REUSE OF SECONDARY MATERIALS

Enabling and Assessing 'Reuse of Secondary Materials' as a Circular Approach for the Façade Industry

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Circular Economy is not about closing loops of volume, but about closing loops of value.

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Abstract

Over the years, the extraction and consumption of raw materials have increased radically, with a 60% increase since 1980. About one-fifth of the material extracted worldwide ends up as waste, corresponding to 12 billion tonnes (Gt) of waste per year. To tackle the increasing consumption and waste in the economy, the Netherlands government introduced the 'Circular Netherlands in 2050' plan in 2016, aiming to reduce 50% consumption of primary resources by 2030 and 100% by 2050. As a result, 95% of the secondary materials from the end-of-service-life demolition process of commercial and non-residential buildings in the Netherlands are recycled. However, comparing different R-option on an R-hierarchy model shows a gradual decrease in value retention of the material with recycling. The research focuses on shifting the facade industry from recycling to reuse by moving up the ladder to retain a higher material value. The thesis explores the research question through design research to support the strategic design and development for reusing secondary materials.

Two cases, ODS Jansen and Buurman, are analyzed for their secondary material flow of steel and timber, respectively, through interviews and inventory analysis. A reuse process is systemized and further elaborated on stakeholders' role (what, how, and when) to support it. A set of design explorations for facades is done to identify potential scenarios for reuse, considering the functional and technical factors that define office building facades in the Netherlands. The proposed hybrid system using the primary and secondary material stream is compared to an alternate non-reuse scenario. The assessment presented a 60% restorative material flow with the MCI score and a saving of 91% for embodied energy (renewable and non-renewable) and 93% for Global Warming Potential with LCIA with reuse of steel mullions in the curtain wall facade.

The research concludes that the reuse of materials for the same function is feasible through R-strategies of direct reuse, repair, refurbish, and remanufacture as long as the embodied value of the material does not change. Furthermore, it is essential to match the demand and supply of secondary materials for establishing the reuse practice at an industrial scale. For this, original material suppliers must take up the role of material resellers in the market. At the same time, manufacturers and architects need to shift their mindset from use of abundant to 'scarce' resources by altering the design process with the three stages of material sourcing, material processing, and material reuse. Sufficient safety margins in design, material inspectors to overcome lack of information, working with the form of supply, changing design habits, and using materials differently are proposed as design solutions to organize the reuse of materials for facades. Lastly, when the existing materials decline, reuse will happen through materials entering the market now. It is essential to consider their design for future reuse to ensure this flow does not face the same set of challenges.

Key Words: Circularity, Reuse, Residual Material Value, Reuse Process, Stakeholders to Support Reuse Process, Design for Reuse, Reuse of Curtain wall facades, Circular Value of Reuse, Environmental Impact of Reuse

The facade of EU Council Headquarters in Brussels has an outer skin patchwork of recycled old oak windows in single glazing from demolition sites and an inner skin of double glazing.

https://worldarchitecture.org/articles/cgmcc/eu_headquarters_facade_is_made_of_harmonised_patchwork_of_oak_windows_and_crystal_like_glazing.html

Contents

Abbreviations

C&DW - Construction and Demolition Waste

CE - Circular Economy

EMF - Ellen MacArthur Foundation

WFD - Waste Framework Directive

EOU - End of Use

EOL - End of Life

EO(s)L - End of Service Life

EOW - End of Waste

DfD - Design for Disassembly

LCA - Life Cycle Assessment

LCIA - Life Cycle Impact Assessment

MCI - Material Circularity Indicator

PERE - Primary Renewable Energy

PENRE - Primary Non-Renewable energy

GWP - Global Warming Potential

VAT - Value Added Tax

Glossary

Background Process - The processes on which indirect influence may be exercised by the decision-maker for which an LCA is carried out.

Cradle-to-gate - An assessment that includes part of the product's life cycle, including material acquisition through the production of the studied product and excluding the use or end-of-life stages. (WRI and WBCSD 2010)

Cradle-to-grave - The assessment considers impacts at each stage of a product's life cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal. (Athena Institute & National Renewable Energy Laboratory draft 2010)

End of Life - It is the period specified by the industry for which an element can perform as required for its designated function.

End of Service Life - It is the period for which a product assembly can be used according to the manufacturer's expectations.

End of Use - When a product is no longer required by the user and reaches a premature end of use.

Foreground Process - The foreground processes are under the control of the decision-maker for which an LCA is carried out.

Life Cycle - Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. *(ISO 2006)*

Life Cycle Assessment - Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Impact Assessment - Phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. *(ISO 2006)*

kgCO2eq. - Metric measure to compare emissions from green house gases on the basis of their Global Warming Potential.

Supply Chain - A supply chain is a system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer.

System boundary - Set of criteria specifying which unit processes are part of a product system. (ISO 2006)

Value Chain - A value chain is a high- level model describing the activities that a firm operating in a specific industry conducts to receive raw materials as input, add value to the raw materials through various processes, and deliver finished products to customers.

01.

INTRODUCTION

The chapter introduces the design outline of the presented research, including background, problem statement, objectives, research question, design question, methodology, and relevance.

1. INTRODUCTION

1.1 Background

Over the years, the extraction and consumption of raw materials have increased radically, with a 60% increase since 1980 (OECD, 2012). About one-fifth of the material extracted worldwide ends up as waste, corresponding to 12 billion tonnes (Gt) of waste per year (ibid.). The dependence on raw materials is further projected to double by 2060 (OECD, 2018), and annual waste generation is expected to reach 70% by 2050 (World Bank, 2018). It has resulted from an increase in living standards due to an expansion of the global economy. The increase in energy for extraction and processing of raw materials is likely to worsen air, water, and soil pollution and contribute significantly to climate change (OECD, 2018) through high levels of CO2 emissions.

The high levels of waste and increased dependency of the economy on the input of virgin materials result from the current linear model of take-make-dispose based on consumption, which entails significant losses of value all along the material flow chain (EMF, 2013). Thus, to reduce the pressure on the existing natural resources, there is an ongoing transition worldwide to a restorative model of a circular economy for efficient material supply security and improved environmental and economic outcomes. As defined by Ellen MacArthur Foundation (2013), a Circular economy is focused on “decoupling economic activity from the consumption of finite resources, and designing waste out of the system.” The model distinguishes between technical and biological cycles. The biological materials are designed to feedback into regenerative living systems while technical cycles recover and restore products, components, and materials through reuse, repair, or recycle (ibid.).

Built environment

According to OECD (2018) claims, the consumption of materials in the building industry dominates the total resource consumption, as shown in Figure 1. Thus, realizing circular economy goals in the building sector is essential to transition to a full circular resource consumption model. The European Commission has devised a Circular Economy Action Plan (EC2015), which aims at a “waste to resource” transition (European Commission, 2015). Furthermore, an EU Waste Framework Directive (2008/98/EC) has set targets to recycle 70% of its non-hazardous construction and demolition waste (C&DW) by 2020 (Wahlström et al., 2020).

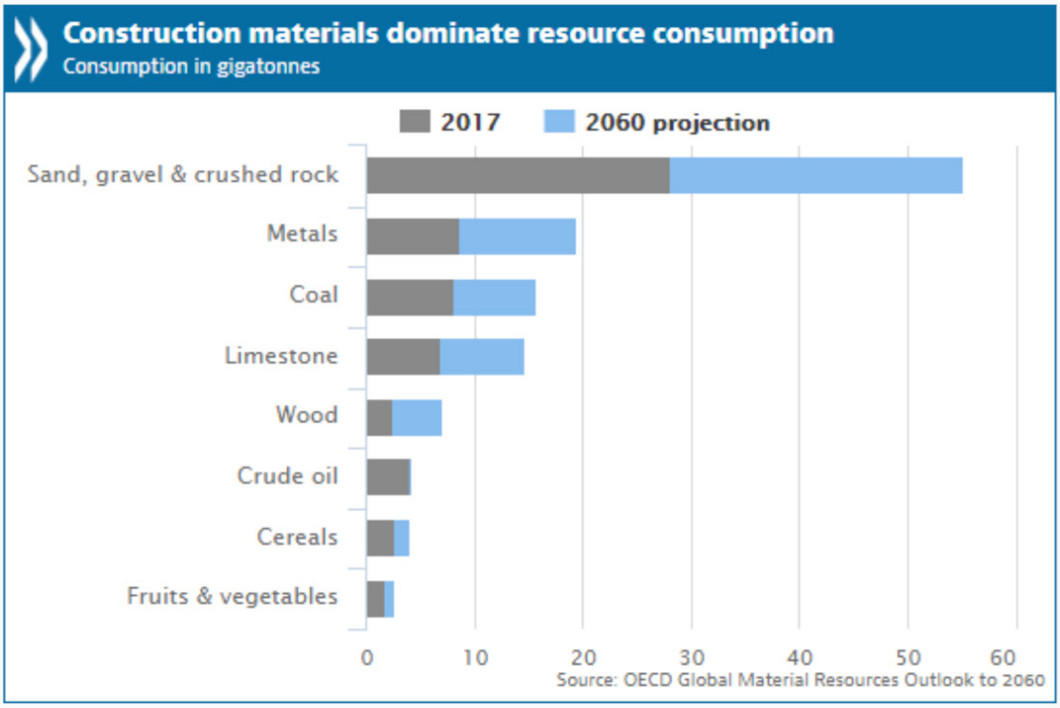


Figure 1 - Projected resource consumption for different materials (source: OECD, 2018)

Circular Economy in the Netherlands

In the Netherlands, the same trend follows for primary material consumption. The construction sector accounts for 50% of all the raw materials used, 40% of the total energy consumed, and 30% of the total water consumed in the country (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016). At the same time, C&DW is the most significant waste stream (40%), with an average volume of approximately 25 million tons (Bio by Deloitte, 2017). It contributes to 35% of the CO2 emissions (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016).

The Netherlands government introduced the 'Circular Netherlands in 2050' plan in 2016, aiming to reduce 50% consumption of primary resources by 2030 and 100% by 2050 (Government of the Netherlands, 2016). The introduction of the National Waste Management Plan (Landelijk Afvalbeheerplan – LAP), EU Waste Framework Directive (2008/98/EC), and a circular resource consumption model has prioritized 'prevention of waste' as one of the goals to achieve circularity objectives in the Netherlands.

1.2 Problem Statement

The buildings that are no longer in their use phase have the usual end-of-life (EOL) scenario of energy recovery or landfill after demolition. According to CBS reports, the share of demolition stock from the residential and non-residential buildings was 10,684 and 4558, respectively, in 2019 in the Netherlands (CBS, 2020). This large volume of building stock can be seen as a potential reservoir of materials and can be mined to provide a secondary resource for new construction (Gorgolewski and Morettin, 2009). According to the reports of the Ministry of Infrastructure and Environment (2016), 95% of the secondary materials from the end-of-service-life (EO(s)L) demolition process of commercial and non-residential buildings are recycled. However, comparing different R-options on an R-heirarchy model used by the Netherlands Government for Waste Management shows a gradual decrease in value retention with recycling. A shift in the focus from recycling to reuse by moving up the ladder can help retain a higher value of secondary materials (Wahlström et al., 2020).

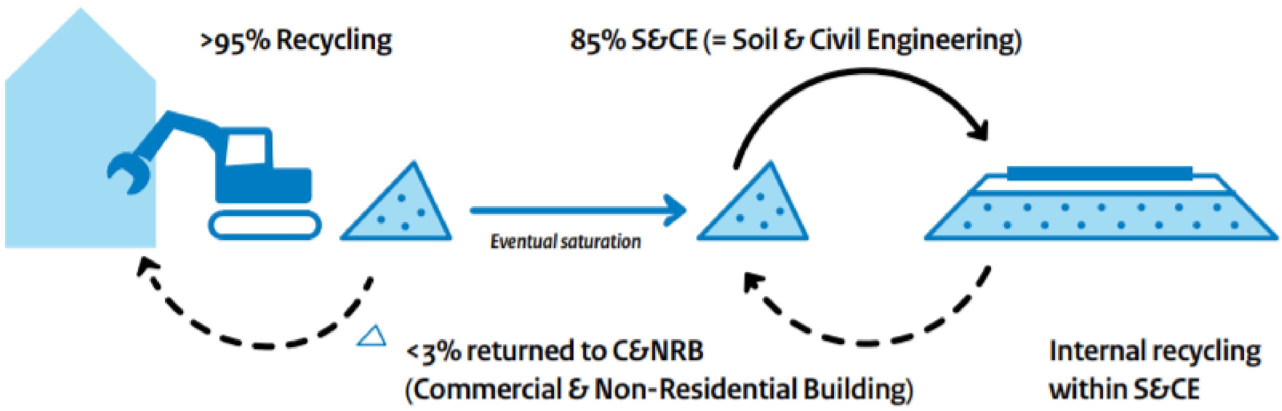


Figure 2 - Recycling of secondary materials in the construction sector (source: Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016)

In the Netherlands, Icibaci (2019) identified over 100 companies working on the harvest and commercialization of reused building products between 2008-2013. However, the reuse of these secondary materials is still limited to 3-4% in the building industry (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2016). The recovered products are not compatible with the new technology and performance standards and cannot compete with the new generation building products. As a result, a large proportion does not make it back to the industry at the same level. The market for secondary materials still has to adapt to develop its higher-grade applications for reuse in products in the building industry.

Building facades are a highly technical component and consist of many materials (Knaack et al., 2014). They account for one-third of the total embodied energy of the building (Hildebrand, 2012). Lack of clearly defined end of service life scenario in place for existing facades (Klein, 2013) often leads to downcycling. It results in a loss of value of materials, components, and products. While the reuse of secondary materials is observed in few projects at a building scale, the practice is not yet investigated at the micro-scale of façades. There lies a potential to reuse secondary materials in the façade industry by preparing them for reuse through innovation and technology in the façade industry.

1.3 Objectives

The main objective of the research is to propose a method to facilitate the reuse of secondary materials from construction and demolition processes in the facade industry. In addition, maintain the circular flow of materials and reduce negative environmental impacts.

The following sub-objectives are formulated to support the research:

1. To understand how R-strategy 'Reuse' affects the circularity of secondary materials.
2. To identify and critically evaluate challenges entailing the reuse of secondary materials in the façade industry.
3. To outline the various stages the facade has to undergo for reuse.
4. To identify the main stakeholders involved in the reuse process and their roles.
5. To identify existing product assessment methods for evaluating the circular value and environmental benefits of reusing secondary materials.

Research Boundaries

Few boundary conditions were set to narrow the scope of the research:

1. Secondary materials can be reused at various scales and various building layers, starting from site to stuff. The scope of this research is limited to its reuse for facades, particularly curtain walls.
2. The research does not delve into product design to reuse facades in the future; instead, it uses existing facades/materials available in the inventory for reuse.
3. The research focuses on the existing materials harvested in the industry and does not focus on new deconstruction methods for reuse.
4. Reuse of secondary materials can be cost-intensive. However, an economic analysis will not be included in this research. The research will only have a general overview of the product's value as the main scope lies within the strategic process design for reuse.

1.4 Research Question

How can secondary materials from construction and demolition processes be reused in the facade industry? Can a reuse process contribute to create a circular value and reduce negative environmental impacts for facades?

The following sub-questions are formulated to support the research:

- SQ1. How does the R-strategy 'Reuse' affect the circularity of secondary materials released from the built environment?
- SQ2. What are the challenges involved in the reuse of secondary materials for designing a facade?
- SQ3. What are the different stages for enabling the reuse of secondary materials for facades?
- SQ4. What are the various stakeholders involved in the reuse process, and how does their role evolve in this system?
- SQ5. What are existing product assessment methods relevant for evaluating the circular value and environmental impact of reuse? Are there any gaps, and if yes, what are those?

1.5 Design Question

How can a circular hybrid steel curtain wall be designed by facade companies reusing the secondary material stream for office buildings in the Netherlands?

The following sub-questions are formulated to support the research:

- SQ1. What constitutes the existing material inventory for the selected case example?
- SQ2. What criteria must be considered to determine the potential scenarios for reusing the secondary materials in curtain walls?
- SQ3. How does the design process change for the curtain wall façade when reusing secondary materials?
- SQ4. What is the circular value of the designed façade?
- SQ5. What is the environmental impact of the designed façade?
- SQ6. How can design solutions be formulated to organize the reuse of secondary material for other cases?

1.6 Expected End Products

The research aims to create a methodology for enabling the reuse of secondary resources through innovation in the facade industry. It will include:

1. Method for enabling the reuse of secondary materials for facades to achieve circularity, including:
    a. Process for reusing secondary materials for facades
    b. Map indicating the stakeholders in the process and their role
2. Design solutions for curtain wall façade reusing secondary materials for the case example of a generic type of office buildings in the Netherlands.
3. Indicators relevant for the assessment of the circular value and environmental impact of 'Reuse.'

1.7 Approach and Methodology

The research is divided into 5 phases: Background Study, Literature Research, Design Research, Discussion, and Conclusion, as shown in Figure 3.

1. **Background Study**

In this stage, background and contextual studies are done on the existing practices to understand the problem in depth. Keywords such as circularity, circular goals, circularity in the building industry, waste in the construction sector, raw materials in the construction sector, and end-of-life building products were done to find research articles, journals, and reports. The study helps in understanding the bigger picture and context of the problem.

2. **Literature Study**

Due to the sheer scale of circularity and its reflection mostly in research papers, a literature study was ongoing throughout the research. After defining a clear problem statement, a literature study was carried out to analyze different topics affecting the main question. It includes parameters relevant for using secondary materials in the facade industry through research on processes, players, and posed challenges. Simultaneously, an analysis of dependencies and functioning of the curtain wall facade system is done to identify the criteria secondary materials need to comply with. Finally, a study on the existing product assessment methods to assess the circular value of reuse and its impact on the environment is done to quantify 'reuse' as a circular strategy.

3. **Design Research**

Field research is undertaken to support the strategic design and development for the reuse of secondary materials through two market cases, ODS Jansen and Buurman. The companies are already involved with reselling secondary materials and components at the end of their service life. They were analyzed for their secondary material flow of steel and timber, respectively, through interviews and inventory analysis. The case example of ODS is further elaborated through a set of structured interviews in their value chain to formulate a reuse process and map the stakeholder network required for its establishment.

A set of design explorations for facades is done to identify potential scenarios for using the identified secondary materials in the inventory of ODS, taking into account the functional and technical factors that define office building facades in the Netherlands. The designed facade reusing secondary materials is then be compared to an alternate non-reuse scenario. The design is evaluated for the circular value of reuse (MCI) and its environmental impact on embodied energy (total renewable and non-renewable primary energy) and carbon emissions (GWP) arising from the reuse of secondary materials.

4. **Discussion**

The objective of the research is to enable reuse of secondary materials for facades. Therefore, the challenges that can arise with the formulated process and mapped stakeholders are discussed to propose opportunities for its acceleration in the market. From the design explorations, the 'Design for reuse' criteria essential for future reuse is recommended. Furthermore, the limitations and strengths of the selected assessment methods are discussed for evaluating 'reuse' as a circular approch.

5. **Bigger Picture and Conclusion**

The research draws a bigger picture specifying how the various actors can take a step towards reuse in the façade industry and relating the research to other building layers. Finally, it is concluded by answering the posed questions.

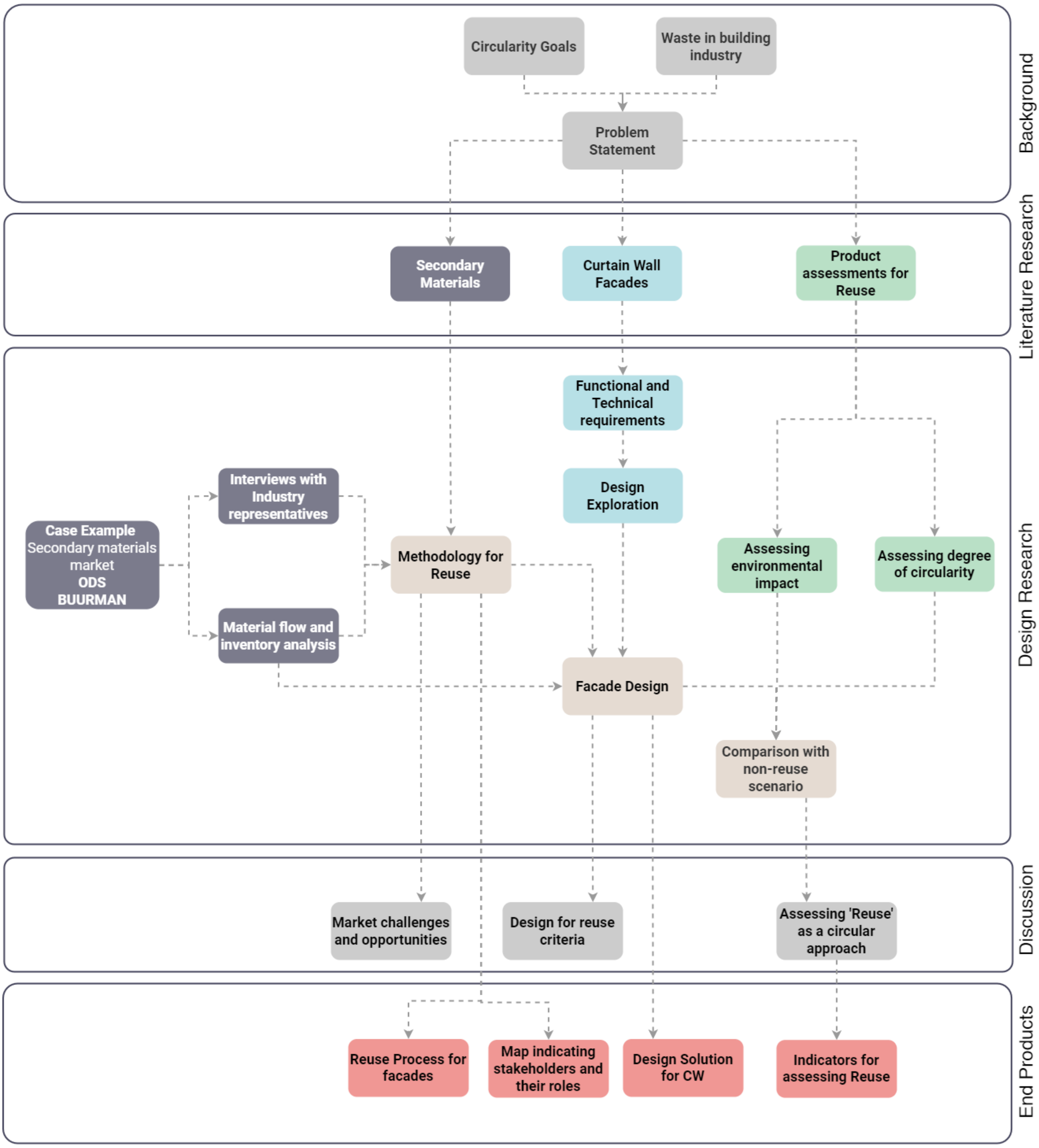


Figure 3 - Flowchart for Research Methodology (source: author)

1.8 Relevance

Scientific Relevance

Recycling is a common strategy for closing material loops at the end of the service life of a material in the building industry. However, it does not retain its functional and embodied value, and closes the loop by creating a new value for the material. The graduation project aims to evaluate 'Reuse of materials' as a circular approach compared to recycling. Reuse enables the use of material by retaining its form, and thus, its embodied value. The building industry has, to some extent, started to focus on reuse as a strategy to achieve the circular goals set by the Government. However, due to its infancy and a lack of an established process, it is only seen in projects initiated with a circular design intent rather than a standard industry practice. As a result, it deviates from the actual problem of inconsiderate material use in the industry. By proposing a method for reuse, the research tries to identify how the practice can be established for the façade industry. In addition, it tries to shed light on the bigger picture of how reuse can be quantified through its degree of circularity and environmental savings.

Societal Relevance

The linear consumption model has increased the demand for raw materials causing severe environmental issues. The demand is even more aggravated in the building industry, where existing resources enter the waste stream after their service life. Reusing existing materials at the end of their service life and designing new materials for future reuse can tackle the existing and future waste problems in society and reduce the dependence on primary materials. While the practice of reusing the existing resources as secondary materials has already started at a building level, it is still a niche scope. This research aims to introduce the circular practice of reusing secondary materials in the façade industry. The conclusion can influence and guide a large audience in the building industry to gradually transition towards reusing secondary materials through a shift in their existing roles in the industry and design methodology.

1.9 Relation to the theme of circularity

The topic of circularity has become relevant over the years to transition towards restorative material use. The circular economy goal of shifting the title of 'waste to resource' and the Netherlands' focus on preventing waste has created a need to look at the current EO(s)L material flow from one industry as a potential resource for another. For the building sector, this means recognizing the existing stocks as material reserves and enabling their reuse in the industry. However, the current linear consumption model shifts the product ownership into the hands of various stakeholders over its lifespan, making it challenging to implement such a model. A circular design entailing the reuse of materials and future reuse then becomes more than a design question. This research is based on design and strategic planning of how such a system can be implemented.

The design process for reusing materials needs consideration regarding material availability, testing, inspection, and assessment. The design which enables future reuse requires research on layers of the product, dependencies of these layers, properties of the material, reversibility of the joints, and potential reuse scenario. These entail a prolonged and collaborative design phase for the product than the current linear practice. The shift in the standard design trajectory can further influence its stakeholders and their existing roles. Therefore, it demands research on materials available, how they influence the design process, and eventually the role of stakeholders.

02.

CIRCULAR ECONOMY

The chapter presents a literature review on circular economy to contextualize the research. It elaborates on the concept of CE and its principles. The Butterfly diagram and R-Hierarchy model are used to analyze the relevance of 'Reuse' as a circular approach. Finally, several business models are discussed for the economic viability of the circular loops.

2. CIRCULAR ECONOMY

2.1 Circular Economy Concept

Circular Economy (CE) emerged as an alternative to the current linear model of consumption based on take-make-dispose to address the economy's natural resource depletion. Even though the transition started in the last decade, the concept of circular economy is not new.

The idea of circular economy has deep-rooted origins and is difficult to trace back to a single author or time. An early foundation to the concept was given by Ayres (1998) in industrial ecology, who observed that the closed cycle of flows stays as long there is a supply of external energy. As a result, there are only two possible ways to close the loop for waste material, recycling/reuse or dissipative loss (Ayres, 1998). McDonough and Braungart (2002) later recognized the importance of closing the "technical" and "biological" loop in a "cradle to cradle" approach. The Ellen MacArthur Foundation (EMF) further built on this and introduced the concept of Circular Economy in 2010. Even though EMF is not the founder of the concept, their contribution is highly valued for accelerating the transition towards a circular economy. The definition of Circular Economy proposed by EMF (2013) is as follows:

> *"A circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design." (EMF, 2013)*

Kirchherr et al. (2017) identified 114 different circular economy definitions in their research. They synthesized the concept of CE as "an economic system that based on models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials to accomplish sustainable development." Both the definitions emphasize the need to change the usual 'end of life' concept with a restorative system that keeps the material in the loop. The three main theories of this idea include designing out waste and pollution, keeping products and materials in use, and regenerate natural systems (EMF, 2013).

2.2 The Principles of Circular Economy

According to EMF (2013), the circular economy concept is based on five principles – design out waste, build resilience through diversity, rely on energy from renewable sources, think in systems, and waste is food. These are summarised below (EMF, 2013):

1. **Design out waste** - "Waste does not exist when the biological and technical components (or 'nutrients') of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and refurbishment." It ensures a high utility of the components at the EOL through its design.
2. **Build resilience through diversity** - "Diverse systems with multiple connections and scales are more resilient in the face of external shocks than systems built simply for efficiency." It refers to prioritizing modularity, versatility, and adaptivity.
3. **Rely on energy from renewable sources** - "Systems should ultimately aim to run on renewable resources, enabled by the reduced energy threshold levels required by a restorative circular economy."
4. **Think in 'systems'** - "The ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts." It refers to a non-linear system where feedbacks lead to multiple consequences and outcomes.
5. **Waste is food** - Using existing materials already out in the chain as a resource for the next cycle eliminates waste from the current system. "On the biological nutrient side, the ability to reintroduce products and materials back into the biosphere through non-toxic, restorative loops is at the heart of the idea. On the technical nutrient side, improvements in quality are also possible; this is called upcycling."

2.3 The Butterfly Diagram by EMF

EMF (2013) proposed the Butterfly Diagram modeled based on living systems that are adaptable, resilient, and model 'waste is food' relation. The materials categorized as nutrients are distinguished based on the cycle they return to rather than their origin, as shown in Figure 4. The biological nutrients are least toxic and can be fed back into the biosphere directly or through cascade reuse. On the other hand, the technical nutrients cannot be fed back into the biosphere and are kept in the cycle as high quality and value as per different strategies. These strategies can be maintenance, prolong, reuse, redistribute, refurbish, remanufacture, and recycle (EMF, 2013).

1. **Maintenance/Prolong** - It is a strategy of keeping products and materials in use by prolonging their lifespan through design for durability as well as maintenance and repair.
2. **Reuse/Redistribution** - It refers to reusing materials and products multiple times and redistributing to new users with little or no enhancement.
3. **Refurbish** - A process of returning the product to good working condition by replacing or repairing faulty components.
4. **Remanufacture** - The product is disassembled to component level and rebuilt to as-new condition.
5. **Recycling** - It is the process of reducing a product back to its basic material level, allowing the materials to be remade into new products.

According to EMF (2013), the tighter the circle, the lesser changes the product has to undergo for reuse, refurbishment, and remanufacturing. Therefore, it makes it faster to return for use again, leading to higher savings on energy, material, and labor in the process.

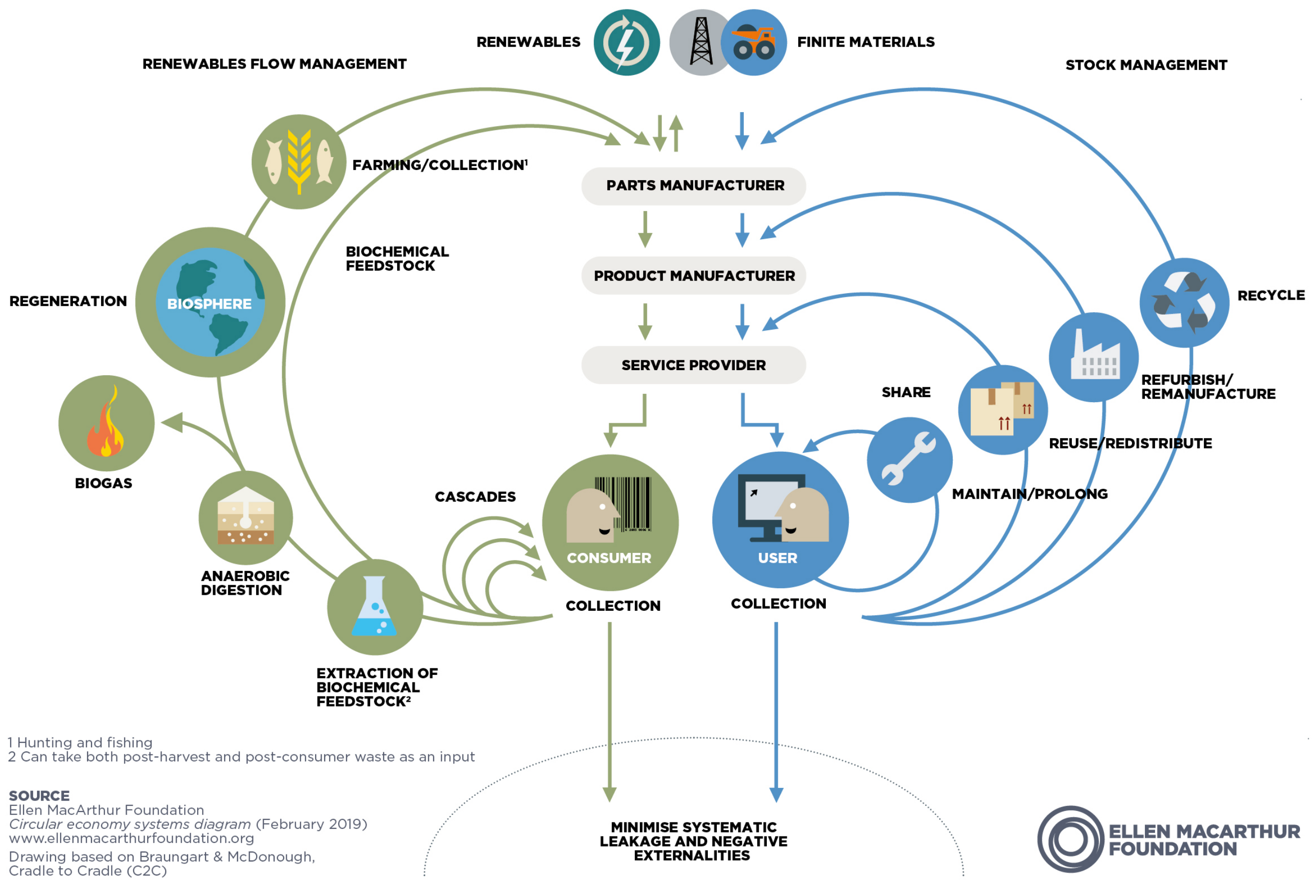
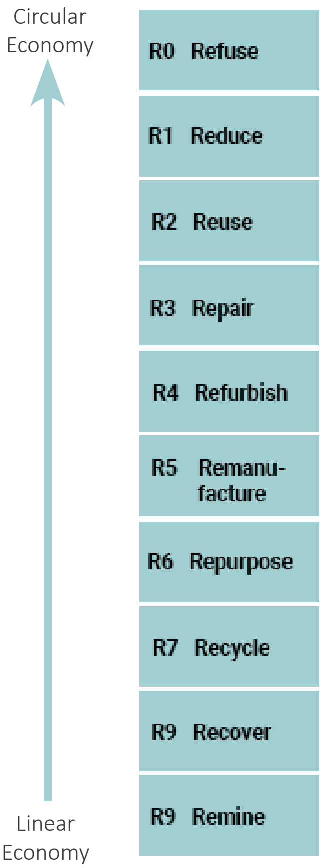


Figure 4 - The Butterfly Diagram, EMF (2019)

2.4 Relevance of 'Reuse' in the R-Hierarchy

An R-hierarchy model is an environmental preference approach to use materials and products. It is based on a hierarchical system to decide the best method from an environmental perspective (Addis, 2006). There are various classifications, from 3, 4, 5 until 10-R imperative for circular economy in the literature. Figure 5 shows a 10-R imperative by Rieke et al. (2018). It indicates the priority order for minimizing primary resources and energy in the product life cycle (Reike et al., 2018). According to the model, smarter product manufacture and use (R0-R1) are preferred over product lifespan extension (R2 -R6). Material recycling, energy recovery from incineration, and re-mining (R7-R9) have the lowest priority in a circular economy (Government of the Netherlands, 2016).



Smarter Product Use and Manufacture	
R0: Refuse	It aims at prevention of waste created by the consumer by buying or using less
R1: Reduce	It can be consumer-oriented or product-oriented and points at the elimination of waste rather than disposal of waste
Extend Lifespan of the product and its parts	
R2: Reuse/Resell	The market transaction needed to bring products back into the economy
R3: Repair	Extending the lifespan by bringing it back to working order
R4: Refurbish	The structure of the product remains the same, while components are replaced to overall upgrade the product
R5: Remanufacture	The whole structure of the product is disassembled, checked, replaced if necessary
R6: Repurpose	Adapting the components for a different function in its second life
Useful application of materials	
R7: Recycle	Processing of mixed streams of post-consumer products using expensive technological equipment. It does not maintain the original structure of the material and can be applied anywhere.
R8: Recover	Extraction of elements at the end of life for energy recovery
R9: Remine	Retrieval of parts after the landfilling stage, extracting value parts from the disposed of material

Figure 5 - 10-R imperative summarized (source: adapted from Rieke et al., 2018)

Reuse is the third strategy in the model and is applied to extend the life of the product and its parts. On the other hand, recycling is the useful application of materials after their life. In addition, reuse forms a tighter circle in the Butterfly Diagram and products have to undergo fewer changes for feeding them back into the circular loop. It means that the value retained with reuse is already higher than recycling. Reuse can be achieved by either designing new products that uphold material value in the future or using the existing waste materials as resources in the current design system. Either way, reuse can eliminate the industry's existing and future waste problems by retaining a higher material value than recycling.

Reuse can eliminate the industry's existing and future waste problems by retaining a higher material value than recycling.

2.5 Resource Loops for Material Flow

Another way to look at the circular material flow is through resource loops. Bocken et al. (2016) built upon the work done by Stahel (2010) on resource loops and defined it as the mechanism by which resources flow within a system. There are two fundamental strategies for cycling resources in a system - reuse of goods and recycling materials. The former deals with slowing the loop while the latter involves closing the loop (Bocken et al., 2016) :

1. **Slowing resources loops** - This refers to increasing the product utilization period by designing long-life goods and service loops for product life extension. It can be done by reusing the product itself or repairing, reconditioning, and technical upgrading for reuse.
2. **Closing resource loops** - Recycling materials can create a circular flow of resources by closing the loop between post-use and production. It does not affect the speed of the material flow in the economy.

A third layer over the two approaches can be applied to reduce the resource flow:

3. **Narrowing resource loops** - This refers to resource efficiency by using fewer resources per product. This approach is not linked to circularity but is a shift towards the sustainable use of resources.

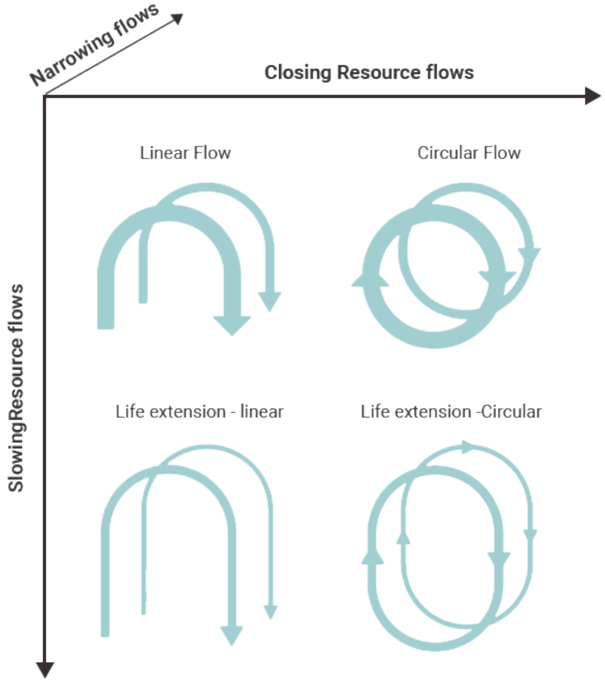


Figure 6 - Resource loops, Bocken et al. (2016)

The three approaches share a different relationship with time. 'Slowing' prolongs the use and reuse of products over time, whereas 'closing' does not influence the speed and ensures circular flow. 'Narrowing' is not specific to cyclic use but an approach to reduce resources associated with the product. It is a sustainable way of using resources and is not in the scope of the presented research. The business models to support the different resource loops are discussed below.

2.6 Circular Business Models

Circular business models are the drivers for the economic viability of circular economy strategies. Sehnem (2019) described the circular business model as value creation by exploring the value retained in old products that can be reused to generate new offers. These models involve regeneration, sharing, reintroducing resources into the product chain, optimization, virtualization, and exchange (Leos, 2020). Bocken et al. (2016) categorized the design and business model strategies according to the resource loops (Bocken et al., 2016):

Slowing the loop

Business models for slowing the loop encourage long product life and reuse of products through business innovation.

Access and Performance Model - The model elaborates on providing capability or services to satisfy users' needs without ownership. It is based on the concept of 'Product Service System,' a combination of products and services to provide users with functionality while reducing environmental impacts. In addition, the business model allows the company to capture financial benefits by offsetting life extension costs with additional revenues from prolonged product use.

Extending Product Value - This involves the exploitation of the residual value of the product through various operations. For instance, remanufacturing is a process to recover products that are not in use anymore, with no new net consumption of materials other than transportation and processing. Such a business case usually involves the original manufacturer through extended producer responsibility. In addition, 'value creation' includes take-back systems and collaborations to organize logistics for product return.

Classic long-life model and encourage sufficiency - Design for durability and repair can support the product's long life. Value creation is focused on high-quality products and services. A 'premium' covers the long-term service and extended warranty over the product service life. Sufficiency is achieved by allowing users to hold the value of the product through high levels of service. The model aims at slower sales and higher services.

Closing the loop

The business model for closing the loop consists of capturing the value from an existing linear business approach, as by-products or 'waste.' It can be approached either at a 'micro scale' by reusing materials in the manufacturing process or at a 'macro scale' where products are disposed of and recycled in an independent network.

Extending resource value - It refers to collecting and sourcing otherwise 'wasted' materials to turn them into a new form of value. The intention is to exploit the residual value of resources by making products appealing to the users. This form of value creation includes new collaborations and take-back systems to source materials. 'Wasted' resources are turned into new products to capture their value. This product value can either be created by the original manufacturers or other companies to develop a business model for resource reuse.

Industrial Symbiosis - It is a process-oriented solution where waste outputs from one process are fed back into another process or product line. These practices take place at the process and manufacturing level and benefit from geographically close businesses. Moreover, the collaborative agreements can induce cost reduction across the whole network.

The presented research addresses the circular business model of extending the product value of existing resources. It can be achieved through either of the two loops - slowing the loop or closing the loop. Closing the loop deals with the 'creation of new value' by ensuring the waste is used in the industry, such as recycling concrete to make bricks for new construction. On the other hand, slowing the loop deals with 'value retention' by ensuring the product can be reused again in the industry, such as remanufacturing a window after the end of its service life. There are benefits associated with either model; however, the selection depends on the condition of the product/resource and the objective behind value extension. 'Reuse' falls under slowing the loop and will be the focus of the presented research.

Closing the loop deals with the 'creation of new value' by ensuring the waste is used in the industry; slowing the loop deals with 'value retention' by ensuring the product is reused again in the industry.

2.7 Summary

The concept of circular economy is studied by numerous researchers in different academic fields. Although there is no fixed definition of CE, common principles can help transition to a circular economy. There are various ways for materials to flow within the system; however, the Butterfly Diagram by EMF and R-hierarchy model indicate a higher value retention with reuse than recycling. Therefore, the focus of the research lies on 'Reuse' for extending the product life by slowing down the resource loop. The contextualization of 'Reuse' as a circular approach will further be elaborated for its application in the built environment.

03.

CIRCULARITY IN THE BUILT ENVIRONMENT

The chapter presents a literature review on the application of circularity in the built environment. The CE principles of 'thinking in systems, designing out waste, and waste to a resource' are discussed for their relevance to the research.

3. CIRCULARITY IN THE BUILT ENVIRONMENT

The high material demand in the built environment has put a strain on virgin sources, and therefore, its role in the transition to a circular economy is vital. A Circular Built Environment is "an approach to achieve sustainable development goals through business models supporting minimizing waste by reducing, reusing, recycling and recovering materials during the whole life-cycle of a product" (Klein, 2019). The three principles of circular economy relevant to 'reuse of secondary materials' are elaborated for their application in the built environment. These are based on the works of Beurskens and Bakx (2015), who applied the framework of circular economy proposed by the Ellen MacArthur Foundation to the building and construction sector.

3.1 Principle 1: Thinking in 'systems'

EMF defines "thinking in systems" as,

> *"the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts" (EMF, 2013)*

CE principles can be applied at different scales of the built environment, including materials, components, buildings, and cities. These scales are integrated through design, technology, flows and resources, society and stakeholders, economy, and management, as shown in Figure 7 (left). A crucial aspect of time that is often skipped in the linear economy is considered in the circular built environment.

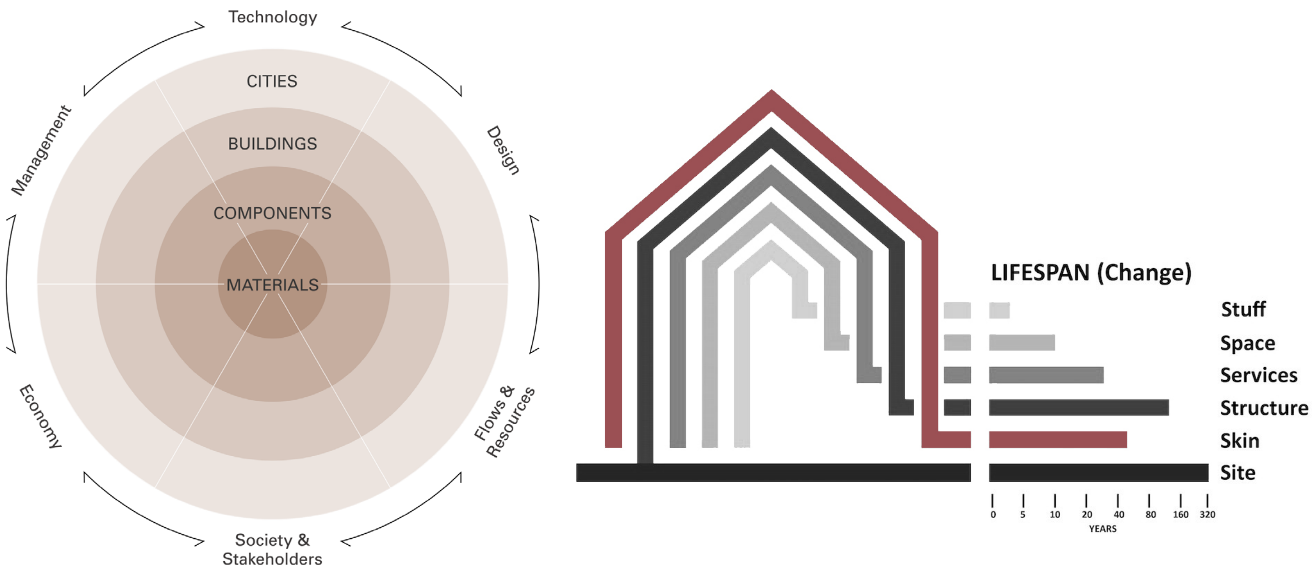


Figure 7 - (left) Circular Built Environment (source: https://www.edx.org/course/circular-economy-for-a-sustainable-built-environ-2), and (right) Shearing layers by Brand (source: https://nxtgenhouses.com/how-buildings-learn/)

Buildings are generally conceived, designed, and constructed as static entities in time. However, they are continuously changing and adapting to the user demands and environmental conditions over their lifespan. Thus, they can be understood as a 'series of different buildings over time' (Beurskens and Bakx, 2015). The relation of time with the building was elaborated in the "shearing layer" concept by Stewart Brand (1994) to examine buildings as a whole regarding space and time. The "shearing layers" consider the building as a collection of functional layers characterized by their lifespans. Figure 7 (right) shows the six identified layers: site (infinite); structure (30-300 years); skin (20-50 years); service (7-15 years); space plan (3-30 years), and stuff (0-3 years). The conception of building as layers in constant change with time is an effective tool for the designer to understand lifespan as a factor for designing circular buildings. The following section discusses how each of these layers can further be divided into product levels.

Hierarchical Range of Building Products

A detailed classification of the layers was proposed in a hierarchical range of industrial building products by Eekhout (2008). It starts from raw materials and goes until the building complex, as shown in Figure 8. The steps between commercial material and buildings are specific to the product domain. This range was simplified by Klein (2013) for façade products and is defined as "product levels." The product levels are classified as follows (Klein, 2013):

- **Material** - the base ingredient without any further shaping or treatment such as glass, steel, or composites
- **Standard material** - the intermediate goods which are available in standard sizes such as I-beams, bricks
- **Commercial Material** - a material shaped specifically for a product or a project such as extruded aluminum profiles for windows
- **Elements** - different commercial materials are assembled to form an element such as IGU consisting of glass plane, spacer, and silicon
- **Sub-component** - a closed assembly of elements with a single function such as a window frame
- **Component** - an independent functioning unit built up from several elements and assembled offsite, such as unitized panel
- **Building Part** - a collection of elements and components with the identical technical primary function, like a curtain wall

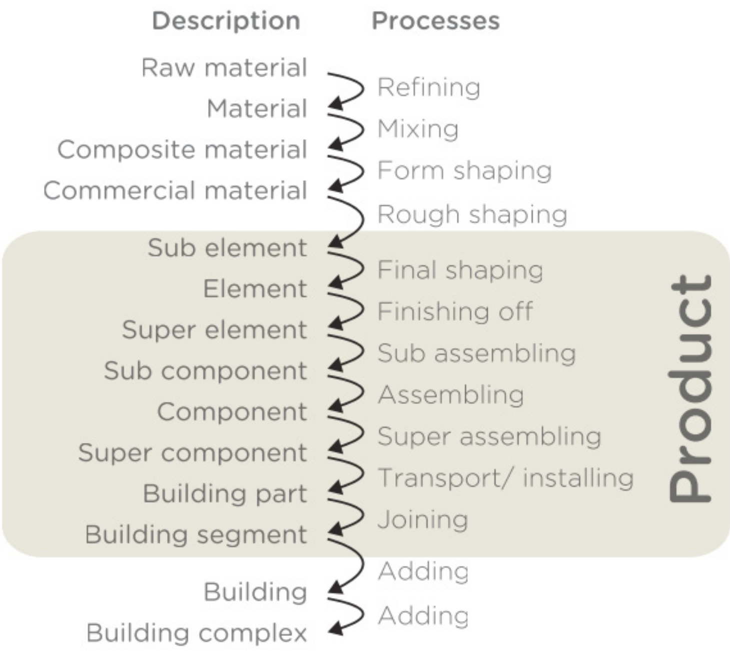


Figure 8 - Eekhout's Hierarchy of building products (source: Beurskens and Bakx, 2015)

Circular Building Product Levels

Beurskens and Bakx (2015) synthesized the two levels, building and product, based on their relationship hierarchically, as shown in Figure 9. The scheme is created in accordance with the 'think in system' principle of CE. The four layers by Brand (1994), excluding site and stuff, were combined with the building product levels to create a complete overview of the circular building product level. The building layers are shown as the primary systems in the design of a circular building. After selecting the primary system, the designer can then look at the sub-system, components, elements, and materials within those systems. The presented research uses this to define the buildings' skin layer through product levels.

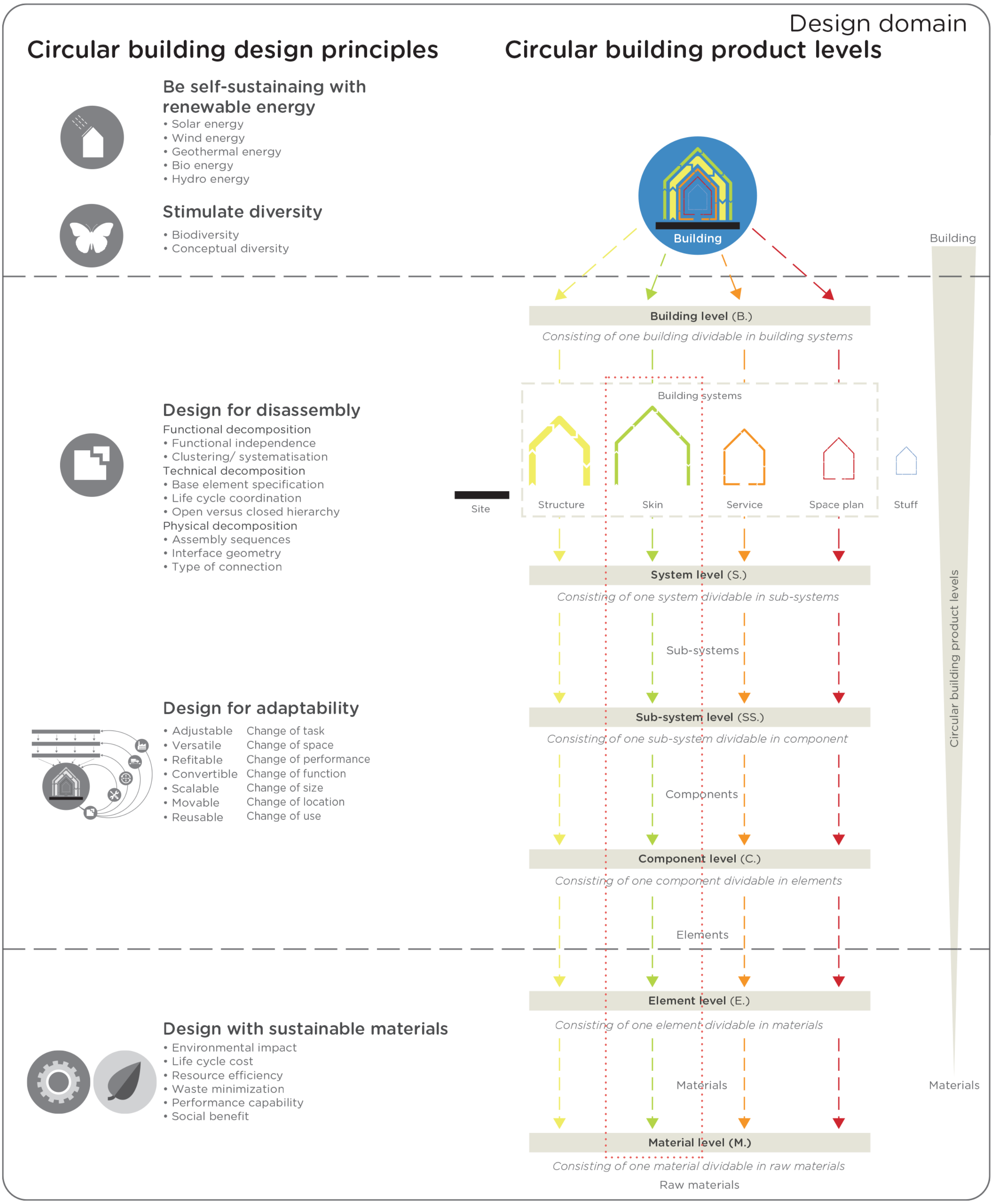


Figure 9 - Design domain - Circular building design principles related to the circular building product levels (source: Beurskens and Bakx, 2015)

3.2 Principle 2: Designing out waste

EMF defines “designing out waste” as,

> *“Waste does not exist when the biological and technical components (or ‘nutrients’) of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and refurbishment.” (EMF, 2013)*

Durmisevic (2006) proposed a hierarchy of materials that considers the technical and physical levels in addition to the functional layers of Brand (1994). This level of distinction in the building characterizes the building as a hierarchy of subassemblies. According to Durmisevic (2006), the material hierarchy can be divided into three levels:

1. **Building level** - represents the composition of systems that have the primary function, e.g., load-bearing, partitioning
2. **System level** - represents the composition of components that represent the system function, e.g., finishing, insulation
3. **Component level** - represents the layered assembly of component functions, allocated through elements and materials at the lowest building assembly

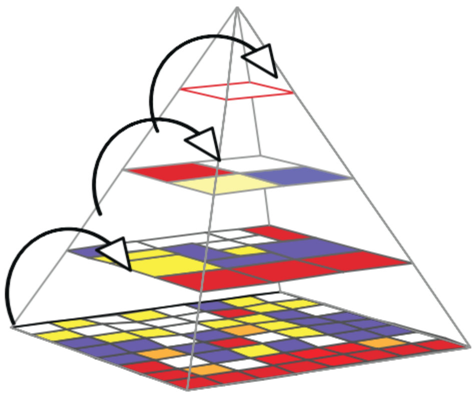


Figure 10 - Hierarchy of material levels (source: Durmisevic, 2006)

For instance, a façade can have a functional lifespan of 25 years, but the components can have different technical lifespans ranging between 10-100 years (Durmisevic, 2006). Therefore, the façade has to be independent on a functional level from other functions, and the arrangement of components and materials within the facade must be independent of the system. This hierarchical approach for buildings and products defines dependencies within a system. It can be helpful to devise strategies to design out waste from the product lifecycle and allow future reuse of materials.

Design for disassembly

Design for disassembly (DfD) is a design approach where products and components are designed for future recovery. Deniz and Doagn (2014) defined DfD as an approach that “enables products, systems, and components to be carefully and methodically decomposed to recover as many parts as possible.” It means disassembling the components and materials will maintain its product level, and thus, the embodied value of the material. Since the concept is relatively new, it can pose challenges to disassemble the existing products. However, approaching design through the physical, functional, and technical hierarchy of materials described by Durmisevic (2006) can inform the future disassembly for products designed today.

3.3 Principle 3: Waste to resource

EMF defines "waste to resource" as,

> *"the ability to reintroduce products and materials back into the economy through improvements in quality" (EMF, 2013)*

Buildings can be understood as a system of three life cycles: the cycle of the building, the cycle of its components, and the cycle of materials used to manufacture the components. The life cycles, even though, become one during the use of the building, is not the same case before the construction and after demolition (Gorgolewski and Morettin, 2009). The life that comes to an end is usually the service life of the material, component, or product. Hence there is a potential to extract these materials, components, and products from the buildings for their residual value after their EO(s)L. Therefore, the buildings can be seen as reservoirs of materials and components that can potentially be used again for the next cycle (ibid.).

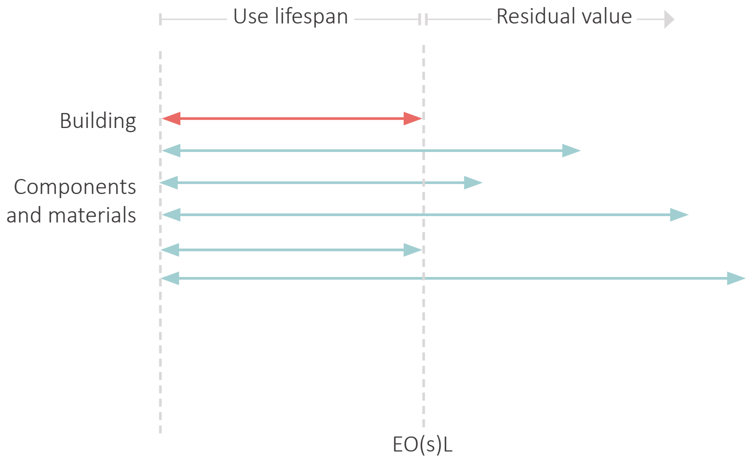


Figure 11 - Building as a system of lifecycles (source: author)

To ensure that this resource is used again at its highest level, the end-of-life disposal can be replaced with a suitable re-life strategy. According to the Butterfly Diagram by EMF and R-Hierarchy model, reuse has a higher value retention than recycling. However, there can be ambiguity with the term 'reuse' in the EMF model and 'reuse of materials.' Therefore, Beurskens and Bakx (2015) redefined the term 'Reuse' in the EMF model to differentiate it from other conditions of reuse. It is defined as the 'process of reusing building products through different loops.' The term reuse can be applied at different circular building product levels, as shown in Figure 12. The 'reuse' is a reaction to the changing user demands from the initial use to prolong their service life through service, reconfiguration, redistribution, remanufacture, and recycling (ibid.). Every option affects the value retention depending on the hierarchy, from the inner to the outer circle.

The life that comes to an end is usually the service life of the material, component, or product; there is a potential to extract them from the buildings for their residual value after their EO(s)L.

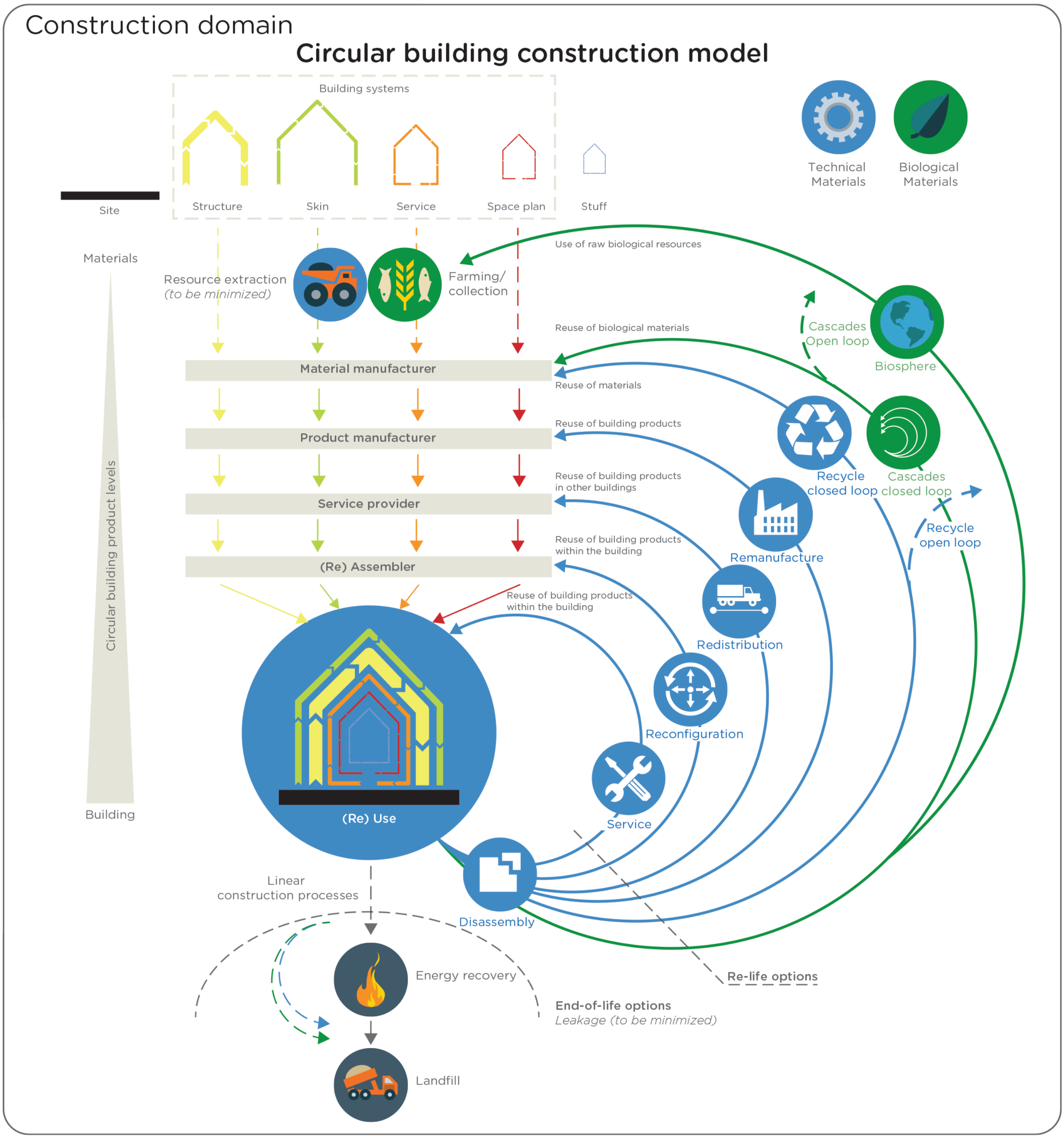


Figure 12 - Construction domain - Circular building construction model (source: Beurskens and Bakx, 2015)

3.4 Summary

Circularity in the Built Environment can be applied at the different building, product, and material scales. These consist of shearing layers on the building scale (Brand, 1994), hierarchical range at product scale (Eekhout, 2008), and material hierarchy (Durmisevic, 2006). This characterization looks at the functional, technical and physical dependencies within a system and directly relates to circular product design. Understanding the built environment as a 'system' helps distinguish the different layers within the building to reuse them at EO(s)L as 'potential resources' for subsequent use. Further, their design can consider disassembly principles to keep them cycling in the loop and 'remove any wastage' in the way.

04.

SECONDARY MATERIALS

The chapter presents a literature review on the secondary materials in the Netherlands. It elaborates on their procurement process, challenges, and accelerators for their reuse in the building industry.

4. SECONDARY MATERIALS

4.1 Background

The existing building stock, which is no longer in the use phase, has the usual end-of-life scenario of energy recovery or landfill after demolition. According to CBS reports, the share of demolition stock from residential and non-residential buildings in the Netherlands was 10,684 and 4,558, respectively, in 2019 (CBS, 2020). This large volume of building stock can be seen as a potential reservoir of materials and can be mined to provide resources for new construction (Gorgolewski and Morettin, 2009). The materials released during the demolition process and are fed back for use in the production process are referred to as 'secondary materials' (Eijk and Brouwers, 2009). Schiller et al. (2017) referred to this stream as 'anthropogenic material stocks' due to its inherent value. Their reuse can reduce waste that needs to be disposed of and reduce primary resource consumption (Gorgolewski, 2008).

According to EU Waste Framework Directive (2008/98/EC), "waste means any substance or object which the holder disregards or intends or is required to disregard." Netherlands uses the EU-defined 'End of Waste' (EOW) criteria (Deloitte, 2015). According to this, any waste that fulfills the criteria for EOW no longer has the status of waste. For this, the waste has to undergo a recovery process and comply with specific criteria. These waste treatment operations can be recycling, reuse, recovery, or backfilling (ibid.).

4.2 Materials harvested in the Netherlands

In the Netherlands, Construction & Demolition Waste is the most significant waste stream (40%), with an average volume of approximately 25 million tons (Bio by Deloitte, 2017). This waste is sorted as mono streams of plastic, metal, stone, wood, sieve sand, and hazardous metals as specified by National Waste Management Plan (Landelijk Afvalbeheerplan – LAP). Figure 13 shows the volume of material flows during the demolition processes and their EO(s)L scenarios. The largest fraction of these flows is stone-based (concrete) products, wood, and metals, each having its own EO(s)L scenario. Stone-based materials are used as base materials, wood is incinerated for energy recovery, and metals are recycled.

