports: Iteration 2. (Screenshots made by the author)

Results displacement iteration 2: The new fixation of supports led to a smaller error of + 0.2 cm (Panel A) and of +0.095 cm (Panel B). The displacements can be seen in Figure 8.4.

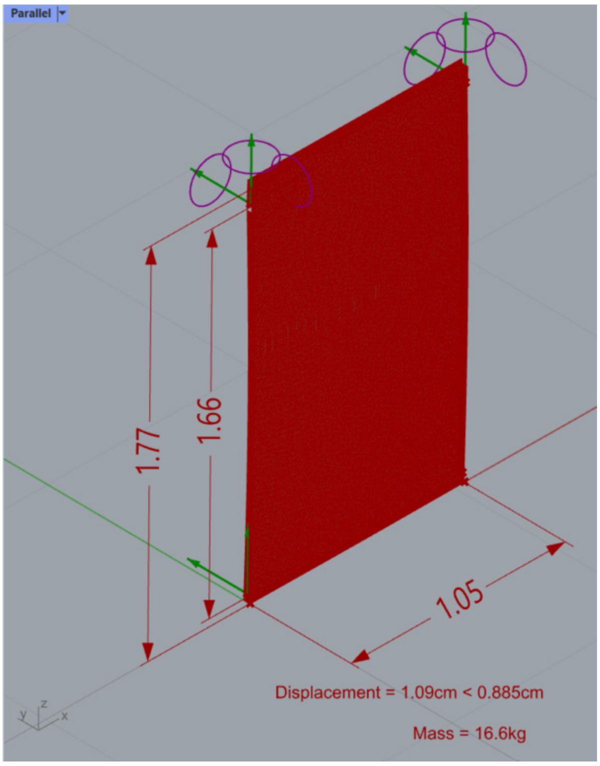


Figure 8.4a SLS simulation: Panel A. Dimensions in m. Displacement = 1.09 cm (Screenshots made by the author)

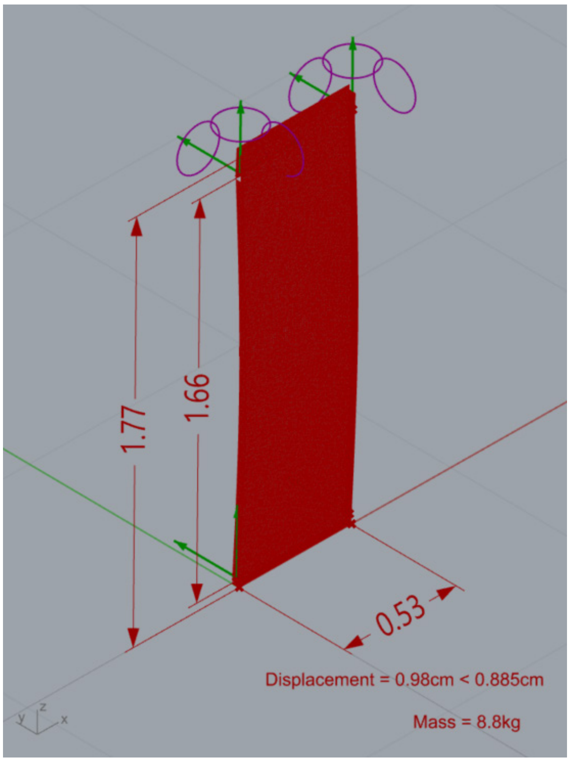


Figure 8.4b SLS simulation: Panel B. Dimensions in m. Displacement = 0.98 cm (Screenshots made by the author)

Results stresses: The stresses were calculated with the ULS load case with a mesh size of 0.008m and the support configuration of Table 8.2. The results can be seen in Figure 8.5. Grasshopper produces automatic scales with the average value in the middle. The errors are of + 15 MPa for Panel A and of + 2.8 MPa Panel B.

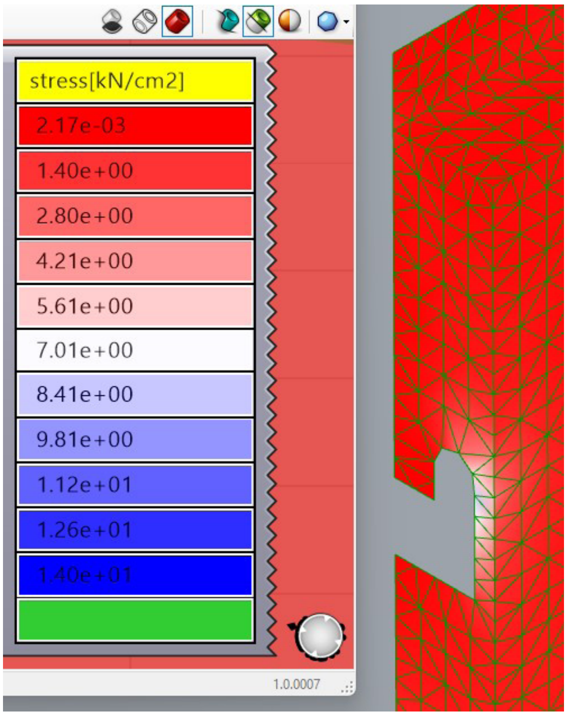


Figure 8.5a ULS simulation: Panel A with a ϑavg. = 70 MPa (Screenshot made by the author)

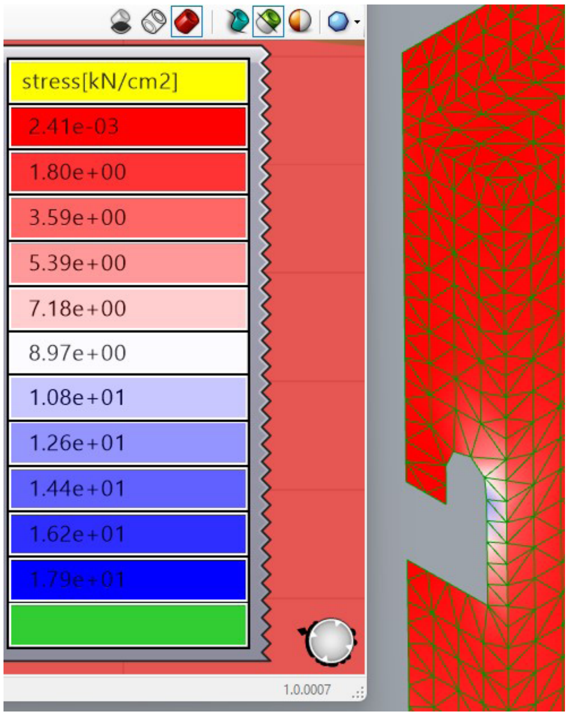


Figure 8.5b ULS simulation: Panel B with a ϑavg. = 89.7 MPa (Screenshot made by the author)

Comparison of FEA models

	Panel A		Panel B	
Variables	Highrise BV	Grasshopper Simulation	Highrise BV	Grasshopper Simulation
Total deformation (mm)	8.48	10.9	8.58	9.8
Nominal stress (MPa)	55.37	70.1	86.9	89.7

Table 8.4 Comparison of FEA models

Analysis:
The evaluated stresses were under the stress limit of 100 MPa. However, the displacements exceeded the limit of 0.005*height of the panel of 8.85mm. Various approaches were applied to reduce the deformation of Panel A as it can be seen in Figure 8.6. Adding two reinforcements reduces mostly the deformation but uses more material for the L-profiles. On the other hand, adding 1 reinforcement and 1 extra bed hook support reduces less the deformation and uses less material.

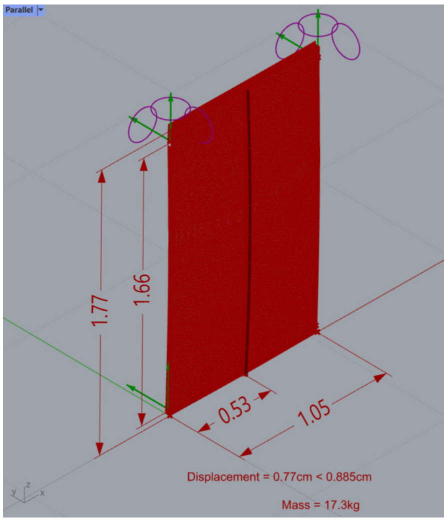


Figure 8.6a Approaches to reduce deformation of Panel A: add 1 reinforcement (Screenshot made by the author)

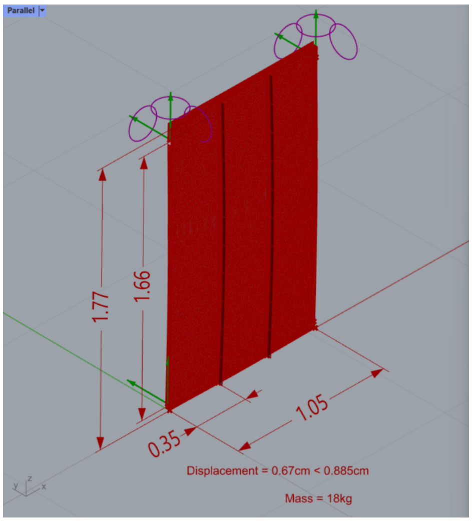


Figure 8.6b Approaches to reduce deformation of Panel A: add 2 reinforcements (Screenshot made by the author)

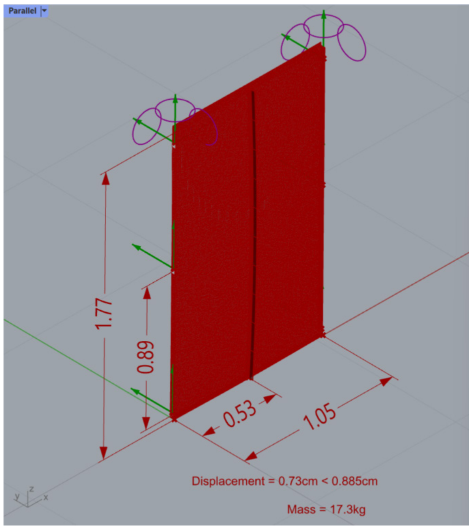


Figure 8.6c Approaches to reduce deformation of Panel A: add 1 reinforcement and a bedhook (Screenshot made by the author)

Opportunities of the structural analysis:
1. It is a quick analysis to know the minimum amount of reinforcement profiles and bed hooks since only the sliders have to be modified and the structural results appear automatically.
2. The script could be modified to analyze a different shape or type of panel system.
3. The engineer can play with different approaches to minimize connections and be within the stress and displacement limits.

Improvements:
1. The script is written in the software grasshopper and it should be translated in the software of CATIA which is used mostly by the company and can handle a smaller mesh size for more precise results.
2. The FEA results have a considerate error margin for both displacements and stresses in comparison with those produced by the Ansys program used by Highrise. Further validation is required to gather more information about the mesh size and support configuration carried out by Highrise.

8.2 Redesign

Goal: The DfD Guideline will be used to redesign the product to be able to certify it and test the guideline usefulness.

Step 1. Take into account the disassembly principles

The following DfD principles will be taken into account in the design:

1. Reduce unnecessary connections
1. Choose demountable connections that use common tools
2. Make parts and fasteners accessible
3. Avoid destructive processes
4. Design modular independent assemblies
5. Clear identification of parts

Step 2. To re-design create a Disassembly Map to identify the barriers

Figure 8.7 shows the 2D drawing detail of a cassette and roof panel with a 20mm gap in between and Figure 8.7 shows its corresponding Disassembly Map.

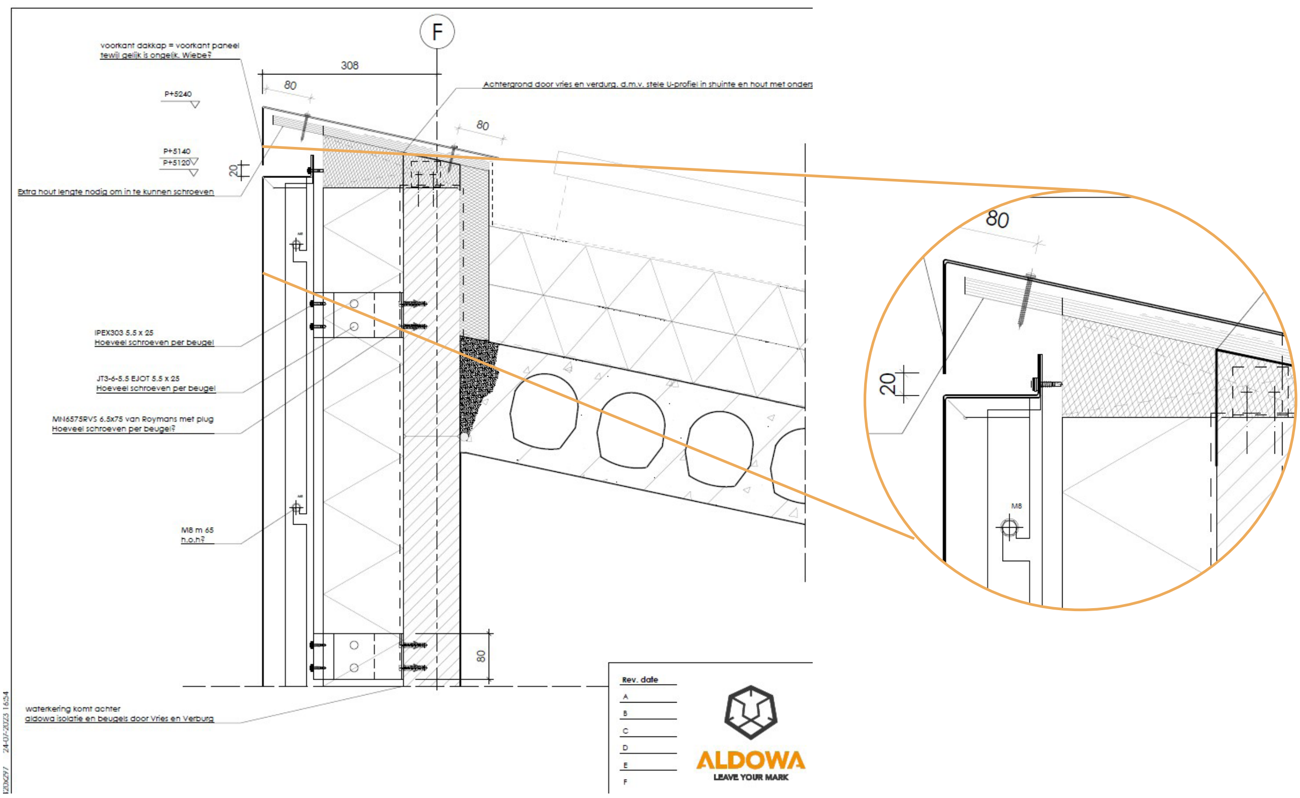


Figure 8.7 2D Drawing of the project Logistiek & Mileu (Drawing by Aldowa)

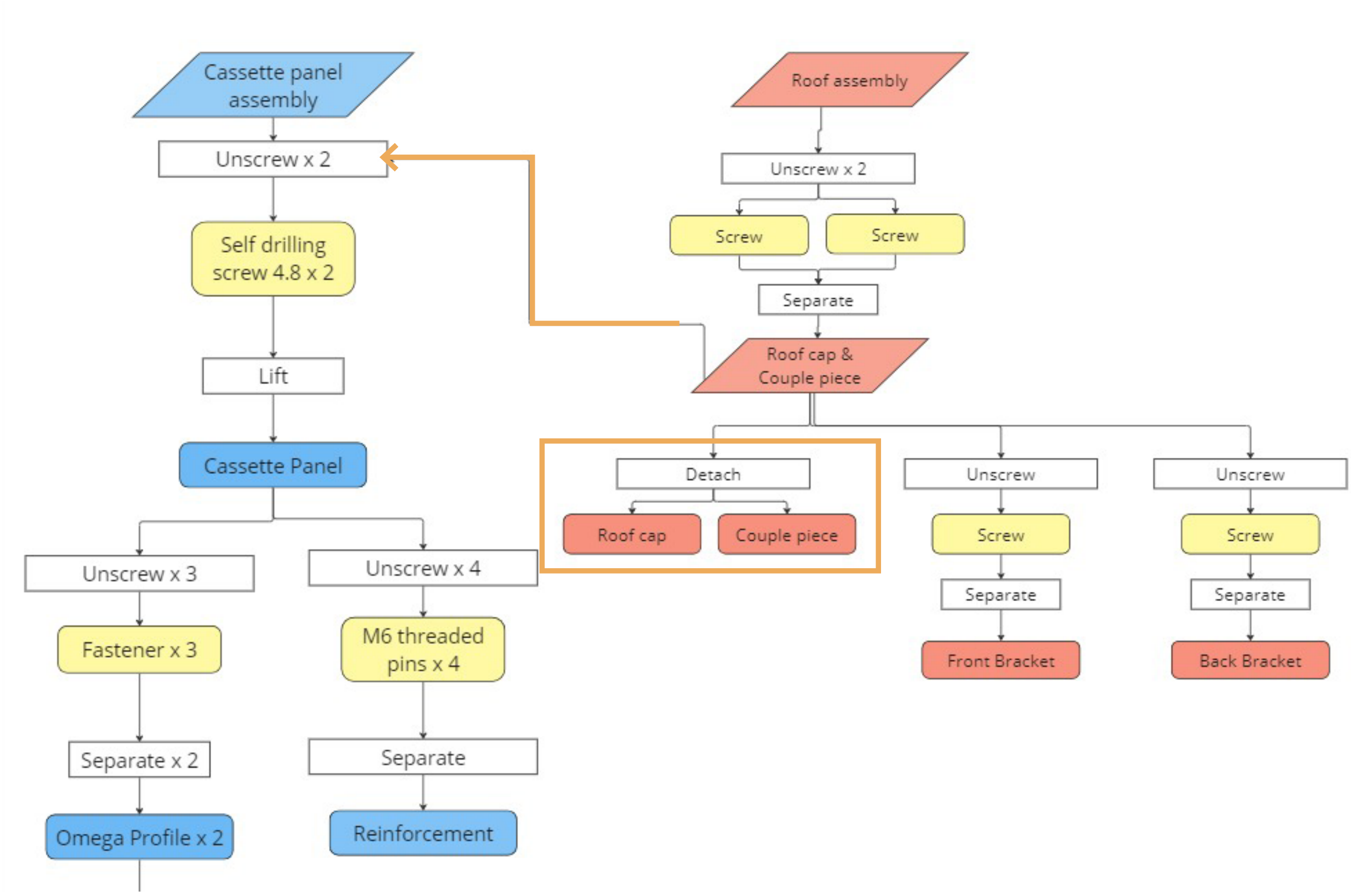


Figure 8.8 Disassembly Map of the 2D Drawing of the project Logistiek & Mileu (Illustration made by author)

In this case the gap between the cassette panel and the roof panel is 20mm which means that both assemblies are independent from each other. This is not always the case in all the projects. If the gap is less than 20mm it will mean that in order to disassemble the Cassette panel assembly (Given in blue) first the roof assembly (Given in red) would have to be disassembled. This theoretical dependency is shown with an orange arrow.

Additionally, there is also a disassembly penalty within the roof assembly since the couple pieces are glued to the roof caps. Consequently, dismantling these parts results in destructive disassembly. Moreover, the adhesive residue left on the aluminum sheet introduces the risk of alloy contamination, potentially leading to down cycling.

The main problem according to the project leaders is that it is not clear in which pallet the couple pieces are placed when arriving at the building site. Most of the time they are missing or there are too many so proper identification or pre-assembly at the building site is necessary.

Step 3. List the design requirements

The following design requirements are stated for each part to redesign the couple pieces and the cassette panel:

Couple pieces connection

1. Desired appearance
    - Material selection: In accordance with the C2C certified materials
    - Create the appearance of continuous roof panels without gaps in between

2. Desired functionality
    - Connect roof panels
    - Separate parts of different materials to recycle and prevent down-cycling

3. Dimension of parts
    - Generic

Cassette panels

1. Desired appearance
    - Material selection: AlMg1
    - Hide screws or fasteners and have a minimum space between panels

2. Desired functionality
    - Easy independent replacement to facilitate maintenance and repair
    - Structural safe cladding in front of a facade

3. Dimension of parts
    - Generic

Step 4. Ask colleagues

Couple pieces connection

The challenge about the connection between the couple pieces and the roof panels was presented to the engineers. They proposed alternatives from very complex to simple solutions. See Figures 8.9 and 8.10 .

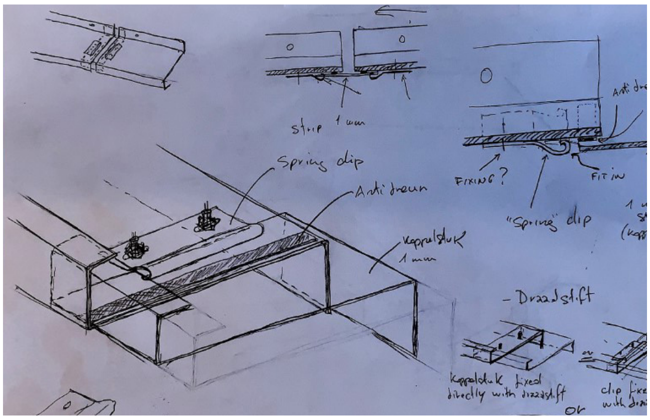


Figure 8.9 Alternative 1: Click system
(Drawing made by an engineer in Aldowa)

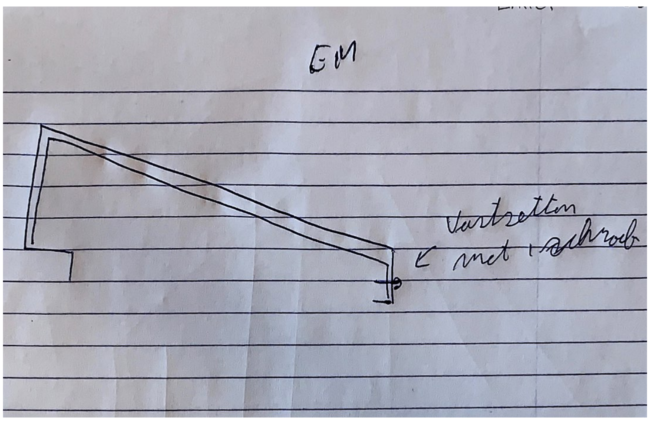


Figure 8.10 Alternative 2: Screw at the back
(Drawing made by an engineer in Aldowa)

Cassette panels

When the engineers were asked with the challenge of designing a cassette panel with a gap of less than 20mm and a detachable independent connection, only one engineer had previous experience with a similar task. This project involved the installation of both cassette panels and PV panels in close proximity. One of the engineers was tasked with designing a cassette panel that could integrate with the TuliPPs PV panel system. In this particular design, no screws were utilized on the top flange, and instead, the company TuliPPs provided a specialized tool for unlocking the mechanism.

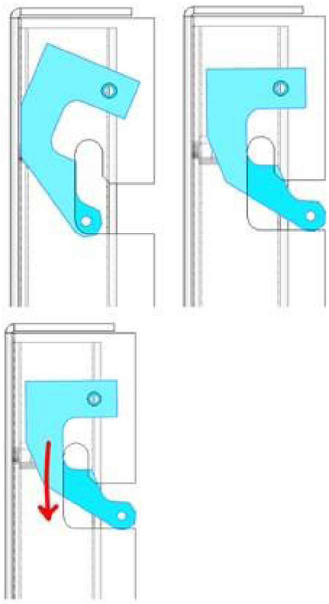


Figure 8.11 Click&Go system without screws
(Illustration made by an engineer in Aldowa)

Step 5. Make sketches and variations

From the feedback of the engineers the following alternative solutions were proposed:

Couple pieces connection

An alternative connection to glue is to weld the couple pieces to the roof panels. The welding would be done with the same alloy which doesn't create impurities.

This is not a common practice because of two concerns:

1. When powder coating is applied, improper drying can result in the formation of unsightly bubbles, negatively affecting the overall appearance
2. If the product is first anodized, the acid during the anodization may stay in between and corrode the panel. Also, the spot where it is welded will tone a different color.

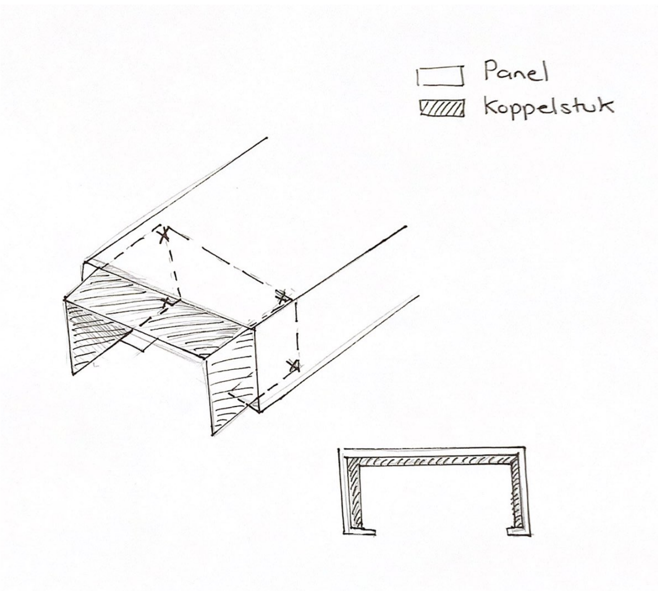


Figure 8.12 Alternative 3: Laser welded couple piece (Sketch made by author)

Cassette panel connection

Among the existing design alternatives, the Click&Go alternative shows the most promise. Nonetheless, additional design alternatives have been considered, drawing inspiration from existing systems:

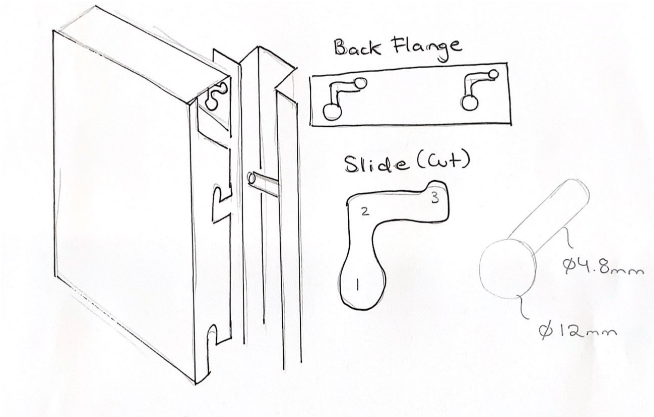


Figure 8.13 Alternative 1: Slide connection (Sketch made by author)

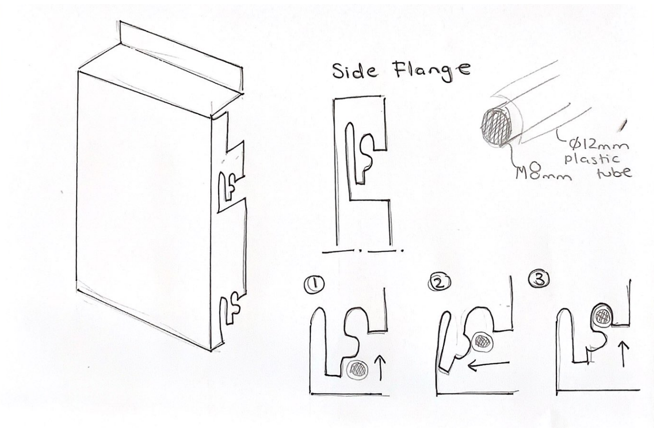


Figure 8.14 Alternative 2: Compliant mechanism (Sketch made by author)

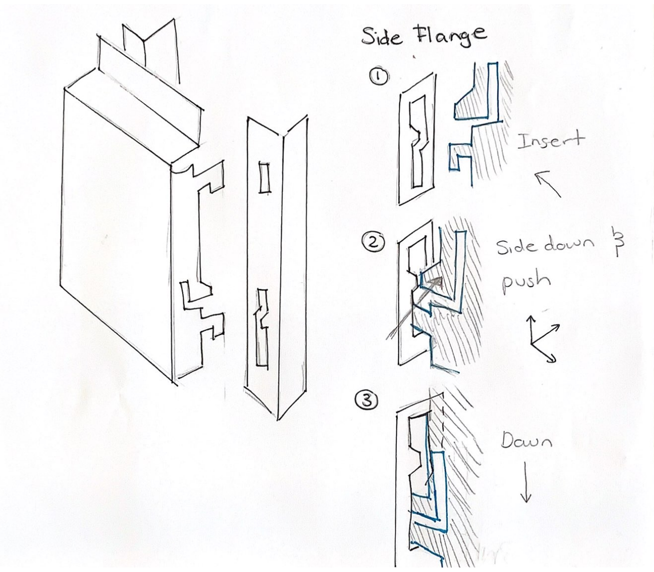
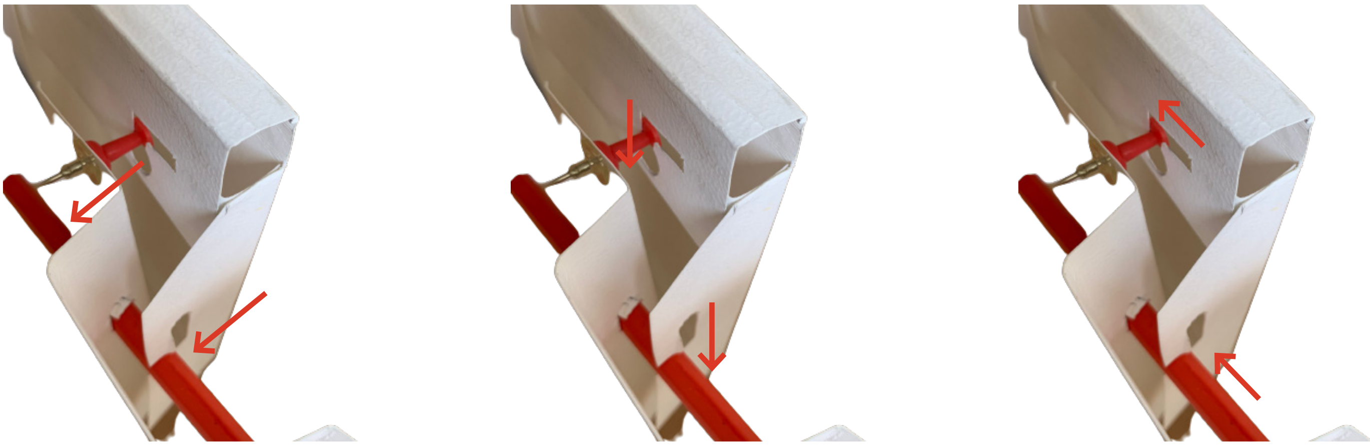


