Cassette Panels Designed for Disassembly

ALDOWA
LEAVE YOUR MARK

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

TU Delft
Delft University of Technology

Colophon
Msc Graduation Thesis Report
Version 1 Report - June 1, 2023 4:58 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
External Supervisor: Rick van Horssen	Aldowa

ALDOWA
LEAVE YOUR MARK

TU Delft
Delft University of Technology

Summary

Acknowledgments

Table of Contents

List of Acronyms

Dfd - Design for Disassembly

...

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:

1.1 Background

Aldowa is a façade cladding company that specializes in manufacturing and assembling aluminium facades. They are committed in providing a more sustainable service and implementing circular strategies in their production process. Their goal is to design products that have a longer lifespan and achieve a cradle-to-cradle certification for their cassette panel. While the company initially aims for the bronze level, they recognize the need for a comprehensive plan to reach higher certification levels. To achieve a closed loop cycle for the product, an integral plan and strategies have to be taken into consideration.

The closed loop cycle entails thorough 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 parts.

1.2 Problem statement

The façade products have a single use life span where a lot of 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 effective strategy and adopting a business model to employ them becomes crucial. 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

To conduct an **evaluation** of Aldowa's **cassette panel** disassembly potential, with a focus on **improving** the **product's life cycle** through **design for disassembly** strategies.

From this main objective the following sub objectives derive:

- To identify the **barriers** facilitating the **disassembly** of Aldowa's cassette panel
- To understand the **impact** of the product **design**, **manufacturing**, and **assembly** on the product's **life cycle**.
- To propose **potential solutions** or design **alternatives** for a more circular product **life cycle**.

1.4 Focus and limitations

This research aims to focus on assessing the disassembly potential of the cassette panel and proposing design improvements to enhance its ease of disassembly and enable future cycling pathways. The study will also provide a general overview of post-disassembly strategies without delving into detailed analysis.

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, the cassette panel represents the most intricate 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 methodology 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 cassette panel be assessed, and what design alternatives can be proposed to comply with the design for disassembly requirements of the Cradle-to-Cradle certification?

From which the following **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?
3. What are the current end-of-life scenarios for aluminium products, and which could be the circular (re) life pathways?

Additionally, the following **design** sub-questions derive:

1. What are the existing design features and characteristics of Aldowa's casette panels that hinder disassembly?
2. What design alternatives can be implemented to enhance the disassembly potential of Aldowa's cassette panel and extend its service life?
3. What is the impact of Dfd alternatives on the production process of Aldowa?

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 and the sources were collected and categorized from Yes very relevant, yes, partly and Not relevant in an excel data base.

#	SEARCH TERM	Read & Relevance	Title	Year	Intext	Citation in report
Re life strategies						
Search:	Google Scholar	Reuse OR Repair Or Refurbish OR Remanufacture OR				
1	End of life strategy AND aluminium AND product	Yes	Granta EduPack	2022	(Granta EduPack, 2022)	
2		Yes - Very Relevant	European aluminium circular aluminium action plan	2020	(European Aluminium, 2020)	European Aluminium. (2
3		Partly	Facilitating greater reuse and recycling of structural steel in the construc	2006	(Gorgolewski et al. ,2006)	ocess. Department of Ar
4		Yes	Production of secondary aluminium	2011	(Wallace, 2011)	mentals of Aluminium M
5		Partly	Status of management of solid hazardous wastes generated during disma	2006	(Asolekar , 2006)	ng of obsolete ships in Ir
6		Partly	Steel Recycling Resulting from Ship Dismantling in India	2008	(Tilwankar et al. 2008)	a : Implications for Gree Glasgow
7		Yes - Very Relevant	Reuse of steel and aluminium without melting	2013	(Cooper, 2014)	luminium without meltin
8		Yes	Sustainable aluminium recycling of end-of-life products: A joining technic	2018	(Soo et al., 2018)	nd-of-life products: A joir
9		Yes	Aluminium Recyclability and Recycling (TSC #2)	2015	(International Aluminium Institute, 2015)	Aluminium Institute. Ret
10		Yes - Very Relevant	Aluminium and Durability (TSC #1)	2014	(International Aluminium Institute, 2014)	Retrieved from https://i
11		Yes	Aluminium and sustainability	2023	(Hydro, 2023)	2023). https://www.hydro

Figure 1.1 Excel literature research data base (Illustration by author)

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

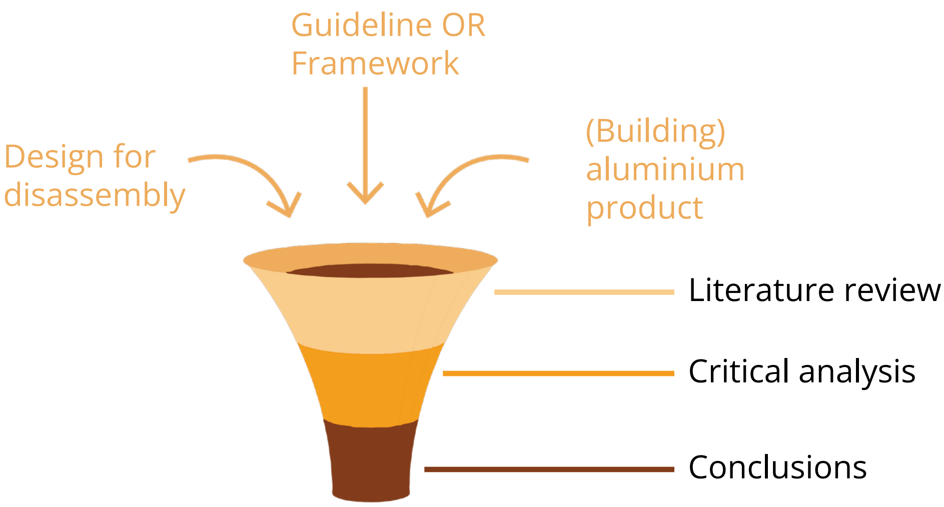


Figure 1.2 Example of the approach for a search query (Illustration by author)

[include case studies method explanation]

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 and case studies (Part II). Once the barriers to disassembly potential of Aldowa's cassette panel are identified, the paper proceeds to present solutions and alternatives (Part III). To assess the impact of the proposed solutions, the paper conducts an analysis about the implications of the proposed design alternatives. Finally, the paper concludes with a summary of key findings and conclusions (Part IV).

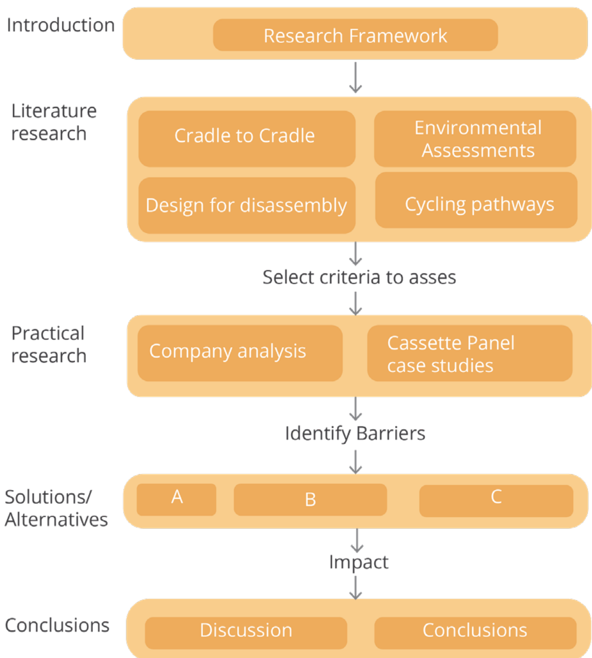


Figure 1.3 Reading guide (Illustration by author)

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 by the book 'Cradle to Cradle: Remaking the Way We Make Things' by McDonough and Braungart (2002). Section 2.1 introduces Cradle to Cradle. Section 2.2 and Section 2.3 explain the main principles of Cradle to Cradle and how they relate to other 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.