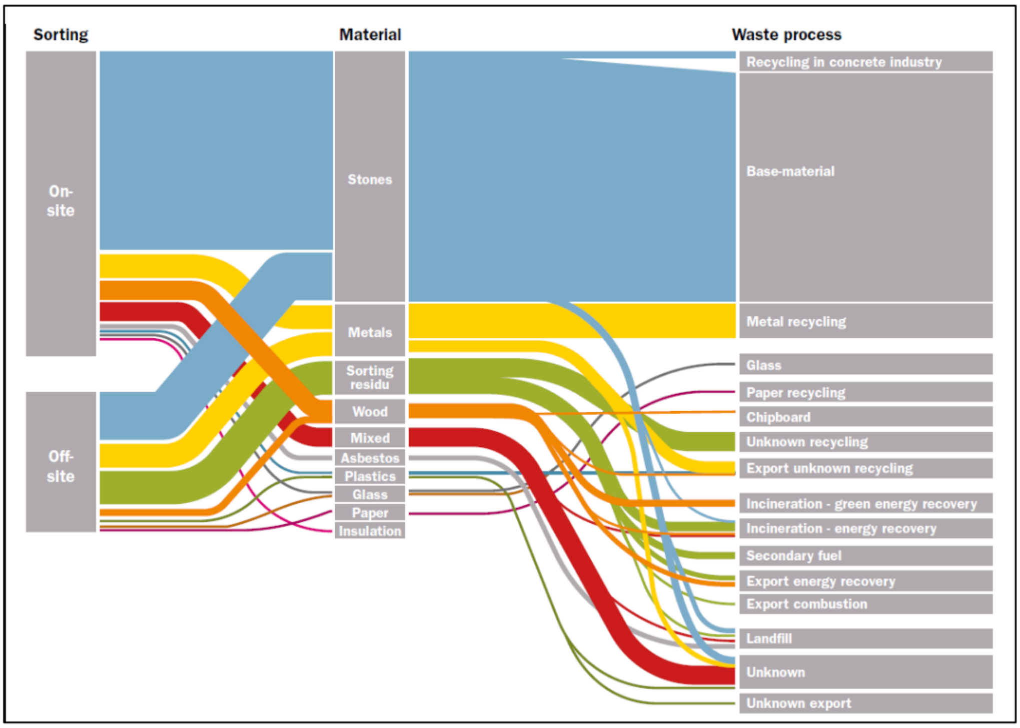


Figure 13 - Sankey diagram of flows of demolition materials in the Netherlands (source: TNO, 2018)

The flow of secondary material is dependent on the construction system of the existing building stock. Circularity and Design for Disassembly are a relatively new concept, and buildings reaching their end of life now did not consider these aspects. As a result, not all waste from demolition processes can be harvested. Therefore, a strategic procurement process at the end of building life is necessary to yield the secondary materials as valuable assets (Gorgolewski, 2008). Icibaci (2019) elaborates that of all the waste materials from demolition processes, certain products (materials) are usually harvested more in the Netherlands due to the ease in deconstruction and economic and environmental benefits attached. These materials and products are summarized below (Icibaci, 2019):

- Wood is most commonly commercialized in the Netherlands due to flexibility in its reconditioning (which is possible even after damages during the deconstruction), resizing, and allowing for cascade reusing.
- Ceramics, including wall bricks, are limited due to the process of removing mortar for its reuse. Clay roof and wall tiles are also limited to renovation projects in the Netherlands.
- Steel components (mainly structural) show considerable environmental and economic benefits for reuse.
- Stone-based products such as concrete are the most significant fraction (approx. 40%) of demolition waste in the Netherlands. The products are hardly harvested due to a more complex process concerning deconstruction, transportation, and storage. It is even more challenging to harvest due to a lack of demand. The products are downcycled as the base material for road construction.

4.3 Procurement Process of Secondary Materials

The secondary materials are harvested from the building stock through an Urban Mining Process. It is defined as "the process of reclaiming components from any kind of anthropogenic stocks, including buildings, infrastructure, industries, and products (in and out of use)" (Cossu and Williams, 2015). According to Icibaci (2019) and Lukkes (2019), this process defines the supply chain of secondary materials and products and consists of three phases: inventorying, harvesting, and distribution. These are described below (Icibaci, 2019, Lukkes, 2019) and summarized in Figure 14:

Inventorying

Inventories are made before the demolition process to get an overview of the availability and reusability of building components that can be harvested, including information about their quality and value. According to the Dutch Building Decree (2019), a pre-demolition and a post-demolition audit are required practices for demolition companies in the Netherlands. The inventory required for the cases describes the available material stock in the building and how it will be handled to prevent landfill and dispose of hazardous substances. A post-examination is done for evaluation of the selected deconstruction process. Therefore, the inventories can become tools to set targets of reusable products from the buildings. The future use of the material determines the information needed for the inventory. Thus, a collaboration between the material users (architects, engineers, manufacturers) and material extractors (demolition companies, building strippers) is essential.

According to Dekker et al. (2018), there are two methods to proceed with the inventory. The first is a theoretical approach focussed on estimating quantities based on key figures and formulas. It can be applied if the information regarding the project is available. A second method involves careful inspection of the building, including measuring, counting, and evaluating components for reuse. The selection of the method is determined by the actor responsible for the estimations. For example, a government agency might hire a consultancy firm that will estimate based on available information; however, a demolition company will take the second approach to inspect and select reusable components.

Harvesting

Harvesting involves recovering products from the building after an inventory has been made. The scale of the project guides the role of demolition companies in harvesting. For a small-scale project, the harvest (doors, windows, furniture) can be collected by building owners without heavy machinery. For a large site, a demolition company or a specialized building stripper can be hired. Due to the economic benefits attached to material reuse (Dekker et al., 2018), demolition companies have started deconstructing rather than demolishing the buildings through selective demolition.

Selective demolition is a practice to remove and separate high-quality usable components carefully. It is closely related to the waste sorting process on the building site. However, it does not reduce the amount of waste generated but allows the recovery of fractions for high-quality reuse (Wahlström et al., 2020). Different phases in selective demolition determine the products harvested for reuse. These involve:

- **Deconstruction** - Removal of interiors and equipment such as doors, windows, gypsum board, stairs to make products available for direct market reuse
- **Dismantling** - Careful removal of bricks, beams, components, and structure for reuse
- **Demolition** - Demolishing and sorting of mineral fraction (concrete), wood, and scrap for recycling
- **Disposal** - The treatment and proper disposal of hazardous and contaminated elements, e.g., asbestos

Distributing

The distribution of harvested components to architects, manufacturers, and individuals is a logistical process consisting of transportation, sorting, processing, and retail. Demolition companies that have storage facilities sell the harvest themselves due to the economic benefits attached. In other cases, a secondary company is contacted for the commercialization of building products. These companies are responsible for the transportation and processing of products before selling.

Harvest can be distributed in three ways depending on the time frame for its reuse.

- **Demand-led harvest** - If the reuse is predetermined, it can be directly transported to the site for temporary storage until reuse, reducing the amount of transportation. This process is opportunity-dependent and is usually done when architects and engineers are pre-involved in the deconstruction process. It allows the building design to be adapted according to the material inventory.
- **Original manufacturer** - The second way is to send it to manufacturers who resell them with the required conditioning of the product, including refurbishment and remanufacturing. This method usually maintains the reuse value of the product. However, in the Netherlands, there is a lack of connection between demolition companies and original manufacturers or manufacturers and distributors of new products. It is due to the change in ownership of the product from the manufacturer to the user.
- **Reused market places** - For the harvest with no predetermined destination, they are sent to the marketplace to be stored until sold. The process is more logistically oriented, and the harvest is made available through a collaboration between demolition companies and retailers of secondary materials. The reuse value, in this case, cannot be predetermined and is solely dependent on the individual reusing the product.

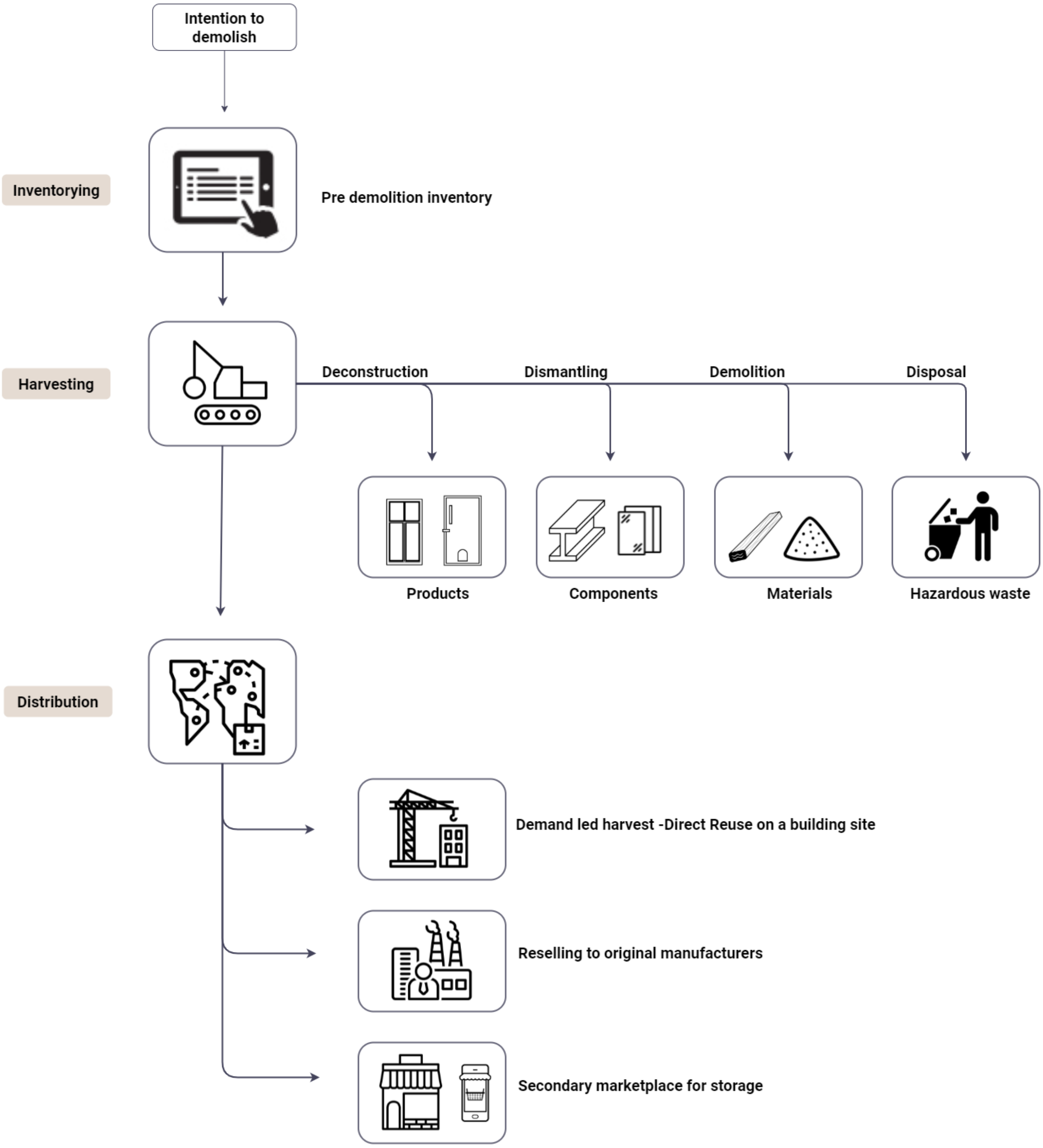


Figure 14 - Procurement process of secondary materials (source: author)

4.4 Stakeholders in the Procurement Process of Secondary Materials

Various stakeholders are involved in procurement, whose roles and participation vary with a change in scale, type of reuse, and economic benefits attached to the harvest. Following critical stakeholders have been identified from the processes discussed above (Icibaci, 2019), and summarized in Figure 15:

- **Building Owner** - For a small-scale project, the building owner plays a significant role in deciding the retail channel for harvest. A demolition company is not necessarily required for the deconstruction of doors and windows. These can be commercialized using online marketplaces such as salvoweb.
- **Building Developer** - If a developer owns the building, the demolition process can be undertaken by them, followed by a contract with secondary companies for retail.
- **Demolition Companies** - For large-scale projects, demolition companies are hired to identify the inventory and proceed with the deconstruction process. Depending on the economic benefits attached to the project, the companies can get involved in the harvest and retail process as a side business.
- **Secondary Companies** - Demolition companies hire secondary companies to dismantle the reusable materials. Their function is to process the waste for demolition companies (harvest) and provide a construction market for designers and engineers. The companies operate under demolition and renovation projects and are dependent on them for commission.
- **Retailers** - They are responsible for creating a commercial channel for selling the materials to different users.
- **Architect** - An architect can be pre-involved for direct reuse of the secondary material on another site. Their role involves the identification of reuse opportunities based on the given inventory.
- **Manufacturer** - For remanufacturing or refurbishing the building products, manufacturers can collect their products and prepare them for reuse elsewhere.
- **Individuals** - For small-scale reuse or a DIY project, individuals can already approach the retail channel of secondary companies (physical or online).

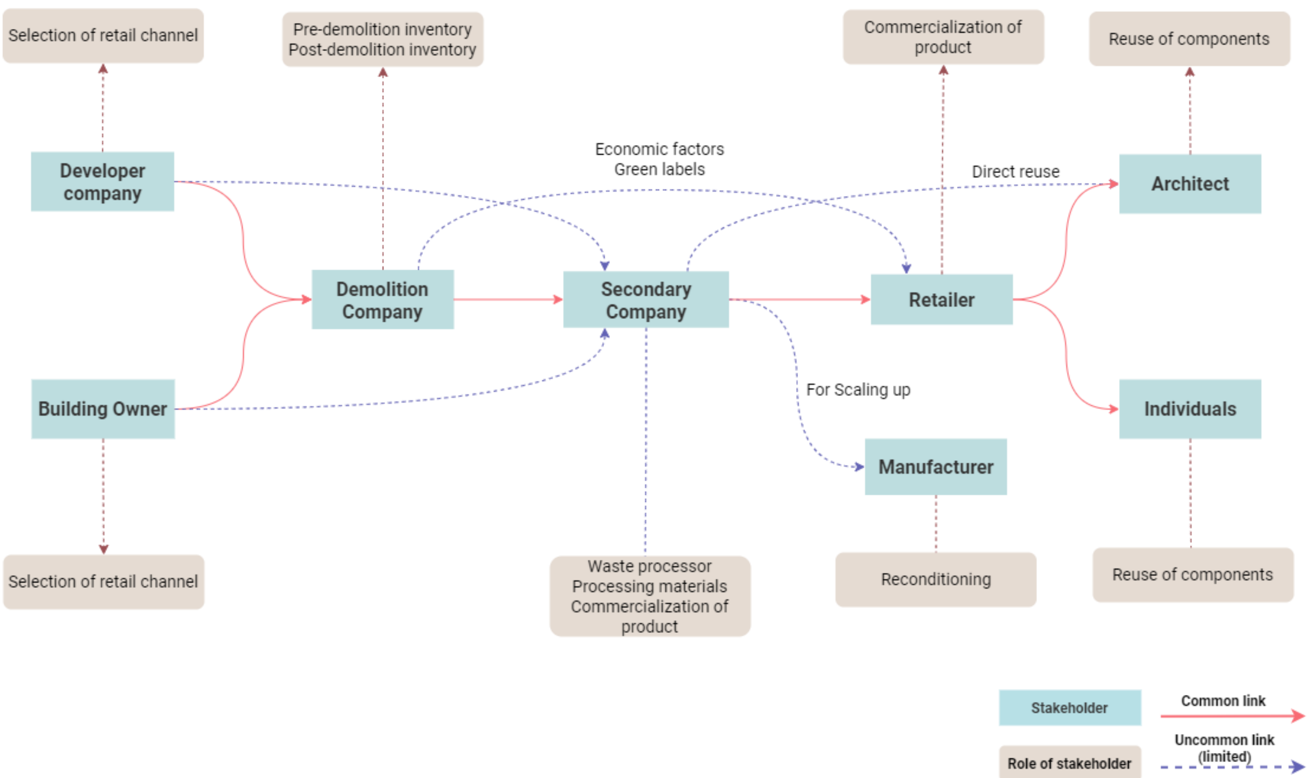


Figure 15 - Stakeholders and their roles involved in the procurement and distribution of secondary materials (source: author)

As can be identified, the chain for procurement of secondary materials is primarily concentrated in activities executed by a few main stakeholders. The distribution channel for reused products is either through an architect (involved in the demolition process since the beginning of design to identify the potential of reuse) or private individuals in small projects (involved with buying from the material inventory). Therefore, the original manufacturers need to become an active part of the chain to accelerate the reuse process of secondary materials. A more vital link between demolition companies and manufacturers can initiate a more efficient supply chain and reduce the dependence on support facilities in between. Furthermore, it can help scale up secondary materials reuse through a systematic deconstruction by demolition companies and distribution to manufacturers.

The original manufacturers need to become an active part of the chain to accelerate the reuse process of secondary materials.

4.5 Challenges Involved in the Availability of Secondary Materials

Specific barriers are identified in the procurement process of secondary materials affecting their availability from the studied literature. These can pose a direct challenge to enabling their reuse. Lack of defined economic incentives and logistics can be seen as underlying reasons behind the main barriers. They can be broadly categorized into three - Organizational, Technical, and Legal:

Organizational Limitations

Lack of coordination - The availability of secondary materials largely depends on its supply and demand cycle. A mismatch of demand and supply in terms of material quality and quantity (Hobbs and Adams, 2017) can result from a lack of coordination between the users and suppliers. This coordination is critical between both demolition companies and retailers and retailers and clients.

Geographical Proximity - Transportation of materials for long distances can significantly increase costs and environmental impacts of reuse (Brambilla et al., 2019). It is essential to look for the resources in close proximity to reuse them. Moreover, the availability of materials from far-off places may not be guaranteed in the future.

Unifying Platform - The building sector lacks a unifying platform for active companies. While there are independent companies operating reuse of building products, there lacks a connection where these companies can come together to provide the information. As a result, the reuse of products is limited to a niche market.

Logistics - The reuse of secondary materials is also a problem of logistics. Additional storage facilities are required between the harvest and retail, adding third-party costs to the process. These often diminish the advantages of using reused products compared to new ones (Hobbs and Adams, 2017). Moreover, the amount of time linked to deconstruction can seem unappealing when linked with its added cost. This time also relates to the timely procedures in the design process where delays can incur significant losses.

Legal Limitations

According to Icibaci (2019), the lack of legislation and incentivization are limiting factors for the availability of secondary materials. Harvesting materials for reuse by demolition companies are not treated as specific activity or sector, resulting in a lack of legal representation and further support in investments for research and innovation (Icibaci, 2019).

Technical Limitations

Availability of information - The reuse of secondary materials in the industry is only possible when sufficient information is available regarding its previous use. Inventories are often limited to material quantities and often lack information about the material quality, availability, and processing methods (Kozminska, 2019). Lack of data available at the right time to the architects, engineers, and manufacturers in the design process can pose a challenge for its reuse in the industry.

Lack of disassembly in design - The existing building stock was not designed using disassembly principles, and thus, their dismantling and deconstruction can lead to added costs, time, and labor.

Lack of protocol - There is no protocol to support and guide the decision-making for disassembly and deconstruction procedures. It can often result in an inadequate supply of materials for reuse (Durmisevic et al., 2017). These decisions are directly linked to economic aspects of the deconstruction and are only undertaken by demolition companies when benefits are highlighted from the very beginning.

4.6 Accelerating the use of secondary material

Hobbs and Adams (2017) have recommended practices to accelerate the use of secondary materials in the building industry. These are based on the evaluation of policies, practices, performance, and stakeholder viewpoint:

Regulation by the government - A law enforcing a minimum percentage of reuse/recycled materials can ensure that both clients and companies make the most reusable products (Ghaffar et al., 2019). Users' unwillingness would become less of an issue as they will have no choice but to use them. Furthermore, it would compel companies to invest in processing technologies to meet specific minimum requirements for reuse.

Managing supply and demand - When reusing products and materials is not possible on the same site, a mechanism should be systematized to match supply and demand for different projects. It can be done through a unifying portal, providing necessary information and connecting users and suppliers in the chain.

Material Inventory as a tool - Rather than mere documentation of materials for waste disposal, material inventory should be seen as a tool. It can regulate waste management on-site and contain data regarding the building typology, use condition of materials, construction system, and other relevant information to give an updated overview of material stock.

Better impact data - There is a need for a distinction between reuse and recycle in calculating impacts. A better impact analysis on the environment in terms of life cycle assessment can accelerate the reuse of building products.

Green Labels - Recently, demolition companies have started deconstruction rather than demolition due to the green ratings associated with reuse. BREEAM, LEED, and other building performance certifications can include reuse as a criterion to encourage reusing secondary materials.

Product declaration and recertification - Extended producer responsibility and certification for secondary materials can reduce the users' reluctance towards reuse. It requires a business model in place to shift the ownership of the product after use.

4.7 Summary

The EOL of a building is not necessarily the EOL of the various materials and components that make up the building. A careful inventorying and harvesting process at the EOL of buildings can generate a new supply source for raw materials.

In the Netherlands, the waste from demolition sites is already separated into mono streams as per the National Waste Management Plan. In addition, materials, components, and products are harvested for reuse by demolition companies and building strippers. According to the literature studied, wood and steel (metal) comprise a high fraction of waste from the demolition process and have a high harvest rate compared to other materials in the Netherlands. Stone-based products are the most significant material stream by weight, but the harvest rate is low due to a more demanding deconstruction process. The most common approach for their commercialization includes direct reuse at another site or resale in secondary markets. A weak link between demolition companies and the original manufacturers is a critical barrier to scaling up reuse practice in the Netherlands. There are various barriers in the industry regarding the supply of secondary materials; however, a careful evaluation can help provide solutions for its implementation in the facade industry.

Furthermore, an important observation includes the shift in the role of demolition companies. In some cases, they were seen to harvest materials according to architects' demands, either due to monetary incentives from material resale or green building certifications. Either way, this shift in their current role raises questions about how the rest of the industry responds and adapts to support reuse.

05.

REUSE OF SECONDARY MATERIALS

The chapter presents a literature review on 'Reuse' as a circular approach for secondary materials, described by the Waste Framework Directive. It is followed by research on the reusability of secondary materials through strategy for their reuse, reuse potential, and future reuse.

5. REUSE OF SECONDARY MATERIALS

5.1 'Reuse' according to Waste Framework Directive (WFD)

Icibaci (2019) stated that the forces that manage the input and output of materials are crucial to define the flow of materials from the existing building stock. In the Netherlands, preventing materials from becoming waste is the driving factor for their reuse. According to EU Waste Framework Directive (2008/98/EC), "reuse is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived." As shown in Figure 16 (left), non-waste products are prevented from becoming waste during their lifetime (use phase). When in compliance with WFD, the products can be directly reused without any additional regulatory restrictions accompanying reuse.

However, the secondary materials are made available at the EOL of the building during the demolition process. More often than not, direct reuse of secondary materials is hardly the case due to reasons outside the control of the building industry (Rose and Stegemann, 2019). Deconstruction damages, changing users' requirements, and upgraded standards make these products non-competitive to the new generation building products. However, specific improvements can be made to secondary materials and products for reuse to ensure they do not become lost resources. As opposed to recycling, improvements of products are not limited to direct reuse; they may include repairing, remanufacturing, repurposing, refurbishing, and reconditioning (Gorgolewski, 2008). Durmisevic (2006) defined the indicators for reuse of a product as:

- Direct reuse; *possibly by someone else*
- Reparation; *rectifying, and amending faults*
- Re Configuration; *using parts elsewhere*
- Remanufacture; *complete processing to ensure performance*

According to WFD, these product improvements fall under 'preparing for reuse,' which is applied to 'waste' products. Therefore, it can negatively affect the users' perception of 'reuse of secondary materials' as 'reuse of waste.' OECD has highlighted a policy change in the WFD to change this status from 'waste' to 'non-waste' in the waste hierarchy system, as shown in Figure 16 (right). This change can increase secondary material reuse in the industry by preparing them for reuse through different strategies.

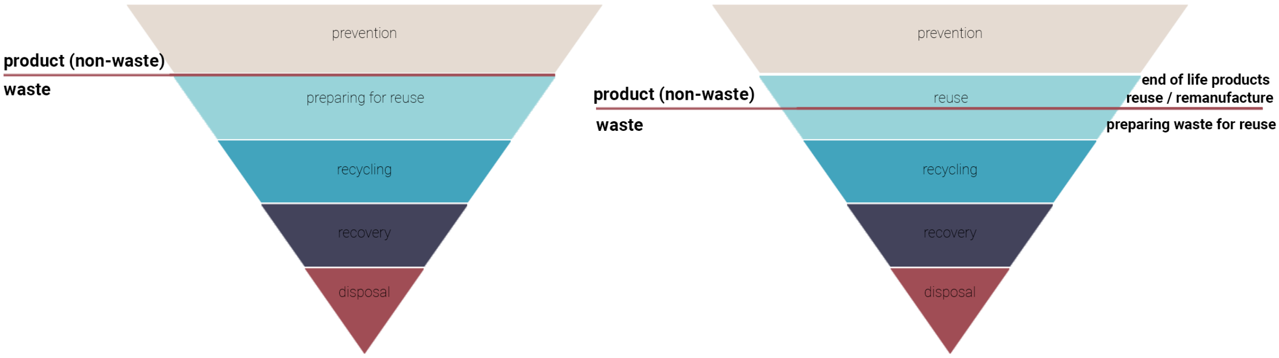


Figure 16 - (left) EU Waste hierarchy (source: WFD (2008/98/EC)), and (right) Waste hierarchy (source: OECD)

As part of this research, "reuse of products, components, and materials" will be considered as the practice of using secondary materials. Moreover, "any processes required to bring up to the standards that can result in its upcycling or use to at least its first product value" will be considered "process for reuse" to ensure maximum utilization of secondary materials in the facade industry.

Furthermore, according to the WFD, a product has to be reused for its original function. It cannot be determined as “reuse” even if no reconditioning is applied in the process of its new use. Using the product for its original use can significantly reduce the quantities of waste in the process. However, this is possible when original manufacturers are an active part of the chain. Since this research focuses on reusing existing secondary materials, reuse is not limited to its original use. Other reuse options will be considered for using the material if reuse is not possible for the same function to ensure maximum value retention.

> According to WFD, product improvements fall under ‘preparing for reuse,’ which is applied to ‘waste’ products; it can negatively affect the users’ perception of ‘reuse of secondary materials’ as ‘reuse of waste.’

5.2 Strategy for ‘Reuse of Secondary Materials’

Reusing façade products may be possible for the same function; however, the materials and components within the façade might require an upgrade in their performance by ‘preparing them for reuse.’ Therefore, any strategy that does not affect the embodied value of the material and components in the R-Hierarchy Model can be applied to make it reusable. According to the R-Hierarchy model by Reike et al. (2018), R0-R3 form the shortest loops, R4-R6 form the medium loops, and R7-R9 form the long loops. Since the loops establish a priority order for value retention of the façade (Reike et al., 2018), the different loops will apply to different product levels within the facade.

For instance, the repair is applicable at the component level; however, refurbishment/remanufacturing is applicable for the elements that constitute the components. Recycling necessitates reuse at the material level and does not maintain its embodied value. Figure 17 shows how different R-strategies can be applied to building product levels described in section 3.1. The diagram indicates that the shortest loops are applied to a higher product level. It means the higher the product level to be re-used, the more considerable the environmental benefit due to the few processes needed for its reuse, such as using the whole facade component instead of its elements.

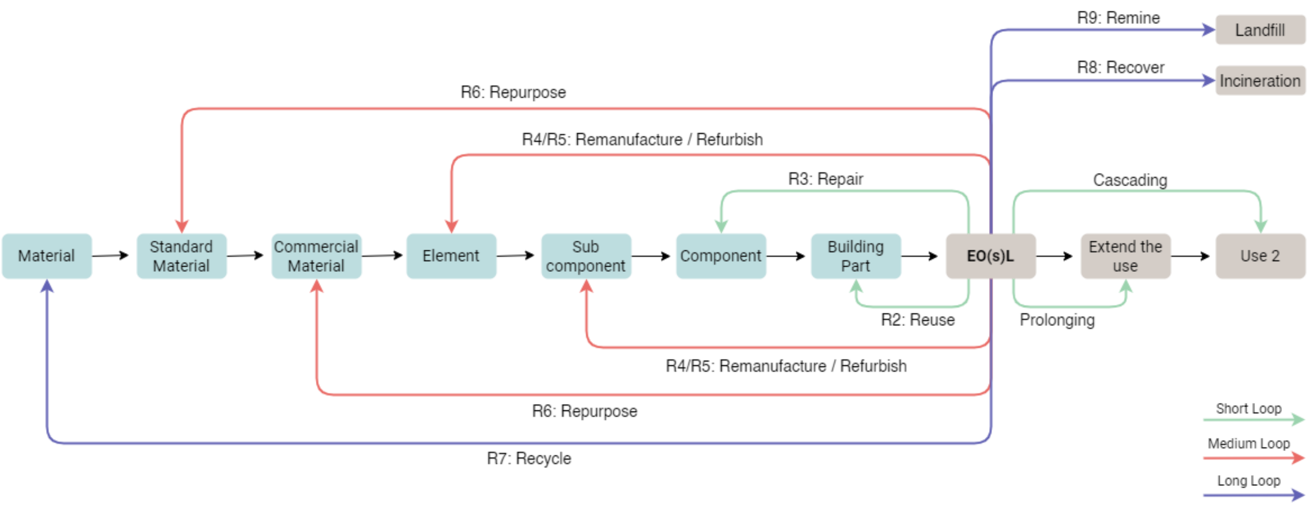


Figure 17 - R-strategy applicable to different product levels (source: author)

Furthermore, every product level comes under the scope of a different stakeholder in the product chain. According to Rieke et al. (2018), products remain closer to the user for shorter loops (R0-R3); however, the involvement of producers is necessary for medium loops (R4-R6). Therefore, every R-strategy applied will correspond to different actors in the product value chain. Extended producer responsibility is defined as the "responsibility of the producers for the environmental impact resulting from the lifecycle of a product" (Vermeulena et al., 2021). Thus, the reuse of materials at different product levels entails an extended producer responsibility of actors at those levels. Figure 18 shows the various actors in the product value chain and how the different reuse strategies apply to them.

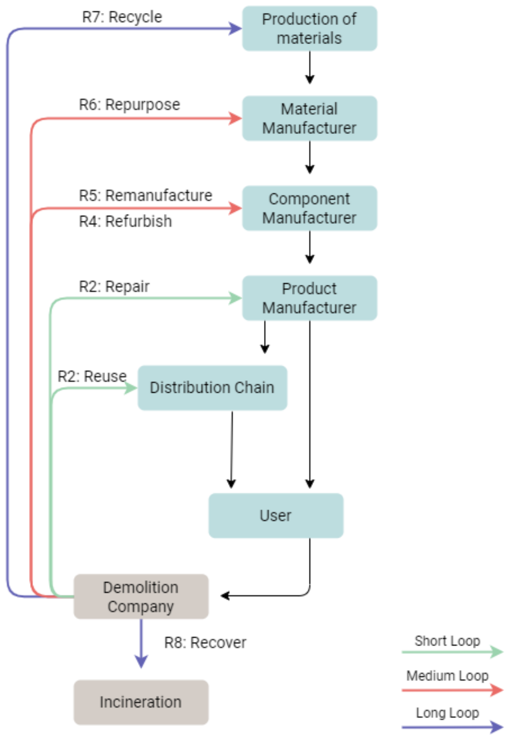


Figure 18 - Stakeholders affected by the applied R-strategy (source: author)

5.3 Reuse Potential of Secondary Materials

The 'reusability' of secondary materials is a condition that changes according to the dynamics of the material contained in building stocks and is defined by the products commercially made available through the supply chain (Icibaci, 2019). Therefore, it is essential to understand the previous use of materials to define how they can be systematically reused. From various literature studied, the following factors are identified as essential to assess their previous use and determine their reuse potential, and are summarized in Figure 19:

Ease of deconstruction - The extraction of materials, including construction site equipment, machine time, transportation, storage, and the efforts required, determine the feasibility of the material for reuse. Lower the efforts in procuring (deconstruction / selective demolition), the more feasible it is to do so (Zabek et al., 2017). Gamerschlag (2020) disassembled a façade unit as part of their research. The process took over 6 hours to disassemble one panel, much more than the assembly time. The main reason identified was the strength of the glued connections (Gamerschlag, 2020). Such a case will negatively affect the reuse potential of the façade.

Embodied energy - From an environmental perspective, it is critical to reuse and reclaim materials and products with higher embodied energy, as savings from them can significantly lower negative impact (Gorgolewski and Morettin, 2009). For example, ECSC (European Coal and Steel Commission) examined environmental benefits associated with the lifecycle of steel. Production of steel amounts to 75% of its whole life cycle impact. Reuse, in this case, can significantly reduce energy for the production of semi-finished products (Durmisevic, 2006).

Lifespan - An assembly consists of various components, each having its lifespan. Together they define the lifespan of the product (Durmisevic, 2019). Closing the loops for secondary materials with a shorter lifespan can affect the lifespan of the product negatively. It might require an early replacement compared to ones with a longer lifespan and become the weak link in the product.

Quantity - Another aspect to consider while reusing a product will be its quantity, directly affecting the amount diverted from recycling (Gorgolewski and Morettin, 2009). Using materials available in large quantities (weight or volume) can scale up reuse from a particular design case to an industrial scale. Although it may be reasonable to use any product/material harvested to prevent waste, this will require a more dynamic process between design and use. Since the quantity keeps varying, the design must be adaptable to accommodate other components in case of a shortage. Additionally, the use of scarce products may pose a problem in the future.

Permitted to be used - National Waste Management Plan imposes restrictions on reusing certain products in terms of toxicity and terms of treatment in its first life. Additionally, the components are required to be permitted for their reuse, for instance, structural load-bearing elements. Testing and certification will be a prerequisite in such a case.

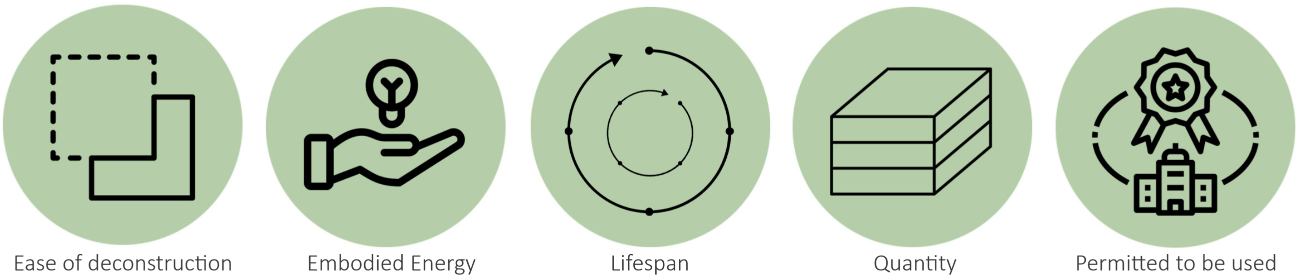


Figure 19 - Factors defining the reuse potential of secondary materials (source: author)

5.4 Future Reuse of Secondary Materials

Another question regarding the reuse of secondary materials is its future reuse. The design has the potential to safeguard the value of materials, and thus, its reuse potential (Durmisevic, 2006). One way to achieve this is by employing reversible design principles or reversible connections for facades. Durmisevic (2019) defines connections as interfaces for the degree of freedom between components and classifies them as - direct (integral), indirect (accessory), and filled. These can either be internal (between components) or external (between product and the building) (Durmisevic, 2019):

Integral connections (direct) - The geometry of the edge forms a complete connection, such as overlapping and interlocked connection. An overlap connection is an external connection between components and depends on the hierarchical position of the different components. The interlocked connection is an internal connection where component edges are shaped differently and allows for sequential assembly.

Accessory Connection (indirect) - Additional parts are used to form these connections and can be internal and external. The internal type has a loose accessory that can be inserted into components. Disassembly of such a system can be difficult due to the sequential assembly process. The external accessory is applied with a cover strip and frame and is easier to disassemble.

Filed Connection - This type of connection is filled with chemicals between components. Assembly of these connections is labor-intensive, and disassembly is nearly impossible, such as welded connections.

The connections can be classified into seven types and ranked based on their reversibility (disassembly), as shown in Figure 20. The most reversible connection is the indirect connection with additional fixing as it allows for complete disassembly of components, whereas a chemical connection is irreversible and allows no reuse.

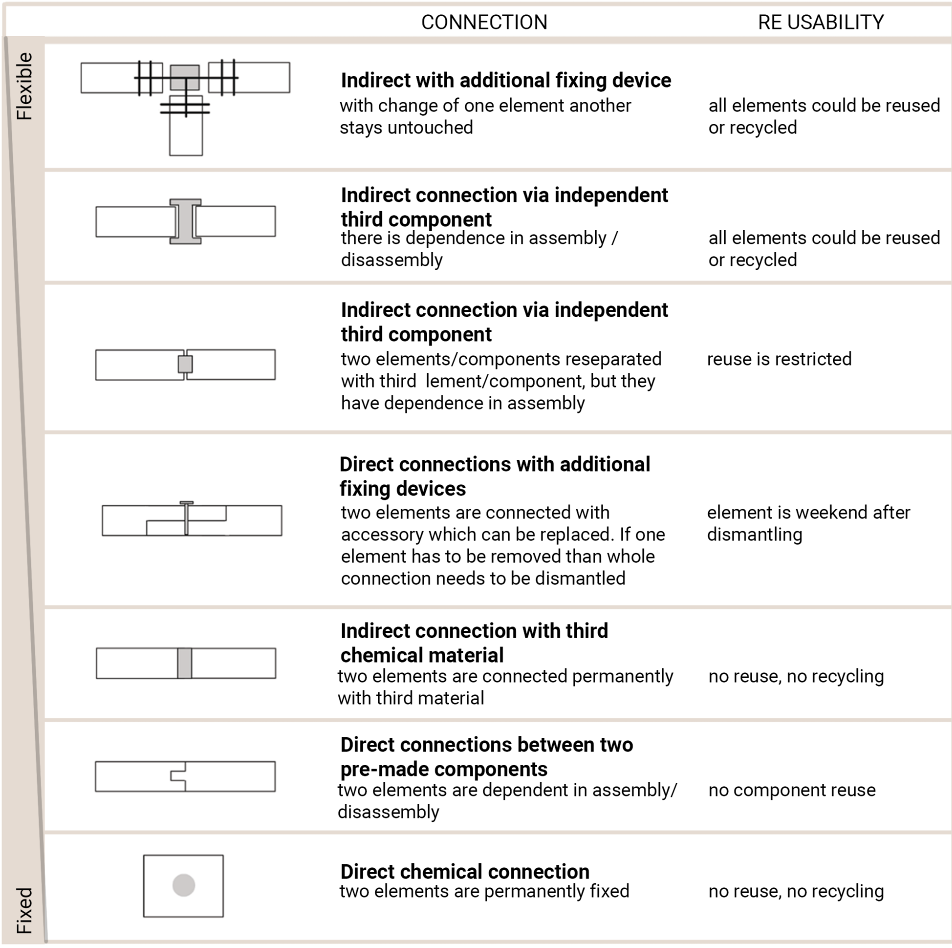


Figure 20 - Reversibility of connections (source: Durmisevic, 2019)

5.5 Summary

Reuse is understood in different ways by the industry. WFD implies the reuse of materials by preventing them from becoming waste; however, this is not always the case with secondary materials that require preparing them for reuse. Direct reuse of products may be possible for the same function, but materials and components within the products may require further processing for reuse. As long as the embodied value of the material is maintained, it can consider other R-strategies to ensure they do not become a wasted resource. To decide the best course of action, information regarding the previous use of materials is essential, including its ease of deconstruction, embodied impact, lifespan, quantity, and permitted use.

Furthermore, reuse is easier when components are designed for disassembly. Therefore, designing for future reuse is vital to ensure a circular flow of materials. It entails engineering reversible connections to make components easy to access for repair, replacement, and disassemble for the subsequent use of facades. The chapter highlighted significant findings for enabling the reuse of secondary materials now and in the future, which brings us to the question of how their reuse can be assessed.

06.

ASSESSING REUSE OF SECONDARY MATERIAL

The chapter presents a literature review on the existing product assessment methods for assessing 'Reuse' for its circular value and environmental impacts during a product's lifecycle.

6. ASSESSING REUSE OF SECONDARY MATERIALS

A duality with the reuse of materials entails the reuse of existing building products or the design of circular products for reuse. The former deals with current waste problems, while the latter deals with preventing future waste problems. The Dutch Ministry of Infrastructure and Environment (2015) defined the need to reuse the materials in a circular designed product. Materials that cannot be used cycle after cycle will pose a problem in another 20-30 years and will continue to demand attention. The discussion is then not limited to the reuse of existing products but a design that allows a circular flow of materials and products (Ministry of Infrastructure and the Environment, 2015). Both primary and secondary materials can qualify for this, as long as high-quality reuse is possible cycle after cycle. Accordingly, the following goals are defined to identify relevant assessments for reuse:

1. **Circular Value of reuse** - This refers to the degree of circularity achieved with the selected material and the product design to ensure reuse cycle after cycle
2. **Impact of reuse** - This refers to the impact of reuse of materials and added process on the environment, for embodied energy and carbon emissions

6.1 Circular Value of Reuse

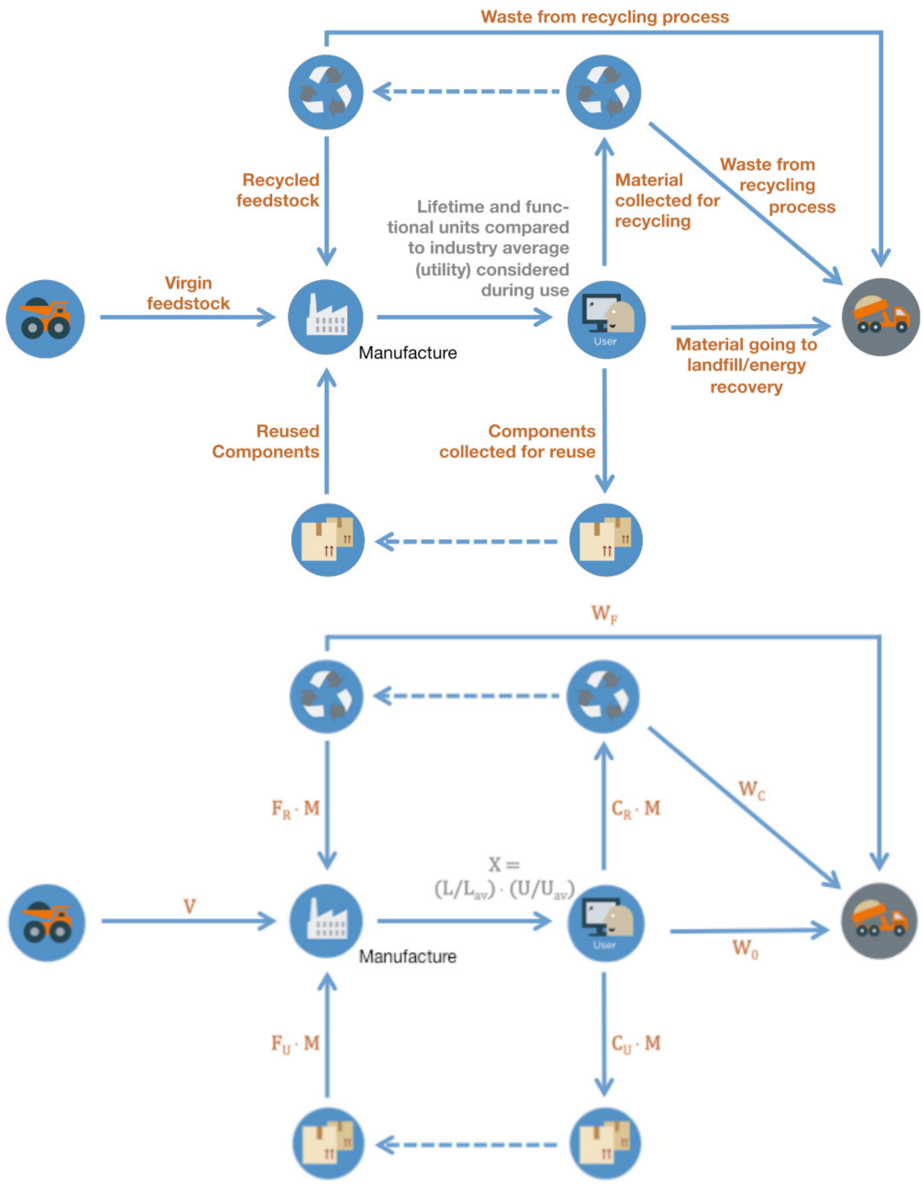
Different strategies can be applied for the transition from a linear to a circular model. The concept behind these strategies can be an efficient use of materials, R-hierarchy, eco-design, zero carbon design, etc. (Corona et al., 2019). The impact or benefits resulting from these strategies are often measured using circularity metrics. Several metrics exist in the academic literature for evaluation, each unique in its way, primarily due to the varied understanding and goals for circularity set by the assessment stakeholders. Therefore, a clear definition of circular economy in line with the defined goals is essential to identify the relevant assessment criteria for a particular case. Corona et al. (2019) identified two categories for assessment:

- Circularity indices concerning the circular flow of materials and assessing circularity of a system
- Circularity assessment to analyze the contribution of strategies to the circular economy principle and measure its impact on the environment.

In the following section, various indicators relevant to this research are described to identify a holistic assessment for reuse at the material and product scale.

6.1.1 Material Circularity Indicator (MCI)

Ellen MacArthur Foundation and Granta (2015), in 'Circularity Indicators: an approach to measuring circularity,' defined an assessment method to evaluate product circularity level. It measures the extent to which linear flow (virgin materials) has been minimized and restorative flow (secondary materials) maximized for its component and materials and how long and intensively it is used compared to a similar industry product (EMF and Granta, 2015). The assessment considers three product characteristics: mass V of virgin raw material used in manufacture, mass W of unrecoverable waste attributed to the product, and a utility factor X that accounts for the length and intensity of the product's use. It identifies linear flow index (input and output of material) and MCI score. Figure 21 shows the diagrammatic representation of the material flows.



Where:

V = Mass of virgin feedstock used in a product;

F_R = Fraction of mass of a product's feedstock from recycled sources;

F_U = Fraction of mass of a product's feedstock from reused sources;

M = Mass of a product;

X = Utility of a product;

L = Actual average lifetime of a product;

L_{av} = Actual average lifetime of an industry-average product of the same type;

U = Actual average number of functional units achieved during the use phase of a product;

U_{av} = Actual average number of functional units achieved ruing the use phase of an industry-average product of the same type;

C_R = Fraction of mass of a product being collected to go into a recycling process;

C_U = Fraction of mass of a product going into component reuse;

W_O = Mass of unrecoverable waste through a product's material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable;

W_C = Mass of unrecoverable waste generated in the process of recycling parts of a product;

W_F = Mass of unrecoverable waste generated when producing recycled feedstock for a product.

Figure 21 - Diagrammatic representation of material flows (source: EMF,2015)

MCI is assessed for different components within the product. Verberne (2016) summarises the steps taken for the calculation of MCI as follows:

1. The material input is determined either as a virgin or recycled. The assessment does not distinguish between reuse, remanufacturing, refurbished materials and classifies them all as recycled based on the assumption that reused content is less harmful than recycled. For each sub-assembly, the fraction of feedstock from virgin sources is given by:

$$V_{(X)} = M_{(X)}(1 - NV_{RC(X)}),$$

The fraction is given in kg/m3 or % of the total mass. If the virgin stock is 0, the input is circular. The summation of different subassemblies calculates the total virgin material for the product:

$$V = \sum_{X} V_{(X)}$$

2. The material output is the destination of the product at the end of life. The assessment again does not distinguish between reused, remanufactured, refurbished, or recycled products. The reusable fraction is the total amount of material that finds a second life. As the product is a single material entity, there is only one type of waste and is not separated into parts and components. If the waste is 0, the output is entirely circular. The amount of waste is given by:

$$W = M\ (1 - F_{RU})$$

3. The utility of the building deals with the lifetime of the product and the lifetime of the system. The length of the product is the length of the product's use phase. The length represents a reduction in the waste stream for a product with a longer or shorter lifespan than other products. A lifetime of a building system deals with product situations in a building system. The utility is given by:

$$X = \frac{L_p}{L_{sys}}$$

4. Defining the linear flow index to measure the proportion of materials flowing linearly. The index takes the value between 0 and 1, where 1 is linear flow, and 0 is restorative flow. It is given by:

$$LFI = \frac{(V + W)}{2M}$$

5. The material circularity indicator can be determined based on the input, output, and utility. MCI score for a product a is given by:

$$MCI_{p\ (a)} = 1 - LFI_{p(a)} . F(X_{p(a)})$$

6. The 'a' is a constant defined by EMF as 0.9. To prevent negative values, bottom line 0 is taken into account to determine the final MCI.

$$MCI_{p(\alpha)} = \max(0, (1 - LFI_{p(\alpha)} \cdot F(X_{p(\alpha)})))$$

A few shortcomings can be identified when applying MCI for identifying the circular value of reuse for secondary materials. Bracquene et al. (2020) and EMF and Granta (2015) summarise these as:

- MCI does not take into account biological cycles for renewable materials and considers only technical cycles. The material quality or the use type of recycled parts varies significantly between the two cycles. Renewable material like wood gets consumed in the process and needs to be considered through material quality indicators.
- MCI assumes the flow of reused materials to be fully circular. However, the material inflow and outflow needs to be demonstrated to be fully circular.

- Further, the method does not consider downcycling and the loss of quality in the reuse process, which is hardly the case when reusing secondary materials. A prerequisite condition for their use is the quality of the product, making it an essential factor in the assessment.
- The method also lacks the specification of reusing secondary material, such as remanufacturing, repurposing, etc., and only considers recycling. While the hierarchy states that the impacts change positively when moving up the ladder, these can vary depending from product to product.

Adaptation of the MCI

Due to the limitations mentioned above, Lonca et al. (2018), in their research, adapted MCI to the needs of the project. The adaptation applies a mass-based weighting methodology to divide the product into components with any unique circularity feature to calculate the new MCI. This represents the weighted sum of each component (MCI) of the assessed product; ni being the number of components and mi their respective mass(Lonca et al., 2018) :

$$MCI_{total} = \frac{\sum_i (n_i \times m_i \times MCI_i)}{\sum_i (n_i \times m_i)}$$

It is one such adaptation for the MCI. Another adaptation is the Building Circularity Index (BCI) by Alba Concepts. It is an assessment method to determine how circular the use of materials is for each product in a building. For this, the product circularity is calculated as a sum of MCI and LI. LI is the releasability index that depends on the connection type, accessibility of the connection, shape inclusion, and crossings (BCI Building, 2021). The product circularity represents the circular potential of a product when it is mounted in a building. BCI uses environmental impact as a weighting factor for the averages. It means that products with a relatively high environmental impact have a larger share in the BCI score. The adaptations of the MCI vary based on the objectives of the assessment and can be altered accordingly.

6.1.2 Disassembly Potential

Verberne (2016) described how the circularity of a product depends on the interfaces and connections between these products. These interfaces and connections can either be internal or external. According to Durmisevic (2006), disassembly is a key requirement to enable future reusability of a building product. Therefore, it is essential to define the future value of a product based on the design of its interfaces and connection systems. Design for Disassembly (DfD) is a design method to facilitate future changes and eventually dismantle parts and components of the product. To assess the disassembly potential of the product, Durmisevic (2006) described the functional, technical, and physical dependencies that define the connections within the system. These are described as (Durmisevic, 2006):

Functional Decomposition (material level) is the functionality of an assembly, and deals with the decomposition of functions as:

- **Functional Independence** - It means a separation of functions within one assembly. It will allow ease of replacement without unnecessary disassembly of the product.
- **Systematization** - It means clustering of components based on functionality, assembly/disassembly, and lifecycle coordination of components to create modular and standard designs.

Technical Decomposition (hierarchy) is focused on different elements, and deals with decision-making as per technical decomposition that defines the order within a configuration.

- **Relational pattern** - Defining open and closed hierarchy to specify the relation between subsystems for subassembly.
- **Base Element** - To provide independence, base elements must be identified for each cluster. This base element integrates all surrounding elements of the cluster.

- **Life cycle coordination** - Identifying product lifecycle and assembly sequences to determine the relation between long-cycle and short-cycle products.

Physical Decomposition (Interfaces) focuses on the performance of interfaces of a product, internal and external. It is related to the manufacturing and construction process.

- **Assembly sequence** - Sequence of assembly between components and products determines its transformations. More parallel than sequential assembly makes deconstruction easier.
- **Geometry** - Designing product edge geometry to allow recovery without any damages.
- **Connections** - Connections allow separation and easy recovery of elements.

Figure 22 shows the dependence between the design domains of transformation configuration, performance criteria, and the disassembly aspects of configuration. Additionally, there can be various design possibilities within each disassembly aspect. Durmisevic (2006) came up with a distributed weighted variable for different design possibility and graded them from zero to one, with zero being the worst impact and 1 being the best impact on disassembly.

Three elements of configuration and corresponding design domain	Performance criteria for transformation	Disassembly aspect of building configuration
Functional Decomposition = Material levels	Independence	Functional Independence Systematization
Technical Decomposition = Hierarchy	Exchangeability	Hierarchy Base Element Specification Lifecycle Coordination
Physical Decomposition = Interfaces		Assembly sequences Type pf connections Geometry

← Design	Evaluation →

Figure 22 - Relation between disassembly aspects and design domain (source: adapted from Durmisevic, 2006)

6.2 Impact of Reuse

The reuse of secondary materials is considered to bypass the impacts of production and demand of raw materials for the original product (Deweerdt and Mertens, 2020). However, the impact of specific operations required for 'reusing' the product is essential to the assessment. Additionally, the impact is not limited to the end-product from reuse and is added in every stage.

6.2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology for evaluating environmental impacts associated with a product, or a service, from a life cycle perspective (Thormark, 2000). Environmental impact refers to the demand for natural resources, emissions to air, water, soil, and solid waste (ibid.). The concept is standardized by ISO 14040-14044 (Corona et al., 2019). The tool is helpful to quantify the benefits/impacts of CE principles by evaluating and comparing the environmental impacts of the selected strategy. LCA consists of four modules – Production and Construction, Use, End-of-Life and, Benefits and Loads beyond system boundary. The assessment is designed as cradle to grave and thus, necessitates defining the material flows generating from reuse. The reuse of materials can happen in two ways (Wolfa et al., 2020):

1. **Upstream Reuse** – Design of new products from reclaimed components that were not designed for reuse, and thus, environmental benefits are evaluated for the newly designed product.
2. **Downstream Reuse** – Design of products whose components are meant to be reused in the future. Thus, the environmental benefits of this product are compared to other end-of-life scenarios.

Since the reuse of secondary material creates multiple-use cycles during its lifespan, it is essential to allocate environmental impacts over these cycles. According to the material flows mentioned above, the reuse of existing secondary materials for facades falls under upstream reuse, whereas design for future reuse constitutes downstream reuse.

In an environmental impact evaluation in the Buildings As Material Banks (BAMB) project in 2019, the circular designed prototype BRIC was assessed for three lifecycles of 20 years each. The results reflected that the impact of production and construction of materials goes to the first cycle of the product and reduces with every subsequent cycle. The impact of demolition at the EOL is directed to the third cycle, where the material reaches an end (Capelle, 2019). For instance, in a three-life cycle situation for the reuse where the first product was not designed for reuse, the impacts can be divided into different life cycles. The benefits of reusing in the 2nd cycle include the directed impact of production to the 1st cycle. The future gains from design for reuse also add to the 2nd cycle of the product by avoiding demolition. Thus, the second cycle of a three-use cycle benefits from both the avoided impact of production and demolition.

Though the impact can be divided into multiple-use cycles through assumptions, LCA will assess the three use cycles of the material individually. It will not evaluate the benefits that can generate from reuse. To identify the value or burden created by the reuse of secondary materials for a circular design, it is crucial to consider the actions taken at their EO(s)L (Cooper and Gutowski, 2015). The benefits of reuse can then be determined by comparing these actions to an alternate non-reuse scenario. Cooper and Gutowski (2015) further described that the impacts are the net effect of "additional processes" for their reuse and "avoided processes" that would have been required to make the product from new materials and to deal with old materials. Figure 23 shows the relevant stages identified in the product cycle for evaluating the impact of reuse. The reuse scenario entails the added process of waste processing and storage at EOL and avoids waste disposal and production.

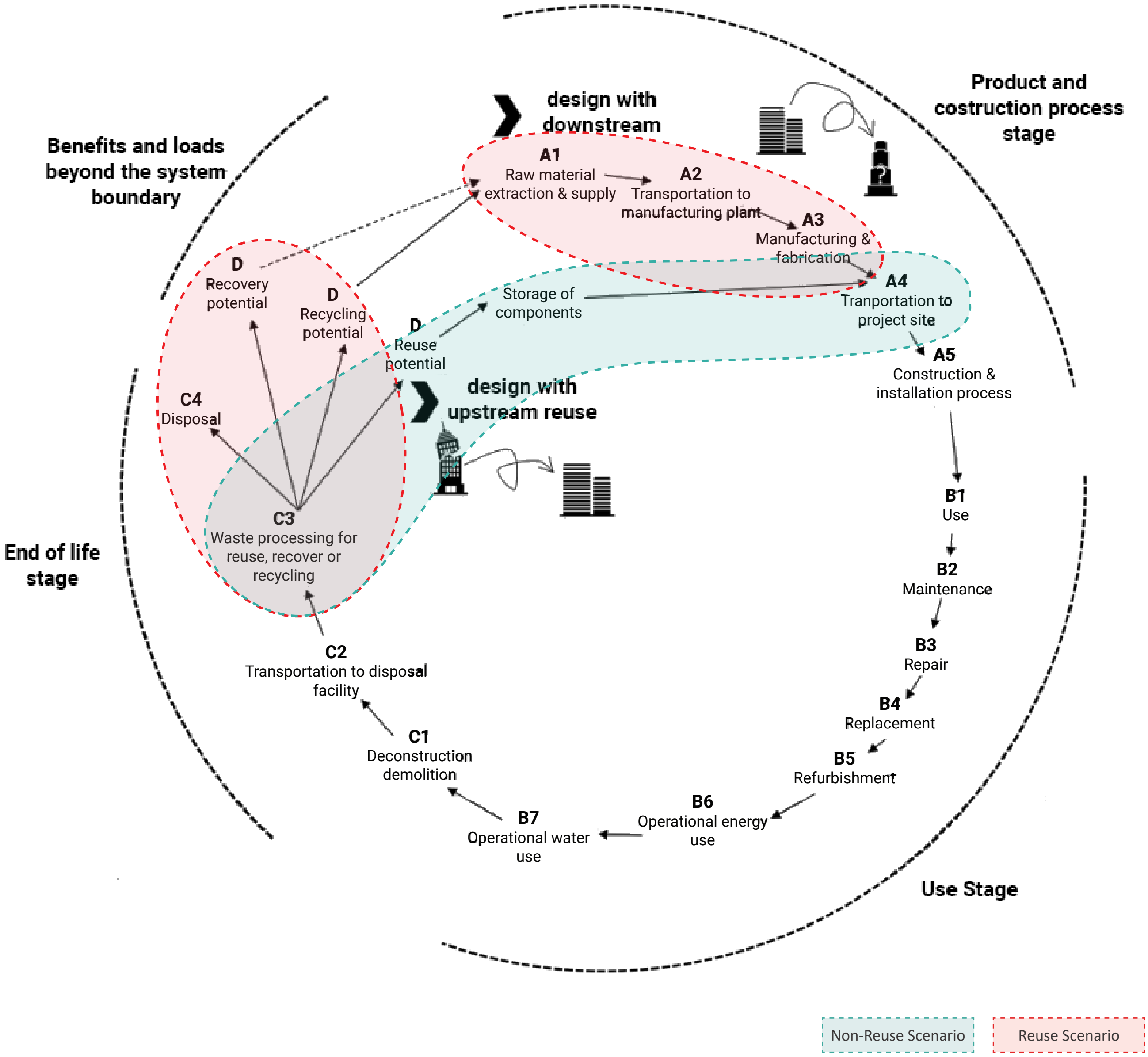


Figure 23 - Relevant stages for identifying impact for reuse and non-reuse scenario (source: author)

Bribián et al. (2009) described a simplified methodology as opposed to an intensive Life Cycle Assessment. The selection of impact categories is made to simplify the process for users such as architects and engineers. Additionally, the selected category considers the energy certification requirements and thus based on embodied energy and carbon emissions. Table 1 shows the selected categories for assessment and stages with lower impact on energy and emissions are neglected (Bribián et al., 2009).

Table 1 - Lifecycle stages for simplifies LCA (source: Bribián et al., 2009)

Stage		***Module***	***Simplified LCA methodology: stages included***
Product stage	**A 1**	Raw materials supply	Yes
	A2	Transport	Yes
	A3	Manufacturing	Yes
Construction process stage	**A4**	Transport	No
	A5	Construction-installation on-site processes	No
Use Stage	**B1**	Use	No
	B2	Maintenance	No
	B3	Repair	No
	B4	Replacement	No
	B5	Refurbishment	No
	B6	Operational energy use	Yes
	B7	Operational water use	No
End-of-life Stage	**C1**	Deconstruction	No
	C2	Transport	No
	C3	Recycling/re-use	No
	C4	Disposal	No

The assessment found that the product's embodied energy accounted for 31% of the total energy requirement during the lifespan of the building and is associated with the production rather than the use phase (Bribián et al., 2009). The identified stages of simplified LCA also overlap with the reuse stage identified in Figure 23 except the EOL stage. Therefore, it will be valid to consider the Production Stage and EOL Stage enough to assess the impact of reuse. Although, it is still recommended to run a complete analysis for the product's entire life cycle for an overall impact.

Wolfa et al. (2020) applied LCA for the environmental impact assessment of reused/recycled products in buildings and identified the following gaps in the current practice for evaluation:

- **Embedded Use Value** – The reuse efficiency depends on the actual function of the product and its embedded value. The assessment does not take into consideration the value of the product used in the next phase.
- **Storage and Transformations** – The reusable components are circulated and stored in between their supply and demand. The environmental impacts related to long storage are essential for the reuse assessment. Additionally, energy may be needed for transformations during reuse.
- **User-Owner Separation** – The user and owner do not remain the same throughout the service life. For a case of reuse, a shared dynamic between the players comes into play. A reusable product can have a Product Service System and thus requires the incentive to be shared.
- **Reusability** – LCA does not consider its ability to be dismantled or remounted. Reuse is not possible if a product cannot be dismantled in the first place and directly impacts future reuse.

These gaps are subjective to the reuse scenario and are reflected upon later in the design case.

6.3 Integration

MCI is a method for assessing the material inflow and outflow and its aggregation as a circularity score. However, it does not consider the factors affecting the input and output of materials in a product. The inflow depends on the value created from the R-strategy for material flow, whereas outflow depends on the physical and functional design of the product.

Disassembly Potential by Durmisevic is helpful for the assessing the product for its reuse potential. The reversibility of connections can be distinguished as a factor for the reusability of the facade components and significant for determining its circular value. Therefore, it can be used for defining the outflow of materials in MCI. However, this evaluation is suitable for guiding the design phase of the product to ensure future reuse, rather than assessing the degree of circularity of the exiting product.

Calculating environmental footprint using LCA for reuse is not the most appropriate method due to the lack of standards for evaluation multiple life cycles. Furthermore, the benefits of reusing building products can only be reached under specific conditions depending on the strategy adopted. It requires an evaluation of the net impacts to compare the different EOL scenarios.

6.4 Summary

There are numerous product assessment methods available in the academic literature. The ones considered relevant for assessing the reuse of secondary materials were discussed in the research. Some methods are applicable towards the end of the product design to identify the circular value and impacts, while others guide the decision-making process. However, no one assessment is all-inclusive for assessing 'Reuse' as a circular strategy. A combination of the circular assessments can be used at different design stages as per their relevance for achieving the defined goals. For example, the disassembly potential guides decision-making during the product design to ensure future reuse. MCI score is applicable towards the end to evaluate the restorative flow generated due to the product design. Finally, environmental impacts can be assessed to reflect on net benefits or load created from reuse. The assessments will further be elaborated in the research for their relevance for assessing reuse of facades, and gaps will be identified.

07.

CURTAIN WALL FACADES

The chapter presents a literature review on the typical curtain wall facade systems available in the market. It elaborates on the system design and outlines the functional and technical requirements that the curtain wall facade for an office building in the Netherlands has to comply with.

7. CURTAIN WALL FACADES

7.1 Background

Facades are a part of the skin layer in the building and act as a mediator between indoors and outdoors. They form an integral part of the building and directly relate to design, use, and building services. They account for one-third of the building's total embodied energy (Hildebrand, 2012) and up to 30-40% of the initial building investment (Leos, 2020). High demands on the building performance render the facade a complex building component consisting of multiple materials (Knaack et al., 2014). According to the current building trends, most buildings use systemized facades (Knaack et al., 2014). It means that specified parts of the structure comprise standardized components provided by facade suppliers. Systematized facades offer better control of the process, from the ease of design to a predictable construction sequence. It also allows manufacturers to test their systems for resistance against water, weather, air, and fire. These systems can be customized according to the design requirement of the projects. Few commonly used facade systems include wall and window systems, curtain wall systems, double facade systems, and integrated facade systems.

Over the years, research done on curtain walls has resulted in their structure reaching a state of optimization in terms of components, functions, and interfaces (Klein, 2013). However, the secondary facades made available today were designed 30-40 years back and did not have this optimization level. Therefore, their design is explained in the following section to outline the design criteria for reusing secondary materials for curtain walls.

7.2 Façade Design Process

Facade planning is an integral part of the design process and requires constant feedback (Knaack et al., 2014). It is a linear process consisting of several stages; these are - pre-design, architectural design, execution design, manufacturing, assembly, use, and EOL. Furthermore, each stage involves a different stakeholder whose role concerns designing, manufacturing, or assembling the façade, as shown in Figure 24. According to Klein (2013), the first three stages involve fixing the facade requirements and customizing the system design as per the architectural design requirements. Architects and consultants play the primary role in these stages. Facade manufacturers are barely involved at this time. After the design is fixed, the following two stages involve the facade manufacturers with the supervision of the architect and consultant from time to time. Next, the use phase involves the actual performance of the facade in the building. The last stage concerns the end-of-life scenarios and depends on the material selection and design by the architect and construction system employed by the engineer (Klein, 2013).