Figure 8.15 Alternative 3: Snap-fit mechanism (Sketch made by author)

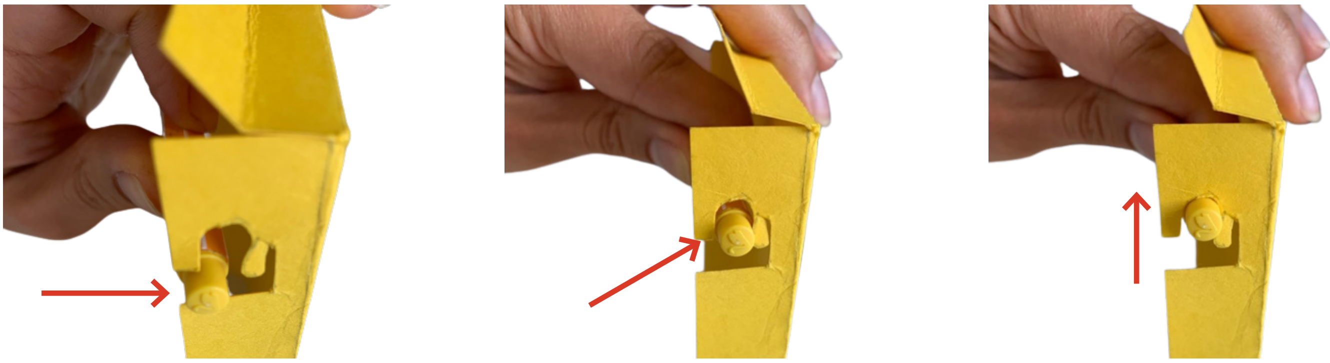
Step 6: Create 3D models

3D models out of cardboard were made to test the steps of the different connections of the cassette panel:



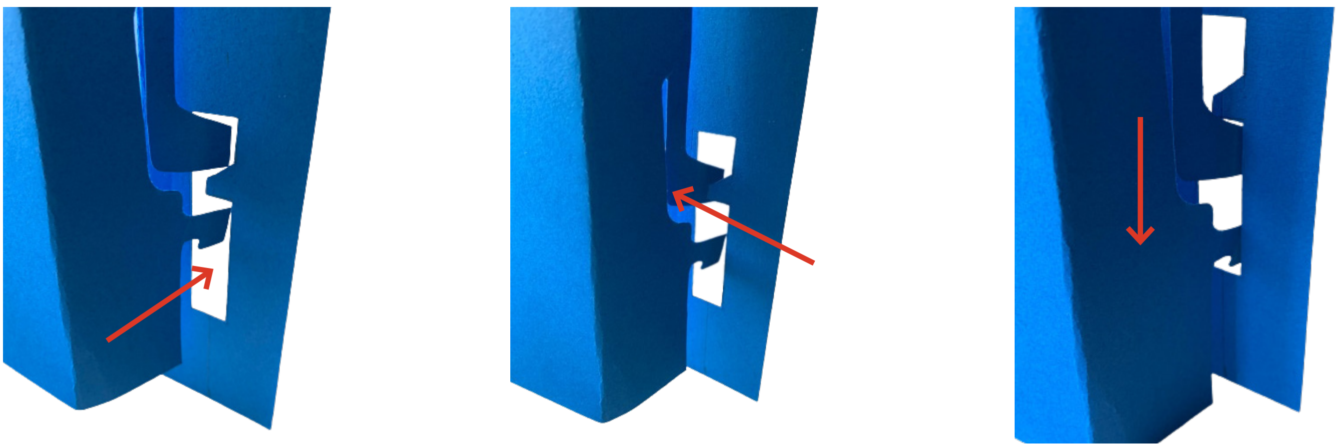
1. Insert 2. Slide down 3. Slide sideways

Figure 8.16 Slide connection model (Pictures made by author)



1. Insert 2. Push 3. Slide up

Figure 8.17 Compliant mechanism model (Pictures made by author)



1. Insert 2. Push 3. Slide down

Figure 8.18 Snap fit connection model (Pictures made by author)

Step 7. Test and evaluate mock ups

Testing bending properties of aluminium
The smallest cut the punching machines at Aldowa can make is of 3mm. Therefore, a test was carried out to understand how much aluminium bends with a 3 mm or 6 mm cut. The arm length was also tested and varied from 43 to 73 mm. This test is necessary to understand how much aluminium can bend and still maintain its stiffness.

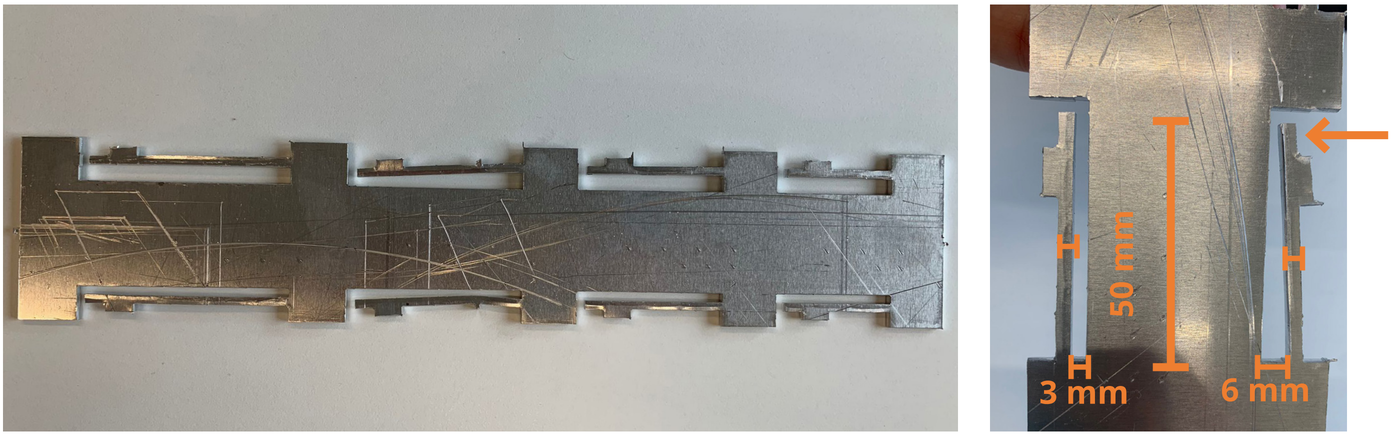


Figure 8.19 Test of the compliant and snap-fit system cuts (Pictures made by author)

Discussion of Results
Following the evaluation of the aluminum plate prototype, it was observed that it requires less effort to move the longer arm lengths compared to the shorter ones due to the increased moment. Both arms had a uniform width of 3 mm, and the sheet thickness remained consistent as well. When an arm with a length of 50 mm is pushed to the end of the 6 mm cut, it exhibits slight deformation and does not return to its original position. It's worth noting that aluminum undergoes plastic deformation without fracturing. This test was conducted to gain insights into the potential of aluminum as a spring-like element for use in various click-type connections, including compliant and snap-fit alternatives.

Slide connection

The slide system did not work as intended. One side of the panel can slide through the screw attached to the omega profile but the other side's hole does not match the position of the screw. See Figure 8.31.

Limitations

- Lack of visibility from the front makes it challenging to determine the exact positions of the holes on the back flange of the panel and the corresponding screws.
- Achieving precise alignment of holes and screws is crucial for the connection, which may pose challenges on-site due to tolerance issues, potentially leading to errors.

Opportunities

- This initial testing phase has highlighted the iterative nature of the design process, emphasizing the importance of incorporating paths along the design roadmap to revisit and improve such errors in the design for disassembly guidelines.
- Notably, the panel's secure attachment on one side via the slide connection to the omega profile demonstrates promising performance and potential. These slide connections could find applications in other ways, although further research and variations are necessary.

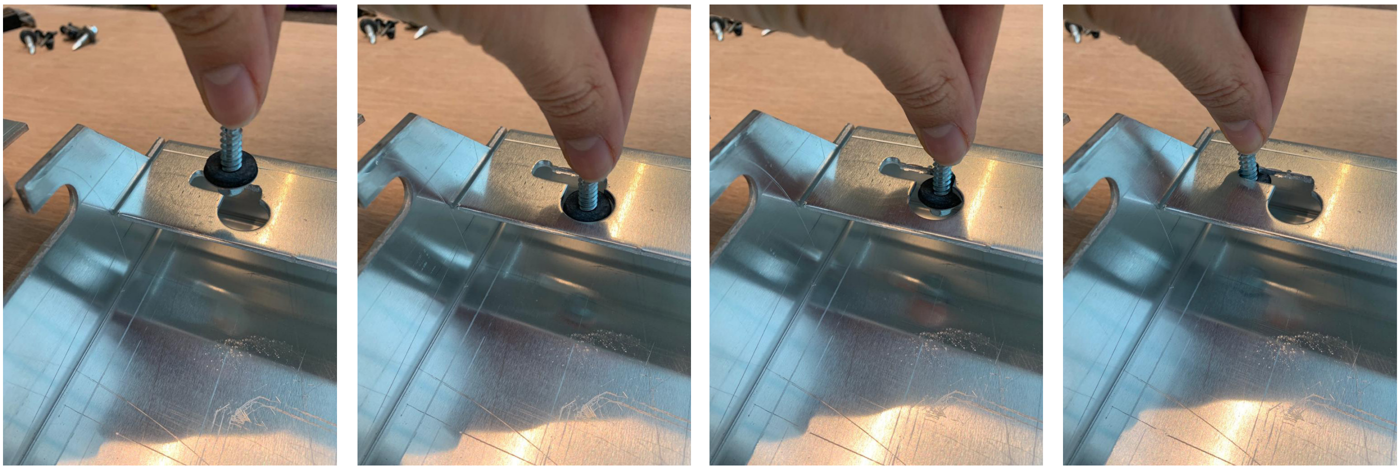


Figure 8.20 Slider connection motion. Back view. (Pictures taken by author)

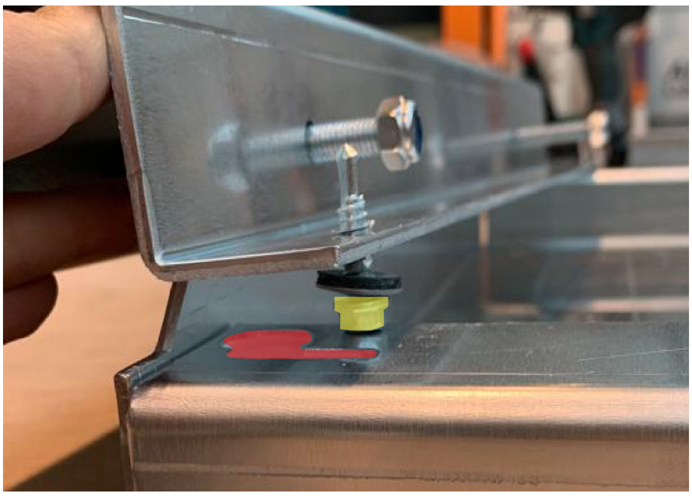


Figure 8.21 Precision error in the prototype: Where the red mark is the hole and the yellow mark is the screw. (Pictures taken by author)

Compliant connection

The compliant system works well when clicked with the plastic tube surrounding the M8 bolt. The most convenient option for clicking is the one with the longest arm measuring 70mm, but the 3mm-wide arm is fragile and prone to breakage. In contrast, the 6mm-wide arm offers more robustness but demands more force for disassembly.

Limitations

- The connection needs to be fixed enough to withstand upward wind but loose enough to be disassembled by a constructor. Structural analysis is essential to assess the compliant mechanism's capacity to withstand various wind loads, including suction, pressure, fatigue and, notably, upward wind forces.

Opportunities

- The test proved valuable in evaluating the functionality of the clicking system, making it feasible for integration into a panel for a more comprehensive understanding of its real behavior

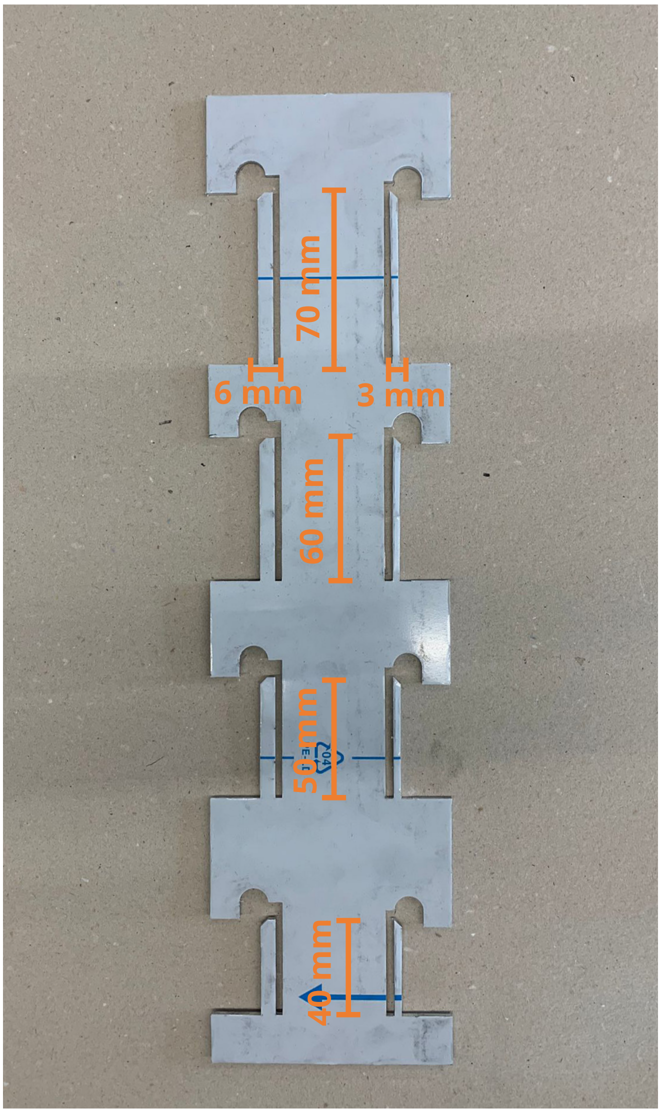


Figure 8.22 Compliant mechanism test plate with plastic foil (Pictures taken by author)

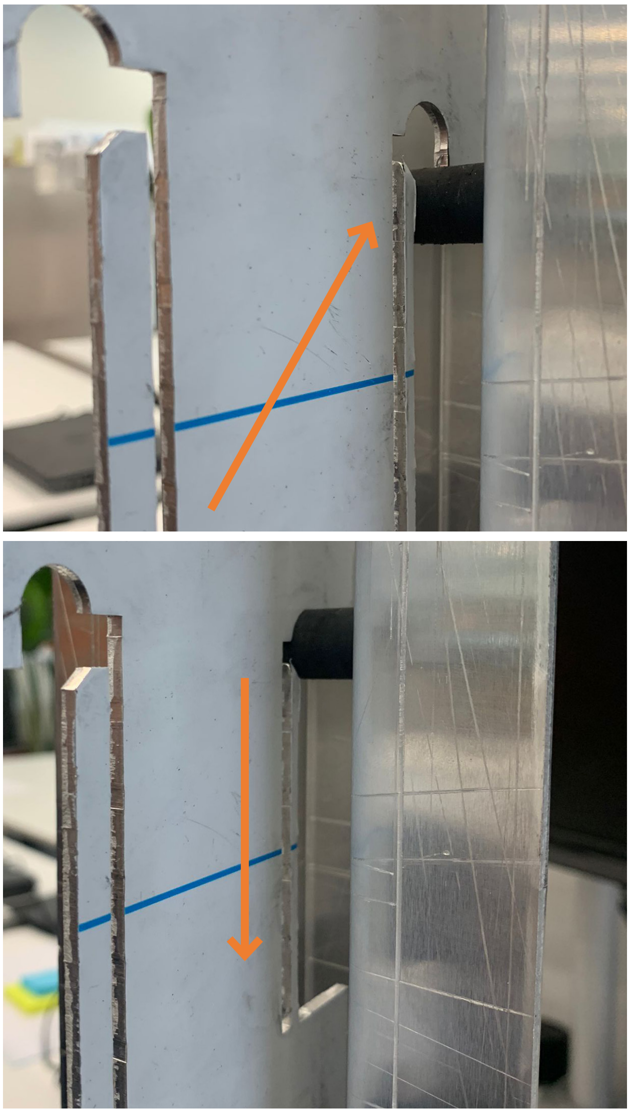


Figure 8.23 Compliant mechanism motion of the 3mm wide and 70 mm long arm. (Pictures taken by author)

Snap-fit connection

This snap-fit assembly method stands in contrast to Aldowa's traditional systems, yet it presents a potential solution for establishing connections without the need for additional fasteners. The test was conducted by emulating the flange of the omega and the side flange of a cassette panel. At this reduced scale, the component can be easily pushed and slid into its locked position, with the same reverse motion for unlocking.

Limitations

- Incorporating this method into an actual panel may prove challenging due to the limited space available (only 20mm) between the panels, making it difficult for fingers to access. It's possible that an additional tool may be required for unlocking.

Opportunities

- This snap system eliminates the necessity for fasteners, as two aluminum plates interlock with each other through the flexibility of aluminum. This results in fewer additional connections, significantly reduces assembly and disassembly steps and uses a single material.

Figure 8.24 Snap fit test plates. Left: Omega front flange. Right: Cassette panel side flange. (Pictures taken by author)

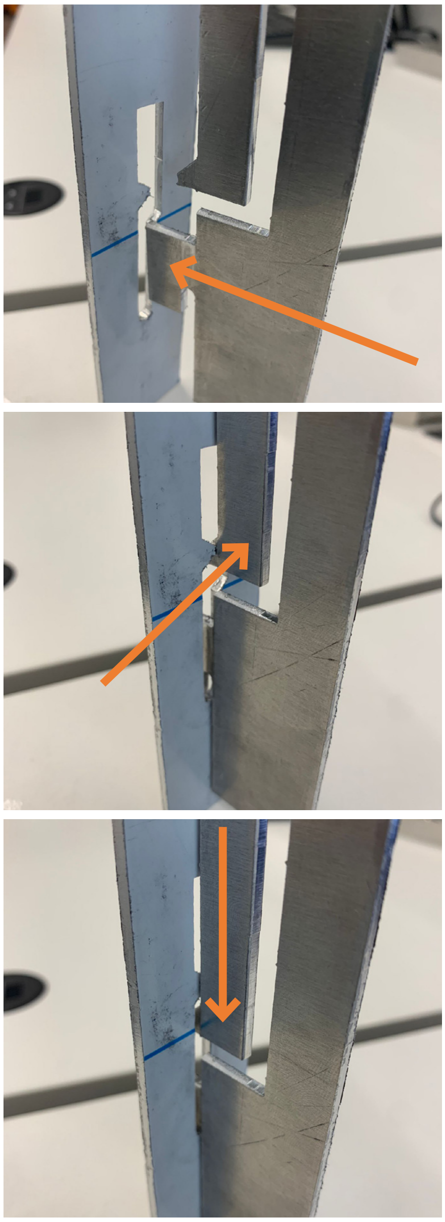


Figure 8.25 Snap fit motion (Pictures taken by author)

Couple piece welded and coated connection
The welded spots on the panel's surface exhibit no signs of discoloration or bubbles, making welding an appropriate choice for panels undergoing powder coating. However, it's important to note that welding is not feasible for panels that undergo anodization, as discoloration may occur in such cases and the parts cannot be welded after anodization.

Limitations:
- This method of connection is exclusively suitable for powder-coated panels. Anodized panels, on the other hand, require an alternative approach, such as securing the components at the back of roof caps. For water sills another alternative is necessary.

Opportunities:
- The pre-assembly of this connection, carried out at the fabrication stage, reduces the risk of losing individual couple pieces. Furthermore, it reduces both assembly and disassembly operations, while promoting the use of a single material type (AlMg1).

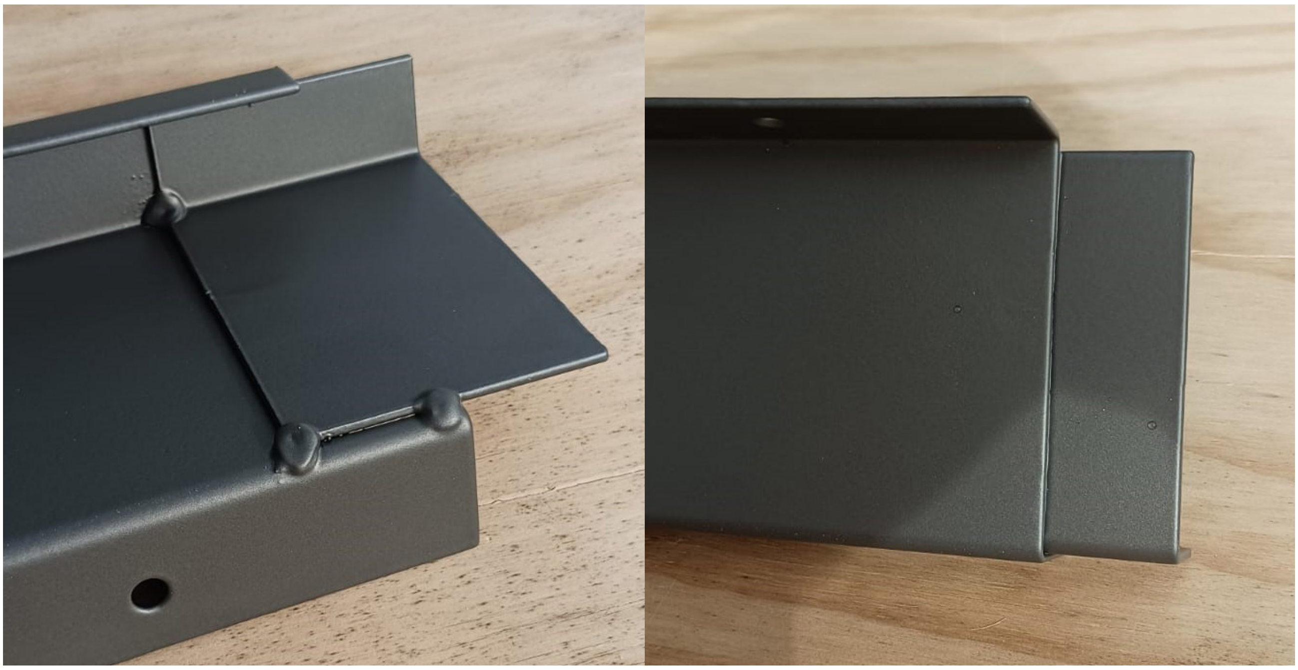


Figure 8.26 Welded couple piece to a water panel. Left: Bottom view. Right: Top view (Picture made by author)

Step 8: Compare variations

The guideline of creating a disassembly map is followed in order to compare the different alternatives. This involves making disassembly maps for each alternative, which are initially compared based on the quantity of parts, fasteners, operations, tools required, and the presence of destructive processes. Ultimately, a detachability score is calculated, with a **higher score approaching to 1**, meaning **highest detachability**. This score is derived from the average values from four distinct categories: connection type, accessibility, interdependence, and robustness.

The **recovery scenario** chosen is **recycling**. This influences the detachability score since what needs to be detached are the parts of different materials.

Roof Panels

These are the disassembly maps for each couple piece alternative:

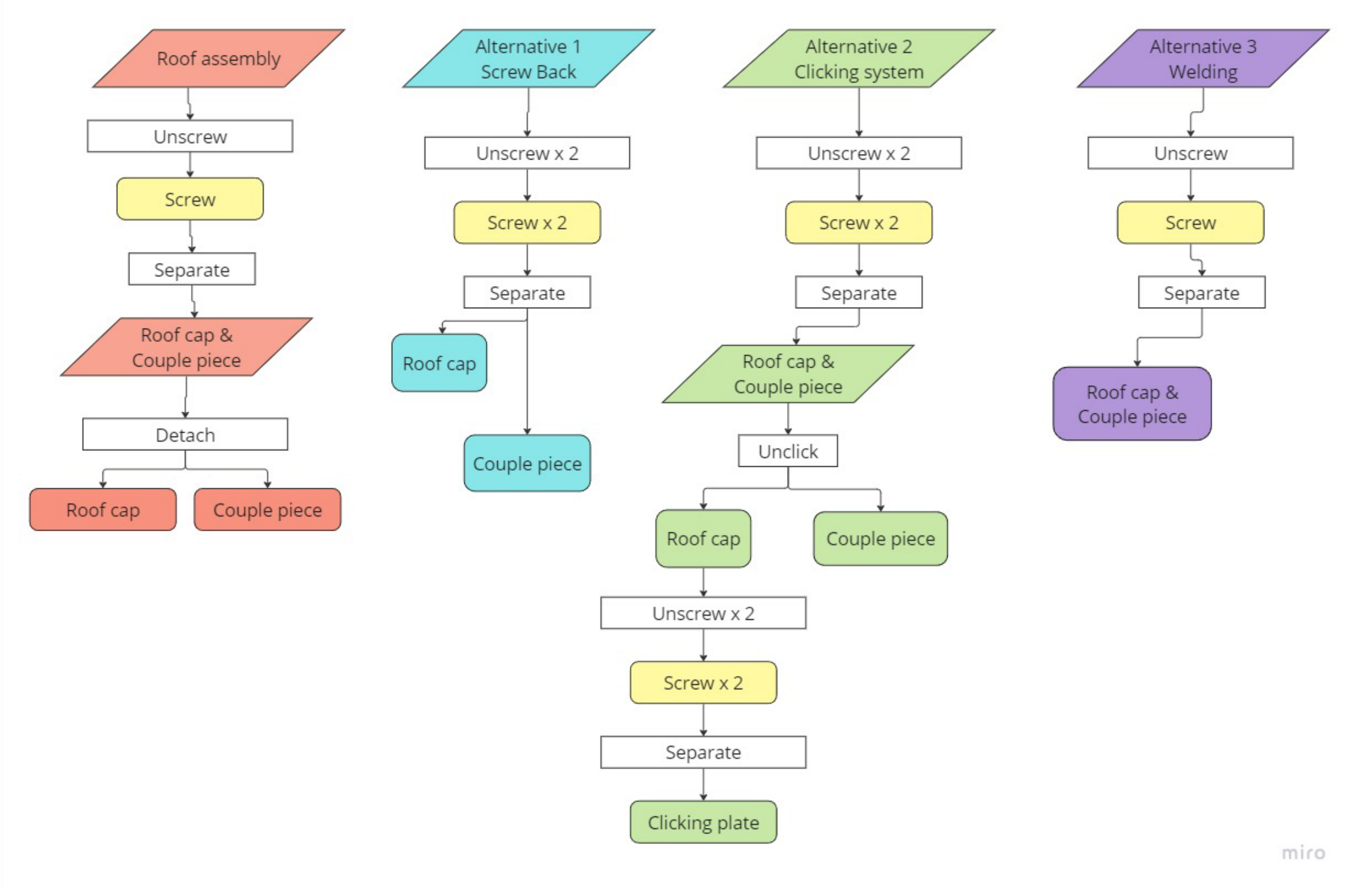


Figure 8.27 Disassembly maps of couple pieces alternative connections (Illustration made by author)