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, with the food and agriculture industries following behind. However, the sector has also 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). This reuse of materials as raw materials aligns with the government's objective of achieving a circular economy by 2050. While reducing energy use has been the primary focus for minimizing environmental impact, the significance of material use is also increasing. As energy use declines, responsible material use becomes crucial in mitigating environmental impact, and recycling and reusing materials can significantly curb transportation-related energy consumption (van den Dobbelsteen, 2004).

The importance of materials 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. Municipalities and regions in the NL. have also adopted C2C as a basis for their plans, though they have encountered difficulties in applying the principles in practice (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:

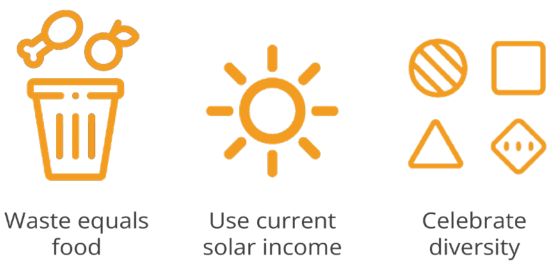


Figure 2.1 Cradle to Cradle principles (Illustration by author) (McDonough & Braungart, 2002)

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.

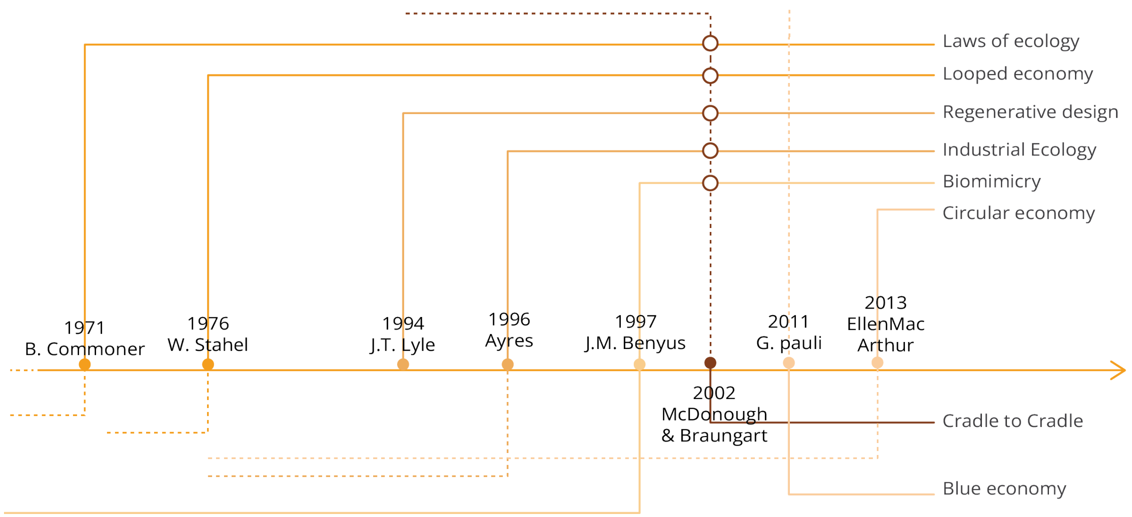


Figure 2.2 Timeline of the eight systems theories (Illustration by author) (Van Dijk et al., 2014) (EMF, 2013)

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 System's Theory Principles

Systems Theory Name	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

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's theory 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

Compared to other environmental assessments that aim to reduce negative impact, Cradle to cradle aims for a positive impact. 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 the C2C certification organization 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 accomplish this first step.

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 still 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 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:

- Does not require any disassembly to be cycled under the intended cycling pathway
- 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 past system theories, Cradle to Cradle aims to create a positive impact instead of minimizing the negative effects. Nevertheless, it is based on principles from other system theories where closed loop systems are preferred rather than linear end of pipe 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 Institue based their certification process. The certification is based on 5 categories. From which product circularity will be the focus of this research paper.

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 and specificity 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 envrionmental 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:

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 Aldowa's cladding product life cycle. 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 Aldowa's cladding product life cycle. 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 Aldowa's cladding product life cycle.

3.2 Existing environmental assessments analysis

In the 1990's the building sector started to be aware of the impact of their actions on the environment. To quantify this environmental impact the environmental performance of buildings needed 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 two technical specifications for the built environment:

- ISO/TS 21929-1:2006 sustainability in building construction — sustainability indicators — Part 1: Framework for development of indicators for buildings (ISO, 2006a).

- ISO/TS 21931-1:2006 sustainability in building construction — framework for methods of assessment for environmental performance of construction works — Part 1: Buildings (ISO, 2006b).

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.

According to Happio & Vietaniemi (2008) literature review on environmental assessments, each tool has a different database, guideline and questionnaires that assess different phases of the life cycle of a product. They found that the expected service life of a building and its components is assumed to be a fixed value without any further examination of how this may impact the outcomes of the environmental assessment (ibid.).

Furthermore, other research papers reveal several 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. A system's **use of recycling/reuse** is merited, rather than meriting a system providing **recyclable/reusable materials**
5. The **DfD** (Design for Disassembly) strategy does **not** realize an **environmental advantage** within the **framework** of the EN standards

Two EPD's of Aldowa's aluminium sheet suppliers were analyzed. In Figure 3.1 the module D has been regarded as not relevant (Assan Alüminyum, 2022) and in Figure 3.2 there is an assumption that recycling is the typical disposal scenario without considering other cycling pathways. For Speira the aluminium that is not recycled is assumed to go to either incineration or landfill. A possibility of reuse is not stated (Speira Karmøy Aluminium Rolled Products VERSA, 2022).

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 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 used 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 Type of connection rating system (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 Accessibility rating system (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 Mold containment rating system (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 Crossings rating system (BCI, 2023)

The rating system of the BCI applies to component-based elements. Evaluating the detachability of each element is crucial, as the adoption of this rating system as a standard by the Dutch government would enable Aldowa's products to align with and potentially outperform its requirements. By considering and improving upon each category and rating score for detachability, Aldowa can enhance its product offerings to meet and exceed the criteria outlined in the rating system, 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, and section 4.5 proposes a methodology to assess the disassembly potential of the cassette panels. Section 4.6 states the main conclusions.

List of Figures:

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.

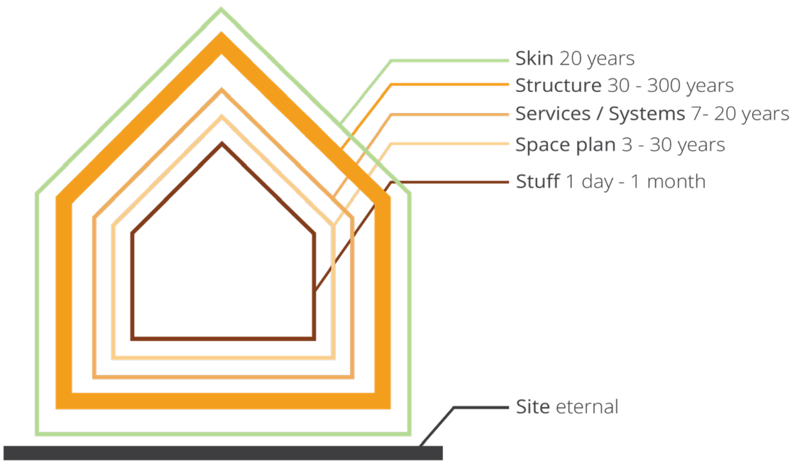


Figure 4.1 Building layers of Brand (1994) (Image adapted by author)

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.