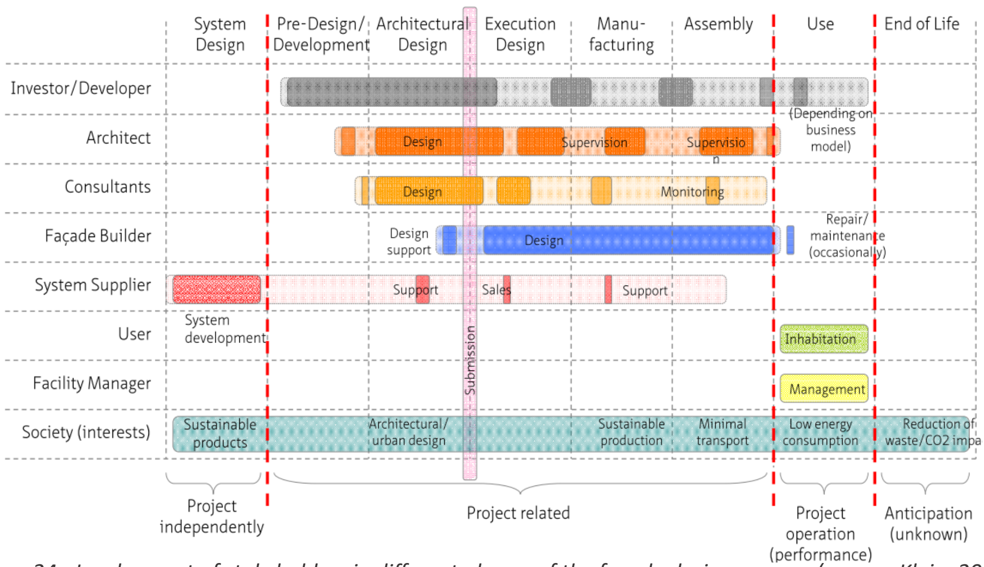


Figure 24 - Involvement of stakeholders in different phases of the façade design process (source: Klein, 2013)

7.3 Curtain Wall Facade System

A curtain wall system is a metal-framed wall system with a transparent / semi-transparent / opaque infill. The construction of curtain walls is entirely independent of the building's load-bearing structure and hangs in front of it (Klein, 2013). The system is designed only for loading conditions arising from self-weight and wind loads. Their design offers flexibility for customization for any project. The functional and aesthetic requirements are the deciding factors for the infill type. For office buildings, the floor-to-ceiling window height is maximized for the vision area using glass infill to allow daylight to penetrate in the interiors (Kawneer, 2018). Curtain Walls are a commonly used façade system for office buildings due to the following advantage offered by their design:

- A smaller façade footprint compared to the floor office area
- Lighter construction due to the non-load bearing system
- Flexibility in layout for open floor offices
- Maximized vision area to let light in for offices
- Fast and Easy installation due to structural independence

According to the type of construction, these can be divided into two - stick system and a unitized system, as shown in Figure 25. Stick systems are assembled on-site with prefabricated parts. It allows for adjustments on-site and provides flexibility for changes in design. The method is suited for small and mid-size buildings. For high rise, a unitized system is preferred where the entire wall system is prefabricated offsite and installed as a whole (Knaack et al., 2014). Offsite prefabrication results in high-quality production and reduces installation time on site. Other factors affecting the choice of construction include labor costs, availability of time, and transportation.

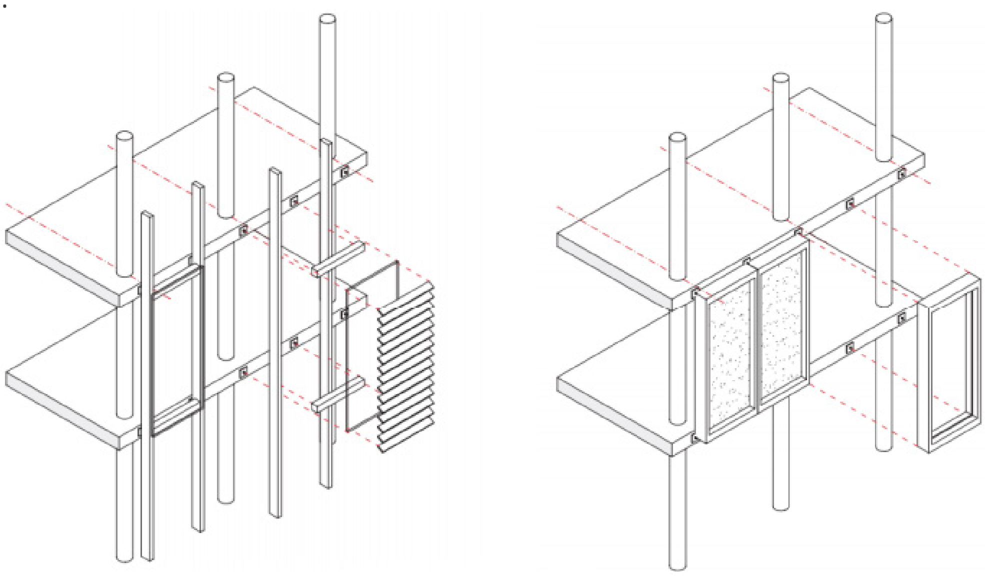


Figure 25 - (left)A stick system on-site with standard components and (right) a unitized system constructed as a series of factory-assembled components (source: Knaack et al.,2014)

The most commonly used materials for the curtain walls are aluminum, steel, and wood. Figure 26 shows the plan view of a typical curtain wall system in aluminum, steel, and a hybrid in timber and aluminum. Aluminum has been a preferred material for years for curtain wall systems due to the ease and flexibility of working offered by the material. Aluminum can be cast into long sections and varied profile shapes, easier compared to steel. However, steel is much stronger than aluminum and can support the necessary deflection with smaller profiles. Steel is often used to reduce overall frame thickness to create uninterrupted sightlines for a slender look. Hybrid systems in aluminum and timber are a recent addition to the curtain wall systems. Timber is used as the mainframe (mullion and transom), while aluminum is used outside (pressure plate) for weather resistance. The hybrid system matches the use of materials regarding the facade's architectural requirements and technical requirements. Even though different in appearance, the three systems adopt a standardized design. The physical and technical dependency of elements remains the same.

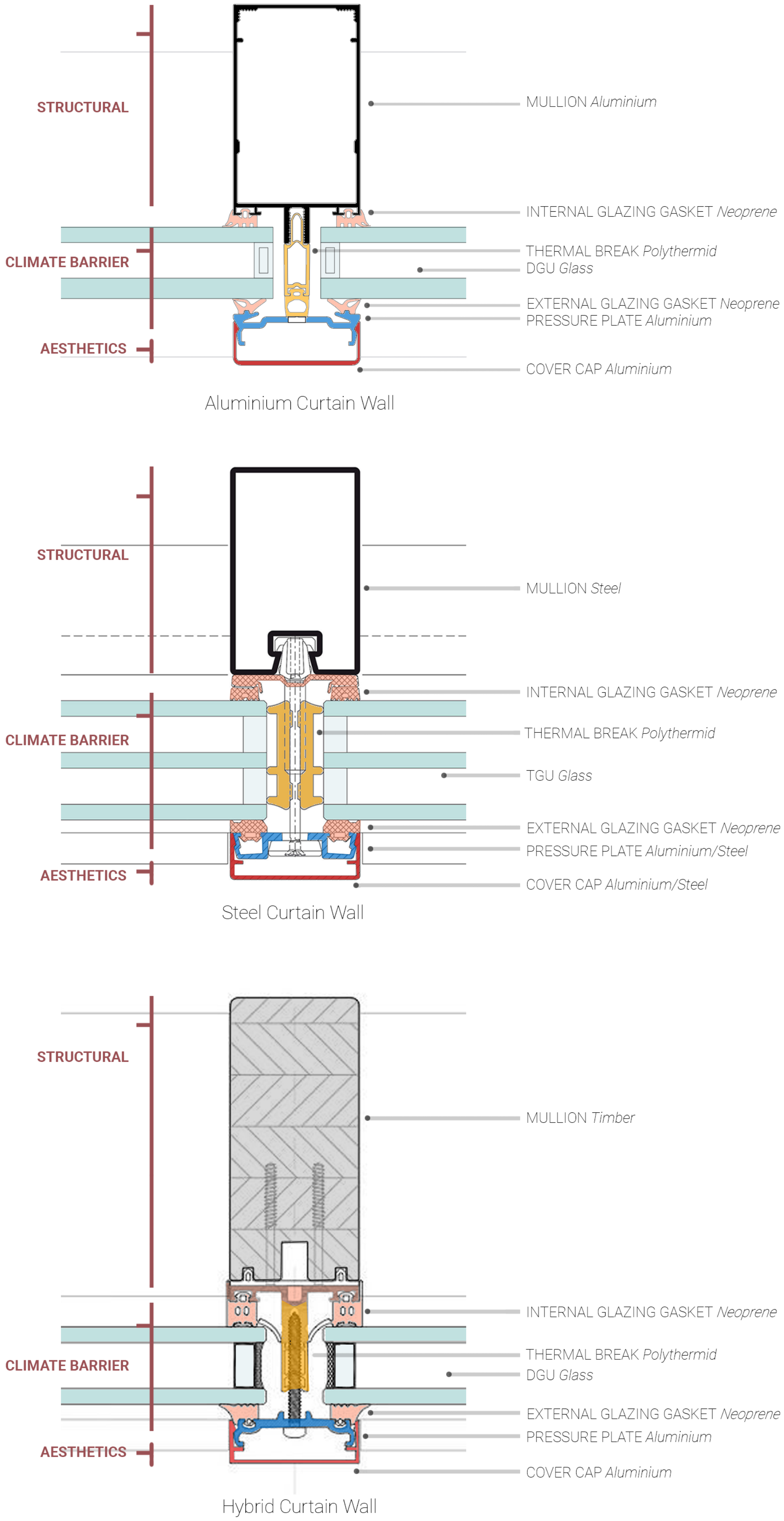


Figure 26 - Plan view of typical curtain wall system in Aluminium, Steel, and Hybrid of timber and aluminum (source: author)

7.4 Functions of Curtain Wall Facade

Considering that the quality and quantity of the secondary material supply can impact the facade design and performance, the system design should be adaptable to safeguard the material's value and reuse potential. It is, thus, logical to define what the facade can do rather than what the facade is (Durmisevic, 2019). The curtain wall has to fulfill the office buildings' technical and functional requirements, as shown in Figure 27.

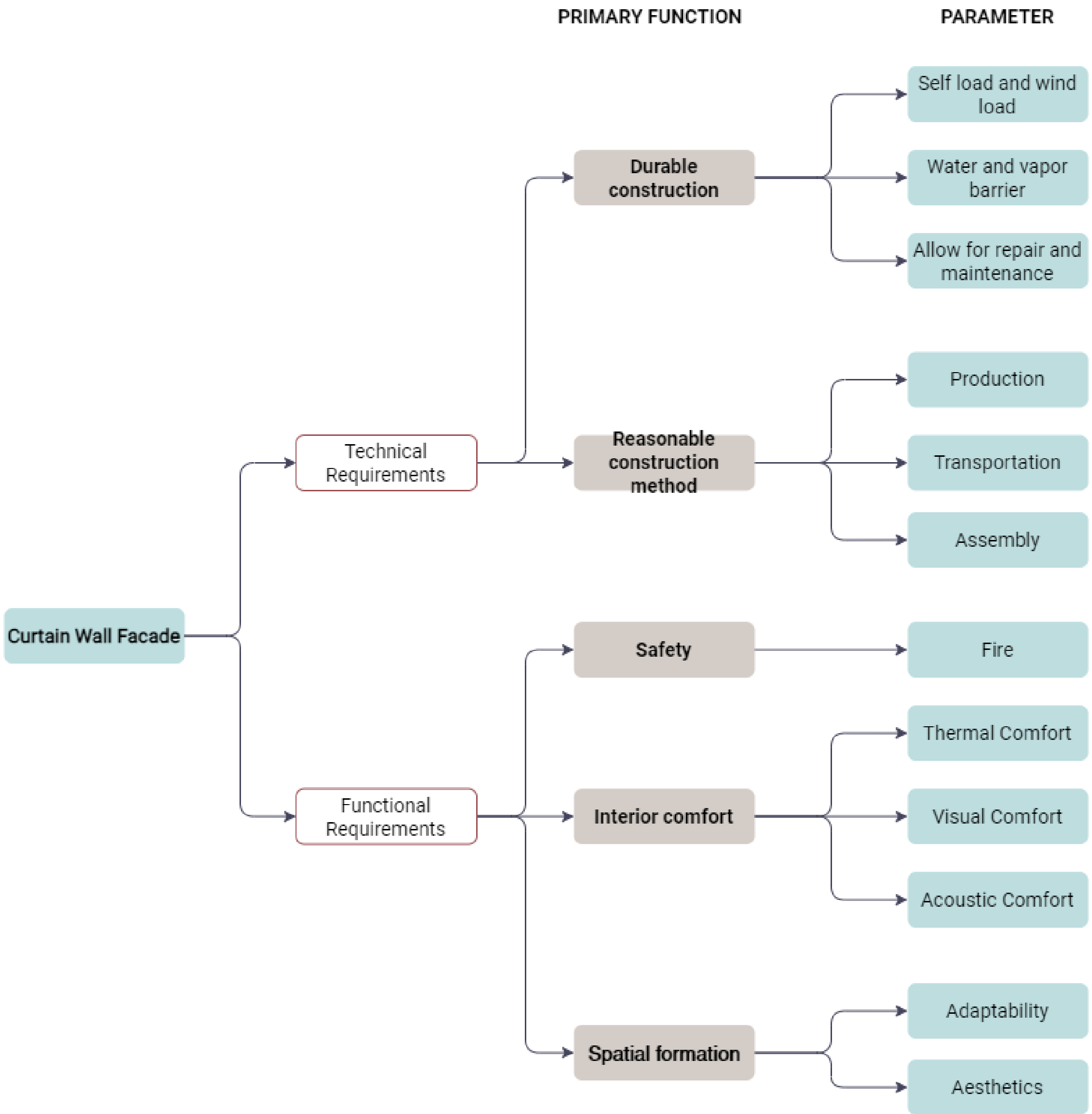


Figure 27 - Facade function tree for curtain wall facades for office buildings (source: adapted from Klein, 2013)

The functions are quantified by the parameters defining them; for instance, the facade has to take wind loads and self-weight for durable construction. Furthermore, these parameters must conform to at least the minimum performance standards specified by Dutch Building Decree Bouwbesluit. Although many buildings now aim towards Green Labels like BREEAM NL, these specify high-performance standards for efficient use. The presented research refers to the Dutch Building Decree (2019) for more feasible design solutions using secondary materials.

The following design outline, in compliance with Dutch Building Decree (2019), sets the requirements that the secondary materials have to comply with:

Durable Construction

Loading - Mullion needs to transfer the dead load of the panel acting downwards and wind loads acting perpendicular to the facade. Dead load depends mainly on the size of the panel and the glazing unit. Wind loads are specific to the region and height of the building and are specified in the Dutch Standards.

Water and Vapour Barrier - EPDM gaskets are used for sealing the system and provide water and vapor tight connection of parts. This component is highly integral in its function; it provides weather tightness and holds the glass in position. They are checked and supplied by the system supplier as per the section size.

Repair and maintenance - The façade needs to be accessible to allow disconnection of different components for additional repair and maintenance during the use phase of the facade.

Construction Method

Production Method - A standardized connection between the mullion and infill is essential to ensure that it can be adapted to suit both solid or transparent panels. Further, the interfaces and geometry edge define the reusability potential for the next phase.

Transportation - Transportation depends on the size and geometry of the panel. A panel of 6m - 9m can be easily transported in standard trucks in the Netherlands. A typical office façade in the Netherlands follows a width of 1.2m - 1.35m for the panels as per its structural grid.

Assembly - Unitized systems provide controlled product quality and ease in installation; however, stick systems provide greater design flexibility and on-site adjustment. The choice depends on the design, which can vary from case to case.

Safety

Fire Safety - It depends on the choice of materials for the curtain wall and the detailing of the fixing system for the curtain wall to close off any fire routes between the floors.

Interior Comfort

Bouwbesluit (2019) has set minimum requirements for the opaque and transparent components of the exterior building envelope, as shown in Table 2. A minimum requirement of daylight is defined according to the floor space. A maximum transparent façade area will allow light penetration for the interiors of an office. Glare control levels for visual comfort in offices require an in-depth study and are not elaborated in this research. It is presumed that internal blinds can be provided for glare control in the offices. The heat resistance and soundproofing requirements affect the selected glass type in the curtain wall.

Table 2 - Comfort requirements for facades (source: Bouwbesluit, 2019)

	Opaque Component	*Transparent Component*
U-Value		< 2.2 W/m^2K (window) < 1.65 W/m^2K (combined with frame)
Rc Value	>4.5 m^2K/W	
Soundproofing	>20dB	

Spatial Formation

The adaptability of the facade depends on program requirements and will be discussed when relevant in the research. Furthermore, various factors come into play with the aesthetics of the secondary materials for the façade, including designers' perception. However, this aspect is beyond the scope of the presented research.

7.5 Connections and Interfaces

According to Klein (2013), the functional structure of the façade depends on the physical components in the assembly. These components are connected by interfaces, which can be physical elements or just descriptions of a particular way of interaction (Klein, 2013). Some components can even perform more than one function and can be an integral solution, such as gaskets - for both water barrier and glass tolerance. The product architecture of facades can then either be integral or modular. The integral system consists of complex mapping of functions with physical elements, while the modular system consists of one-to-one mapping. Modular systems allow changing to individual elements without disturbing the assembly, such as a computer. In contrast, the whole product must be replaced in an integral design such as a laptop (ibid.). Figure 28 shows the complex mapping between the physical components of the curtain wall facade and its functions.

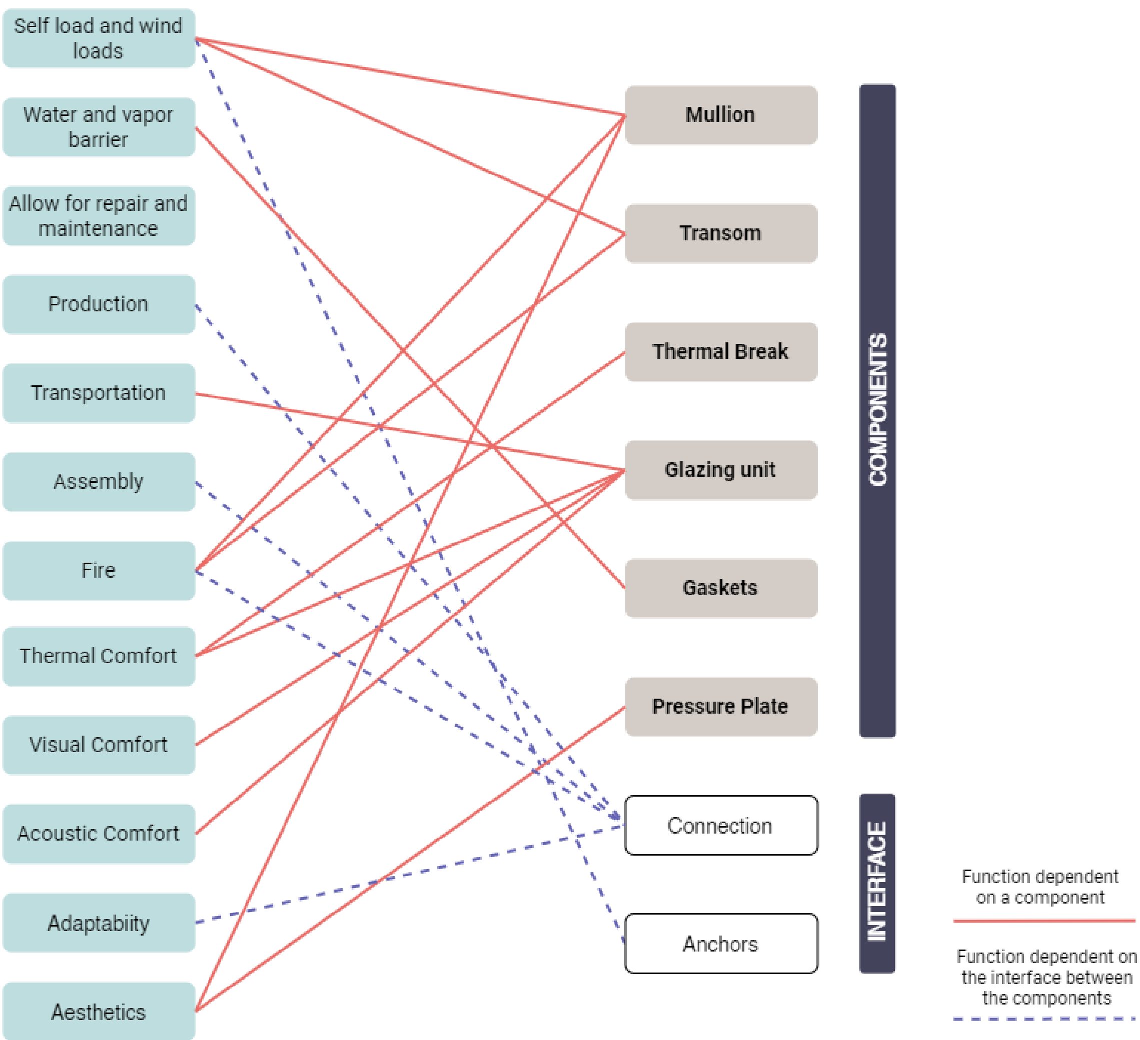


Figure 28 - Typical curtain wall components with associated functions (source: author)

7.6 Lifespan of Curtain Wall Facade

The different components in the curtain wall assembly have different lifespans. Table 3 shows the lifespan of various materials and components in a curtain wall assembly. Often, the ease of replaceability of the weakest link determines the product's life span and depends on this component's technical hierarchy and physical accessibility. The lifespan can affect the reuse of secondary materials in two ways. Firstly, for selecting materials that still have a remaining lifespan, and secondly, for coordinating the lifespans in the designed product.

Table 3 - Lifespan of different components in the curtain wall assembly, adapted from Leos (2020)

	Element	***Material***	***Expected Lifespan (years)***
Curtain Wall Assembly	Extruded profile	Aluminum	75
	Extruded profile	Steel	75
	Extruded profile	Timber	35 - 40
	Thermal break	Polyamide	40
	Rubber gasket	EPDM	30
	Glazing Bead	Aluminum	75
	Brackets	Steel	30 - 50
	Glazing Unit	Glass	25 - 30

7.7 Summary

The product level focus of the presented research, curtain wall façades, has a complex structure. Therefore, it is relevant to address these complexities to approach the design problem systematically. The functional and technical requirements of the curtain wall facades require examining the product as a system constituting multiple materials and components with different lifespans. It guides the design using secondary materials on three levels - selection of reusable components in the curtain wall, design of fixing system for future reuse, and minimum requirements that the façade has to comply with for its technical feasibility.

08.

MARKET SCENARIO FOR REUSE IN THE FACADE INDUSTRY

The chapter presents field research on the market scenario for reusing secondary materials for facades in the Netherlands through interviews, material flow and inventory analysis, and a case study. The identified challenges are critically evaluated to propose design solutions for reuse.

8. MARKET SCENARIO FOR REUSE IN THE FAÇADE INDUSTRY

The research approaches the investigation of the market scenario for reuse in the Netherlands through multiple methods. Primarily it includes findings of semi-structured interviews with actors currently working with secondary materials for their reuse. Further, a study of the harvest map set up by ODS for its products and secondary market of timber set up by Buurman Rotterdam analyzes the type of materials available, their quality and conditions, and treatment required to make them reusable. Lastly, a case example for reuse is analyzed where the façade from a building could be reused at another location through remanufacturing.

8.1 Semi-structured Interviews with Industry Representatives

Various people were approached for a semi-structured interview to recognize the market scenario for reusing secondary materials in the Netherlands. The interviews aimed to highlight the pre-requisites for material reuse and investigate the reuse approaches. The interviewees were chosen based on their contribution to the reuse process. They are either a part of the ODS value chain for the project titled "Cooperation is Key" or independent players in the market actively working to reuse materials in the built environment. The former project aims to establish a market for secondary facades through a collaborative platform between the stakeholders.

Table 4 shows the list of interviewees with their organization, position, and role in the research. The questions drew input from the literature study and were formulated specifically to the role of the interviewee. Details regarding the relevance of each interviewee and the interview transcripts can be found in Appendix A. The findings from the interviews were analyzed, and three main themes emerged - the practice of reuse of materials, reusability of different components within the curtain wall, and remanufacturing steel profiles for new facade for reuse. These are discussed in the following section.

Table 4 - Interviewees and their relevance to the research

Interviewee	***Organization***	***Role in organization***	***Relevance in research***
Ron Jacobs	Kloeckner ODS	Brand and sustainability Manager	Material Reseller
Marie-Sophie Res	A lba concepts	Circular Buildings and Environment Consultant	Circularity assessment company
Tessa Bloembergen	Buurman Rotterdam	Interim Management	Market for secondary materials
Astrid Heystee	Circular Marketing Solutions	PR for the Harvest Bay Project	Marketing
Emile Kranendonk ***Antonio van Tienderen***	Kloeckner ODS	Supply Chain Manager	Reverse supply chain
Renee Schuurman ***Martijn Schuurman***	Blonkstaal metal worker	Owner	Façade Remanufacturer
Erik Koremans	New Horizon	Director for Material Balance	Urban Miner

8.1.1 General Assertions on the Practice of Reuse of materials

The critical findings from the interviews and how they inform the reuse process are discussed below:

Requirements of Material Supply for reuse

- All interviewees indicated the importance of identifying materials before demolishing the building as an essential step for reuse. Hence, setting up harvest maps by the manufacturing companies for their products can become one way to identify and source materials. Currently, the façade manufacturers and buyers only meet and communicate during the sale of the product. As a result of this limited interaction, the manufacturer has no more extended access to the product or information about its use location and performance over the use phase. The only source of information is sale receipts from projects and other internal documentation in archives. Communication with the client to ensure they stay in the loop is essential for tracing materials available for reuse. Since this is not feasible for the already in-use facades in the building stock, a different approach is required to incentivize material harvesting for the current owners. It can be through a state-regulated demolition permit mandating harvesting the materials or a monetary incentive in the form of tax reduction for harvesting materials for the building owners. It will ensure that the materials are harvested and actively supplied for reuse before becoming a wasted resource.

- Multiple interviewees indicated that identifying a material source for reuse does not necessarily entail access to it. Gaining access to the building requires a transfer of ownership to ensure a consistent material supply. It can help scale up the reuse approach from a project to an industrial scale. It entails a shift in the ownership of resources from the current building/resource owner to an actor working with an established reseller or producer network in the market.

Storing materials for reuse

- An interviewee mentioned that the secondary material suppliers generally collect, store, and sell materials with high resale value and are attractive to the buyer. It ensures that the materials in the storage keep rotating faster. The storage then becomes a mere step in the process until the identification of a suitable buyer. If a material or product that is difficult to reuse or the methodology for its reuse is not in place, storage will become a limiting factor in the chain. The material will take up space until its reuse is identified, adding to storage cost and limiting the space that could have otherwise been used for materials sold faster. Besides, a material stored for a longer duration until its reuse is identified would add pressure to extract virgin resources in its place that otherwise could have been recycled. It would mean a material that can no longer find high-value reuse within a fixed duration of time would potentially save both storage cost and added extraction energy for the virgin material through recycling.

- An interviewee indicated that when the materials are sourced from various locations, it is beneficial to leave the materials at their original site until they are required to remove/shift the stock. It could either be the facility of the raw material supplier with production waste, at a façade builder’s premise with overstock, or a vacant building with reusable facade components. It ensures no added cost and emissions during transportation to the warehouse for its storage. This approach cannot create a physical market for reuse; however, it can create a virtual market for materials even before they are physically available for reuse. It will save a lot of time and logistics by already reserving the materials for reuse.

Ensuring future reuse of materials

- Interviewees indicated that lack of information about the performance during the use phase inhibits the reuse of materials at the same value. Hence, to ensure that the material continues to find a high-value reuse cycle after cycle, assigning the material identity and monitoring its performance over the use is a pre-requisite. For short-term reuse, the product can be designed by predetermining a future reuse scenario and accommodating that design requirement. For long-term reuse, one can only suggest how a material can be used, but its actual reuse will depend on the circumstances at that time and the person responsible. Providing information regarding what a material is and what a material can do will help ensure its reuse in this scenario.

Assessing reuse

- Interviewees indicated that the circular value of reuse depends on the percentage of reuse components, product design, and detachability from the construction. Furthermore, how reuse affects circularity requires evaluating the total Life Cycle Impact for reuse, including where the material is coming from and how much energy is required to release it.

Business case for reuse of materials

- All interviewees mentioned that the operational cost for retrieving and storing the materials and logistics regarding the clear division of work could be high, especially when one does not know when the opportunity will arise to sell it. In addition, methodology for making the material reusable can require investment in technology, procuring certification for the material, and marketing strategy. Thus, developing a business case is essential to facilitate the reuse of materials. It includes specifying the role of actors and defining economic benefits for each.

8.1.2 Reusability of different components within the curtain wall

Curtain walls consist of multiple materials and components, and few have higher reusability than others. From the interviews, the reusability of the different components identified is described below:

- **Steel mullion** is fixed on the interior part of the system and has a high potential for reuse due to the longer lifespan of the material.

- **EPDM gaskets** have perforations, which are seldom the same for two facades and are often destroyed while dismantling. Besides, EPDM fixing is relatively new, and the facades made available from existing buildings can constitute structural sealants that are harder to separate.

- **Aluminum cover caps** are sensitive parts and usually break if not handled carefully during dismantling.

- **Aluminum pressure plates** are secured inside the cover cap and are almost 100% reusable due to the longer lifespan of the material.

- The lifespan of the **Glazing unit** is the shortest compared to other components and defines the lifespan of the curtain wall. The component consists of a glazing bead and glass and has an industry-specified average lifespan of 25-30years. The gas between the panes expands and contracts due to reaction to the temperature, further expanding and contracting the glazing bead (KLG Glass, 2020). Over time, the seal breaks and reduces the glazing efficiency, giving it a shorter lifespan. Moreover, contamination of glass during its use phase makes it difficult to separate for reuse. The separation of the glazing unit into standard material and delamination of the glass requires a large amount of energy for reuse compared to its primary production. Additionally, constant upgrade in its energy requirements as a climate barrier makes it difficult to reuse directly. Therefore, their reuse comes with a different set of challenges, requiring research in itself. They will not be discussed in the presented research due to the limited time frame.

8.1.3 Remanufacturing Steel Profiles for New Facade

The incoming material stream from the existing stock necessitates material inspection followed by processing to bring the material to a suitable level to work. Moreover, the inspection is specific to the material reused. Based on the discussion with the ODS Supply Chain Manager and Blonkstaal Façade worker (Appendix A), the following points highlight steps essential for remanufacturing steel profiles for a new facade, and are summarized in Figure 29:

- Steel is used not only for structural members of the building but also for non-load bearing facades due to their sleek shape and slender profile. Their reuse for structural purpose generates questions regarding the stability of the structure and the safety of the people. It requires an assessment and certification by the concerned actors in compliance with the building codes. Reuse of steel in non-load bearing facades does not require as high a safety factor as structural steel. The purpose of the element is only transfer of loads and can be feasible with secondary materials.

- The first step to reuse steel involves a physical inspection to verify its dimensional properties and assess damages. The Facade Builder mentioned that the damages usually occur at the end of the profile near the connection points and can be visually assessed. These ends and other damaged parts are removed before reusing the material. Additionally, the steel profiles and sections derive their strength from their cross-sectional shape and cannot be changed without prior testing of the new section.

- Furthermore, most resellers of structural steel components, including ODS, cannot formally attest to the resold product's technical capabilities. For example, the fatigue loading that steel might have undergone during its use is unknown and requires testing the element's molecular position to attest. Nonetheless, they are entitled to provide an opinion as per their observation and experience, which can be helpful to gain insight into the material.

- The material needs to be handled carefully, especially for polluting and toxic elements that it might contain or contact during its use. Previously, the steel facades were fixed with mastic adhesive for keeping the glass in place rather than beading. It usually contained a percentage of asbestos. It requires a specialized company that can carefully remove the polluting components from the material. Other contamination may include foreign elements such as bolts, welds, fasteners, and end plates. Removal of connections from the steel is possible through surface grinding to get a smooth finish for the steel profiles; any perforations can be filled in through welds. The connections and perforations do not affect the profile's strength, and removing or keeping them is usually a design choice made by the architect. New perforations can be added, and connections can be bolted or welded on top.

- The steel profiles usually have coatings from their first use. The coating life is not as long as the material itself and requires removal and addition of new. For this, they are dipped in a solder bath to remove their coating, followed by adding a three-layer zinc coating. The coating is also the determining factor for its lifespan and warranty for subsequent use.

- Connections play a critical role in fixing a façade. The connection is designed for a fixed use cycle and needs testing for its efficiency and performance. They are exposed to high wind and dead load acting on the façade and may require an upgrade. Besides, the connections used then may be outdated or incompatible with the construction systems used today.

After processing the profiles and making it suitable for reuse, the sections can be cut to the required lengths according to the technical drawings. Then, they can be built with gaskets and new connections in the factory. Finally, any shortage in the secondary material is dealt with their primary substitute.

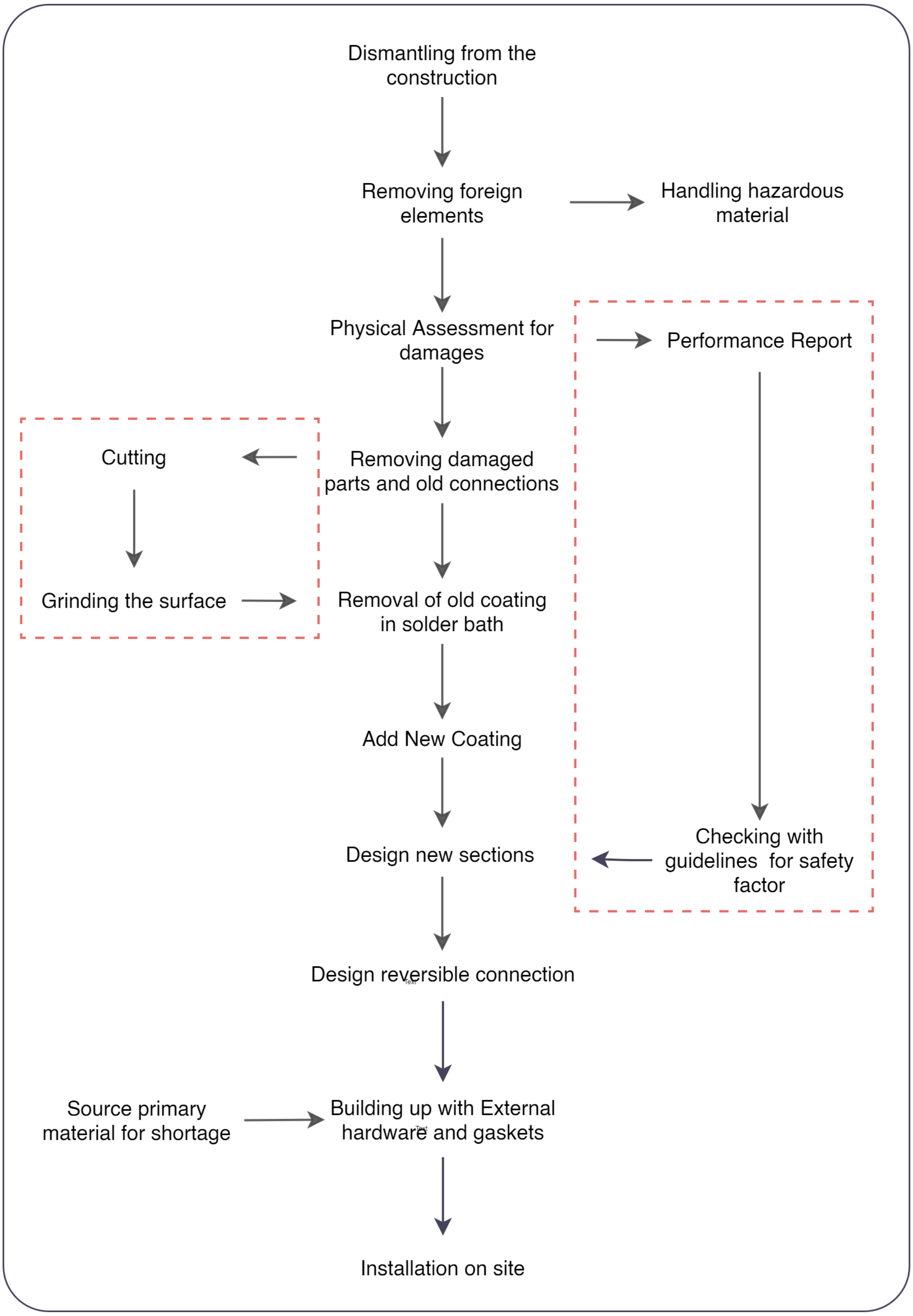


Figure 29 - Steps for remanufacturing steel profiles for new facade (source: author)

8.2 Analysing the Material Inventory

The market for secondary materials can vary from seller to seller. Every company operates differently as per its business model, having its specialization and set of actors involved. Two markets for the secondary stream, ODS and Buurman, are selected for further research. ODS is developing a market for secondary facade products. Their harvest is studied to analyze the various materials available for reuse in facades through an inventory analysis and mapped for their existing material flows through interviews. Buurman has established a secondary store for reclaimed timber. The materials are not specific to the functional layers of a building. Due to their market experience in procurement and distribution of secondary materials for quite some time, they are studied for their material flows. It must be noted that material inventory was studied through their online web stores, as the current stores are closed due to the Covid-19 lockdown in the Netherlands. Furthermore, the material inventory keeps rotating as per the incoming stream, and it is available only at the moment in time. The material inventory was investigated in February 2021.

8.2.1 Klockener ODS by Jansen

ODS is a distributor of steel windows, doors, and curtain walls for the Swiss Company Jansen in the Belgian and Dutch markets. Their current role includes the fabrication, storage, and distribution of the products. Additionally, they offer engineering and technical advice to the architects. The company is establishing a secondary facade market to ensure a circular business model for its products. ODS has recently established its harvest map, which already exhibits some of its products available for reuse. They are now expanding the initiative under the Flanders Circular “Circular Building: Cooperation is Key,” funded by the Belgian government by setting up an open-source Harvest Bay Platform with their partners.

Harvest Bay

Harvest Bay consortium consists of Harvest, Design, and Build partners to set up a second-hand shop for facades. Currently, the following key partners are involved in the project:

- Technical Consultancy/Architect - Bureau Bouwtechniek
- Façade Builder - Lootens
- Raw Material Supplier - ODS
- Demolition Company - Franck
- Secondary Material Store/Workshop - Buurman Antwerp

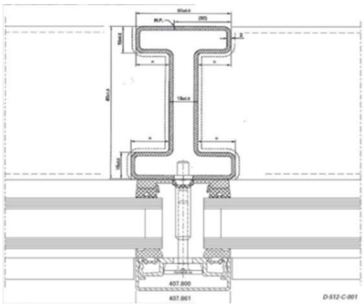
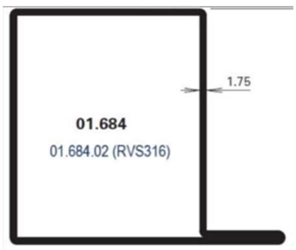
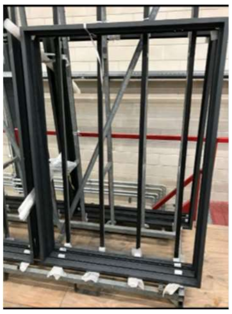
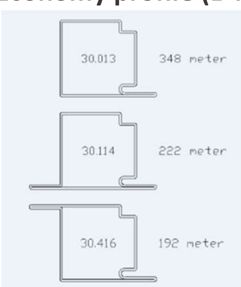
Harvest Bay is a cooperation working on commercial projects with secondary materials. Another layer above this is the Harvest Bay Foundation, which will include research and development with the government to tackle reuse challenges for the benefit of the industry.

Available materials in the harvest

ODS has already done a few projects through the Harvest Bay chain. In an interview with Ron Jacobs, Brand and Sustainability Manager at ODS, it was highlighted that the products in their harvest are not limited to the end-of-service-life resource from the existing building stock. Other profiles such as the overstock and the production leftover of new profiles also end up on their harvest map. Many a time, a project requirement can demand a custom design for a profile. These are produced in a minimum quantity of 3000 m running length, usually resulting in an overstock of material. Besides, cut pieces are often left during the manufacturing of new profiles due to their standard dimensional size. These also add up to the production waste of facades. However, one significant difference between the two streams is the extraction process of the profile for its reuse. For the former source, they dismantle the façade from the building, while for the latter, they just purchase back the material from their customers and transport them to their warehouse.

The research studied the current material inventory in the harvest map of ODS. The harvest map is still under development and does not reflect all the different materials in their stock and consists primarily of construction overstock. Table 5 shows the documentation of their material inventory, suitable for facades and available in significant quantity as of 18th February 2021. An inventory analysis showed that the products include façade and construction profiles, doors, windows systems, and frames. Few products are available as a complete system, such as doors and windows, and can directly be reused by identifying the new buyer. Others require remanufacturing due to their availability as components, such as façade profiles. Furthermore, the harvest map does not provide relevant information for most materials, including construction and performance detail of the material. Direct reuse of these materials is, thus, not possible by the users.

Table 5 - Documentation of available materials in the harvest map of ODS (source: https://www.jansenbyods.com/oogstkaart/)

Available product	Use	Source	Form of harvest	Information available
I Profile 	Façade Construction profile	Construction Overstock	Standard Material	Quantity, size, finish, price, Nibe certificate, construction detail
Economy 60 RVS 316  	Jansen Door and window profile	Construction Overstock	Standard Material	Quantity
Janisol ARTE 	Window frame	Construction Overstock	Component	Quantity, Construction drawings
Economy profile (L-T-Z)  	Jansen Door and window profile	Construction Overstock	Standard Material	Quantity, dimensions

Janisol Window 	Fixed Window	Construction Overstock	Assembly	Quantity, Construction drawings
Skellet Profile 	Construction Profile	Monitored during use and will be available in future	Standard Material	Quantity

Material Flow

The materials are sourced by ODS from several locations, each involving a different approach. Figure 30 shows the different inflow and outflow of materials in their harvest map. ODS contacts its clients for the overstock of material and gives out a form to fill about their surplus materials. After this, a price for the material is negotiated. This price is usually between the material's scrap value and the original selling price to ensure both parties benefit from this sale. Next, for their products in the existing buildings, the owner or the facility manager is contacted. It is usually done by a manual approach of checking the existing sales receipts and archived magazines, identifying if the building is still in use, and finding out the ownership through the building's facility manager. Furthermore, ODS also provides maintenance service for some projects and has information regarding products up for renewal.

ODS then identifies new clients (architects) to devise a suitable method for reusing their products - repair, refurbishment, remanufacturing, or collection of façades for reuse in other projects. The dismantled products are available for reuse through their open-source harvest map. Architects or engineers can directly contact the supplier through their harvest map to get advice and other information regarding the material. Until then, ODS provides storage for materials available. The façade is built up according to the required design at their façade builders' facility. While some of their customers are already on board to build with secondary materials, most are not.

The intention for using a secondary stream usually begins with the circular design motives of the architect or the client, which makes ODS partner up with circularity assessment companies for their products. They also work with third-party material database providers such as Cirlinq for their material passports to monitor the use phase of the secondary stream. Furthermore, through maintenance service and take-back systems for their new products, they are trying to create a consistent supply of materials in the future.

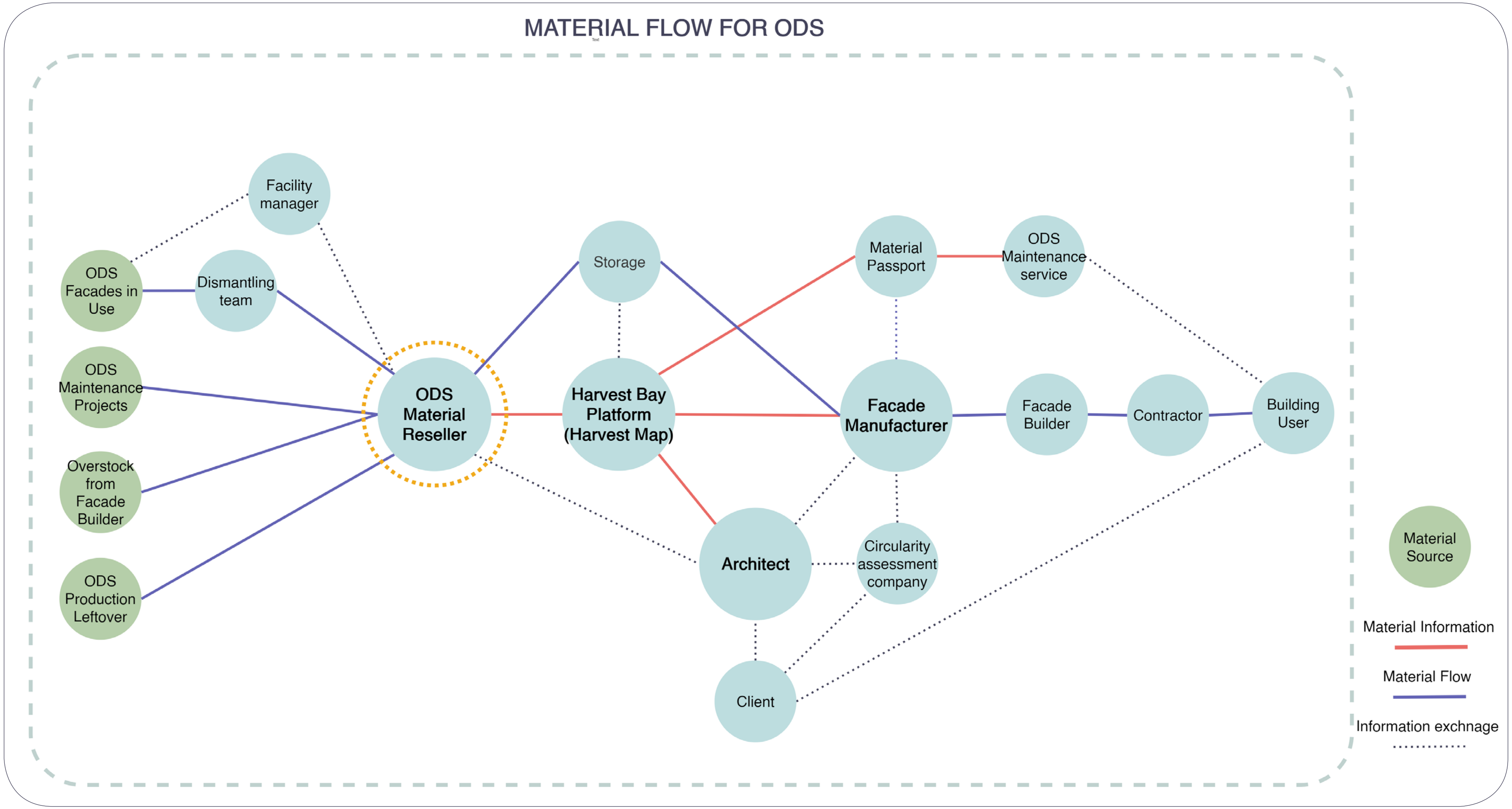


Figure 30 - Secondary Material flow for ODS (source: author)

8.2.2 Buurman, Rotterdam

Buurman is a secondary market for reclaimed components for local use and specializes in reused timber. Their current store offers storage for materials and a workshop that the locals can use for building their stuff. They collect materials which are seen as a waste by building industry, harbor and milling factory. Buurman sells these materials in the shop and provides advice and courses in furniture making so that consumers know how to build with the reused materials. They aim to give a longer life span to existing waste by reusing them again locally.

Available materials in the store of Buurman

Buurman is selective in its material choice for the inventory and does not sell every secondary material supplied to them. Tessa Bloembergen, responsible for Interim Management at Buurman, mentioned that they sell materials that are attractive to their buyers and have a high market value. The size, dimension, and type of wood keep varying depending on the material supplier. Specific forms of wood - beams, boards, and slates are primarily available in the store. Other secondary products in their stock include wooden sections, doors, windows, and steel hardware.

Spruce Beams

Spruce Boards

Hardwood beams and planks

Pine Beams

Douglas Beams

Dutch Douglas Boards

Figure 31 - Different types of timber available in the Buurman store (source: https://www.buurmanrotterdam.nl/buurmanmaterialen)

Material Flow

Buurman is a reseller of timber and works with regular suppliers monthly. These include construction companies, museums/art studios, and material suppliers for the harbor. In this way, they become a waste processing company for their suppliers. Other sourcing channels include collecting material from local users through Buurman containers placed at waste collection points. They only collect clean materials from the suppliers to limit the energy, labor, and time that comes with processing on their part. A social enterprise helps them with preliminary processing such as de-nailing, plaining, and cleaning on a fortnightly basis. The target audience includes local customers and small-scale projects.

They do not work with material passports due to the extra time required. Furthermore, the materials' application is mainly indoors and does not require additional certifications, making it easier to sell secondary materials. They prefer providing information about the materials through advice and workshops physically from their store. There is a web store for customers to select materials; however, it does not show the exact quantities and available sizes. Figure 32 shows the different inflow and outflow of materials in their store.

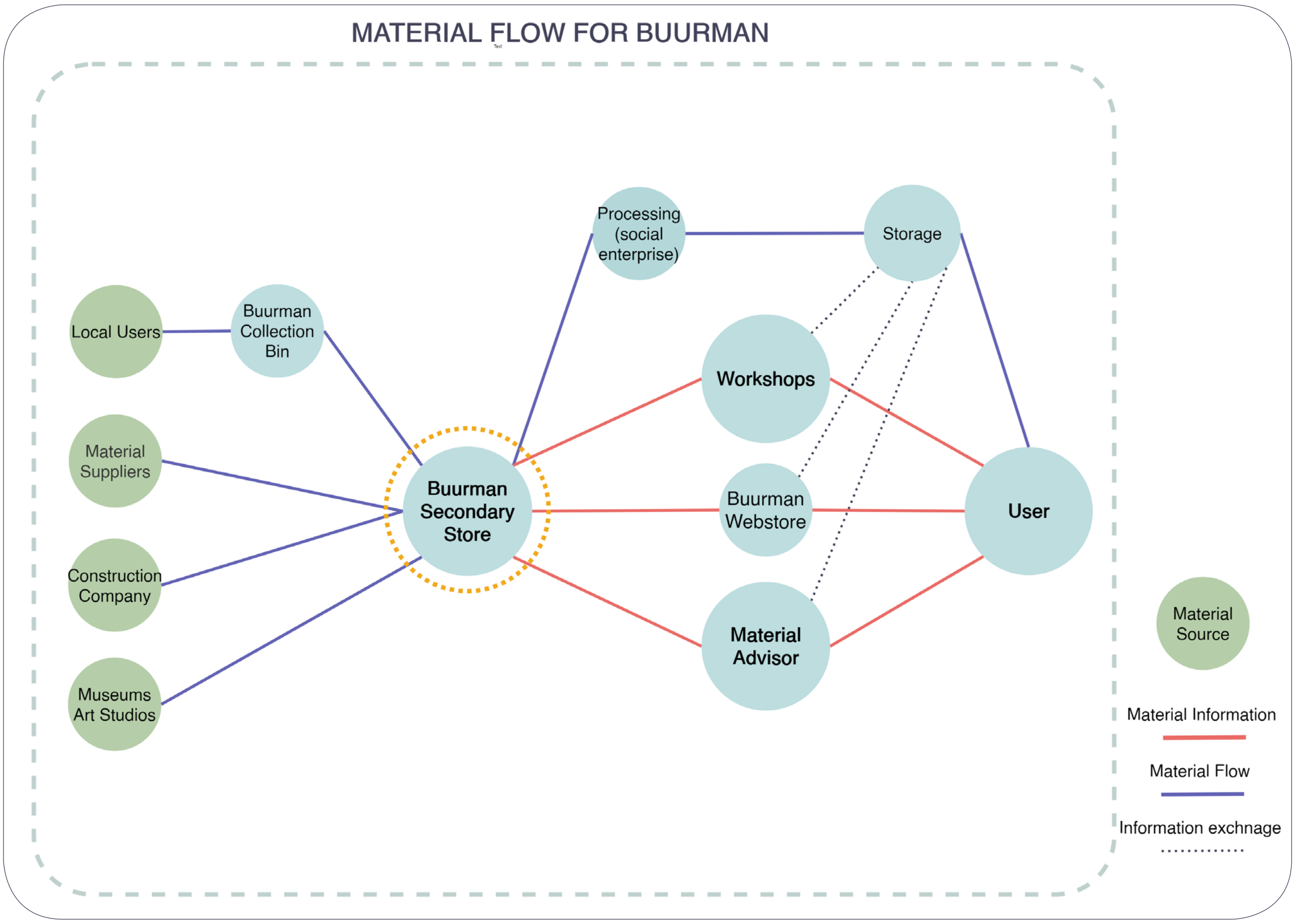


Figure 32 - Secondary Material flow for Buurman, Rotterdam (source: author)

8.3 Case Study: Brussels to Leiden Façade Reuse by ODS

Figure 33 - (left) Mockup facade for Gare Maritime, Brussels, and (right) Reused façade for The Field, Leiden (source: Harvest Bay Platform)

Neutelings Riedijk Architecten and Bureau Bouwtechniek proposed a demountable curtain wall façade in steel for the Gare Maritime in Brussels, Belgium. A part of the façade was constructed with steel profiles and a few glass panes for the mockup by the façade builder Lootens using the ODS steel profile, as shown in Figure 33 (left). The mockup was in use for approximately two months, after which it came to a premature End of Use due to its defined use function.

The contractor decided to demolish the façade due to a requirement of its clearance within three days. However, raw material supplier ODS identified that the façade held a high value for its reuse. Due to a short-term extraction requirement, an in-house logistics team of ODS arranged for its dismantling. The façade was constructed without any gaskets and sealants and did not require any expertise with its dismantling. Five people deconstructed it within a day and transported it back to their warehouse in Barendrecht, Netherlands. The transportation to the site and back to the warehouse between the two countries resulted in high transportation costs.

The product was put up on ODS's harvest map (an online platform) with its original construction drawing to identify a new use for the façade. As there was no suitable project predetermined for its reuse, the components were stored in the warehouse for approximately a year, adding to its storage cost. The product found a new use for The Field project in Leiden. It is a circular hotspot that showcases circular building opportunities. The project's intent made the reuse of the secondary façade a viable option. ODS worked as a link between the architect and the new façade builder, Blonkstaal, and transported the material from the storage to the remanufacturing facility in Schoonhoven.

The architect provided a rough sketch with the desired look and opening required for the façade, and technical detailing and adjustments were within the façade builder's scope. The size of the new façade was smaller than the mockup and required changes. Two technical draftsmen analyzed the existing construction drawings in the façade builder facility to identify reusable components and make a façade suitable for the new project. It was followed by cutting and resizing the façade as per the new technical drawings. It involved removing damaged parts close to the connection and adding new perforation on the top of the new length profiles. The connections for fixing the façade were reused. Two factory workers built up the complete façade with EPDM gaskets and external hardware in the factory. The hardware and the steel profiles were 100% reused from the available stock. The shortage in material, two glass panes, were ordered new from the primary material supplier. No additional changes were required in the coating as the product was not in use for long in the first phase, and the coating was still in good condition. They packaged and supplied material to the site in Leiden, where it was finally installed in place by three people.

ODS collaborated with CirlinQ, a material management database, to ensure that the product could still be reused in the next cycle. The façade has a material passport in the form of a QR code to monitor its use phase. However, the time required to identify a project and material handling in the hands of multiple actors resulted in an economic cost higher than the client's budget. As a solution, the façade is leased for five years (defined use span) and will be collected back by ODS afterward. Figure 34 shows the remanufacturing process of the facade.

Figure 34 - Remanufacturing of the facade at the Blonkstaal Factory and installation on site (source: Blonkstaal Facade Builder)

8.4 Lessons Learned

As can been seen from the market analysis, there are several barriers with direct reuse of secondary materials for facades. Identifying and critically evaluating these challenges is essential to ensure material reuse at the highest value. Therefore, the research draws the following set of critical design challenges based on the interviews with industry representatives, evaluation of ODS's and Buurman's material inventory, and an analysis of the case study:

- **Lack of information** - A lack of information about the previous use condition limits the direct reuse of the facade. It includes the performance of the product in terms of its loading design and thermal resistance. Furthermore, repair and maintenance information over the product's use is essential to determine its residual value. The only information about the materials from existing building stock is available from the supplier's sales receipts, often limiting to provide enough information to reuse facades.

- **Wear and tear affecting safety** - The material undergoes wear and tear over its use phase due to exposure to external and internal surroundings which can affect the safety of the facade. It includes corrosion, degradation due to UV exposure, or discoloration due to chemicals. These conditions are dependent on the building function, location, orientation of the facade, and maintenance over its use phase. Moreover, the material is susceptible to damages during dismantling and degradation due to the fatigue loading over its use phase. These properties cannot be inspected visually and require a proper testing facility to reuse the profile in a similar situation.

- **Inconsistency in supply** - The supply of material stream from the existing building stock is inconsistent in quantity, quality, and shape. Additionally, the incoming stock is available only after identifying a source, making the stream unpredictable.

- **Customized products** - The project requirements often result in the customization of facade dimensions. It is seldom a case where one can find a new project with the exact specifications. As every project has its requirements, direct reuse cannot be assured. Furthermore, many projects use customized profiles that may not comply with the connections designed today. Therefore, it is difficult to identify a buyer or a project to reuse the façade as is.

- **Obsolete Performance** - Many profiles from the current building stock and manufacturer's overstock turn obsolete when made available for reuse. The manufacturing companies keep upgrading the products based on upgrading standards for energy performance, new connection systems, or aesthetic upgrades in section sizes, rendering the old profiles outdated. Even though the profile may not have damages over its use phase or maybe straight out of overstock, it cannot be added to the current supply of profiles directly due to its obsolete performance or discontinued accessories for its connection.

The research formulates design solutions to organize reuse of secondary materials for facades from the identified, and summarizes in Figure 35:

- **Material Inspectors** - Most resellers of material cannot formally attest to the technical capacity of the materials due to a lack of information. However, an inspector can be hired to physically assess the material based on their experience and report its performance. In addition, they can be involved at various stages in the process, including deconstruction of the façade product, which can help them commit or advise on the quality of the batch.

- **Sufficient safety margins** - To overcome the degraded performance of the sections, profiles can be over-dimensioned for sufficient safety margins during sizing calculations. However, defining the percentage of margin will require testing or assessing the components by an expert. A common database for tested façade section sizes and guidelines for safety measures can become tools to overcome any uncertainty about reusing materials.

- **Form of supply** - The supply from the existing building stock is inconsistent, and the harvest will always be at that moment in time. Therefore, recognizing the form of supply can be insightful. This form can either be - assembly, component, or material, depending on the highest residual value for its reuse. The form of supply can be matched with the project's requirements to enable system reuse by adjusting the design to available sizes or enable material reuse to remanufacture new products as per the design requirements. Using this form of supply for designing would mean creating a reuse system irrespective of the profile's shapes, sizes, or dimensions.

- **Changing Design Habits** - Architects, designers, and engineers need to change their design habits when working with secondary streams. Standard façade products are customized for every project to suit the design needs; however, reusing the secondary stream implies customizing design requirements to suit the available material stream. Every supply is different, so the design generating out of it needs to account for the differences. It requires engineering new connections for the system and tweaking the materiality and dimensions of the project as per the available material streams.

- **Using material differently** - The obsolete profiles and systems can be reinforced with different materials to make them structurally and thermally suitable for reuse. The material suitable for reinforcing depends on the change in performance and loading requirements for the new condition. It will open opportunities to look at materials differently and use them in unconventional ways that they were not designed for in the first cycle of use.

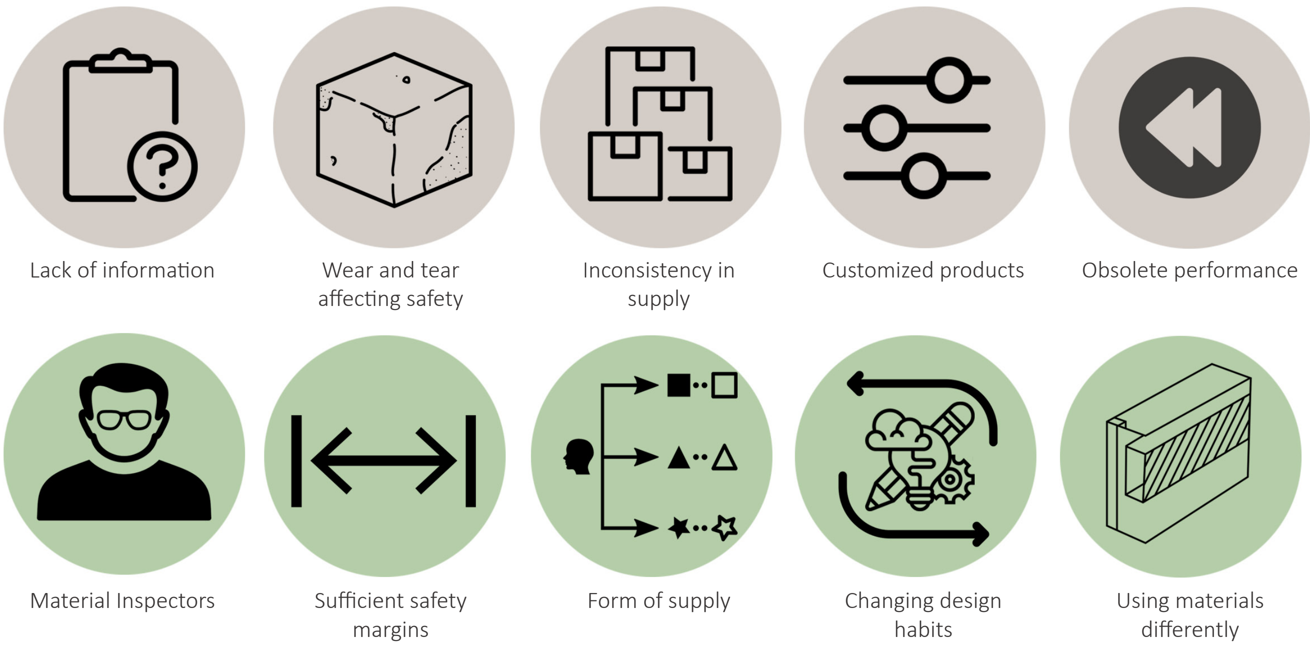


Figure 35 - Design challenges and opportunities for reuse of secondary materials for facades (source: author)

09.

SYSTEMATIZING THE REUSE PROCESS

The chapter presents the methodology for enabling the reuse of secondary materials for facades by formulating the reuse process and mapping the stakeholders (what, when, how) to support the process. These are the two main products of the presented research. It is followed by identifying the market challenges for establishing the process and proposing solutions.

9. SYSTEMATIZING THE REUSE PROCESS

9.1 Mapping the Reuse Process for Facades

The research synthesizes the findings from literature research, market analysis, and proposed designed opportunities and carefully maps the reuse process for the façade industry. The objective of mapping is to present the steps necessary to steer the secondary material from the construction and demolition process to create a market for secondary facades. The process consists of three main stages - material sourcing, material processing, and material reuse,as shown in Figure 36.

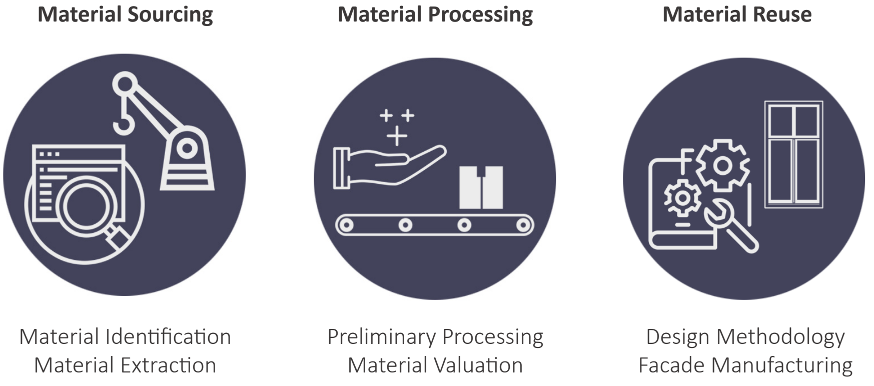


Figure 36 - Three Stages of Reuse Process

Figure 38 shows the complete process formulated for the reuse of secondary materials for facades. As indicated in Figure 37, the green circles indicate the source of materials from different lifecycle stages and at different product levels. The brown circles highlight the steps required to retrieve, extract and process the materials for reuse. The blue circle indicates the step to start the next stage in the sequence. Decisions that need to be made within the process are shown in the decision rhombus. The dotted black arrow represents the sequential flow of steps. The diagram represents two kinds of material flows with solid blue and red lines, respectively showing the physical flow of materials and the virtual flow of material (through a shared database). The process can happen either at one facility or distributed amongst the facilities of the actors. These depend on the services available at the premises of the actors. Therefore, the physical flow of material may or may not result in additional transportation depending on the available facilities. The grey circle indicates the main facilities or shift in location necessary for the processes that will add to transportation miles. The purple box indicates the tools proposed to accelerate the particular step. The choice made for each step can further impact labor, energy, cost, and time requirement for the reuse process.

The page size does not do justice to the diagram, and each stage is explained in parts in the following sections. Appendix B can be referred to for zoomed-in parts of the complete process.