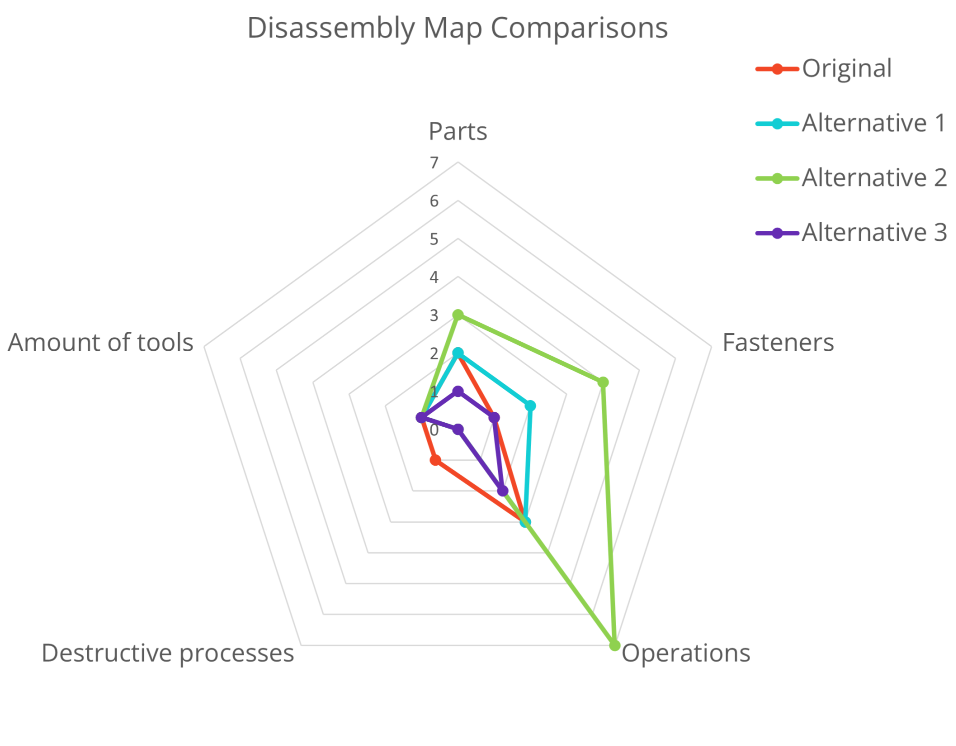


Figure 8.28 Initial comparison of the disassembly maps of the couple pieces alternative connections (Illustration made by author)

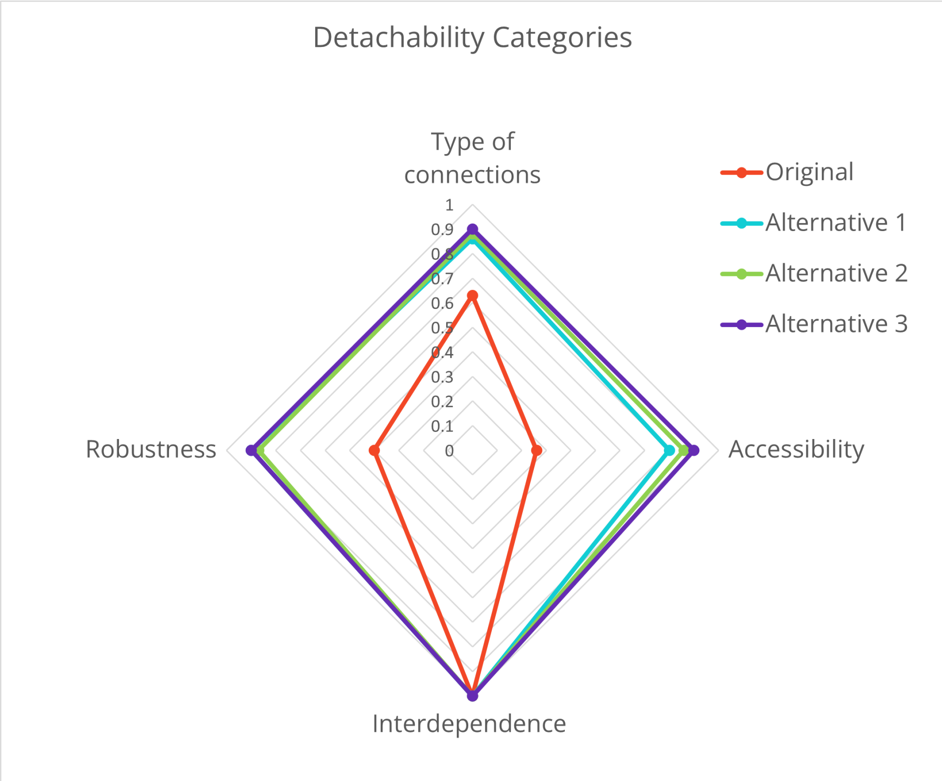


Figure 8.29 Detachability criteria scores of couple pieces connection. Where for each category the highest score is of 1 . (Illustration made by author)

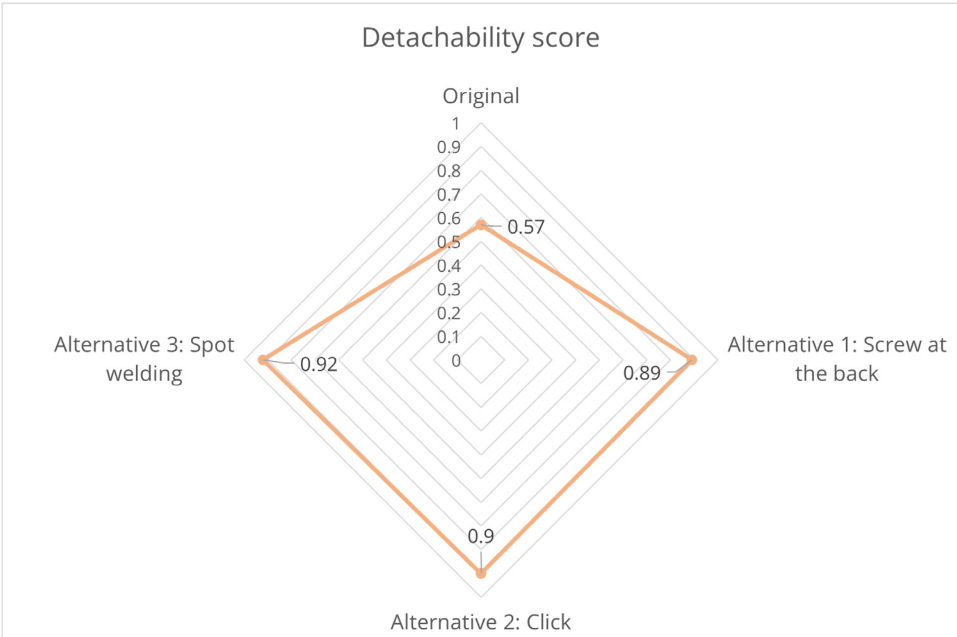


Figure 8.30 Final detachability scores of couple pieces connection. Where a score of 1 means a completely detachable connection. (Illustration made by author)

Discussion of results

Alternative 3, the welded connection, scores the best in the overall Detachability score (0.92). Alternative 2 follows second (0.90) but according to the disassembly map comparisons (Figure 8.28) it has the most amount of operations, fasteners and parts. Therefore, alternatives 1 and 3 score as the best variations.

Cassette Panels

These are the disassembly maps for each cassette panel connection alternative:

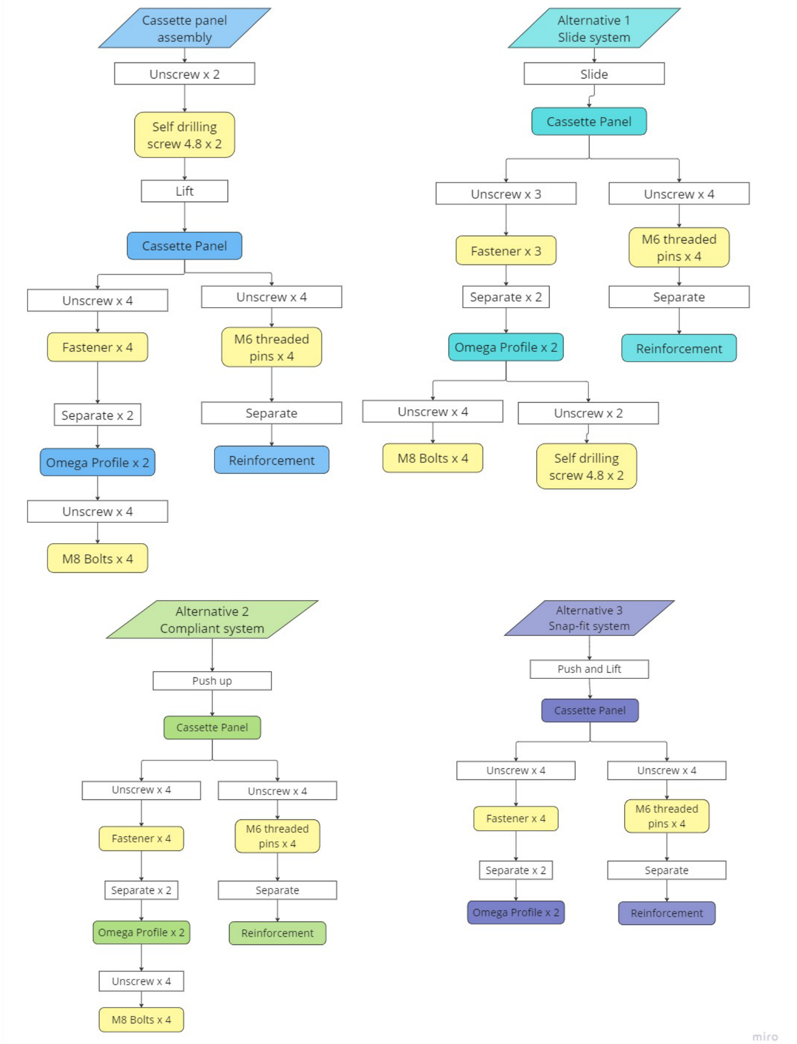


Figure 8.31 Disassembly maps of cassette panel alternative connections (Illustration made by author)

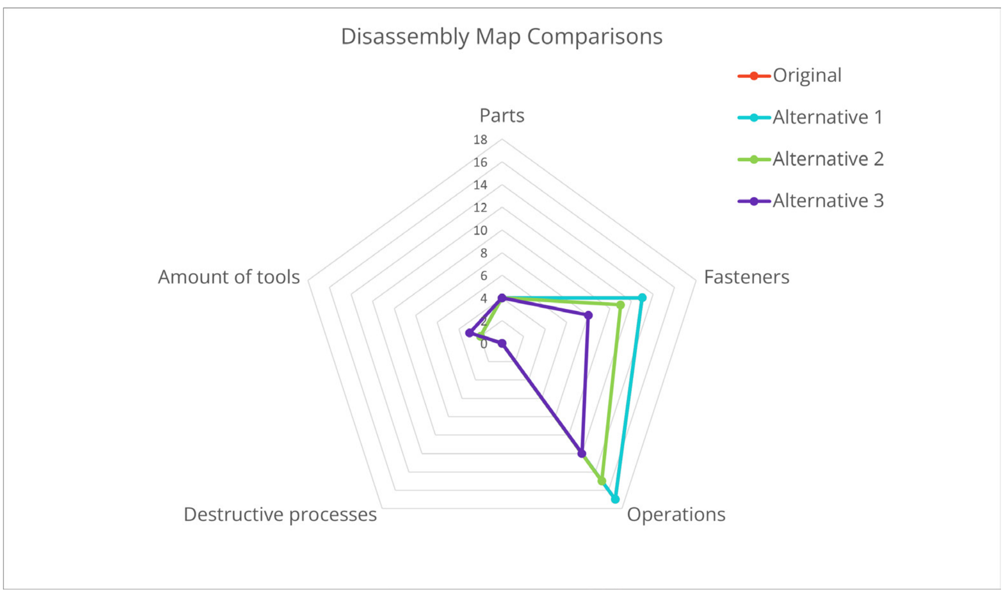


Figure 8.32 Initial comparison of the disassembly maps of the cassette panel alternative connections (Illustration made by author)

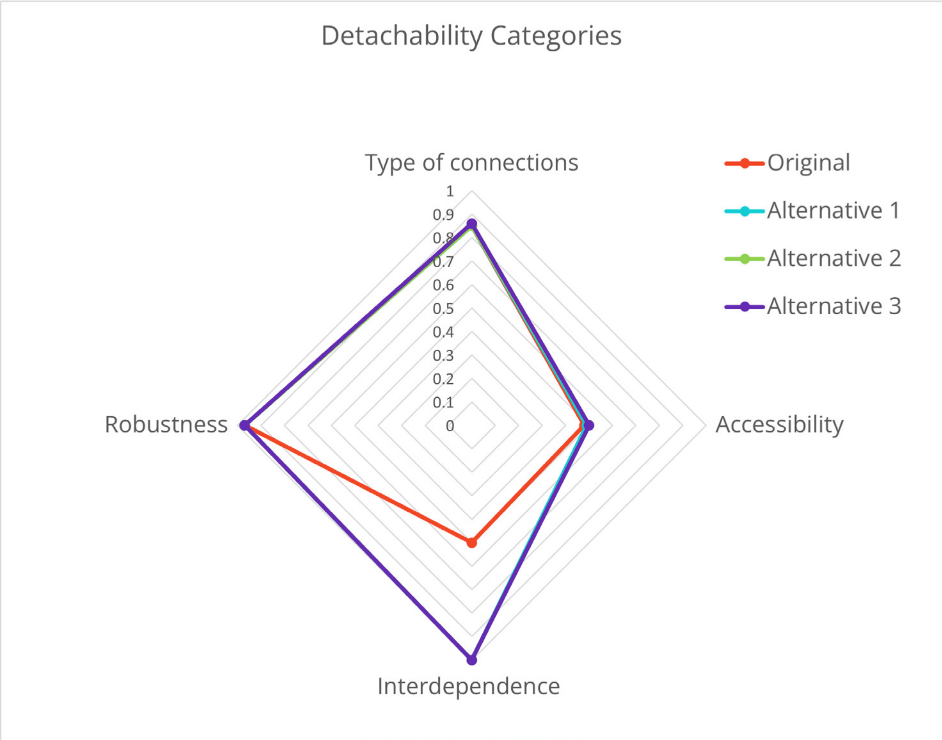


Figure 8.33 Detachability criteria scores of cassette panels. Where for each category the highest score is of 1 . (Illustration made by author)

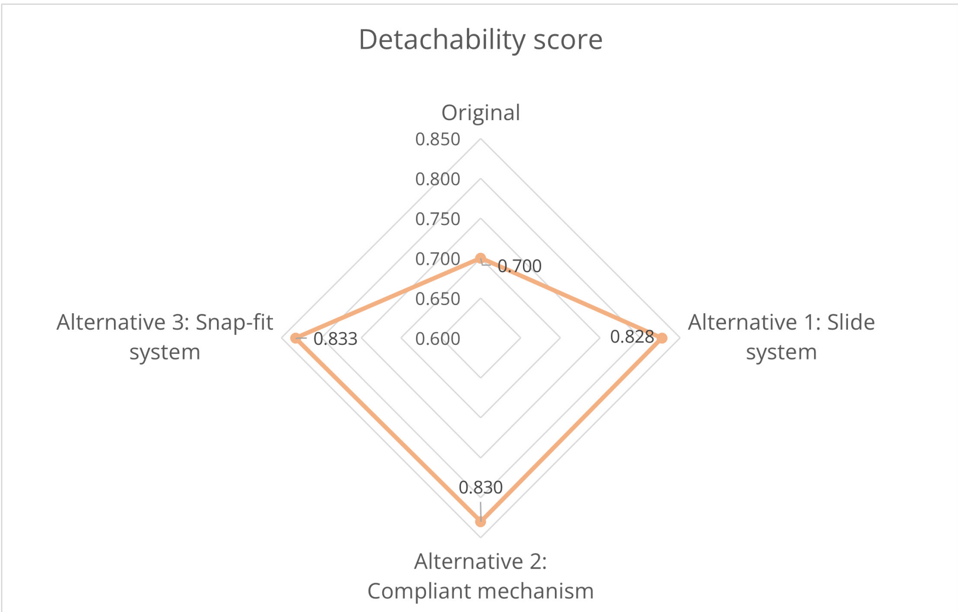


Figure 8.34 Final detachability scores of cassette panels. Where a score of 1 means a completely detachable connection. (Illustration made by author)

Discussion of results

The alternative's detachability score are similar (Figure 8.34) and the differences are seen in the initial comparisons (Figure 8.32). Alternative 3 has the least amount of fasteners but it require an extra tool to disassemble the panel. Both alternatives 2 and 3 score as the best variations according to the detachability score.

8.3 Evaluating the guideline

After testing the guideline, an evaluation will be conducted to verify the fulfillment of the requirements of the DfD Guideline outlined in Section 6.5.

Requirements	Fulfillment explanation
Present a flyer about Aldowa's C2C products	The flyer includes Aldowa's C2C vision, information about the certified product and the Cradle to Cradle philosophy and certification requirements.
Answer FAQ about C2C and DfD	FAQ are answered in the flyer as well.
Present an Excel file that calculates • If the design aligns with the C2C bill of materials • If the connections are detachable (BCI index)	An extra excel sheet has been added to the excel file "Standaard_calculatie" for a project budget of the sales department. This C2C check runs automatically. Materials and fasteners can be further added.
Help engineers improve the disassembly of an existing design.	Two options have been proposed to achieve this: 1. With a disassembly map to identify the barriers facilitating disassembly and calculating a detachability score. 2. With a parametric structural analysis that indicates the minimum amount of connections.
Help engineers design a new product for disassembly	An A3 poster has been created that outlines a road map to design or re-design a new product for disassembly.
Ensure that their design aligns with the requirements of Design for Disassembly of the Cradle to Cradle manual:	This is accomplished by initially ensuring alignment between the sales department and the client regarding certified materials and detachable connections. Subsequently, the engineering department can enhance the project's disassembly potential.
Let project leaders know which Cradle to Cradle Design for disassembly checklist needs to be completed or agreed upon during a project workflow	A project workflow where the Guideline can be used is presented in Figure 6.12 which could be useful for project leaders to identify the key moments for Dfd.
Give advice to engineers on when to reach out to the Production/Transport department for their approval of the design.	In the A3 poster for designing a new product for disassembly, there is a step where it is advised to talk to colleagues, including the production/transport department.
Further advice	Further advice has been provided in pg.74 of Section 7.1

Table 8.4 Evaluating the overall DfD Guideline

The DfD Guideline has the following limitations:

1. **Diverse Documentation:** It comprises a collection of distinct documents rather than a single unified guideline.
2. **Company-focused:** Tailored specifically to the project workflow within Aldowa, its applicability in different contexts remains uncertain.
3. **Varied Design Roadmaps:** While it presents a (re)design roadmap derived from a general design framework, the sequence of steps may vary among engineers, and the DfD process may involve additional or fewer steps.

4. **Parametric Structural Analysis Challenge:** The most significant limitation lies in the parametric structural analysis of the cassette model, as its immediate implementation within the company is unfeasible. To incorporate structural calculations and parameterization into the cassette panel design, the company would need to integrate these processes into its existing Catia software. Moreover, for FEA (Finite Element Analysis) analysis, an additional Catia plugin would require a separate license purchase, adding to the overall cost.

8.4 Conclusions

In this section the application of the proposed DfD Guideline, as outlined in Section 7, is applied through user testing and a case study. The findings are summarized as follows:

I. Excel Sheet calculation testing:
The implementation of an automated Bill of Materials calculation has proven advantageous, offering an efficient means to verify material quantities against certification standards and average detachability score (Type of connections). However, ongoing material and fastener modifications are required post-certification.

II. Disassembly Map:
The Disassembly Map presents several opportunities, particularly in the early design stages, as a quick tool for assessing the disassembly potential and visualizing disassembly barriers. It serves as a foundational reference for re-design efforts. Nonetheless, it should be noted that time considerations, subjectivity, and the absolute value of the detachability score are not the ultimate measure for disassembly.

III. Structural Optimization:
The structural analysis provides a quick means to determine reinforcement profiles and bed hook requirements, offering engineers flexibility in optimizing connections while adhering to stress and displacement limits. Transitioning the script to CATIA software is a recommended step, alongside the acknowledgment that results from Grasshopper and Karamba need to be further validated. Further inclusion of thermal expansion parameters is also essential in determining design tolerances and proposing modifications.

IV. Redesign:
The application of the re-design roadmap, exemplified in the Cradle to Cradle case study, demonstrated its utility in generating and testing design variations.

To avoid destructive processes during material separation, an alternative connection method has been proposed – a welded connection of identical materials (AlMg1) for the couple pieces and panels. This pre-fabricated connection not only reduces the risk of loose components but also reduces disassembly operations. However, it is only suitable for powder-coated parts.

Among the three other alternatives explored for disassembling cassette panels independently, the compliant mechanism and snap-fit connection have shown a better performance. These alternatives will undergo further testing to assess their practical viability.

It's important to acknowledge that while the redesign roadmap's steps were used to arrive at these design alternatives, the specific sequence and order of these steps may vary among engineers.

V. Overall evaluation:
In the final assessment, the overall application of the guideline underwent an evaluation ensuring alignment with the requirements specified in Section 6.5. The evaluation also highlighted inherent limitations of the guideline, including its diverse documentation, company-focused approach, variable design roadmaps, and the challenge of parametric structural analysis.

09.

Product development

Section 9.1 provides a further evaluation of the current design, while also defining the necessary requirements to advance the product's development. Section 9.2 delves into design analysis, utilizing Ansys modeling to showcase design improvements. Section 9.3 showcases the final product and further improvements are discussed.

List of Figures:

Fig. 9.1 Analysis of the existing design.
Fig. 9.2 2D drawing of the new facade assembly.
Fig. 9.3 2D Vertical detail of the connections.
Fig. 9.4 2D Horizontal detail of the connections.
Fig. 9.5 Calculation of the forces on the connections
Fig. 9.6 Comparison of the vertical displacement of the bolts with respect to the other bedhooks.
Fig. 9.7 Resultant force to carry out the displacement.
Fig. 9.7 Overview of iterations for the clicking connection.
Fig. 9.8 Clicking connection iteration 1
Fig. 9.9 Clicking connection iteration 2
Fig. 9.10 Clicking connection iteration 3
Fig. 9.11 Clicking connection iteration 4
Fig. 9.12 Clicking connection iteration 5
Fig. 9.13 Clicking connection iteration 6
Fig. 9.14 Clicking connection iteration 7
Fig. 9.15 Clicking connection iteration 8
Fig. 9.16 Forces applied on snap fit connection
Fig. 9.17 Snap part stress results
Fig. 9.18 Snap part iteration 1
Fig. 9.19 Snap part iteration 2
Fig. 9.20 Snap part iteration
Fig. 9.21 Design iterations of the snap part.

9.1 Program of requirements

Analyzing the existing design

The previous chapters focused on designing connections for disassembly. Nevertheless, to further develop the connections other aspects need to be considered such as gaps, tolerances, strength, and other functionalities. Therefore, the current system is analyzed to identify the current advantages and disadvantages in order to improve it and incorporate the connection variations to it.

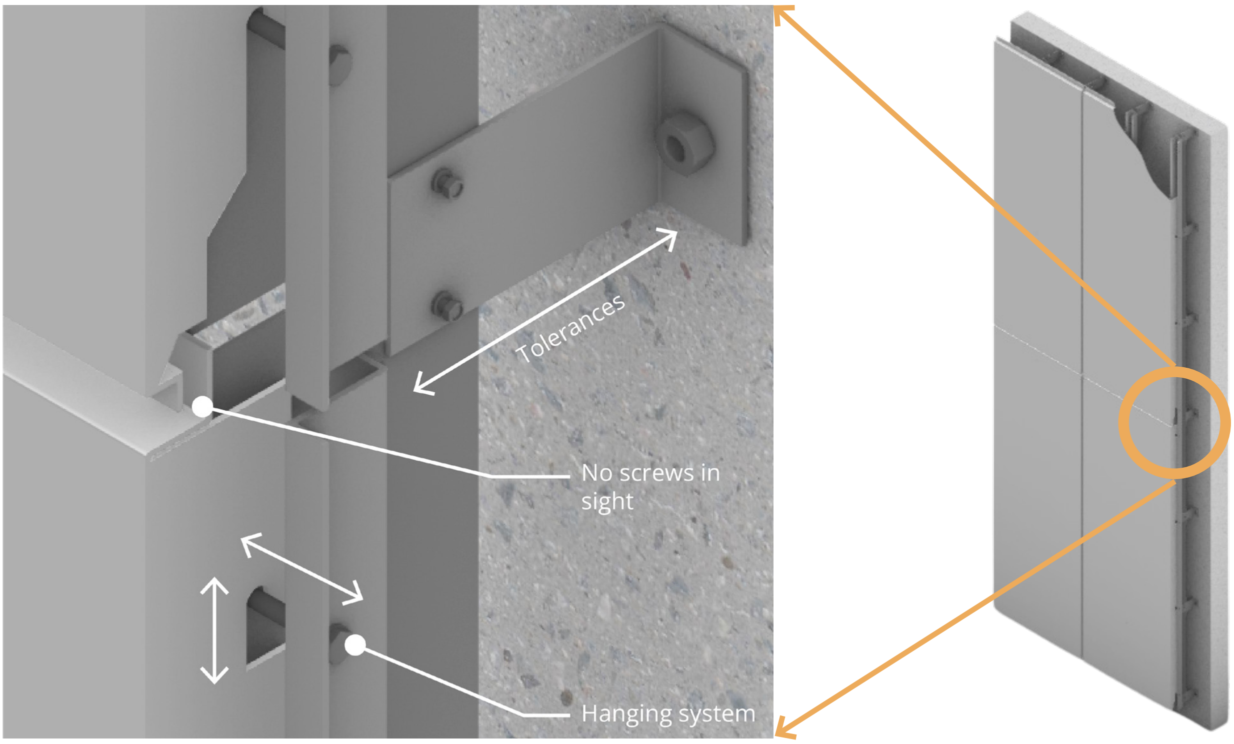


Figure 9.1 Analysis of the existing design. (Illustration made by author)

Advantages

- No screws in sight
- Small gaps
  - Gaps sideways: +- 20mm
  - Gaps top/bottom: +- 16mm (dependent assemblies)
- Overcomes tolerances of width and depth
  - Depth: the brackets and L profile
  - Width: +- 10mm
- Hanging system that is easy to mount
- Sound vibrations and sliding prevented by the plastic tube around bolt
- Modular system that works in many situations including corners

Disadvantages

- More expensive than the box panel system because it has more material, parts, connections, etc
- Dependent assemblies (Top/bottom panels) that can become difficult to demount

The program of requirements is composed of five categories:

1. **Appearance**
- No screws in sight
- The gaps should not be bigger than the current ones (+/- 20 mm sideways and +/- 16 mm top/bottom)

2. Production
- The system should be able to be produced by the current production process and materials at Aldowa

3. Assembly & Disassembly
- The system should be (de)mounted with as few operations as possible
- The system should have as few parts and fasteners as possible
- The connections should take into account +- 10 mm tolerances
- Maximum 2 people should be able to carry it (20kg per person)
- The system has a detachability score above 0.6
- The connections should allow the panels to be disassembled separately for maintenance
- The connections should allow the different material parts to be separated for proper recycling/reuse/repair, etc

4. Strength
- The system is intended for residential, office and public buildings of CC2 medium consequences

5. Durability ***
- Aldowa offers a 15-year warranty for their aluminium products and advises that the product be cleaned annually. Following the initial 15-year period, the product should be inspected for maintenance. The system must support assembly and disassembly for at least two legal service lifetimes, in alignment with the 15-year guarantee.

*** Durability category is a goal rather than a requirement

The unknown fields are the areas where the connections have to be further developed and tested:

Category	Design Requirement	Current Cassette Panel	Compliant Connection	Snap fit Connection
Appearance	No screws in sight	Yes	Yes	Yes
	Small gaps	Sideways = +/- 20 mm Top/bottom= +/- 16mm	Unknown	Unknown
Production	Can be produced at Aldowa with the current machinery and materials	Yes	Yes	Yes
Assembly	Few parts/ fasteners	18	16	12
	Few (de)assembly operations	18	16	12
	Overcomes at least +/- 10 mm tolerances	X-direction Y-direction Z-direction	Unknown	Unknown
	Prevents vibrational sound	Yes	Unknown	Unknown
Disassembly	>0.6 Detachability score	0.700	0.830	0.833
	No penalties present	No	No	Unknown Extra tool?
	Independent disassembly	No	Yes	Yes
Strength	CC2 / CC3 conse-quence class proof	Yes	Unknown	Unknown
Durability	2 x 15 year legal service lives	Unknown	Unknown	Unknown

Table 9.1 Identifying areas of improvement to meet the program of requirements.

9.2 Improving design

The orange highlighted cells of Table 9.1 will be further improved for each connection and integrated into a product.

9.2.1 Gaps and Tolerances

The following figures show the possible assembly of the two connections. The gaps are given in color blue and the tolerances in red.