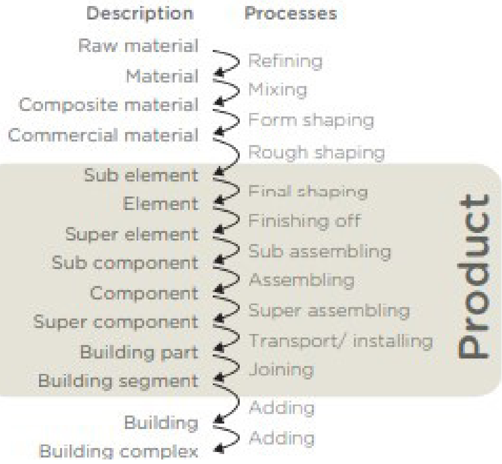


Figure 4.2 Hierarchy of building products of Eekhout (1997)

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.

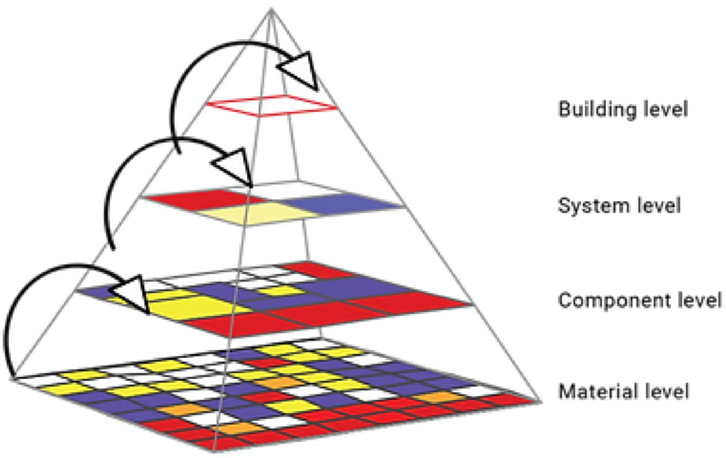


Figure 4.3 Hierarchy of material levels by Durmisevic (2006)

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.

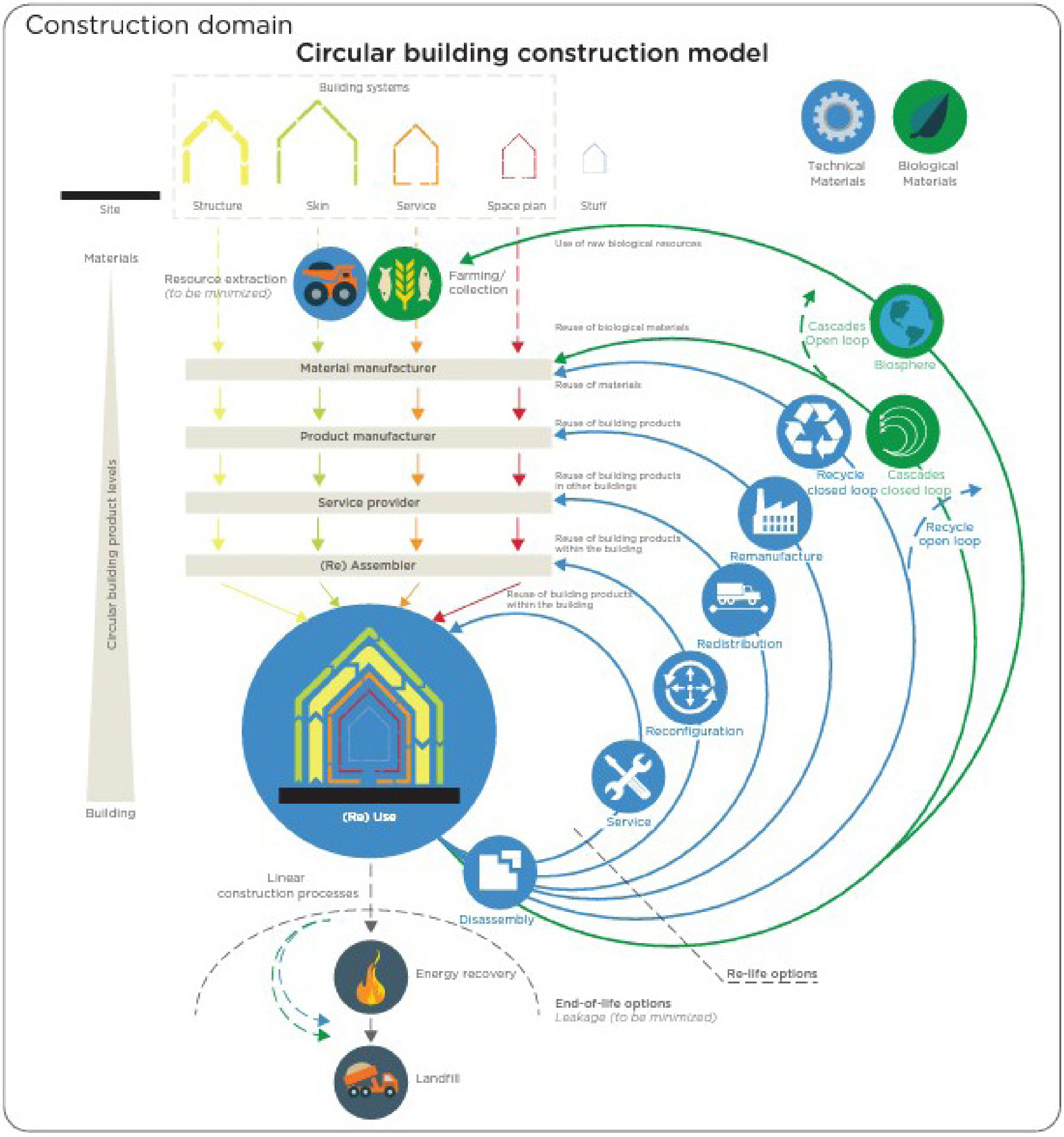


Figure 4.4 Circular construction model by Beurskens and Bakx (2015).

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.