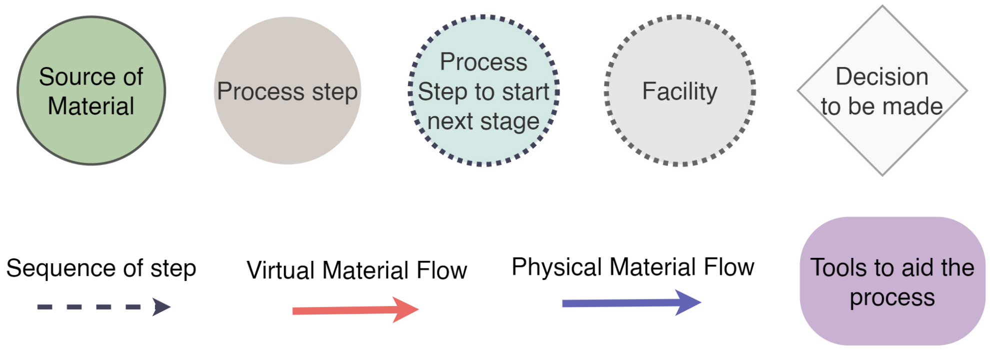


Figure 37 - Legend depicting the various flows and steps in the reuse process diagram

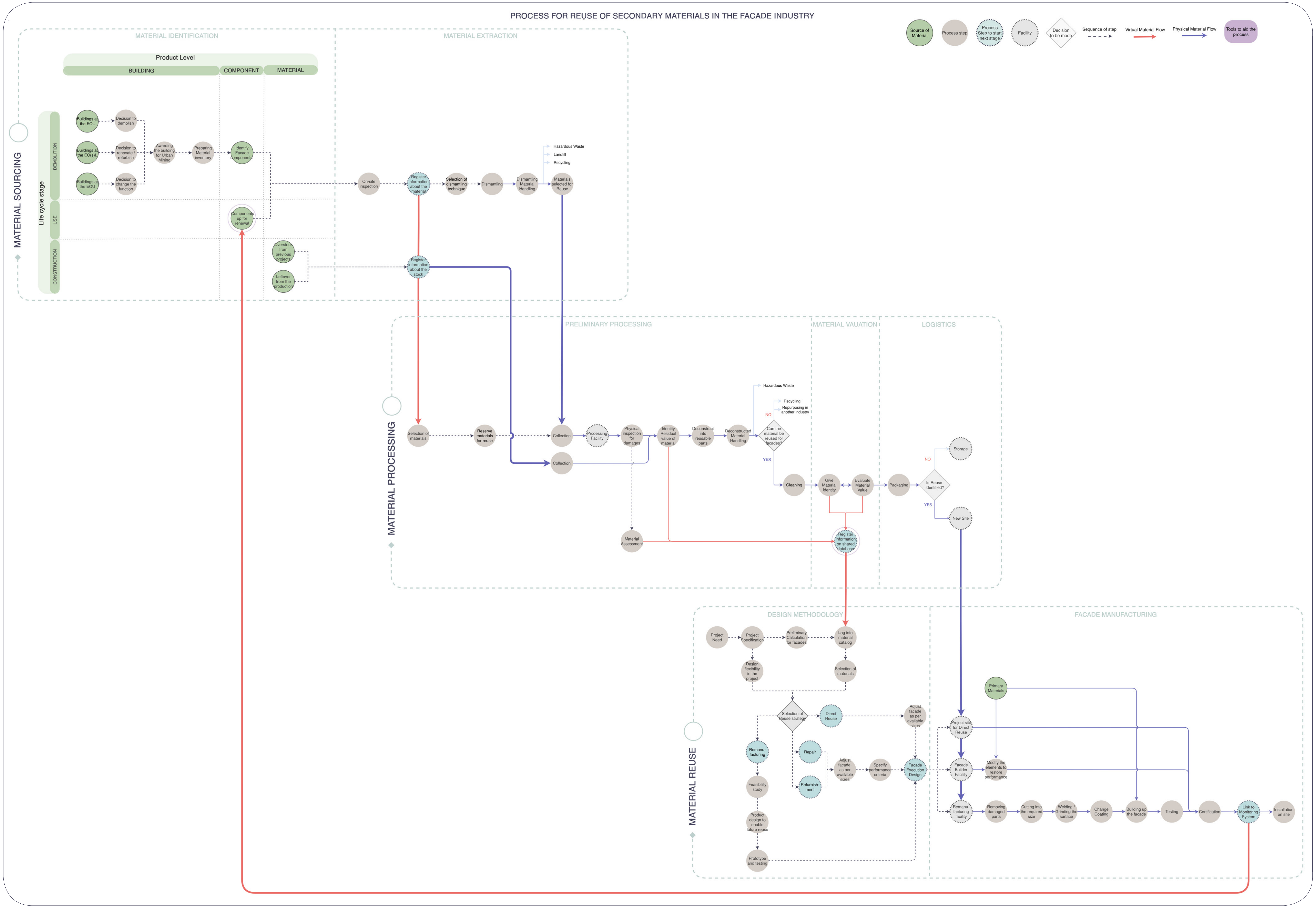


Figure 38 - Process for reuse of secondary materials for facades (source: author)

9.1.1 Material Sourcing for Facades

The materials sourcing is the first stage for accessing the materials and determines their quality and quantity. As shown in Figure 39, it consists of two phases - material identification and material extraction. The materials can be identified during both the construction and demolition stages. Both the streams constitute the stock of waste for the current material owner and can become a significant supply source. The difference between the two streams is the quality and the extraction process accompanying them. The former source was not never put into use and does not require extraction. In contrast, the latter requires specialized deconstruction for extraction and has to be dealt with the damages during its dismantling. Another stream of materials that will be made available from future building stock is from the use phase and will require a monitoring system for identification. Once the materials are identified, a suitable technique for material extraction has to be selected. It will entail on-site inspection of materials and connection systems to opt for appropriate dismantling strategy, careful material handling to avoid any damages, and registering this information for resellers to select the materials in the next stage.

Sourcing Potential

- **Buildings at the end of their life** - When the building owner decides to demolish the building at the end of its life, there lies a potential to extract the products for reuse. It entails a decision on the owner's part to harvest the building materials rather than demolition. In this case, the building becomes a material bank and can constitute the secondary materials for different construction sectors.

- **Buildings at the end of their service life** - When the building owner decides to refurbish or renovate the building for a new use, certain building products and components might render waste for the owner. Suppose the façade is no longer required for the new function; in that case, it can be carefully dismantled from the construction for repair or refurbishment for a new use, reducing the materials in the waste stream.

- **Buildings at the end of use** - When a building reaches an end of use due to its predefined use, various building products can reach a premature end of use, including façades. The materials can still hold a functional and economic value and can potentially be reused directly to utilize their residual value.

- **Façade products and components up for renewal** - Certain components and elements within the facades require early maintenance, repair, or renewal compared to the whole system. Thus, they can become a significant supply source. Information about this stream requires a facade monitoring system and can be made available through facade maintenance companies and facility managers.

- **Façade Builder's overstock** - The construction of facades usually has leftovers from the overstock of materials ordered. It can either be due to a requirement for a customized design produced in a minimum running meter of length or a communication error leading to an unsuitable product for the particular case. The latter results in disqualifying the lot and accumulating large material quantities at the builder's facility.

- **Production waste** - The system supplier delivers materials in the required quantity to the façade builder. There are often cut pieces left from the manufactured length at the production facility. It is usually a result of the difference between the casted production lengths and the standard façade dimensions, leaving production waste at suppliers' facilities. The material holds equivalent value compared to its in-use part; however, not used because of its undesired length.

Stakeholders involved

- Building owner
- Building user
- Façade Maintenance Company
- Façade Builder
- System Supplier
- Urban Miner
- Specialized Demolition Company

Tools to accelerate the stage

- **Digital mapping of existing buildings** - Mapping the existing building stock, including demolition and refurbishment projects, to feed a generalized database with digitized information of building projects at the national level. It can be done with drones, photogrammetry, laser scanning to facilitate urban miners', resellers', and designers' access to secondary material sources.

- **Original documentation** - As-built drawings and façade system details for the original construction can help the on-site inspector identify potential reuse strategies for the façade and select the appropriate technique for dismantling.

- **Monitoring system** - The current monitoring programs are mainly used for operational energy consumption in the building. However, monitoring materials during their use phase can be essential to preserve materials by following and assessing all the changes it undergoes, including repair and replacement over the use period. It will help make informed decisions regarding repair, refurbishment, or remanufacturing for subsequent use. It is a relatively new system and is not in place for the existing buildings; however, it is vital to ensure future reuse. It can be done using Radio Frequency Identification (RFID) chips incorporated into the components or simpler systems such as QR codes and Bar codes pasted on the material's surface.

Limitations in the current market

- A critical factor that needs to be considered at this stage is the geographical location of the source and its new reuse. The source has to be close to its processing, remanufacturing, and reuse site. In research by Brambilla et al. (2019), the results highlighted that reuse's environmental benefits begin to diminish when the distance increased beyond 1000km.

- There can be high pressure to finish the deconstruction process as quickly as possible. The tight project schedule can lead to inefficient disassembly of the buildings and lower the percentage of the reusable building component's recovery. Moreover, the time required to dismantle the product carefully can increase the cost of the process.

- There is a lack of government incentive for the building owner to harvest materials during the end-of-life demolition process. Besides, the estate owner has little knowledge about the environmental benefits of harvesting materials. As a result, they either opt for a cheaper alternative or leave the choice open for the demolition company.

- Since the existing buildings are not designed with circularity principles, building components are prone to deconstruction damages. They can decrease the material quality and affect their reuse potential negatively.

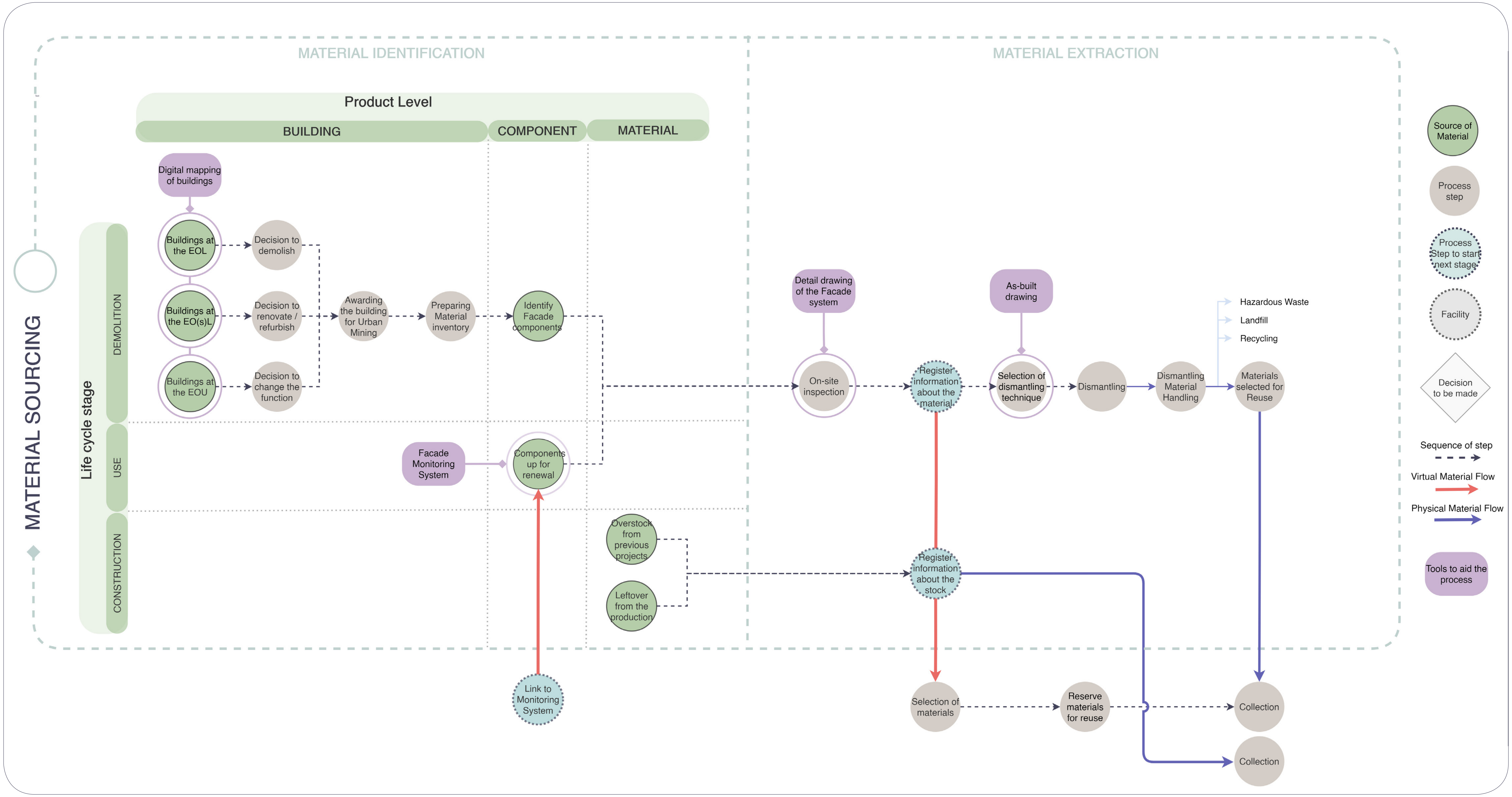


Figure 39 - Stage1: Material Sourcing for Facades (source: author)

9.1.2 Material Processing for Facades

Preliminary Processing

After identifying the suitable sources of the incoming material stream, the reseller must reserve the components for its collection after dismantling. The material is then collected and transported to their processing facility. At this stage, the product's residual value should be determined to identify its performance and decide whether it has to be deconstructed into simpler parts. It will require materials to undergo a physical assessment for damages by a material inspector followed by assigning it a digital value for architects and engineers to design. Furthermore, the deconstructed components have to be handled carefully to dispose of any hazardous waste released. Many materials used in old constructions are rendered toxic by the new building codes, including asbestos in the mastic adhesives used for sealants. They require a specialized company for its proper disposal. Additionally, materials that cannot be reused due to damages, shorter lifespan, or contamination are sent to recycling or a different industry for repurposing.

Material Valuation

Since the material coming from existing building stock undergoes various stages to make it reusable, it acquires a value. This value can be quantitative, such as economic or environmental, or qualitative, such as aesthetic, social, cultural, and heritage. The quantitative values can be calculated, taking into account the process cost and its impact. On the contrary, the qualitative values are subjective to the person using the materials and require expertise and knowledge to assess. The qualitative values are beyond the scope of this research and will not be discussed hereon.

At this stage, the material needs to be assigned an identity to ensure its reuse cycle after cycle. It must also include information regarding the material damages, residual value, and acquired economic and environmental value in the process. This material identity database will serve as a material catalog (market) for the façade engineers and architects to design new facades. Figure 40 shows the Material Processing stage.

Stakeholders involved

- Material Reseller
- Material Inspector
- Façade Deconstructor
- Material Processing Person
- Material Database Provider
- Material Valuator
- Marketing Representative
- Storage Provider

Tools to accelerate the stage

- **Material passport** - There exist multiple material passports in the market for resource management. These are needed for both material identity and registering information about the residual material value to ensure their use cycle after cycle. Further, it requires a standard specification method for the minimum information needed to reuse materials by the different stakeholders. The passport can also include a manual on taking apart and rearranging parts of the designed facade in the next phase.

- **Blockchain Technology** - The material passport needs to be accessible through a common platform to all stakeholders in the value chain to prevent information loss. Blockchain offers transparency, enhanced security, and improved traceability of material databases. It is a potential tool for scaling up reuse amongst the partners in the chain. It can be used either as a public blockchain for sharing a resource or as a private blockchain for sharing resources within a specific value chain. A global value chain can be created using blockchain to secure information from fraud or mismanagement of information.

- **Damage Assessment Guidelines** - A set of guidelines is necessary to assist the existing visual grading methods for materials. It will entail a material-specific assessment for damages resulting during the usage and dismantling process. Furthermore, it will include directives regarding acceptable damages for reuse as façade components.

Limitations in the current market

- Making materials suitable for reuse and determining the strategy for reuse in the design process is time-consuming. Thus, a lack of predetermined reuse can strain the existing warehouse facility, increasing the storage cost and the product's price.
- Facades designed 20 years back were not monitored and did not have data about their performance. Therefore, material testing and performance assessment will require an investment in technology and experts to certify their properties.
- Material handling during the deconstruction of the façade in the facility will require a specialized company for handling materials deemed hazardous according to the building codes. It will add to the overall cost of processing.
- Technology, like material passports and blockchain, is only effective when used by every actor in the chain. However, every company in the façade industry currently uses its platform and database for material management and lacks a shared platform between partners.

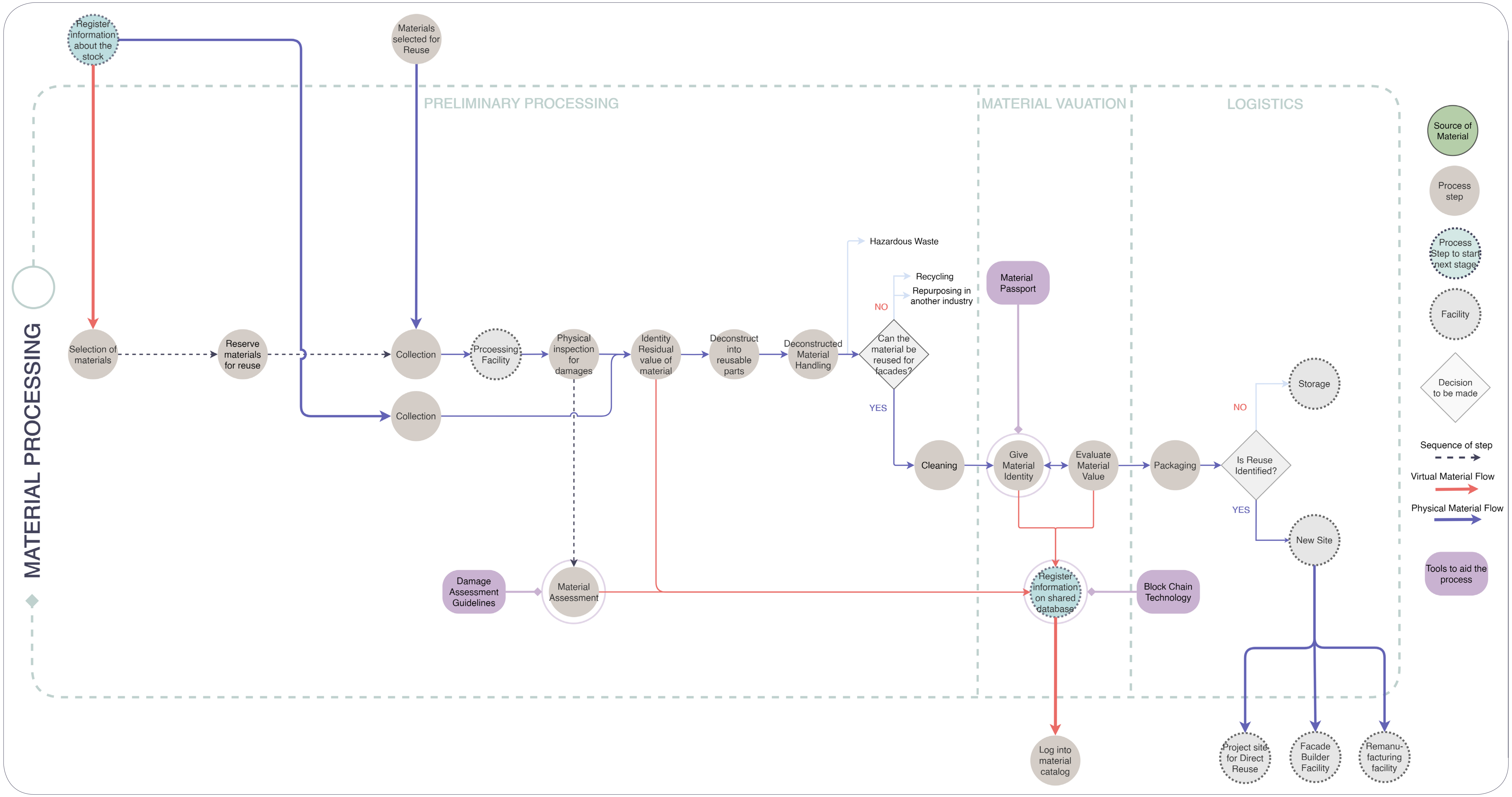


Figure 40 - Stage2: Material Processing for Facades (source: author)

9.1.3 Material Reuse for Facades

Design Methodology

Designing with a nearly unlimited supply of material is different from designing with an available material inventory. It requires looking for available materials by logging in the material database and modifying design, details, and requirements accordingly. There are two ways to go about designing with the secondary stream. Either it is the architect and the client's intention to opt for circular design, or there are engineered products with secondary materials available in the market and are opted by the client over regular products because of their benefits. The research identified that both methods are prevalent in the current market. The former design method is appropriate for large-scale projects or products constituting multiple materials such as curtain wall facades or insulating wall panels. On the other hand, the latter is more appropriate for products constituting homogeneous material usages such as bricks or timber. Both require research for feasibility, prototyping, and testing products suitable for use, either by façade engineers and builders or an independent innovation company.

There are two methods for reusing secondary materials - designing from the stock or designing with the stock. The former entails adjusting the façade design for a higher-value reuse strategy, such as direct reuse/repair of facades available in material stock. It offers less design flexibility for the architects but can present better environmental savings due to minimal processing of the stream. The latter involves designing new façade systems with the available stream of secondary materials to suit the façade design requirements. It consists of reuse at a slightly lower value, such as refurbishment/remanufacturing. Therefore, it offers a higher degree of flexibility for designing as per the architects' requirements. The selection of the method, or, more specifically, the reuse strategy, depends on multiple factors affecting the residual value of the secondary materials and available design flexibility in the project. The assessment of residual value is explained in the following section 9.2.

The project begins with an intent given by the client to the architect to set project requirements. Consequently, a façade consultant/engineer can perform preliminary calculations for the designed facade based on its materiality. Then, the materials and the performance requirements can be searched on the database of secondary facades to select materials for the new function. The database will operate on just in time-basis to avoid the storage of materials in the previous stage. If the designed façade cannot be adjusted according to the residual value of the available material stream, another material stream can be searched for in the database.

Façade Manufacturing

The reuse strategy selected will determine the facility required for its fabrication. Direct reuse of façade only requires transportation to the new site. In contrast, repair and refurbishment entail repairing known issues and upgrading product performance either by the product's original manufacturer or an independent façade manufacturer. Remanufacturing the façade entails building up the façade to new design requirements set by the architect at the remanufacturers' facility. Furthermore, it involves buying primary materials to compensate for any shortage with secondary material and engineering connections for new use. Finally, the designed product needs to be tested, certified, and assigned a new lifespan before it is made available for the market. Moreover, the façade will need to be monitored in its use phase by the façade monitoring and maintenance companies to ensure the reusable components can be traced for the subsequent use cycle.

Figure 41 shows the two phases of Material Reuse - Design Methodology and Façade Manufacturing.

Stakeholders involved

- Building User/Owner/ Client
- Architect
- Façade Consultant/Engineer
- Façade Re(Manufacturer)
- Circularity Assessment company
- Façade Assessment company
- Façade Monitoring and Maintenance Company

Tools to accelerate the stage

- **Database for tested sections** - Standard structural materials, such as structural steel beams, have databases for pre-tested and certified sizes and shapes of various sections available in the market. Similarly, a database for façade profiles can be created along with a material strength chart for steel and aluminum sections, wood species, strength, and performance (for different wood types) to effectively serve as base information for existing secondary materials in the market for reuse.

- **Guidelines for safety margins** - Materials can be over-dimensioned to account for safety and remove any ambiguity with its reuse. For this, guidelines specifying the percentage for safety margins (in terms of strength grade to reduce) for various materials are required in the existing building codes. Depending on the new loading and the assessed material grade by the material inspector, the engineers can design structurally sound and safe façade systems.

- **Intelligent interfaces** - Design of new interfaces are needed to accommodate varying shapes and sizes of the secondary materials and, in case of shortage, primary sections. Besides, many interfaces used in the existing facades are either outdated or discontinued by companies. Therefore, the design of new interfaces will ensure that the components can be used again.

- **Reversible connection system** - To enable the reuse of facades in the future, reversible and accessible connections for ease in product assembly and disassembly are required. These include both internal and external connections in the product.

- **CE Certification for Quality Requirement** - The material needs to be environmentally friendly and technically suitable for reuse. Therefore, the façade products prepared for reuse need to meet the criteria standard for its specific end-use and any criteria specified by the customer. A pre-requisite condition for reuse includes extraction of undamaged products through selective deconstruction and removing any contamination that can be harmful and affects its technical and environmental suitability. Specifying material quality in terms of numeric value for environmental and technical standards and quality control guidelines for the secondary stream can aid the façade manufacturer in manufacturing products conforming to these requirements. All construction products in Europe require a CE marking since 2012, indicating that the products meet safety and performance criteria (Ministry of Economic Affairs and Climate Policy). However, there is no clear indication regarding the CE marking for reclaimed materials already in use before 2012. Clear guidelines regarding CE marking for reuse elements will reassure the quality of the material for safe reuse. The quality requirements are material-specific and depend on its application. In general, the quality must match the primary material stream used for the product. The research identifies the following considerations are required for quality assurance:

    a. Checking for toxic contaminations over the use of the material. Many incoming materials from old construction systems were exposed to compounds and chemicals banned according to today's guidelines.

b. The previous use condition has not affected the technical properties of the material and, thus, its safety.

c. The material is not exposed to severe damages during deconstruction.

- **EPD and BREEAM NL** - An Environmental Product Declaration (EPD) is a standardized document informing about a product's potential environmental and human health impact under EN15804 standard (MRPI). The general goal of EPDs is to use verifiable and accurate information to encourage the demand for and supply of products that have a lower negative impact on the environment (ibid.). Therefore, they are often a requirement in green public procurement (GPP) and building assessment schemes such as LEED and BREEAM. Stichting MRPI is the operator for EPD in the Netherlands.

  The revision in the EPD standards in 2019 has mandated all four stages of LCA, including stage D (EOL Potential). Additionally, the 2020 revision in BREAAM NL specifies, for new construction, the use of as much reuse/recycle materials from demolition waste and design to enable future reuse, as per the R-hierarchy specified in the National Waste Management Plan. It specifies the mapping of demolition waste through a material inventory for reuse at higher-value and sales mapping of demolition waste for existing construction. Further mandates by the governments in EPD and BREEAM NL certification requirements can become tools to promote reuse of secondary materials among the supplier,s manufacturers, and designers.

Limitations in the current market

- Due to a lack of an established market, extra time and logistics are required to find the reused elements. Sometimes, the purchase of the identified secondary components is necessary at an early stage in the project to cope with uncertainty about availability.
- The luxury of fabrication of the cross-section to the required shape does not exist with reused components. The available profile/section properties dictate the façade system's geometry and require working with the façade engineer since the project starting. In the current design scenario, façade engineers are rarely involved with small-scale projects.
- The remaining capacity of the reused components is usually unknown. It happens when the information about the characteristics, details, certificates, and drawings of the reused components are unavailable. Therefore, to secure the facade's safety, the new components are over-dimensioned, resulting in overdesigned components that can be bulky both in appearance and weight.
- Designing a longer span is usually a limitation with secondary components. The components are not readily available and are cut from the usable part of reclaimed material, limiting its size. Moreover, there is a difference in the old and the new buildings' loading requirements, and the mismatch between the old sizes and the new features could limit spans.
- Certifying performance of material against fire and thermal resistance is possible through an independent third-party assessor. However, material properties that have undergone unknown fatigue loading require testing of material. The research for testing the alterations to the chemical properties of materials is still under investigation and cannot be certified yet.
- Reused steel components often have existing connection holes and welds, which entails preparing these components before reusing them. It often results in material handling in the hands of multiple actors, which might increase the overall cost of fabrication due to the extra time, labor, and machinery required.

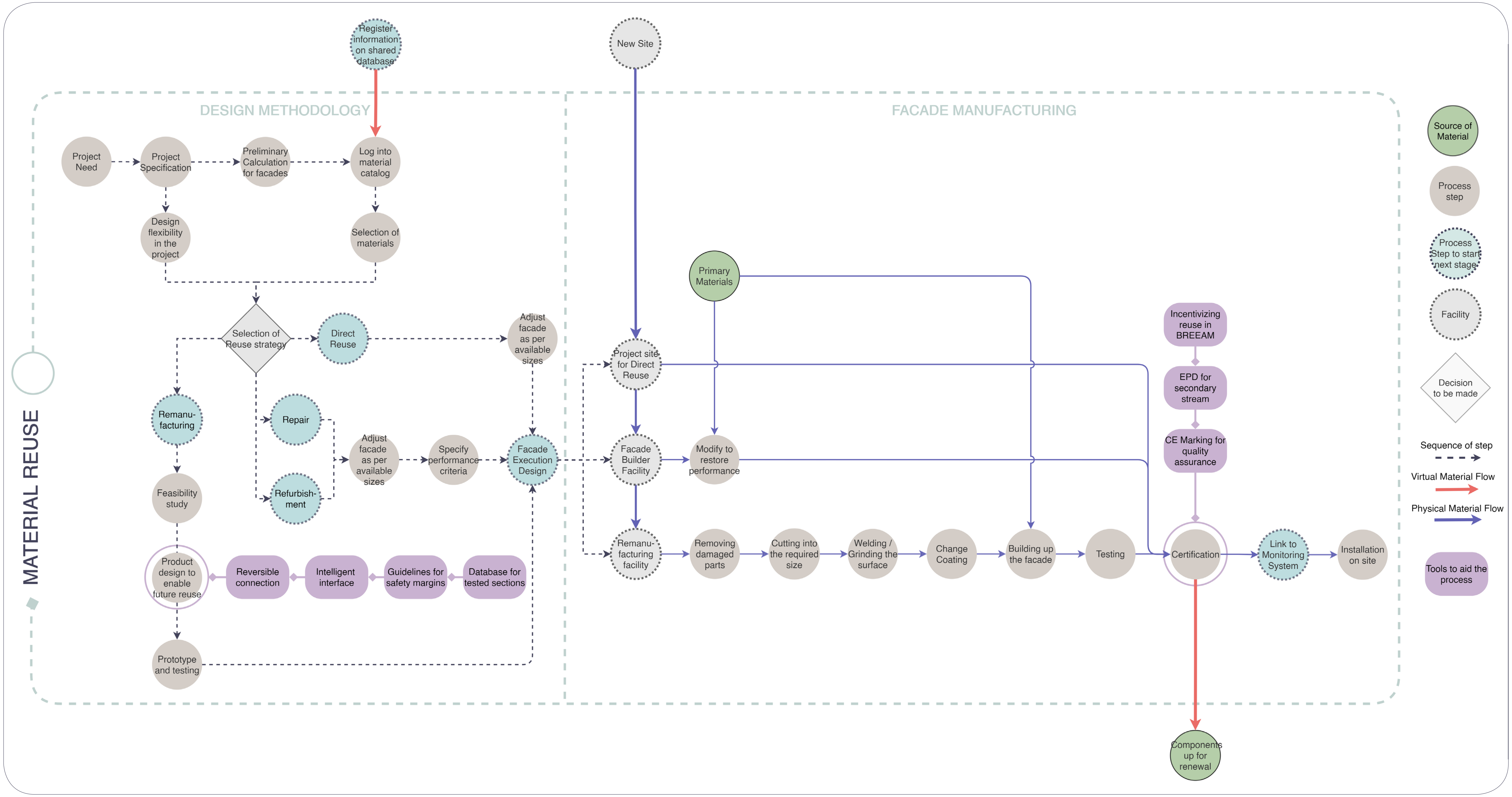


Figure 41 - Stage3: Material Reuse for Facades (source: author)

9.2 Assessing the Residual Material Value

The secondary materials can be made available from different life cycle stages of the project, at different product levels depending on its extraction process and utilized for different life spans. Together, these factors can affect the residual value of the product and help determine the potential scenario for their reuse again in the industry. Therefore, the residual value must be assessed accurately to ensure that the materials retain their highest value at reuse. This value can be evaluated by material inspectors during the material processing stage so that the decisions can be made quickly on the next steps required in the process. Consequently, this value can guide the architect to select a strategy for reuse. The research defines the factors affecting the residual values, as explained in the following section. It must be noted that the terminology discussed below used will be continued throughout the research.

1. **Source of Harvest**

The source of harvest is the life cycle stage of the building from which the façade components are harvested. It could either be from the demolition stage at the EOL of the building or overstock and production leftovers during the construction stage of the façade. Moreover, if the facades are monitored during use, harvest can also be made available from their maintenance stage.

2. **Form of Harvest**

The form of harvest is the dismantled form of the harvested material from the existing building stock, overstock, or production leftovers. It can be either at the system level - assembly reuse, or at the unit level - component or material reuse. An analysis of the current market showed that the form is dependent on the original construction system (stick or unitized) and ease of dismantling the system from the construction.

- **Standard Material** - The standard material is the simplest part of the system (assembly) that it can be disassembled into, such as steel profile, EPDM gaskets, aluminum cover cap. Each material has its lifespan; therefore, separation into this smallest unit can maximize the utilization of the remaining life of the material during reuse. The deconstruction of the façade to individual materials is possible if the product was initially designed for disassembly. A lack of this approach in most of the existing façade products can result in an added cost of labor, time, and energy for the process.
- **Component** - A component is a union of standard materials. It can either be homogeneous (such as a steel window) or heterogeneous (such as a glazing unit). Various materials within the component can have different technical lifespans, and an inability for its separation might render the component unfeasible for reuse. Additionally, a component might get contaminated over its use due to its interaction with the adjacent materials making it unfit for reuse, as in the glazing unit.
- **Assembly** - An assembly is a manufactured façade entity consisting of standard materials and components built by the façade builder. Direct reuse of the assembly in its next phase is possible when the technical lifespans of various materials and components are not utilized thoroughly. It requires selective dismantling from the existing construction and processing at a system level for reuse. It is easier to reuse the product at an assembly level because no further deconstruction is required.

3. **Extraction Process**

The extraction process refers to the added steps of dismantling or deconstructing the façade to get it at a reusable level. Existing buildings may not have been designed with the Design for Disassembly principle; thus, not all components within the facade can be deconstructed with the existing technology without damage. For materials from the demolition stage, it entails the ability or inability to deconstruct the façade into uncontaminated parts from the construction. On the contrary, secondary materials from the construction stage only require buying and collecting the materials from their original owner.

4. **Use life span of the facade**

The use life span is defined as the period of facade usage in the building compared to its life certified by the manufacturer. A difference between the two can help determine the remaining technical lifespan to reuse at the highest value.

- **End of Use (EOU)** - When a facade has reached its end of use and has not fulfilled its designated service life. It can be due to the requirement of an upgraded product, the no more prolonged need for the product, or a preference change (Rahman et al., 2019). Alternatively, the time for the functional requirement of the facade may have been less than expected for the products' service life. In either case, the expected service life is not fully utilized. Reuse of facades in this scenario requires the least amount of processing as they can still be under the manufacturer's warranty. Besides, there is a potential that the components do not require a performance upgrade, and the façade retains the highest value as an assembly. It can then be extracted as a whole (or a high percentage) for its direct reuse. The reuse will offer low flexibility in design. The architect will have to find a project with similar requirements to that of the secondary façade or adjust the size as per the available façade.
- **End of Service Life (EO(s)L)** - It is the period for which a façade assembly can be used according to the manufacturer's expectations. The service life depends on the lifespan of various components within an assembly and is usually decided by the weakest link. It means an assembly can reach the end of its service life, but not all components have reached the end of their life. These components and materials can be extracted and reused for a similar/different purpose again. The flexibility offered for design is higher as the components extracted can be modified as per the design and requirements set by the architect. However, the percentage reuse of façade components may not be as high due to the need for upgraded performance of some components or damages resulting from disassembly.
- **End of Life (EOL)** - This is the period for which an element or a component within an assembly can perform as required for its designated function. A careful inspection of the element can enable reuse by repurposing for alternate applications where the performance requirements are not that high. The element can continue to be used through a cascade and extend the element's usable life. It offers high design flexibility to reuse materials.

The research formulates the potential reuse scenarios by evaluating the residual value of the incoming material streams according to the factors mentioned above, presented in Table 6.

Table 6 - Potential scenario for reuse of materials as per their Residual Material Value (source: author)

Availability of incoming materials				***Potential Reuse Scenario***			
Source of harvest	**Form of harvest**	**Process for extraction**	**Use Lifespan**	**Residual Material Value (significance)**	**Strategy for reuse**	**Stakeholder**	**Use function**
Demolition Stage of the Building	Standard Material	Deconstructed to disassemble into standard material	EO(s)L	Elements can still perform for their desired function	**Remanufacturing** *processing and treating the material for a new facade*	Raw Material Supplier, Façade Manufacturer	Reuse for the same function
				Elements have been exposed to fatigue loading over their use phase and cannot be reused for the same purpose	**Repurposing** *Defining an alternate function for the material*	Raw material supplier/ Secondary material market	Reuse for a different function/industry
				Extracting maximum value from the element that has developed a very high degree of wear and tear over its use	**Recycling** *Reusing the material in the existing scrap market*	Collection company (on-site), Recycling company	Recycled / downcycled
	Component	Deconstructed to disassemble into components	EO(s)L	The component is uncontaminated and different materials within have a similar technical lifespan	**Remanufacturing** *Processing and treating the component for a new facade*	Component manufacturer, Façade Manufacturer	Reuse for the same function
		Inability to disassemble to uncontaminated material	EO(s)L	Extracting maximum value from components that have been contaminated over the use phase and cannot be disassembled	**Recycling** *Reusing the material in the existing scrap market*	Collection company (on-site), recycling company	Recycled / downcycled if contaminated
	Assembly	Dismantling the system from the building	Reaches EOU prematurely	The facade is in sufficient working condition and is under existing product certification	**Direct reuse** *Reusing for the same purpose without any need for repair or testing*	Original Manufacturer, Façade Consultant, Architect	Reuse for the same function in the same condition
				Enabling product to complete its expected service life	**Repair** *for known product issues*	Repair and maintenance facility - façade builder	Reuse for the same function

Availability of incoming materials				*Potential Reuse Scenario*			
Source of harvest	**Form of harvest**	**Process for extraction**	**Use Lifespan**	**Residual Material Value (significance)**	**Strategy for reuse**	**Stakeholder**	**Use function**
Demolition Stage of the Building	Assembly	Dismantling the system from the building	EO(s)L	Enabling new partial or full-service life for the product for the purpose that was originally intended	**Refurbishing** *Modifying the product to restore its performance and/or functionality or meet technical standards*	Refurbishing facility - façade builder	Reuse for the same function
				Enabling new service life for the product for the purpose that was originally intended	**Remanufacturing** *Disassembling, processing, treating, and reassembling the components or part of a product*	Remanufacturing facility - façade builder	Reuse for the same function
Construction Overstock	Standard Material	Buying back the material at scrap value from façade manufacturer	Use phase never started	Enabling material to utilize the service life it is designed for and red uce the total stock of material at the warehouse	**Direct Reuse** *Reusing the material for the same purpose*	Raw Material Supplier, Façade Manufacturer	Reuse for the same function in a different condition
	Component	Buying back the material at scrap value from façade manufacturer	Use phase never started	Enabling component to utilize the service life it is designed out and reduce the total stock of material at the warehouse	**Direct Reuse** *Reusing the component for the same purpose*	Component manufacturer, Façade Manufacturer	Reuse for the same function in a different condition
Production leftover	Standard Material (Cut pieces)	Buying back the material at scrap value from element producer	Use phase never started	Extracting maximum value from leftovers profiles in varying sizes, shapes, and quantities	**Repurposing** *Defining an alternate function for the element*	Secondary Market	Reuse for a different function/industry

9.3 Mapping the Stakeholders and their Roles to Support the Reuse Process for Facades

As described in the previous section, the reuse process consists of multiple steps within each stage, making the process relatively complex. The question that arises next is who will take charge and be accountable for the different steps. The critical stakeholders needed to support the process and their roles are defined through the literature research, market research, and an understanding of how the secondary façade industry can operate. Furthermore, the stakeholders can either work independently or be part of a company operating at a higher level. These aspects depend on the actor's particular business model to sustain themselves by ensuring a continuous flow of revenue. The research only defines the expertise required to take over the specific role in the process but does not necessitate how they must operate their business.

The actors can be categorized as per their contribution to the overall process, including use, harvest, reseller, design, build, assessment, maintenance, and regulatory. Figure 43 shows the mapping of the different roles as per the interaction and collaboration required through the different stages in the second life of the material. The diagram is divided into three sections according to the previously discussed three stages for reuse. A key role played by the regulatory body is shown as an overarching role necessary to establish the process. The green circles represent the actors who have information about the existing secondary materials and are the starting point for their subsequent use cycle. In the future, these actors will change to those who already have information about this stream and continue to close the material loop cycle after cycle. The dotted line represents an exchange of information between the actors in the form of dialog, instruction, drawings, or consultation. The purple dashed line represents the regulation required for the particular role at the state, national, or European levels through Green Building Ratings, Product Certification, or Circularity Indicators. Some new roles are added to the value chain and highlighted as yellow dotted circles. There are critical stakeholders, represented by the size of the circle, while others feed in to provide service at various steps in the process.

Figure 42 - Legend depicting the stakeholder categories in the stakeholder network map

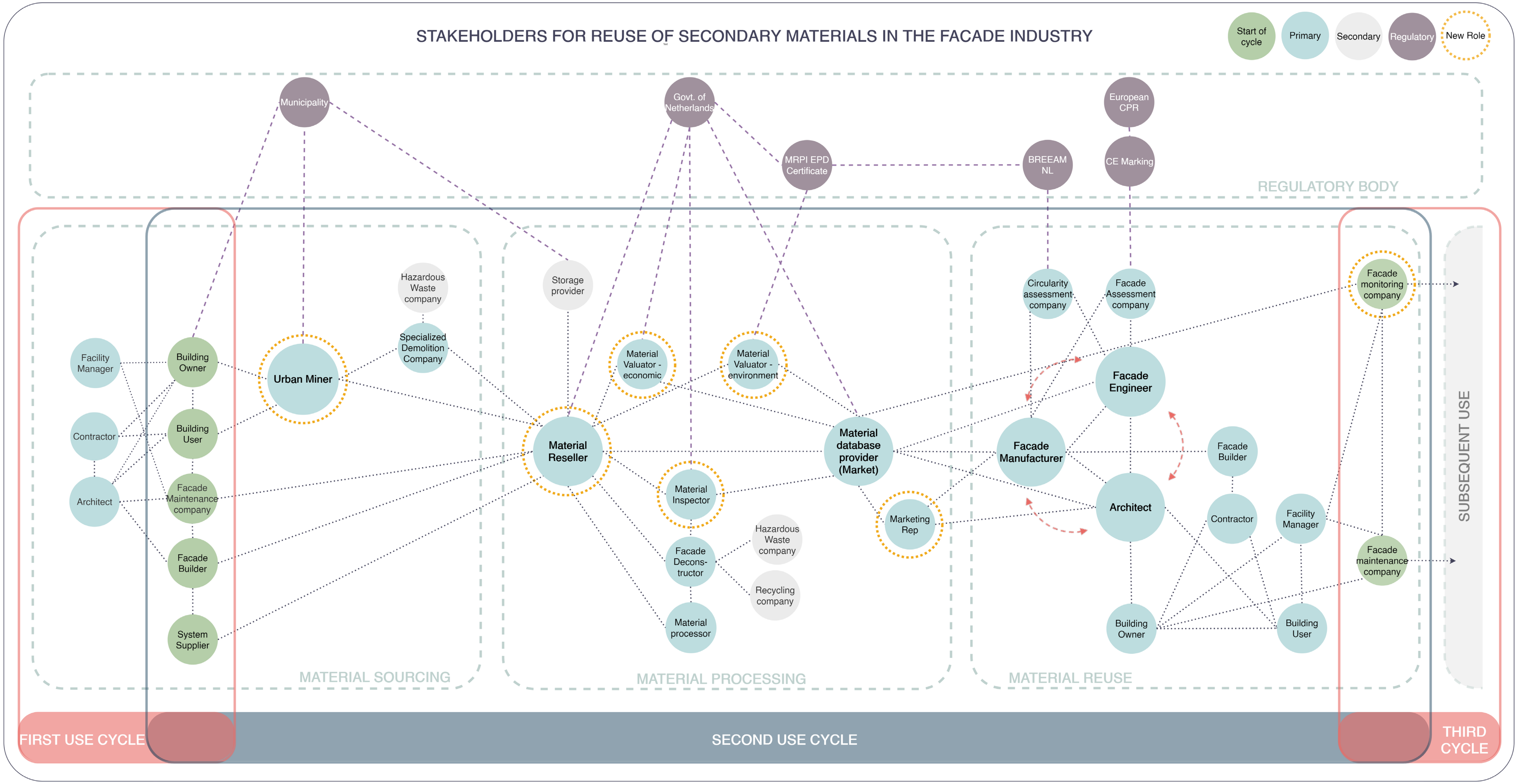


Figure 43 - Stakeholder Network Map for reuse of secondary materials for facades (source: author)

9.3.1 Stakeholders for Material Sourcing for Facades

1. **Building owner/user** - Reuse of materials from the demolition process can begin if the real estate owner supports it. Currently, the owners are indifferent to the demolition or mining process as long as it does not cost additional time and money. However, motivation on their part will positively affect decision-making regarding the mining of materials for reuse rather than demolition. They need to understand the process, its benefits, and its drawbacks. Education, demonstration through existing cases, incentivization by the government, or enforcement by the municipality are few methods to help them make an informed decision. Due to a niche market for reuse in the existing context, the harvesting of materials often results in the owner paying for the added cost of dismantling.

2. **Urban Miner** - This is a new profession beginning to shape up in the market, requiring shared expertise between demolition companies and building inspectors. An urban miner is essentially a scouter of secondary materials from various sources. They can investigate the buildings at the EOL, EO(s)L, or EOU to carefully harvest materials for their next cycle, potentially generating a higher revenue than the existing demolition process. The volume of the material harvested will increase as their demand increases in the market. A building consists of multiple products, and to ensure that each material finds suitable reuse, it is crucial to transfer the ownership of materials from the building owner to the urban miner. In the Netherlands' market, the existing demolition companies have identified profits associated with harvesting materials and have shifted their roles to some extent. Often without regularization, the materials that are non-profitable do not find high-value reuse. Thus, the role requires an objective attitude or a partial regulation by the state to reuse maximum materials in the building. Currently, New Horizon is the most significant player for urban mining in the Dutch market and works in partnership with 25 producer companies.

3. **Specialized Demolition Company** - The harvesting process requires skilled labor, equipment, and techniques to extract products and components from the buildings undamaged. It can either be done by providing clear instructions by the urban miner to the demolition company or, better yet, a specialized demolition company with expertise and knowledge about dismantling and deconstruction techniques. There is an assumption that manual labor for extraction will lead to higher costs and time required on their part. However, benefits from reselling reused materials may lead to significant recovery amounts.

4. **Façade Maintenance Company** - Maintenance companies are often sub-contracted by the building owner during its use phase. They have information about the facade components and materials no longer needed and are up for repair, refurbishment, or renewal. The maintenance companies can bridge the gap and provide this information to the reseller to collect materials no longer required for reuse. The company will also play a significant role in future reuse of the products by monitoring the performance of secondary façade over their use.

5. **Façade Builder** - The materials from the overstock and leftovers of the façade construction are essentially a waste for the façade builder. Instead of disposing of the materials in the scrap market or adding it to the storage, they can be resold to the reseller to find a useful second life.

6. **System Supplier** - The leftovers from the production process often have no value for the supplier and can be resold to the reseller. They can actively participate in the value chain by giving away materials that are no longer valuable to them.

9.3.2 Stakeholders for Material Processing for Facades

1. **Material Reseller** - This can be a player or a set of players operating a facility for selecting, collecting, and preliminary processing the material from the urban miner, façade builders, and system suppliers. Ideally, it is an extension of the role of existing material suppliers in the market, such as ODS as a secondary supplier for steel. The role currently exists in various profiles - highly specialized actors, those who sell a bit of everything, actors setting up harvest maps for their products, actors who find suitable materials according to project requirements. Each actor remains autonomous in its orientation, methods, and offers. An extension of the role involves employing actors who can select & collect materials, assess the material for its residual value, de-construct the façade, and provide preliminary material processing. The actor will provide the facility and logistics for these services, including processing space, packaging, and materials transportation to the new site. A geographically distributed network of resellers can help in lowering the cost and emissions of transportation. The reseller needs to be regulated by the state to ensure standardization in material valuation and processing at their facility.

2. **Material Inspector** - A material inspector is essential to identify the material's residual value and determine its property. They need to physically inspect the materials to identify degradation caused due to usage and dismantling damage and offer advice on the deconstruction of the façade system. They can also recommend the most suitable reuse as per the residual value of the material. The government can support this role by either certifying the material inspectors or establishing a system to authorize them to issue certification for assessed materials. It will provide insurance and guarantee critical properties of the reused materials and components, such as residual capacity and potential degradation ratio under certain environmental use conditions.

3. **Material Database Provider**- There exist multiple autonomous material passports in the market but lack standardization and regularization by the state. A central organization needs to assume accountability for specifying information needed for reuse, providing the materials an identity, and registering the information about its assessment on a shared platform. Various actors in the reuse chain can use this database to ensure a smooth exchange of information.

4. **Material Valuator** - The secondary material's value is dependent on several factors, processes, and people handling the material. The person responsible for valuation will depend on the type of value and can vary from an architect for qualitative values to an impact assessor for quantitative values such as LCA, LCIA, or LCC. All the processes that the material has undergone until this stage will affect its value. To ensure parity among the values of the secondary materials, they require a set of guidelines by the authority to keep it in check.

5. **Marketing Representative** - Awareness about the availability of the secondary material and how it can be reused requires a communication channel/person between the material reseller, remanufacturer, and the architect. It entails marketing the value of reuse through EPDs, Green Building Certifications, and Circularity Assessments to the decision-maker in the design process.

6. **Storage Provider** - If the material does not find immediate reuse, storage will be required. Ideally, this should be at the resellers' facility to limit any unnecessary transportation of material. Besides, the warehouses can be operated by the state to not add to the material cost.

9.3.3 Stakeholders for Material Reuse for Facades

1. **Building Owner/User/Client** - Current building projects with secondary materials or secondary façade products supplied only get a market value when appreciated by the client. It either starts with the intention of the client opting for a green building certification or a motivation for a circular built environment. As a result, there is a niche market for reuse. Creating an active market requires motivation amongst the clients. It can be made possible by showing them the economic and environmental savings from products or projects designed with the secondary stream.

2. **Architect** - The architect plays an essential role in building design and sets the facades' aesthetic, material, and system requirements. In the Netherlands, the architect is seldom involved with its detailing, leaving it in the facade builder's scope. A façade consultant sometimes consults the architect about the performance requirements of the project. The architect's role needs a significant shift. Instead of designing a façade and then specifying its materials, it will start by looking for materials and then adjusting the façade design to make it suitable according to the materials. It is crucial to understand that the final design may not be final and may require flexibility to change according to the available material stream. It entails collaborating with a façade engineer/consultant and a façade manufacturer from the very beginning of the project.

3. **Façade Consultant/Engineer** - This role requires technical design expertise for facades to ensure the engineering of new solutions with secondary materials. In the Netherlands, often projects only have a façade consultant as an advisor to the architect. A technical draftsman in the façade builder company is responsible for making technical drawings for the façade with the profiles selected by the architect. The existing two roles need a shift, either as an extension on the consultant's part or a collaboration between the two to ensure new products for the minimum performance standards and required technicalities. The products can be developed with the available design tools - database for tested sections, guidelines for safety margins, intelligent interfaces, and reversible connections. In addition, the secondary material database will serve as a pre-available material catalog for raw materials for these products, which can be tested for feasibility studies and prototyped for the market.

4. **Façade (Re)Manufacturer** - The actor needs to be aware of the benefits from secondary materials and be willing to provide facility, equipment, and labor to repair, refurbish or remanufacture products as per the façade engineer's design out of secondary materials. They will also deal with designing new connections for the system, providing any additional hardware required for the façade, and sourcing any required primary material to fill in any shortage with the secondary stream.

The three roles mentioned above, architect, façade consultant/engineer, and façade re(manufacturer), have a different dynamic in the present scenario. Reuse necessitates the architect to closely examine and control the material flow and work with the engineer and manufacturer. If the supply-driven design continues to increase in the future, the manufacturer will work as the primary decision-maker and inform the architect about reuse.

5. **Circularity Assessment Company** - Circular product design is needed to ensure that the subsequent reuse cycle does not face the same dismantling issues. An independent company/consultant can advise on the circular design criteria for facades during the design stage and also help in assessing its environmental impact for the Building Certification criteria.

6. **Façade Assessment Company** - An independent company needs to assess the façade system designed with secondary materials before using them in the project. The products have to undergo testing for all the minimum standards required for façade products, including but not limited to fire safety, thermal resistance, structural performance, and security.

7. **Façade maintenance and monitoring company** - The monitoring company needs to monitor the performance of the façade over its use through material passports and provide information to the sub-contracted maintenance company and facility manager for easy repair, refurbishment or remanufacture of products for reuse in the next phase.

9.3.4 Stakeholders for Regulating the Reuse for Facades

1. **Regulation at the state or national level** - Municipality is responsible for providing demolition permits. Currently, the only requirement for a waste audit is a material inventory for strategizing waste disposal. However, it can mandate harvesting materials over demolition so that building owners can proactively participate in the process. An incentivization through tax reduction or subsidy on the harvesting process can further motivate them to harvest more. Furthermore, they can increase the points for reuse in building certification to increase reuse.

2. **Dutch Building Codes** - The benefits of re-use can be significantly improved if building codes emphasize the construction's environmental aspects. The immediate goal should be to enable material re-use by establishing clear guidelines for the material grading and safety of elements designed from the secondary stream.

9.4 Market Challenges and Opportunities

A process for reuse and a shift in the existing roles to support the process can further add to the existing challenges of designing with the secondary stream. Since the construction industry in the Netherlands is already under an ongoing transition to achieve circularity goals set by the Government, there lies a prospect for its forward momentum by critically evaluating the challenges. Therefore, the research draws the following critical market challenges that can generate from the proposed process for the façade industry:

1. **Cost of material handling** - The secondary materials have to undergo more stages to make them suitable for reuse than their primary stream. Therefore, it leads to material handling in the hands of multiple people. The environmental cost of material handling is often not as high as the total energy required to extract virgin sources. Nevertheless, the economic cost increases significantly due to increased transportation, on-site labor wages, and logistics due to the lack of a prevailing reuse method, burdening its final cost.

   Cost of material - The cost of the material depends on the value that people believe it holds. There is no predefined value of the materials coming from the secondary stream. Its economic value drops when the title changes from 'resource' to 'waste,' resulting in a low scrap value for materials. This material cost needs to remain as low as possible to ensure that it can help overcome the added cost of material handling. During the research, it was seen that ambiguity in the material value often results in the owner's reluctance to sell material at scrap value. Every actor in the chain wants to profit once they know that the material is a 'resource' and no longer a 'waste.' This adds a burden on the actor responsible for supplying materials, making them opt for cheaper primary material alternatives. Further, the cost of transactions of secondary materials is taxed with VAT. It means the same material undergoes the VAT twice, further increasing its cost.

2. **Hands-on approach** - As the market for reuse is still in its infancy, the number of projects is limited. Besides, there is a lack of knowledge about reuse in the industry, affecting partners' willingness to work towards reuse. Hence, reuse projects are started small and approached hands-on. Even though this approach will limit the risks associated with reusing materials, it amplifies the cost of reuse in the supply chain. It can even result in low or zero monetary benefits for the stakeholders in the chain. For example, in a project done through the Harvest Bay chain by ODS, extensive material handling and processing cost exceeded the user's budget, resulting in no profits for the material suppliers.

3. **Labor Intensive** - The reuse process of the secondary stream from existing building stock requires additional efforts. It is mainly because of its design lacking the ease to enable its reuse. It, thus, requires expertise for decision-making and execution at various stages, making it a labor-intensive process. Moreover, the laboring efforts aggravate as one moves up the R-ladder. The requirement for extraction of clean products, expertise in disassembly, assessment of material for damages, processing, and valuation of the materials increases with selecting an environmentally preferable R-strategy with higher value retention.

Lower R-strategies, such as recycling, require collecting, separating, and cleaning scrap for recycling in a factory. There is no emphasis on the quality of the extracted material, and it is suitable after the demolition of the building. There is a need for careful dismantling with reuse, refurbishing, and remanufacturing to extract the materials as high a quality as possible, followed by assessing materials to identify their damages and processing, making it a labor-intensive process. Consequently, the number of people required for the process increases proportionally to an environmentally preferred reuse strategy.

4. **Ownership of materials** - In the current linear consumption model, the ownership of the façade shifts to the building owner during the sale. As a result, the façade suppliers do not have access or rights to the facade. The current owners, who have limited knowledge about the possibilities of a second life, often opt for demolition as it is a cheaper and time-saving option. Additionally, when secondary materials are procured from the building, they require a transfer of ownership of the different materials present within the buildings. The ownership in the hands of people less knowledgeable about material use leads to ambiguity regarding the person accountable for decision-making regarding reuse.

The research anticipates the following opportunities to overcome the above-mentioned challenges, and are summarized in Figure 44:

1. **Regulation of material cost** - Suppose the economic value of 'waste' is regulated by a central authority and kept minimal. In that case, the difference in the marginal cost of primary and secondary material could counterbalance the added cost of material handling. Further, the cost of the material can be coupled with the environmental savings made from the selected reuse strategy. It would mean that material ending up as scrap for recycling should have a higher economic cost due to lower environmental benefits than material ending up repairing or refurbishing options with higher environmental savings.

2. **Scaling Up** - Doing something new might result in limiting the scale and, thus, benefits. The interviewees highlighted that the economic benefits from reuse are usually seen in the second or third cycle of material use. Therefore, scaling up reuse from project to industrial-scale through increased collaboration with the partners is necessary to sustain the value chain. It entails marketing the value of this stream among the various stakeholders through economic benefits and building certifications.

3. **New Roles** - Although the current process will initially be labor-intensive, the reuse model will ultimately increase job opportunities. One of the most prominent opportunities entails the role of material experts. Their involvement at various stages will ensure a smooth reuse process. Starting from the first stage of material sourcing of identification and extraction, an on-site expert (urban miner) will be needed in addition to the demolition company to assess the conditions and reusability of materials. Moreover, other stages will also require new roles and result in new job opportunities for the economy. Certain professions will require a transition in their existing roles and an extension of their business model. As the number of people required is directly proportional to an environmentally preferable reuse option, economic opportunity and environmental benefits will increase with the reuse of materials.

4. **New Business Models** - The manufacturers can extend services of take-back systems after their service life is completed to extend the product's life. They can assume the accountability of materials after their use and arrange different ways of taking them back. By systematically using the materials in their value chain or resale to other partners, they can gain opportunities to increase customer loyalty and business opportunity by a second retail channel. From an environmental point of view, it will shift the ownership and the responsibility to handle materials for reuse in the hands of people with more knowledge in the field to make better decisions for reuse cycle after cycle.

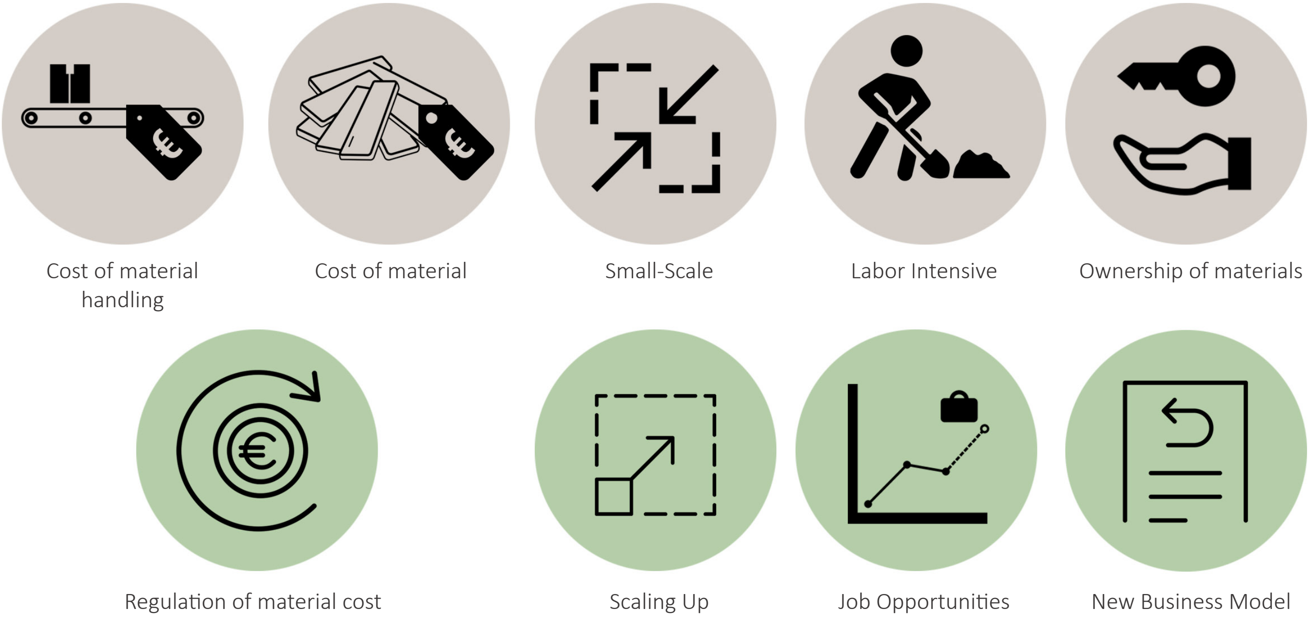


Figure 44 - Market challenges and opportunities for reuse of secondary materials for facades (source: author)

9.5 Summary

Formulating the reuse process revealed essential aspects that are critical to consider for the reuse of secondary materials. Firstly, not all secondary materials have the same residual value, and therefore, do not have the same reuse potential. Therefore, this value must be assessed at the very beginning to retain its highest value during reuse. Secondly, reuse is only possible when explicit information is available about the materials. Due to a lack of this information for existing materials, it necessitates manual inspection and assessment. Nevertheless, it is crucial to safeguard future reuse of materials by securing this information using material passports to trace and monitor materials in the future.

The reuse process has multiple steps within each stage, requiring various actors to support it. While few roles are already transitioning in the circular setting, others are yet to be recognized by the industry. In addition, there are overlaps between the roles that can create a shared dynamic between the actors. For example, reuse often results from the architect's intention to build circular in the current scenario. In the future, when the supply-driven design scales up, active participation by the raw material suppliers and façade manufacturers is required to match the demand and supply. Several market challenges can arise with the process and the people; however, their identification is necessary to compel the state to address them for the forward momentum of reuse in the façade industry.

10.

DESIGN APPLICATION

The chapter intends to apply the formulated process to a quantifiable product by designing a façade using the identified secondary materials. The design is a product of the presented research and is further used to propose the Design for Reuse criteria.

10. DESIGN APPLICATION

A hypothetical design case has been developed to illustrate the generic applicability of the reuse process for façade design through discussions with the mentors and ODS. The case tries to present a design methodology to employ secondary material and develop a quantifiable design to assess the environmental impact and circular value of reuse.

10.1 Design Case

As a raw material supplier, ODS has to supply a facade for a lifespan of 15years for a ten-story high office building. The building is located in Limburg and has to comply with the minimum energy standards specified in Bouwbesluit. Figure 45 shows the skeleton structure of the building where the façade has to be fixed.

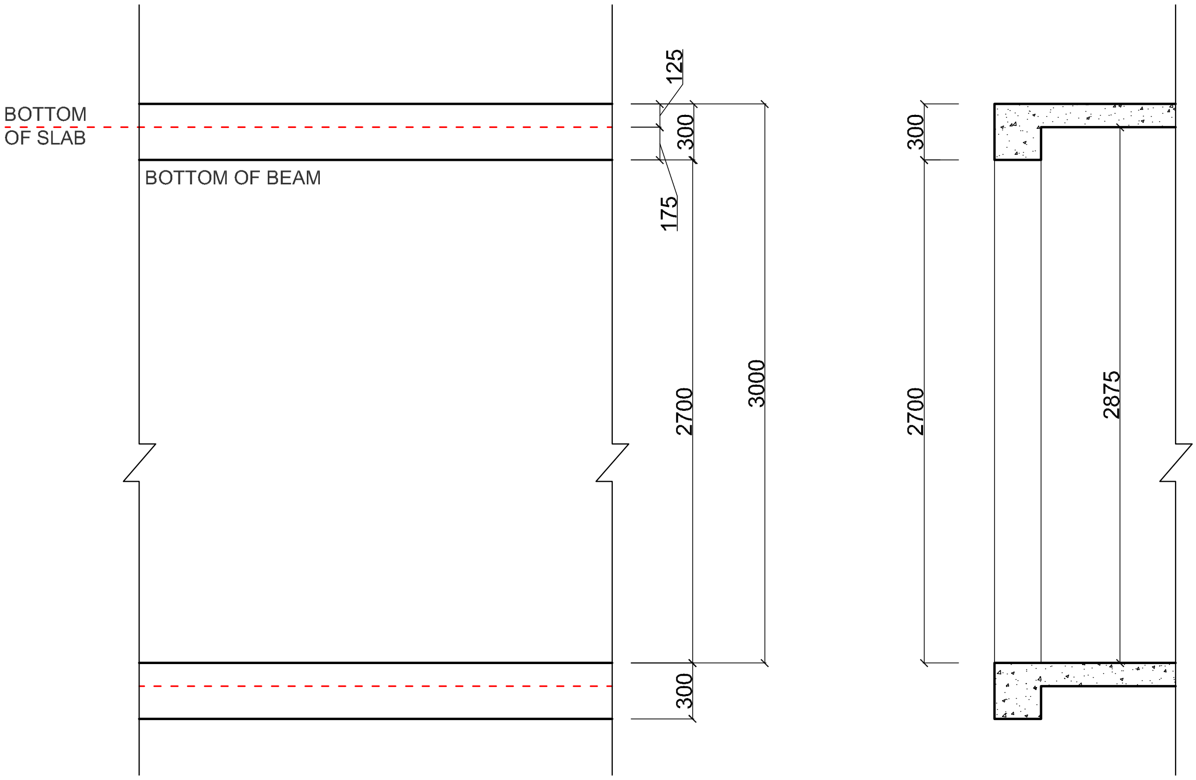


Figure 45 - Sectional details of the existing structure (source: own)

The following project requirements are devised according to the site location and design criteria outlined in section 7.4:

- Glazing unit of 8-14-6 with low e-glass to reach a u-value of 1.2W/m2K as specified in Bouwbesluit
- Wind speed of 0.56KN/m2 acting perpendicular to the façade according to the Peak velocity in Zone III for level 10 in the Netherlands (refer to Appendix C for details)
- The facade has to prevent spread of fire through any potential route
- Demountable connections to ensure façade can be collected back by ODS after 15years for subsequent use

10.2 Material Identification

The online harvest map set up by ODS was investigated to identify the profiles available for reuse. Their inventory, however, is still in the process of being updated. As mentioned in section 8.2.1, it does not show all the materials available in their stock. As a result, Ron Jacobs from ODS was approached to get a more precise overview of available materials. It was highlighted in a discussion that the Jansen Viss profile 76.664 went out of their catalog in 1999, and its remaining stock is available for reuse. The profile was discontinued for two reasons. Firstly, ODS shifted their production line from 40mm face width to 50mm and 60mm options. Secondly, there was a shift in their sealing system from wet fixing of silicon sealant to dry fixing of EPDM gaskets. As a result, the dry fixing accessory was not manufactured for the remaining lot of the profile. Therefore, the last set of profiles became obsolete over the years and added to their construction waste. Currently, it is stored at a rented facility in their customer (façade builder) Looten's premises located in Turnhout, Belgium. Figure 46 and Figure 47 show the profile stored in the warehouse and standard fixing detail. The profiles are currently available in a total length of approximately 190m in 6m long sections.