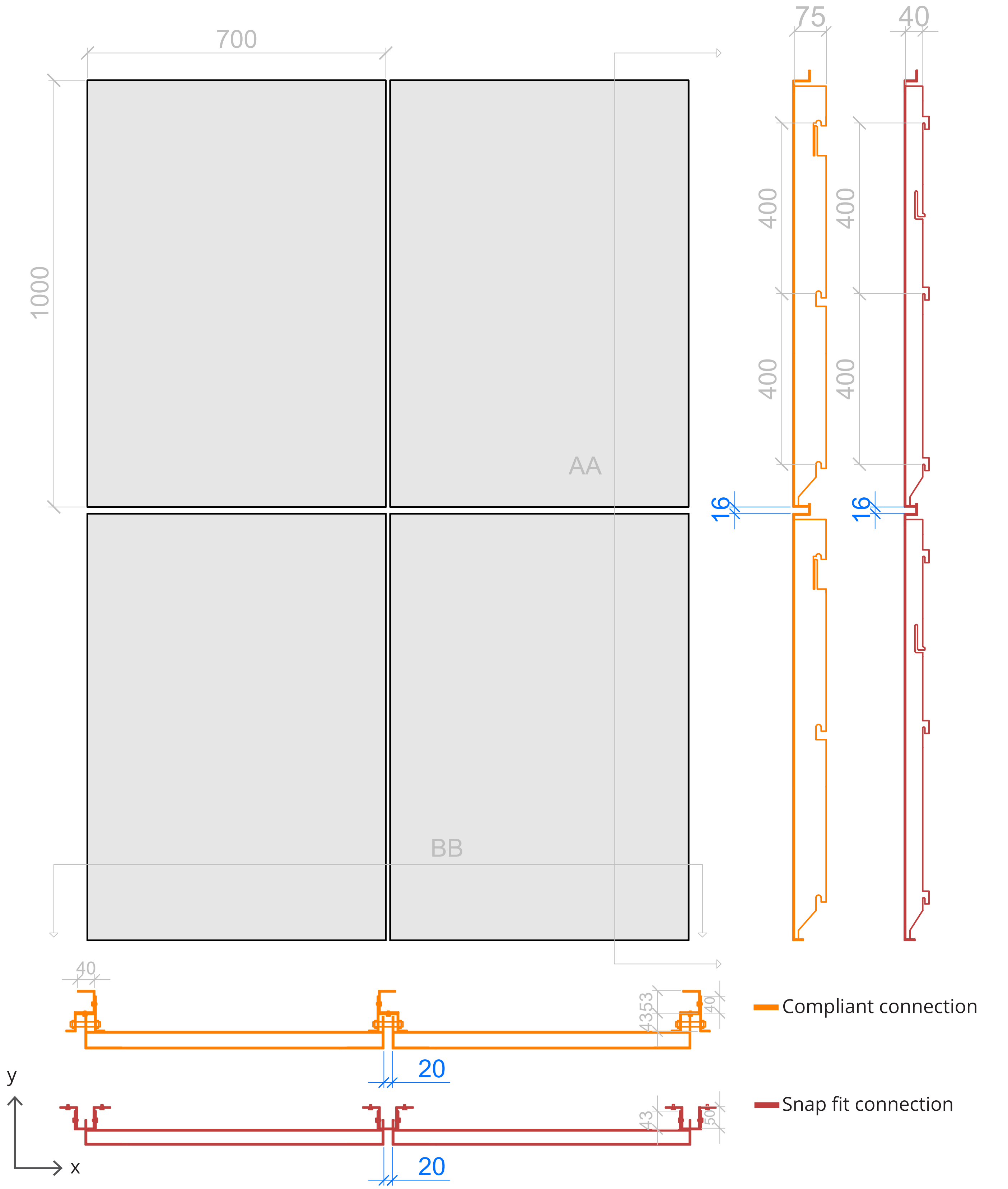
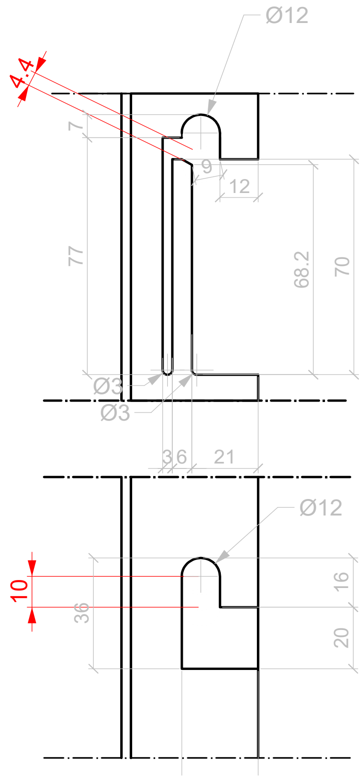


Figure 9.2 2D drawing of the new facade assembly. Ratio1:20 . (Drawings made by author)

Vertical Detail 1:5

Clicking connection



Snap fit connection

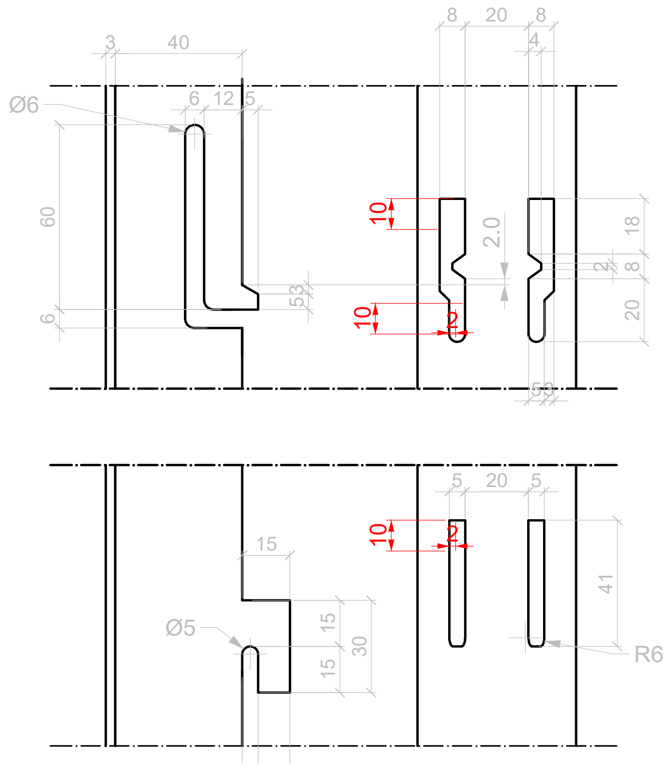
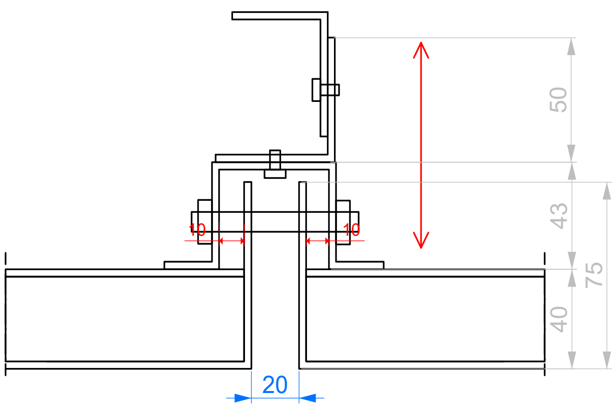


Figure 9.3 2D Vertical detail of the connections. Ratio 1:2. (Drawings made by author)

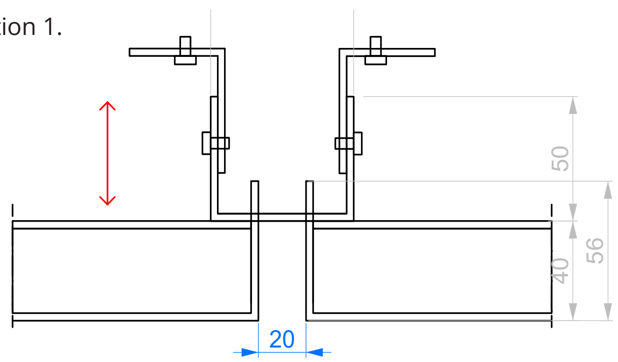
Horizontal Detail 1:5

Clicking connection



Snap fit connection

Option 1.



Option 2.

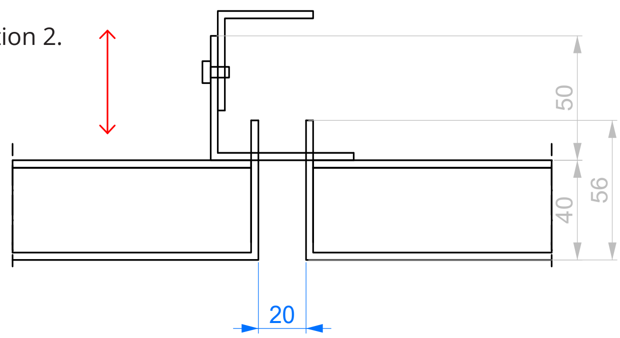


Figure 9.4 2D Horizontal detail of the connections. Ratio 1:5. (Drawings made by author)

9.2.2 Strength

In this section the connections are structurally optimized to withstand the loads. This is carried out with the program Ansys with an FEA (Finite Element Analysis).

Defining the forces on the panel connections

The panel used to analyze the connections measures 1000 x 700 mm (height x width) with an area of 0.7m2. It has four connections per side. One preventing upward movement from vertical loads and the other three preventing horizontal loads. Redundancy is integrated to guarantee that in the event of a connection failure, the panel remains securely fixed to the facade. Consequently, the horizontal wind load on the panel will be distributed among 5 connections, instead of 6, while the vertical loads will be supported by a single connection, instead of the initial 2.

Load combinations

The following safety factors are applied for a building with a consequence class (CC2) as described in NEN-EN 1990:

$ULS = 1.2*G + 1.5*Q + \sum 1.5*Q_i$

Where:
ULS = Ultimate limit state
G = Permanent loads
Q = Variable loads
(NEN, 2019)

Defining the loads

Facade panels undergo mostly suction and pressure due to wind loads. According to Article 7.5 of NEN EN 1991 1-4 upwards wind load is caused by wind friction on the panel causing it to move upwards. This upward load can be 1% of the suction or pressure wind load. A conservative approach was carried out where 2% of the horizontal wind load was taken into account for the upward wind load.

The following formula is used to calculate the horizontal wind force (Q):

$Q = CsCd * Cf * q_p(ze) * A_{ref}$

Where:

Q = Wind force [N]
CsCd = Structural factor (Mostly 1) [-]
Cf =Force coefficient for structural component [-]
$q_p(ze)$ = Peak velocity pressure [kN/m^2]
A_{ref} = Reference area on structural component [m^2]
(NEN, 2020)

The highest pressure coefficient ($C_{pe} = -1.4$) is considered on the corners of a facade. Since the building is of CC2 the maximum height is of 65m and is located at the coast wind area II. The forces on the connections are calculated and presented in Figure 9.5.

GRAVITY FORCE		
Area Panel	**0.7**	**m2**
Number of connections	**5**	Prevents horizontal motion
Number of connections	**1**	Prevents vertical motion
Sheet Thickness	0.003	m
Density AlMg1	2710	kg/m3
Weight	55.8	N
Safety Factor permanent load	1.2	-
G	67.0	N
G / 5 connections	13.4	N

Figure 9.5a Calculation of the forces on the connections: Gravity force (G). (Screenshot from excel made by author)

WIND FORCE			
Height Building	**65**	**m**	
Area Panel	**0.7**	**m2**	
Number of connections	**6**	Prevents horizontal motion	
Number of connections	**2**	Prevents vertical motion	
Peak velocity pressure	1.86	Coastal Area II	
Cf coefficient	1.4	-	
Safety Factor variable load	1.5	-	
Wind pressure/suction (qp)	3.906	kN/m2	
Wind upwards (qu)	0.078	kN/m2	(2% of qp)
$Q_{vertical}$	54.68	N	qu / 1 * Area * 1000
$Q_{horizontal}$	546.84	N	qp / 5 * Area * 1000

Figure 9.5b Calculation of the forces on the connections: Wind force (Q). (Screenshot from excel made by author)

The connections need to overcome the $Q_{vertical}$ force . Therefore the force to unlock (F_{unlock}) the system has to be greater than $Q_{vertical}$.

$$F_{unlock} < Q_{vertical}\ (55\ N)$$

Material Properties Ansys

Ansys provides a variety of Aluminium alloys. In this case, the alloy 5005 is chosen which has a small amount of magnesium such as the aluminium sheets (AlMg1) Aldowa orders from the company Roba.

Material Aluminium 5005, H14
Yield strength 145 MPa (Edupack Granta, 2023)
Safety factor material 1.1 (NEN-EN 1999 : Eurocode 9)

$$\vartheta max < 132\ MPa$$

9.2.2.1 Clicking connection

Model set up

A reverse engineering approach is employed where the force (F_{unlock}) needed to unlock the panel is calculated as well as the areas where the stress limits are exceeded. This is carried out through displacement control where the bolt is assigned a displacement of 6.5mm in the vertical direction as it can be seen in Figure 9.6. The results show the force needed to be applied in order for the displacement to occur and therefore unlocking the system. See Figure 9.7. This resistance force (F_{unlock}) is then compared to the vertical force ($Q_{vertical}$) it would have to withstand depending on the height and position of the building.

The following two criteria need to be fulfilled:

- $F_{unlock} > Q_{vertical}$ (55 N)
- $\vartheta_{max} < 132$ MPa

The following settings were used for the model:

- Mesh size = 2mm with refinement at corners
- Material for the plastic tube around the bolt = PTFE
- Friction coefficient plastic and aluminium = 0,2
- Formulation = Augmented Lagrange
- Detection mode = Nodal-Normal from contact
- Interface treatment = Ramped effects

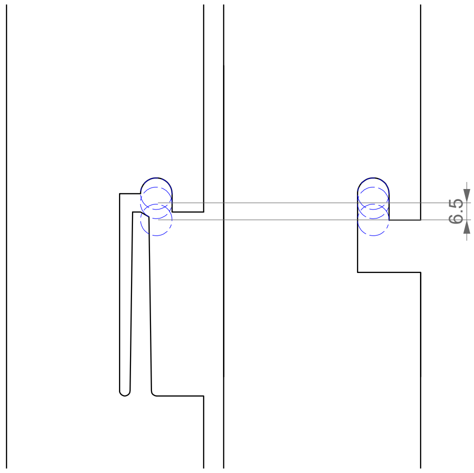


Figure 9.6 Comparison of the vertical displacement of the bolts with respect to the other bedhooks. (Drawing made by author)

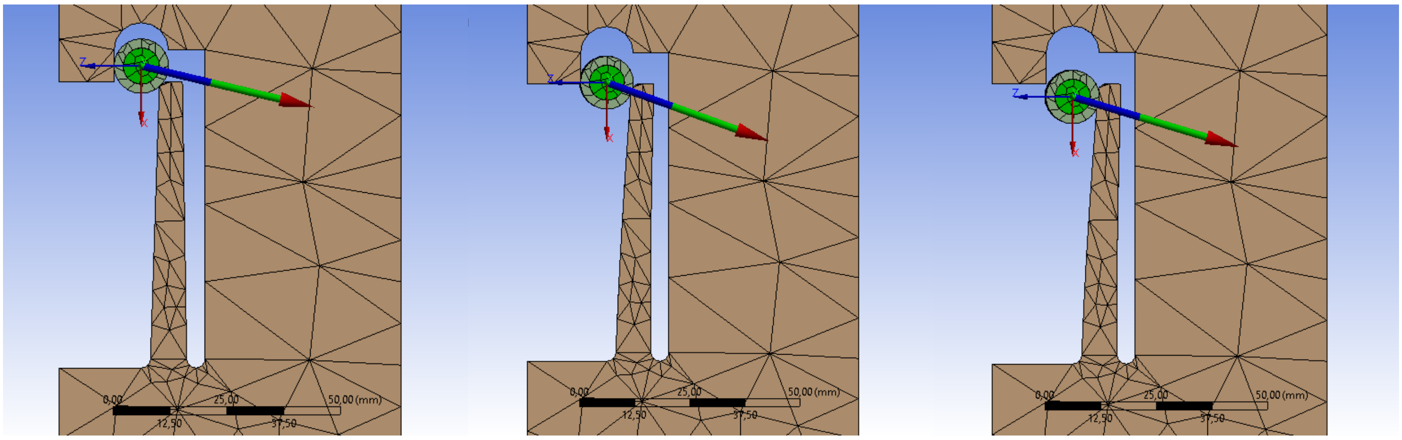


Figure 9.7 Resultant force to carry out the displacement. (Screenshots made by author)

Iterations

Eight different iterations were carried out with the following variables:

- Length of the arm [mm]
- Arm width [mm]
- Corner radius [°]
- Gap opening [mm]

An overview of the dimensions of each iteration can be seen in Figure 9.7 and the results can be seen in Figures 9.8 - 9.15.

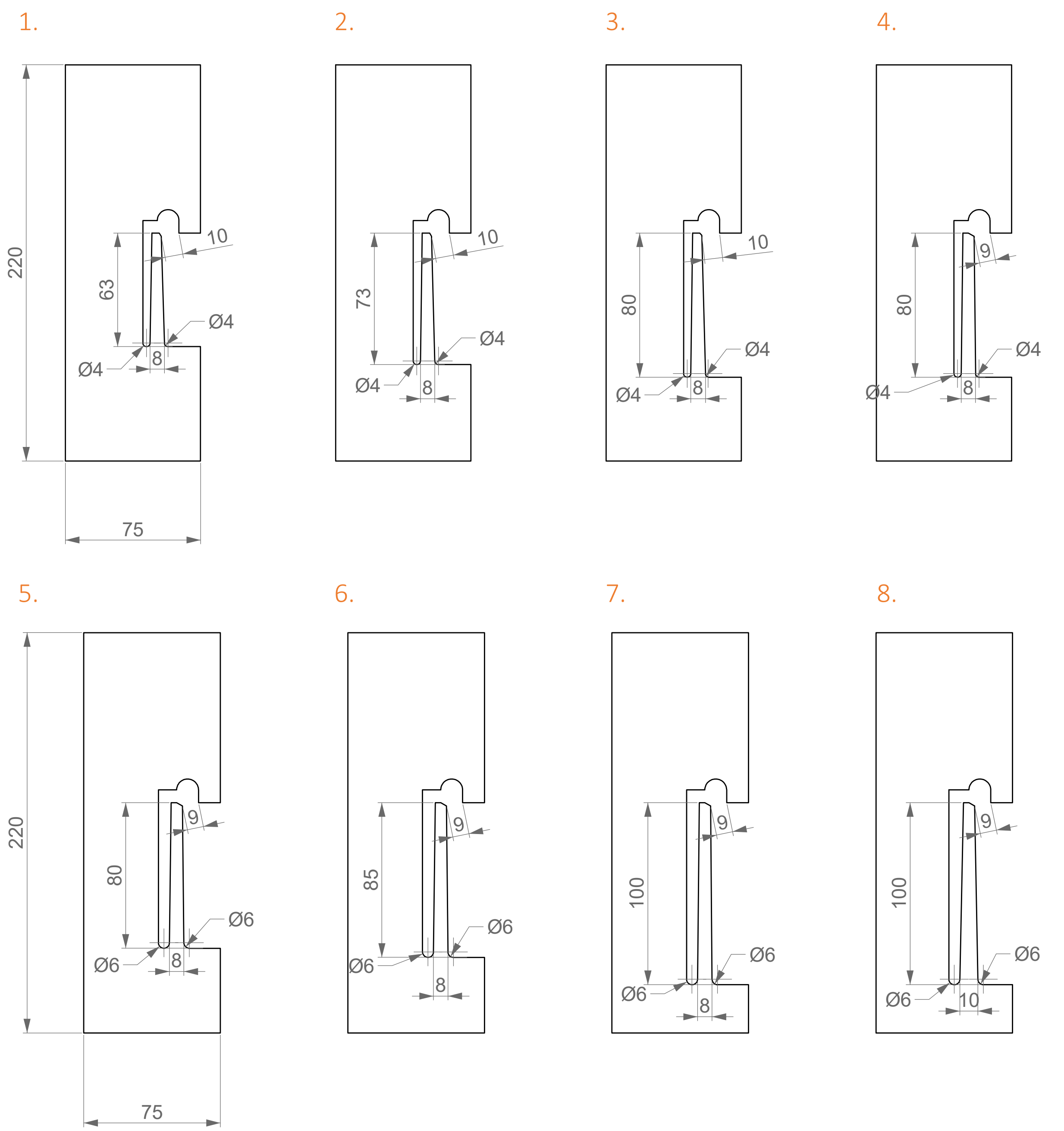


Figure 9.7 Overview of iterations for the clicking connection. (Drawing made by author)

Clicking connection iterations

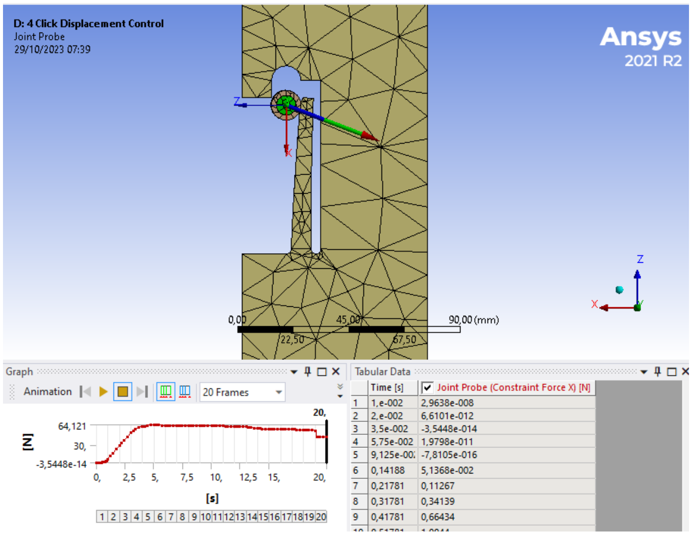


Figure 9.8a Clicking connection iteration 1: F_{unlock} = 64 N
(Screenshot made by author)

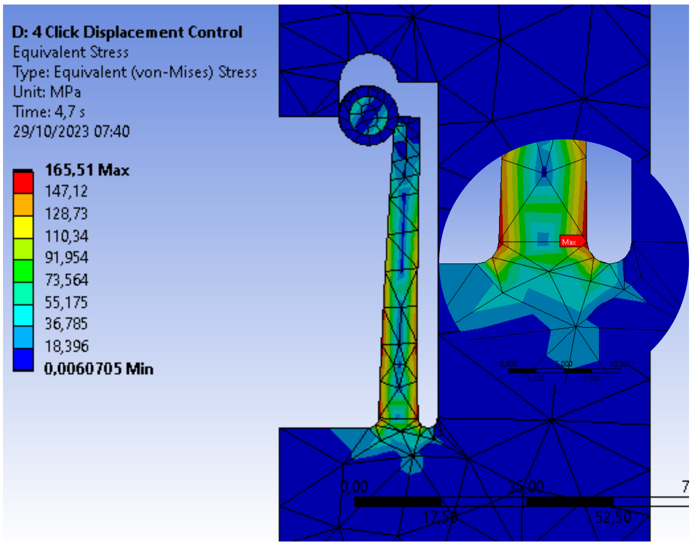


Figure 9.8b Clicking connection iteration 1: ϑmax = 165 MPa
(Screenshot made by author)

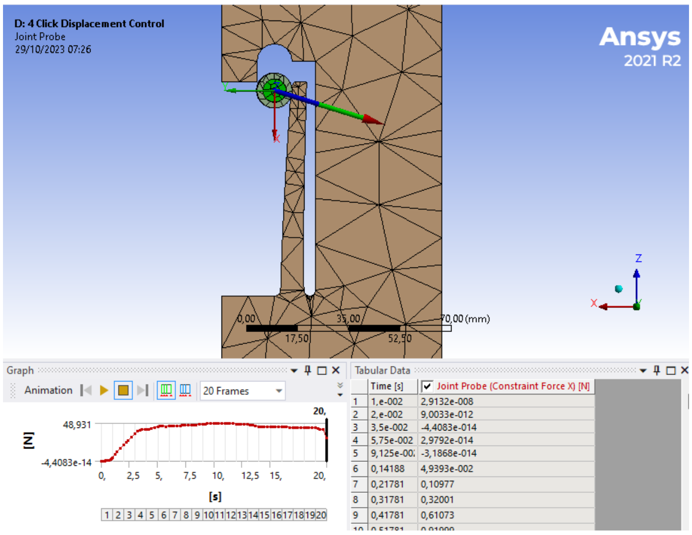


Figure 9.9a Clicking connection iteration 2: F_{unlock} = 48 N
(Screenshot made by author)

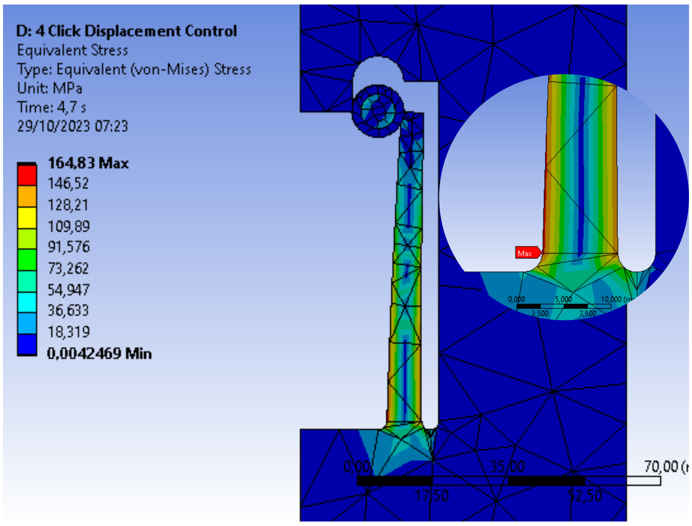


Figure 9.9b Clicking connection iteration 2: ϑmax = 164 MPa
(Screenshot made by author)

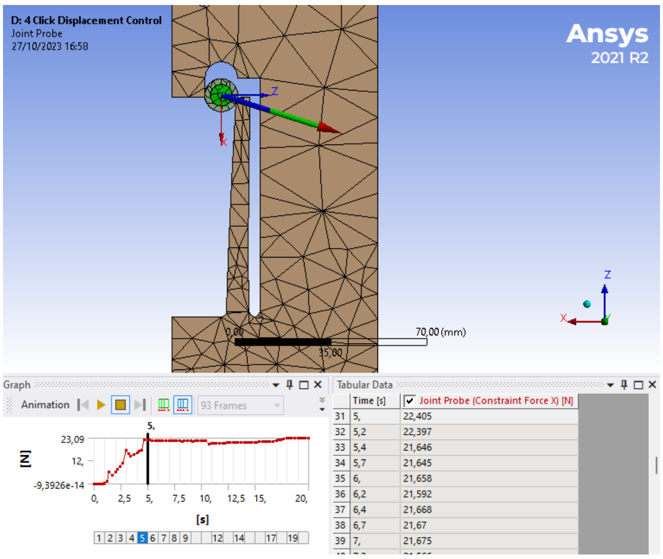


Figure 9.10a Clicking connection iteration 3: F_{unlock} = 23 N
(Screenshot made by author)

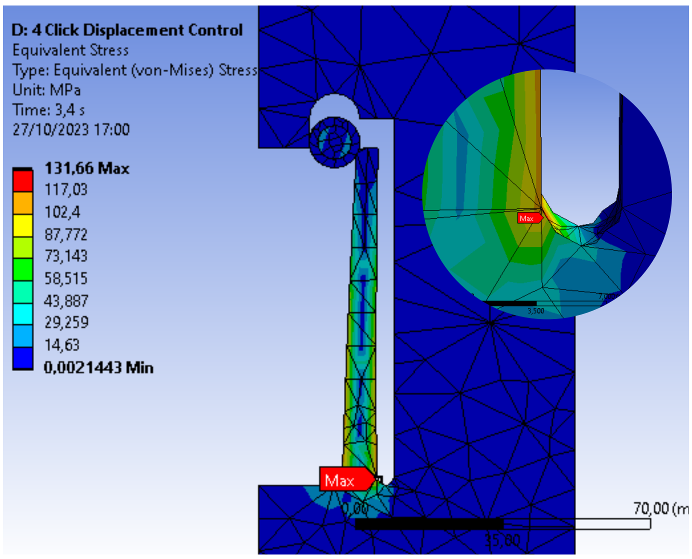


Figure 9.10b Clicking connection iteration 3: ϑmax = 132 MPa
(Screenshot made by author)

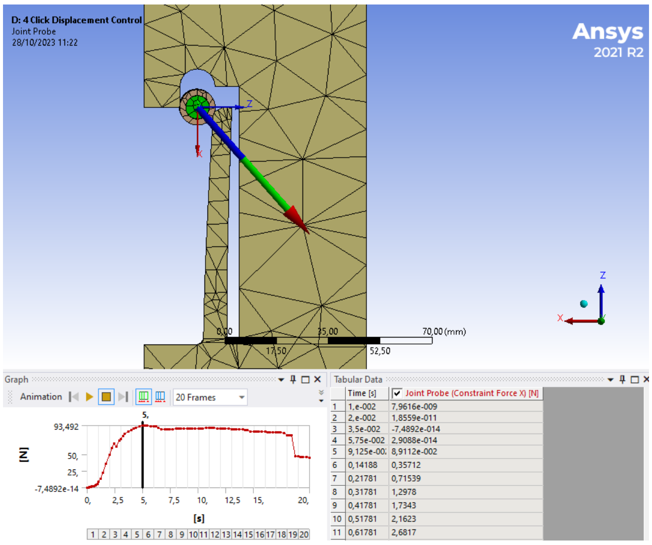


Figure 9.11a Clicking connection iteration 4:
F_{unlock} = 93 N
(Screenshot made by author)