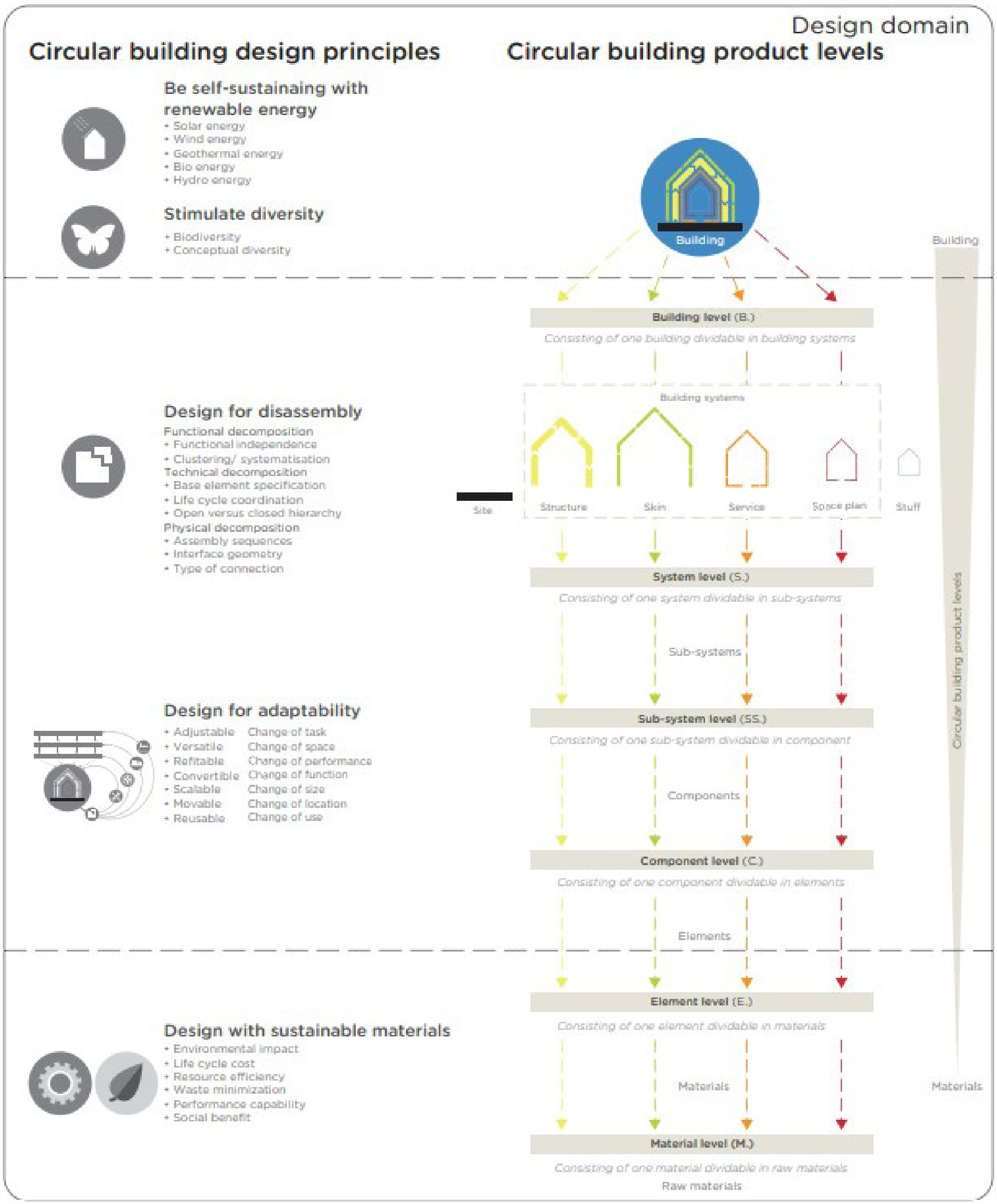


Figure 4.5 Circular building design principles by Beurskens and Bakx (2015).

The following Dfd factors affecting the potential for disassembly of a product from Durmisevic (2006) and Beurskens and Bakx (2015) are outlined:

Functional factors

1. Functional Separation: Ensuring clear separation of functions within the building components to facilitate disassembly and reuse.
2. Functional Dependence: Understanding the interdependencies between different components and their functions to facilitate efficient disassembly.
3. Structure of Material Levels: Considering the hierarchical structure of building materials, systems, and components to optimize disassembly.
4. Clustering: Grouping related components to simplify disassembly processes and enhance material recovery.

Technical Decomposition:

1. Base Element Specification: Specifying standardized base elements that can be easily separated and reused.
2. Type of Relational Pattern: Selecting appropriate connection types and patterns to enable disassembly without compromising structural integrity.
3. Technical Life Cycle/Coordination: Considering the lifespan of components and coordinating their replacement or maintenance activities.
4. Life Cycle of Components and Elements in Relation to Size: Considering the varying life cycles of building components and elements based on their sizes.

Should I explain all the factors or just list them?

Physical Decomposition:

9. Assembly Direction based on Assembly Type: Determining the optimal direction of assembly to facilitate future disassembly.
10. Assembly Sequences regarding Material Levels: Planning assembly sequences to align with the hierarchical structure of building materials and components.
11. Geometry of Product Edge: Designing product edges that allow for easy disassembly and minimize material damage.
12. Standardization of Product Edge: Promoting standardized dimensions and interfaces for improved compatibility and disassembly efficiency.
13. Type of Connection: Selecting connection methods that allow for easy disassembly and reassembly.
14. Accessibility to Fixings and Intermediary: Ensuring accessibility to fasteners and intermediaries to simplify disassembly.
15. Tolerance: Incorporating appropriate tolerances to accommodate variations and ease disassembly.
16. Morphology of Joints: Designing joints that facilitate disassembly and minimize material loss or damage.

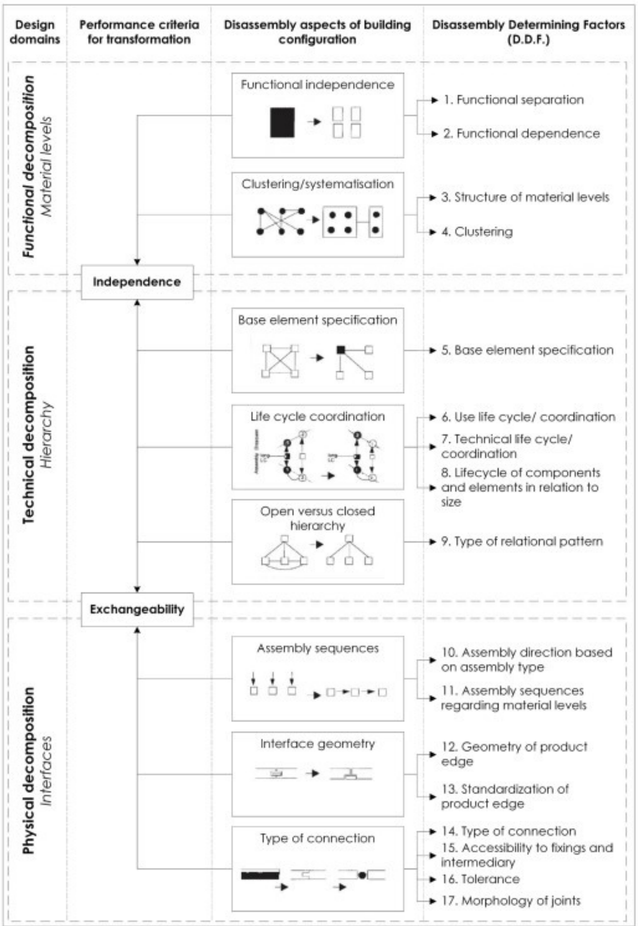


Figure 4.6 Transformation Capacity Scheme. Image by Durmisevic (2006).

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.

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 compo-

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." These factors are represented in the Disassembly Map using "action blocks," which are positioned next to the line connecting the component circles. See figure 3.# for a better interpretation of the action blocks. The author applies methods such as MOST, the eDiM method, and Kroll's evaluation chart to determine these factors and time estimates.

Is this necessary?

					Disassembly				Assembly				Total tool time
	Force intensity	Fastener type	Tool	Action block representation	Tool Change Time (s)	Tool Positioning Time (s)	Tool action Time (s)	Disassembly Total Time (s)	Tool Change Time (s)	Tool Positioning Time (s)	Tool action Time (s)	Reassembly Total Time (s)	Total Operation Time (s)
Single motion disassembly action	Force < 5N	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	1,8 s	0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	1,8 s	3,6 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	3,2 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	3,2 s	6,4 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	1,8 s	0,0 s	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	1,8 s	3,6 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s L_1	3,2 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	0,4 s F_1	3,2 s	6,4 s
	5N < Force < 20N	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	2,5 s	0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	2,5 s	5s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	3,9 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	3,9 s	7,8 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	2,5 s	0,0 s	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	2,5 s	5s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s L_3	3,9 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	1,1 s F_3	3,9 s	7,8 s
	20N < Force	Snap fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	4,7 s	0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	4,7 s	9,4 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	6,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	6,1 s	12,2 s
		Friction fit	Hand		0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	4,7 s	0,0 s	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	4,7 s	9,4 s
			Spudger		1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s L_6	6,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	1,4 s $A_1B_0P_3A_0$	2,2 s F_6	6,1 s	12,2 s
Multiple motion	9 wrist turns	Screw	Screw-driver		1,4 s $A_1B_0G_1+A_1B_0P_1$	2,5 s $A_1B_0P_6A_0$	7,2 s $L_{16}+A_1B_0G_1+A_1B_0P_1$	11,1 s	1,4 s $A_1B_0G_1+A_1B_0P_1$	2,5 s $A_1B_0P_6A_0$	2,2 s F_6	11,1 s	22,2 s

Figure 4.7 Overview of the action blocks and their corresponding disassembly/assembly times. Image by De Fazio et al. (2021)

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 4.8 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 expanded in the legend:

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

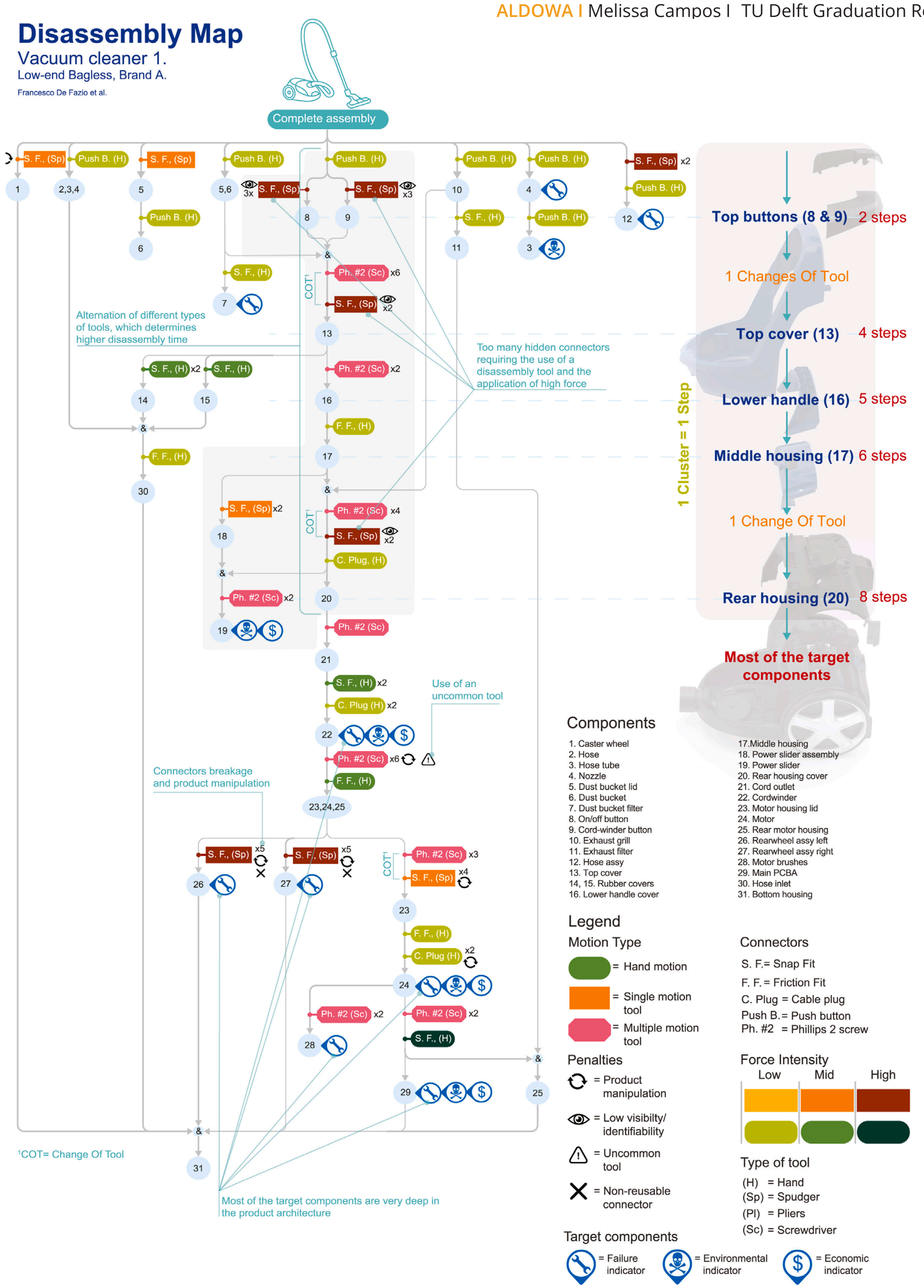


Figure 4.8 Disassembly Map of the redesigned vacuum cleaner. Image by De Fazio et al. (2021)

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.

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.

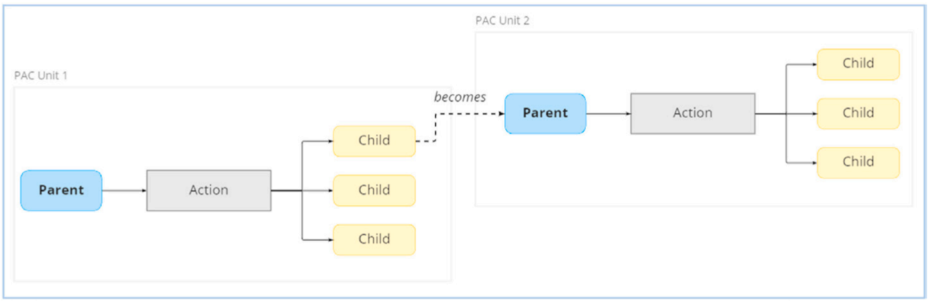


Figure 4.9 Template for the Parent- Action-Child (PAC) model. Image by Formentini and Ramanujan (2023).

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)

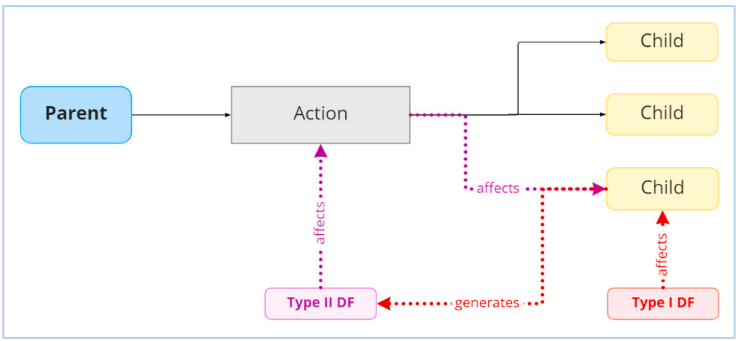


Figure 4.10 Example of Type I and Type II Disassembly Failure. Image by Formentini and Ramanujan (2023).

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 4.11 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

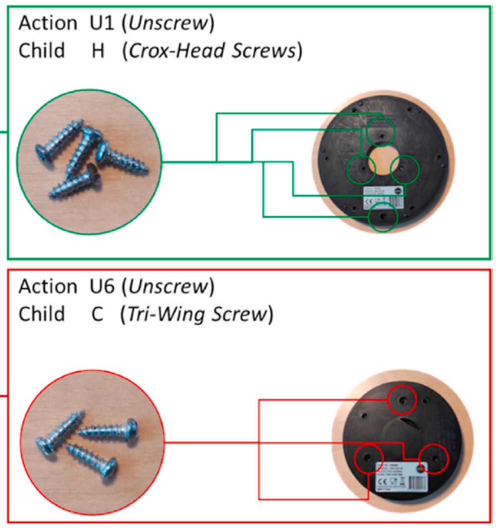


Figure 4.11 Assessing DEI (Design effort index) score depending on the disassembly failure. Image by Formentini and Ramanujan (2023).

Results

The final PAC model results in an excel sheet such as Figure 4.12 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 4.12: 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 Methodology to assess Design for Disassembly

Based on the previous literature and the Cradle to Cradle requirements for DfD from chapter 1, the following methodology to assess the disassembly potential of the cassette panel can be implemented:

Cradle to Cradle	Requirements	Dfd Assessment Instructions
Disassembly	Fewer fasteners	Count number of fasteners
	Decreased number of disassembly operations	Count number of operations
	Elimination of destructive processes	Count number of destructive processes
	Minimized the tools needed to disassemble the product	Count number of tools needed
	Use of detachable/resolvable fasteners	Calculate the detachability index used by the BCI
	Full accessibility to critical parts	
	Increased automation of disassembly	Review the assessment at the end and improve design
	New feature	Identify the disassembly penalties • Product manipulation • Low visibility/identifiability • Uncommon tool • Non-reusable connector
		Identify possible disassembly failure scenarios
		Identify possible end of service scenarios
Instructions	A description of each step in the disassembly operation	Elaborate a disassembly sequence according to the visualization options with a description of each step
	How to access components and parts	
	Identification of parts and components	Identify parts and assemblies
		Identify target components 1. High failure/functional importance 2. High embodied environmental impact 3. High economic value
	The type of connectors involved	Identify type of connection
	Tools required for each step	Identify tools and corresponding actions needed
	Accompanying audio or visual instructions or diagrams (e.g., disassembly precedence graph, disassembly tree, state diagram, hypergraph)	Visualization options: - Disassembly map tree - PAC model flow chart - 2D Assembly drawings - 3D Exploded image

DfD Assessment

1. Build a disassembly sequence

1.1 Data needed

1. Assembly drawings
2. Product passport
3. IFC file

1.2 Categorize assemblies, parts and actions

To categorize them use these definitions:

Assembly - It is a group of parts

Part - elementary item of an assembly and cannot be disassembled (Example: a screw)

Use the product ID from Aldowa's data base.