Figure 46 - Jansen Viss Profile 76.664 stored in Looten's warehuse (source: ODS)

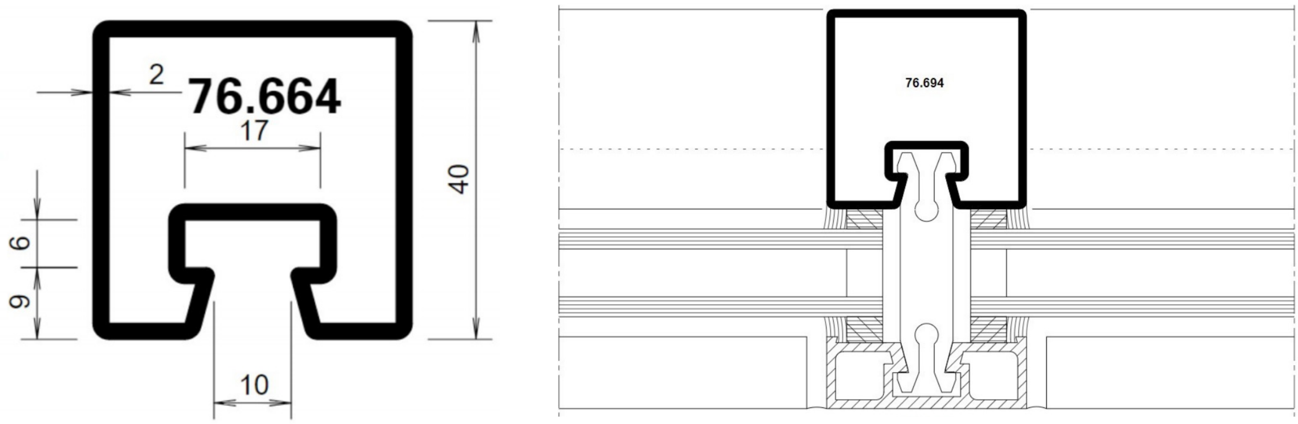


Figure 47 - Jansen Viss Profile 76.664 (left) cross-sectional detail, and (right) original fixing detail with structural sealant (source: ODS)

10.3 Design Scenario 1

Design Methodology for reuse

The material is available at the product level of standard material from the construction stage (overstock) of the lifecycle. The profiles have not been used before and do not require any further deconstruction. Based on the defined conditions, the profile can be reused for a new curtain wall glazing system. From the information provided by ODS, the following weak links are distinguished with the reuse of this profile:

- The profiles were designed as per the loading condition almost 30 years back. Therefore, the material strength may not be enough to resist the dead weight of the glazing unit and wind loads stated in the present-day building codes.
- The profiles were intended to fix the glazing using a silicon sealant interface. However, this connection system can no longer be used due to the lack of ease in its disassembly and its irreversibility.
- The product is obsolete, and Jansen does not supply customized accessories for this product, including the EPDM gaskets, pressure plates, and cover caps.

Figure 48 shows the conceptual ideas proposed to suit the design to the program requirements for the three stages of the reuse process:

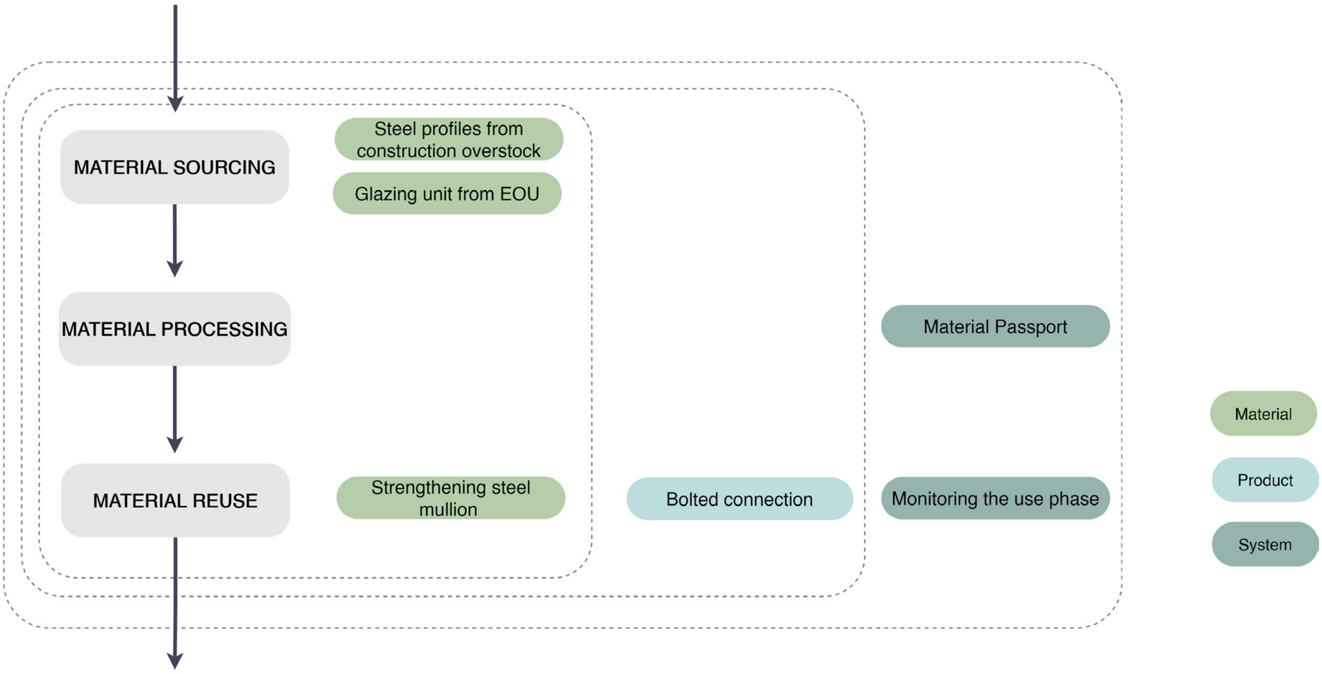


Figure 48 - Conceptual ideas for the design

- Since the profiles are available in 6m length, they can be cut into two parts of equal size. These parts can either be connected adjacent to each other or back-to-back to strengthen the mullion. Cutting the profiles into equal halves will also limit any wastage of the material. In discussion with the façade builder, it was indicated that the standard method of reinforcing the steel section is through welding another steel strip to it. However, welding makes it an irreversible connection. Therefore, a bolted connection for the profiles is preferred to ensure that the connection is reversible and the profile can still be reused for the next phase. Furthermore, the viss in the profile gives the advantage of fixing the bolt without puncturing; only one profile will need to be perforated. Besides, steel is a flexible material, and any holes and perforation on its surface made for the bolts can later be filled in and grinded to get back to the original condition.

- The size and shape of the viss in the profile are the same for all ODS Jansen products. As a result, the existing dry bolt connection available with ODS for their current market series with 50mm profile widths can be used for fixing the glazing on the selected profile. EPDM gaskets, pressure plates, and cover caps are essential components of the façade system and require design precision to the last mm. Therefore, it is essential that the material supplier, in this case, ODS, supply the accessories to fix the obsolete façade profiles through various suppliers in the market. Although they can be sourced from independent suppliers in the market through system drawings supplied by the manufacturer, the material supplier must check the system to ensure its compatibility.

- Another idea discussed at the material level is to source glass from the EOU stage of a project. In that case, the glazing unit will still hold the manufacturer's warranty. However, such reuse will require the length and width of the curtain wall to adjust as per the available size of the glazing unit. After a discussion with mentors and Ron Jacobs from ODS, it was indicated that, although possible, such a solution will require accepting the energy standards and light transmittance the glazing unit is designed for in the first place. Even though the idea has potential, it was not explored further as no market supplier could be identified at this stage with an EOU overstock for glazing units.

- The glazing unit could not be reused at this stage due to limited technologies and a lack of secondary supply in the market. Nevertheless, the size of the glazing unit used can be such that it can be reused after 15years and leaves minimum construction waste. After discussing with façade builder and ODS, it was indicated that 1200mm is a standard glass size with minimal production waste. The width also fits well with the standard structural grid in the Netherlands and will further ensure standardization in the panel size for subsequent reuse.

- It is essential that the facade gets a material passport at the system level and is monitored during its use phase to ensure that it can still be reused after its defined lifespan of 15years.

Design Concept

Objective - Strengthening the steel mullion by bolting two profiles back to back.

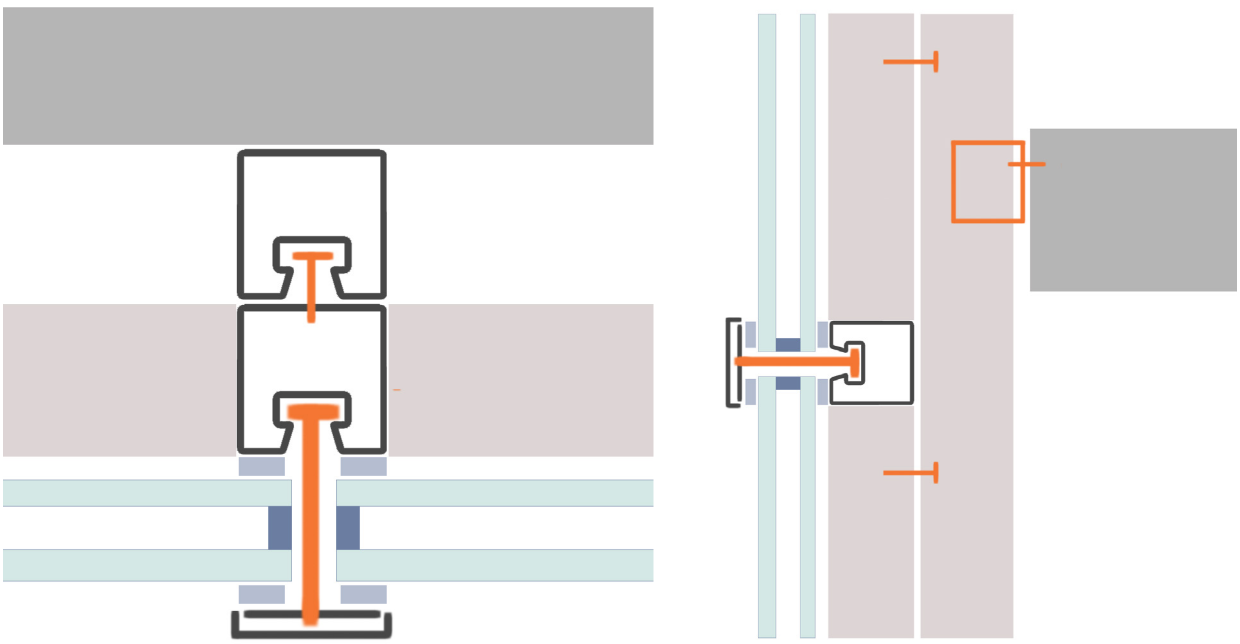


Figure 49 - Design ideas for strengthening and fixing the mullion in (left) plan, and (right) section (source: author)

Description - The different discussions with mentors recommended connecting the two mullions back-to-back and provide separation in depth. It works with the principle of transferring the wind load acting on the glass and does not interrupt the transom fixed to the primary mullion. Further, the viss of the secondary mullion is kept inwards and used to the advantage of fixing the bolt to the primary mullion, as shown in Figure 50.

Since both the steel mullions are in the interiors and exposed to the same temperature, it can be assumed they will act as one mullion, and thermal expansion will be the same. Hence, they will not require any additional tolerance between them. In addition, the climate barrier, a glazing unit of 8-14-6, can be connected through standard fixing details as shown in Figure 51.

Figure 52 shows the sectional view of curtain wall fixing to the slab edge using a standard Halfen connection available in the market. The connection connects to the mullion using a bolted connections with a bracket, which can be unbolted for dismantling after use.

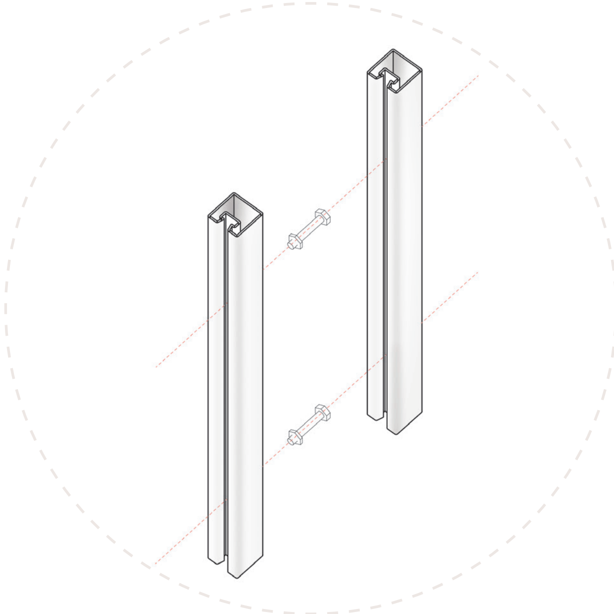


Figure 50 - Bolting the mullions through the viss (source: author)

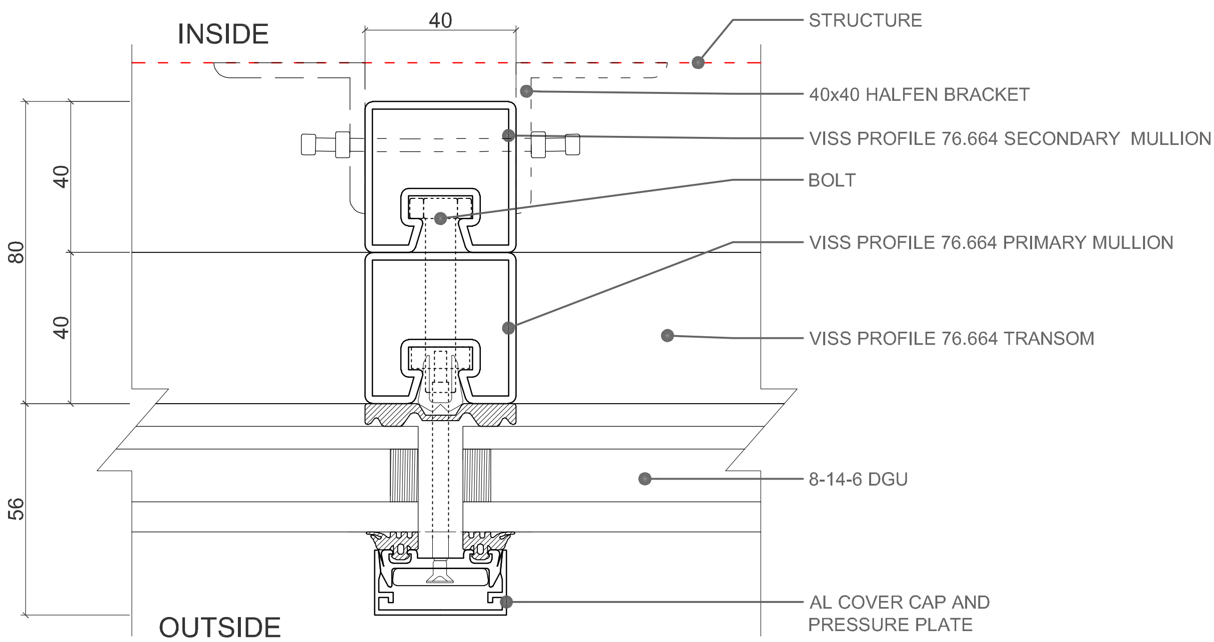


Figure 51 - Plan view of the detail (source: author)

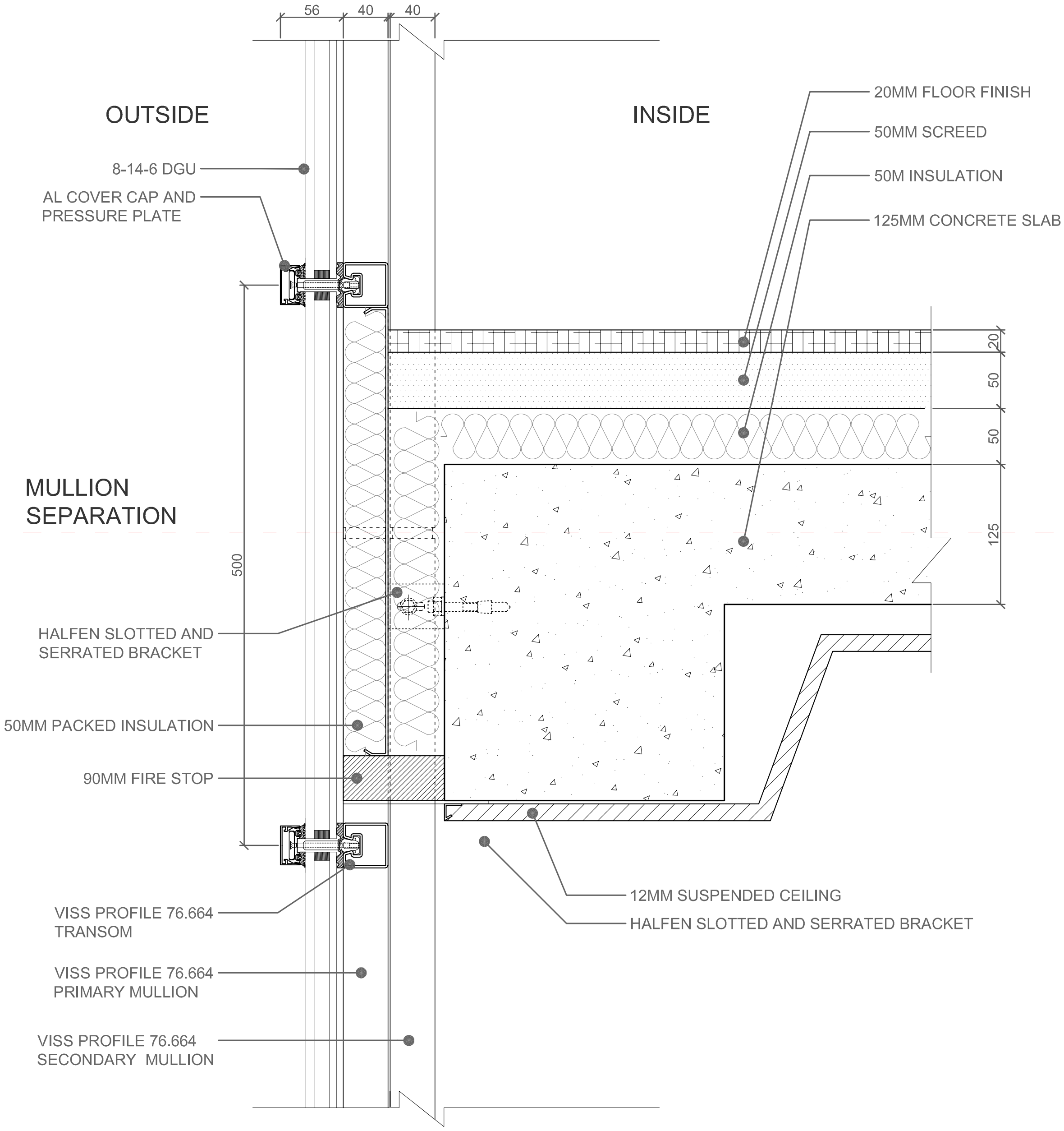
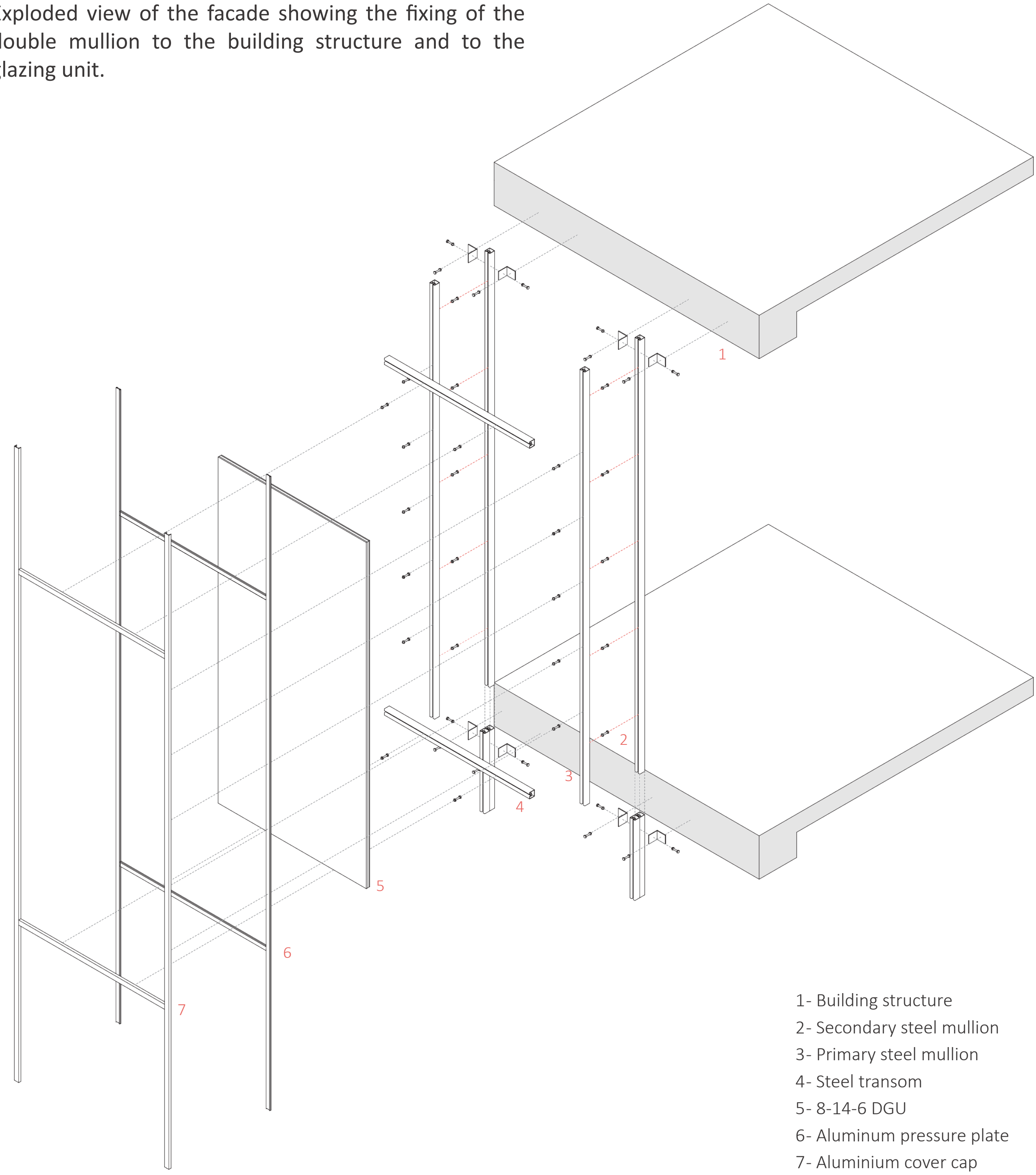


Figure 52 - Sectional view showing the fixing of the strengthened mullion to the structure (source: author)

Exploded view of the facade showing the fixing of the double mullion to the building structure and to the glazing unit.



1- Building structure
2- Secondary steel mullion
3- Primary steel mullion
4- Steel transom
5- 8-14-6 DGU
6- Aluminum pressure plate
7- Aluminium cover cap

Figure 53 - Exploded view of the facade (source: author)

Figure 55 shows the assembly stages for fixing the façade to the structure.

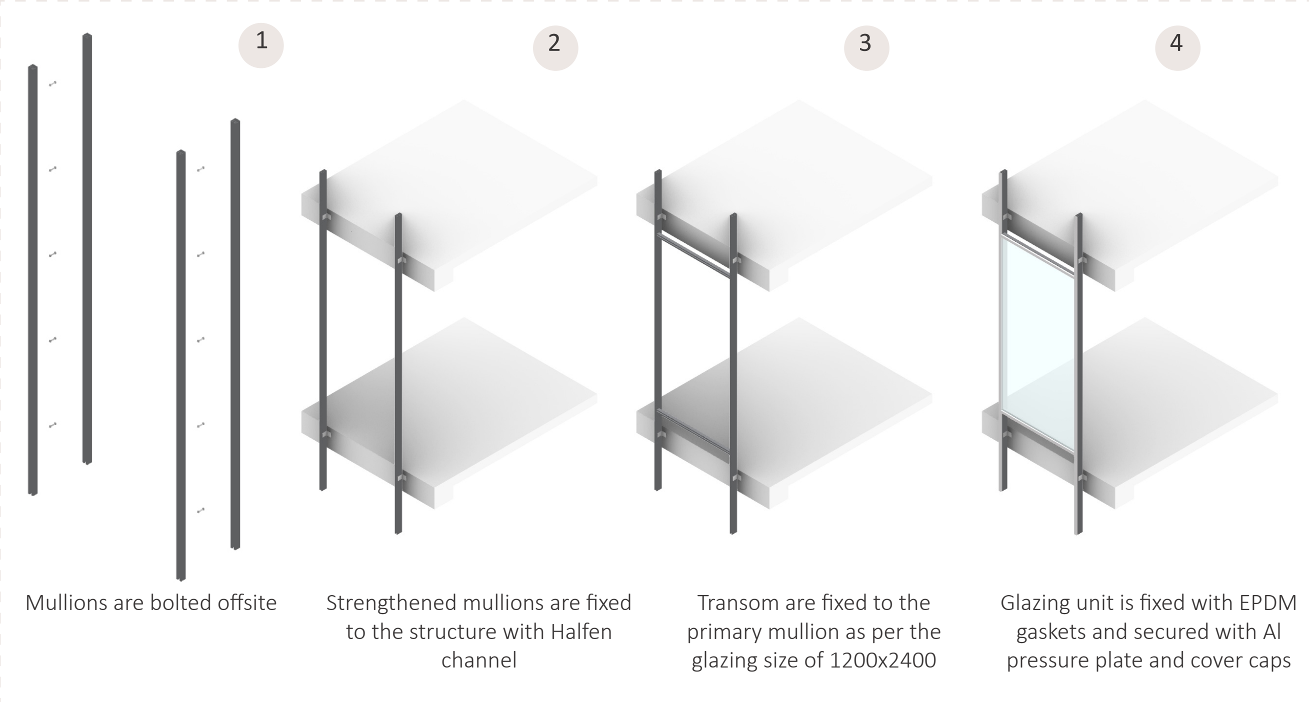


Figure 55 - Assembly for fixing of the system (source: author)

Structural Performance

To further check that the cross-section of the new mullion is sufficient, hand calculations are performed. The mullion is mainly subjected to the horizontal pressure of the wind uniformly distributed along its length and to the vertical forces due to its weight and load of the glass panels (Mestre and Calderón, 2007). For this, the maximum deflection of the rigid component (mullion) and resistance of the cross-section is examined as per the European Product Standard EN 13830. The calculations reflect admissible cross-section stress of 676.3daN/cm2 and deflection of 0.75cm, both of which are within the permitted limit. Appendix C shows the details for the calculations. Moreover, the profiles were not subjected to any loading previously and did not require over dimensioning its size for unknown fatigue.

Another calculation was performed to check the cross-section size required if the façade is designed with a primary stream for the same loading condition. Accordingly, a suitable profile was selected from the Jansen catalog for comparison, details in Appendix C. Profile 76.671 was selected and had a smaller cross-section for the same conditions. It reflects that the level of optimization that the primary stream gives is much higher, and the same design with the secondary stream can result in oversized sections requiring more material.

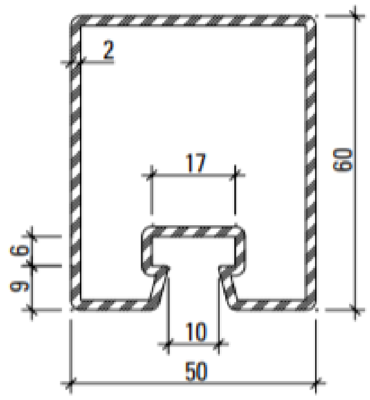


Figure 54 - Cross sectional detail of the 76.671 (source: Jansen VISS-Fassade-LP)

10.4 Design Scenario 2

The weak links associated with the design using secondary materials can vary as per their supply source. Therefore, an alternate scenario was conceptualized to reuse materials from the demolition process to comprehend how the design adapts to the varying material sources. Due to a lack of façade systems from the demolition stage in the current material harvest of ODS, a design scenario is hypothesized. For this, the same available stream of Jansen profile 76.664 is considered to be made available from the end-of-life of a building project. Although there can be endless alternatives, the design exercise serves as food for thought for further research.

The following assumptions are made based on the lessons learned from the interviews and the market analysis about materials from the demolition process:

- The dismantling of the profile from the construction will be either through unbolting the connection or cutting the profiles near the connection points. The former can result in damaged ends at the perforation and have cracks resulting from tension exerted on the connection points. The latter will result in smaller and uneven lengths for the steel profiles. In either case, the length of the profiles will be smaller than the required length of 3m.
- The façade system was exposed to the dead weight of the glazing acting downwards and wind load acting perpendicular to its surface. As a result, the material could have undergone damages requiring over dimensioning to ensure safety from its use in the next cycle.
- The system was connected using dry fixing; however, all the material cannot be retrieved due to the possible damages during dismantling. Thus, a material recovery of 90% is assumed for steel mullion, 60% for aluminum cover caps, and 80% for aluminum pressure plate as per the dismantling barriers of the different components in the curtain wall. Glass and EPDM are not up to the standards required and cannot be reused for this case.

According to the defined assumptions, the following design challenges are identified in addition to the ones in Design Scenario 1:

- The profiles require strengthening, like in the previous case. However, the quantity is dependent on the recovered material. Unlike construction waste, the demolition waste is not in excess length that can be cut for reinforcing the profiles. It means reinforcing the materials requires a different material either from the primary or secondary stream.
- Currently, the guidelines for safety margins associated with material damages are not in place. Therefore, there are no indications about the safety margins to consider with the reuse of secondary steel.
- The shorter and variable profile lengths require a flexible system for fixing the façade.

In addition to the already discussed design solution for the previous scenario, Figure 56 shows the ideas proposed to accommodate the additional challenges with the material from the demolition stage:

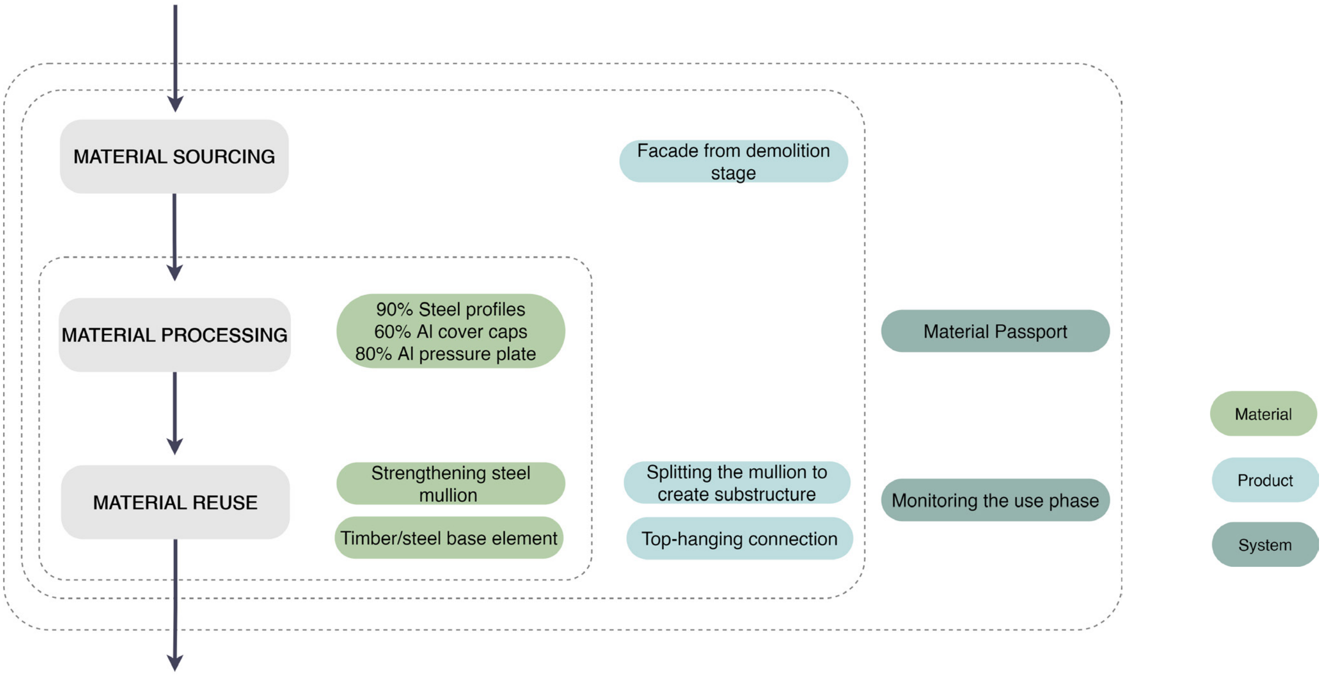


Figure 56 - Conceptual ideas for the design

- **Decoupling the functions of the mullion by splitting them into two parts** - The two functions of the mullion are split into two parts - the base element connected with the load-bearing slab and the interface element fixed with the thermal barrier, i.e., glass. The standard fixing systems for curtain walls require the length of the mullion to be the same as the floor height. Splitting the mullion for a functional separation in depth will ensure that only the base element is connected to the slab and needs to be of the floor height. The interface element can function independently and can accommodate varying mullions lengths. In this way, the base element works as reinforcement for mullion and substructure for fixing the façade.

- **Timber/steel base element** - The base element for the substructure can be in any material depending on the available connection system. Two options in primary steel and secondary timber are explored for the substructure. Steel-steel fixing can be done through bolting, as in Design Scenario 1. For timber, Douglas beams are selected from Burman's material inventory to propose conceptual ideas. The presented scheme is hypothetical and does not intend to develop a detailed design. It requires another research in itself, including prototyping and testing connection systems to bring concrete solutions.

Design Concept

Objective - Strengthening the mullion and providing a flexible fixing system.

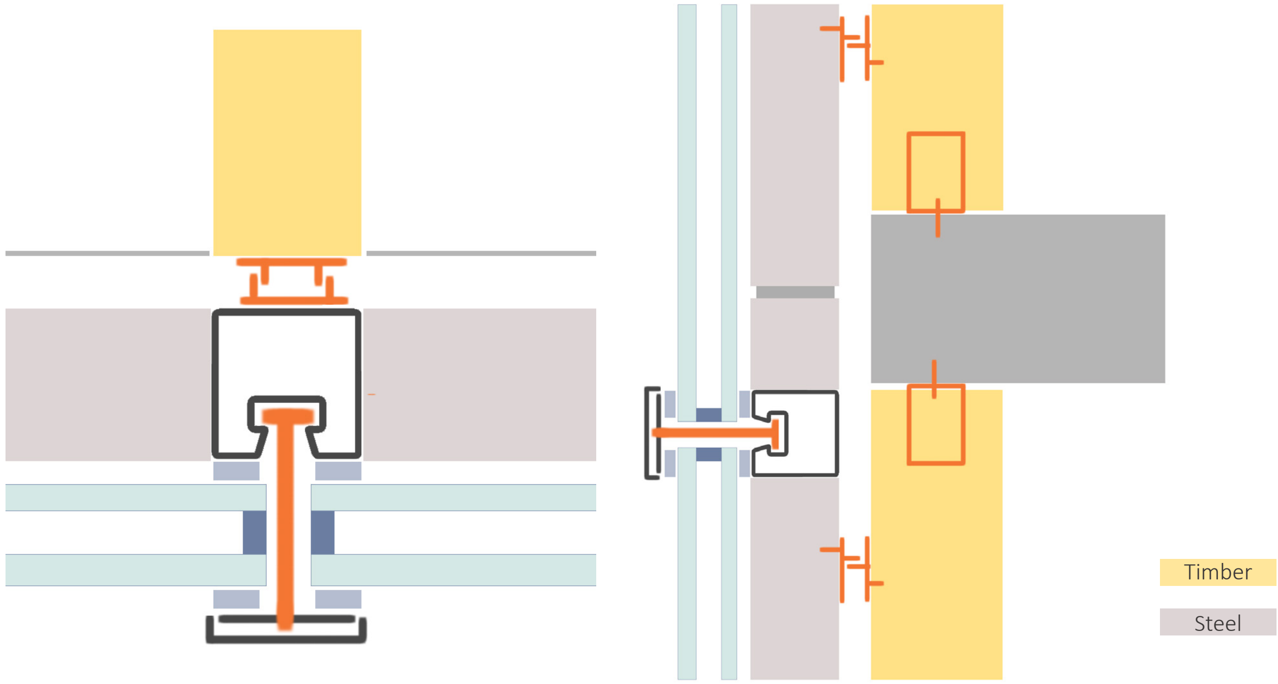


Figure 57 - Design ideas for strengthening and fixing the mullion with timber substructure in (left) plan, and (right) section (source: author)

Description - A different connection is proposed for the timber sub-structure that lets the steel mullion hang on top of the timber substructure, allowing the transfer of load between the mullion parts, as shown in Figure 57. The profile edge and the interface geometry determine the ease of assembly and disassembly (Durmisevic, 2006); therefore, the two parts are designed not to penetrate while fixing. The connection acts as an independent fixing element and does not disturb the flat interface; the fixing system will provide a higher degree of reversibility for future reuse, as discussed in section 5.4. An existing connector in the market, Ricon by Knapp, is selected for this. It is designed to transfer structural loads in beams between steel and timber sections. Assuming load transfer in curtain wall facades is much smaller, the connection can be customized to the requirements. It can be screwed to the timber support and bolted to the surface of the steel mullion, as shown in Figure 58.

Since the steel mullion and timber support will expand differently in thermal expansion, a 15mm distance between the mullions is provided sufficient tolerances for the material as shown in the plan view in Figure 59.

Figure 61 shows the sectional detail for fixing the substructure to the building structure, and the mullion to the substructure. The space between the two is closed off with a fire stopper between the floors. The vertical spacing of 15mm between the mullions allows it to be lifted to slide out for dismantling after use.

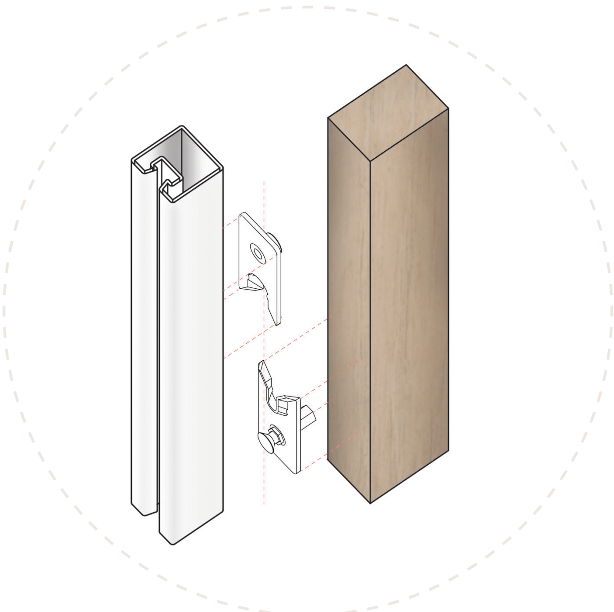


Figure 58 - Top hanging Ricon connector for fixing steel and timber (source: author)

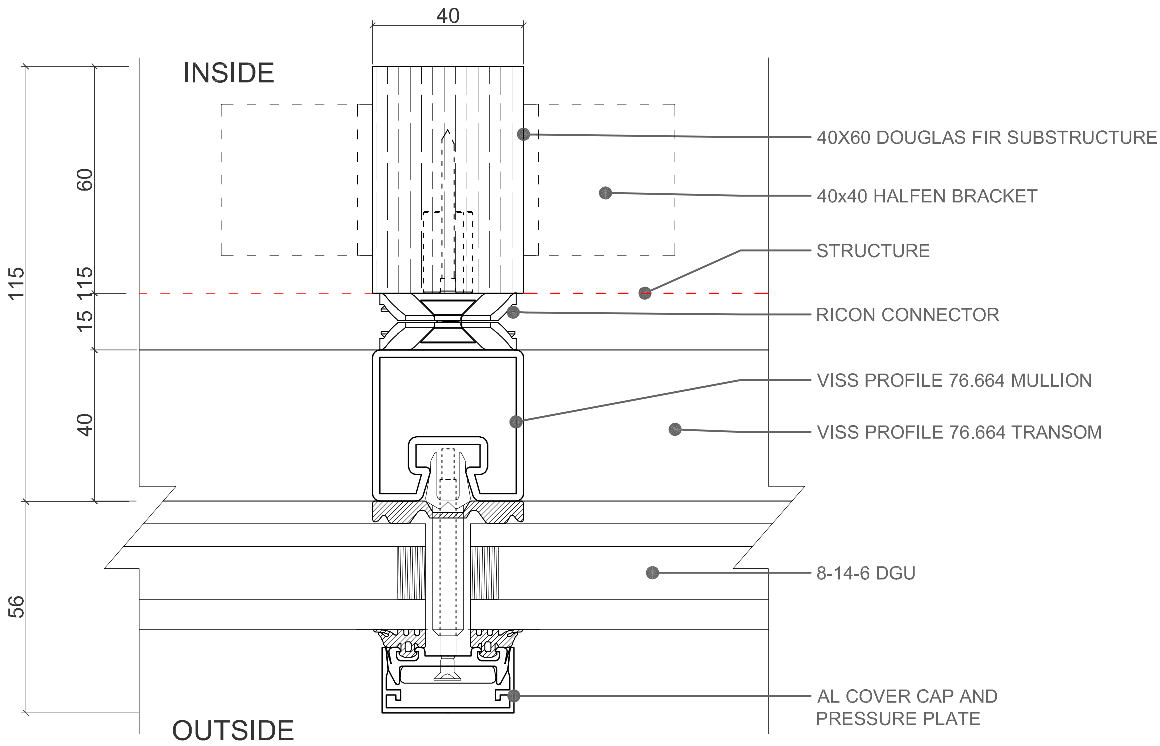


Figure 59 - Plan view of the detail (source: author)

Figure 60 shows the assembly stages for fixing the façade to the structure.

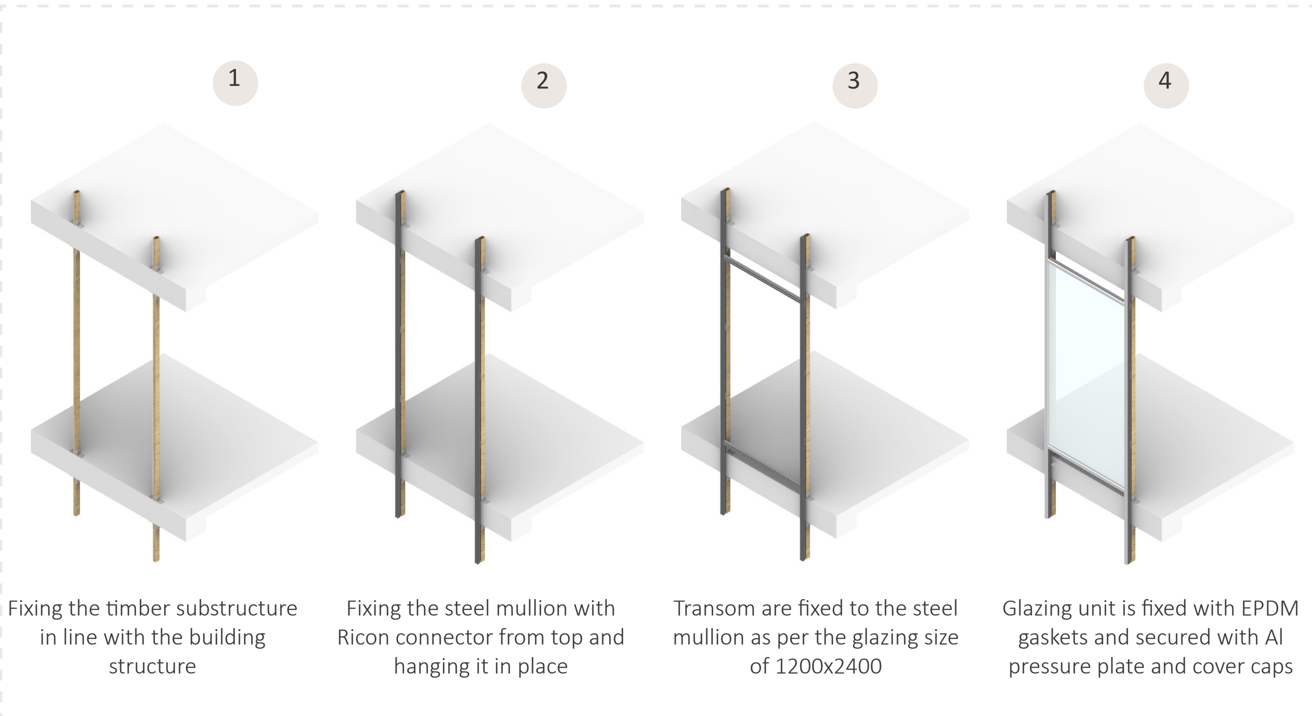


Figure 60 - Assembly for fixing of the system (source: author)

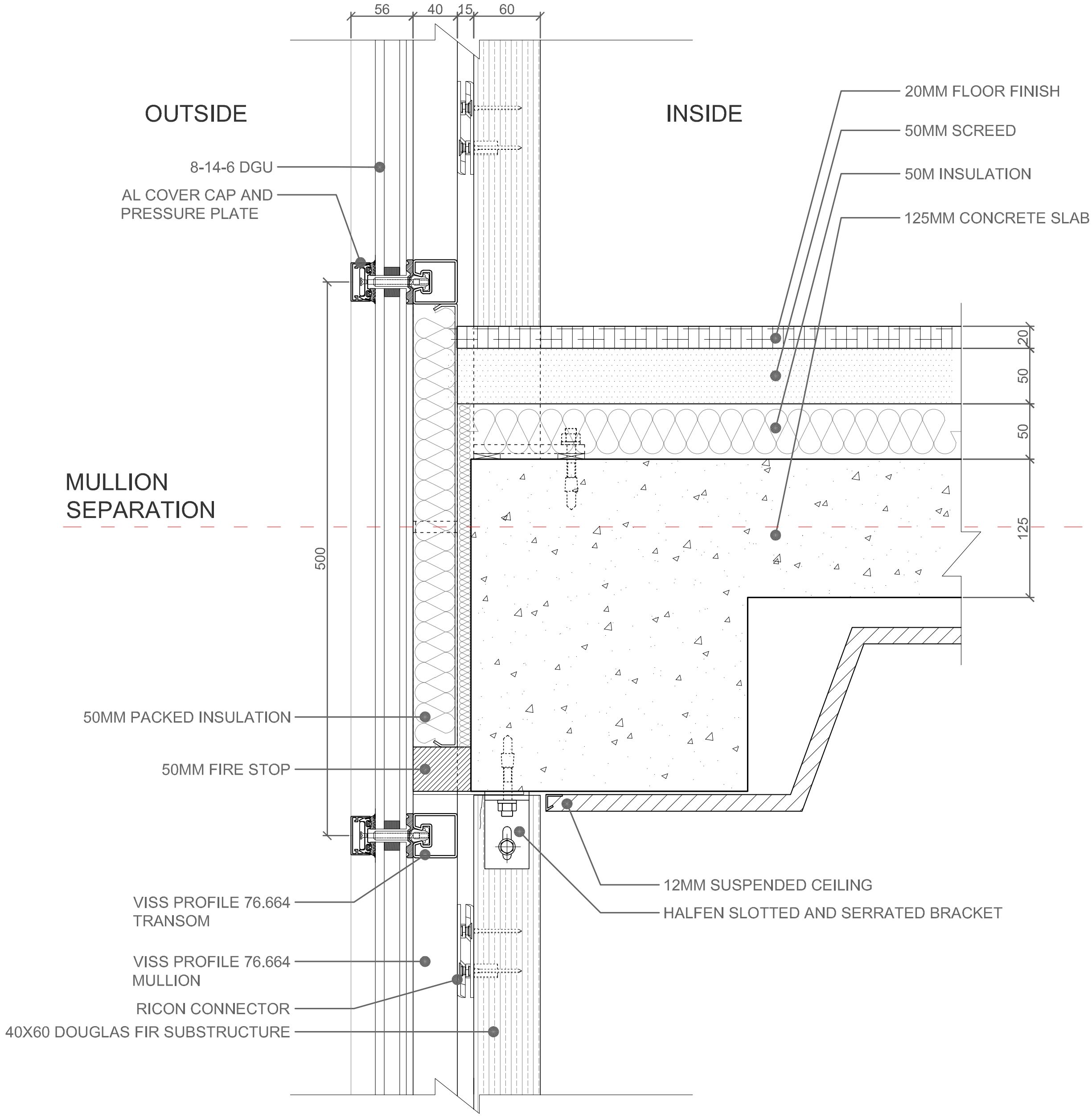
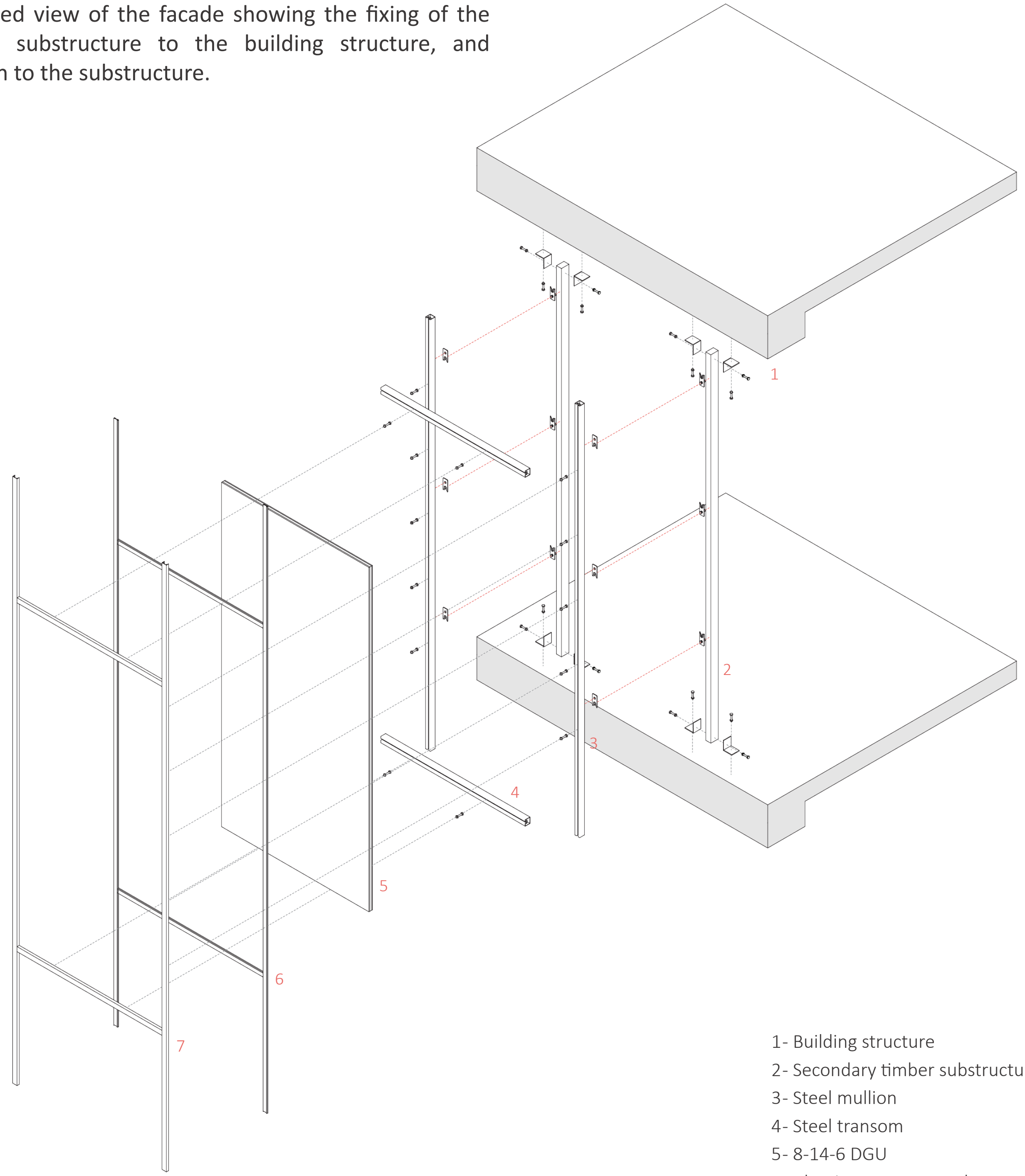


Figure 61 - Sectional view showing the fixing of the mullion to the timber substructure (source: author)

Exploded view of the facade showing the fixing of the timber substructure to the building structure, and mullion to the substructure.



1- Building structure
2- Secondary timber substructure
3- Steel mullion
4- Steel transom
5- 8-14-6 DGU
6- Aluminum pressure plate
7- Aluminium cover cap

Figure 62 - Exploded view of the facade (source: author)

10.5 Discussion

The two cases constitute the secondary materials from the construction overstock and demolition process. The former requires buying the material from the overstock of the façade manufacturer. At the same time, the latter necessitates intricate methods of retrieving façade from the building, either cutting the profiles towards the end or unbolting them, to ensure high material quality for reuse. The different procurement methods affect the quality of the secondary materials. As a result, the profiles from the construction stream can skip the material inspection as long as technical information regarding its use is available. On the other hand, a feasibility study is essential for the profiles from the demolition stream through material inspection, adding additional stages that can affect the time, labor, and cost required to reuse them, as shown in Figure 63.

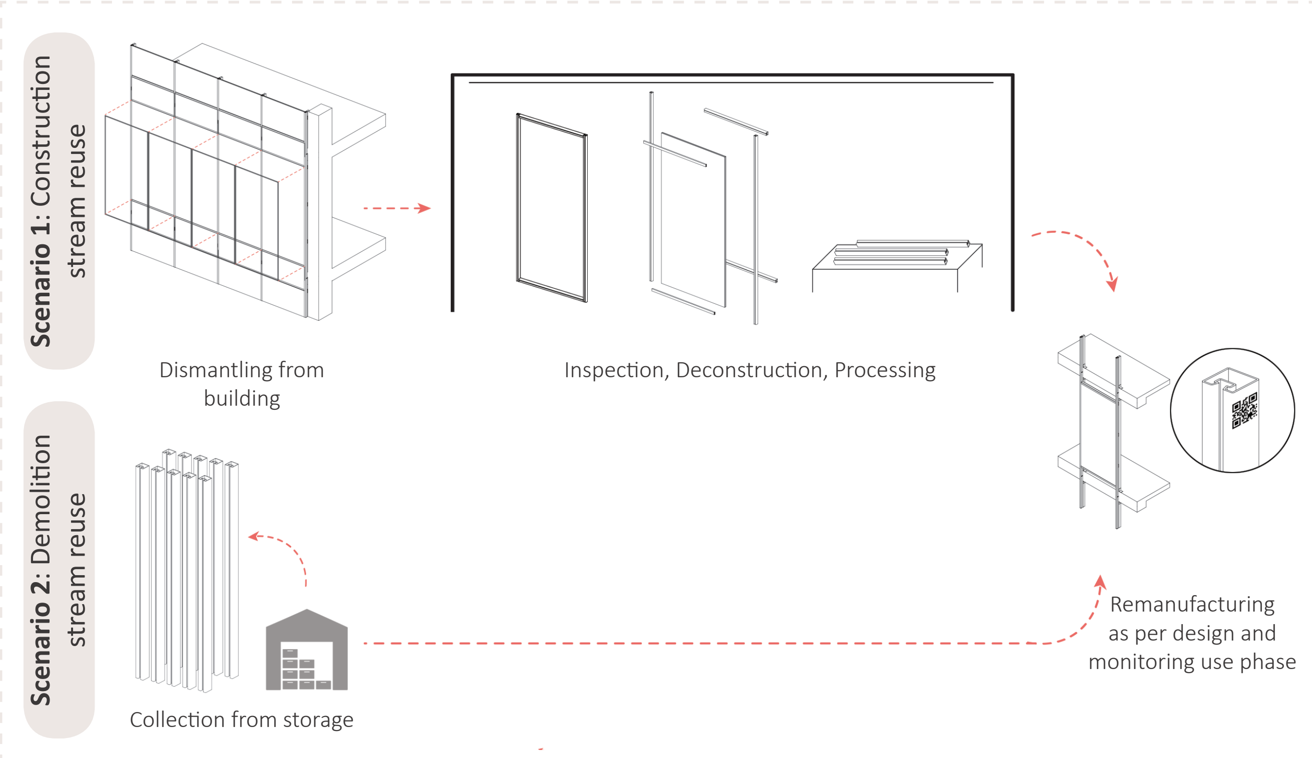


Figure 63 - Reuse process for the two scenarios (source: author)

Furthermore, the design adaptation required for the two cases was different, thus, the designer's role. The construction stream was unused material and only required an adjustment to upgrade its performance. On the other hand, the demolition stream required higher design flexibility to accommodate uncertainties with the material availability and physical condition. Moreover, a standard curtain wall does not require a different fixing system than the one in place by the system supplier. The concept for strengthening the mullion opted for the two cases is similar, but the fixing system varied significantly. For a standard curtain with primary materials, the cross-section is optimized for the required thermal performance and the loads acting on the surface. This luxury of optimization is not available with secondary materials. The structural calculation showed that the dimensions are slightly oversized for the same performance, making the profile bulky in appearance. Furthermore, the Ricon connector is customized from an available system for structural fixing and does not exist for facades, and requires engineering and testing, adding an extra step to fix the façade.

In addition, the reuse of secondary materials necessitates finding accessories for its fixing. Generally, the accessories are a part of the façade system and are supplied by the façade supplier. Therefore, there is no added effort required by the architect, facade engineer, or manufacturer to source these. Although ODS does not supply the accessories for the system anymore, they need to source the materials from independent suppliers to ensure design precision. Furthermore, recovery of only 60% of the aluminum cover cap and 80% pressure plates will end in ODS supplying for the material shortage. The lack of sufficient material quantity adds a step of finding an alternate supply source, either primary or secondary.

For the two scenarios, the storage of the construction stream, processing facility, and manufacturing facility are provided by the same façade builder Lootens in Belgium. Thus, no substantial transport miles are added during material handling among the various processes. However, these could be separate locations increasing logistics and transportation. Comparing this to a façade with primary materials, the product is supplied from ODS's production factory in Switzerland for use in the Netherlands. This transport is still higher than the secondary materials sourced from local sites and suppliers.

The explorations primarily look at the reuse of mullions due to their availability. However, the curtain wall also consists of other components. Therefore, it will be of added value to continue researching procurement of these components, including glass, from the EOU stage to see how the design can be adapted to reuse this stream. Furthermore, the aesthetics of the two design schemes were not part of the research; it is an important aspect and drives the demand for secondary materials. It can become a barrier if not explored.

10.6 Design for Reuse

The design explorations tackled the technical challenges for the reuse of secondary materials for curtain wall façades. Further, the design applied circular strategies to ensure detachability for future reuse. However, since these secondary materials already exist, only a little could be done to their design. Therefore, the research proposes conceptual 'Design for Reuse' criteria to inform future design of façades for reuse at any stage in their lifecycle. It must be noted that the criteria specified below represent research findings and do not aim to provide an exhaustive design list.

Transformability

- Most façade systems designed for high energy performance are fixed and do not accommodate easy adaptations. It often results in demolition, and thus, waste creation when they cannot keep up with the upgrades in the energy standards. The design must allow the transformation that can adapt to these requirements. For instance, the design of the glazing unit should allow the replacement of glass panes without hampering the system or accommodate new glass panes to be still able to perform to the minimum energy standards.
- The future reuse of facades cannot always be specified; therefore, its design must allow reuse for different contexts. It entails designing facades through a system of modular components that can be used to create a kit of parts. This inventory with standard sizes can then be adjusted for different facade requirements.

Detachability

- The transformations within one shearing layer should not affect the other layers. It means the façade is independent and demountable to allow repairs/replacements without affecting other layers.
- Facades can consist of multiple components and materials. Therefore, reversible connections and lifecycle coordination are essential to ensure that the different components can be reused. For instance, an independent dry connector can prevent dependence between the components by avoiding penetrations. In addition, the connections must be accessible and allow for easy disassembly to reduce the effort and time required.

Durability

- Harvesting materials can be a time-consuming process. Therefore, it is essential to use durable materials that sustain a longer life and are still worth harvesting for the subsequent use cycle.

- The connections are designed as static entities but can be exposed to dynamic loading during their use. Thus, their design must be durable and allow repair/replacements of parts that wear off to sustain multiple use cycles. Moreover, the design of motor-based accessories like shading systems needs to accommodate the maintenance of parts that burn out through remanufacturing.

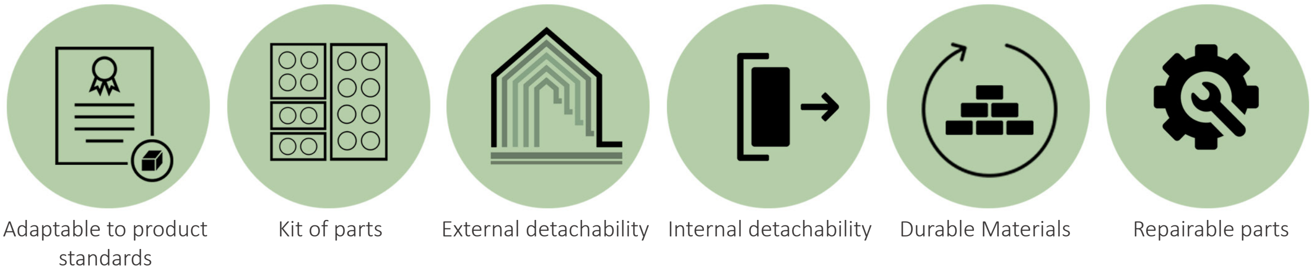


Figure 64 - Design for Reuse criteria (source: author)

10.7 Summary

The design exercise shows important findings. Firstly, most materials coming from the existing secondary stream cannot be directly designed into a new standard product. Therefore, it is essential to assess their residual value to provide design solutions. There can be multiple ways of providing this solution, and the research only highlights one of them. The two cases, construction overstock and EO(s)L façade, came with their challenges and required different levels of design adaptation for fixing. Even though the facades are not at the dismounting stage yet, it was essential for both the designs to be dismountable to reuse them for the next case. Therefore, the design of the interface and its detachability became more critical while reusing secondary streams. Lastly, explicit information provided by ODS regarding their previous use condition and system drawings served as tools for finding ways to embed them in the new construction system.

11.

DESIGN ASSESSMENT

The chapter intends to quantify the circular value of 'Reuse' and its environmental impacts by evaluating the design scenarios of the previous chapter. The results are then used to propose indicators relevant for the assessment of 'Reuse' as a circular approach, which is another product of the presented research.

11. DESIGN ASSESSMENT

11.1 Introduction

This section assesses the two design scenarios proposed in chapter 10. The design explorations showed that the reuse of secondary materials requires additional efforts by the material supplier and higher design adaptation by the engineer and the architect. Therefore, such a process will only be feasible and acceptable by the industry if it yields benefits. The objective of the assessment is to quantify benefits from the directed impact of the energy from material extraction to processing secondary streams for reuse and its impact on the circularity of a product. For this, two assessments are carried out, the environmental impact of the process in terms of its embodied energy and carbon emissions and circularity assessment of the façade through MCI to evaluate the percentage of materials reused and still reusable in the next phase. The description regarding the choice of assessment is provided in chapter 6.

The two design scenarios are compared to a traditional design scenario 3, as shown in Figure 65. Scenario 3 consists of recycling secondary materials at the EO(s)L and use of primary materials with a proportion of recycled content in the supply for the design of new facade. Jansen Viss profile 76.671, available in the catalog of ODS, is selected for the new facade. The profile has the closest performance with loading conditions as in the two design cases. The choice of the profile, supported by calculations, can be found in Appendix C.

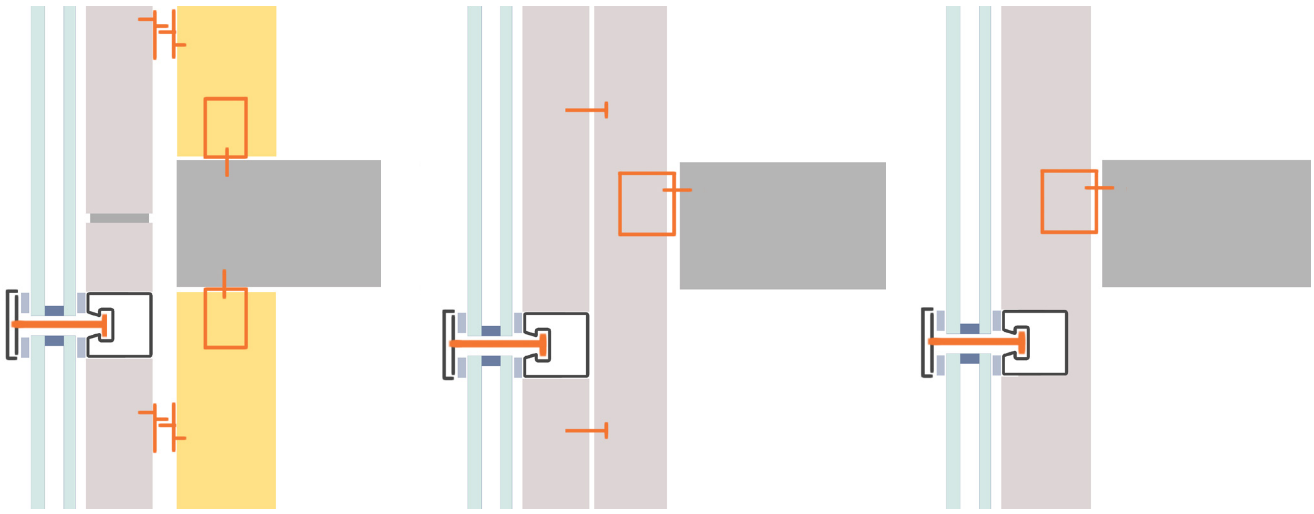


Figure 65 - Three Design Scenarios for the assessment (source: author)

Table 7 - Design Scenario conditions for assessment (source: author)

Scenario	***Condition***	***Secondary Material from Reuse***	***Secondary Material from Recycle***
Scenario 1	**Reuse** of Construction overstock	Steel mullion	
Scenario 2	**Reuse** of materials from Demolition	Steel mullion	
		Timber for reinforcement	
		Al cover cap	
		Al pressure plate	
Scenario 3	**Recycling** of materials from Demolition and use of primary materials with recycled content		Recycled steel in mullion
			Recycled steel in mullion

11.2 Contextualization for the assessment

The goal of the assessment is to evaluate 'Reuse' as a circular strategy and the environmental impact of this strategy as an EOL scenario for the existing sources of secondary materials in the built environment. Two circularity assessments were described in chapter 6, at the material level and product level. At the material level, the MCI score assesses the restorative flow of materials within the product. However, this value depends on the product's design, which can be assessed through the qualitative assessment of Disassembly Potential. The assessment is applicable during the initial design stage of the product to guide the decision-making process. Since the secondary materials used in the design cases in chapter 10 already exist in the environment, they come with a particular cross-section size, shape, and strength. Therefore, only a little can be done to reuse them for the new condition. Nonetheless, the connections used for fixing the façade must be reversible, demountable, and easily accessible to facilitate future reuse.