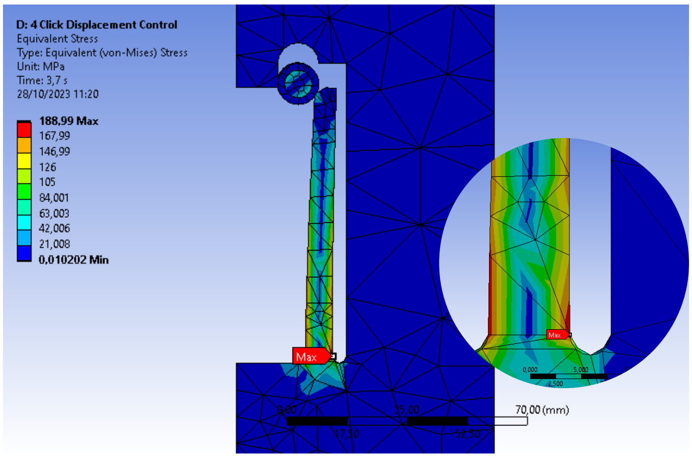


Figure 9.11b Clicking connection iteration 4:
ϑmax = 188 MPa
(Screenshot made by author)

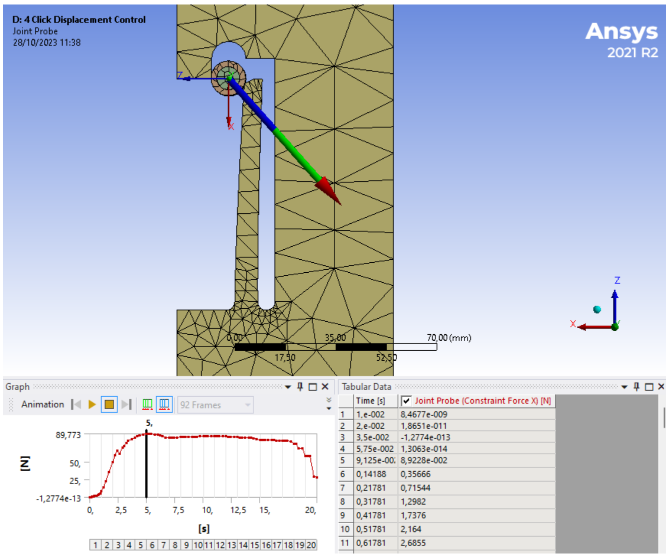


Figure 9.12a Clicking connection iteration 5:
F_{unlock} = 90 N
(Screenshot made by author)

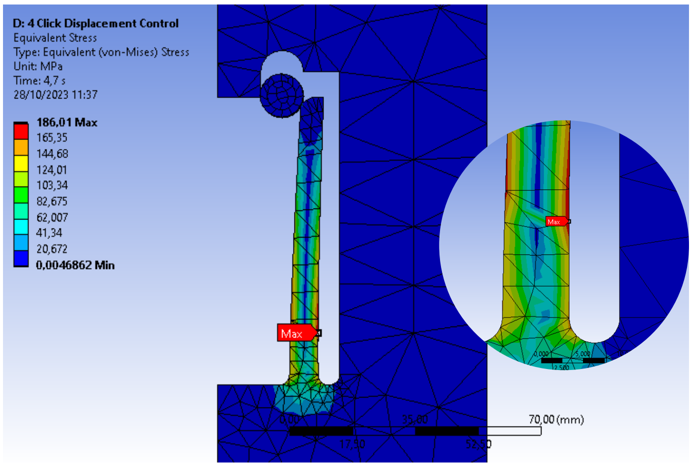


Figure 9.12b Clicking connection iteration 5:
ϑmax = 186 MPa
(Screenshot made by author)

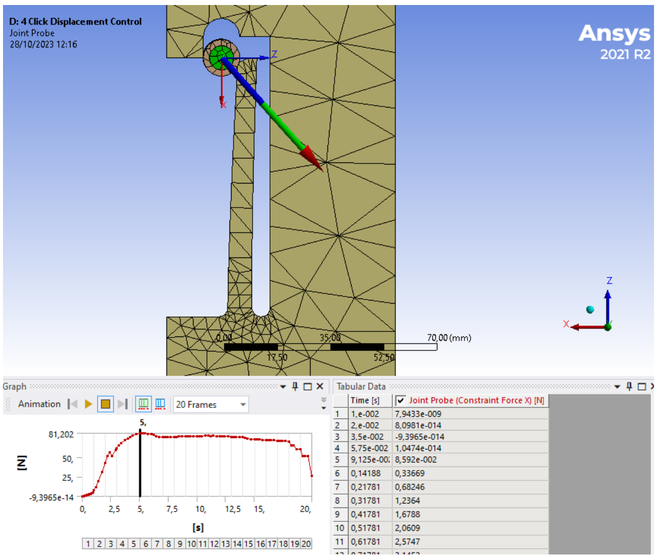


Figure 9.13a Clicking connection iteration 6:
F_{unlock} = 81 N
(Screenshot made by author)

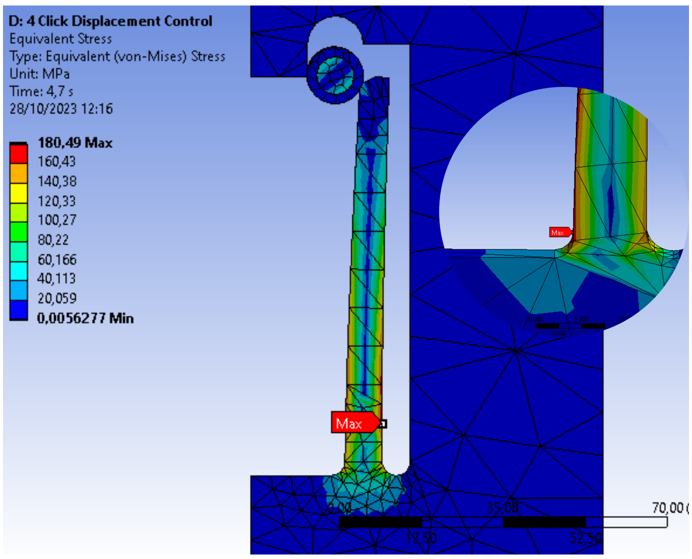


Figure 9.13b Clicking connection iteration 6:
ϑmax = 180 MPa
(Screenshot made by author)

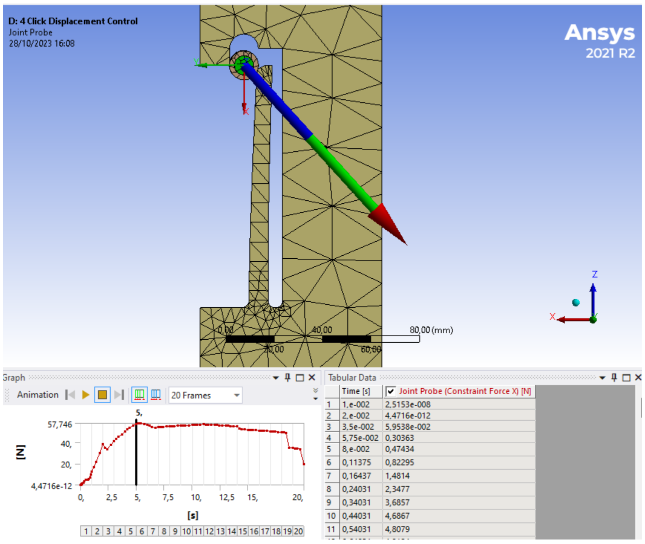


Figure 9.14a Clicking connection iteration 7:
F_{unlock} = 57 N
(Screenshot made by author)

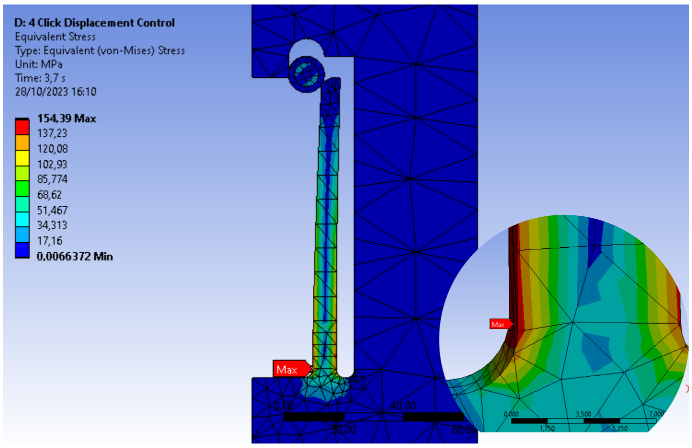


Figure 9.14b Clicking connection iteration 7:
ϑmax = 154 MPa
(Screenshot made by author)

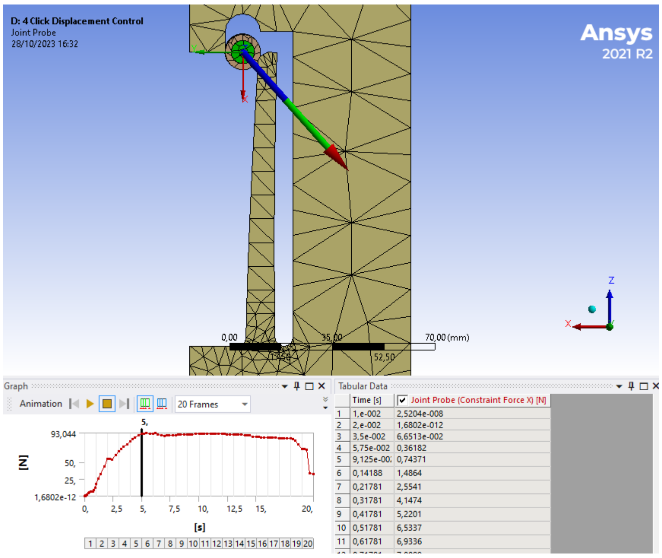


Figure 9.15a Clicking connection iteration 8:
F_{unlock} = 93 N
(Screenshot made by author)

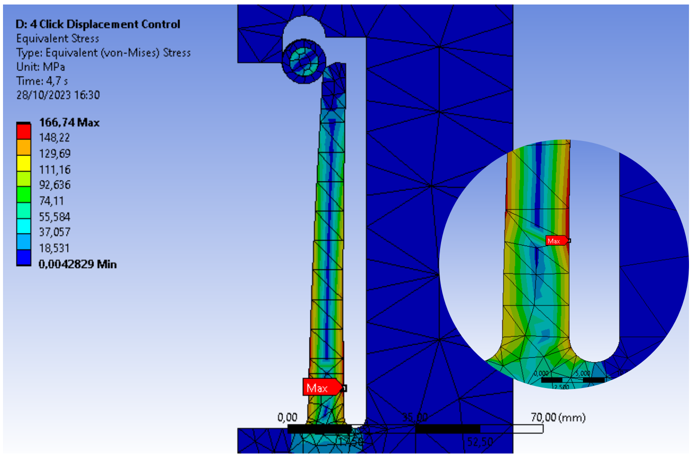


Figure 9.15b Clicking connection iteration 8:
ϑmax = 166 MPa
(Screenshot made by author)

Overview of the results

The iterations and respective results can be seen in Table 9.2.

Iteration	F_{unlock} [N]	Stress ϑ_{max} [MPa]	Arm Length [mm]	Arm width [mm]	Corner radius [^{o}]	Gap opening [mm]
1	64	171	63	8	4	10
2	48	164	73	8	4	10
3	23	131	80	8	4	10
4	93	188	80	8	4	9
5	90	186	80	8	6	9
6	81	180	85	8	6	9
7	57	154	100	8	6	9
8	93	166	100	10	6	9

Table 9.2 Results of the clicking design iterations.

The following conclusions are derived:
1. The longer the arm length the less force is needed to unlock it.
2. The wider the arm the greater the force needed to unlock it.
3. Bigger corner radius cuts reduced the stresses on these areas.
4. The bigger the gap opening the less force is needed to unlock it.

In conclusion, the clicking connection can overcome the force $Q_{vertical}$ of 55 N but further iterations are necessary to find the right proportions and dimensions to reduce the peak stresses at the corner areas. The average stresses on the connection were within the elastic limit but in a smaller scale (zoomed in) this limit is exceeded.

9.2.2.2 Snap fit connection

In this section the snap fit connection's strength is tested.

Model set up

Different models were created with a mesh size of 2mm since different parts needed to be tested. The forces applied can be found in the Figures 9.16. In this case, to unlock the system the snap part has to move a certain displacement (2 - 3 mm). This occurs when a horizontal force is applied (See Figure 9.16a). This force is assumed to be carried out by the constructor when disassembling the panel. The area where the horizontal push force is applied is 20 x 30 mm.

The following settings were used for the model:
Mesh size = 2mm with refinement at corners
Material= Aluminium 5005, H14
Large deformations = On

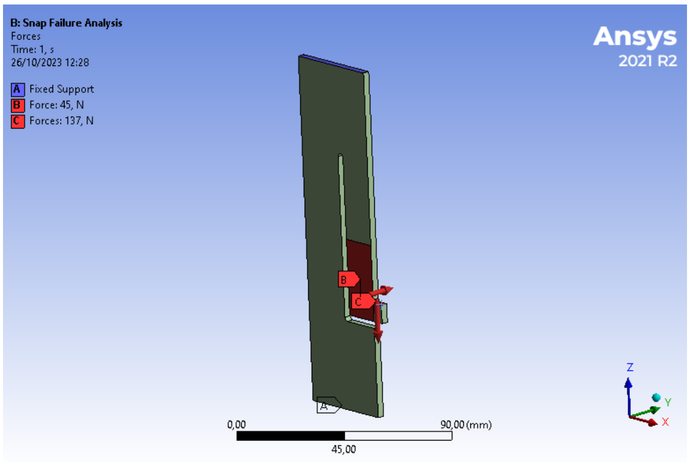


Figure 9.16a Forces applied on snap fit connection: Snap part. (Screenshot made by author)

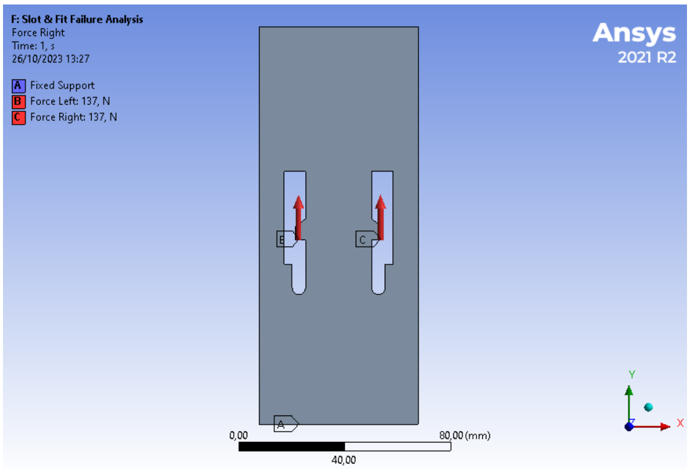


Figure 9.16b Forces applied on snap fit connection: Fit part (Screenshot made by author)

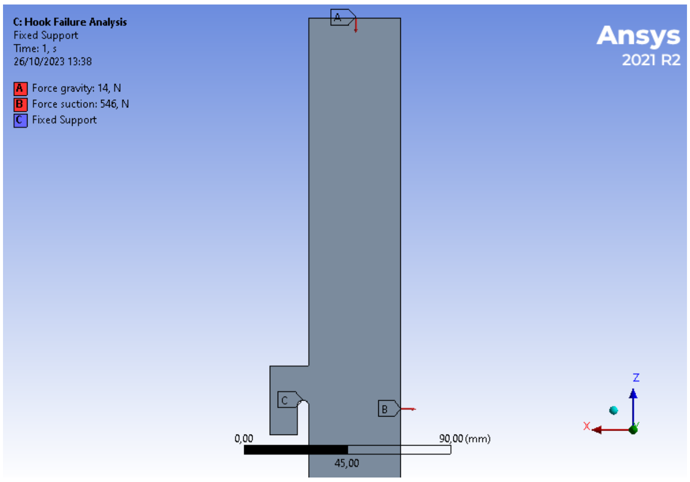


Figure 9.16c Forces applied on snap fit connection: Hook part (Screenshot made by author)

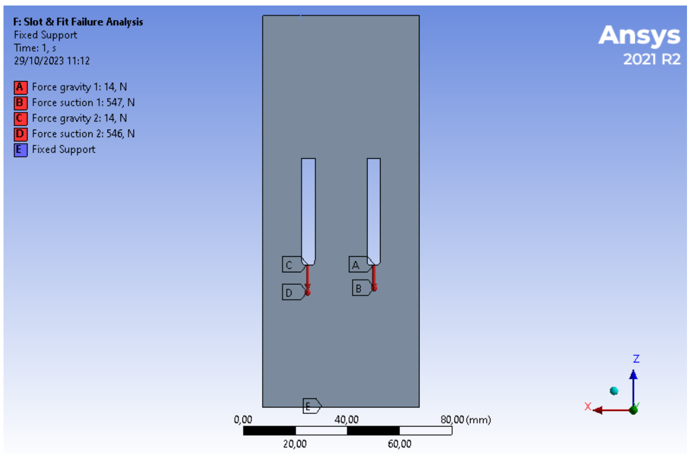


Figure 9.16d Forces applied on snap fit connection: Slot part (Screenshot made by author)

FEA results under wind and gravity forces

In these models only wind and gravity forces are applied to the parts. Other iterations are carried out on the snap part to find out how much force is needed to unlock the connection. The parts were modeled separately, which means that further modeling is necessary to understand the interaction between parts due to friction.

The following criteria needs to be fulfilled:
$\vartheta_{max} < 132$ MPa

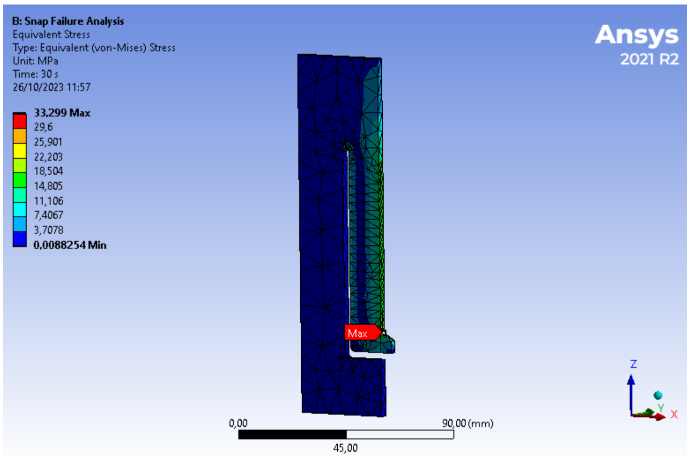


Figure 9.17a Snap part stress results: under vertical wind load ϑmax = 33 MPa (Screenshot made by author)

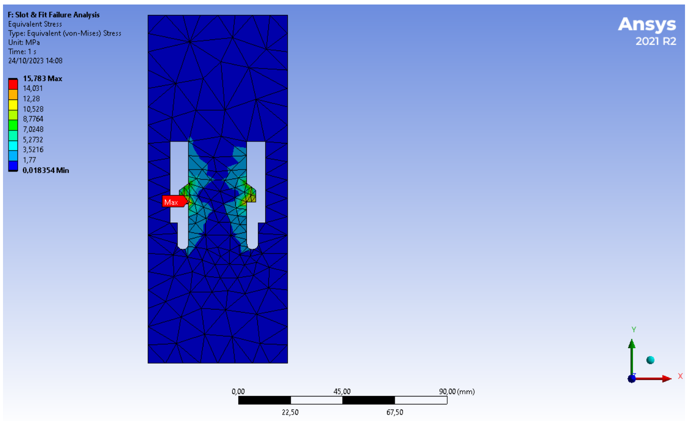


Figure 9.17b Fit part stress results: ϑmax = 16 MPa (Screenshot made by author)

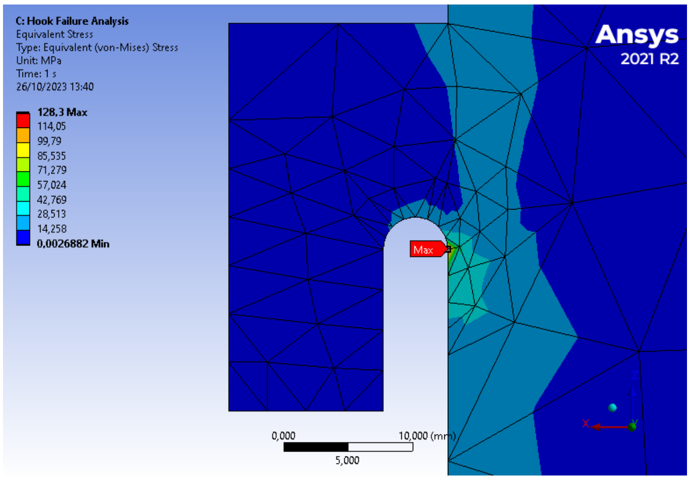


Figure 9.17c Fit part stress results: ϑmax = 128 MPa (Screenshot made by author)

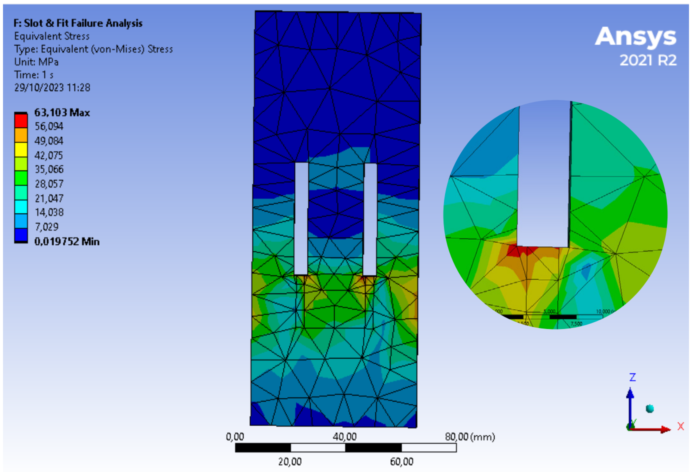


Figure 9.17d Fit part stress results: ϑmax = 63 MPa (Screenshot made by author)

Snap Part Iterations

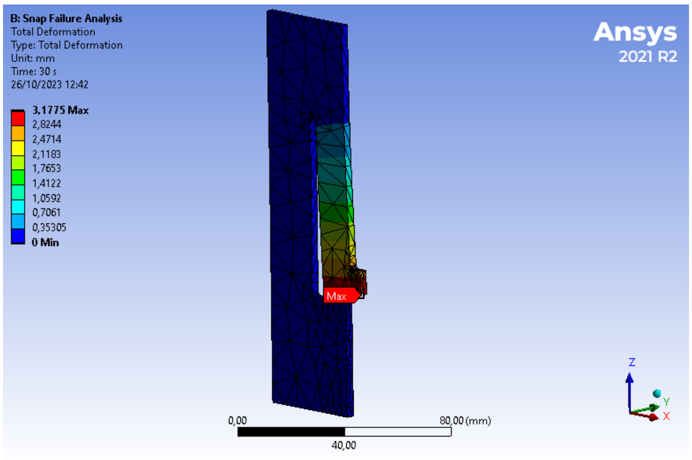


Figure 9.18a Snap part iteration 1:
Force applied = 60 N
Displacement = 3,1 mm
(Screenshot made by author)

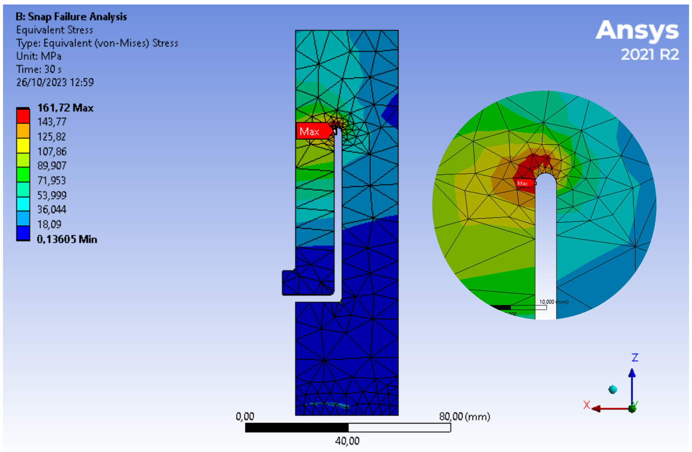


Figure 9.18b Snap part iteration 1:
Force applied = 60 N
ϑ_{max} = 161 MPa
(Screenshot made by author)

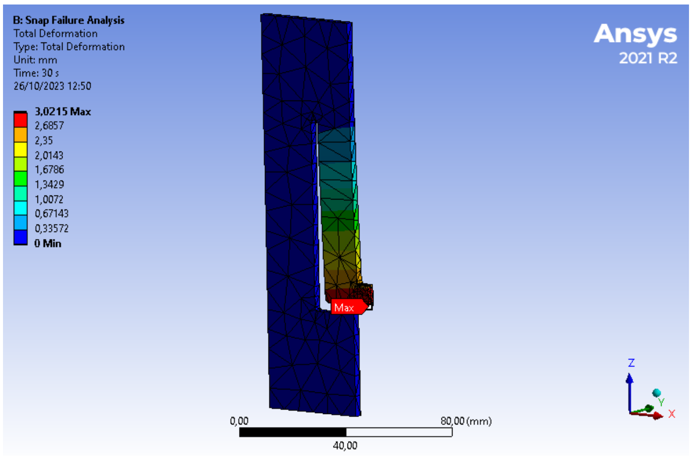


Figure 9.19a Snap part iteration 2:
Force applied = 47 N
Displacement = 3,0 mm
(Screenshot made by author)

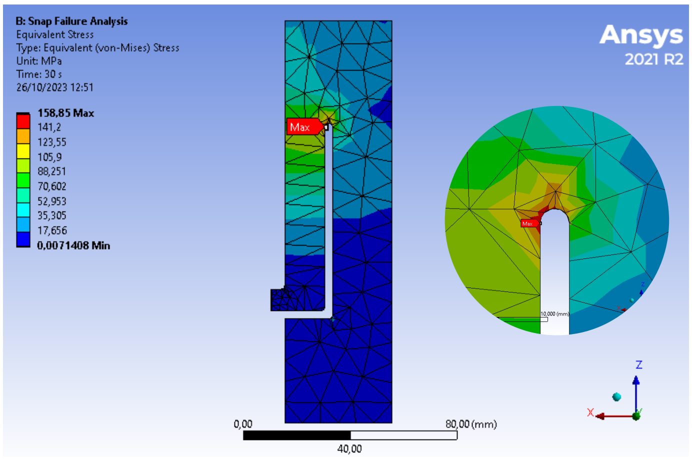


Figure 9.19b Snap part iteration 2:
Force applied = 47 N
ϑ_{max} = 158 MPa
(Screenshot made by author)

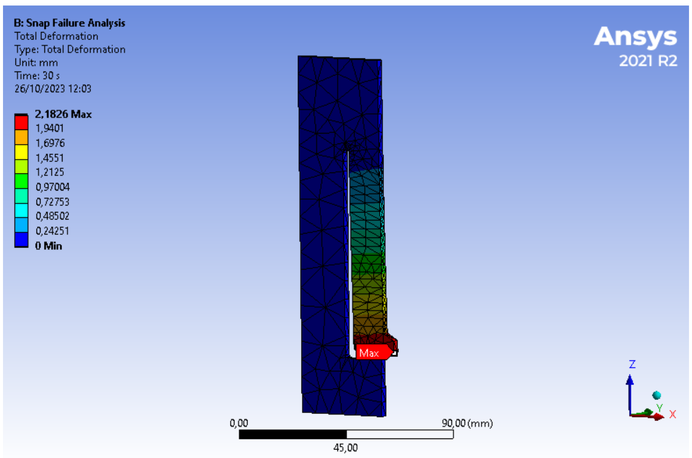


Figure 9.20a Snap part iteration 3:
Force applied = 20 N
Displacement = 2,2 mm
(Screenshot made by author)

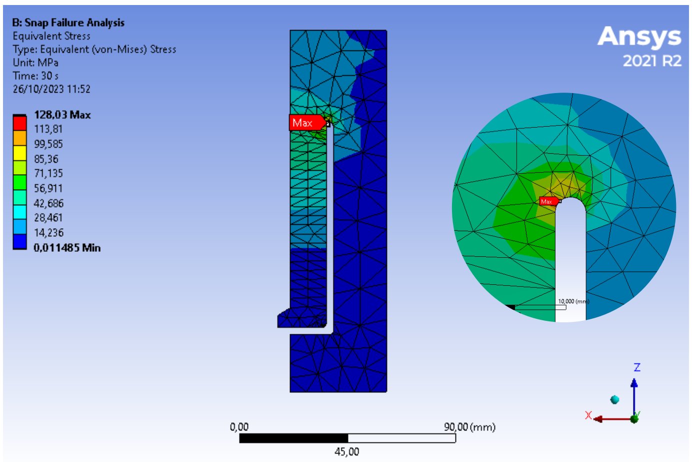


Figure 9.20b Snap part iteration 3:
Force applied = 20 N
ϑ_{max} = 128 MPa
(Screenshot made by author)

Overview of the results

Three different iterations were carried out for the snap part where the arm is increased from 65 - 70 - 85 mm as it can be seen in Figure 9.21 and the results in Table 9.3. The longer the arm, the less force is required to move it a certain distance. The last iteration has stresses below 132 MPa when applied a force of 20N. This force is relative to lifting 2kg. The final iteration also has a bent at the end of the tip allowing a displacement of 2mm. Further testing and iterations need to be done in order to find the right proportions of the arm length and force applied to reach a higher displacement within the elastic limit.