1.3 Identify target components that have the following characteristics:

- High failure risk and functional importance
- High embodied environmental impact
- High economic value

1.4 Indicate a potential End of Service (EoS) scenario for each component assuming the part is in good state after use.

Table 1.1 Assembly and parts identification

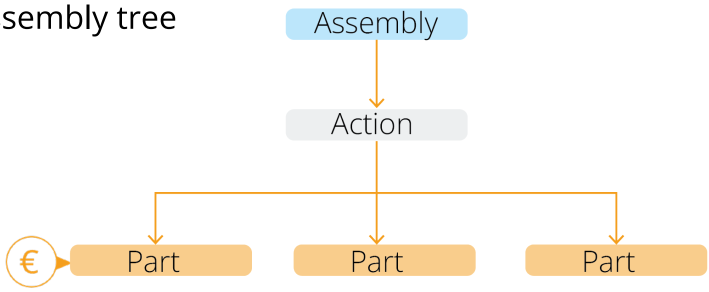
Assembly	Parts	ID	Target component	Potential EoS scenario
ID	Name/ description	Part ID	Yes/No	Reuse
	Name/ description	Part ID	Yes/No	Recycle
	Name/ description	Part ID	Yes/No	Remanufacture
	Name/ description	Part ID	Yes/No	Refurbish

1.5 Rules to create a sequence of operations

- An assembly can only be subjected to one action.
- An assembly subjected to an action can generate one or more parts.
- A set of "assembly - action - part" elements creates a Unit, and represents a complete disassembly cell, in terms of disassembly action and parts.
- Within a Unit, parts represent the final outcome. They cannot be subjected to any further disassembly action.
- When it is desired to further disassemble a part, the select part needs to be transformed into an assembly and initiate a new part unit
- The transformation of a part into an assembly is performed by expressing the will to further disassembly the selected part.
- Assembly, parts and actions have different colors

Example of sequences can be the following disassembly trees:
1. Horizontal disassembly tree

2. Vertical disassembly tree



1.6 Identify the connections
- Record the action and corresponding tools needed to disassemble it.
- Record if any disassembly penalties occur

Table 1.2 Connections Identification

Disassembly Action	Tool needed	Disassembly Penalties		
		Low visibility	Uncommon tool	Reusable connector
Unscrew	screw driver	Yes/No	Yes/No	Yes/No
Name/ description	Name			
Name/ description	Name			

2. Assess detachability

2.1 Assess the following categories based on the BCI detachability score:

1. Type of connection
2. Part's Accessibility
3. Assembly's Accessibility
4. Crossings

The score tables can be found in Chapter 3. Where 0 is completely linear and 1 completely circular.

Table 2.1 Type of connection detachability rating

Disassembly Action	Type of connection
Unscrew	1
Name/ description	
Name/ description	
Total score	#

Table 2.2 Additional detachability rating

Part ID	Accessibility	Crossing Form	Containment	Total score
Part ID	0.8	0.2	1	2
Part ID				
Part ID				
Part ID				

3. Assess sequence

3.1 Fill in the following information

Number of fasteners used ______________

Number of actions in the sequence ______________

Number of destructive processes ______________

Number of tools needed ______________

4. Failure scenario

4.1 Forecast a possible failure scenario (FS) for the target components and indicate which EoS scenario would apply for that case

Table 4.1 Failure Scenario

Assembly	Parts	ID	FS 1	Potential EoS scenario
ID	Name/ description	Part ID		Reuse
	Name/ description	Part ID		Recycle
	Name/ description	Part ID		Remanufacture
	Name/ description	Part ID		Refurbish

4.2 Rewrite the previous sequence by taking into account the following:

- Which failure(s) has the biggest probability to occur?
- How would that change the sequence of disassembly?

4.3 Assess the new sequence again:

Number of fasteners used ________________
Number of actions in the sequence ________________
Number of destructive processes ________________
Number of tools needed ________________

Explain more the FS

5. Improve design

5.1 Reflect on the following questions to improve the design?

- How can the disassembly penalties be eliminated?
- How can the detechability index become more circular? Which connections rate the lowest and how can they be improved?
- How can you reduce the actions of the sequence?
- How can you reduce the amount of fasteners?
- How can you replace the destructive processes?
- How can you standardize the connections to reduce the amount of tools?

4.6 Conclusions of Chapter 4

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, two additional frameworks, namely the PAC Model and Disassembly Map, attempt to account for real-life scenarios. These frameworks propose disassembly sequences that identify components, 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.

Based on the research from this and previous chapters, a design for disassembly assessment is proposed to evaluate the disassembly potential of the cassette panel. This assessment has to be first tested to evaluate its usefulness in a real life scenario.

add recommendations about what to include in the product passport?

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:

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 material in the Earth's crust but requires significant energy for extraction and processing (European Aluminium, 2020). Aluminium is 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).

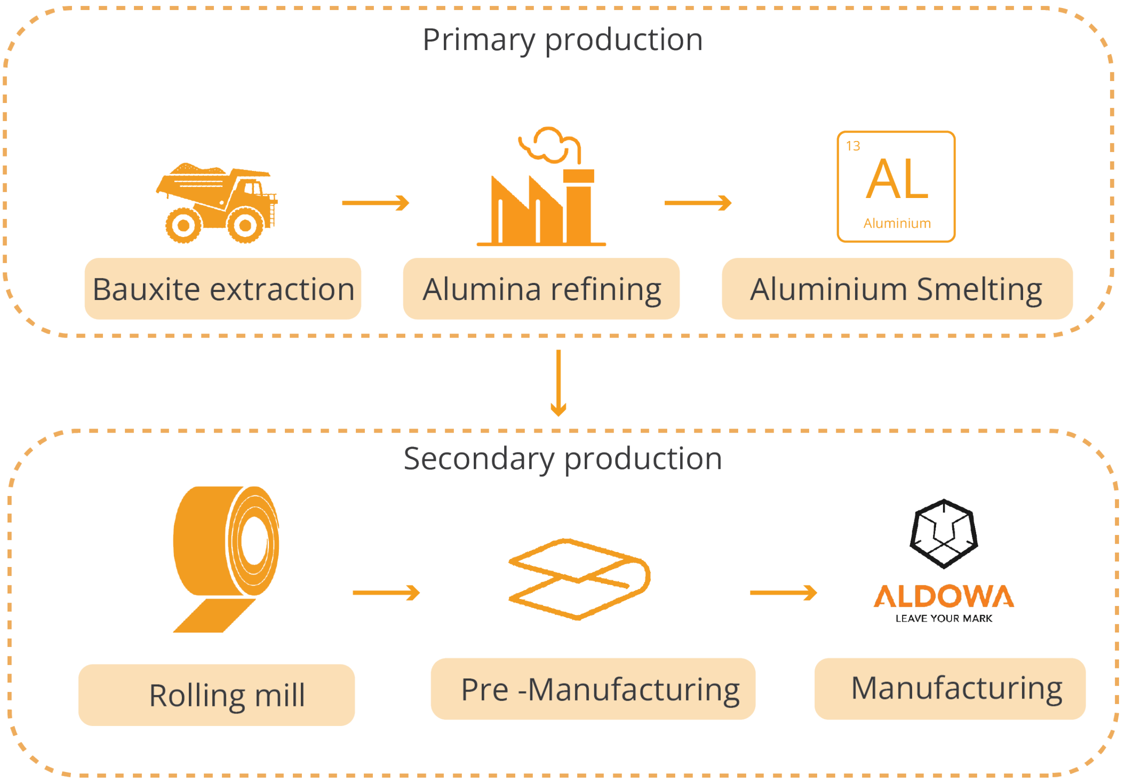


Figure 5.1 Aluminium primary process (Image by author)

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 100 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.