Design scenario 1 reuses the steel mullions from the construction overstock. Other materials for the curtain wall are supplied in conventional ways containing a proportion of recycled content. The strengthened mullions are connected using a bolt that is fixed through the viss of the secondary mullion. Other components of the facade are fixed using the standard Jansen dry fixing. The dismantling of the façade, as shown in Figure 66, entails removing the cover cap, unscrewing bolts to remove the pressure plate, and removing the insulated stud to take out the glazing unit. The two mullions are bolted together and are required to be dismantled first from the construction. They are then unbolted to get the two mullions for subsequent use. The primary mullion was punctured for the bolt, requiring filling it with weld and grinding the surface for reuse.

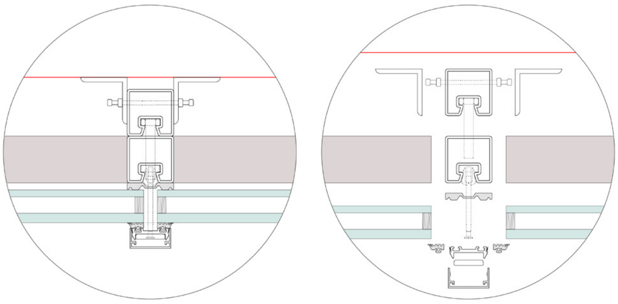


Figure 66 - Dismantling of facade in scenario 1 for future reuse

Design Scenario 2 reuses the steel mullion, aluminum cover caps, and pressure plates. Any shortage in the material is supplied through the primary stream with recycled content. The steel mullion and timber substructure are fixed using a Ricon connector that lets the steel mullion hang on the substructure and makes it independent of the building structure. As shown in Figure 67, dismantling the cover cap, pressure plate, and glazing unit follow the same steps as the previous case. The steel mullion is demounted from outside, starting from the top floor by lifting it and sliding out, followed by the mullion on the floor below. The timber substructure is then unbolted from the structure from the inside. Finally, the Ricon connector has to be unbolted from the steel mullion and unscrewed from the timber surface for subsequent use.

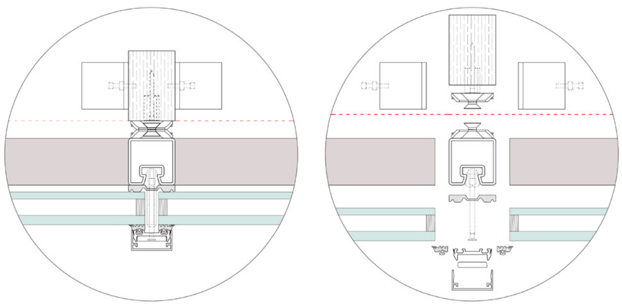


Figure 67 - Dismantling of facade in scenario 2 for future reuse

Design scenario 3 uses a standard detail provided by ODS for fixing the curtain wall. The system is fixed using dry fixing and follows similar steps as the previous case to demount the cover cap, pressure plate, and glazing unit. In addition, the steel is unbolted directly from the construction, and no additional steps are needed, as shown in Figure 68.

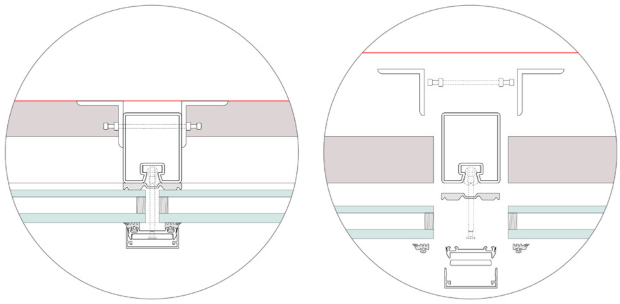


Figure 68 - Dismantling of facade in scenario 3 for future reuse

Although it is of utmost importance to see the accessibility to these connections, these are specific to the building. Therefore, the research assumes that the described condition for dismantling can be facilitated for all three cases to ensure future reuse of the façade. For scenario 3, the fraction of material recycled at the EOL is taken from the National Milieu Database (2020) for the Dutch building sector. The recycled content in primary production is taken from an average estimation of recycled content in supply from the Granta CES software, as depicted in Table 8.

Table 8 - Inflow and outflow of materials for assessment (source: author)

Scenario	*Condition*	*Secondary Material from Reuse*	*Secondary Material from Recycle*	*Fraction of mass from reuse/recycle (inflow)*	*Fraction of mass for reuse/recycle (outflow)*
Scenario 1	**Reuse** of Construction overstock	Steel mullion		1.0	0.90
Scenario 2	**Reuse** of materials from Demolition	Steel mullion		0.90	0.90
		Timber for reinforcement		0.90	0.90
		Al cover cap		0.60	0.60
		Al pressure plate		0.80	0.80
Scenario 3	**Recycling** of materials from Demolition and use of primary		Steel	0.57	0.95
			Aluminum	0.44	0.94

11.3 Environmental Impact Assessment

A process-based Life cycle Impact Assessment (LCIA) methodology to study the directed impact of embodied energy from primary renewable and non-renewable energy and carbon emissions has been conducted. There are several databases available for input flows for the study, including Ecoinvent, Gabi, ICE. The inventory input is used to evaluate the impact on the environment and resource consumption through LCA software. For this research, the German database Oekobaudat is used for inventory data. The selected database provides 'quick LCA results' as the aggregated impact of environmental indicators for the building materials for the lifecycle stages (A1-A3, B1-B7, C1-C4, and D), making it possible to calculate the LCIA without any impact assessment method (Emara and Ciroth, 2014). The input flows for the process are specified as energy density coefficient, transportation coefficient, recycling/processing coefficient. The presented research uses the reference of an existing LCIA study by Hartwell (2019) based on the same database for the reuse potential of glass. The dataset is traceable, freely accessible, and complies with ISO-14040 for LCA assessment. Any value that could not be taken from the dataset will be explained in the following section.

Functional Unit

A function unit (FU) provides a functional basis for a fair comparison of impacts (Hartwell and Overend, 2019). The functional unit for the assessment is defined as a 3000mm x 1200mm double-glazed steel curtain wall façade designed as a stick system. Figure 69 shows the percentage composition of material masses for the three cases. These are obtained using manual calculations for the design cases based on construction drawings and material densities, which can be found in Appendix D.

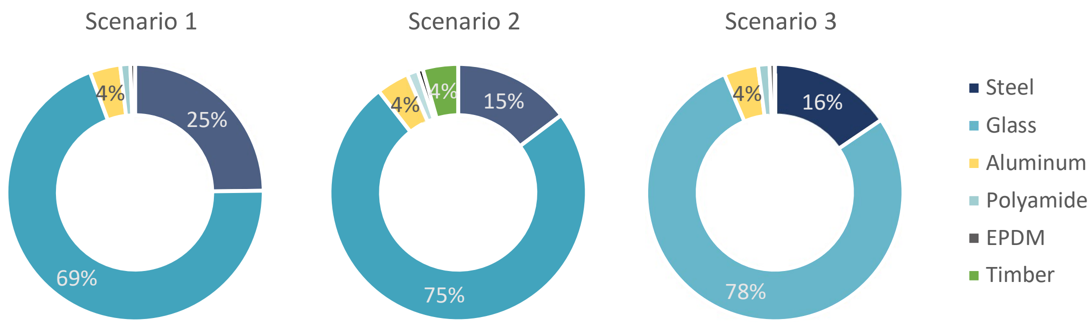


Figure 69 - Material mass composition for the three scenarios

System Boundary

The dataset is used to calculate the net impact of reusing secondary materials in terms of resource use through primary renewable (PERE) and non-renewable (PENRE) energy, excluding energy used as raw materials in MJ and carbon emissions in kgCO2eq. of Global Warming Potential (GWP). The evaluation only considers the foreground processes; any background process to support the reuse of materials is beyond the scope of the analysis. Three scenarios are evaluated for the savings incurred from the selected EOL stages and avoided stages for production. The system boundary is described below and summarized in Figure 70.

Two flows are defined to estimate the avoided impacts from the reuse of secondary materials:

- The savings made from the disposal of existing materials in the ecosystem are indicated in the Module C (End-of-Life Disposal) of the life cycle. It entails the on-site demolition energy (C1), transportation to waste processing (C2), waste processing (C3), and disposal of the remaining stream (C4).
- The savings made from the production of primary materials for the designed façade with secondary materials and are indicated in the Module A (Product Stage) of the life cycle, including raw material supply (A1), transportation (A2), and manufacturing (A3).

The added impacts from the reuse of secondary materials can be defined as follows:

- The substituted end-of-life impact arising from careful dismantling of materials and processing to make them reusable. It will include onsite/offsite disassembly and deconstruction energy (C1), transportation to a processing facility (C2), processing energy (C3), and disposal of the leftover stream (C4). Moreover, the impact stages are different for the construction and demolition streams and will be considered accordingly for the assessment.

The impact of construction module (A4 - A5) and use module (B1 - B7) is assumed to be negligible on the benefits/loads resulting from the reuse of secondary materials and are not included in the system boundary; this choice is explained in section 6.2.1.

The assessment considers the following impacts for the three scenarios, and summarized in Figure 70:

- **Scenario 1** consists of secondary materials from construction overstock, which are used for the new façade. The impact of the production of this stream was accounted for in its first cycle. Therefore, its reuse can be counted as savings from the production of virgin materials. Only steel mullions are used in this scenario, while the other materials are still from primary sources.

- **Scenario 2** consists of secondary materials from the demolition process. Steel mullions, timber, and a percentage of aluminum pressure plates and cover caps are reused for the façade. The EOL evaluation of this stream accounted for the recycling of material in the first use phase. Therefore, reuse of the stream can be counted as savings from its current EOL recycling and production of virgin materials.

- **Scenario 3** entails recycling secondary materials at the EOL as accounted originally by the manufacturer. It avoids production of primary materials for a quantity equivalent to the fractional proportion of the recycled content in the supply.

There is no design alteration for EPDM gaskets, polyamide thermal break, and glazing unit for the three scenarios. Although these components are crucial for a curtain wall system, no reuse condition could be created for their existing secondary stream. Therefore, these are left outside the scope of the environmental impact assessment.

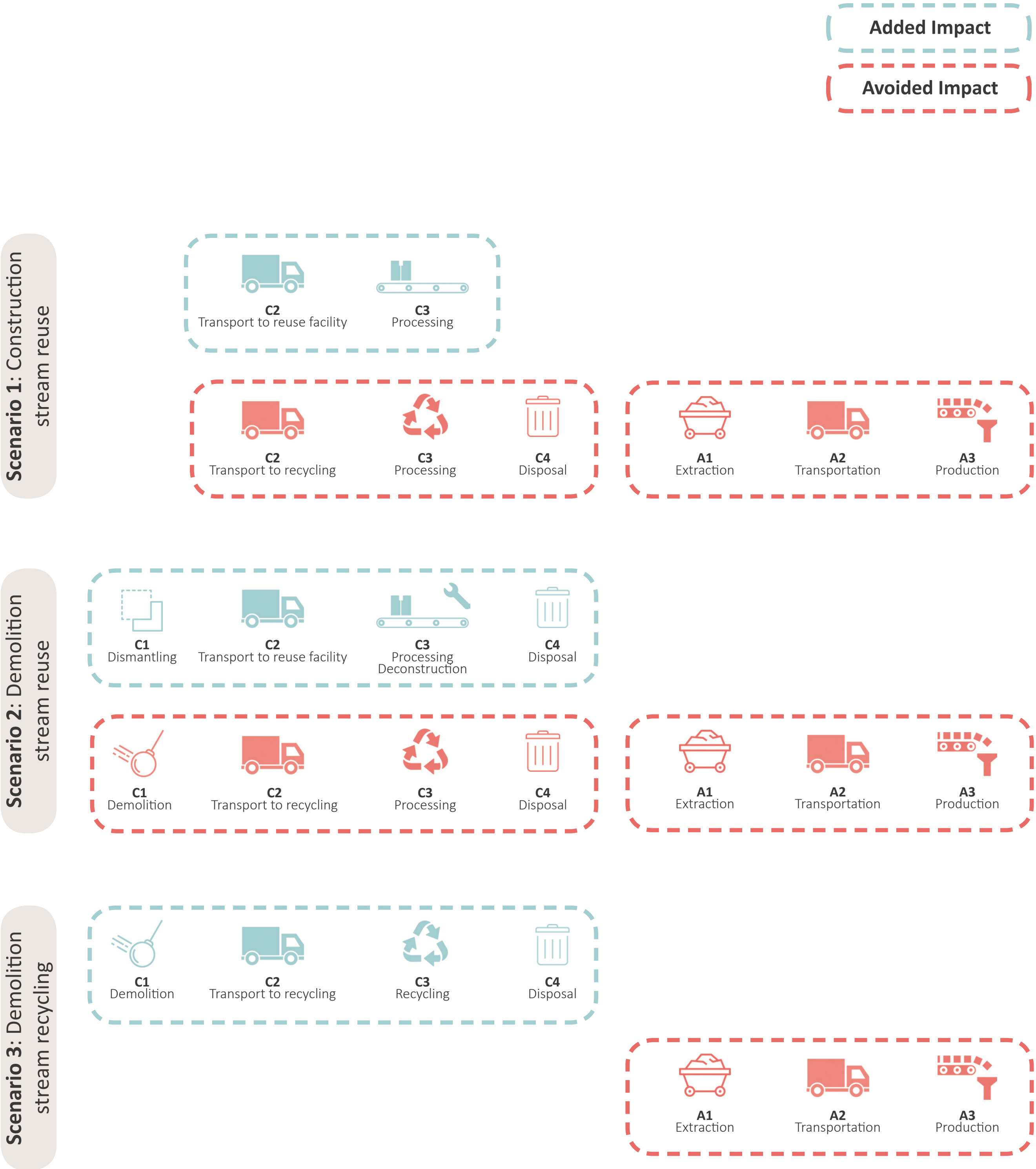


Figure 70 - System boundary for LCIA for the three scenarios (source: author)

Production

$E_{production}$ is the environmental impact of extraction, transportation, and processing of raw materials into specific façade components. It is calculated as:

$$E_{production} = \text{Volume x Density x Energy density coefficient (A1-A3)}$$

Transportation

$E_{transportation}$ is the environmental impact of transportation resulting from transporting materials from site or storage to the collection, processing, and manufacturing facilities as per their defined end-of-life conditions. It is calculated as:

$$E_{transportation} = \text{Transportation energy per unit mass \& distance x Product mass x Distance}$$

The total transportation is the sum of all the distances traveled by the material from gate to grave or gate to cradle. The average transport distances are determined whether the material is taken directly from site to factory or an intermediate facility and then to the factory, as depicted in Table 9. For the assessment, an assumption is made that materials reused will have to travel long distances to reach inspection and processing facilities over the materials to be recycled. It is because the collection points for separation and inspection for recycling are already established within the cities. However, the last mile traveling of materials (for recycling) to the individual manufacturing plants for production in Europe is not considered for this evaluation.

Table 9 - General scenario for transportation (in km) for materials

EOL Scenario	***Means of transportation***	***Average transportation distance***		
		Site to collection facility (km)	Inspection to processing facility (km)	Processing to remanufacturing facility (km)
Reuse	14 tonne 2 axle truck	100	100	200
Recycling		50	50	-

Dismantling/Demolition energy

It is crucial to distinguish between the energy required for dismantling for reuse and demolition for recycling. Dismantling energy can be higher due to detailed instructions for the required material quality for reuse. Since the Design for Disassembly is a relatively new topic, most EPDs of existing building products do not specify the energy required during the dismantling of façade systems. Additionally, deconstruction often consists of exclusively manual operations and adds to the man-hour required in the process (Allacker et al., 2013). This energy is often unaccounted for in the embodied energy assessment, but it can significantly impact the feasibility of the whole process.

Due to limited literature in this aspect, research done in Athena Institute is used for this particular data. The research analyzed an office building to determine the energy used in the demolition/disassembly of the structure at its end of life (Gordon Engineering, 1997). Table 10 summarises the energy used for on-site disassembly/demolition in two material options. The study concluded that the energy required for steel (metals) is higher than wood due to additional machinery required to handle heavy steel sections on site. Furthermore, dismantling energy for reuse is higher than demolition energy for recycling because of the prevalent use of machines, including cranes for hoisting and supporting the bearing elements. Though this research constituted the dismantling of structures, it can be assumed that the equivalence between energy for dismantling for reuse and demolition for recycling will be similar for facades and have been used to estimate the C1 stage of the lifecycle.

Table 10 - Energy used (in MJ/kg) for demolition/dismantling of the building structure (source: Gordon Engineering, 1997)

	Demolition for recycling (MJ/kg)	*Dismantling for reuse (MJ/kg)*
Steel frame	0.239	0.432
Wood frame	0.323	0.176

An earlier graduation research converted demolition energy (MJ/kg) to carbon emissions (kg CO2eq.) using the standard carbon emission factors for fuels in the Netherlands. It assumes the energy values based on Gas/ Diesel oil, and the same energy source is used to obtain a value of 74.3kg carbon emissions per GJ of energy (Grover, 2020). There are no practical studies to measure the off-site deconstruction of secondary facades yet. Despite that, an earlier LCA study by OVAM considered diesel consumption for mechanical operations as taken as 0.0437 MJ/kg, regardless of the material composition for deconstruction (Allacker et al., 2013). The same is considered for this research.

The energy is calculated as:

$$E_{demolition} = \text{Product mass x Demolition coefficient}$$

$$E_{dismantling} = \text{Product mass x Dismantling coefficient}$$

$$E_{deconstruction} = \text{Product mass x Deconstruction coefficient}$$

Processing energy

Processing energy is the environmental impact associated with recycling or reusing the demolished or dismantled facades, respectively. For demolished streams, it will include recycling materials for energy recovery. Timber is assumed to be downcycled in another industry, and diesel consumption of 0.0437 MJ/kg is considered for mechanical operations for its use. For dismantled stream, it entails cleaning, inspection, repairing, and recoating of materials. Due to limited literature on the energy required for processing for reuse, an assumption is made that all materials will have to undergo reapplication of coating to ensure reuse in the next phase. The energy required for trimming, cutting, repairing, and building up the façade is not considered because it comes under the construction stage A4 of the analysis and is outside the scope. The values for evaluation of processing energy is given as follows:

$$E_{recycling} = \text{Product mass x Recycling coefficient}$$

$$E_{processing} = \text{Product mass x Reapplication of coating coefficient}$$

Net Impact

The net impact in energy savings from the avoided and added process is calculated as:

$$E_{net} = E_{added} - E_{avoided}$$

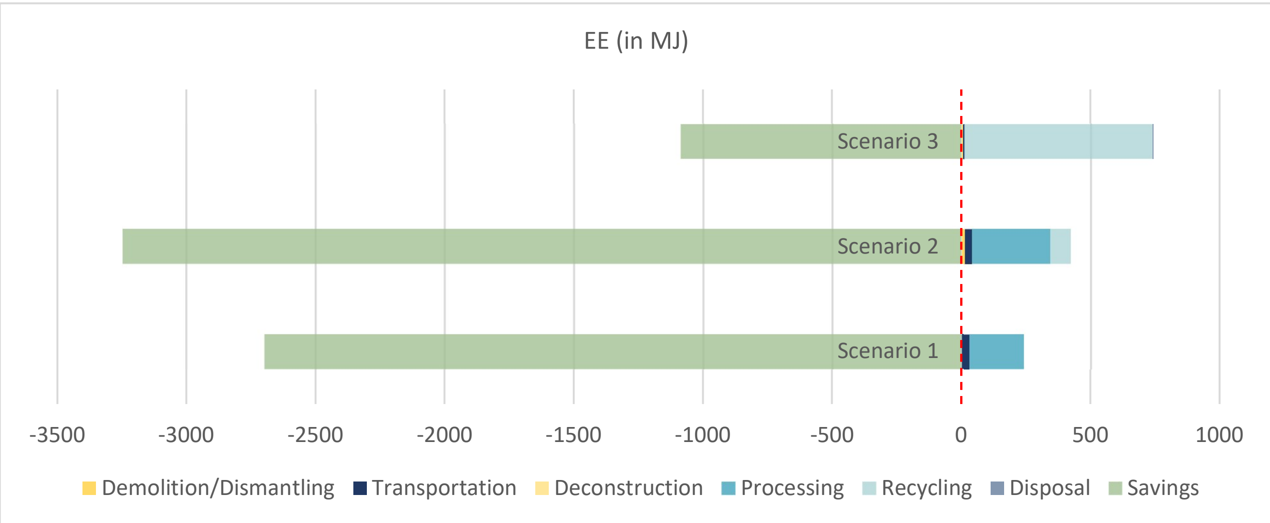
The percentage benefits from reuse are calculated as:

$$E_{benefits} = [(E_{added} - E_{avoided})/ E_{avoided}] \times 100$$

11.3.1 Results

The environmental impact for the three scenarios, in terms of the total of primary renewable energy (PERE) and non-renewable energy (PENRE) and the Global Warming Potential (GWP), is evaluated. Appendix D shows the calculations for the different scenarios, and the summarised results are presented graphically in Figure 71. The negative embodied energy and carbon emissions indicate savings incurred with the different EOL substitutions, while the positive energy and carbon emissions indicate the added impact with EOL for the materials already existing in the environment.

- Scenario 1 has an added impact of 243MJ and 14kgCO2eq and an avoided impact of 2938.1MJ and 222kgCO2eq, respectively, for EE and GWP.
- Scenario 2 has an added impact of 424MJ and 25.7kgCO2eq and an avoided impact of 3671MJ and 254.3kgCO2eq, respectively, for EE and GWP.
- Scenario 3 has an added impact of 744.9MJ and 60.44kgCO2eq and an avoided impact of 1831.6MJ and 118.3kgCO2eq, respectively, for EE and GWP.



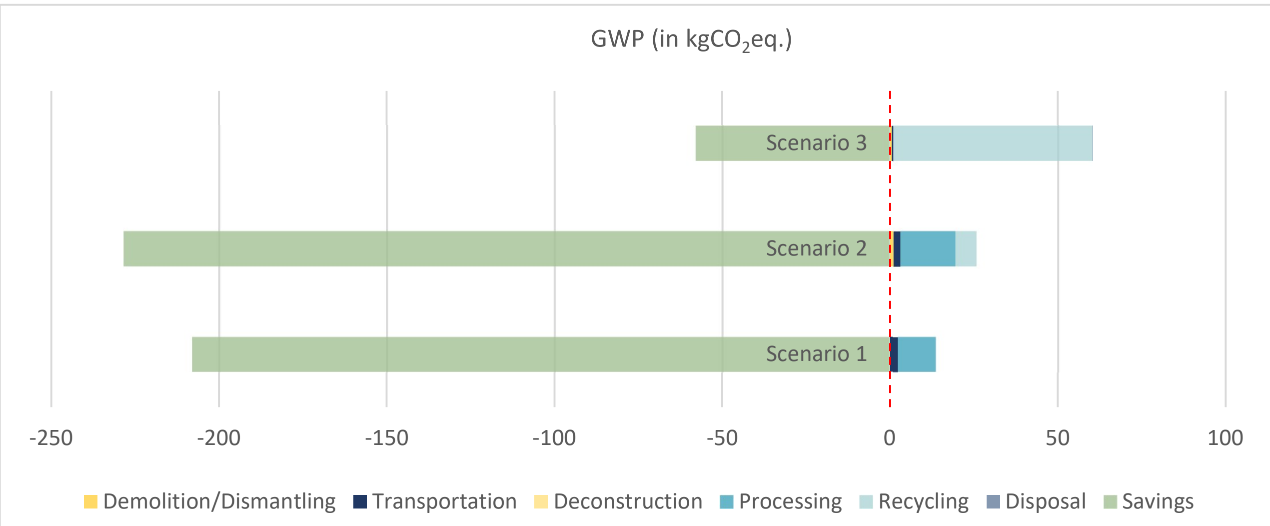


Figure 71 - Comparison of total EOL environmental impact in terms of i) EE (in MJ) and ii) GWP (in kgCO2eq.)

All three scenarios show a saving in energy required due to avoided impact with raw materials production. Reuse of secondary material from the construction stream shown in Scenario 1 led to a saving of 91% for EE and 93% for GWP. Only the steel mullions are reused in this case, constituting a 9% share by volume of secondary material in the facade. Scenario 2 can be made possible through careful dismantling and deconstruction of facades for reuse, constituting a 25% share by volume of secondary material in the facade. It has a potential savings of 88% for EE and 89% for GWP. The high savings for Scenario 2 highlight that the environmental impacts associated with dismantling and deconstruction have little contribution to the overall process. Scenario 3 considers recycling materials from demolition resulting in savings of 59% for EE and 49% for GWP.

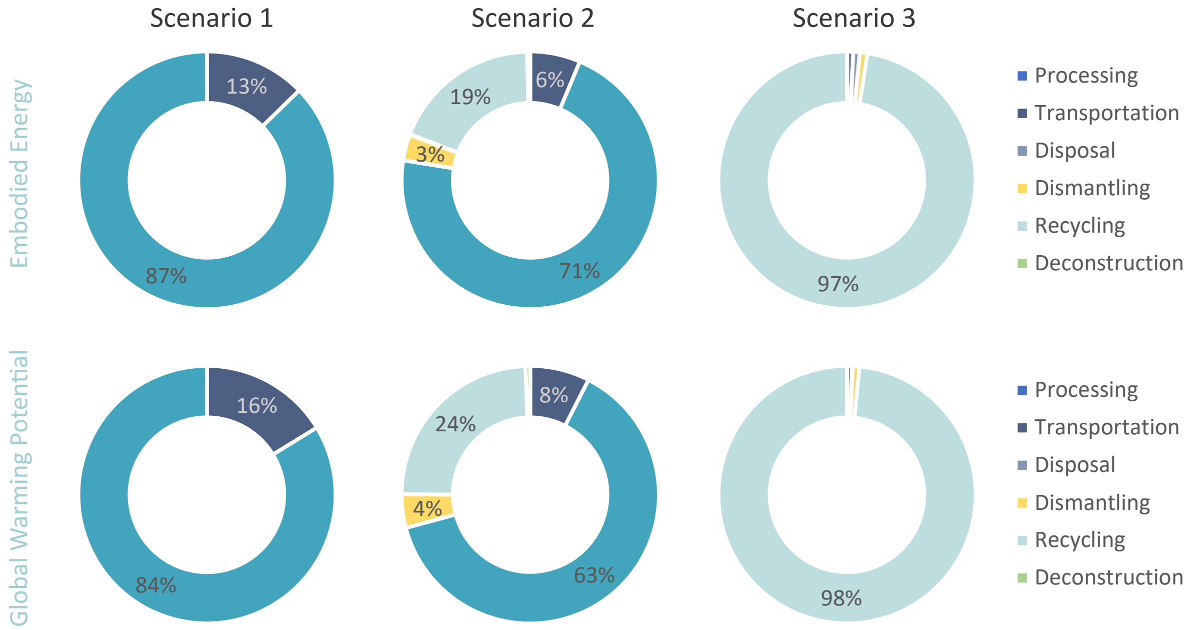


Figure 72 - Percentage contribution of substituted EOL processes for the three scenarios to i) EE and ii) GWP

- Figure 72 shows the contribution of various EOL processes to the primary energy requirement and carbon emissions for the substituted stages. Most of the energy in the EOL Module of Scenario 3 is associated with recycling secondary materials. Scenario 1 and 2 are less affected by this stage because reuse will not require melting down materials for use in the next phase. As shown in the pie-chart, the processing of materials has the highest contribution to the energy required for reuse. Only a change of coatings for the next phase was considered for the calculation, but it significantly contributed to the overall energy required for both the reuse scenarios.

- Although the transport energy is less than material processing, it substantially contributes to the reuse scenarios 1 and 2 compared to the recycling scenario 3. Following the mentioned assumption, collection and processing facilities for reuse are likely to be situated farther than the already established recycling facilities in the region.

- Onsite dismantling energy is most prominent for Scenario 2 and has a minor contribution for Scenario 3, where materials are demolished. Off-site deconstruction has almost no impact in Scenario 2. Most of the energy required for deconstruction is manual labor over automated operations, adding to the time factor of the process rather than energy. No additional energy is required for Scenario 1 as it only entails collecting materials, again adding to manual labor rather than environmental impact.

11.3.2 Discussion

For the LCIA, the substituted EOL for reusing the secondary materials from the construction stream (Scenario 1) has the lowest impact on the primary energy EE (PERE + PENRE) and carbon emissions in the environment (GWP) of 243MJ and 14kgCO2eq, respectively. Nevertheless, the materials from the demolition stream (Scenario 2) resulted in the highest overall savings, for both EE and GWP, from the avoided production of raw materials for curtain wall facades, 3213.9MJ, and 224.5kgCO2eq respectively. It is because, despite the added stage of dismantling and deconstructing the facade, a higher share by volume of the secondary stream (aluminum, steel, and timber) saved on the extraction of a higher share of primary materials. Moreover, the energy spent in dismantling and deconstruction has little contribution to embodied emissions and the release of particulate matter in the environment. The energy required for these stages is manual labor resulting in man-hour and can increase the time exponentially. It is challenging to quantify the time required in manual operations and logistics over reducing the environmental impacts of the materials. Recycling of demolition stream (Scenario 3) led to a total saving in the production of raw materials of 1119.7MJ and 62.98kgCO2eq, respectively, for EE and GWP. Despite recycling the materials and using recycled content in production, smaller savings result from the little fractional contribution of the recycled content in the industry for primary production.

Although taken on the higher side, transportation has a marginal impact compared to processing. It was highlighted as one of the challenges in the interview, probably, due to the logistics and costs added with the step. The percentage savings in environmental impacts of 88% for EE and 89% for GWP in Scenario 2 with the reuse of only 25% secondary materials by volume suggest that reuse of secondary materials can significantly lower embodied energy and carbon emissions and must be preferred. However, a limitation of this evaluation includes disregard of energy required for running the processing facilities, which can potentially increase the overall impact.

11.4 Circularity Assessment

To assess how the secondary material flow affects the degree of circularity of a product, the MCI score has been calculated. In addition to the three design scenarios for environmental impact, the circularity index is calculated for two different EOL conditions of the façade. It entails two use lifespans for the façade, as shown in Table 11. For the first condition, the façade reaches an EOU after 15 years and is repaired/remanufactured for the subsequent use of 15years. Another condition assumes that the façade completes its service life of 30 years, and the subsequent reuse is determined according to the residual value of the secondary material stream used for the façade. For both cases, the curtain wall façade will complete its specified service life of 30 years. Since MCI does not take multiple cycles and considers outflow with reuse to be 100% circular, an adaption is made to MCI. For 15year EOU conditions, the fraction of reusable secondary material for subsequent use is reduced based on the assumption that transformation during reuse can incur a material loss. Percentage loss of reuse is taken from research findings regarding the reuse of various components of the curtain wall, as already described in Table 8. Appendix E shows the conditions of the assessment and detailed calculations for the MCI score.

Table 11 - EO(s)L conditions for MCI assessment

Scenario	***Material Stream***	*Already used lifespan*	***Use Life Span of the facade***	***EOL scenario after EOU/EO(s)L for MCI***
Design Scenario 1	Construction	30	15	Directly reused for another building
		30	30	Refurbished/remanufactured for next use
Design Scenario 2	Demolition	30	15	Refurbished/remanufactured for next use
		30	30	Materials are recycled for the next phase
Design Scenario 3	Demolition	NA	15	Directly reused for another building
		NA	30	Materials are recycled for the next phase

11.4.1 Results

Design Scenario 1

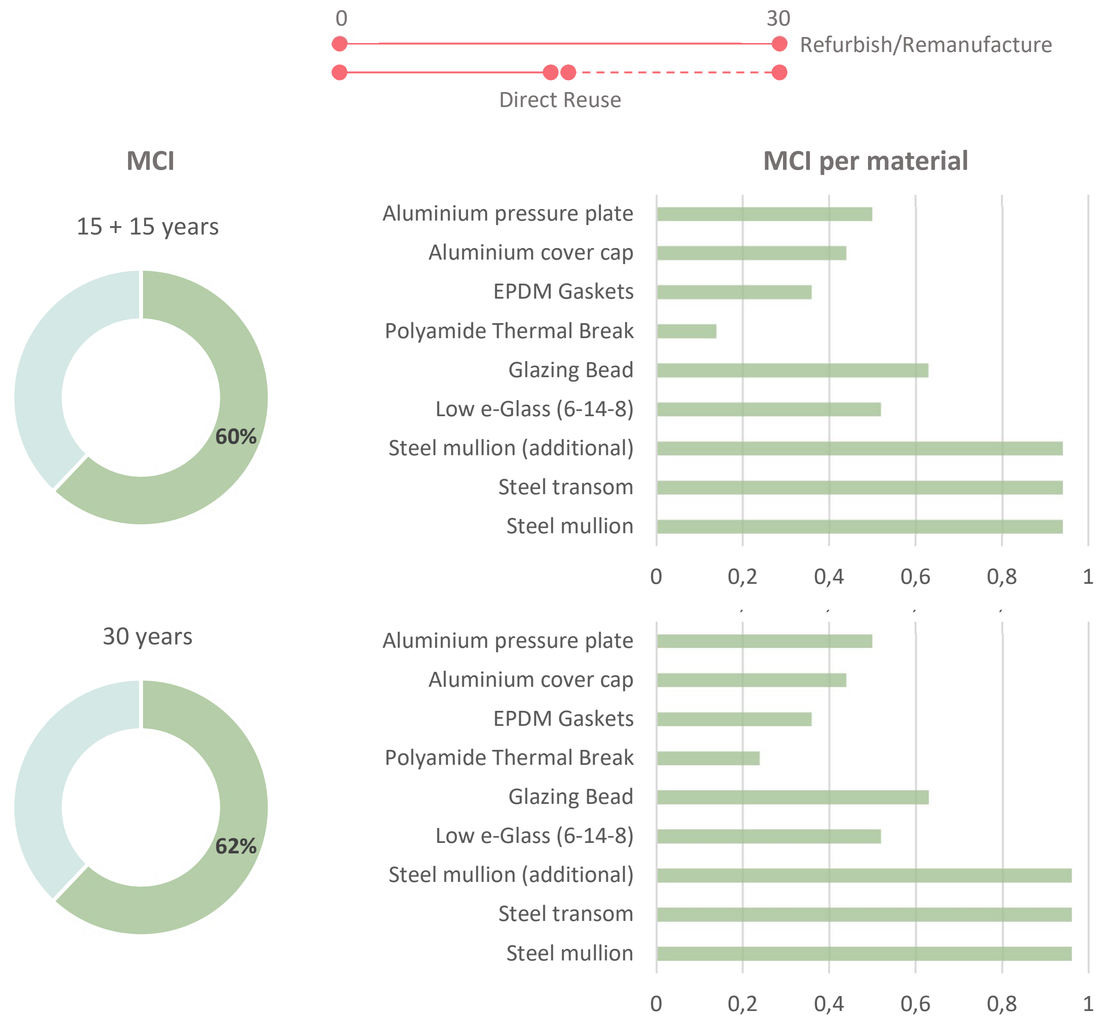


Figure 73 - MCI assessment for scenario 1

- The construction stream scenario reflects a circularity index of 62% for the whole façade system that will complete its assigned service life of 30 years. This index is not much different from when the façade is reused directly for another situation after 15 years. It can be credited to the fact that the materials were not used to their full potential and can still complete their designated service life without multiple upgrades. As long the façade is used for the same lifespan, MCI does not consider how the façade will be reused in the next life. The slight deviation is because of a small percentage loss of material accounted for after 15 years.

- Secondary steel components show almost a 100% restorative flow due to their prolonged presence in the environment for almost 30 years before they could be utilized for their designed function. Moreover, it can still complete its designated service life within the product, leading to exceeding the average lifespan specified by the industry.

Design Scenario 2

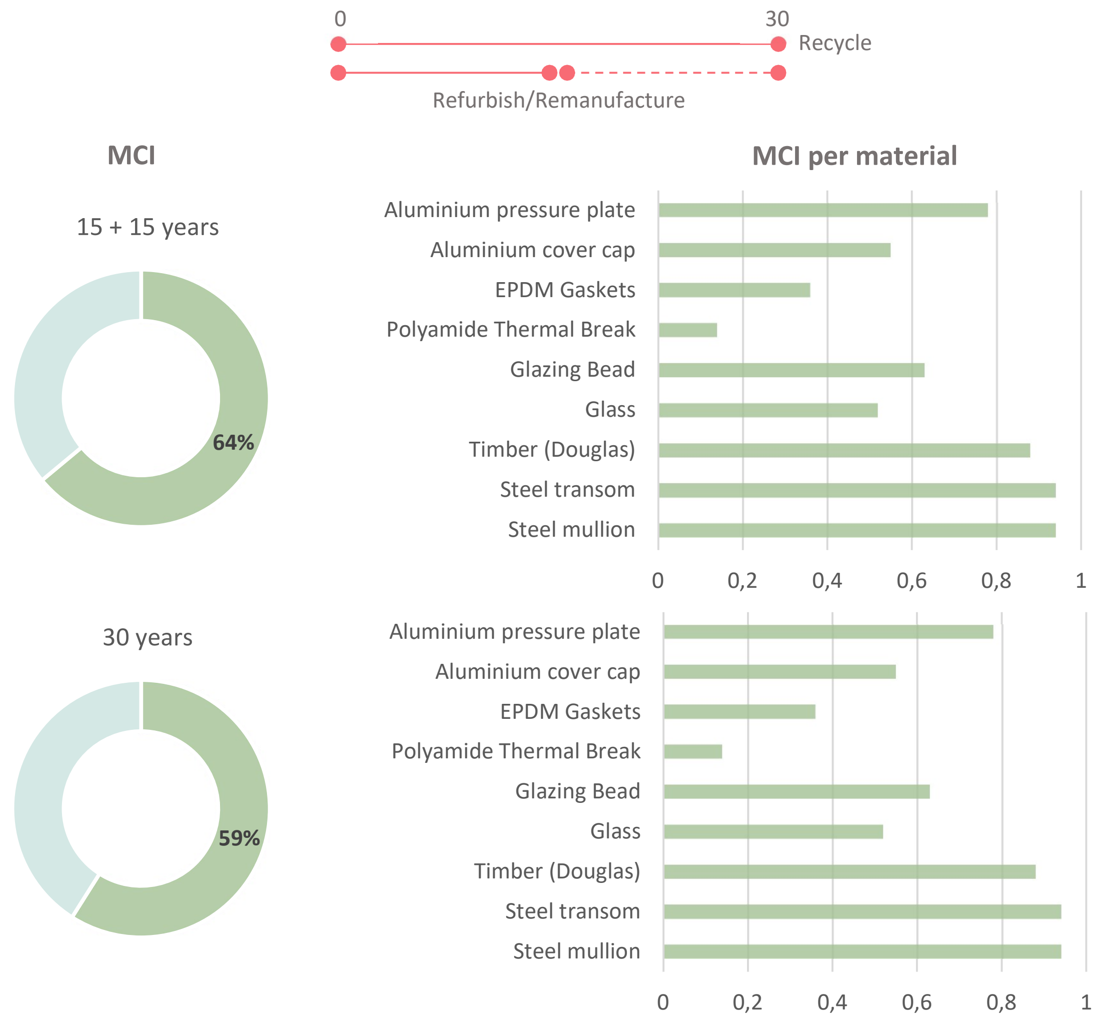


Figure 74 - MCI assessment for scenario 2

- The percentage share of secondary material is higher in the demolition stream scenario due to the reuse of steel, aluminum, and timber; however, MCI does not significantly differ from the construction stream. It shows a circularity index of 59% for the whole façade system that will complete its designed service life of 30 years.
- The circularity index for 30years is lower than a facade used for 15 years and remanufactured for the next 15years because of its EOL material flow. The secondary materials reused through remanufacturing in a new façade after 15 years have a higher fraction of secondary material content than secondary materials recycled after 30years. Moreover, the efficiency of the recycling process is not 100% resulting in additional waste in the process.
- The MCI for steel for the two EOL conditions is the same. However, aluminum shows a deviation. It is linked to the assumption that the reuse percentage of aluminum is lower than steel because of its location in the curtain wall system. Aluminum cover caps are located outside and are exposed to the environment. As a result, they often break while dismantling, resulting in a material loss for reuse.

Design Scenario 3

Figure 75 - MCI assessment for scenario 3

- The recycling of demolition stream scenario reflects a circularity index of 25% for a façade manufactured with materials with recycled content and recycled after finishing its service life of 30 years. It is due to a lower fraction of recycled material in the current supply and material loss in the recycling process.
- For a façade manufactured with recycled materials and is reused again after 15years for the next phase, MCI shows a circularity index of 32%. It shows a higher index than recycling after 30 years but is much lower than the other scenarios.
- Aluminum components show almost a 100% linear flow because of a small fraction of recycled material being used in the current supply, downcycling of materials for the next phase, and loss of material due to the efficiency of the recycling process. Although the facade is used for its service life of 30years for both cases, this length is less than the industry-specified lifespan of the material, i.e., 75 years for aluminum.

11.4.2 Discussion

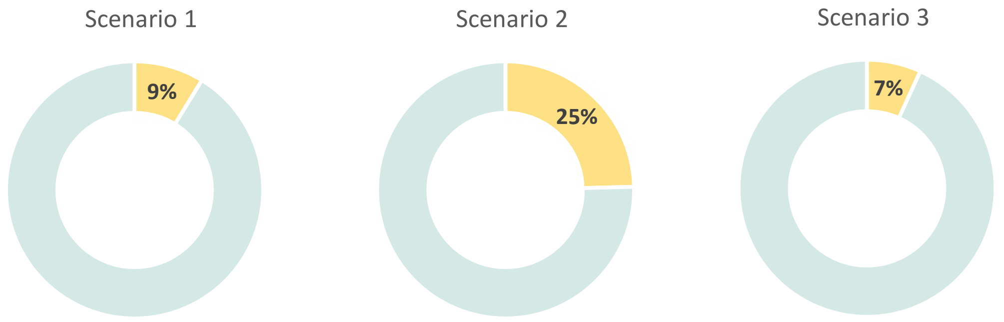


Figure 76 - Percentage share by volume of secondary material in the three scenarios

Starting with the MCI of the whole façade, the difference between Scenario 1 and 2 for reuse is not significantly evident despite the higher percentage of secondary material in Scenario 2, as depicted in Figure 76. On the contrary, there is a significant difference with the MCI of the recycling scenario. Scenario 2, with demolition stream material remanufactured after 15 years, show the highest MCI of 64%.

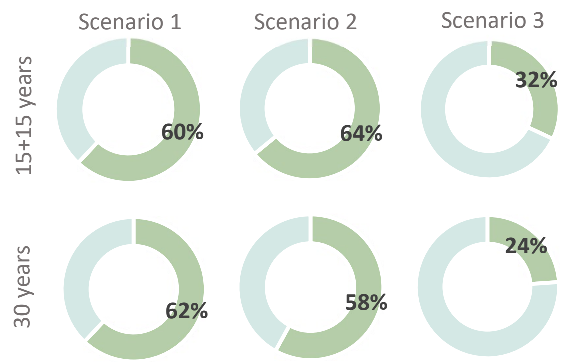


Figure 77 - MCI score for the three scenarios

Since the MCI formula does not consider the specificities of reuse and recycling, the difference in the two EOL scenarios can be due to the fraction of secondary material content. The secondary material content for recycling was not as high as most of the material is downcycled; however, reuse for the same case significantly increased the fraction of secondary material. Moreover, the MCI does consider the wastage with recycling which further reduced the MCI, however, no waste is considered for reuse. The only wastage accounted for with the reuse is due to the assumption of material loss, as mentioned earlier. The results, in this case, are based on the average percentage of recycled content in the current market supply according to the CES Granta software. However, it can vary from manufacturer to manufacturer, which can further affect the results.

MCI for individual materials within the façade shows almost a 100% restorative flow for steel for the reuse case due to their presence in the environment for way too long, extending their lifespan. Although with the same lifespan, aluminum did not show as high a result due to its dependence on the adjacent components, which affects the fraction of material available for reuse. It indicates that reusing a higher number of secondary materials may not necessarily increase the restorative flow within a product.

Furthermore, the different lifespans of 15+15 and 30 years do not affect the circularity of the product. As long as the lifespan is the same, materials reused for another design midway through its service life do not impact the flow of materials. However, it is hardly the case; as any transformation loss due to the selected R-strategy can reduce the reusable components in the next phase. MCI does not differentiate between the types of reuse, including remanufacturing, refurbishing, or repair.

11.5 Discussion on the Assessment for 'Reuse' as a Circular Strategy

The evaluation for the two assessments is based on multiple assumptions due to limited literature for the assessment of 'Reuse' as a circular strategy. Nevertheless, the evaluation does raise critical questions that need attention for future quantification of 'Reuse of Materials' as a circular design approach.

Life Cycle Impact Assessment

A critical discussion revolves around assigning the impact during the material's lifecycle to its multiple-use cycles generated during reuse. As the secondary materials used in the design exercise already existed in the environment and their end-of-life scenario was never conceived for future reuse, it is justifiable to direct the production impact to the first cycle. However, 'Design for Reuse' necessitates allocating the production impact to all the multiple-use cycles since the beginning. Furthermore, though the industry can outline the different cycles for the material during its design phase, the actual use cycles will depend on the conditions at the time of reuse. It raises the question regarding the allocation of the EOL disposal impact when it can no longer be reused. Therefore, for reuse to become an active strategy for a circular built environment, it is essential to distribute impacts over its multiple-use cycles to make significant environmental savings with every use.

In addition to the environmental impact, the economic impact of the material needs to be allocated to the different use cycles to make reuse feasible. Since the user and owner do not remain the same during the different use cycles, dividing the savings amongst all the use stakeholders is necessary to incentivize reuse.

Further, the assumption that the repair/refurbishment/remanufacturing will result in a full lifespan for the facade with no performance deterioration is not always valid. It can affect the environmental impacts and should, ideally, be evaluated through a life cycle analysis for the use phase of the designed product. Additionally, the inventory datasets constitute EPDs of materials designed for one function, cradle to gate/grave, without considering the impacts of lifecycle extension through repair, refurbishment, or remanufacturing midway. A clear indication of how different EOL circularity options affect the environmental impact in EPDs is necessary to provide a wholesome assessment for reuse.

> For reuse to become an active strategy for a circular built environment, it is essential to distribute impacts over its multiple-use cycles to make significant environmental savings with every use.

Material Circularity Indicator

Looking at the MCI, the formula segregates the inflow and outflow of materials from reuse and recycling; however, it does not consider their specificities. As long as the material's lifespan stays the same, the circularity of the product does not get affected if it is reused, refurbished, or recycled. Reuse retains the existing material value, whereas recycling creates a new value. However, the MCI does not differentiate between the different R-strategies used to extend the lifespan of the material, thereby negating the functional, embodied, and economic value generated with reuse. For instance, a steel beam can constitute the recycled content for a steel mullion. In this way, the functional and embodied value of the material itself is reduced during recycling. On the contrary, if the steel mullion is used for the same purpose through refurbishment, its functional and embodied values are maintained. Thus, the MCI score defeats the whole purpose of reusing materials and misguides the user regarding their value. The value retained must be indicated for a restorative material flow.

Furthermore, it does not consider the reusability of the product itself. Different product assessments available in the market can qualitatively assess reusability. However, there is a missing link between product reusability and the outflow of materials in MCI. A façade product consists of multiple materials; therefore, a reusable design may/may not be 100% reusable. It can incur losses during transformations between use cycles that are unaccounted for in the MCI formula.

Lastly, the evaluation of the MCI score only holds validation when the design is tailored for the reuse of components. An assumption was made that designed connections can be demounted to facilitate reuse. However, the ease and accessibility of demounting the connections can directly impact the willingness of the industry to do so. It is challenging to quantify the efforts required to make reuse feasible; therefore, it must be incentivized by clearly dividing the profits with every use cycle.

11.6 Indicators for the Assessment of 'Reuse' as a Circular Strategy

Based on the two assessments, the research identifies relevant indicators to assess the value of 'Reuse' as a circular approach. It must be noted that the indicators specified below represent research findings and do not aim to provide an exhaustive list.

- Environmental impacts and savings incurred over the multiple-use cycles of the material.
- Benefits and burden added on the various actors responsible for enabling reuse.
- The extended lifespan of the material with every use, taking into consideration the performance deterioration.
- Additional repair/maintenance added during the lifetime of the material.
- Product design tailored to facilitate reuse.
- The outflow of materials generated from the product design and loss incurred during transformations.
- Functional, embodied, and economic value generated from Reuse.

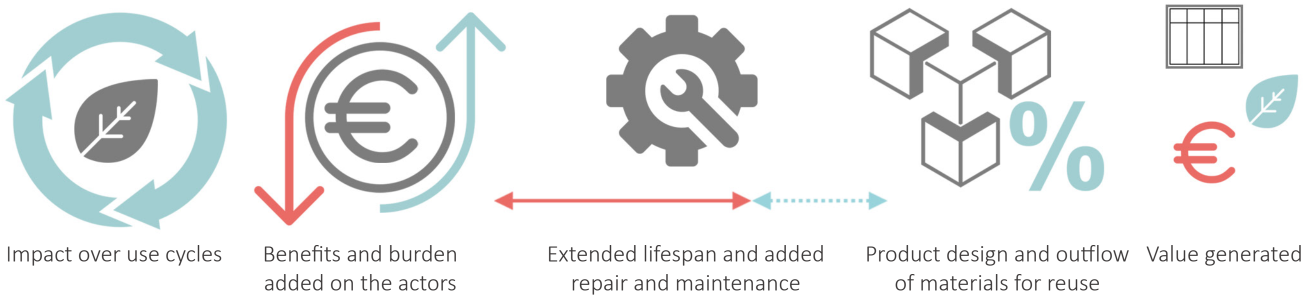


Figure 78 - Indicators for assessing reuse (source: author)

11.7 Limitations

Some limitations of the assessment include:

- LCIA only focussed on Embodied Energy (PERE and PENRE) and Global Warming Potential of the environmental indicators, i.e., primary renewable and non-renewable energy from resource consumption and CO2 equivalent of greenhouse gases. It does not consider other impacts, such as acidification, eutrophication, etc.
- LCA evaluation did not consider reusing secondary materials for EPDM, Polyamide, and Glass. It only estimated MCI as per the recycled content. These components are equally important. Any improvement in using their secondary stream from recycling to reuse can affect the overall circularity of the curtain wall façades.
- LCA did not consider the background process of running the facilities required for reuse, which can potentially add to their overall impact.
- The scenarios discussed for future reuse after 15 or 30 years are hypothetical can only be made possible if the facades are designed with the Design for Disassembly principle during the product stage. Therefore, it requires an assessment during the product design stage itself, using disassembly indicators to ensure the outflow of materials.
- The three design scenarios were tested using manual calculations to perform for the same loading conditions. Though they all are suitable for the defined condition, their performance can be varied depending on the available section sizes from the secondary stream and the reference section selected from the facade supplier's material catalog of the façade supplier.

There may be gaps in the assessment; however, the results are satisfactory to conclude and include in future studies.

11.8 Summary

The embodied energy and carbon emissions were evaluated using LCIA for the three scenarios. Even with a high initial investment for the reuse process, the environmental impact analysis shows a saving of 91% for EE and 93% for GWP with a 9% share by volume of secondary material from construction stream, and a saving of 88% for EE and 89% for GWP with a 25% share by volume of secondary material from demolition stream. Furthermore, the MCI score shows almost a 60% circular flow for the reuse scenarios and 25% for the recycling scenario. The assessments were performed with certain assumptions due to a lack of defined assessment for reuse, which raised critical questions necessary to assess reuse. These include allocating the impacts over the multiple-use cycles and defining the functional, embodied, and economic value generated with reuse. Lack of clearly defined value in the assessment can misguide the decision-maker between the R-strategies.

Furthermore, relating the results to the reuse process provides a clearer picture of why the materials are not being used at any industry-wide scale. The added stages in the reuse process, including dismantling and deconstruction, can significantly increase the manhours. These efforts cannot be quantified in environmental assessment but need to be resolved through the product's design and business case to make reuse viable. Thus, the stakeholders have an immense responsibility to facilitate the process to ensure that the industry gains from the incremental savings in environmental impacts from reuse.

12.

BIGGER PICTURE

The bigger picture zooms out to present how the reuse of materials will affect the industry. It presents the value of reuse, the material trends and the role of the government, and the material reseller for accelerating reuse. It further projects how the design process and the architect's role will evolve once reuse is an established practice. Finally, a few real-life examples from other building layers are discussed to understand the viability of reuse.

12. BIGGER PICTURE

12.1 Value of Reuse

According to WFD (2008/98/EC), "waste is any substance or object which the holder disregards or intends or is required to disregard." As a result, many materials are titled 'waste' every day in the building sector, resulting in their 88% recycling rate in the Netherlands. However, the material is only regarded as waste because it is not valuable to its current owner for the same function. Therefore, understanding the value that materials hold and the value generated with their reuse is essential to steer the industry towards a material reuse practice.

Secondary materials are melted during recycling and processed again at the raw material level. It necessitates the material to undergo all the stages to reach the product level for use in the industry, discarding the original embodied value of the material. Moreover, not all that is recycled goes back for the same use. For instance, most of the float glass from glazing units is recycled as packaging glass, discarding the functional value of the material. Apart from the functional and embodied value, the material still holds a residual economic value, and with minimal repair and maintenance, it can be sold again for reuse. However, as the secondary materials are regarded as waste, the owner pays for all the added stages during disposal or recycling, discarding any economic value it holds as a resource. Thus, reuse maintains the functional, embodied, and economic value of the existing materials in the environment. Furthermore, it can safeguard these values for new materials being input every day in the building sector.

Let us consider the case of steel reuse. Steel production has increased globally tenfold, from 189Mt in 1950 to 1809Mt in 2019. It is further projected to increase 1.5 times to meet the population's growing demands (World Steel Association, 2018). Of this, 51% is used in the building construction industry. Despite the high recovery rate of 85% steel from the construction sector, high efficiency of magnetic separation, and little wastage during recycling, there is only 37% of recycled content in the new steel. Most steel remains in use for decades due to its durability (ibid.); thus, not enough is available for recycling to meet the growing demands of the industry. Reuse of steel by extending its life through repair, refurbishing, or remanufacturing, in this case, will extend the average lifespan specified by the industry for that function and save on the extraction of virgin materials in its place for that amount of time. It will give the industry enough time for its current stock to reach its end of life and be available for recycling in the next phase, reducing the amount of virgin materials in the entire cycle.

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12.2 Material Trends

There are different material flows in the built environment. A vast stock of material constitutes the outflow from the various lifecycle stages of the existing building stock. It is due to a requirement of new products to match the ongoing improvements in the performance standards. Since these materials already exist in the environment, the assessment in the previous chapter showed that their reuse could significantly reduce negative environmental impacts. At the same time, an increase in the current demand for new buildings results in a large amount of virgin raw material input in the building sector. Metabolic and EIB (2020) mapped the material flows in the Netherlands' construction sector. The report presents a yearly demand for 17million tonnes of material for construction and renovation projects (EIB and Metabolic, 2020).

Two material flows can be identified from the material trends - materials outflow (released from existing buildings) and material inflow (used in the construction sector). In the future, when material outflow from existing building stock reduces, the materials used today will constitute the share of material outflow. Therefore, it means that reuse will happen through materials entering the market now. However, since the existing building stock was not designed with circularity principles, technical and organizational barriers hinder their direct reuse. Nevertheless, new material and products can still safeguard their value to enable future reuse through reversible design principles, securing data about materials, and managing the value chain. Thus, it will ensure the reuse of facades at any stage in their lifecycle, for any context.

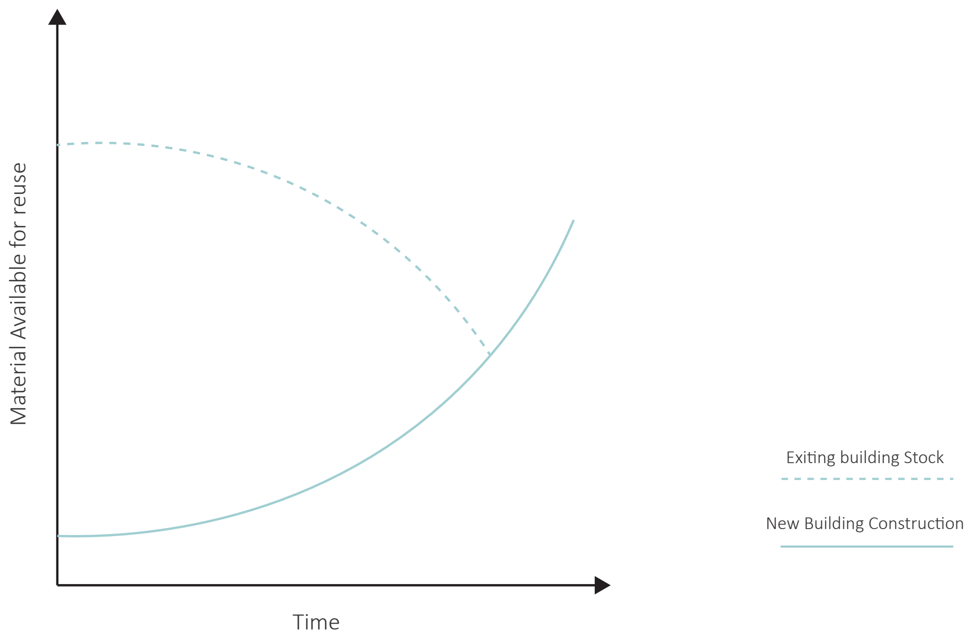

Figure 79 - Projected scenario for material flow from the built environment, (source: adapted from KM ODS Building Stock approach)

12.3 Role of Government

Every society has its challenge regarding reusing materials, including government policies, cooperation, and opinion on the Circular Economy. The Netherlands is already transitioning to a circular economy model to achieve 50% material reduction by 2030 and 100% by 2050. The goal set by the government is a key driver to mobilize the industry and the actors in the value chain to limit their dependence on primary materials. However, the lagging regulations to match the high aspirations are a limiting factor for most of the industry's forward momentum.

Over time, the low price of virgin materials and lack of directives regarding the value this limited resource holds have resulted in its inconsiderate use worldwide. Approximately two-thirds of the price in the construction process constitutes the labor cost, while the remaining is material. Out of this labor cost, 40-60% is the tax amount. Further, the VAT is paid twice on the reuse of secondary material, which increases its overall cost.

Thus, the low virgin material cost, high labor cost, and tax on secondary materials are barriers to establishing its industry flow. Therefore, the reuse of materials demands a shift of the industry from economic games to environmental games, which is possible only when laid through clear directives. It can be done through policies that mandate the reuse of materials, either through an environmental tax on carbon emissions from the use of virgin materials or shift in existing tax from renewable resources (labor) to non-renewable resources (materials) to lower labor costs and increase the virgin material cost. Furthermore, enforcement of The Universal Declaration of Material Rights formulated by Rau et al. (2015) and shifting the title of preparing for reuse (repair, refurbish, remanufacture) from waste to non-waste in the WFD model can potentially change the outlook of people towards the reuse of materials.

12.4 Role of Material Reseller

Material resellers operate the reuse process by matching the supply of secondary materials for facades from different sources to their different users in the market, including façade manufacturers, builders, and architects. It places them right in the middle of the value chain, making them responsible for processing the material and finding a marketing channel to sell the material. Currently, there are independent markets for all sorts of secondary materials. However, the original raw material suppliers know the specificities of the material and their demand in the market and must take up the role. They can balance the demand and supply by organizing a reverse supply chain for their materials and selling them through an already established network of partners to widen reuse at an industrial scale. The following points suggest steps that the raw material suppliers can take to reuse secondary materials in their supply:

Data

- Develop harvest maps for the available secondary facades and assign material passports to ensure future reuse of facades. In addition, they should provide explicit information about materials, including their source, form, and used lifespan, to assess their residual material value.
- Track and monitor materials during the use phase to ensure they can be extracted and reused in the subsequent cycle.

Design

- Lack of accessories and components suitable for secondary material reuse is bound to come. As the raw material supplier for facades, there is a need to expand the sales product from own products to manufacturing/sourcing accessories for other façade systems, including the facades made available from the existing building stock. Moreover, this can also be done through collaborations with different material partners in the chain.
- Provide alternate material options by collaborating with different suppliers to overcome challenges offered with secondary material and offer higher design flexibility to the architect and the engineer.
- Facades need to perform at least enough to meet the performance requirements set by the building codes. Collaborate with third-party assessment companies that can inspect, test, and certify facades for new use.
- Include maintenance and repair services and take-back options in the contract from the beginning, either themselves or through third-party contracts, to provide confidence to the users regarding the reuse of secondary materials.

Management

- Share information through a secured database among partners regarding the secondary materials.
- Extend direct contact with the end-users and customers of the facades to establish a consistent source of secondary materials. It will increase both customer loyalty and business opportunity by creating a second retail channel from this source.
- Mobilize multiple build partners within the existing network by showing the economic and environmental benefits of secondary materials. It will help create a distributed network for remanufacturing facades to reduce transportation miles and logistics.
- Set up a reverse logistics supply chain for own products.

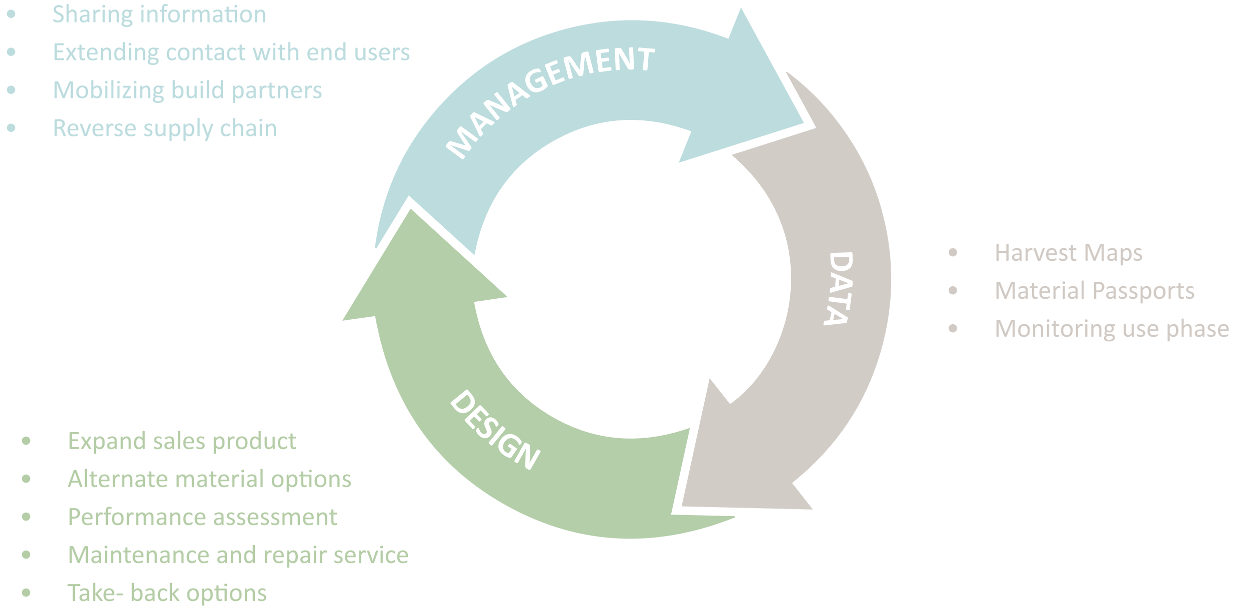

Figure 80 - Steps to accelerate reuse of materials by the original raw material

Original material suppliers can balance the demand and supply by organizing a reverse supply chain for their materials and selling them through an already established network of partners to widen reuse at an industrial scale.

12.5 Design process and role of the architect

An architect plays a crucial role in the design process and forms the link between the end-users and material suppliers. Looking at the role from the perspective of façade design entails specifying the aesthetics, materiality, and performance requirements of the façade. A change in material supply from primary to secondary stream will impact the design of facades and, eventually, the architect's role in the design process.

The curtain wall façade design and manufacturing process usually consists of customizing the existing systems in the market according to the requirements of the design project. An architect provides the set of design instructions, and the manufacturers and suppliers comply with them. Furthermore, the architect consults with a façade engineer or a builder about the material only after the preliminary design stage. Since most decisions are already made, it will seldom lead to reusing secondary steam due to added time required for adjustments. Reuse of secondary stream entails the involvement of both the architect and the material reseller from the very beginning of the project to adjust the design as per the ‘available material stream.’ It necessitates a much-needed transition in design thinking from ‘abundant resources’ to ‘scarce resources.’ This change in mindset is the first driver to enable circular design, specifically, for this case, the reuse of secondary materials.

Any extension in the life of secondary materials that have already existed in the environment for way too long can yield benefits if one can design around these resources. However, since this material stream is inconsistent, the challenges of designing standardized façade products by the industry are even more pronounced. If done, it can further limit the design options available to the architect. Besides, it is easier to adapt what does not exist (design) than what is already available (materials), and the degree of adaptation can directly affect the environmental savings. Hence, there lies an obligation for the architects to innovate by decoupling design value from materialization; without compromising the aesthetics and quality of the design. Although the technical challenges with the reuse of materials for facades are not as high as seen in the design case, finding alternative ways of using materials is essential. It will make the materials work for conditions that they were no longer intended for in the first place. It can be through adjustment in facade dimensions in the design, engineering new fixing systems, or finding invisible ways of using materials.

The building industry is already taking steps to enable reuse through material harvesting by the urban miner and secondary market by material resellers. However, if the architects’ demand for secondary materials is not high enough, the industry will never sustain the reuse practice. Few architects have already reused secondary materials for façade. Lendager group in Denmark developed a methodology to upcycle brick modules from demolition projects for reuse in their Resource Row projects. In the Netherlands, Super Use studio reused construction waste from an overstock of ODS profiles for the façade KEVN pavilion in Eindhoven. There are still more examples, and it is evident in all that the reuse could be made feasible by the architect taking an extra step of starting the design with the available stream and innovating around it. The architect is a resourceful actor whose role will become less about designing and more about creating alignment within the value chain. Thus, by changing the perception of what a design is and how one can design, they can help the clients look ahead and envision a future with the circular economy.