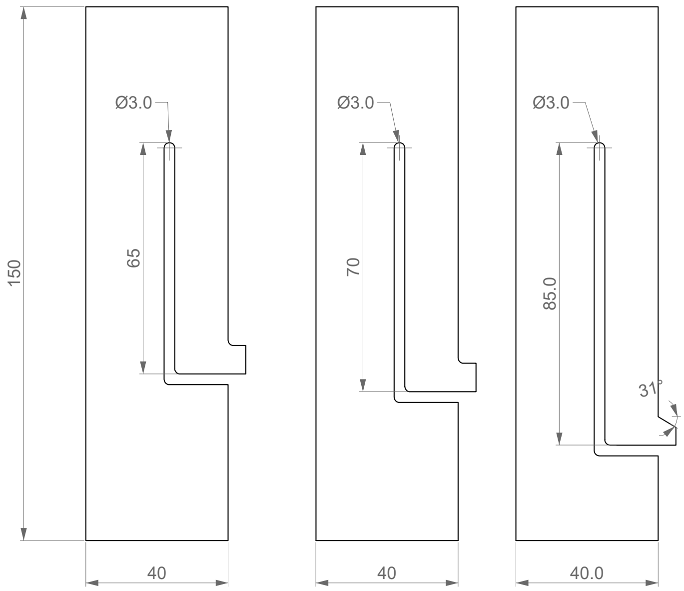


Figure 9.21 Design iterations of the snap part. (Drawing made by author)

Iteration	F_{push} [N]	Displacement [mm]	Stress ϑ_{max} [MPa]
1	60	3,1	161
2	45	3,0	158
3	20	2,2	128

Table 9.3 Results of the snap design iterations.

In conclusion, the parts remain under the maximum stress limit when the wind and gravity forces are applied. Further iterations are necessary to find the right dimensions of the snap part to cover larger displacements and therefore increasing the (un)locking force (F_{push}). Furthermore, a model showing the interaction between parts can be useful to understand the forces due to friction and stresses in contact areas.

9.3 Final product design

Prototypes for both the clicking and snap-fit connections were fabricated to assess their practicality. It's important to note that the dimensions of these connections do not represent the final parameters evaluated in the Ansys model iterations. However, they do serve as an initial testing phase and show the principle of the connection. The production drawings can be found in the appendix.

Clicking connection prototype

The prototype demonstrates the concept of a click-based mounting and demounting system, operable with a simple upward or downward force. It showcases a straightforward mounting mechanism with a 70mm arm length and a consistent 6mm width. However, these dimensions have proven insufficient to withstand CC2 wind forces, as indicated by the Ansys model. They were initially chosen as a starting point to illustrate the principle of the clicking motion on a small-scale panel.

There exists a noticeable gap between the black tube surrounding the bolt and the arm that secures it. This gap can potentially lead to vibrations and, consequently, sound during a windstorm. To address this issue and establish a more secure connection, further iterations and improvements are necessary.

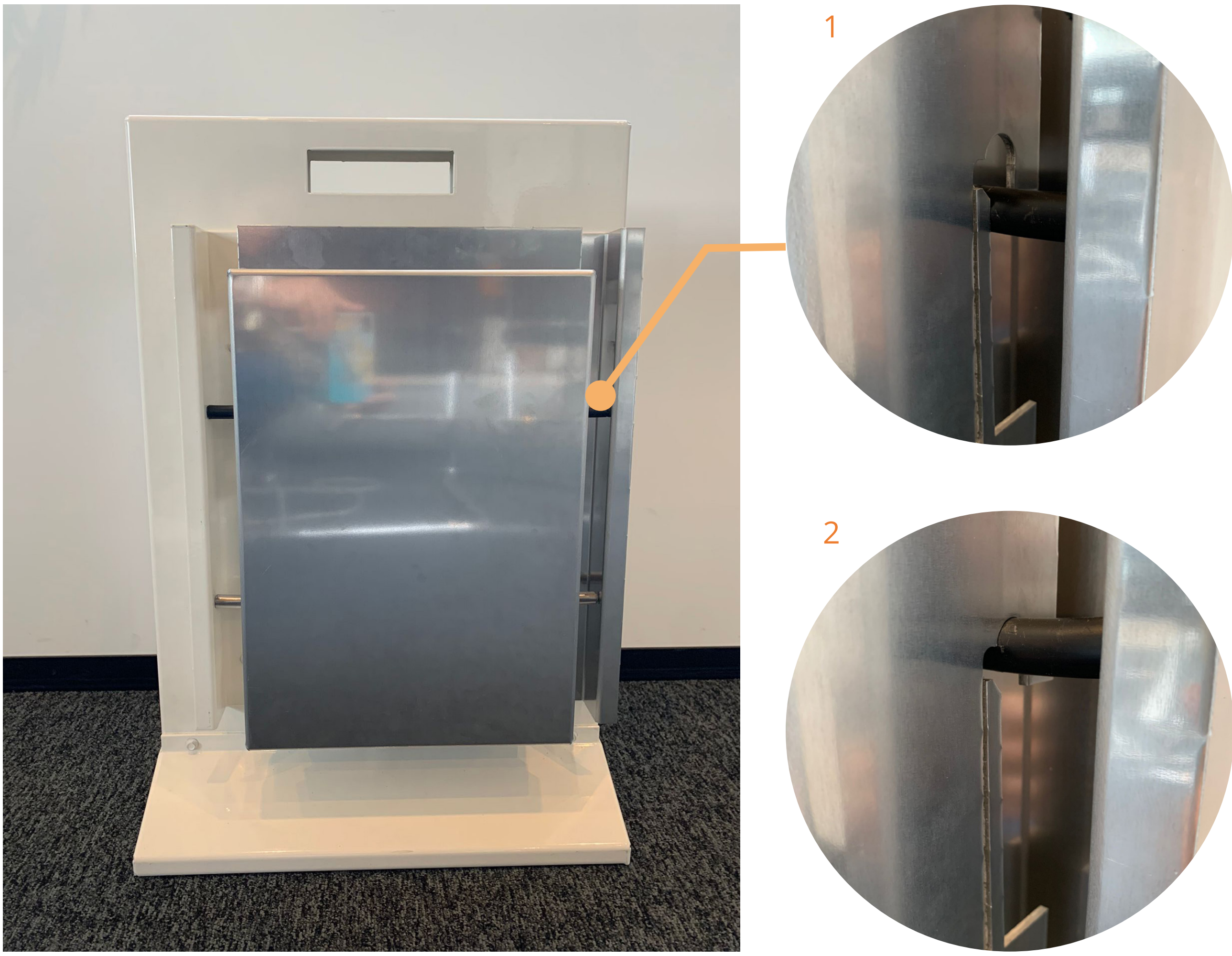


Figure 9.22 Prototype of the clicking connection in a cassette panel in the first position (1) and locked position (2) (Pictures made by author)

Snap fit connection prototype

The prototype demonstrates a potential locking and demountable connection. The arm has a length of 70 mm and needs to be pushed to reach a lateral displacement of 3mm to unlock it. The model doesn't show signs of plastic deformations at eye level but according to the Ansys model they appear mostly at the corner cuts.

In this case, only aluminium parts are used and no plastic or RVS screws are used. This system is characterized by its monolithic structure, consisting on precise cuts to securely fix the panels. Nevertheless, this prevents having lateral tolerances in comparison with the clicking system.

It's important to note that the prototype is not coated, but for future applications, consideration should be given to the coating thickness in relation to the hole dimensions. The prototype requires only manual lateral pressure to (un)lock the panel. In instances where additional force is needed, an extra tool capable of accessing the arm may be required. For larger and consecutive panels, unlocking this system may necessitate the collaboration of at least two individuals.

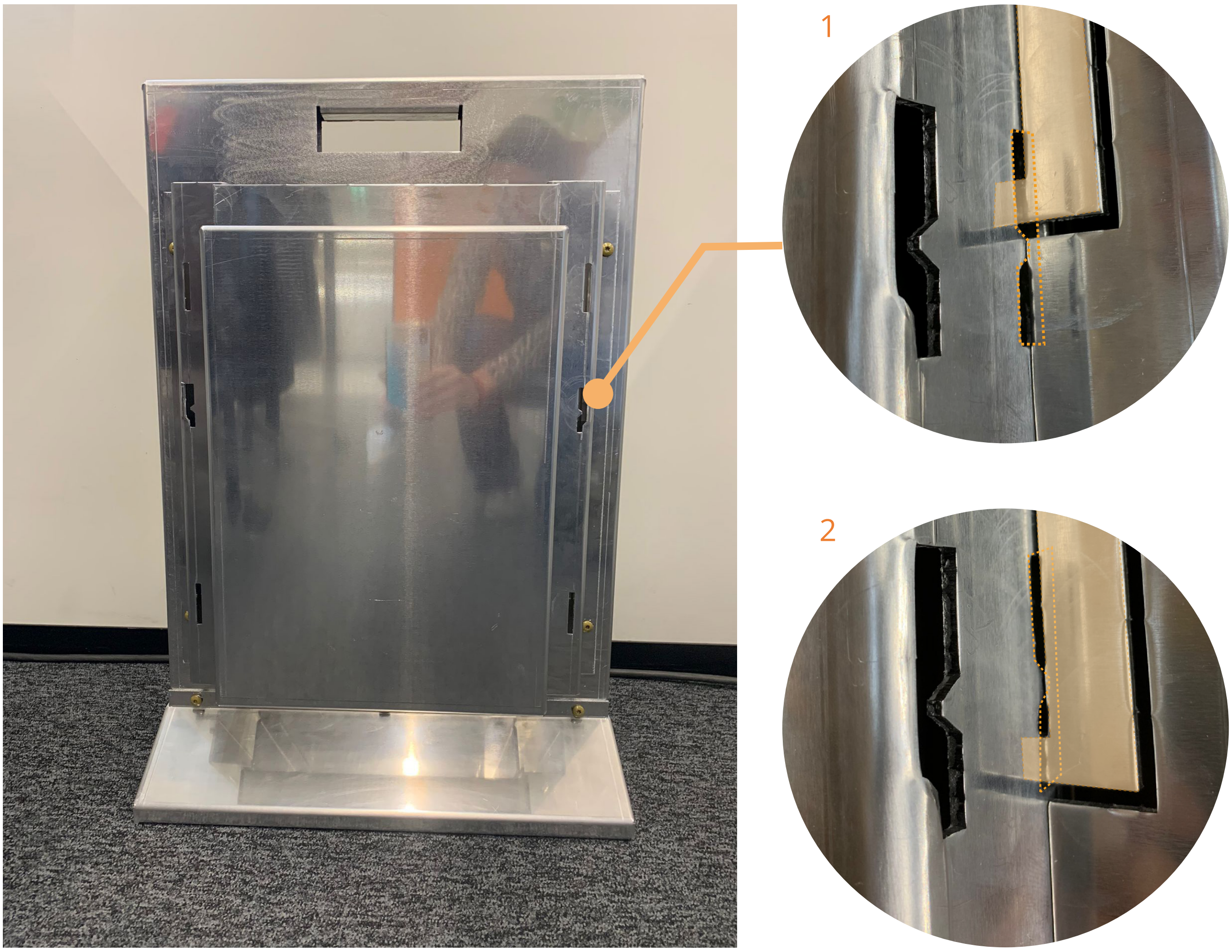


Figure 9.23 Prototype of the snap-fit connection in a cassette panel in the first position (1) and locked position (2) (Pictures made by author)

Conclusions and further improvements

The prototypes demonstrate that both compliant connections represent a promising detachable locking mechanism. These designs score a higher detachability rating while minimizing the number of fasteners and operations required, all the while ensuring a secure panel attachment to the underlying structure.

Referencing Table 9.4, it is evident that further improvements are necessary to refine the connection dimensions and reduce the occurrence of high-stress peaks, particularly in the corners. Furthermore, fine-tuning these dimensions can increase the force necessary to unlock the system, making it suitable for applications in building designs exceeding consequence class 2. Wind tests can be conducted to evaluate the acoustic properties of panels with these connections. Additionally, including the tolerances for the snap-fit connection in the z-direction, accounting for thermal expansion and coatings, is an essential consideration for its practical use in real life scenarios.

Category	Design Requirement	Current Cassette Panel	Compliant Connection	Snap fit Connection
Appearance	No screws in sight	Yes	Yes	Yes
	Small gaps	Sideways = +/- 20 mm Top/bottom= +/- 16mm	Sideways = +/- 20 mm Top/bottom= +/- 16mm	Sideways = +/- 20 mm Top/bottom= +/- 16mm
Production	Can be produced at Aldowa with the current machinery and materials	Yes	Yes	Yes
Assembly	Few parts/ fasteners	18	16	12
	Few (de)assembly operations	18	16	12
	Overcomes at least +/- 10 mm tolerances	X-direction Y-direction Z-direction	X-direction Y-direction Z-direction	Y-direction Z-direction
	Prevents vibrational sound	Yes	Wind facade testing necessary	Wind facade testing necessary
Disassembly	>0.6 Detachability score	0.700	0.830	0.833
	No penalties present	No	No	No
	Independent disassembly	No	Yes	Yes
Strength	CC2 & CC3 consequence class proof	Yes	Only CC2. Further iterations are necessary	Only CC2. Further iterations are necessary

Table 9.4 Evaluating if the connections for disassembly fulfill the program of requirements

10.

Conclusions

Section 10.1 aims to answer the research question and Section 10.2 states the limitations and further research.

10.1 Revisiting the research question

In this thesis, research was carried out to propose a design for disassembly guideline for the company of Aldowa. The following main research question was formulated:

How can the disassembly potential of Aldowa's cladding products be assessed, and what design guideline can be proposed to comply with the design for disassembly requirements of the Cradle-to-Cradle certification?

To find an answer to the main research question, the thesis was divided into several sub questions which were answered by literature and practical research. The sub-questions are answered below:

Literature research sub-questions

SQ1 What is the scope and significance of the Cradle to Cradle certification, and what differentiates it from other environmental assessments?

Cradle to Cradle certification stands as a valuable compass for sustainability, emphasizing a positive impact on the environment and promoting circularity over linear waste streams. While it offers a framework for assessing the circularity of products, it is important to acknowledge that the certification does not quantify specific environmental impacts but rather provides flexible criteria for companies to demonstrate their adherence to the principles.

In contrast to existing environmental assessments, which often overlook the influence of design decisions on a product's end-of-life scenario, Cradle to Cradle integrates a unique criterion for design for disassembly. A fundamental requirement is the specification of the target end-of-life scenario or cycling pathway for a product's components to receive certification. In this case, Aldowa will first focus on recycling as an end-of life scenario and wants to research other possible cycling pathways to extend the service life of their products.

Disassembly is a crucial step to achieve any of these pathways so an assessment to determine the disassembly potential is necessary. Notably, the Building Circularity Index (BCI) has a rating system for assessing detachability. If adopted as a standard in the Netherlands, the BCI could enhance Aldowa's market competitiveness and align its products with industry standards.

SQ2 What are the available guidelines for Design for Disassembly and can a new guideline be developed specific to Aldowa's products and design workflow, to promote higher material recovery?

Several approaches to assess disassembly and deconstruct buildings into individual material components have been presented by Brand (1994), Eekhout (1997), and Durmisevic (2006). While most design for disassembly frameworks assume ideal conditions during disassembly, the PAC Model endeavors to account for real-world scenarios. The PAC model and the Disassembly Map compute disassembly sequences, identifying components, actions, tools, and incorporating time considerations. The Disassembly Map also takes into account target components and disassembly penalties, whereas the PAC Model incorporates disassembly failure scenarios and a circularity index.

Based on these existing assessments several criteria are selected to inform the newly developed guideline presented in this research:

Cradle to Cradle Requirements

The criteria includes the requirements of C2C 5.8 Product Designed for Disassembly:

- Reduce amount of fasteners
- Reduce amount of operations
- Reduce amount of destructive processes
- Reduce amount of tools needed to disassemble the product

BCI - Detachability score

- Type of connection
- Accessibility
- Interdependence: Mold containment and crossings

Disassembly Map & PAC Model

- Disassembly sequence
- Identification of assemblies and parts
- Disassembly penalties
- Disassembly risk of failure: robustness score

SQ3 What are the current end-of-life scenarios for aluminium products, and which could be the circular (re) life pathways?

Most of aluminium product's end of life scenarios are currently in a landfill or a recycling facility, largely due to inadequate alloy separation leading to downcycling. Given aluminum's durability and the substantial energy embedded in its production, prolonging its service life becomes crucial to maximizing resource utilization. Therefore, various cycling pathways to extend its service life were analyzed and the opportunities and challenges of case studies implementing those cycling pathways were summarized. Design for disassembly showed to be a crucial initial step to enable strategies such as reuse, repair, refurbishment, or re-manufacturing. By considering these strategies, a robustness scoring was proposed to identify the risk of damage an aluminium part may already have when carrying out the disassembly process based on the expected legal service life stated by the company. This score was added to the disassembly criteria.

User research conducted at Aldowa highlights the role of stakeholders in shaping end-of-life options and design choices. Aldowa places a primary emphasis on recycling as its main recovery method, prioritizing the separation of parts made from different materials. However, even when considering alternative recovery methods, Aldowa can use the same guidelines, concentrating on disassembling and prioritizing specific parts or connections designed to the desired recovery process. The practice of designing products for ease of disassembly promotes more environmentally sustainable end-of-life outcomes.

Practical research subquestions

SQ4 How does Aldowa's production process impact the disassembly potential of its products? The analysis of Aldowa's production process revealed an essential observation. It becomes apparent that decisions made during the initial project phases, particularly those related to client agreements and budget considerations, play an important role in enabling the implementation of design for disassembly. Essentially, the integration of design for disassembly must start at the project's initial phase to ensure its effective application in the later stages of a product's lifecycle. Once the foundational agreements are established, engineers then have the opportunity to enhance the disassembly potential of the products.

SQ5 In what scenarios and for which stakeholders will the proposed guideline prove beneficial?
A typical internal workflow of a project has been mapped out by interviewing the potential users and the key moments to implement the DfD guideline. The guideline can be used before a project starts, during a project agreement with clients, at the early engineering design stage and when re-designing a new connection for disassembly. It is composed of different documents designed to benefit both the sales department and engineering teams. This guideline aids in client communication, budget calculations to fulfill Cradle-to-Cradle requirements, and offers systematic approaches for improving the design for disassembly of products.

The DfD Guideline includes the following documents:

- Cradle to Cradle products flyer (PDF file)
- C2C_Check_Bill_of_Materials (Excel file)
- Poster: How to make a Disassembly map (PDF file)
- Poster: Redesign process (PDF file)
- Structural analysis calculation (Grasshopper file)

SQ6 What are the feasible design alternatives that can be integrated into Aldowa's products to improve their disassembly potential and extend their lifespan?
The proposed guideline was applied to the Cradle-to-Cradle certification case study. Alternatives were proposed to replace a glue connection between panels and couple pieces as well as to improve the independence of cassette panels during disassembly. The following designs provide an alternative solution where the disassembly potential is improved:

Couple piece connections
Alternative 1: Spot welding the couple pieces to the panels offers an alternative connection were the same type of material is used (AlMg1). This pre-fabricated connection not only reduces the risk of loose components but also reduces disassembly operations. However, it is only suitable for powder-coated parts.

Cassette panel connections
Alternative 2: The clicking connection is based on the same system of cassette panels and uses a compliant mechanism to (de)mount the panels from the M8 bolts. This can allow constructors to easily assemble and disasssemble the panels independently from each other.

Alternative 3: The snap fit system is a different system from the ones Aldowa uses. Two aluminium parts interlock with each other. This reduces the amount of fasteners and only one type of material is used (AlMg1).

These alternatives require further refinement to address stress concentration points and enhance the safety of the locking mechanism in real-world building applications. Nevertheless, they represent a potential compliant mechanism, simplifying the disassembly process while ensuring a secure panel attachment to the underlying structure.

Conclusion
In conclusion, **criteria** from existing disassembly models found in the research literature has been adapted into Aldowa's DfD Guideline to **assess** the **disassembly potential**. This guideline has been created to specifically align with Aldowa's project workflow and primarily serves the sales and engineering departments. Its primary function is to help Aldowa **improve** their **product's life cycle** through **design for disassembly** strategies and meet the **requirements** of the **Cradle-to-Cradle certification**. Two connections using a compliant mechanism prove to improve the ease of disassembly and can be further developed for their integration in Aldowa's products.

10.2 Discussion, limitations and further research

The guideline application is discussed and followed by its limitations. Further research on the design alternatives is recommended and the wider research challenge is addressed.

Guideline's Application

The study demonstrates the implementation of a newly developed "Design for Disassembly" guideline within Aldowa.
Upon receiving certification, an essential task is to update the Excel spreadsheet containing the list of materials and fasteners. This update will help the sales department in assessing the proper material quantities and detachable fasteners for their project budgets.

Meanwhile, the engineering department can proactively make the Disassembly Maps, to increase awareness of the ease of disassembly in their designs. This gradual shift in design mentality will aid Aldowa in the creation of products purposefully designed for disassembly.

The Re-design guideline functions as a general design roadmap, providing the engineers a sequence of steps that take into account design for disassembly strategies. While its adherence to common work and design practices may be regarded as extra time during the design process, it can save time and effort during and in a post disassembly scenario.

Limitations

The structural analysis script must first be further validated with other case studies to get more accurate results. This will inform the minimum required connections for a panel at a certain position and height in a building. Consequently, it has to be translated into Catia's Gen-x program to be used at Aldowa.

The alternative connections that have been suggested were limited to testing in a CC2 (Consequence class 2) building. There is room for further refinement in terms of dimensions and design to reduce stress concentration areas that exceed the elastic limit.

Further research

Additionally, the presented design alternatives need to undergo further experimental testing to maintain the compliant mechanisms within the elastic phase of the material without causing plastic deformation at the corners. Different variations can be modeled and more FEA (Finite Element Analysis) can be carried out to calculate the forces needed to unlock the systems and identify the areas with high stress. Mechanical tests can be carried out to test the tensile strength of the aluminium sheets Aldowa uses. Furthermore, wind testing could also be carried out to certify the safety of the connection under a certain wind load. Finally, the tolerances of the connections could be increased in order to facilitate its application in real-world construction scenarios.

These connection alternatives, along with the welded connections for roof panels, can be incorporated into the Cradle to Cradle certification, given that the materials are already listed in the Bill of Materials. Further research is required to provide alternative design solutions for the connections in anodized parts.

Lastly, the design guideline's applicability extends to improving other products for future certifications. Depending on Aldowa's chosen post-disassembly scenario, the guideline can be adapted to include aspects like design for reuse, refurbishment, repair, or remanufacture. These scenarios can be compared with LCA's to identify the most suitable recovery strategy. The adoption of a new business model supporting these scenarios can also benefit Aldowa. Expanding research in this direction will enable Aldowa to create products with a more meaningful purpose beyond recycling at the end of their service life.

Design for Disassembly

In conclusion, the challenge of waste generation in the building industry is very significant with environmental, economic, and societal implications. Designing for disassembly is a key strategy to mitigate this challenge, as it prolongs the service life of products, reduces waste, and aligns with the principles of Cradle to Cradle. This thesis primarily focused on the integration of Design for Disassembly (DfD) strategies into Aldowa's production processes. Beyond this specific case, it stands as a valuable example and source of inspiration for other construction companies aiming to embrace these strategies and foster more sustainable practices.

11.

Bibliography

A

Accenture's Maynard assets. (2023). MOST Online. Retrieved from https://hbmaynard.com/

Asolekar, S. R. (2006). Status of management of solid hazardous wastes generated during dismantling of obsolete ships in India. In Proceedings of International Conference on"Dismantling of Obsolete Vessels.". Glasgow, UK

ASQ. (2023). FAILURE MODE AND EFFECTS ANALYSIS (FMEA). ASQ - EXCELLENCE THROUGH QUALITY. Retrieved August 14, 2023, from https://asq.org/quality-resources/fmea

Assan Alüminyum. (2022). Environmental Product Declaration (S-P-02230). The International EPD® System.

Azcarate Aguerre, J. F., Klein, T., Konstantinou, T., & Veerman, M. (2022). Façades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope. Applied Sciences, 12(3), [1267]. https://doi.org/10.3390/app12031267

B

Bach, V., Minkov, N., & Finkbeiner, M. (2018). Assessing the Ability of the Cradle to Cradle CertifiedTM Products Program to Reliably Determine the Environmental Performance of Products. Sustainability, 10(5), 1562. https://doi.org/10.3390/su10051562

Bakker et al. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production (69), 10-16.

Bakker, C., Wever, R., Teoh, C., & De Clercq, S. (2010). Designing cradle-to-cradle products: a reality check. International Journal of Sustainable Engineering, 3(1), 2–8. https://doi.org/10.1080/19397030903395166

Bakx, I. M. J. M., Beurskens, P., Ritzen, M., & Lichtenberg, J. (2016). A morphological design and evaluation model for the development of circular facades. ResearchGate. https://www.researchgate.net/publication/301230962_A_morphological_design_and_evaluation_model_for_the_development_of_circular_facades

Beurskens, P. and Bakx, R. (2015). Built-to-rebuild. Master thesis. Eindhoven University of Technology.

Boorsma, N., Peck, D., Fischer, S., Bakker, C., & Balkenende, R. (2018). Remanufacturing workshops with professionals to overcome barriers-outcomes of two eu projects. Proceedings of Concerence Going Green—Care Innovation.

Boorsma, N., Tsui, T., & Peck, D. (2019). Circular building products, a case study of soft barriers in design for remanufacturing. In Proceedings of the International conference of Remanufacturing.

Brand, S. (1994). How buildings learn. New York: Viking.

Braungart, M. &. Douglas, M. (2010). Cradle To Cradle criteria for the built environment. EKONOMIAZ. Revista vasca de Economía, 75 (04), pp. 182-193.

C

CB'23. (n.d.). Retrieved from https://platformcb23.nl/over-platform-cb-23

Centraal Bureau voor de Statistiek. (2019, November 3). Meeste afval en hergebruik materialen in bouwsector. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/nieuws/2019/45/meeste-afval-en-hergebruik-materialen-in-bouwsector
chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://assets.website-files.com/5d26d80e8836af2d12ed1269/63dbc3f642b96760b6b7fed8_Making%20cycling%20circular%20-%20The%20case%20of%20Swapfiets%20-%20White%20paper.pdf

CircularX: Circular Economy - an Introduction. (TU Delft online course). (www.edx.org/course/circular-economy-in-troduction-delftx-circularx). Accessed on April 22th, 2023

Cooper, D. (2014). Reuse of steel and aluminium without melting. https://doi.org/10.17863/CAM.14065

Cooper, T., & Salvia, G. (2018). Fix it: Barriers to repair and opportunities for change. Subverting Consumerism, 147-165.

Cordella, C., Alfieri, A., & Sanfelix, J. (2019). Analysis and development of a scoring system for repair and upgrade of products. EUR 29711 EN. https://doi.org/10.2760/725068

Cottafava, D., & Ritzen, M. M. (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. Resources Conservation and Recycling, 164, 105120. https://doi.org/10.1016/j.resconrec.2020.105120

Cradle to Cradle Products Innovation Institute. (2021). CRADLE TO CRADLE CERTIFIED® VERSION 4.0 Product Standard User Guidance. C2C®. https://cdn.c2ccertified.org/resources/V4.0_User_Guidance_FINAL_101921.pdf

D

De Bont, M. (2023, March 1). Swapfiets schrijft ruim €11 miljoen af op kapotte en verdwenen barrels. Quote Net. https://www.quotenet.nl/zakelijk/a43118916/swapfiets-jaarcijfers-2021-kapotte-fietsen-pon/

De Fazio, F. Maartens, T. (2021). Making circular innovation work: Design for disassembly. Koninklijke Philips N.V.