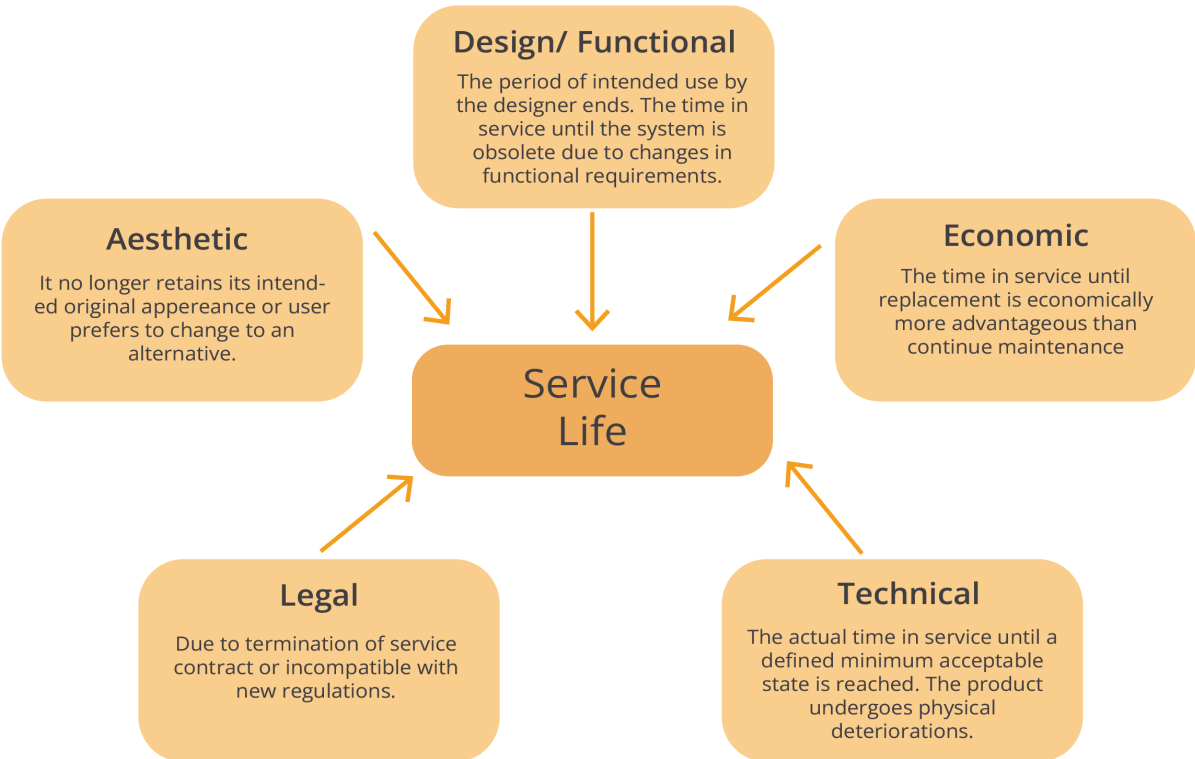


Figure 5.2 Factors affecting service life . Image adapted from Hartwell and Overend (2020) and Cooper (2014)

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.

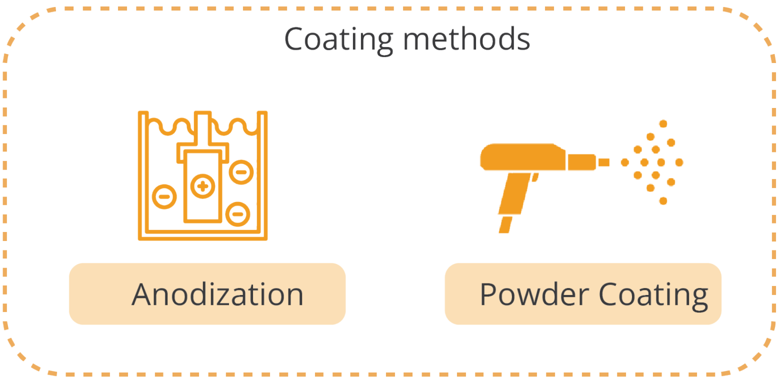


Figure 5.3 Coating methods (Image by author)

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. 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 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.

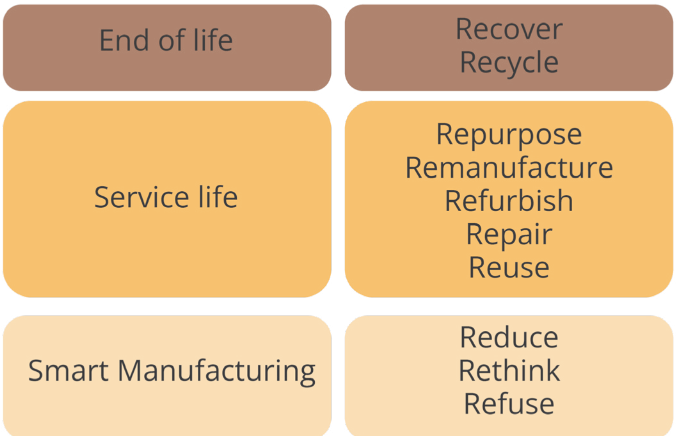


Figure 5.4 R-strategies.
Image adapted by author based on CircularX: Circular Economy - an Introduction. TU Delft online course

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. In the construction sector, Gorgolewski et al. (2006) conducted an assessment of structural section reuse in Canada, revealing that although the steel possesses good mechanical properties, limited reuse (approximately 10%) is observed due to uncertainties regarding its origin and a lack of available stock.

Opportunities

In his PhD thesis, Cooper (2014) focuses on the potential for reuse of steel and aluminium components without melting them. Through an extensive investigation involving product descriptions and interviews with industry experts, Cooper's research draws upon a comprehensive review of academic and company literature. 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:
    a. Several authors have noted the difficulty of disassembling products or buildings without causing damage to potentially reusable components.
2. Unknown properties of reclaimed parts:
    a. The lack of demand for reclaimed components is attributed to the uncertainty surrounding their properties and performance. Mechanical testing is required to determine its current strength and ductile properties and chemical testing for its welding properties. However, these tests are expensive for a practical use.
3. Obsolescence of reclaimed parts:
    a. Products that undergo rapid technological advancements face challenges in finding buyers for older, obsolete components, resulting in reduced demand.
    b. 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 component passport with the information stated above is necessary to control its service status. 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 manufacturer should offer trade-in and refurbishment programs to increase its profits. Three models are presented:

1. No program
2. Trade in program only
3. Trade in and refurbishment

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) [source].

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.

Based on the research of Hu et al. (2023) a company can opt for a trade in and refurbishment program if it meets the following criteria:

- Manufacturers with the best control over their new product's production costs
- Manufacturers with moderate production costs of their new products

Furthermore, if the manufacturer implements a refurbishment program then his profit decreases when the cost of refurbishment goes up, but it will increase when the rate of successfully restoring the quality of refurbished products improves (Hu et al.,2023) .

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.

Overall, refurbishment allows manufacturers to extend the lifespan of their existing products and obtain similar performance and functionality while still profiting. It opens the door to a new market for those who may not be able to afford brand-new products or are looking for more sustainable products.

Challenges

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

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.

Management Challenge:

1. 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.
2. 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.