Reuse necessitates a much-needed transition in design thinking from ‘abundant resources’ to ‘scarce resources.’

Figure 81 - Resource Row Project by Lendager Group; (left) brick elements cut from building, and (right) upcycled brick wall in the building (source: https://lendager.com/en/architecture/resource-rows/#materials)

Facades are the face of the building and a site that reflects the architect's vision of the project and has a significant share in the aesthetics of the entire building. Although aesthetics of secondary materials was beyond the scope of this research, it is interesting to consider this an indispensable barrier to the reuse of secondary materials. Some materials can hold a heritage value from their previous use and have a high value among the architects and the end-users for their aesthetic. However, this will only be the case for a selected few projects. Most materials will come from local projects that do not hold these values and may create questions about societal perceptions. Therefore, it is critical to question this notion of architectural aesthetics, which must be created with the materials available locally.

Figure 82 - KEVN Pavilion Eindhoven by Superuse Studios; (left) steel profiles from construction overstock, and (right) reused steel profiles in the pavilion clicked by Frans Hanswijk (source: ODS)

12.6 Expanding the Reuse Practice to Different Building Layers

Buildings are understood through a series of functional shearing layers, each having its independent lifespan. Since the formulated reuse process indicates material sourcing as the first step for reuse, the flexibility and dependencies in the design of these layers and their product level will affect their reuse. For example, the building structure is designed according to the functional requirements of the design, making it different for every case. It is a relatively fixed layer, and its reuse would mean taking care of all the other layers. On the other hand, building service installations and stuff layers are more generic in design, have a shorter lifespan, and installed as accessories to the fixed layers, making their reuse relatively easier for different contexts. Moreover, the number of stakeholders are involved with the layers are different, like architects, engineers, and construction companies for structures, whereas installation companies for building services. Thus, the reuse of materials can have different implications for every layer. Few examples from exiting reuse projects for the different building layers are discussed below to recognize the viability of 'Reuse' as a circular approach.

Philips introduced its Circular Lighting solution to reuse own product in their value chain. The product is designed with future-proof components and service tags that allow retrieving information about the parts, easy servicing, and upgrading the parts to extend its service life. Furthermore, the business model allows the user to only pay for lighting and not the equipment. The service contract allows maintenance and optimization of the product during its use without the user paying the costs of its innovation. Finally, a clearly defined reverse logistics supply chain allows them to profit by creating a secondary retail channel for their product.

ODS Jansen started Harvest Bay Project to reuse its façade products in their value chain. Although recently started, they could remanufacture a reused façade in Belgium for a new project in the Netherlands. For this, an in-house was responsible for its dismantling, an open-source Harvest Map for creating a retail channel, and an existing build partner for remanufacturing the façade. The façade is assigned a material passport to monitor its use phase to ensure it can be reused. In addition, it is contracted on a five-year lease to reduce the initial investment by the user. The contract allows maintenance during the use phase and a take-back system for reuse for another project afterward.

The Temporary Court House Building by Cepezed in Amsterdam is designed with a Design-Build-Maintain-Remove contract to maximize its residual value after its initial use. It is designed with a flexible configuration that facilitates changing uses by changing users on changing locations. For this, the structure is designed as a kit of parts using a special mounting system for the hollow-core floors that optimally facilitates decoupling and re-use of the slabs elsewhere. The customizable structure can easily be assembled, disassembled, and reassembled. Lastly, the contract allows maintenance during the use phase and removal and reuse of the building after its use.

In all cases, it can be seen that future reuse was pre-embedded through design, data management, and contracts. Thus, they could avoid the added cost, logistics, and unwillingness towards reuse by safeguarding the economic and design value of the material. Though reuse can have a different implication for every layer, it is essential to expand the practice to all the layers to transition towards circular materials use in the built environment.

12.7 Future Vision

A future vision is drawn as to how the industry will change with the 'Reuse of Materials.' For the existing building stock, when the current owner will no longer require a façade, an aware user about the environmental and economic savings of harvesting materials will pro-actively reach out to an urban miner to get it dismantled for subsequent use. The urban miner will use their technical knowledge to inspect and select suitable dismantling techniques and, at the same time, find the material reseller closest to the site. The reseller can collect, assess and deconstruct the façade as per its residual value and provide a digital value to the assessment to make it available for the designer for the next stage.

The architect will work with the end-user and the façade engineer to select material from the database, adjust the dimensions and requirements of the projects as per the available stream, design and prototype to build new facades with the façade manufacturer. A third party will certify this system and monitor its use phase. At the same time, any new materials being used for facades will be embedded with material passports. The exchange of information will happen through a secure and collaborative platform between the users. Product Design, Contracts, and Monitoring Systems will be essential tools to safeguard future reuse. Finally, the regulations and policies by the government will mandate reuse and make it feasible for the market. Thus, by taking the necessary steps in the industry, reuse as a circular approach for material use can be established.

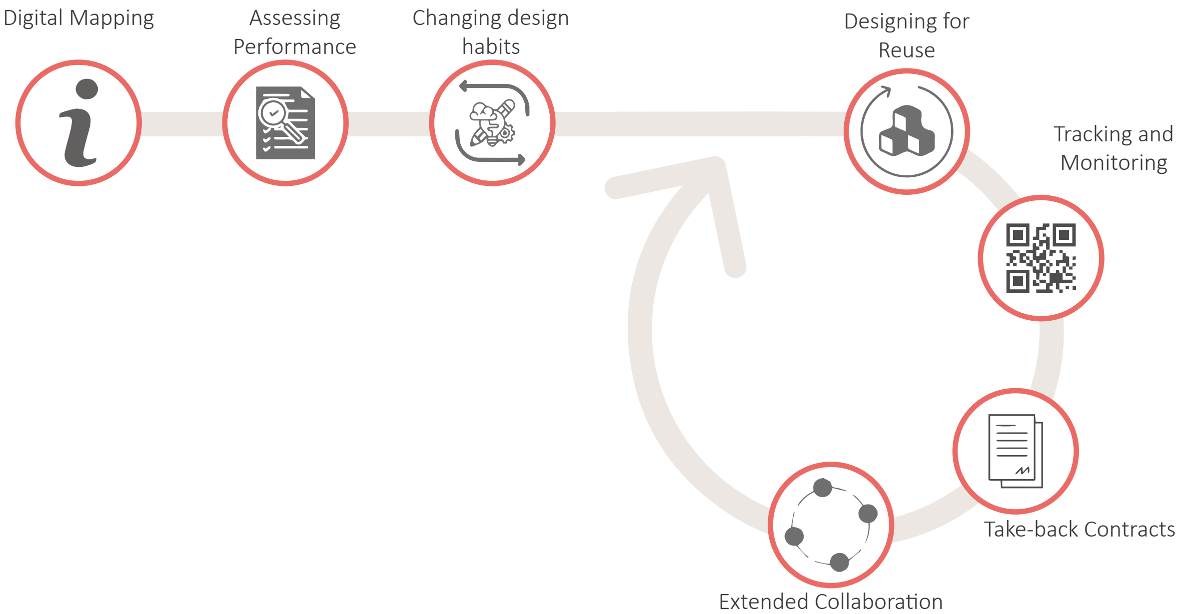

Figure 83 - Future vision to reuse materials cycle after cycle

12.8 Summary

The chapter tries to synthesize the research by tying the loose ends regarding reuse in the industry. With the already established circularity goals by the government, the industry has the potential to limit its high dependence on primary resource use. Furthermore, advancements in technology for setting harvest maps and material passports and extended collaboration between the actors are the first steps to transition towards reuse in the industry. Secondary materials are already reused to some extent when the motivation is to build circular by the architect. All that has to be done now is to establish an effective system, state facts and insights about this source, and present benefits with the decision-makers in the project to enable an industry-wide use. A shift in the mindset from using 'abundant resource' to 'scarce resource' is key to encourage the actors to come halfway in this transition and reduce the efforts required in the overall chain.

The designed façade highlighted multiple challenges, including designing and engineering new connections, sourcing discontinued materials from alternate sources, added system testing for thermal and structural performance, and the time required by the engineer. Despite all the challenges offered with secondary material, the environmental savings incurred can be incremental. Continuing on the line, material suppliers, manufacturers, and architects can align their business with the circularity goals set by the Netherlands government on reduction in primary material consumption.

Reuse is already seen for building products in other shearing layers like service installations. Therefore, it is essential to learn from these practices to understand the feasibility of the reuse practice through design and management. Finally, 'Design for Reuse' for new products used in the industry is of utmost importance to safeguard their value and future reuse.

13.

CONCLUSIONS

The chapter answers the posed question in the introduction, followed by future works and limitations of the presented research. A final reflection on the work is also included.

13. CONCLUSIONS

The presented research aimed to study and propose the methodology for establishing the reuse of secondary materials in the facade industry. Doing so, evaluate the circular value and environmental impact of 'Reuse' as a circular approach. For this, a set of research and design questions were posed in Chapter 1. The following section answers these questions and presents the research limitations and the scope for future works.

13.1 Research Question

How can secondary materials from construction and demolition processes be reused in the facade industry? Can a reuse process contribute to create a circular value and reduce negative environmental impacts for facades?

The existing stock of secondary materials poses challenges for their direct reuse for facades. Therefore, other R-strategies including repair, refurbishing, and remanufacturing can be employed to enable material reuse, as long as the embodied value of the material does not change. Thus, a reuse process is systematized to identify the stages necessary to enable material reuse. The assessment of the process indicates environmental savings and a higher degree of circularity with the reuse of materials; however, it also presents market challenges. As a result, reuse is only seen in cases where urban miners actively procure secondary materials, facade suppliers create a secondary retail channel, or architects intend to build circular. These actors have extended their roles to some extent. However, a transition is still required for the industry to establish reuse practice, which is only feasible when economic benefits are clearly identified for every actor in the value chain.

The following sub-questions help to break down the answer further:

SQ1. How does the R-strategy 'Reuse' affect the circularity of secondary materials released from the built environment?

Circularity can be described as an economic system to keep the materials cycling in a loop by replacing the end-of-life concept with reducing, reusing, recycling, and recovering materials for sustainable development. CE principles are applied to the built environment through a series of building layers, distinguished as per functional, physical, and technical relation to each other. Secondary materials are released from these layers during construction and demolition processes and are regarded as 'waste' by the industry. They are majorly recycled to ensure a closed-loop resource flow for this stream and create a new value for subsequent use. However, by changing the value from 'waste to resource' and 'moving up the R-ladder from recycling to reuse,' the secondary materials can retain their original value. Reuse slows down the resource loop for the material already present in the environment by extending their life and, in the meantime, reduce the strain of primary material extraction in their place.

SQ2. What are the challenges involved in the reuse of secondary materials for designing a facade?

Circularity is a relatively new topic, and therefore, the existing building stock was not designed with these principles. As a result, there are various challenges involved with the reuse of secondary materials for facades. These are summarized as:

- Lack of information about previous use conditions of the material, including its structural and thermal performance, and repair and maintenance over its use phase, creating ambiguity about its residual value.
- Materials undergo wear and tear during their use phase due to exposure to internal and external surroundings, including corrosion, degradation due to UV, or discoloration due to chemicals, affecting the safety of facade for the next phase.

- In terms of its quality and quantity, an inconsistent secondary material supply often does not match the market demand of facades. Besides, the availability of this supply depends on identifying the source, which makes the supply unpredictable.
- The project requirements often lead to customization of the facade system for the design. It is seldom a case where one can find a new project with the exact specifications for reuse.
- Many systems turn obsolete over time due to upgrading standards for energy performance, new connection systems, or aesthetic upgrades in section sizes. Their obsolete performance and discontinued accessories by the suppliers affect their reuse negatively.

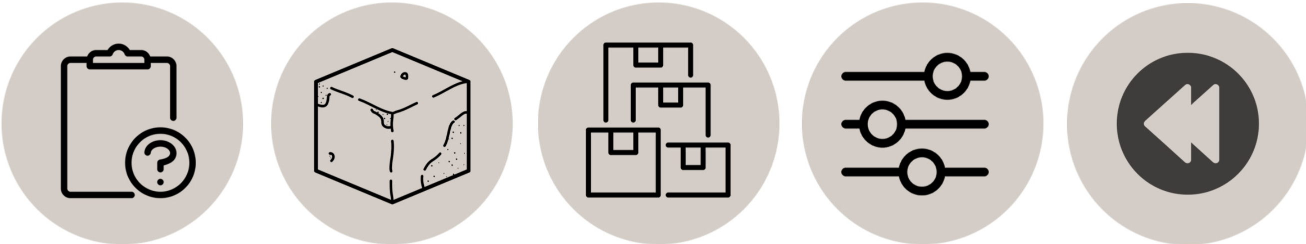

Figure 84 - Design challenges for reuse of secondary materials for facades (source: author)

SQ3. What are the different stages for enabling the reuse of secondary materials for facades?

Unlike a regular design process, where facades are customized according to the design requirements, the secondary material stream already exists in the environment. Therefore, the reuse process begins with an available material inventory and then finding ways to incorporate them into the design. The process is divided into three stages:

- **Material Sourcing** - This is the first stage for accessing the materials and determining their quality and quantity. It consists of two phases - material identification and material extraction. The materials considered 'waste' by the current owner are identified at different lifecycle stages, followed by steps necessary for its extraction. It entails on-site inspection of materials and connection systems to opt for appropriate dismantling strategy and careful material handling to avoid any damages in the process.
- **Material Processing** - It entails collecting and transporting the material to the nearest processing facility to inspect the façade for further damages and deconstruct it as per its residual material value. It is followed by giving the assessment a digital value and assigning the materials an identity. The information is shared between the stakeholders through an open-source platform. The database serves as a material catalog for the façade engineers and architects to design new facades with the secondary stream.
- **Material Reuse** - It involves designing facades with the available material stream by logging in the material database, selecting materials according to preliminary façade calculations, and finding a suitable strategy for reuse as per the residual value of the available stream. According to the available design flexibility, material reuse can be done in two ways: designing from the stock or designing with the stock. The former entails adjusting the façade design for a higher-grade reuse strategy, such as direct reuse or repair of facades available in material stock. The latter involves designing new façade systems with the available stream of secondary materials to suit the façade design requirements. It consists of reuse at a slightly lower grade, such as refurbishment or remanufacturing. According to the strategy selected, the façade can then be manufactured, tested, and installed. It is monitored during its use phase to ensure subsequent use.

Material Sourcing

Material Processing

Material Reuse

SQ4. What are the various stakeholders involved in the reuse process, and how does their role evolve in this system?

The three stages of the reuse process entail multiple steps within each. Therefore, various actors come into play to support the process. According to their contribution to the overall process, the stakeholders can be classified into use, harvest, processing, design, build, assessment, maintenance, and regulatory. While few stakeholders are already transitioning their roles, many are yet to be recognized by the industry. These stakeholders are:

- **Use** - It refers to the users of the secondary facades, such as the building owner and building user.
- **Harvest** - It includes the urban miner and specialized demolition companies to identify materials at EOU/ EO(s)L / EOL from the building and extract them using dismantling techniques at the highest possible quality.
- **Reseller** - The actor bridges the gap between the source and its supply by making the material reusable for subsequent use and should ideally be the original material supplier. The role includes collecting materials, inspecting damages, deconstructing reusable components, and assigning the material identity for reuse in the next stage.
- **Design** - It includes the architect and facade consultant/engineer responsible for realizing the materials in facade design. Their role includes selecting material suitable for the design from the available material catalog, followed by a feasibility study, product design, prototype, and testing.
- **Build** - It includes the façade manufacturer (original or independent), the façade builder, and the contractor to repair/ refurbish or remanufacture the façade as per the design specifications and install it on site.
- **Assessment** - It includes actors assessing the materials for its economic and environmental values and assessing the product for its performance to ensure it conforms to the CE and EPD product guidelines specified by the European and Dutch Building Codes.
- **Maintenance** - It includes façade monitoring companies, maintenance companies, and facility managers to monitor the use phase of secondary facades, provide maintenance and repair during their use, and trace them back for reuse in the next phase.
- **Regulatory** - It includes the Municipality, Government of the Netherlands, and European CPR, who can enforce and mandate circularity through taxation, subsidies, and building certifications. In addition, formulate guidelines to assess material damages and set safety margin standards for secondary materials.

SQ5. What are existing product assessment methods relevant for evaluating the circular value and environmental impact of reuse? Are there any gaps, and if yes, what are those?

Circularity principles propose keeping the material cycling in resource loops to lower the environmental impact associated with their use. However, how these materials flow within the loop is determined by input and output flow and product design. There are numerous assessments available in the market to assess the flows and product design. Some provide an objective overview of circularity by quantifying an index for materials' inflows and outflows within a product, like MCI designed by EMF and Granta Design. It is evaluated towards the end of the design to identify the restorative/linear material flow within a product. On the other hand, there are more subjective methods for decision-making to ensure an outflow of materials. They assess the product design, including its geometry, connections, and accessibility, during the design phase to ensure the product can detach from the building and deconstruct for subsequent use, like the Disassembly Potential by Elma Durmisevic.

However, there is a missing link between product reusability and the outflow of materials in the MCI score. For example, a façade product consists of multiple materials; therefore, a reusable design can incur losses during transformations between use cycles, unaccounted for in the MCI formula. Another circularity indicator used in the Netherlands is the Building Circularity Index (BCI) by Alba Concepts. It evaluates the releasability index (LI) to assess the detachability of products from the construction and disassembly of elements in addition to MCI to calculate BCI. However, the assessments fail to distinguish between the functional, embodied, and economic value generated from 'Reuse,' defeating the purpose of reuse over recycling.

Environmental impacts can be assessed through quantitative assessments regulated by ISO-14040 for Life Cycle Assessment. However, the LCA methodology lacks a clear indication of the multiple lifecycles created with reuse making it uncertain which cycle to direct the benefits and loads. Life Cycle Impact Assessment (LCIA) is another way to assess the impacts and evaluate the net benefits emanating from the reuse. The added impacts to enable reuse for existing materials are compared to the avoided impacts from EOL disposal and extraction of primary materials in its place. A limitation of the assessment is the available inventory datasets. It constitutes EPDs of materials designed for one function, cradle to gate/grave, without considering the impacts of lifecycle extension through repair, refurbishment, or remanufacturing midway. A clear indication of how different EOL circularity options affect the environmental impact in EPDs is necessary to provide a wholesome assessment for reuse.

Though LCIA could be performed for the existing secondary materials, when 'Design for Reuse' becomes a common approach, it will be necessary to allocate the production impact to all multiple-use cycles of the product to ensure benefits in every use cycle. Besides, the user and owner do not remain the same during the different use cycles and necessitates dividing the incentives amongst all the use stakeholders. Lastly, the quality loss of material can result in additional repair during its lifetime and needs to become a part of the assessment.

13.2 Design Question

How can a circular hybrid steel curtain wall be designed by facade companies using the secondary material stream for office buildings in the Netherlands?

Evaluating the design challenges for facades could lead to proposing a solution for a hybrid curtain wall using primary and secondary streams. The curtain wall consists of multiple components. Therefore, depending on their technical lifespan and dependency on the system, some can be reused more efficiently than others. Hence, potential scenarios for reuse were devised for the different materials in the available secondary stream. The materials that cannot be reused at EO(s)L can still be sourced from different lifecycle stages, like a premature EOU for glazing units, to prevent them from becoming waste. The design explorations proposed solutions for strengthening the mullion through a combination of steel and timber sections for reinforcement and designing a sub-structure for fixing, which offered a new perspective to reuse materials.

The following sub-questions help to break down the answer further:

SQ1. What constitutes the existing material inventory for the selected case example?

The secondary materials available for reuse in the inventory vary from seller to seller. It is because every company operates differently in the market as per its business model with its specialization. Furthermore, the material inventory keeps rotating as per the incoming stream, and it is available only at the moment in time. For the two examples studied, Buurman has created a secondary market for waste wood for local reuse, and ODS is harvesting their steel facades, windows, and doors for new projects.

- Buurman's inventory comprises waste timber from the construction and demolition stages of a project and other materials made available by the suppliers. There is a constant supply of materials; however, the type of wood, quantity, and sizes vary depending on the suppliers' stock. As a reseller of timber and having gained market experience has influenced their inventory, with materials having a higher demand and market value. The materials are made available to users through their physical stores in Netherlands and Belgium.
- ODS's inventory consists of their facades currently monitored during the use phase, façade at the EOU from demolition projects, material overstock in facade builders' warehouse, and production leftovers from own warehouse. Due to a lack of contact with end-users for their existing façade stock, there is no consistent supply of secondary facades in their inventory yet, making it a hands-on approach to reuse. The materials are available for users to buy through an open-source harvest map from the Harvest Bay Platform.

SQ2. What criteria must be considered to determine the potential scenarios for reusing the secondary materials in curtain walls?

Curtain walls constitute many materials and components within their structure, each having its own technical and functional lifespan. Additionally, there are dependencies between these components affecting their reuse in the assembly. Over the years, research done on curtain walls has resulted in its structure reaching a state of optimization in terms of components, functions, and interfaces. However, the secondary facades made available today were designed 30-40 years back and did not have this optimization level. As a result, not all components within the system can be directly reused. It is, therefore, essential to identify the criteria defining the residual value that the secondary materials hold to determine the potential reuse scenario. These can be identified as:

- **Source of Harvest** - The source of harvest is the life cycle stage of the building from which the façade components can be harvested. It could either be from the demolition stage at the EOL of the building or overstock and production leftovers during the construction stage of the façade. Moreover, if the buildings are monitored, harvest can also be sourced from the maintenance stage of the building.
- **Form of Harvest** - The form of harvest is the product level of the harvested material from the existing building stock, overstock, or production leftovers. It can be at the assembly level to enable system reuse or at the unit level to enable component or material reuse.
- **Extraction process** - It entails the ability or inability to deconstruct the harvest into uncontaminated parts from construction to retrieve materials from the demolition stage with the existing technology. On the contrary, materials from the construction stage only require buying and collecting from their original owner.
- **Use life span of the product** - The use life span is the period of façade usage in the building compared to its life certified by the manufacturer. A difference between the two can help determine the remaining product value and strategy for its higher-value reuse. It could either be EOU, EO(s)L, or EOL.

SQ3. How does the design process change for the curtain wall façade when reusing secondary materials?

The research proposed two design solutions for the hybrid curtain wall for reusing materials from the construction and demolition stream. Both came with distinct challenges requiring different levels of adaptation in the design process.

- The profiles from the construction stream were available as standard material and only required buying material from the supplier. The longer length of the material could be used to the advantage of cutting in two parts for strengthening the mullion without the need for any additional material. Other materials still need sourcing from the primary stream through a façade supplier. The profiles were connected through a reversible bolt connection to ensure their reuse in the next cycle. Thus, the mullions act as one profile, and no additional design adaptation was required for fixing.
- The profiles from the demolition stream were available as an assembly requiring dismantling into reusable materials and components. Steel mullions, aluminum pressure plates, and to some extent, cover caps could be reused. For fixing and strengthening the mullion for new use, a higher degree of flexibility was necessary for the design to accommodate the shorter mullion lengths. The mullion was functionally split along its depth into two parts to create a substructure for fixing and strengthening the mullion. Secondary timber was explored for its viability and was connected with a reversible Ricon connector that does not weaken the material for subsequent use. The assembly required substructure elements to be connected first to the structure, followed by the steel mullions and remaining components from outside.

Both the systems followed the same grid of 1.2m, the same loading condition, and the same internal interfaces. Moreover, the concept for strengthening the mullion was similar, but the fixing system varied significantly. When comparing this to a standard curtain wall using primary stream, it can be seen that the cross-section is optimized for the required structural performance and fixed using the system supplied by the system supplier.

SQ4. What is the circular value of the designed façade?

Two design solutions proposed from the construction and demolition stream were compared to a recycling scenario for the two EOL conditions using MCI. The reuse cases had a tiny difference between their scores but reflected a significant difference compared to the recycling scenario. The lower percentage of recycled content of secondary materials in the current market supply and wastage in the recycling process lowered their fractional content for both input and output flow. Thus, even with a small percentage of secondary material by volume, reuse could significantly improve the restorative material flow for steel.

Although reusing all the materials from the demolition stream of the facade was not possible due to technical challenges, the hybrid system with the combination of primary and secondary material stream resulted in a circularity index of almost 60% for all the reuse cases. The design incorporated reversible connections for external interfaces but did not redesign internal interfaces. The two scenarios for future reuse after 15+15 and 30 years do not vary much, highlighting that MCI does not consider the value generated from reuse as long as the lifespans are the same. However, the assessment only stands valid when demounting of the façade can be facilitated, as stated in the description. In the future, when facades are designed for reuse, the degree of reversibility of connections must be evaluated separately for an overall circular value.

SQ5. What is the environmental impact of the designed façade?

The environmental impact evaluated with LCIA for the primary energy EE (PERE + PENRE) and carbon emissions in the environment (GWP) showed substantial savings for both reuse cases. Reuse of construction stream showed a saving of 91% for EE and 93% for GWP, with a 9% share by volume of secondary materials. Furthermore, the reuse of the demolition stream showed a saving of 88% for EE and 89% for GWP, with a 25% share by volume of secondary materials. This stream presented the highest potential saving of 3246MJ, almost three times the recycling scenario due to a large volume of materials available for reuse.

Despite the higher energy requirement for dismantling than demolition, its contribution is still less than the energy required for melting materials for recycling. Nevertheless, the energy associated with dismantling requires additional labor adding to manhours. Therefore, it would not add to the environmental impact; however, it can significantly affect the industry's willingness to reuse. Further, the assumption that the remanufacturing process for the two cases will result in a full lifespan for the facade with no performance deterioration was a limitation for the evaluation. It can affect the environmental impacts and should, ideally, be evaluated through a life cycle analysis for the use phase of the designed product.

SQ6. How can design solutions be formulated to organize the reuse of secondary material for other cases?

If the process and people are in place, reuse of materials can be established for the façade industry. Design solutions that will help its forward momentum include:

- **Material Inspector** - Most resellers of material cannot formally attest to the technical capacity of the materials. However, an inspector can physically assess based on their experience and provide a report for its performance. In addition, if involved at various stages in the process, including deconstruction, they can commit and advise on the quality of the batch.
- **Sufficient safety margins** - To overcome the lack of information about the loading condition, the profiles can be over-dimensioned for sufficient safety margins during sizing calculations. However, defining the percentage of margin will require testing or assessing the components by an expert. A common database for tested façade section sizes and guidelines for safety margins can become tools to overcome any uncertainty about reusing materials.
- **Form of supply** - The supply from the existing building stock is inconsistent, and the harvest will always be at that moment in time. Therefore, recognizing the form of supply can be insightful. The form can be matched with the project's requirements to either design from the stock by adjusting the design to

available sizes or design with the stock to remanufacture new products as per the design requirements. Using this form of supply for designing would mean creating a reuse system irrespective of the profile's shapes, sizes, or dimensions.

- **Changing Design Habits** - Architects and engineers need to change their design habits when working with secondary materials. Standard façade products are customized for every project to suit the design needs; however, reusing the secondary stream implies customizing design requirements to suit the available material stream. Every supply is different, so the design generating out of it needs to account for the differences. It requires engineering new connections for the system and tweaking the materiality and dimensions of the project as per the available material streams.
- **Using materials differently** - The obsolete facade systems can be reinforced with different materials to make them structurally and thermally sound for reuse. The material suitable for reinforcing depends on the change in performance and loading requirements for the new condition. It opens possibilities to look at materials differently and use them in unconventional ways that they were not designed for in the first cycle of use.

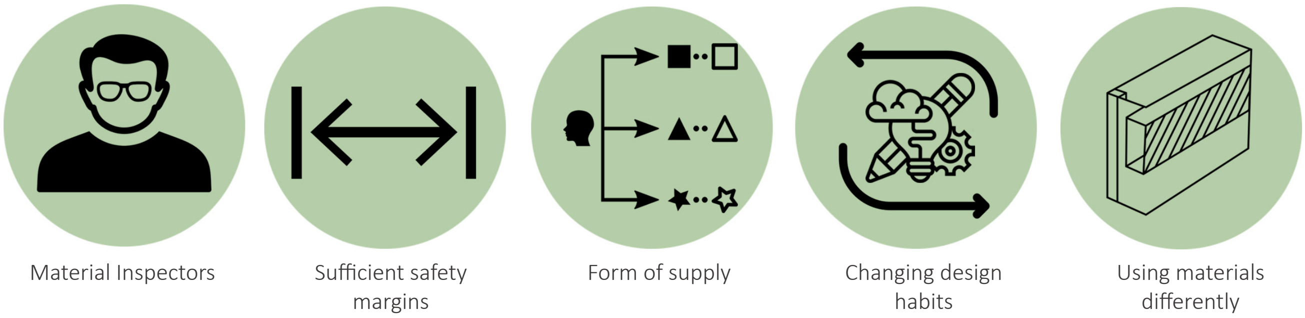

Figure 85 - Design opportunities for reuse of secondary materials for facades (source: author)

13.3 Limitations

The presented research tried to cover an overall picture for material reuse from existing buildings. However, due to time constraints, it lacks in-depth research in certain aspects:

- The design exercise proposes conceptual ideas; however, it is essential to check the viability of these ideas through physical testing of models and prototypes.
- Not all components of the curtain wall could be reused in design. The presented research looked at mullions and external fixing details and did not focus on the glazing unit and the internal interface design for future reuse.
- Only the facades' essential functional and technical requirements were tackled; the research does not go deeper into the climatic and aesthetic requirements. However, the ever-improving energy performance standards of the construction are relevant to the research topic and could pose a big challenge.
- The research only presented environmental benefits from directed impacts through LCIA but could not evaluate the benefits/loads that can occur from reuse during its use phase through an LCA.

13.4 Future Work

The reuse of secondary materials has already started in bits and pieces. With the circularity goals in place, it will further take forward momentum in the industry. Still, extended communication and collaboration between policymakers, stakeholders, and users are essential for raising awareness in the industry. Research on topics mentioned below can further benefit the reuse of materials:

- There are two material flows - secondary materials from existing stock and new materials used for current building projects. The former is available in large quantities, and the research presented a reuse process for it; the latter will increase in the future. Further research on how the façade design can incorporate a circular strategy to safeguard future reuse can provide a tangible design approach for reuse.
- The reuse of existing materials is still under research, and no practical studies measure the energy required for dismantling, collection, and inspection processes. Further research to include these aspects of energy in the product EPDs can enrich the database for meaningful assessments and results.
- Material passports are already available by various suppliers; however, they lack a shared database. Therefore, it limits building an extensive and transparent database in the industry. More research on how the existing database can be brought together to add value for the whole industry can prove beneficial.
- As highlighted in the research multiple times, economic cost and benefits are essential aspects of reuse. Further research on the circular business model, including lease contracts, take-back systems, and quantifiable economic benefits from reuse, can increase its viability in the industry.
- Most materials will require documentation for future reuse. Further research on the information required for material reuse for the different stakeholders can benefit the material management platforms.
- The Glazing unit is an essential component in facades. Research on how its reuse can be made possible with technology and innovation can help to significantly increase the fraction of secondary material used in the façade industry.

13.5 Reflection

This section reflects on the graduation process on the aspects: the theme of graduation studio and the chosen topic, research method and results, research and design, and the issues encountered in the project.

Placing the graduation topic in the Building technology (BT) track of the Master program (MSc AUBS)

The Sustainable Design Graduation Studio focuses on scientifically driven innovation to contribute to a sustainable society. In this context, the graduation project focuses on reusing materials in the façade industry to tackle the high resource consumption in the building sector. Buildings are responsible for 40% of the total resource consumption, and it is essential to consider this sector to achieve the Netherlands' goal of reducing resource consumption by 50% in 2030. Although it is easier to design with the primary material stream, it is an unsustainable construction method and leads to a massive waste problem in the environment. The research tries to answer how the reuse process can be formulated for secondary materials already existing in the environment, taking into account the technical and functional factors of the façade, directly linking the topic to the Building Technology Masters track. Another aspect of the research tries to evaluate 'Reuse' as a circular approach by evaluating its degree of circularity and environmental savings generated in the process compared to the existing approach of material recycling in the building sector. The circular theme of the research further led to research in the aspects of the market challenges of the proposed process to make the project applicable and viable for the façade industry.

Reuse of materials belongs to the theme of circularity under 'Circular Built Environment.' Therefore, the research collaborates between the Chair of Façade and Product Innovation and the Chair of Climate Design and Sustainability. The combination of the two distinct chairs integrates the relevance of the topic for the architecture and built environment.

Elaboration on research method and results

Various research approaches were taken to address the main question of the reuse of secondary materials. Extensive literature research was done in the beginning to understand the context of the problem in the Netherlands. As a result, it was seen that the idea of reuse is not new in the industry and is happening in local projects through a hands-on approach. However, an industry-wide system was not seen in any example.

In the next phase, various people were interviewed to get a detailed insight into this practice. These proved to be very informative and led to critical findings obstructing its application for facades. It was also seen that waste is not limited to the building's end-of-life resource but is seen at other stages during the design and construction. Reflecting on the findings from the interviews led to formulating the process to see what stages a material has to undergo to ensure that it can be reused again at the same value. The complexity of the process brought to light the significance of various actors required to support reuse. It then became essential for the research to identify these challenges that can hinder the feasibility of the process.

The initial idea of the research was to create a standardized product from the reuse of secondary materials; however, it was identified that there is no possible way to do so with the identified challenges during the research. Every material is different, and so is its reuse potential. After discussions with mentors, a system for reusing secondary materials for curtain walls was proposed for two different material streams. An important realization during the design explorations was that technical design is a minor aspect of reuse compared to its impact on the environment and the efforts required by the people. Therefore, it is crucial to identify the worth of doing this. The new value created for the material must be weighed against the cost and concerns added to make it happen. The insight gave the direction to the research, making it essential to change the design approach. The design was then assessed for its environmental impact and circular value to quantify benefits from reuse. The designed façade reflected the results as expected. The design case with the highest proportion of reused materials by volume presented the highest savings in Embodied energy and carbon emissions and had the highest restorative flow as per the MCI score. However, the designs were assessed with the assumption to facilitate easy demounting in the future. Thus, 'Design for Reuse' was recognized as a crucial aspect of façade design to ensure the future reusability of materials.

Curtain wall systems are one of the widely used façade systems for commercial projects. It was one of the reasons for the selection of the façade type. The facade system consists of multiple elements, and glass is a significant component of the curtain wall for office buildings. With the current technologies for the reuse of glass, no supplier for secondary glass could be identified in the market. Its reuse required in-depth research for its properties and was not part of the scope. It limited the design component of the graduation project to the reuse of available material inventory, i.e., the structural component of the curtain wall; the climate barrier could not be studied.

Relation between research and design

The graduation project followed the methodology of Design Research. The research on the market reuse scenario and interviews with the industry representatives guided the design of the process to enable the reuse of materials in the façade industry. The process raised the question about the changing roles of various actors. Thus, an ideal scenario for how the stakeholder supports the process was mapped. To further see the application of the process for a real-life scenario, the research proposed design ideas for curtain wall façade reusing secondary materials for a generic office building in the Netherlands, considering its functional and technical requirements. A hybrid curtain wall system with secondary materials was designed as a solution. Since not all materials are reusable, engineering façade solutions from a combination of primary and secondary streams could provide a feasible case for reuse.

Though the design explorations started with designing a new product, they soon shifted towards designing a system for reuse. This idea raised critical questions regarding the design adaption needed for secondary material, effort in designing a technical solution for the feasibility and aesthetic of such a system. Even though not all were tackled in this research, these aspects are crucial for future research. A tangible design solution through a flexible fixing system was proposed to evaluate and quantify the impacts of the reuse process. The design was assessed for restorative material flow, Embodied Energy (MJ), and Global Warming Potential (CO2kgeq).

Issues encountered

The government has set high goals regarding the circular consumption of materials. However, a lag in the regulation to support this has limited reuse in the industry. Not many people know about reuse and, more importantly, the benefits it can bring economically and environmentally. As a result, many people are reluctant to opt for reusing secondary materials in the industry. Throughout the research, reuse was seen as an initiative by one of the actors in the project. It often drains the resource of that one actor in what is supposed to be a multi-actor process. Moreover, the research indicated that waste from a premature end of use has a high reuse potential, even for materials such as glass. However, no supplier could be identified with EOU material waste. Therefore, it will be of added value to continue researching procurement of this stream to see how the design can further be adapted for their reuse.

One of the biggest challenges that I faced during the research was accepting the design that generates with reuse of materials. I found that the design question posed initially was too specific for a project like this because the available materials guide what and how one can design. I selected curtain walls due to their common use. Maybe it would have been better to look at the materials available and then design the façade around it. It is this adaptability that one has to accept while reusing materials. Nevertheless, it was a learning experience, and I sincerely hope that we are one step closer to reusing materials in the industry with this research.

Hopefully, the reuse process formulated and the roles identified will help the facade industry embed the reuse of secondary materials in their standard operating models. Even better, if the design proposed can show the environmental benefits of reuse and shift the mindsets of decision-makers. Then, maybe, if the design and the designer comes halfway, the efforts required for the entire chain will be reduced.

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APPENDIX

APPENDIX A - Interviews

Circularity Assessment Company: Alba Concepts
Interviewee: Marie-Sophie Res
Date: 08.02.2021
Purpose of the interview: To identify how the reuse of materials from existing buildings (secondary materials) impacts the circular value. Alba Concepts uses the BCI indicator for assessing circular material use and assess circularity at the material level, product level, and building level.

1. **What are the critical stages in the product design Alba Concept considers when evaluating the circular value of reuse? Why?**
   The critical stages for product design for reuse is all the way in the beginning. If your process for product design is not made for reuse of the product, you should consider changing the process with critical questions, such as, how do I want to disassemble my product, on element level or product or component. That is what we see in the industry now; years ago, buildings and construction work were not made for reuse. If we put the ability of disassembly on a number one priority in product design, your product should evolve around that priority.

2. **How does the assessment at the three scales - material, product, and building inform each other?**
   We say that different products are connected to each other. For example, the connection of a window frame within a wall opening. In the BCI, we check how that connection is, and the connection of the window frame and its different elements within.

3. **Does the method distinguish between reuse / remanufacture / recycling of materials and components?**
   Yes, we base the Material Circularity Index on different factors:
   a. Detachability
   i. Type of connection
   ii. Accessibility of the connection
   iii. Crossings
   iv. Confinement of the edges.
   b. Origin scenario
   i. % New components within the material
   ii. % Recycled components within the material….etc
   iii. % Biobased
   iv. % Reuse
   c. Future scenario
   i. % New components within the material
   ii. % Recycled components within the material….etc
   iii. % Biobased
   iv. % Reuse
   So a product with a higher proportion of Biobased material with Reuse scenario in the future, will score higher on the MCI and therefor has a better BCI of the building.

4. **What factors of a product do you consider for defining the outflow of materials?**
   Out of a building, we consider the following factors:
   a. % New components within the material
   b. % Recycled components within the material….etc
   c. % Biobased
   d. % Reuse

5. **If the material is not a direct waste from existing buildings but is an overstock waste, will it still be equally valuable when assessing reuse?**
   Definitely! Overstock waste can be more interesting because sometimes you do not have the damages unlike the materials that comes out of building.

6. **Do you also consider how the circularity achieved through the reuse process can affect the environmental impacts?**
   Yes most definitely, but it is important to consider the total LCA and environmental impact of CO2 of the reuse process. Where is the reused material coming from? How much energy was needed to realise the material from a building (if it was the case). And how much is the environmental impact of the whole cycle.

7. **What added challenges do you face when assessing the circular value of reuse? How does the evaluation deal with these? (such as the remaining lifespan of different reused components)**
   Good question and really hard. For now, if reused materials are marked as brand new, we give the same lifespan as they already had. But it also depends on the guaranties and safety regulations of the materials.
   Also, the MKI (environmental impact)-score is not always in line with the BCI score. For example, steel construction can be more reusable and detachable in the future compared to concrete or wood, but the environmental impact to make new steel construction is very high. Also, the reuse of steel construction can be difficult due to the current regulations, so it is still easier to make new construction, window frame, door etcetra.

Supply chain manager, ODS

Interviewee: Emile Kranendon, Antonio van Tienderen

Date: 25.02.2021

Purpose of the interview: To identify the logistics added with the secondary material reuse and facilities required to use it. The interviewee is responsible for managing the logistics associated with the demand and supply of the material within ODS.

1. **What does the current supply chain for ODS looks like?**
   We are a global company. Our headquarter is based in Germany with locations in the US and all over Europe. We are a traditional wholesaler in the steel market and have suppliers all over Europe. The material gets delivered to our warehouse in the Netherlands and Belgium. We have two warehouses in the Netherlands, at Barendrecht and Ridderkerk. From these warehouses, we ship them out to our customers.

2. **How did you supply the façade from Brussels for reuse in Leiden?**
   For the Brussels project, it was a short-term organization. Ron Jacobs, sales manager for Jansen, called on Wednesday 13th March 2019. There was a problem with a facade in a mockup of the Gari-Maritime building in Brussels. They wanted to throw it away, and it was a valuable product. It was short-term because if we do not remove it before Friday (2days), it would go to scrap. It was a high-value product, almost 50000 euros at that moment. Ron asked how can you dismantle and transport the product back to Barendrecht for resale. Through my network, we arranged a whole battalion of people on Thursday to dismantle the façade and transport it back to Barendrecht. It was a difficult job but we could do it. We placed it in stock, and Ron was searching for the next client in the Netherlands. Once he found the client, we could sell the second-hand façade. After selling, we installed it in the new building, and we collaborated with CirlinQ for the material passport. On the door, we have a QR code that shows where the material is and what it consists of. We linked with CirlinQ so that it is always traceable.

3. **This was a short-term project, but how would the process go about in an ideal situation?**
   The ideal situation will include a partner for dismantling. At the moment we have partners who can arrange people and equipment in a short duration of time. Return flow, ideally, will have a company like cirlinQ or other harvest maps that are centralized and where people can pro-actively put their materials and buildings. We, as a company, can identify what they can reuse and select the material. Then, as soon as the building is demolished, we can collect and store it in our warehouse and make it available again via the same platform. We can sell it either in the same state or a bit modified with new products we have and sell it to the customer interested. The main driver for this will be the harvest map to know what is available in the market and where it is. The existing buildings do not have that but there is a rising emergency for new buildings. When we have the harvest map, the architect can design with these products so that we do not have to adjust the sizes in or return flow. This can already start with the design of the new building.

4. **What proportion of façade could you recover in the short duration of time?**
   We dismantled the whole façade and moved it to our stock. We removed glass as well, and everything is reused. It was a mockup, so it was just a wall without any sealants. It does not fit in the new situation, so we remanufactured it for the new project.

5. **How will the online material hub (Harvest Bay platform) support the chain of reused façade products?**
   In an ideal situation, every material we will ship out will have a material passport on the material in the form of a QR code that we can put on a database. The database will show us what the material consists of and where it is placed. So that when it is dismantled again in 20-30 years, you know where to get it from so you can restore the materials. Of course, it is a big challenge to have these materials in a harvest map. Because you can either choose to do it yourself as you know what material you want, but the best way is through a party in the marketplace that has already developed a database. The problem is when everyone has their own database, you will still not know what is there in the complete building. So, it is good if you have a third party who compiles this data and a complete overview of the building. At the moment, there are few parties in the marketplace - CirlinQ, Oogstkaart, etc.

6. **What are the additional resources required for the reuse of facades?**
   One of the most difficult things in the supply chain is the return flow. You need a separate supply chain for the returns. Currently, we do not have that fully set up yet. We are working on that to see how we can implement that. But at the moment, it is more like a hands-on job. When we get a call for materials that should be retrieved, we put in the right companies that can help us with that. Also, the volume is not significant, that we are forced to set up a process for that yet. It is growing, but we are at the beginning of the market.
   Also, you need to start thinking of what you can do with the materials when they come back in 5 months or 20 years. So we are going to keep that awareness of where the material is. We now have a harvest bank, but then we also need to invest in the supply chain to integrate this into our current process. You have to add the cost of retrieving the material and then storing it in the warehouse. The process can use a professional upgrade. When you get a façade, like in Brussels, you do not know when the opportunity arises to sell it. This highlights the importance of a harvest map; the more we can show where our material is, the more it will sell.

7. **How can you ensure a regular product supply with an inconsistent material stream?**
   There are two flows, current buildings with all the materials and new buildings where you can put the material passports and monitoring systems to track materials. The problem with the existing buildings is you need to go in, look around and identify what can still be used. Companies like New Horizon are more advanced. But it is difficult for us because the market needs to know you are available, that you are searching for these materials. Because when the building is to be demolished, they just demolish it. They are not even considering it yet to reuse the material. So you need to put yourself out there to say if you are going to demolish the building, we are interested in some of the materials that are still valuable in the building, more than what you know.

8. **How will you ensure that the facade continues to perform the way it is supposed to be?**
   The buildings are designed as stationary, but the products keep moving due to external factors, and their performance cannot be guaranteed. Some students in Delft, are in the process of making steel box scanners to test if the molecules are still in the right position to make a good guess if steel is reusable for the next cycle. Once we have a system, we can probably certify the materials again but now.

9. **Do you also consider repair/maintenance of the reused products during their use?**
   It is important to realize that a lot of expertise is required to manage these supply chains. You need a lot of specialized companies to help maintain the high product quality. As a wholesaler and the role we are in, we are capable of doing it, and neither is it in our strategy.

10. **Will the change in the supply chain affect the business model for ODS?**
    Yes, because you have to deal with a completely different type of product. The products we get from suppliers in factories, we know the quality it has, the certificate it holds, know the price, and know the market and demand. It is an entirely different market. We now sell only steel, but when you get facades back you are selling the entire product with all the different materials, so the selling product changes. We can have a warehouse with both reused and virgin parts; when an order comes in, we combine the shipment and supply both. We can show the prices to the customer for them to choose from.

Circular Marketing, Harvest Bay

Interviewee: Astrid Heystee
Date: 12.02.2021
Purpose of the interview: To identify the different partners in Harvest Bay, the functioning of the online portal, and information provided about the secondary materials to enable their reuse. The interviewee is responsible for giving the online platform what it needs to be working as a consortium for secondary products.

1. **What is Harvest Bay? What are the different stakeholders involved in this platform?**
   The consortium is focused on the network chain and collaboration opportunities between partners. It is a project-based collaboration. The harvest bay website combines the project website and a consortium website because we needed that for the Flanders circular project. There are structural partners, like the hubs, knowledge institutions like TU Delft, and people out there who have a link to the circular economy, which got the subsidy from Flanders Circular to help the project financially. And then you have design partners who help with the design. The third layer is the build partners. One of the design partners constructed a design for a tiny house mock-up model. And then, the build partner Lootens is assembling the products that Jansen ODS delivers. Then we have the use partners, CirlinQ, that has to do with the component's platform. Then is the harvest partner, extracting the material from the demolition site but also registering the valuable components that can be used and placed in the Oogstkaart. These partners are working within the sphere of the circular economy network in the Netherlands and Belgium. Harvest bay is connecting the dots between different projects, and it gives a platform for all collaborations, which are usually loose components and projects. The consortium is bringing them together so they can start collaborating. Behind this, there will be a foundation above it for knowledge sharing about everything learned in these projects and to bring the industry to a higher level. So, there is a commercial part where collaborations between projects are happening and the foundation part, which is not yet officially established.

2. **Will this platform be limited to façade products?**
   The platform looks at the whole circular built environment and is not limited to facades.

3. **At what stage in the process and how do you plan to collaborate with the users?**
   There is a sales stage, which is specific to ODS. For Harvest Bay, there is no structure yet as it is still in the beginning phase. There are few architects already working but more still have to be inspired to start building from Oogstkaart and database. So that is part of our target group.
   On the other hand, the other group consists of contractors. At the time of request for proposal (RFP) procedures, when they are getting the price quotes, there is one component where the government can dictate the percentage of reuse materials. That is one way of how the change will come. On the other hand, as a supplier of material, how we answer the RFP and use the text to explain the circular process. We explain how the material is used, focus on PSS rather than just one-off sales, and what is needed for them like 3D visualization model, specifications about getting material out from the building, how maintenance has to work that is going to be developed in Flanders circular project. The material is not there because nobody has done that yet. That is why Cooperation is Key is an important project.

4. **What is your method to get/share information about the already existing materials in the building?**
   There is a lot of technical information about the building, but the economic value is not developed yet. The assessment of secondary material's worth is not available at this point. The first step is to get the secondary material because, at this point, ODS has no connection to the project. They have a contact moment when the architect requests information about profile for design phase, and there is another moment during RFP to see if there is an actual sale. After that, they do not have any contact with the client anymore. Sometimes, a year or two later, they realize there is a building built with their profile. It is like they don't stay in touch in the linear economy because sales are a one-off transaction. So, the first hurdle is to stay in contact with the developer and ask for the materials to be reused to make a deal during the sale to extract it out again and generate that stream of secondary material. Because at this moment, it is happening at a very limited scale. First, we need to get the material and then see if you can put a price tag on it. The whole extraction process is also a part of this.
   There is a lot of learning to do about what is there and what kind of steps are needed to reuse them, and

then there is another stream of overstock and the bits and pieces left during production. But then the question is if this is secondary material or primary material because it has never been used and was just discarded as trash. You can do different things with different materials, for example, if you extract an entire façade, you can touch it up and reuse it as is. But what ODS did with Buurman, they had some cutting waste and overstock, and they combined that to a table. They made something completely different and new which is totally not their core business, but that is why it is a different process.

If you look at materials from projects ten years ago, it is quite hard to assess what is in there. That is where the demolition part comes in; if a building is available for demolition, then the demolition partner can assess what is in there. When you have buildings that you want to refurbish or demolish, the experts can assess what is in the building and what is suitable for reuse. That is a very important step because, indeed, the information is not there for buildings designed 10, 20, 30, or 50 years back.

5. **Currently, there is a harvest map with ODS and a different Harvest Bay platform. Will you be linking the two platforms?**
   I think in the end, when we look further, we will take that functionality of Harvest Map but transfer its database to Harvest Bay as it is interesting for other parties as well. Harvest Map is only for Jansen now, so it is a timing thing, but there will be a redevelopment of the whole database. It is really costly and probably more than 100,000 euros to redesign the database if you want to make it a complete components platform. And there are other existing components platforms like CirlinQ; the question is how will that develop. So, it will definitely be linked, but for now, we keep it like this.
   In the future, there will be redevelopment or different use of existing databases like CirlinQ to have the data about the availability of different reusable or harvested material and at what time. Because sometimes they use the project for few years and material come back after that. So, it is not only the technical aspects and money wise but also when it can be harvested. If you look at the harvest map, it will give some details, but when you click on interested, you will be contacted by sales. Usually, for all the projects sold by ODS, a custom offer is made. It is not something you can buy on a webshop. It is always so complemented that you get advice from somebody who is going to work on the proposal. That is is why the economic component can't really be labeled on the website. That is a conversation between the sales manager and the client.
   One of the other hurdles of the startup project is if you need to get that information, you need to insert the data on the database because you are only as good as your data. So if you have the sales happening and there are contacts made about reuse but if you don't log the data, you will not be able to use it. Sometimes you forget, or sometimes you don't follow up, and the data is lost. You can't design with things you don't know. There are issues of getting information and getting the approval to reuse because not everyone is on board. The issue of getting the secondary material is something, not a given at this point, we all want, but it is harder than reality.

6. **Will the platform be used for providing some certification regarding the materials and products available?**
   I can't really answer that question; it is not decided.

7. **Will there be a possibility to buy back the leftover materials from clients after the reuse?**
   Ron did have conversations with the client. Since clients are not used to it, and the material is not worth as much as the new price, this is one of the challenges of buying back the material. It is not formally structured yet. Ron did buy material from the client, but it is again not easy because the economic value is not the same as new, and they cannot buy it back for the same price, obviously. There are examples but no defined process as of now.

8. **Is there a defined lead time between the extraction of secondary material and its reuse for the next project?**
   No, there is nothing in this perspective. The flow of material is not there yet. What happens now is that there is no fixed medium because it is still in the beginning phase. It could be that the material overstock over the years in the warehouse of the client is used again now. But there is no defined lead time because the volume of material is not big enough. Further in the process, when there will actually be flow coming in, then you can definitely say there is the lead time between extraction and sale. Lead time is not interesting just yet because there are all these hurdles to get the process flowing. In 5-10 years, when it is a normal

process, when every material sold will come back then, you think about how fast you can find a new use. Flanders Circular is important because it is a collaboration between material hub with Buurman for timber, material hub with Lootens for steel, and with Franc for stone. One of the project's aims is to figure out how to extract and store material, how does the logistical component work.

9. **What is the role of ODS in Harvest Bay?**
   ODS is the supplier of Jansen profiles. They do not produce it themselves and specialize in its distribution. Jansen is like a connecting partner bringing people together and doing a little bit of logistics for Harvest Bay. They are not doing any hands-on work in the material hub but are distributing products. In a linear model, they move inventory from the factory to the client. And they are licensed to that by the factory in the Dutch and Belgium market.

10. **What, according to you, are the challenges in the process from a marketing perspective?**
    From a marketing perspective, communication with the client is very important. Normally they do not talk to the client anymore once the sales have been made. So, they need to extend their client relationship on a project basis. They are still in contact with clients but for a different project, so they need to establish some way to track those projects. Oogstkaart is definitely one of the methods to do that. But they also need to incorporate getting the data and logging it so it becomes available. Convincing the architects to start using secondary materials as a starting point of design instead of designing something pretty, and then we think about what is available is a challenge. Then there is a logistical component of how does that looks like when new contracts are made, how do we buyback, how do we do the maintenance. And then the collaboration of who is doing what and who is making money on what part and what is the economic value. It all costs labor, so who is going to pay for that. It is never going to be profitable with small bits and pieces of projects here and there. It is only when it scales up when there is a defined process, a flow of material, and a volume of material, then the cost will go down, and the economic model could be better. Now it is costing more money than it is generating, but that is not a sustainable model. The economic part is definitely very important.

Buurman, Rotterdam

Interviewee: Tessa Bloembergen
Date: 09.02.2021
Purpose of the interview: To identify the different material flows for a secondary material market. Buurman has already established a market for secondary facades and knows material flows.

1. **What is the procedure for the collection and setting up of the material inventory? Do you have a harvest map?**
   We do not have a harvest map. So, we work with several suppliers, some of them on a regular basis, let us say once a month or once every two months. Other parties actually call us, and we are a company that's known for five years now because we work locally usually, we are in people's network which means that they contact us in case there is something, so it is quite reactive. Sometimes we do a round of calling local contractors or big building companies to ask if they have materials or they want to work together. So, it is not one system, and in that case, we do not have a map, more like a list of potential suppliers. But sometimes, we all of a sudden hear that there is a party in the harbor that has a lot of left-over wood that seems to fill containers so that the containers, when shipped, are more balanced. I guess that is the procedure.

2. **What is your business model with the different material streams?**
   Well, what we do is we try to collect materials that are seen as waste by the building industry or harbor or milling factories, and there is not really a way to get those materials to consumers. So that is what we do. For the company, it is nice because we come and pick up the material, so they do not have to put the time or effort or pay money to throw it away. And for us, it is good because we sell the material which we get in our shop and we also give courses in furniture making and workshops to make sure that people also learn how to build with reused materials. So that is the combination of a shop and a workshop that makes our business model. But our mission is super broad in the sense that we just want to make sure that what is considered as waste, that those materials get longer life span. So now we have to show up in workshops, but in the future, it could also change to something else as long as materials get a longer life as per the Reuse ladder. So, we want to try to stay in the second spot of the ladder, which is reuse, and underneath that is recycle. We want to keep the material as long as possible in this reuse loop.

3. **Do you have materials other than wood in the inventory?**
   We do; I think 80% is wood. We have like 5 tons of material this year that we extracted from the industry and will sell or use in the workshop. 80% of that is wood, and the rest is a lot of different materials. This is also a big experiment for five years already to see what sells and what does not sell. Before, we used to have tiles, but that always is a bit difficult because you get it in a few sq m and is something which is always leftover. So, we do not do that anymore. We do have windows, doors, sometimes we have steel, not a lot, though. We also do trees from the cities which are being cut down, so it can be quite random. Sometimes we have furniture, desk tops. If you look at our website, you will get an idea.

4. **Is there a standardization in the products? Such as in terms of a particular type of wood or particular sizes that are always available?**
   Yea, we do. We always have beams or slats. It depends on our suppliers as well, for how many we have and in which sizes. We do know what kind of material will always sell and can be reused in a good way, so doors and windows. We have a list, but it is ever-changing because the amount of material being offered to us is huge. We are a bit selective, and we are becoming more selective for a year now as it is quite expensive if you have stuff on the shelf that you can sell to someone but is not quite popular.

5. **What is your target audience?**
   It is a broader audience, but it is mostly consumers and smaller businesses that just need something and know perhaps we will have it. Or it is the neighbor next door who has a shop and wants to repair something. So we specifically choose not to become a party with very big amounts of material because then you get a completely different set of users.

6. **Do you provide any certification for reusing the wood available in your inventory?**
   No, we do not. We do not have any material passports because it takes too much time. Also, most of our products are used for interior building and not really for use for construction, so that makes it easy to reuse. We know, for instance, Buurman Utrecht is built with reclaimed materials, and they needed some certification. This is quite tricky because how do you know if it is still safe and you need like someone in the council who is on your side and willing to cooperate. Right now, the whole system is not built for that.

7. **Do you sell materials online or prefer the customer coming over?**
   We prefer them coming over because sometimes our shop is not just a shop, but we also offer more advice than a regular store like gamma. Online is difficult as we do not have a set stock list. We can say we have beams, but someone is always looking for certain types of beams. It takes a lot of time, and we have to go and see if we have it. If people come to the shop, we can also talk and ask what they want to make, and if we do not have that material, we can provide alternatives. So going to the shop is definitely better.

8. **Who is responsible for the transportation and delivery of materials?**
   Usually, the buyer. If they buy like a large amount or if they do not have a car, we can arrange something. During covid the price is 25euros, but normally it is 50euros. So, the delivery has to be worth it if someone really buys a lot. It costs us time and is not in our business model.

9. **There are other branches of Buurman in the country. So do you have a maximum area that you service to?**
   One Buurman per province would be nice. Right now, we deliver like in and around Rotterdam, which is like 40km. But usually, we prefer around 12-15 km.

10. **Who is responsible for de-nailing of wood, removing additional coatings, or any added processing before making it suitable for reuse? Does it come under your scope and the buyer's scope?**
    We are responsible for it and have several ways. We also work together with the waste points in Rotterdam. There is a container from Buurman in each of them, and there are like 6 of them, where consumers who want to throw things away, they can put them there. And we get the material from that. We go there every two weeks and pick the material up. And usually, that material has a lot of nails, and we work together with a social enterprise that comes to us usually once a week to do all this de-nailing.
    If companies or suppliers offer us material, we are quite strict with them. We see sometimes people offer us everything for free, but we have to deconstruct it. But right now, that is not worth it. So, we have to do an estimation, see pictures to know if it is worth going there, and decide if we take it on. But we prefer clean material that we can sell one on one and don't have to put much work. Otherwise, it becomes too pricey.

11. **How do you collaborate with other Buurman stores?**
    Well, Buurman can be seen as a franchise but not a classical one. Right now, we are working on making Buurman as a name and a concept like cooperation and then create a network of all the other Buurman's around it but also share knowledge with each other. Perhaps take on bigger advice projects. It is sort of like a midpoint, and every branch or every city can have its own activities as long as it fits within the concept. So, it is not a super strict franchise. It is more like collaboration, but there are some rules to make sure that the program is the same.

12. **What would you say are the challenges to design a façade product out of reclaimed materials?**
    The hardest thing of making a product out of reused material is that your incoming material stream is inconsistent. So that would be like the biggest issue to tackle. It is to see what material stream is always big enough and is always there that you can make a new product. Or which method you can use to create from an inconsistent material stream to make a consistent product out of it.

New Horizon Urban Miners

Interviewee: Erik Koremans
Date: 11.03.2021
Purpose of the interview: To understand the material harvesting process in the Netherlands. New Horizon is the biggest Urban Miner in the Netherlands.

1. **What is your scope of work as an urban mining company?**
   We believe in a circular economy in comparison to a linear economy. What we are doing is we do not demolish, but we harvest. For example, we can make new concrete out of old concrete and new bricks out of old. So we work together with producers, and producers get our materials and raw material from the building. The companies collected themselves in a collective called urban mining. And we work with 25 organizations, and together with them, we bring circular products to the market. So our materials and raw materials will be used in new building products. With our harvest, we bring materials back into a new building process. That is what our company is doing.

2. **What kind of companies are a part of this organization?**
   The organization that brings back materials and raw materials into a new building process are producers, concrete producers, brick producers, gypsum producers, so all industry-related companies. So those are the companies we work with, and they get our harvest to make new materials out of it. We also work with demolition companies. They work for us, and we develop, together with them, a protocol to harvest material. So, we are the first suppliers in that way, and those companies work with our instructions. The producers need clean material, without metal, wood, or anything, so we need a special protocol for harvest. So that is what we are developing, and we call it urban mining.

3. **Are the demolition companies specialized?**
   Well, they used to be demolition companies, and they still are. Together with those demolition companies, just a few, we develop a new profession of urban mining. The producers of materials tell us how they want the materials from the building. They give us the instructions, and we translate them as a protocol to the demolition company.

4. **Do you actively seek out for buildings to recover material from using databases, or building owners approach you?**
   What we are doing is good marketing. We have a very good network in real estate. We know a lot of owners of buildings, and we also know a lot of real estate owners. When we contact them, we tell them what we are doing and tell them we believe in a circular economy. When they have plans to develop new products and a building has to be demolished, we ask them if they can donate their building to us because we can help them to reduce the environmental cost by using our materials. Our material reduces environmental costs and carbon footprint. That is what the real estate world wants, and they want to build with materials with low environmental costs. When we are in contact, we tell them our story, and we tell them also that a building built with our materials is a better story and a better promise to the future than a building built with virgin material. Our strategy is to show the market that it is possible now and make the transition. That is our goal for the coming years. The building owner donates the building to use. We call it a donation building. We need these buildings to promise the market we can deliver materials and raw materials. We close the circle.

5. **What happens to the ownership of the products within the building when it is donated for mining?**
   We get the rights, and we are the owners. The building owners pay us to demolish at this moment. We are working to make a difference. Now we get paid, but the more we deliver the materials, the less we get paid so we can attract all the donation buildings from the market. So we have the ambition to deliver as much as possible so we can bring down the cost. We believe it is possible that we pay the building owner; that is the transition we are working towards. But, it is a slow process, and we want to get the market moving in that way.

6. **How do you collaborate with the producers to reuse the harvested material?**
   What we are doing together with the producers is we are developing a business case. It is a completely different business case to develop concrete without virgin materials. Only when there is a business case are we able to bring the material back into the building process. So we have to invest in technology; for example, for concrete, we invested in the smart liberator technology. It uses our concrete harvest and makes the original material of what concrete is made of - sand, gravel, and cement. So we get clear original material with the technology, and when we have those raw materials back again, we can use them to make new concrete. The new concrete has the same certifications, same guarantees as virgin concrete. So that is what we are doing now, we can produce new concrete with original materials out of the liberator made using our harvest that makes the environmental cost and carbon footprint substantially lower, and that is important. For example, of the total carbon footprint in the world, 10% is caused by concrete. With our concrete, we reduce at least 60%, we are making an impact, and that is what we are showing the world.

7. **Do you store the materials in a warehouse, or do you look for direct buyers and re-distribute?**
   Our materials are not virgin materials, and they still have a function. So what we do is add value to and do the work. So the producers do not need to buy virgin materials and get materials for their production from us. We do not have to store the material because we have appointments with the producers on a certain quality. So, producers take the material into their storage.

8. **What happens to the material that does not find the user?**
   We have to take the materials in the traditional way. So we try to find solutions for every material, but we have not found the solutions for everything. That is how we also developed our collective. We started in 2017 with 13 organizations, and at this moment, we have 25 organizations.

9. **What is the time required in the process, and what additional facilities are needed?**
   It takes no longer, not more expensive, much more fun, and more circular. When it takes no longer and not more expensive, then owners do not need to have a circular ambition to give the order to us. No other facilities, but other protocols and instructions to the demolishers. We need to develop a new profession - urban mining, and we are working on it for six years now.

10. **Do you have a tool or software to identify what materials can be harvested in a building?**
    In the last years, we worked on a database of all the information we have about the materials. We can make an indication of how many materials will come from a building, from a house, or from an office, or from a store, or from a hospital. It is all different, but we created a database so we can make an indication of what we will harvest. We know the different materials and different sources of real estate.

11. **In what way do you expect product passports to improve or streamline your current processes, and what information should they contain, especially for building facades?**
    We make a harvestkart, and it is like a material passport. But a material passport, we think, is important in new buildings than in existing buildings because in the past we never built to take back and for the future, we want to build to take back. So for the future, it is more useful to know what kind of materials are there in the building. For the existing buildings, we have our database, and we know what is useful and not. We did not build to take back in the past, so it is a struggle for us, and together with our partners, we are solving those struggles.

12. **Who looks into the challenges of harvesting materials that were not designed for reuse?**
    It is our role to look at those challenges. We are looking for organizations in the market that can solve those problems we have now and make a solution to make something new. Maybe the architect can creatively use the material. Our role is to make the solution, make a difference, and transition to a circular economy. When we have found an organization/architect who wants material, it is our role to give the instructions to demolishers. We also organize urban mining games with organizations. We go to a house/office that is going to be demolished, and together with the people, we ask them what they can use in your project just to make them aware of the fact that material in the existing buildings has a worth. That is our added value that we can bring back materials, and we make people aware of that.

Blonkstaal Metal Workers
Interviewee: Martijn Blonk, Renee Schuurman
Date: 11.03.2021
Purpose of the interview: To identify how secondary materials can be remanufactured into new façades. The facade manufacturer has already worked with ODS for a reuse project and has experience with secondary materials.

1. **What is your role as a façade engineering company?**
   We have some engineers who make technical drawings for the customers. If the customer approves, then drawings are used to build the façade in our factory. After that, we have our own contractors who build and install the façade on location as per our technical drawings.

2. **What was the intent for remanufacturing the façade for The Field project in Leiden?**
   Ron Jacobs from ODS came to us with the project saying that we have an old façade from Brussels that we can use for the project in Leiden. We made some technical drawings for that. They brought all the materials here in the truck at our factory, and we inspected all the materials to see what is good, what we can reuse, and which things we cannot reuse. Some of the parts were damaged. Also, the façade in Brussels was higher and larger than in Leiden, so we cut the good pieces out that we can perfectly reuse.