De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. Journal of Cleaner Production, 320, 128552. https://doi.org/10.1016/j.jclepro.2021.128552

Dodd,N., Donatello,S., & Cordella.M. 2020. Level(s) indicator 2.3: Design for adaptability and renovation, User manual: overview, instructions and guidance (publication version 1.0)

Dodd N., Donatello S. & Cordella M., 2021. Level(s) indicator 2.4: Design for deconstruction user manual: introductory briefing, instructions and guidance (Publication version 2.0)

Dokšanović, T., Džeba, I., & Markulak, D. (2017). Applications of aluminium alloys in civil engineering. Tehnicki Vjesnik-technical Gazette, 24(5). https://doi.org/10.17559/tv-

20151213105944

Durmisevic, E., 2006. Transformable building structures - Design for Disassembly as a way to introduce sustainable engineering to a building design and construction (Doctoral dissertation). Delft, Netherlands: Cedris M&CC.

Durmisevic, E., 2006. Transformable building structures - Design for Disassembly as a way to introduce sustainable engineering to a building design and construction (Doctoral dissertation). Delft, Netherlands: Cedris M&CC.

E

Ellen MacArthur Foundation. (n.d.). Circular Buildings Toolkit. Retrieved June 20, 2023, from https://ellenmacarthurfoundation.org/articles/circular-buildings-toolkit

European Aluminium. (2020). European aluminium circular aluminium action plan. In European Union. Retrieved May 16, 2023, from https://circulareconomy.europa.eu/platform/en/knowledge/circular-aluminium-action-plan-strategy-achieving-aluminiums-full-potential-circular-economy-2030

European Committee for Standardization (CEN). (2012). Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (CEN - EN 15804). Retrieved from https://standards.globalspec.com/std/14306124/EN%2015804

Evans, R., & Guest, G. (2002). The aluminium decoating handbook. Stein Atkinson Stordy Ltd.

F

Flipsen, B., Bakker, C. A., & de Pauw, I. C. (2020). Hotspot Mapping for product disassembly: A circular product assessment method. In M. Schneider-Ramelow (Ed.), Electronics Goes Green 2020+ (EGG): The Story of Daisy, Alexa and Greta

Formentini, G., & Ramanujan, D. (2023). Design for circular disassembly: Evaluating the impacts of product end-of-life status on circularity through the parent-action-child model. Journal of Cleaner Production, 405, 137009. https://doi.org/10.1016/j.jclepro.2023.137009

Fu, J., Krantz, M. S., Zhang, H., Zhu, J., Kuo, H., Wang, Y., & Lis, K. (2011). Investigation of the recyclability of powder coatings. Powder Technology, 211(1), 38–45. https://doi.org/10.1016/j.powtec.2011.03.016

G - H

Gorgolewski, M., Edmonds, J., Mackinnon, D., Humphries, M., & Straka, V. (2006). Facilitating greater reuse and recycling of structural steel in the construction and demolition process. Department of Architectural Science, Ryerson University. Available at: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca.minerals-metals/files/pdf/mms-smm/busiindu/rad-rad/pdf/re-ste-fin-eng.pdf

Grace, M. & Centre for Sustainable Construction. (2000). BREEM - A practical method for assessing the sustainability of buildings for the new millennium (1st ed.). International Conference Sustainable Building 2000. https://www.irb.fraunhofer.de/CIBlibrary/search-quick-result-list.jsp?A&idSuche=CIB+DC3011

Haapio, A., & Viitaniemi, P. (2008). A critical review of building environmental assessment tools. Environmental Impact Assessment Review, 28(7), 469–482. https://doi.org/10.1016/j.eiar.2008.01.002

Hartwell, R., & Overend, M. (2020). End-of-life Challenges in Façade Design: A disassembly framework for assessing the environmental. . . ResearchGate. https://www.researchgate.net/publication/357516952_End-of-life_Challenges_in_Facade_Design_A_disassembly_framework_for_assessing_the_environmental_reclamation_potential_of_facade_systems

Hartwell, R., Macmillan, S., & Overend, M. (2021). Circular economy of façades: Real-world challenges and opportunities. Resources Conservation and Recycling, 175, 105827. https://doi.org/10.1016/j.resconrec.2021.105827

Hogewoning, A. (March, 2023). Facade Panels project 221031. Highrise BV.

Hu, S., Zhu, S. X., & Fu, K. (2023). Optimal trade-in and refurbishment strategies for durable goods. European Journal of Operational Research, 309(1), 133–151. https://doi.org/10.1016/j.ejor.2023.01.032

Hydro. Aluminium and sustainability. Chapter2. (2023). https://www.hydroaluminiumdesign.com/en/manual/chapter2/#2.7

I - K

Ijomah, W., & Chiodo, J. (2010). Application of active disassembly to extend profitable remanufacturing in small electrical and electronic products. International Journal of Sustainable Engineering, 3(4), 246–257. https://doi.org/10.1080/19397038.2010.511298

International Aluminium Institute. (2014). Aluminium and Durability . International Aluminium Institute. Retrieved from https://international-aluminium.org/resource/aluminium-recyclability-and-recycling-towards-sustainable-cities/

International Aluminium Institute. (2015). Aluminium Recyclability and Recycling - Towards Sustainable Cities. International Aluminium Institute. Retrieved from https://international-aluminium.org/resource/aluminium-recyclability-and-recycling-towards-sustainable-cities/
International Organization for Standardization. (2006). Sustainability in building construction — Sustainability indicators — Part 1: Framework for development of indicators for buildings (ISO/TS 21929-1:2006). Retrieved from http://www.iso.org/iso/catalogue_detail?csnumber=63787

Konstantinou, T. (2015). A Facade refurbishment toolbox supporting energy upgrade of residential building skin. TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid:1983b7c2-68cc-4a36-a219-11a16f9fb742?collection=research

Kvithyld, A., Meskers, C., Gaal, S., Reuter, M. A., & Engh, T. A. (2008). Recycling light metals: Optimal thermal de-coating. JOM, 60(8), 47–51. https://doi.org/10.1007/s11837-008-0107-y

M - N

MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2(1), 23-44.

Mazzolani, F. M. (2006). Aluminium structures in refurbishment: Case of the real Ferdinando bridge on Garigliano river. Structural engineering international, 16(4), 352-355.

McDonough, W. F., & Braungart, M. (2002). Cradle to cradle: remaking the way we make things. Choice Reviews Online, 40(02), 40–0914. https://doi.org/10.5860/choice.40-0914

McDonough, W., & Braungart, M. (2005). Cradle to cradle. McGraw-Hill Education.

McDonough, W., Braungart, M., Anastas, P. T., & Zimmerman, J. B. (2003). Peer reviewed: Applying the principles of green engineering to cradle-to-cradle design. Environmental science & technology, 37(23), 434A-441A.

Minkov, N., Bach, V., & Finkbeiner, M. (2018). Characterization of the Cradle to Cradle CertifiedTM Products Program in the Context of Eco-labels and Environmental Declarations. Sustainability, 10(3), 738. https://doi.org/10.3390/su10030738

Nederlands Normalisatie Instituut. (1991). NEN 6702 "Belastingen en vervormingen"TGB 1990. NNI, Delft

NEN. (2019). NEN-EN 1990+A1+a1/C2/NB. Delft: NEN Connect.

NEN. (2020). NEN-EN 1991-1-4+A1+C2/NB+C1. Delft: NEN Connect.

NEN. (2011). NEN-EN 1999-1-4+A1+C1:2011 nl Delft: NEN Connect.

O - R

O'Grady, T., Minunno, R., Chong, H., & Morrison, G. M. (2021). Design for disassembly, deconstruction and resilience: A circular economy index for the built environment. Resources Conservation and Recycling, 175, 105847. https://doi.org/10.1016/j.resconrec.2021.105847

Overend, M., & Hartwell, R. (2020). End-of-Life Challenges in Façade Design: A disassembly framework for assessing the environmental reclamation potential of façade systems. Paper presented at Facade Tectonics 2020 World Congress , Los Angeles, United States.

Partners for Innovation (2020) LIFE-CYCLE ASSESSMENT & CIRCULARITY OF SWAPFIETS (life cycle assessment, commissioned by Swapfiets).

Rasmussen, F. N., Birkved, M., & Birgisdottir, H. (2019). Upcycling and Design for Disassembly - LCA of buildings employing circular design strategies. ResearchGate. https://www.researchgate.net/publication/331224392_Upcycling_and_Design_for_Disassembly_-_LCA_of_buildings_employing_circular_design_strategies
Retrieved from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://img1.wsimg.com/blobby/go/a2683815-e637-4d29-914b-3016244d2fb1/downloads/Circular%20Steel%20Boards%20Combined_reduced.pdf?ver=1686497355789

Ritzen, M., Oorschot, J.Van, Cammans, M., Segers, M., Wieland, T., Scheer, P., Creugers, B., Abujidi, N., 2019. Circular (de)construction in the superlocal project. IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/225/1/012048.

S - T

Soo, V. K., Duflou, J., Paraskevas, D., Compston, P., Doolan, M., & Duflou, J. (2018). Sustainable aluminium recycling of end-of-life products: A joining techniques perspective. Journal of Cleaner Production, 178, 119–132. https://doi.org/10.1016/j.jclepro.2017.12.235

Speira Karmøy Aluminium Rolled Products VERSA. (2022). Environmental Product Declaration. In Epd-norge (NEPD-3441-2042-EN). The Norwegian EPD foundation.

Steinhilper, R., & Weiland, F. (2015). Exploring New Horizons for Remanufacturing an Up-to-date Overview of Industries, Products and Technologies. Procedia CIRP, 29, 769–773. https://doi.org/10.1016/j.procir.2015.02.041

Sumter, D., Bakker, C., & Balkenende, R. (2018). The Role of Product Design in Creating Circular Business Models: A Case Study on the Lease and Refurbishment of Baby Strollers. Sustainability, 10(7), 2415. https://doi.org/10.3390/su10072415

Tilwankar, A. K., Mahindrakar, A. B., & Asolekar, S. R. (2008). Steel Recycling Resulting from Ship Dismantling in India : Implications for Green House Gas Emissions. In Proceedings of International Conference on Dismantling of Obsolete Vessels (pp. 1–10).
Glasgow

U - Y

Uitgebreide toelichting | BCI. (n.d.). Retrieved from https://bcigebouw.nl/uitgebreide-toelichting/

Van den Dobbelsteen, A.A.(2004). The Sustainable Office – an exploration of the potential for factor 20 environmental improvement of office accommodation. [Doctoral thesis, TU Delft]

Van Dijk, S. C., Rychtarikova, M., & Van Den Dobbelsteen, A. (2014). Continuing the building's cycles: A literature review and analysis of current systems theories in comparison with the theory of Cradle to Cradle. Resources Conservation and Recycling, 82, 21–34. https://doi.org/10.1016/j.resconrec.2013.10.007

VMRG. (n.d.). Windbelasting. Retrieved September 15, 2023, from https://vmrg.nl/kwaliteitseisen/kwaliteitseisen-en-adviezen/constructies/doorbuiging/windbelasting

Wallace, G. G. (2011). Production of secondary aluminium. In Fundamentals of Aluminium Metallurgy (pp. 70–82). https://doi.org/10.1533/9780857090256.1.70

Wind Interactive. (2022). Buildwise. https://www.buildwise.be/nl/expertise-ondersteuning/buildwise-tools/wind-interactive/

Yang, S., Ngiam, H. K., Ong, S., & Nee, A. Y. C. (2015). The Impact of Automotive Product Remanufacturing on Environmental Performance. Procedia CIRP, 29, 774–779. https://doi.org/10.1016/j.procir.2015.01.017

12.

Appendix

12.1 Building site interviews
12.2 DfD Guideline Documents
12.3 Production drawings
12.4 Highrise structural analysis

12.1 Building site visits

The goal of the visits was to understand how assembly takes place at the building site and have an idea of how disassembly would take place after a certain amount of period when the panels are no longer new and the circumstances are not ideal.

Findings 1st Building site

The building was at Oranjekade in Helmond. In this interview, two assemblers were present and the main findings regarding the assembly and potential disassembly of panels at a building site are as follows:

a. The current assembly process involves products (material components) delivered in pallets with identification. The products are listed with order and suborder numbers, descriptions, quantities, and colors.

b. Products are delivered as the assemblers progress on each floor or section of the building due to limited space. Prioritization of required products for assembly is crucial.

c. One challenge encountered during assembly was that the engineers received drawings without insulation, but insulation was already in place at the building site. This required a complete change in the assembly method, including redesigning and producing the back structure. Over 500 brackets already produced and specifically bended a certain degree had to be disregarded.

h. Coated panels are more likely to require attention or maintenance over time due to their aesthetic and structural function.

j. Disassembly of cassette panels can be challenging because a whole row needs to be demounted. The panels are interdependent, making repair complicated.

l. Most fasteners used are screws that can be unscrewed, but they cannot be reused. Theoretically, every panel could be demounted.

o. Assemblers primarily use 2D drawings when assembling panels, but they can refer to 3D models on their iPads or phones for clarification.

q. When replacing a panel, assemblers rely on assembly drawings and details to understand how it is composed and then figure out how to disassemble it.

s. When disassembling panels that are 10-20 years old, limited space at the building site should be taken into account to avoid accumulating disassembled components.

u. Care should be taken to avoid damaging panels when dismantling, particularly when un-drilling screws to prevent scratching. Powder-coated panels can only be recoated three times.

x. Assemblers indicated that the design responsibility lies with the engineers. They will follow the assembly drawings provided and find alternative on-site solutions if needed.

These findings provide insights into the current assembly process, challenges faced, maintenance considerations, and the potential difficulties and limitations that may arise during disassembly of the panels.

Findings 2nd Building site

The building was in Leiden. In this interview, two assemblers were present and the main findings regarding the assembly of panels at a building site are as follows:

a. In contrast to the past construction site that utilized scaffolding, the assembly process involved the utilization of an aerial work platform to efficiently assemble the panels. This means they have less space where to place the tools and panels for mounting.

b. The panels, being the final components to be installed, hold significant visual significance. The primary challenge encountered was effectively managing the diverse tolerances inherent in the steel construction and achieving an aligned facade. To address these tolerances, plastic filler plates were extensively employed. Additionally, a sanding machine and cutter were utilized to modify the panels and ensure a better fit.

c. The assembler at this building site had a lot of experience and knowledge. Their preferred approach involved utilizing an iPad to reference both the 3D model and accompanying details. On occasion, or when necessary, they would also consult physical 2D drawings.

This short site visit showed how different the assembly process can be and how overcoming tolerances plays a significant role in the aesthetic result of the facade panels. The current panels are designed with tolerances of 1-2mm and to overcome the building site tolerances they have to be modified sometimes. The Ipads allow the assemblers to document these modifications and store the data for future reference.

Vision

Up to 80% of products' environmental impact is determined in the design phase. By adhering to the Cradle to Cradle principles since the start of a project, Aldowa ensures that their products receive a Cradle to Cradle certification. The primary objective is to establish a closed-loop life cycle for these products, where no waste is generated, and materials can be continuously reused or recycled.

CERTIFIED cradle to cradle® PRODUCTS PROGRAM

OUR PRODUCT

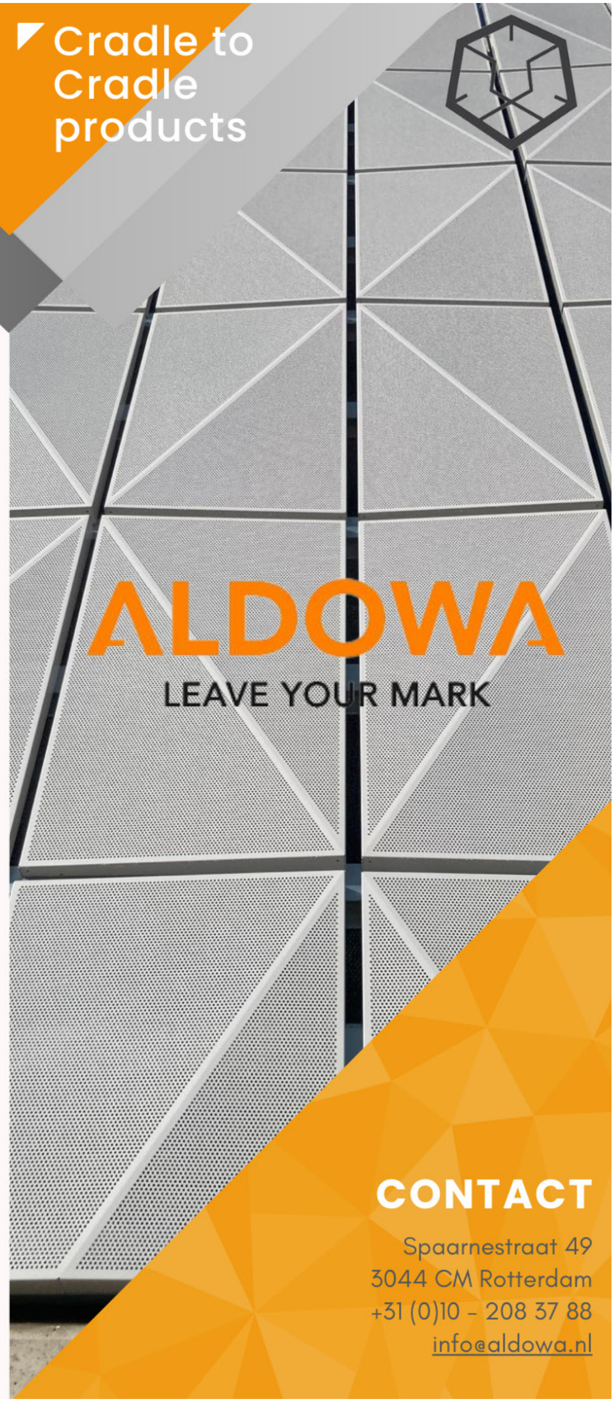
Uniqueness with Circular Elegance - Cradle to Cradle Certified Facade Cladding

We understand every building is unique. Architects and contractors, therefore, need solutions that allow them to design their building projects in a way where uniqueness meets sustainability. This is possible with our facade cladding products:

- Use of toxin-free materials, ensuring high standards of material health
- Customizable to the desired shape and color in accordance to the C2C criteria
- Durable and demountable system
- 90% made out of aluminum with recycled content and which can be continuously recycled
- Close partnerships with our suppliers for a circular facade system
- Use of renewable energy throughout our production process

Our process and products are assessed every **2 years** to check if we are complying to the requirements of the certification

Cradle to Cradle products



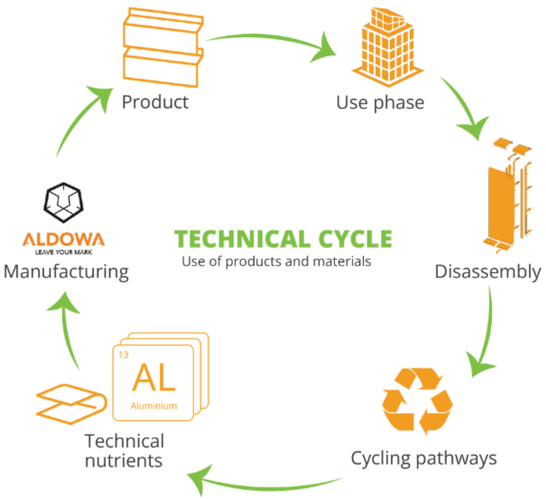
CONTACT

Spaarnestraat 49
3044 CM Rotterdam
+31 (0)10 - 208 37 88
info@aldowa.nl

ABOUT CRADLE TO CRADLE

A concept by Michael Braungart and William McDonough

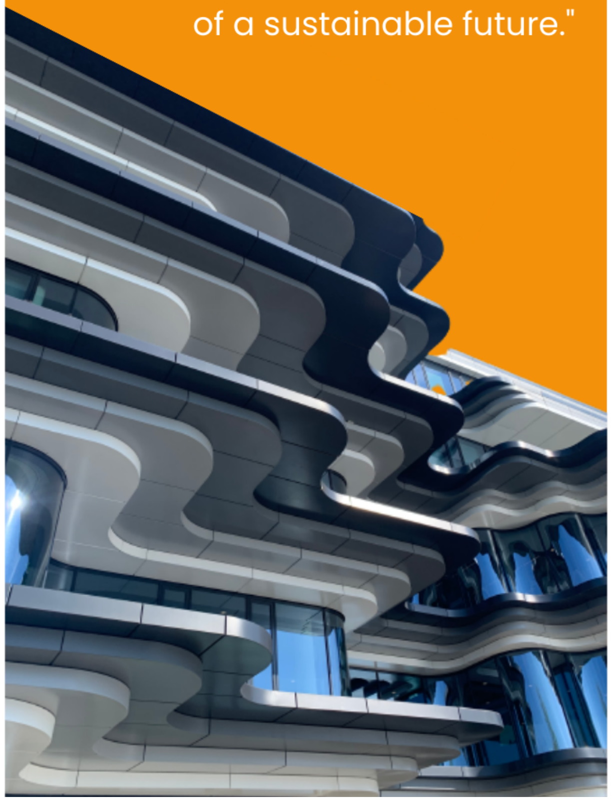
This visionary approach prioritizes positive impacts by prohibiting the use of toxic materials and engineering products that undergo continuous recycling or repurposing throughout their life cycle.



Our products can be deconstructed into raw materials at the end of their lifecycle, transforming our cladding systems into valuable resources for creating new products, thus eliminating waste and enabling potential reuse.

For more information on Cradle to Cradle visit: https://c2ccertified.org/

"It is necessary to rethink how we design our products and integrate sustainable practices from the beginning to the end of the production process. By adopting this approach, we can construct products that possess long-term value and meet the demands of a sustainable future."



CRITERIA FOR CERTIFICATION

To attain Cradle to Cradle Certified® Product Standard certification, products must undergo evaluation against five extensive criteria, each carrying equal weight. Among these requirements is the design for disassembly, which Aldowa incorporates into their C2C products.

1. Material Health
Ensuring the use of environmentally safe and healthy materials. No certification is granted if a material is listed in the restricted substances list.

2. Product circularity
Engineering products to extend their service life and ensure recycling at the end of their life cycle.

3. Climate protection
Striving to utilize renewable energy sources and implementing carbon management practices to minimize the product's carbon footprint.

4. Water & Soil Stewardship
Employing conscious water management strategies to conserve and handle water & soil responsibly.

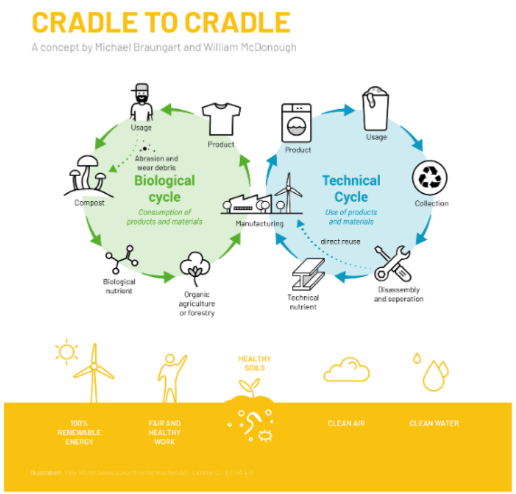
5. Social fairness
Promoting ethical practices and social responsibility, ensuring fair labor practices.

FAQ

Frequently asked questions

1. What is Cradle to Cradle?

The foundation of Cradle to Cradle stems from the book authored by Michael Braungart and William McDonough. Their approach, distinct from other system theories aimed at minimizing negative impacts, is centered around generating a positive impact. This is achieved through a twofold strategy: firstly, by NOT using toxic materials, and secondly, by creating products that can undergo continuous recycling or repurposing at the conclusion of their life cycle. By adopting this approach, waste generation is eliminated, and the environment remains unharmed.



For more information on Cradle to Cradle visit: https://c2ccertified.org/

2. What does a Cradle-to-cradle Certification mean?

The Cradle to Cradle Products Innovation Institute (C2CPII), located in San Francisco, has developed an evaluation system aimed at creating, assessing, and certifying products that meet the C2C requirements. In response to the increasing demand for building certifications like LEED, BREEAM, and DGNB in recent years, there has been a corresponding rise in the need for sustainable materials and products.

C2C certification serves as an independent confirmation of a product's quality, encompassing various aspects. It verifies compliance with harmful emissions throughout installation, usage, and dismantling processes. Moreover, the certificate holds weight as evidence of sustainability, making it valuable for use in tender specifications that prioritize eco-friendly solutions.

3. Why do the products need to be demountable?

Design for disassembly means that the product is designed in such a way that the product can be demounted from the building and dismantled into assemblies and further into parts in a non-destructive way. After the disassembly process the parts can be recovered, sorted and inspected to apply an R-strategy (Reuse, refurbish, repair, remanufacture or repurpose) to extend its service life.

4. How does the certification work?

To achieve the certification, Aldowa must demonstrate strict adherence to all the certification standards, documenting and providing corresponding certificates and measurements as evidence. The certification body conducts a conformity check based on the submitted documents. Only upon meeting all the requirements, Aldowa is granted the certificate. It's worth noting that the certification needs to be renewed every two years.

If any materials are found to be in the RSL (Restricted substances list), Aldowa must replace them with other material alternatives. This process ensures that the company's facade products meet the highest environmental and sustainability standards. Due to the strict analysis of the composition of materials, which extends deep into the supply chain, Aldowa involves suppliers and subcontractors in the process. To protect sensitive information, such as production processes, suppliers may use non-disclosure agreements (NDAs) to safeguard their business secrets.

5. What is the difference between general recycling and Cradle to cradle recycling?

Recycling, especially aluminium recycling, faces challenges due to impurities, leading to "downcycling" where materials lose their technical quality. Cradle to Cradle recycling aims for consistent, high-quality circulation by proper disassembly, separating materials to prevent contamination and preserve their value from manufacturing and finishing processes.

CONTACT

Spaarnestraat 49
3044 CM Rotterdam
+31 (0)10 - 208 37 88
info@aldowa.nl

DESIGN FOR DISASSEMBLY

DISASSEMBLY MAP

ALDOWA
LEAVE YOUR MARK

CAN YOU DISASSEMBLE YOUR DESIGN

Test it with a Disassembly Map

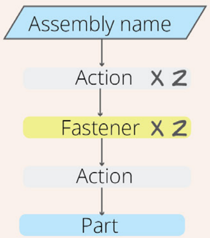
START

1 Select an assembly of a project and gather a 2D drawing or a 3D model of it.

2 Use this legend to categorize each component. An assembly is defined as a group of parts and a part is defined as an item of an assembly and cannot be disassembled further down, such as a bracket.

LEGEND
- Assembly
- Parts
- Fasteners
- Disassembly action

3 Make a disassembly map to visualize in what order the assembly can be disassembled and what actions are needed. Remember to use a disassembly action box before reaching a fastener/part box:

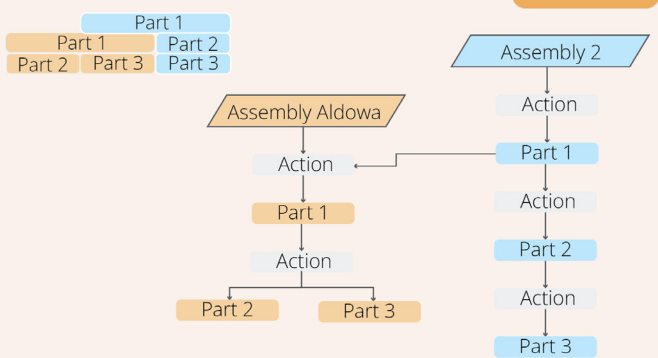


4 If you have enough information, record the amount of times (X AMOUNT) the disassembly action needs to be done and the amount of fasteners.

5 Map all the parts and corresponding disassembly actions by answering these questions:

- ? Which next disassembly step(s) is required to reach the next part?
- ? Is there any other operation that could be carried out first?
- ? Is there any other operation that could be carried out in parallel with the one just completed?

6 Take into account other assemblies of products. If a part from another assembly (even if it is not from Aldowa) needs to be first demounted before accessing the assembly you have chosen, add it to the disassembly map.



7 Draw your map by hand or in Miro. Then, assess your disassembly map by calculating the amount of :
- ✓ Fasteners
- ✓ Disassembly actions
- ✓ Parts
- ✓ Amount and list of tools

8 Make sure to identify the penalties and try to eliminate them in step 10!!!!

- Uncommon tools
- Destructive processes**

9 Calculate the detachability score based on the scores below:

	AVERAGE SCORE
TYPE OF CONNECTIONS (Action boxes)	
ACCESSIBILITY (Part & fastener boxes)	
ROBUSTNESS (Part boxes)	
INTERDEPENDENCE (Assemblies)	

TYPE OF CONNECTION

- 1 Dry connection: Click, Velcro, Magnet
- 0.8 Extra elements: Bolt & nut, Screw, Other extra element
- 0.6 Integral connection: Spike, Nail
- 0.2 Soft chemical connection: Mastic (kit), Pur connection (Polyurethaan)
- 0.1 Hard chemical connection: Glue, Laser / welded, Cement, Chemical anchors

ACCESSIBILITY

- 1 Freely accessible
- 0.8 Accessible with additional actions that do not cause damage
- 0.6 Accessible with fully repairable damage
- 0.4 Accessible with partially repairable damage
- 0 Not accessible: irreparable damage to the product or surrounding products

ROBUSTNESS

- 1 No risk of damage at end of its service life
- 0.8 Repairable risk of damage
- 0.4 Notable risk and repair might be challenging
- 0 High risk and reassembly not possible

INTERDEPENDENCE

- 1 Independent
- 0.5 Ocassional dependencies
- 0 Full dependence

10 Improve the design for disassembly by analysing the map and asking yourself:

- ? Is this part absolutely necessary or is there another way to make a connection without it?
- ? How can the disassembly penalties in the design be reduced?
- ? What is the lowest detachability score and what measures could improve it?