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.

add swap fiets fail scenario

Conclusions

Refurbishment is a compatible cycling pathway for the cassette panel because it 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 considering the following technical factors to determine the suitability of a product for re-manufacturing:

1. **Regeneration rate:** The ratio of products brought into the re-manufacturing process to the number of products and components successfully re-manufactured.
2. **Technical effort and complexity:** The level of effort and complexity required to complete the process of re-manufacturing.
3. **Product usage time per life cycle:** The longer the product's life cycle, 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 CO2 emissions and mitigating environmental impacts.
4. **Cost savings:** Remanufacturing offers substantial cost advantages. It can provide production cost savings of 20-80% when compared to conventional manufacturing methods (Ijomah & Chiodo, 2010). By utilizing used components and bypassing resource-intensive processes, remanufacturing reduces production costs and enhances overall profitability.
5. **Landfill and pollution reduction:** Remanufacturing helps divert a significant portion of production waste from landfills. This not only reduces pollution associated with landfills but also helps alleviate the pressure on limited landfill space. By extending the lifespan of products through remanufacturing, the overall environmental impact is reduced.

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. Speed and cost of disassembly also affects the potential of a product to be remanufactured.
2. **Limited availability of core products:** Remanufacturing requires a steady supply of used products or components, commonly referred to as "cores." If there is a scarcity of cores in the market or difficulty in obtaining them, it becomes a significant barrier to scaling up re-manufacturing operations.
3. **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. The façade manufacturer is not always directly in contact with the client.
4. **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. In worse cases, consumers may not be aware of the benefits of remanufactured building products or may have misconceptions about their quality.
5. **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
6. **Lifespan of building products:** 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.
7. **Regulatory and legal considerations:** Compliance with regulations related to product warranties, labeling, and safety can pose challenges for remanufacturers. Ensuring that remanufactured products meet all relevant legal requirements adds complexity and may require additional resources.

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. According to Ijomah and Chiodo (2010) re-manufacturing general technical guidelines are, "the minimization of damage to parts to be re-used and isolation of expected damage to removable and replaceable parts."

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 these guidelines 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).
A meeting was arranged with Lars, the representative from Roba, one of Aldowa's primary suppliers of aluminum, to explore the potential for establishing a closed cycle. 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.

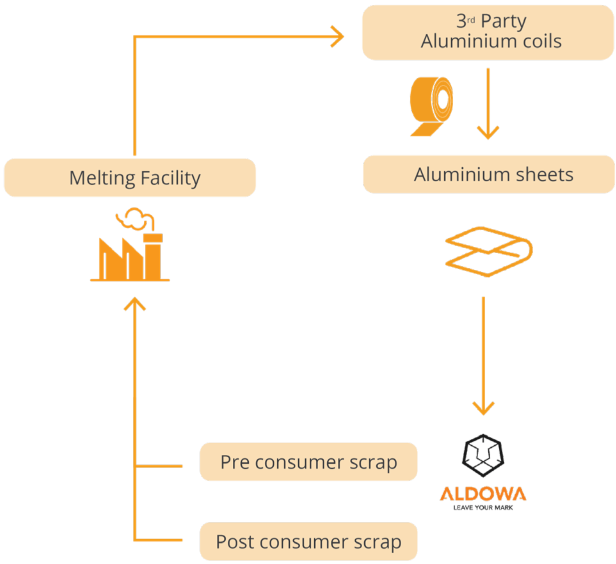


Figure 5.5 Possible recycling scenario with Roba (Image by author)

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.
6. **Infrastructure and Capacity:** As the demand for recycling larger volumes of post-consumer aluminium increases, investment in infrastructure is necessary to maintain high recycling rates and ensure high-quality output.

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. Discussions with Roba are still taking place to plan a future strategy.

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.

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 cassette panels lack modular or standard connections in their cassette panels. 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.

Post-disassembly plan

By taking into account the criteria for each cycling pathway a future cycling plan for a circular cassette panel has been mapped out in Figure 5.6.

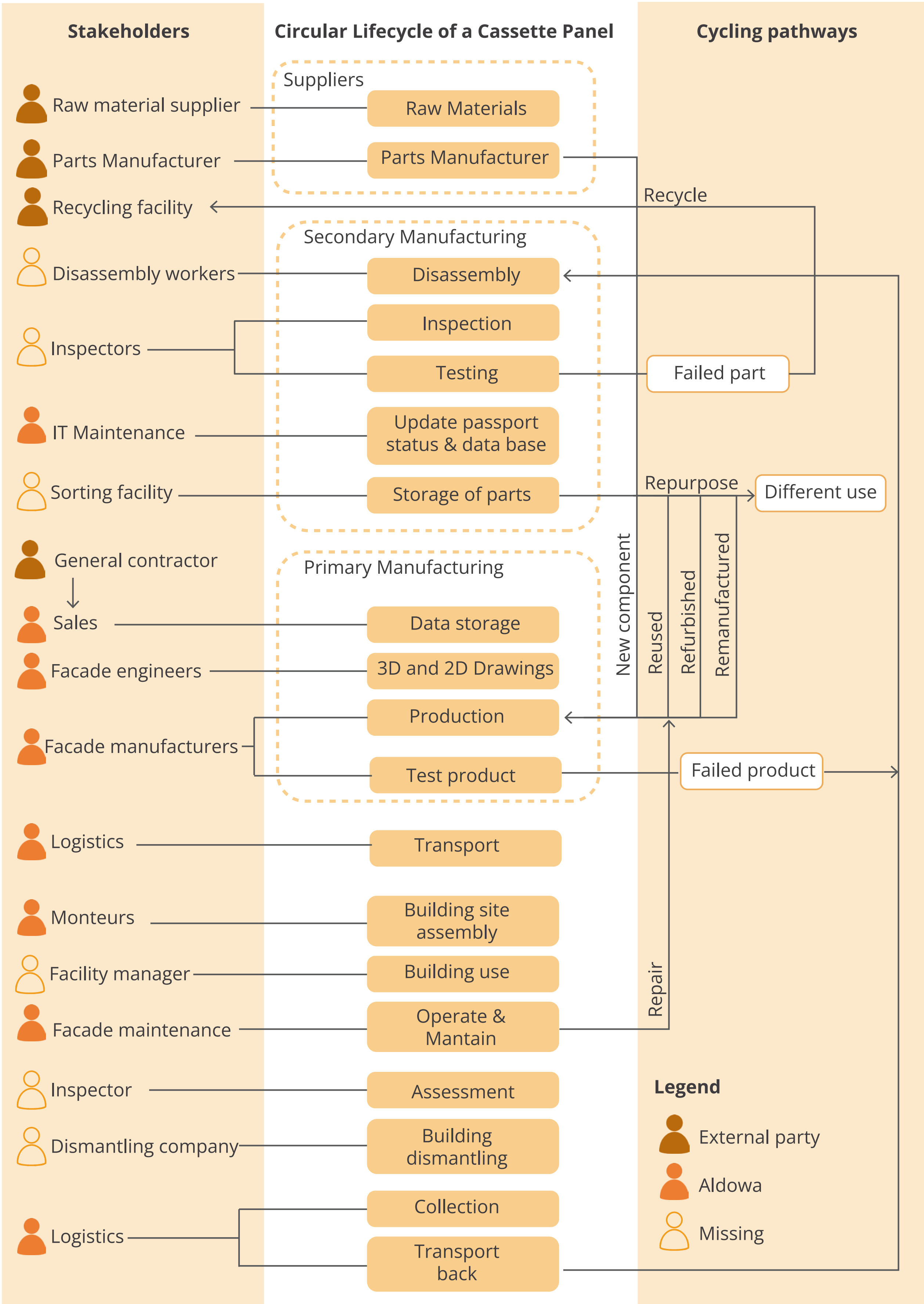


Figure 5.6. Cycling plan of a circular cassette panel (Image by author)

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 different, various cycling pathways were analyzed and the opportunities and challenges of case studies implementing those cycling pathways were summarized. 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

By considering these strategies, a post-disassembly plan was proposed to address the missing stakeholders, steps, and procedures in the production process and life cycle of a cassette panel that require integration.

06.

Company Analysis

text text text

List of Figures:

6.1 About Aldowa

6.2 Cassette panel overview

6.3 Case Study

0#.

Bibliography

text text text