**dismantling a part in a way that causes damage

DESIGN FOR DISASSEMBLY

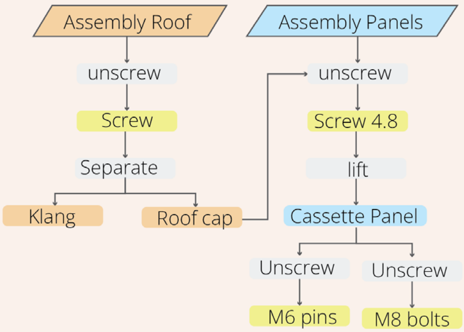
RE-DESIGN

ALDOWA
LEAVE YOUR MARK

To design a new connection or product for disassembly it is important to take into account the **disassembly principles**:

- CHOOSE DEMOUNTABLE CONNECTIONS THAT USE COMMON TOOLS
- MAKE PARTS & FASTENERS ACCESSIBLE
- AVOID DESTRUCTIVE PROCESSES
- DESIGN MODULAR INDEPENDENT ASSEMBLIES
- CLEAR IDENTIFICATION OF PARTS
- REDUCE UNNECESSARY CONNECTIONS

To re-design an existing design first create a **Disassembly Map** to identify the barriers facilitating disassembly. Otherwise go to the next step.



1

2

3

List the **design requirements**

- Desired appearance
- Desired functionality
- Dimension of parts
- Production & Transport requirements
- Building codes

4

Ask your colleagues

Before designing again an existing design, ask your colleagues if they have been encountered with a similar design challenge/situation.

5

Make **sketches** and **variations**. Record the redesign process.

IMPROVE

None of the variations meet the requirements.

6

Create 3D models out of paper or alternative materials, or produce a **Mock-up**.

7

Test and evaluate the mock-up.

8

Compare the variations

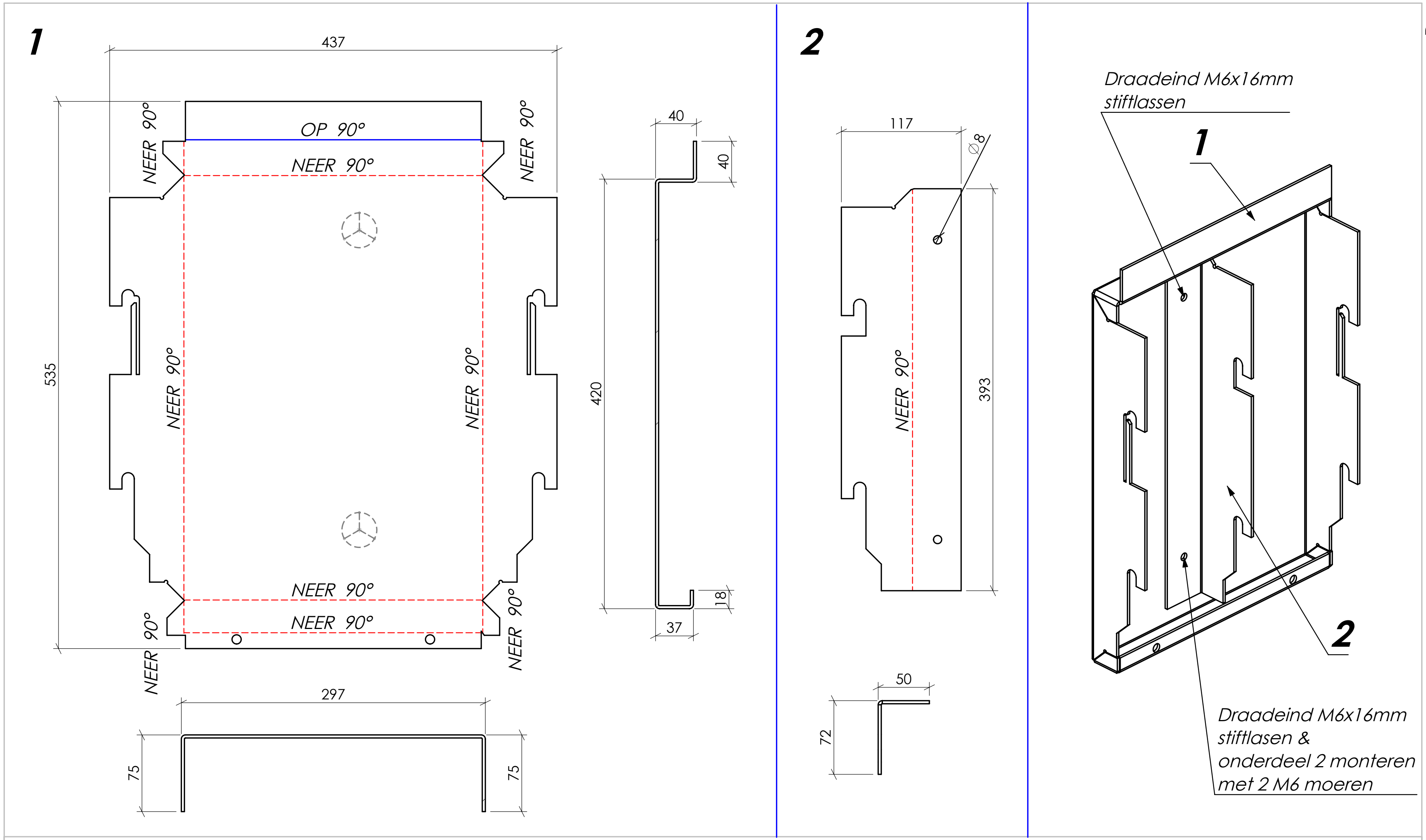
- ✓ Design requirements
- ✓ Detachability score >0.5
- ✓ Structural analysis

Choose the best scoring solution and integrate it in the product.

Share your (re) design!

12.3 Production drawings

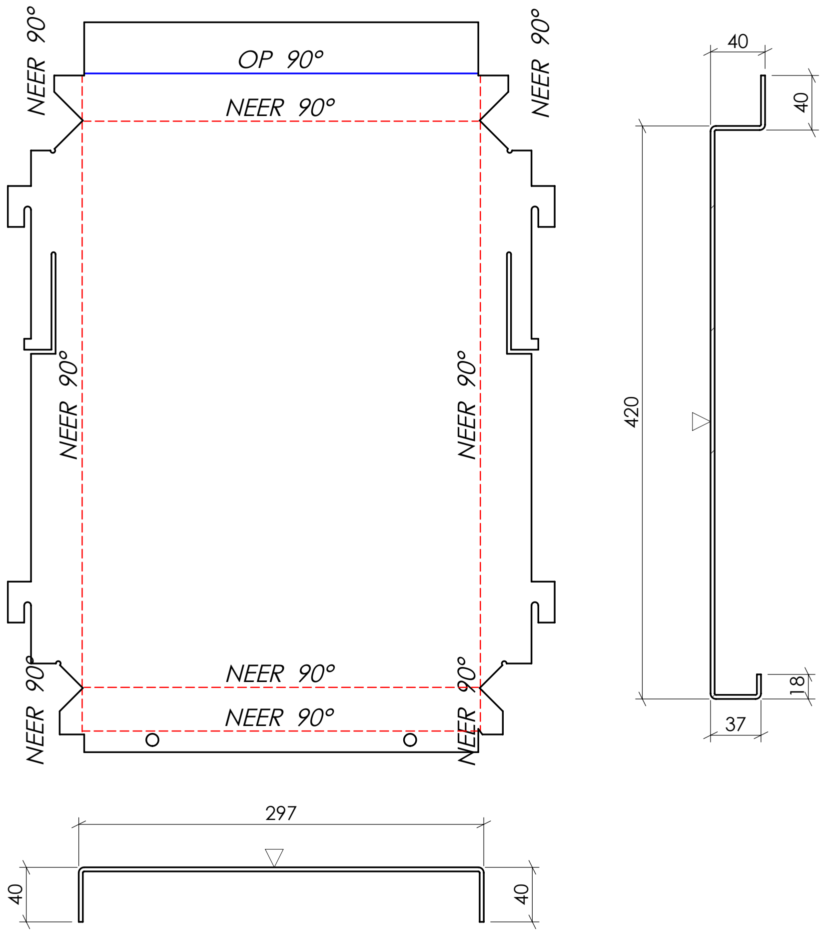
210mm*297mm

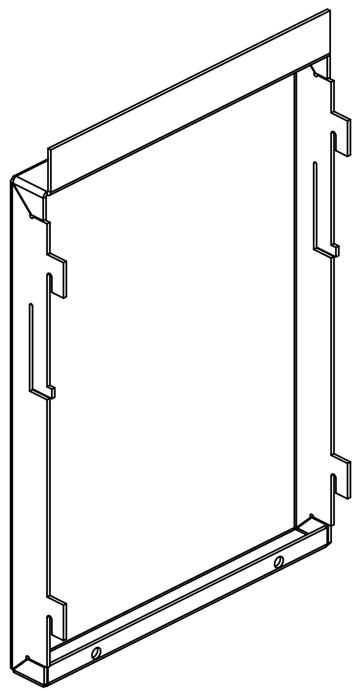


Draw. no. 500023.PRO005	**Comments**	**Project** Mock-up & Proefjes	**Rev.** A
QT drawn	**Dimensions** X	**Description**	**Date** 27-09-2023
QT mirrored	**Finish** Brute	**Project no.** 500023 — **Drawn By** RVH **Released by**	**Scale** 1:5
Material 3 mm AlMg1	**Color**		**Size** A4

ALDOWA
LEAVE YOUR MARK

1

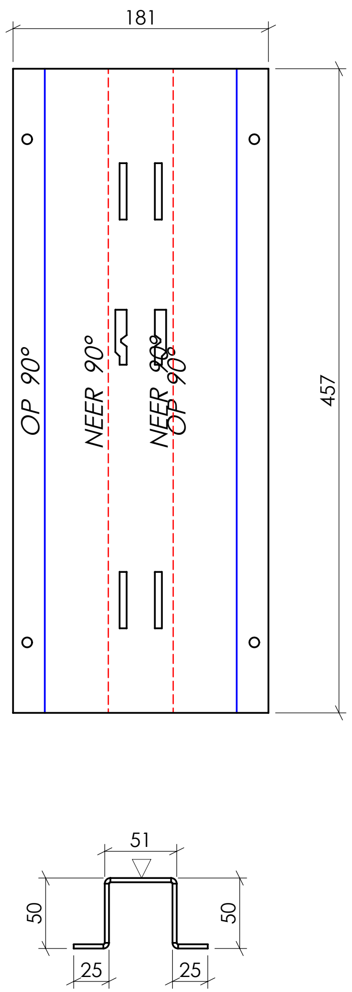




210mm*297mm

Draw. no.	50023.C2C_Cassettepaneel_A3_DFD_Rev.A	Comments		Project		Rev.	
QT drawn		Dimensions	535 x 401	Description		Date	27-10-2023
QT mirrored		Finish	Brute	Project no.	Drawn By / Released by	Scale	1:5
Material	3 mm AlMg1	Color			RVH	Size	A4

ALDOWA
LEAVE YOUR MARK



Draw. no.	50023.C2C_Omega profiel_Gecoat_A3_DFD_Rev.A	Comments	
QT drawn		Dimensions	457 x 181
QT mirrored		Finish	Brute
Material	3 mm AlMg1	Color	

ALDOWA
LEAVE YOUR MARK

Project		Rev.	
Description		Date	27-10-2023
Project no.	Drawn By: RVH / Released by:	Scale	1:5
		Size	A4

210mm*297mm

12.4 Highrise structural analysis

	Rev 00	
TULiPPS Solar System Solutions	Designbase Facade Panels	ALDOWA LEAVE YOUR MARK

ONTWERPBASIS

Project Name:	Facade Panels project 221031
Customer:	Aldowa
Doc ID:	23019-00R01 rev A
Project ID:	23019
Author:	Albert Hogewoning, Highrise BV

A	03-04-2023	For Approval	AH		
0	30-03-2023	For Review	AH	-	-
Rev	Date	Description	Prepared by	Checked by	Approved by

Content:

1. Introduction **3**

2. Code-frame **4**

2.1 Codes *4*

3. Design Base **4**

3.1 Accelerations *4*

3.2 Wind load *4*

3.3 Snow and/or Icing *4*

3.4 Other loads *4*

4. Load combinations **5**

4.1 Load combinations per Eurocode *5*

4.2 Acceptance criteria for SLS loadcases *5*

5. Materials **6**

5.1 Plate Material *6*

5.2 Material factors per Eurocode 9 *6*

5.3 Acceptance criteria stresses *6*

6. Windloads **7**

7. Results of the Finite Element Analysis (FEA) **9**

1. Introduction

Aldowa has designed a standardized passive aluminium panel, based on their Cassette-system. This panel will be used on facades of building at various locations where vertical solar-panels will not fit.

The standard panel(s) will be used in various sizes and will be located on various façade-positions, at various heights and at various locations in the Netherlands.

The standard panel must sufficiently cover a broad range of possible structural specifications (in terms of maximum possible wind load) that various projects may require.

To assess this, this calculation will firstly verify the maximum resistance against negative pressure (a.r.o. wind suction) per EN 1991-1-1 of two different designs of Aldowa.

In a second step such maximum resistance will be set against an array of possible relevant project conditions that will determine maximum wind conditions in a project:

- location of the building
- location of the panel onto the building
- elevation of the panel
- reference-period

2. Code-frame

2.1 Codes

- NEN-EN 1990 : Eurocode 0 : Grondslagen van het constructief ontwerp
- NEN-EN 1991-1 : Eurocode 1 : Belastingen op constructies
- NEN-EN 1999 : Eurocode 9 : Ontwerp en berekening van aluminiumconstructies
  Deel 1-1: Algemene regels

3. Design Base

3.1 Accelerations

Only gravity: (9.81 m/s^2).

3.2 Wind load

Wind suction is deemed governing for the failure-mechanism of the panel(s).

3.3 Snow and/or Icing

No impact of snow or icing is taken into consideration.

3.4 Other loads

No other loads are taken into consideration.

4. Load combinations

4.1 Load combinations per Eurocode

The load combination factors are pending the consequence class (CC3)

The combinations for CC3 are stated:

	EC 1990	Permanent Lasten	Variabele Lasten
ULS FC1	6.10a	1,5	1,65*0,8=1,32
ULS FC2	6.10b	1,3	1,65
SLS IC1	6.14a	1,0	0,8
SLS IC2 (not relevant)	6.15a	1,0	0,2

4.2 Acceptance criteria for SLS loadcases

No specific values provided from customer.

Conservatively we apply 1:200.

In case SLS will be governing, we may decide to apply 1:100 as a more lenient criterium.

5. Materials

5.1 Plate Material

Plate material Panels : EN-AW-5005 (t-3mm)

Material fixation pins : A4-70 – M10 (hole 11 mm)

Material and type rivets : Aluminium

5.2 Material factors per Eurocode 9

For member $\gamma_{M1} = 1.1$

For connections $\gamma_{M1} = 1.25$

5.3 Acceptance criteria stresses

Items	Material	f_0	f_u	f_0/110%	f_u/125%
Plate material panels	5005 H24	110	145	100	116
Stainless steel fixations	A4-70	450	700	409	560
Rivet Materials	TBD	TBD	TBD	TBD	TBD

6. Windloads

Base is Table NB.5 from the Dutch National Annex (NA).

Stuwdrukwaarde volgens tabel NB.4 van NEN-EN 1991-1-4 (NB)

h in m	q_p in kN/m²							
	GEBIED I			GEBIED II			GEBIED III	
	kust	onbebouwd	bebouwd	kust	onbebouwd	bebouwd	onbebouwd	bebouwd
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13
80	2,30	1,86	1,66	1,92	1,55	1,39	1,28	1,15
85	2,32	1,88	1,69	1,94	1,58	1,42	1,30	1,17
90	2,34	1,91	1,72	1,96	1,60	1,44	1,32	1,18
95	2,36	1,93	1,74	1,98	1,62	1,46	1,33	1,20
100	2,38	1,96	1,77	1,99	1,64	1,48	1,35	1,22
110	2,42	2,00	1,81	2,03	1,68	1,52	1,38	1,25
120	2,45	2,04	1,85	2,05	1,71	1,55	1,41	1,28
130	2,48	2,08	1,89	2,08	1,74	1,59	1,44	1,31
140	2,51	2,12	1,93	2,10	1,77	1,62	1,46	1,33
150	2,54	2,15	1,96	2,13	1,80	1,65	1,48	1,35
160	2,56	2,18	2,00	2,15	1,83	1,67	1,50	1,38
170	2,59	2,21	2,03	2,17	1,85	1,70	1,52	1,40
180	2,61	2,24	2,06	2,19	1,88	1,72	1,54	1,42
190	2,63	2,27	2,08	2,20	1,90	1,75	1,56	1,44
200	2,65	2,29	2,11	2,22	1,92	1,92	1,58	1,46
225	2,70	2,35	2,35	2,26	1,97	1,97	1,62	1,62
250	2,74	2,40	2,40	2,30	2,01	2,01	1,66	1,66
275	2,78	2,45	2,45	2,33	2,05	2,05	1,69	1,69
300	2,82	2,5	2,5	2,36	2,09	2,09	1,72	1,72

For the pressure coefficients we refer to NB.6 also per Dutch NA.

Tabel NB.6 – 7.1 — Uitwendige drukcoëfficiënten voor verticale gevels van gebouwen met rechthoekige plattegrond

Zone	A		B		C		D		E	
h/d	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	−1,2	−1,4	−0,8	−1,1	−0,5		+0,8	+1,0	−0,7	
≤ 1	−1,2	−1,4	−0,8	−1,1	−0,5		+0,8	+1,0	−0,5	

The panels will typically be mounted in sector A.

And as this is the panel and not a larger support structure of the building,

factor apply for $C_{pe,1}$ -> we need to consider factor $C_{pe,1}$ = -1.4 on corners of the buildings.

That makes the governing loadcase for the panels considering wind load at a panel on the façade of a building at a certain elevation is defined per Eurocode 1991-1-4:

5.2 Wind pressure on surfaces

(1) The wind pressure acting on the external surfaces, w_e, should be obtained from Expression (5.1).

$$w_e = q_p(z_e) \cdot c_{pe} \qquad (5.1)$$

where:

$q_p(z_e)$ is the peak velocity pressure

z_e is the reference height for the external pressure given in Section 7

c_{pe} is the pressure coefficient for the external pressure, see Section 7.

And we use

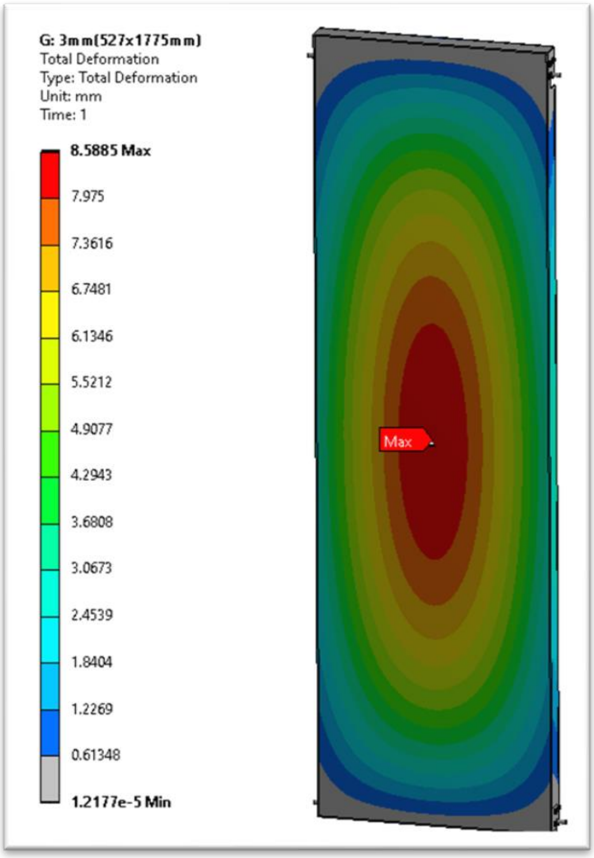
- load factor 1,65 (as per par 4.1 of BOD) for ULS situation.
- Load factor 1,00 for the SLS situation

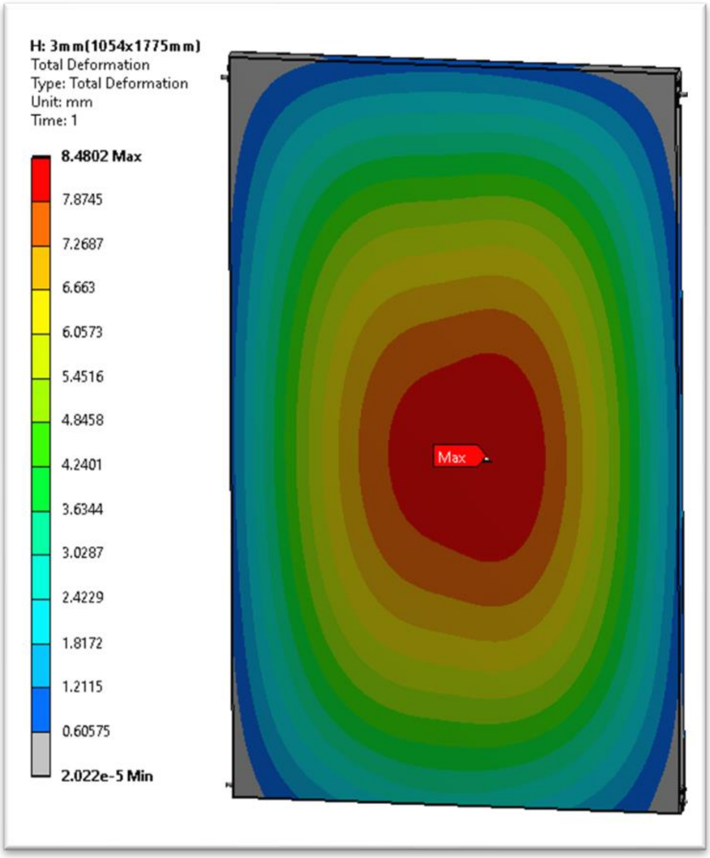
7. Results of the Finite Element Analysis (FEA)

For detailed information on the FEA we refer to ppt report

"23019_Facade Panels_FEA_Results_20230329"

For both panels the deformation criteria is governing. At 1:200 a deformation of 8.5 mm is the boundary.



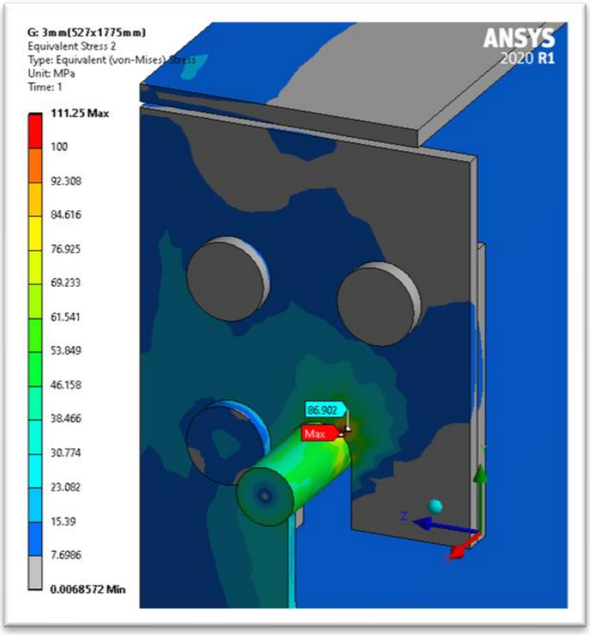


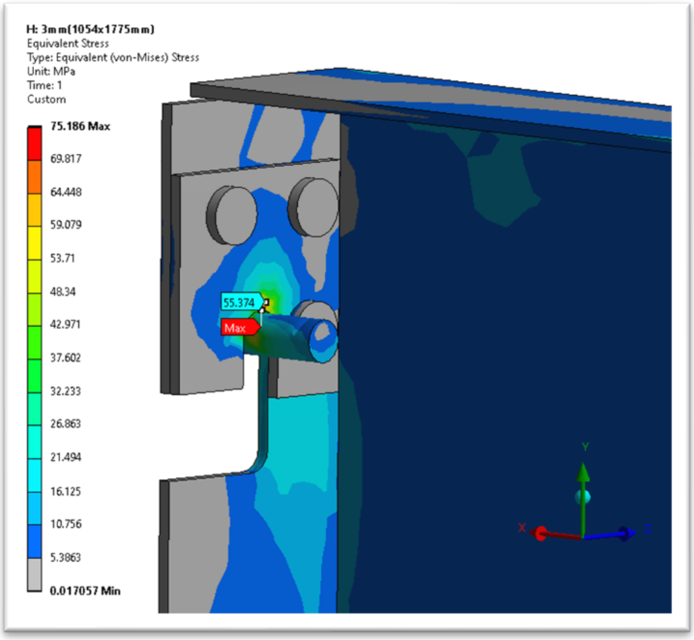
This level of deformation is reached :

- For the narrow panel at suction of 1.15 MPa
- For the wide panel at suction of 0.49 MPa

At that level of pressure peak stresses are found at the pressure contact between pins and plates:

- For the narrow panel 87 MPa
- For the wide panel 55 MPa





Reported max pressures for the panels is coherent with a deformation criterium of 1:200.

Pressure 1.15 MPa for the narrow panel -> $q_{p.max}$ = 1.15/(1.00x1.4) = 0.82 MPa

Pressure 0,5 MPa for the wide panel -> $q_{p.max}$ = 0.49/(1.00x1.4) = 0.35 MPa

For the ULS loadcase a stress level of 116 MPa is acceptable as peak stress under EC 9.

Present SLS evaluation narrow panel : 87 MPa - > 133%

So the estimated boundary for a ULS evaluation of the narrow panel 1,33 x 87 = 1,52 MPa

Present SLS evaluation wide panel : 55 MPa -> 211%

So the estimated boundary for ULS evaluation of the wide panel 2,11 x 55 -> 1,06 MPa

(these are only fair estimates, to steer next steps. Not a valid prediction for structural evaluation).

As a result these figures present the following levels of q_p that are to beexpected as max under ULS loadcase:

Pressure 1.15x133% MPa for the narrow panel -> $q_{p.max}$ = 1.52/(1,65x1.4) = 0.66 MPa

Pressure 0,49x211% MPa for the wide panel -> $q_{p.max}$ = 1.06/(1.65x1.4) = 0.46 MPa

That would imply that the use of panels on elevated buildings in present design is fairly limited, based on the deformation criterium overall and acceptable peak stresses of the hooks.

See in colour the various relation to the national table for wind areas in the Netherlands. The SLS values are quite low: as a result

Next action is to seek improvement in design and alignment with a proper deformation criterium.

Tabel NB.5 — Extreme stuwdruk in kN/m² als functie van de hoogte

Hoogte	Gebied I			Gebied II			Gebied III	
m	Kust	Onbebouwd	Bebouwd	Kust	Onbebouwd	Bebouwd	Onbebouwd	Bebouwd
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13

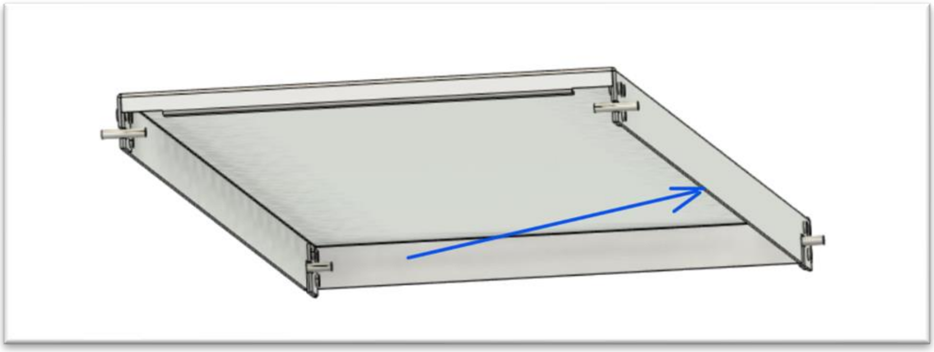
8. Conclusion

Present design of the panels are not stiff enough to meet a deformation criterium of 1:200.

First step is to review the acceptance criterium for deformation for the panels.

But even pending this possible more lenient acceptance criterium for deflection, it is expected that redesign of the panels is required to increase stiffness.

- A bended flange at the sides of the panels (bleu arrow)
- If needed a double bended flange (C-type arrangement)
- If needed cross stiffener(s)



For the wide panel:

- Improved bending resistance stiffener: Z-profile or Omega profile