3. **What instructions did you receive from the architect regarding the façade design?**
   From the architect, we just got a sketch of what they want. And then our draftsmen make the technical drawings from which you can make a façade product with all the details.

4. **What proportion of the façade could you reuse for the project?**
   We reused 100% steel from the available lot. All we bought new was two pieces of glass. All the steel profile, locks, and other accessories were reused.

5. **How do you inspect damages in the secondary material?**
   We visually check the façade for damages and corrosion. The powder coating was good, so it did not require any coating.

6. **How do you usually change the coatings for secondary materials?**
   We powder coat the façade again. For this, it goes into a solder bath, and the old coating comes off. Then it goes into a cabin where the new coating is sprayed. It again comes with a minimum ten years guarantee for corrosion. Also, the powder coating is build of three layers - a layer of zinc, a layer of color, and then a layer of definite color.

7. **Did you redesign the connections for the façade?**
   We reused all the old connections. At some points, we made some extra holes in it. We can get new bolts to place in it, but all the other connection points we resued.

8. How do you provide a warranty for the secondary façade?
   We check the façade and build it from our drawings. All the facades, doors, windows are tested like a system is tested with a maximum of height, length, and width. Then the draftsman checks if it is not too big and into the proportion of the dimensions of the test. We only draw what is tested. We make everything from the drawing, so we can always lay back on the test. We can say this façade is tested from 'there' for 'that' dimensions. So we can get a guarantee of the façade construction by the test, and then we can guarantee the powder coating.

9. **Is this testing for primary materials or secondary?**
   The testing is for primary materials, but we reuse only those materials that we can also buy new. So we know what the quality is; we know if it is good or not good. When we have a stock of reused materials, and it is not enough for a façade, we can buy one or two new pieces, and we can together make a whole new façade. For some projects, you do not have enough reuse materials, but you can say like, 80% façade is

reused, and 20% is new. So then you do not have to buy a 100% new facade. If it is possible, make a 100% reused facade, but if not, you can make a combination.

10. **What is the process for remanufacturing façade?**
    There are two ways. When you build something and say you want a façade from reused materials, then you check the dimensions and look where you can find the stock of material to make this from. With the stock of material, you can say if it is enough to build. But it is very difficult to identify what you can reuse out of that stock. For example, if you reuse the glass, you will check if it fits, what type of glass you need, and if that is available, what kind of state it is in. The tricky part is the facade is always build to resist the wind loads, and the higher the facade, the bigger the profiles need to be. So you always need to have information about the size of the facade, the wind loads, how many doors do I need in it, and then you can look at the stock of materials you can reuse.
    But if you have a drawing from the architect and say what they want, we must look if we have our own batch of materials for reuse. Then we make our own technical drawing, and we get it into the factory. We dismantle the façade, cut the pieces to the required dimensions, lay them together, weld them, and grind them. We then build it up here in the factory. If it is all good, it goes to the powder coater to get off the old layer of coating and finish with a new layer of powder coating. Then we build it in the factory together with locks (accessories), gaskets, rubbers. At the location, we finally install it.

11. **What are the added challenges with secondary materials over primary?**
    The profile dimensions are checked if they are suitable for wind loads, if it is high enough, or if the dimensions are suitable. Can you make all the connections with the reused profiles, and is it possible to reuse the old material with some new material.

12. **Do you provide additional certificates for the reused façade?**
    Now, it does not require a certificate. But I think, in the future, it will be a good thing to distinguish your company through these certifications.

13. **What about the performance of the reused façade? How do you assign a lifespan?**
    The lifespan will be the same as you get the façade with a new layer of powder coating on it and is designed according to wind load. We inspect the material visually, and if there is no corrosion, you can use it for the same lifespan.

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14. **What are the additional efforts required for reusing secondary materials?**
    Savings are a lot because you do not have to manufacture the base material. But you do have to transport material to our place and then to the new location. It also adds to the time, because otherwise you just order in 5 minutes and they bring it here, and that is it. And because it is starting, you need to see if you can have enough stock of reused materials to produce the entire façade. So it needs some more time now because it all starting. But maybe, if ordering from ODS, we can order not only new but reused materials. Then you can say that you first want to have reused products and see if that's enough to make the things we want, and then we can order the new ones. But now it is more challenging as it all starting up. It takes a lot of time and physical energy.

15. **If I design a façade with reused components, what product performance criteria will be necessary to make it suitable for the market?**
    There is nothing different when you make a façade from reused materials than new materials. The only thing is you need to get off the old layers of coating, glue, and old connections. But that's the only thing that makes it different from new material. The good thing is they do not have to make the new materials, but you do need to clean them before you can reuse them.

16. **How do you remove the old connections and welds that are not compatible with the fixing system available now?**
    We cut off the welded connections, and with our machinery, we make new connections with bolts. They do this while engineering the façade, they make the technical drawings to remove these old connections, and

we get a new type of coupling at that point that we can make with bolts. The other thing we do is simply get it off, and then you do not have to cut it. You simply unbolt or unscrew to get it off each other.

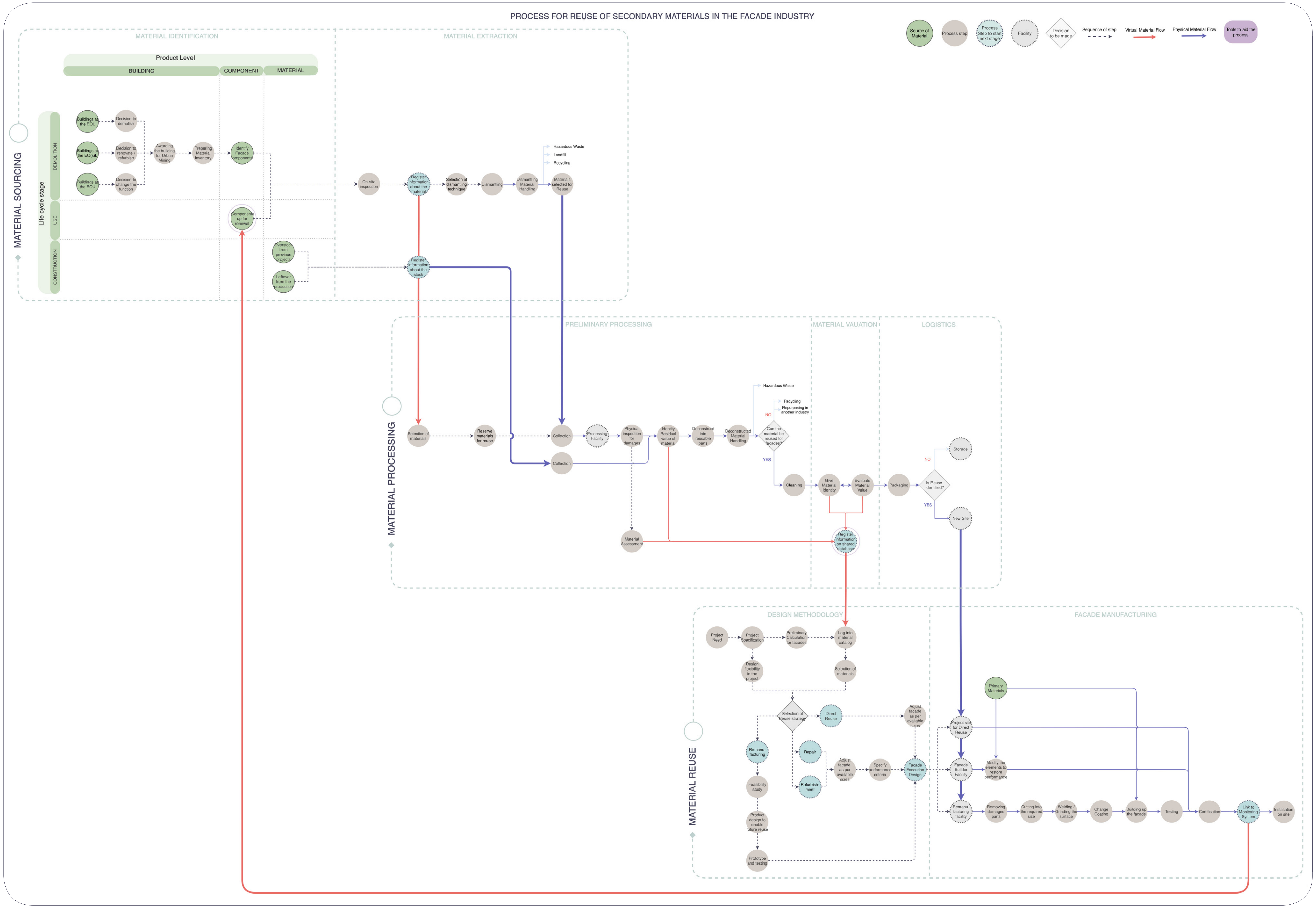
17. **What is the difference when between repairing and remanufacturing a façade?**
There are two different kinds of reuse. We prefer to repair or make some changes to give it a longer life, instead of making a new one. It cuts down the cost, and the customer can get a facade not for 10 or 15 years but 30 or 40 years. You also do not have to transport from site to our factory and back to the site. When you have a façade on a location, and they say we want to make two doors or make it higher, then we think you can better repair it according to the new wishes of the client for another 10-15 years. I think it is better than taking it out from a building, and remake a new product out of it and install it on another building. But there are also a lot of buildings that will demolish. The facade sitting in those buildings, you can reuse all the suitable materials from it.

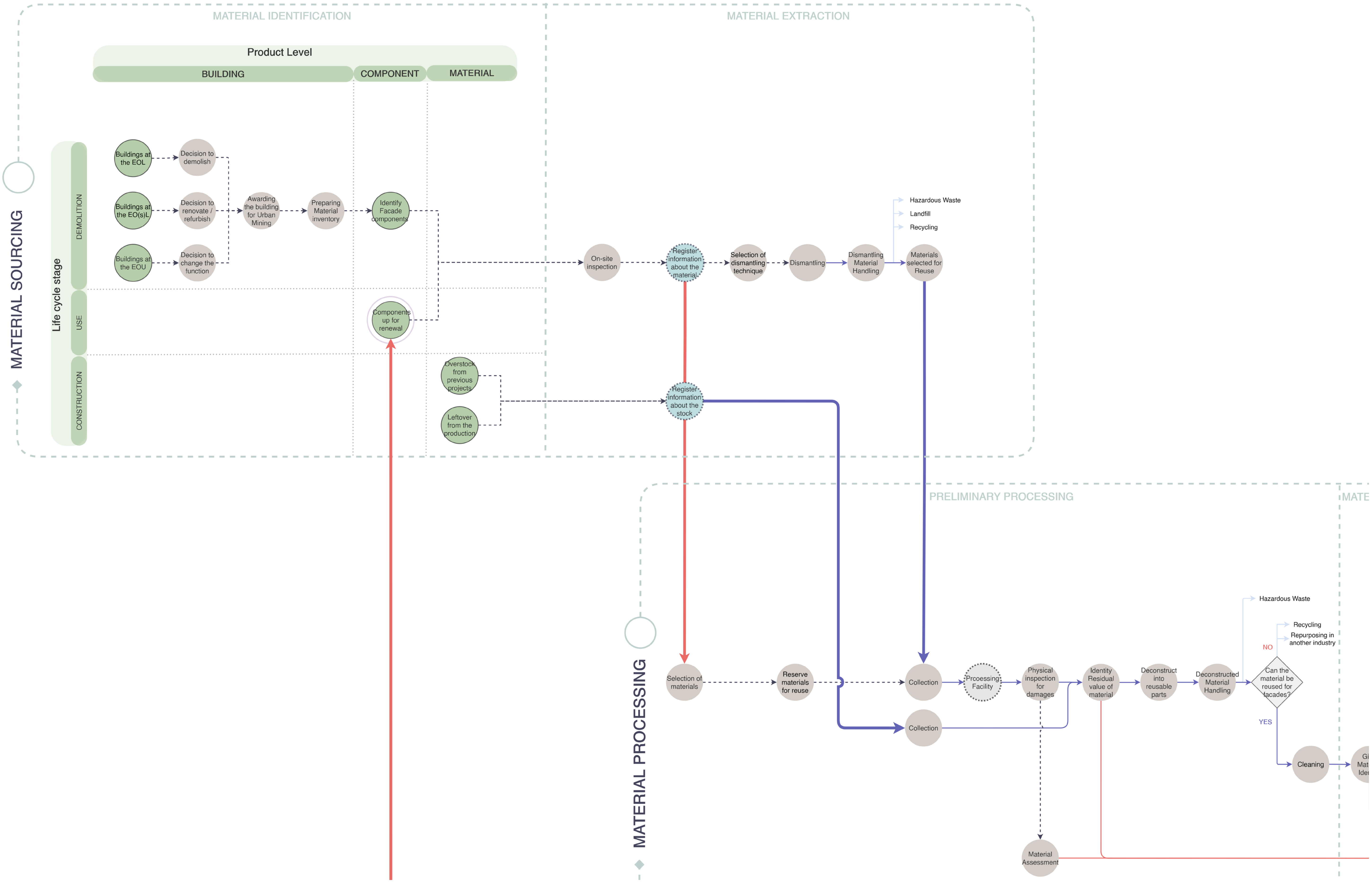
18. **Does monitoring the façade during its use phase help in its reuse?**
Yes, that helps us a lot when a facade is monitored for a few years. Because then you can see which profiles or pieces of the facade are good for reuse and which pieces are already at the end of their life.

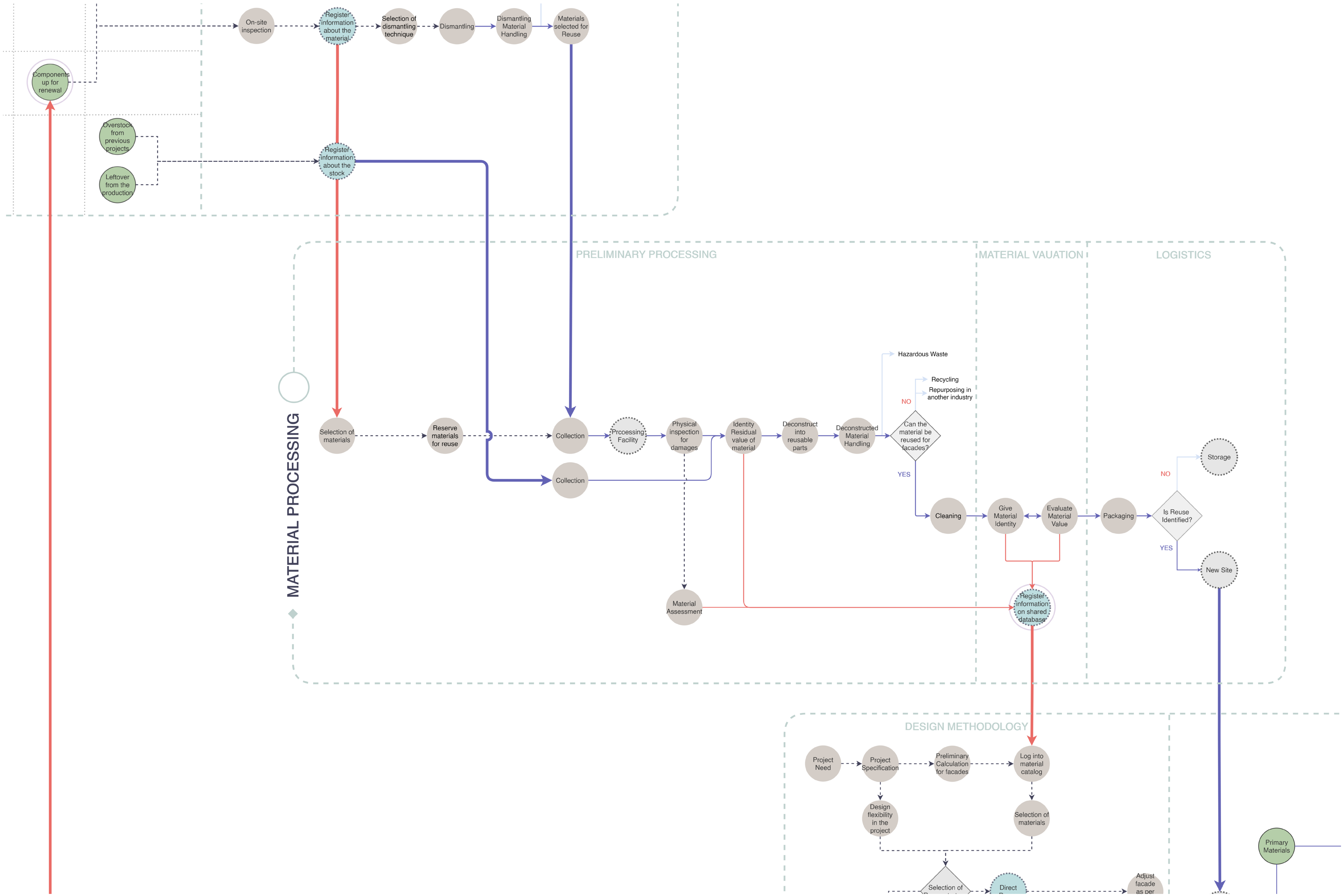
19. **Can you also manufacture a façade with a combination of steel and timber?**
Yes, I think for a whole façade, the framed construction on the outside can be wood. But for the façade, it is better only to use steel. Because, to make the seals for the air-tightness, it is better to have one material. The rebate for installing glass is different for different materials. It is very thick for wood than steel. If it is not the same on all sides of the glass, then you will not get an air-tight façade. It is difficult to make it, like, for example, if you have mullion in steel and transom in wood.

20. **How do you evaluate the cost of reused materials?**
It is very difficult to get a price on reused material because it does not have to be high or the same as the new material. For example, if you have to get off the old coatings, then there is a lot more handling than when you buy a new profile. So it costs more to make a product out of it. So I think the cost of reused materials needs to be very low.

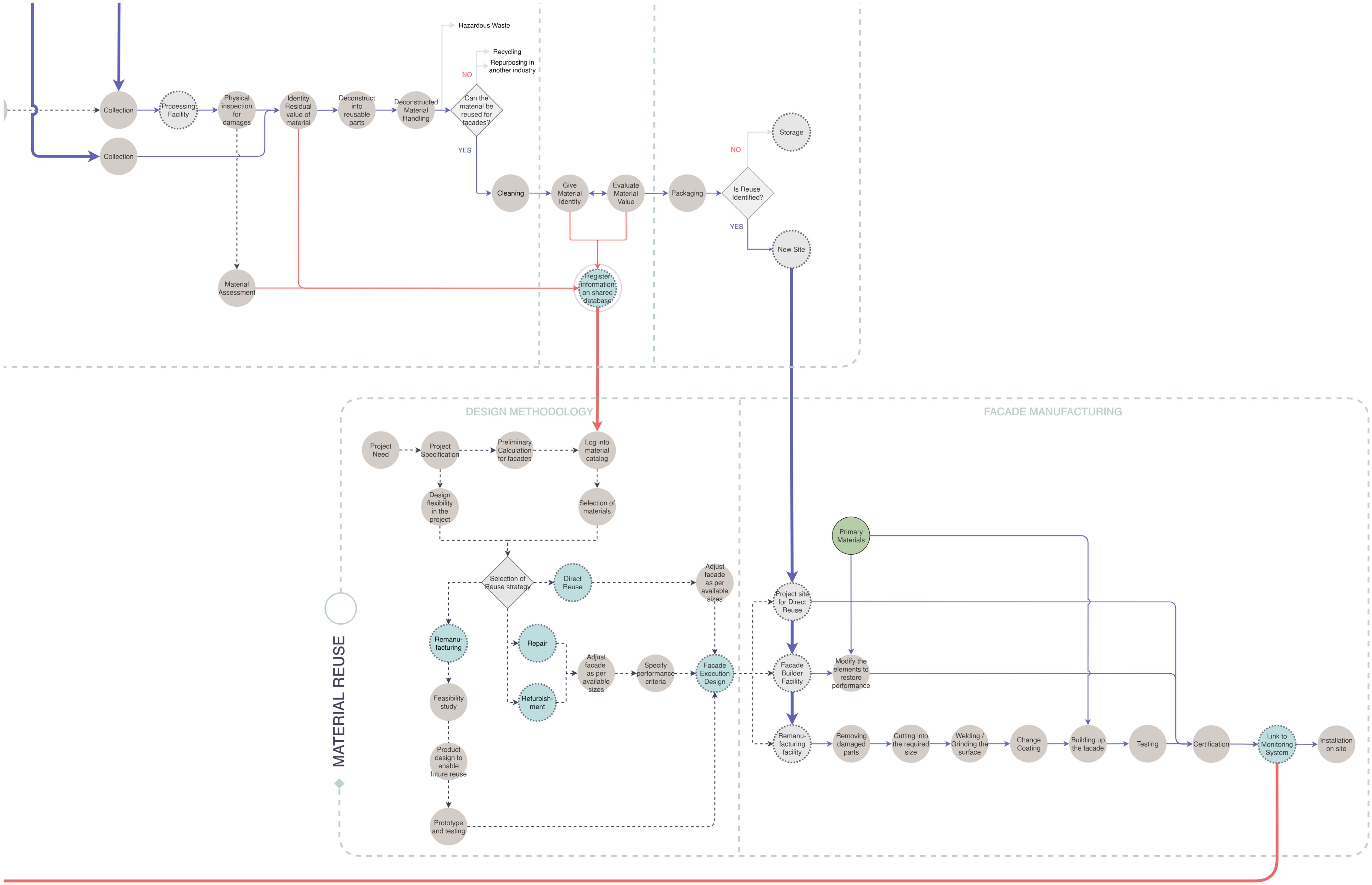
Appendix B - Reuse Process




MATERIAL SOURCING
MATERIAL IDENTIFICATION
MATERIAL EXTRACTION
Product Level
BUILDING
COMPONENT
MATERIAL
Life cycle stage
DEMOLITION
USE
CONSTRUCTION
Buildings at the EOL
Decision to demolish
Buildings at the EO(s)L
Decision to renovate / refurbish
Buildings at the EOU
Decision to change the function
Awarding the building for Urban Mining
Preparing Material inventory
Identify Facade components
Components up for renewal
Overstock from previous projects
Leftover from the production
On-site inspection
Register information about the material
Selection of dismantling technique
Dismantling
Dismantling Material Handling
Materials selected for Reuse
Hazardous Waste
Landfill
Recycling
Register information about the stock
MATERIAL PROCESSING
PRELIMINARY PROCESSING
MATE
Selection of materials
Reserve materials for reuse
Collection
Collection
Processing Facility
Physical inspection for damages
Identity Residual value of material
Deconstruct into reusable parts
Deconstructed Material Handling
Can the material be reused for facades?
NO
YES
Hazardous Waste
Recycling
Repurposing in another industry
Cleaning
Material Assessment



Components up for renewal
Overstock from previous projects
Leftover from the production
On-site inspection
Register information about the material
Selection of dismantling technique
Dismantling
Dismantling Material Handling
Materials selected for Reuse
Register information about the stock
MATERIAL PROCESSING
PRELIMINARY PROCESSING
MATERIAL VAUATION
LOGISTICS
Selection of materials
Reserve materials for reuse
Collection
Collection
Processing Facility
Physical inspection for damages
Identity Residual value of material
Deconstruct into reusable parts
Deconstructed Material Handling
Hazardous Waste
Recycling
Repurposing in another industry
NO
Can the material be reused for facades?
YES
Cleaning
Give Material Identity
Evaluate Material Value
Packaging
Is Reuse Identified?
NO
Storage
YES
New Site
Material Assessment
Register information on shared database
DESIGN METHODOLOGY
Project Need
Project Specification
Preliminary Calculation for facades
Log into material catalog
Design flexibility in the project
Selection of materials
Direct
Primary Materials


Hazardous Waste
Recycling
Repurposing in another industry
NO
Collection
Prcoessing Facility
Physical inspection for damages
Identity Residual value of material
Deconstruct into reusable parts
Deconstructed Material Handling
Can the material be reused for facades?
YES
Collection
Cleaning
Give Material Identity
Evaluate Material Value
Packaging
Is Reuse Identified?
NO
Storage
YES
New Site
Material Assessment
Register information on shared database
DESIGN METHODOLOGY
FACADE MANUFACTURING
MATERIAL REUSE
Project Need
Project Specification
Preliminary Calculation for facades
Log into material catalog
Design flexibility in the project
Selection of materials
Selection of Reuse strategy
Direct Reuse
Adjust facade as per available sizes
Remanu-facturing
Repair
Refurbish-ment
Adjust facade as per available sizes
Specify performance criteria
Facade Execution Design
Feasibility study
Product design to enable future reuse
Prototype and testing
Primary Materials
Project site for Direct Reuse
Facade Builder Facility
Modify the elements to restore performance
Remanu-facturing facility
Removing damaged parts
Cutting into the required size
Welding / Grinding the surface
Change Coating
Building up the facade
Testing
Certification
Link to Monitoring System
Installation on site

Appendix C - Structural Calculations

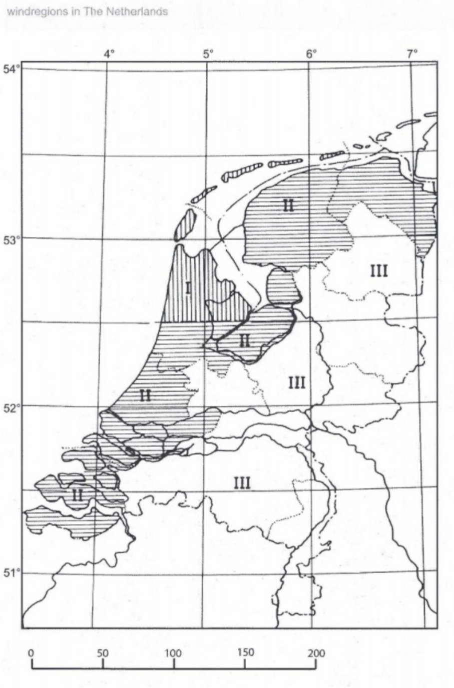
The mullion is mainly subjected to the horizontal pressure of the wind, uniformly distributed along its length, and to the vertical forces of its own weight and the load of the glass and panels. To confirm the correct resistance of the section, σtotal (calculated stress) must be shown to be less than the σadm (permitted stress) of the aluminium, and the deflection from the application of these loads should not exceed the values set out in the standards (Mestre and Calderón, 2007). According to the European Product Standard EN 13830, the maximum deflection of the rigid components of a lightweight façade should not exceed values of L/200, or 15mm, when exposed to the force of the wind. All the formula mentioned are taken from Design of Lightweight Facades Handbook by Mestre and Calderon (2007).

The cross resistance of the section is checked using:

$$\frac{M^*}{W} \leq \sigma^*_{adm}$$

The maximum deflection is calculated using:

$$f_{max} = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I_x} \quad (*)$$



peak velocity pressure

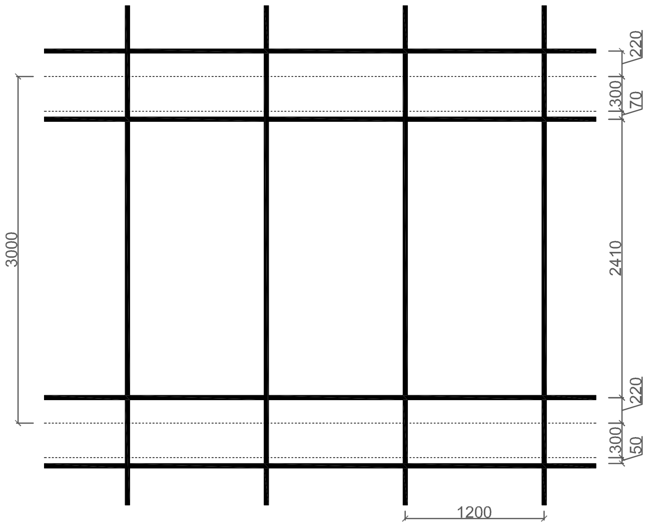
z_e [m]	Area I Coastal	$q_p(z_e)$ [kN/m²] Rural	Urban	Area II Coastal	Rural	Urban	Area III Rural	Urban
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0.49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58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

Figure 86 - (left) Wind zone in the Netherlands, and (right) Peak Velocities at different levels (source: Quick Reference, edition 2014)

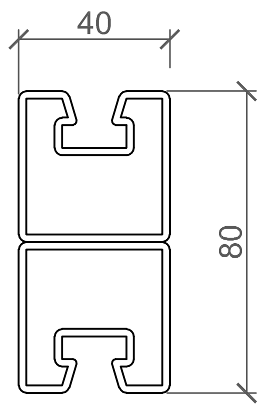
Designed Façade (from secondary stream)

Designed Facade						
Material	**Quantity**	**Cross section area (m2)**	**Length (m)**	**Volume (m3)**	**Density (kg/m3)**	**Mass (kg)**
Steel mullion	2	0.000379	3	0.002274	7900	17.964600
Steel transom	2	0.000379	1.16	0.000879	7900	6.946312
Steel mullion (additional)	2	0.000379	3	0.002274	7900	17.964600
Low e-Glass (6-14-8)	1	2.4 x 1.2		0.040300	2500	100.750000
Glazing Bead	1	0.000103	7.9	0.000814	2710	2.205127
Polyamide Thermal Break	2	0.000266	4.16	0.002213	1020	2.257382
EPDM Gaskets	2	0.000263	4.16	0.002188	850	1.859936
Aluminium cover cap	2	0.000098	4.16	0.000815	2710	2.209626
Aluminium pressure plate	2	0.000114	4.16	0.000948	2710	2.570381
					Total	154.727964

Case: Checking the designed façade with secondary materials for the loads acting on the mullion:



L = 300cm
a = 120cm
b = 241cm



Structural calculations for the Designed Facade			
N*	Increased normal force due to own weight and weight of the panel	154.728	daN
A	Cross sectional area	7.58	cm2
Ixx	Second moment of area about X-axis	44.711	cm4
Iyy	Second moment of area about Y-axis	15.46	cm4
y	Max. distance from neutral axis	4	cm
Wxx	Resistance module of the cross-section (*Ixx*/y)	11.1778	cm3
Q	Total wind load	56	daN/m2
q	Force of wind uniformly ditributed (Qxa)	0.672	daN/cm
M	Increased deflection moment due to wind (qL^2/8)	7560	cm-daN
E steel	Modulus of Elasticity	2100000	daN/cm2
	Condition 1 : σ *total* (calculated stress) must be less than the σ *adm* (permitted stress) of the steel		
M*	Service moment calculation (load increase coefficient x M)	7560	cm-daN
σ adm	Tensile stress	2500 - 3950	daN/cm2
σ total	**Calculated stress = M* / W**	**676.34363**	**daN/cm2**
σ adm	Max. permitted stress (with a safety factor of 2)	1250- 1975	daN/cm2
	Condition 2 : checking the maximum deflection must be less than f *max or 1.5cm (as per codes)*		
f *max*	Maximum allowable deflection (L/15)	2	cm
f *total*	**Calculated deflection**	**0.75485**	**cm**
f *max*	Permited by codes	1.5	cm

Figure 87 - Calculations for the facade designed with secondary materials (source: author)

Reference façade (from primary stream)

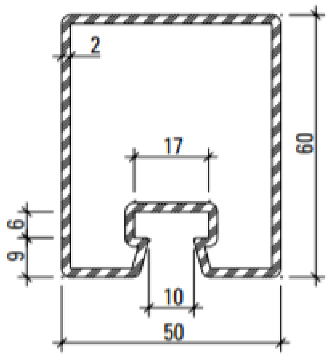
Case: For the same loading condition of the glass, calculating the size of the mullion required if designed with primary stream:

Calculation the moment for the cross section using,

$$I \geq \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot f}$$

Selected the profile from Jansen catalog,

Profil-Nr.	G kg/m	F cm²	Ix cm⁴	Wx cm³	Iy cm⁴	Wy cm³	U m²/m	L mm
76.094	4,090	5,2	15,2	5,8	15,2	5,8	0,280	6000
76.096	7,437	9,5	83,8	20,5	83,8	20,5	0,391	6000
76.666	7,910	10,1	241,3	32,3	43,7	17,5	0,412	6500
76.671	3,860	4,9	23,3	7,2	17,3	6,9	0,260	6500
76.679	7,120	9,1	162,2	25,2	37,9	15,2	0,373	6500
76.680	3,390	4,3	3,2	2,4	11,1	4,4	0,182	6100
76.682	2,120	2,7	2,2	1,7	7,2	2,9	0,190	6000
76.692	1,900	2,5	0,9	1,0	5,9	2,4	0,176	6000
76.694	3,500	4,5	14,7	5,6	15,0	6,0	0,240	6500
76.696	4,450	5,7	47,6	11,1	21,9	8,8	0,300	6500
76.697	6,100	7,9	90,2	17,6	31,0	12,4	0,330	6500
76.105	5,190	6,6	97,6	13,6	22,7	9,1	0,338	6000
76.114	3,820	4,9	15,4	4,1	9,8	3,9	0,251	6000
76.115	4,920	6,3	54,8	9,3	10,4	4,2	0,321	6000
76.116	5,710	7,3	105,0	14,3	10,8	4,3	0,371	6000



76.671

Figure 88 - (left) Cross section details of available facade products and (right) selected profile (source: Jansen VISS-Fassade-LP)

Rechecking the cross section of the selected profile using,

$$\frac{M^*}{W} \leq \sigma^*_{adm}$$

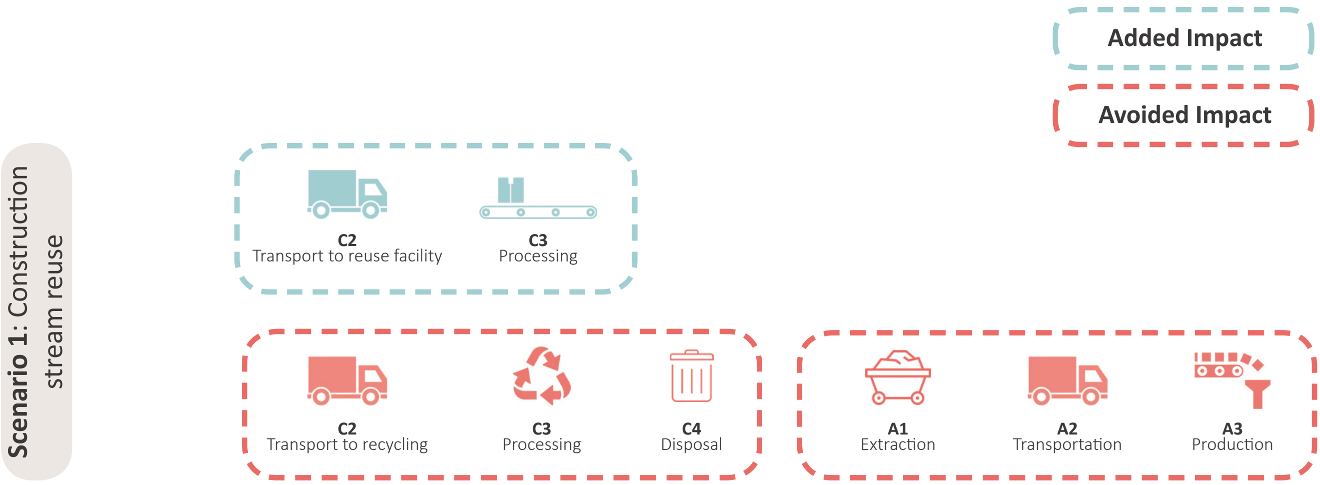
	Structural calculations for the selected the mullion from primary stream		
Q	Total wind load	56	daN/m2
q	Force of wind uniformly ditributed (Qxa)	0.672	daN/cm
E steel	Modulus of Elasticity	2100000	daN/cm2
f *max*	Permited by codes	1.5	cm
	Condition 1 : checking moment for selection of cross-section for mullion		
Ixx total	**Calculated moment**	**20.2817**	**cm4**
Profile selected from Jansen Catalog (76.671)			
Ixx	Moment of the selected profile	23.3	cm4
Wxx	Resistance module of the selected profile	7.2000	cm3
	Condition 1 : σ total (selected profile) should be less than σ adm		
M*	Service moment calculation	7560	cm-daN
σ adm	Tensile stress	2500 - 3950	daN/cm2
σ total	**Calculated stress = M* / W**	**1050.00**	**daN/cm2**
σ adm	Max. permitted stress (with a safety factor of 2)	1250- 1975	daN/cm2

Figure 89 - Calculation for identifying the mullion size from primary stream (source: author)

Appendix D - Environmental Impact Assessment

Design Scenario 1: Reuse of Construction Stream

Primary Renewable Energy (PERE) + Primary Non-Renewable Energy (PENRE) in MJ



Designed facade with secondary materials										Substituted EOL			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Dismantling (MJ)	Transportation to reuse facility (MJ)	Deconstruction (MJ)	Processing (MJ)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	12.935	0	88.69392
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	3.875677	1.419929985	0	5.001	0	34.2949824
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	12.935	0	88.69392
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.301385	81.3898545				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.230345	1.314026282				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.259501	3.573918944				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.619491	2.109418324				
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.232855	1.316706979				
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.434138	1.531679547				
					Percentage of secondary components			23.92228481	8.764395427	0	30.870	0	211.6828224
									Total (MJ)				243

Designed facade with secondary materials										Avoided Module C			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (MJ)	C2 Transportation to waste processing (MJ)	C3 Waste processing for recycling (MJ)	C4 Disposal (MJ)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	3.234	323.3628	3.59292
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	3.875677	1.419929985	0	1.250	125.033616	1.3892624
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	3.234	323.3628	3.59292
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.301385	81.3898545				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.230345	1.314026282				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.259501	3.573918944				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.619491	2.109418324				
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.232855	1.316706979				
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.434138	1.531679547				
					Percentage of secondary components			23.92228481	8.764395427	0	7.718	771.759216	8.5751024
									Total (MJ)				788

Reference Design Facade											Avoided Module A	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	A1 Extraction (MJ)	A2 Transportation (MJ)	A3 Production (MJ)
Steel mullion (galvanized)	Primary	2	0.00062	3	0.00372	7900	29.39	16.593623	6.033544561		1551.09864	
Steel transom (galvanized)	Primary	2	0.00062	1.16	0.0014384	7900	11.36	6.416201	2.332970564		599.7581408	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	71.144566	81.74479728			
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.245102	1.319756777			
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.274607	3.589504876			
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.626921	2.11861754			
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.247642	1.322449165			
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.451338	1.538359233			
										Total (MJ)		2150.86

Design Scenario 1: Reuse of Construction Stream

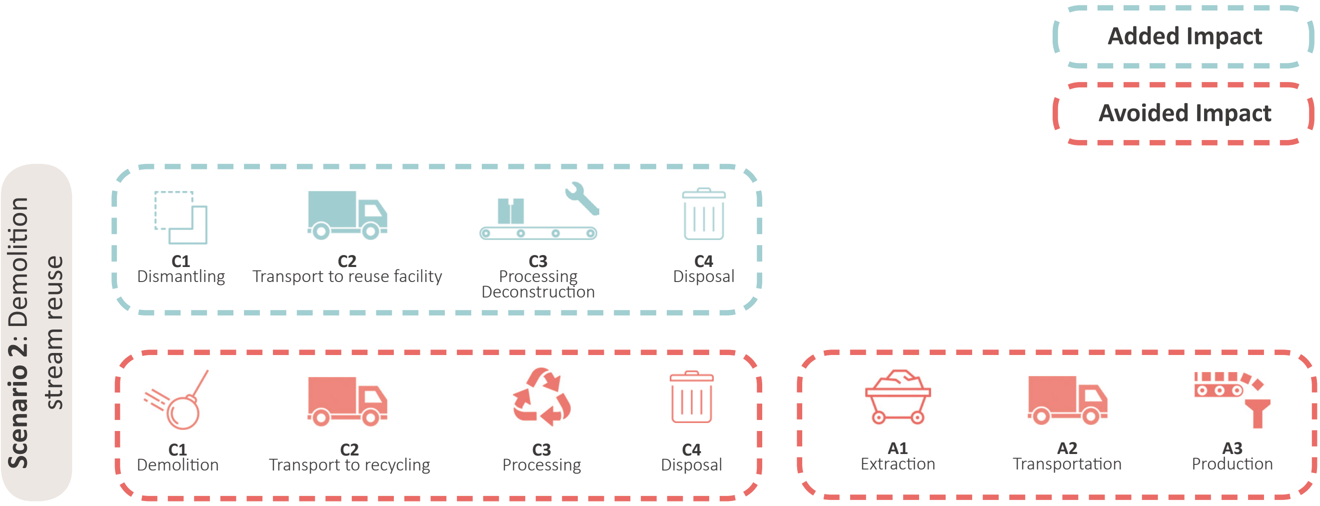
Global Warming Potential in CO2kgeq.

Designed facade with secondary materials										Substituted EOL			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Dismantling (CO2kg)	Transportation to reuse facility (CO2kg)	Deconstruction (CO2kg)	Processing (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	0.934	0	4.80984
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	3.875677	1.419929985	0	0.361	0	1.8598048
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	0.934	0	4.80984
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.301385	81.3898545				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.230345	1.314026282				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.259501	3.573918944				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.619491	2.109418324				
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.232855	1.316706979				
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.434138	1.531679547				
					Percentage of secondary components			23.92228481	8.764395427	0	2.230	0	11.4794848
									Total (CO2kg)				14

Designed facade with secondary materials										Avoided Module C			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (CO2kg)	C2 Transportation to waste processing (CO2kg)	C3 Waste processing for recycling (CO2kg)	C4 Disposal (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	0.234	26.8391124	0.02515044
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	3.875677	1.419929985	0	0.090	10.37779013	0.0097248368
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.023304	3.672232721	0	0.234	26.8391124	0.02515044
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.301385	81.3898545				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.230345	1.314026282				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.259501	3.573918944				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.619491	2.109418324				
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.232855	1.316706979				
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.434138	1.531679547				
					Percentage of secondary components			23.92228481	8.764395427	0	0.557	64.05601493	0.0600257168
									Total (CO2kg)				65

Reference Design Facade										Avoided Module A		
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	A1 Extraction (CO2kg)	A2 Transportation (CO2kg)	A3 Production (CO2kg)
Steel mullion (galvanized)	Primary	2	0.00062	3	0.00372	7900	29.39	16.593623	6.033544561		113.1438	
Steel transom (galvanized)	Primary	2	0.00062	1.16	0.0014384	7900	11.36	6.416201	2.332970564		43.748936	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	71.144566	81.74479728			
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.245102	1.319756777			
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.274607	3.589504876			
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.626921	2.11861754			
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	1.247642	1.322449165			
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	1.451338	1.538359233			
										Total (CO2kg)		156.89

Design Scenario 2: Reuse of Demolition Stream



Primary Renewable Energy (PERE) + Primary Non-Renewable Energy (PENRE) in MJ

Designed facade with secondary materials										Substituted EOL				
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Dismantling (MJ)	Transportation to reuse facility (MJ)	Deconstruction (MJ)	Processing (MJ)	Waste processing for remaining material (MJ)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.643763	3.131792264	7.7607072	12.935	0.78505302	88.69392	
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.115588	1.210959675	3.000806784	5.001	0.3035538344	34.2949824	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	74.653160	69.41175466					
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.306506	1.120641761					
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.337466	3.047947271					
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.657839	1.798976397					
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.309171	1.122927942	0.9545582592	1.591	0.09656063872	97.8891264	50.37946368
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.522913	1.306263116	1.110404506	1.851	0.112325641	80.9467776	29.30234112
Timber (Douglas)	Secondary	2	0.0024	2.7	0.01296	580	7.52	4.453594	17.84873691	1.3229568	5.412	0.32848416	0	0
					Percentage of secondary components			22.04502972	24.62067991	**14.149**	**26.790**	**1.625977294**	**301.8248064**	**79.6818048**
									Total (MJ)					**424.072**

Designed facade with secondary materials										Avoided Module C			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (MJ)	C2 Transportation to waste processing (MJ)	C3 Waste processing for recycling (MJ)	C4 Disposal (MJ)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.643763	3.131792264	4.293539	3.234	341.3274	1.79646
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.115588	1.210959675	1.660169	1.250	131.979928	0.6946312
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	74.653160	69.41175466				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.306506	1.120641761				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.337466	3.047947271				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.657839	1.798976397				
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.309171	1.122927942	0.528101	0.398	118.3917396	0.265155072
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.522913	1.306263116	0.614321	0.463	137.7210033	0.308445696
Timber (Douglas)	Secondary	2	0.0024	2.7	0.01296	580	7.52	4.453594	17.84873691	2.427926	1.353	0.32848416	
					Percentage of secondary components			22.04502972	24.62067991	**9.524056**	**6.697389**	**729.748555**	**3.064692**
									Total (MJ)				**749.034692**

Reference Design Facade										Avoided Module A		
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Fraction of material from reuse	Percentage of share by volume	A1 Extraction (MJ)	A2 Transportation (MJ)	A3 Production (MJ)
Steel mullion (galvanized)	Primary	2	0.00062	3	0.00372	7900	29.39	1.00	6.033544561		1551.09864	
Steel transom (galvanized)	Primary	2	0.00062	1.16	0.0014384	7900	11.36	1.00	2.332970564		599.7581408	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00		81.74479728			
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21		1.319756777			
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26		3.589504876			
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11		2.11861754			
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	0.6	1.322449165		302.2767821	
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	0.8	1.538359233		468.8374579	
										Total (MJ)		**2921.971021**

Design Scenario 2: Reuse of Demolition Stream

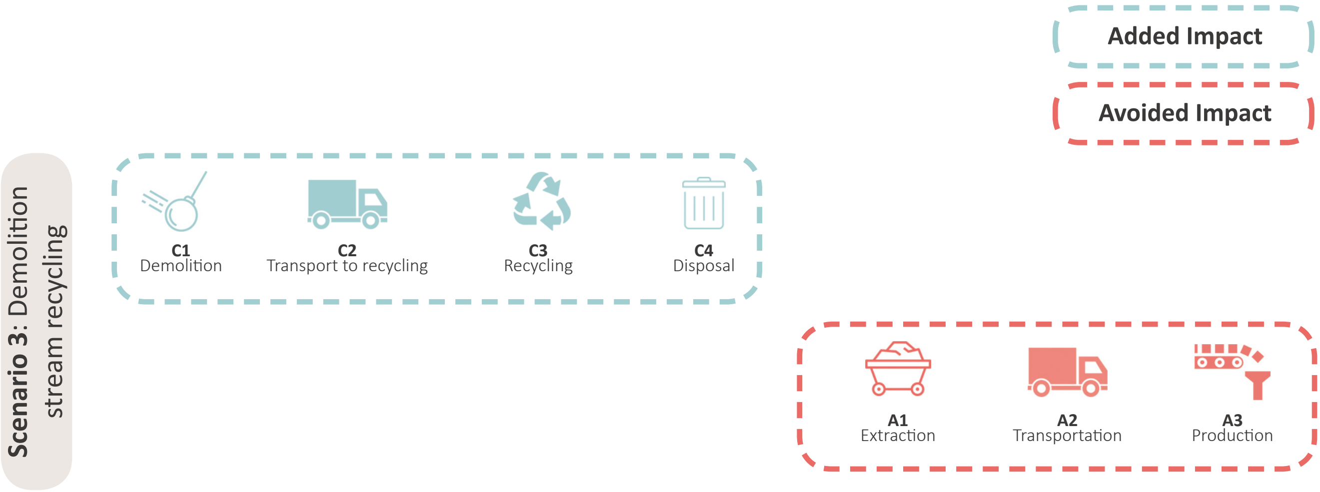
Global Warming Potential in CO2kgeq.

Designed facade with secondary materials										Substituted EOL				
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Dismantling (CO2kg)	Transportation to reuse facility (CO2kg)	Deconstruction (CO2kg)	Processing (CO2kg)	Waste processing for remaining material (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.643763	3.131792264	0.5748672	0.934	0.05748672	4.80984	
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.115588	1.210959675	0.222281984	0.361	0.05748672	1.8598048	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	74.653160	69.41175466					
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.306506	1.120641761					
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.337466	3.047947271					
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.657839	1.798976397					
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.309171	1.122927942	0.0707080192	0.115	0.00707080192	5.3084928	3.97732608
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.522913	1.306263116	0.0822521856	0.134	0.00822521856	4.3897152	2.31334272
Timber (Douglas)	Secondary	2	0.0024	2.7	0.01296	580	7.52	4.453594	17.84873691	0.0977184	0.391	0.02405376	0	
					Percentage of secondary components			22.04502972	24.62067991	**1.048**	**1.935**	**0.1543232205**	**16.3678528**	**6.2906688**
									Total (MJ)					**25.795**

Designed facade with secondary materials										Avoided Module C			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (CO2kg)	C2 Transportation to waste processing (CO2kg)	C3 Waste processing for recycling (CO2kg)	C4 Disposal (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	10.643763	3.131792264	0.323363	0.234	28.3301742	0.01257522
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.115588	1.210959675	0.125034	0.090	10.95433402	0.0048624184
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	74.653160	69.41175466				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.306506	1.120641761				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.337466	3.047947271				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.657839	1.798976397				
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.309171	1.122927942	0.039773	0.029	9.346716288	0.001856085504
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.522913	1.306263116	0.046267	0.033	10.87271078	0.002159119872
Timber (Douglas)	Secondary	2	0.0024	2.7	0.01296	580	7.52	4.453594	17.84873691	0.180403	0.098	0.02405376	
					Percentage of secondary components			22.04502972	24.62067991	**0.714840**	**0.483700**	**59.527989**	**0.021453**
									Total (MJ)				**60.747982**

Reference Design Facade										Avoided Module A		
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Fraction of material from reuse	Percentage of share by volume	A1 Extraction (CO2kg)	A2 Transportation (CO2kg)	A3 Production (CO2kg)
Steel mullion (galvanized)	Primary	2	0.00062	3	0.00372	7900	29.39	1.00	6.033544561		113.1438	
Steel transom (galvanized)	Primary	2	0.00062	1.16	0.0014384	7900	11.36	1.00	2.332970564		43.748936	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00		81.74479728			
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21		1.319756777			
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26		3.589504876			
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11		2.11861754			
Aluminium cover cap 6060 alloy	Primary	2	0.000098	4.16	0.00081536	2710	2.21	0.4	1.322449165		16.96992461	
Aluminium pressure plate	Primary	2	0.000114	4.16	0.00094848	2710	2.57	0.2	1.538359233		19.74052454	
										Total (CO2kg)		**193.6031852**

Design Scenario 3: Recycling of Demolition Stream



Primary Renewable Energy (PERE) + Primary Non-Renewable Energy (PENRE) in MJ

New Facade										Module C for recycling of materials			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (MJ)	C2 Transportation to waste processing (MJ)	C3 Waste processing for recycling (MJ)	C4 Disposal (MJ)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	11.139889	3.812226552	4.2935394	3.234	341.3274	1.79646
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.307424	1.474060933	1.660168568	1.250	131.979928	0.6946312
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	78.132881	84.49262014				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.367404	1.364119941				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.399808	3.710164831				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.688502	2.18983413				
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.370194	0.010	0.5281005184	0.398	118.3917396	0.265155072
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.593899	1.590070642	0.6143210112	0.463	137.7210033	0.308445696
					Percentage of secondary components			18.411405	6.886358127	**7.096**	**5.344**	**729.4200709**	**3.064691968**
									Total (MJ)				**744.925**

Existing Facade											Avoided Module A		
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Fraction of material in current supply from recycling	A1 Extraction (MJ)	A2 Transportation (MJ)	A3 Production (MJ)
Steel mullion (galvanized)	Secondary	2	0.00062	3	0.00372	7900	29.39	16.422184	5.967511711	0.57		666.9724152	
Steel transom (galvanized)	Secondary	2	0.00062	1.16	0.0014384	7900	11.36	6.349911	2.307437862	0.57		257.8960005	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.409529	80.85015867				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.232238	1.305312978				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.261438	3.550220301				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.620444	2.095430779				
Aluminium cover cap 6060 alloy	Secondary	2	0.000169	4.16	0.00140608	2710	3.81	2.129316	2.255591093	0.4		521.2732262	
Aluminium pressure plate	Secondary	2	0.000125	4.16	0.00104	2710	2.82	1.574938	1.668336607	0.4		385.55712	
										Total (MJ)			**1831.698762**

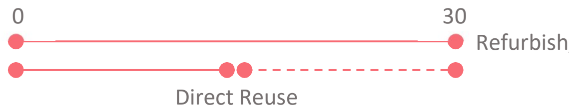
Global Warming Potential in CO2kgeq.

Existing facade										Module C for recycling of materials			
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	C1 Demolition (CO2kg)	C2 Transportation to waste processing (CO2kg)	C3 Waste processing for recycling (CO2kg)	C4 Disposal (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.000379	3	0.002274	7900	17.96	11.139889	3.812226552	0.3233628	0.234	28.3301742	0.01257522
Steel transom (galvanized)	Secondary	2	0.000379	1.16	0.00087928	7900	6.95	4.307424	1.474060933	0.125033616	0.090	10.95433402	0.0048624184
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	78.132881	84.49262014				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.367404	1.364119941				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.399808	3.710164831				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.688502	2.18983413				
Aluminium cover cap 6060 alloy	Secondary	2	0.000098	4.16	0.00081536	2710	2.21	1.370194	0.010	0.0397732608	0.029	9.346716288	0.001856085504
Aluminium pressure plate	Secondary	2	0.000114	4.16	0.00094848	2710	2.57	1.593899	1.590070642	0.0462668544	0.033	10.87271078	0.002159119872
					Percentage of secondary components			18.411405	6.886358127	**0.534**	**0.386**	**59.5039353**	**0.02145284378**
									Total (CO2kg)				**60.446**

New Facade											Avoided Module A		
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	Percentage of share by mass	Percentage of share by volume	Fraction of material in current supply from recycling	A1 Extraction (CO2kg)	A2 Transportation (CO2kg)	A3 Production (CO2kg)
Steel mullion (galvanized)	Secondary	2	0.00062	3	0.00372	7900	29.39	16.422184	5.967511711	0.57		48.651834	
Steel transom (galvanized)	Secondary	2	0.00062	1.16	0.0014384	7900	11.36	6.349911	2.307437862	0.57		18.81204248	
Glass (6-14-8mm)	Primary	1	3.0 x 1.2		0.050400	2500	126.00	70.409529	80.85015867				
Glazing bead	Primary	1	0.000103	7.9	0.0008137	2710	2.21	1.232238	1.305312978				
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.00221312	1020	2.26	1.261438	3.550220301				
EPDM Gaskets	Primary	2	0.000157	4.16	0.00130624	850	1.11	0.620444	2.095430779				
Aluminium cover cap 6060 alloy	Secondary	2	0.000169	4.16	0.00140608	2710	3.81	2.129316	2.255591093	0.4		29.26446182	
Aluminium pressure plate	Secondary	2	0.000125	4.16	0.00104	2710	2.82	1.574938	1.668336607	0.4		21.645312	
										Total (CO2kg)			**118.3736503**

Appendix E - Material Circularity Indicator

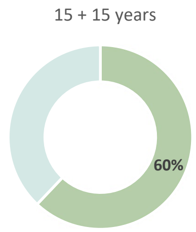
Design Scenario 1: Reuse of Construction Stream



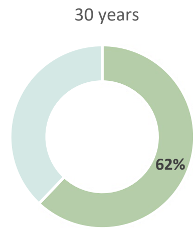
15+15 years

Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Steel transom	Secondary	2	0.000379	1.16	0.000879	7900	6.946312	0	1	0	0.9
Steel mullion (additional)	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Low e-Glass (6-14-8)	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.1	0	0	0.9
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0	0.9
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1020	2.257382	0.1	0	0	0.6
EPDM Gaskets	Primary	2	0.000263	4.16	0.002188	850	1.859936	0.1	0	0	0.6
Aluminium cover cap	Primary	2	0.000098	4.16	0.000815	2710	2.209626	0.44	0	0	0.6
Aluminium pressure plate	Primary	2	0.000114	4.16	0.000948	2710	2.570381	0.44	0	0	0.7

Facade Specification	Recycling Efficiency		Virgin Stock	Unrecoverable Waste			
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	1	0.9	0.000000	1.796460	0	0.000000	1.796460
Steel transom	1	0.9	0.000000	0.694631	0	0.000000	0.694631
Steel mullion (additional)	1	0.9	0.000000	1.796460	0	0.000000	1.796460
Low e-Glass (6-14-8)	0.8	0.25	113.400000	12.600000	0	37.800000	31.500000
Glazing Bead	0.8	0.8	1.234871	0.220513	0	0.242564	0.341795
Polyamide Thermal Break	0.1	0.1	2.031644	0.902953	0	2.031644	1.918775
EPDM Gaskets	0.4	0.1	1.673942	0.743974	0	1.673942	1.580946
Aluminium cover cap	0.8	0.8	1.237390	0.883850	0	0.243059	1.005380
Aluminium pressure plate	0.8	0.8	1.439413	0.771114	0	0.282742	0.912485



Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.050000	75	60	0.80	1.125000	0.94
Steel transom	0.050000	75	60	0.80	1.125000	0.94
Steel mullion (additional)	0.050000	75	60	0.80	1.125000	0.94
Low e-Glass (6-14-8)	0.534884	30	30	1.00	0.900000	0.52
Glazing Bead	0.347932	35	30	0.86	1.050000	0.63
Polyamide Thermal Break	0.714286	40	30	0.75	1.200000	0.14
EPDM Gaskets	0.714286	30	30	1.00	0.900000	0.36
Aluminium cover cap	0.493917	75	60	0.80	1.125000	0.44
Aluminium pressure plate	0.445255	75	60	0.80	1.125000	0.50
	Total					0.603



Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Steel transom	Secondary	2	0.000379	1.16	0.000879	7900	6.946312	0	1	0	0.9
Steel mullion (additional)	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Glass	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.1	0	0	0.9
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0	0.9
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1020	2.257382	0.1	0	0	0.8
EPDM Gaskets	Primary	2	0.000263	4.16	0.002188	850	1.859936	0.1	0	0	0.6
Aluminium cover cap	Primary	2	0.000098	4.16	0.000815	2710	2.209626	0.44	0	0	0.6
Aluminium pressure plate	Primary	2	0.000114	4.16	0.000948	2710	2.570381	0.44	0	0	0.7

30 years

Facade Specification	Recycling Efficiency		Virgin Stock	Unrecoverable Waste			
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	1	0.9	0.000000	1.796460	0	0.000000	1.796460
Steel transom	1	0.9	0.000000	0.694631	0	0.000000	0.694631
Steel mullion (additional)	1	0.9	0.000000	1.796460	0	0.000000	1.796460
Glass	0.8	0.25	113.400000	12.600000	0	37.800000	31.500000
Glazing Bead	0.8	0.8	1.234871	0.220513	0	0.242564	0.341795
Polyamide Thermal Break	0.1	0.1	2.031644	0.451476	0	2.031644	1.467299
EPDM Gaskets	0.4	0.1	1.673942	0.743974	0.000000	1.673942	1.580946
Aluminium cover cap	0.8	0.8	1.237390	0.883850	0	0.243059	1.005380
Aluminium pressure plate	0.8	0.8	1.439413	0.771114	0	0.282742	0.912485

Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.050000	75	75	1.00	0.900000	0.96
Steel transom	0.050000	75	75	1.00	0.900000	0.96
Steel mullion (additional)	0.050000	75	75	1.00	0.900000	0.96
Glass	0.534884	30	30	1.00	0.900000	0.52
Glazing Bead	0.347932	35	30	0.86	1.050000	0.63
Polyamide Thermal Break	0.632653	40	30	0.75	1.200000	0.24
EPDM Gaskets	0.714286	30	30	1.00	0.900000	0.36
Aluminium cover cap	0.493917	75	60	0.80	1.125000	0.44
Aluminium pressure plate	0.445255	75	60	0.80	1.125000	0.50
	Total					0.618

F_R	Fraction of mass from recycled
F_U	Fraction of mass from reuse
C_R	Fraction of mass for recycling
C_U	Fraction of mass for reuse
E_C	Efficiency of recycling process at EOL
E_F	Efficiency of recycling process used for production
V	Virgin Feedstock
W_0	Waste going to landfill or energy recovery
W_C	Waste generated in recycling process
W_F	Waste generated to produced recycled content
LFI	Linear Flow Index
L	Use Life span of material
L_{av}	Industry specified lifespan

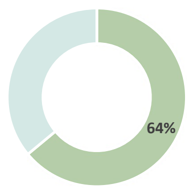
Design Scenario 2: Reuse of Demolition Stream

15+15 years

Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Steel transom	Secondary	2	0.000379	1.16	0.000879	7900	6.946312	0	1	0	0.9
Steel mullion (additional)	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0	0.9
Glass	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.1	0	0	0.9
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0	0.9
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1020	2.257382	0.1	0	0	0.8
EPDM Gaskets	Primary	2	0.000263	4.16	0.002188	850	1.859936	0.1	0	0	0.6
Aluminium cover cap	Primary	2	0.000098	4.16	0.000815	2710	2.209626	0.44	0	0	0.6
Aluminium pressure plate	Primary	2	0.000114	4.16	0.000948	2710	2.570381	0.44	0	0	0.7

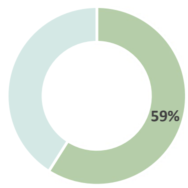
Facade Specification	Recycling Efficiency		Virgin Stock	Unrecoverable Waste			
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	1	0.9	0.000000	1.796460	0	0.000000	1.796460
Steel transom	1	0.9	0.000000	0.694631	0	0.000000	0.694631
Timber (Douglas)	0.001	0.001	0.000000	2.255040	0	0.000000	2.255040
Glass	0.8	0.25	113.400000	12.600000	0	37.800000	31.500000
Glazing Bead	0.8	0.8	1.234871	0.220513	0	0.242564	0.341795
Polyamide Thermal Break	0.1	0.1	2.031644	0.902953	0	2.031644	1.918775
EPDM Gaskets	0.4	0.1	0.999274	0.444122	0	0.999274	0.943758
Aluminium cover cap	0.8	0.8	0.897379	0.897379	0	0.000000	0.897379
Aluminium pressure plate	0.8	0.8	0.448689	0.448689	0	0.000000	0.448689

15 + 15 years



Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.050000	75	60	0.80	1.125000	0.94
Steel transom	0.050000	75	60	0.80	1.125000	0.94
Timber (Douglas)	0.150000	40	45	1.13	0.800000	0.88
Glass	0.534884	30	30	1.00	0.900000	0.52
Glazing Bead	0.347932	35	30	0.86	1.050000	0.63
Polyamide Thermal Break	0.714286	40	30	0.75	1.200000	0.14
EPDM Gaskets	0.714286	30	30	1.00	0.900000	0.36
Aluminium cover cap	0.400000	75	60	0.80	1.125000	0.55
Aluminium pressure plate	0.200000	75	60	0.80	1.125000	0.78
	Total					0.64

30 years



30 years

Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Secondary	2	0.000379	3	0.002274	7900	17.964600	0	1	0.95	0
Steel transom	Secondary	2	0.000379	1.16	0.000879	7900	6.946312	0	1	0.95	0
Timber (Douglas)	Secondary	2	0.0024	2.7	0.012960	580	7.516800	0	1	0	0.6
Glass	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.1	0	0.7	0
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0.4	0
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1020	2.257382	0.1	0	0.6	0
EPDM Gaskets	Primary	2	0.000157	4.16	0.001306	850	1.110304	0.1	0	0.8	0
Aluminium cover cap	Secondary	2	0.0000995	4.16	0.000828	2710	2.243446	0	0.6	0.94	0
Aluminium pressure plate	Secondary	2	0.0000995	4.16	0.000828	2710	2.243446	0	0.8	0.94	0

Facade Specification	Recycling Efficiency		Virgin Stock	Unrecoverable Waste			
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	1	0.9	0.000000	0.898230	0	0.000000	0.898230
Steel transom	1	0.9	0.000000	0.347316	0	0.000000	0.347316
Timber (Douglas)	0.001	0.001	0.000000	3.006720	0	0.000000	3.006720
Glass	0.8	0.25	113.400000	37.800000	18	37.800000	65.520000
Glazing Bead	0.8	0.8	1.234871	1.323076	0	0.242564	1.532563
Polyamide Thermal Break	0.1	0.1	2.031644	0.902953	1	2.031644	2.528268
EPDM Gaskets	0.4	0.1	0.999274	0.222061	1	0.999274	0.988171
Aluminium cover cap	0.8	0.8	0.897379	0.134607	0	0.000000	0.345491
Aluminium pressure plate	0.8	0.8	0.448689	0.134607	0	0.000000	0.345491

Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.025000	75	60	0.80	1.125000	0.97
Steel transom	0.025000	75	60	0.80	1.125000	0.97
Timber (Douglas)	0.200000	40	50	1.25	0.720000	0.86
Glass	0.682692	30	30	1.00	0.900000	0.39
Glazing Bead	0.622829	35	30	0.86	1.050000	0.35
Polyamide Thermal Break	0.926606	40	30	0.75	1.200000	0.00
EPDM Gaskets	0.809955	30	30	1.00	0.900000	0.27
Aluminium cover cap	0.290661	75	60	0.80	1.125000	0.67
Aluminium pressure plate	0.185729	75	60	0.80	1.125000	0.79
	Total					0.59

F_R	Fraction of mass from recycled
F_U	Fraction of mass from reuse
C_R	Fraction of mass for recycling
C_U	Fraction of mass for reuse
E_C	Efficiency of recycling process at EOL
E_F	Efficiency of recycling process used for production
V	Virgin Feedstock
W_0	Waste going to landfill or energy recovery
W_C	Waste generated in recycling process
W_F	Waste generated to produced recycled content
LFI	Linear Flow Index
L	Use Life span of material
L_{av}	Industry specified lifespan

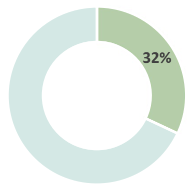
Design Scenario 3: Recycling of Demolition Stream

15+15 years

Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Primary	2	0.00062	3	0.003720	7900	29.388000	0.57	0	0	0.9
Steel transom	Primary	2	0.0002	1.16	0.000464	7900	3.665600	0.57	0	0	0.9
Glass	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.25	0	0	0.9
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0	0.9
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1150	2.545088	0.1	0	0	0.6
EPDM Gaskets	Primary	2	0.000157	4.16	0.001306	850	1.110304	0.1	0	0	0.6
Aluminium cover cap	Primary	2	0.0000995	4.16	0.000828	2710	2.243446	0.44	0	0	0.6
Aluminium pressure plate	Primary	2	0.0000995	4.16	0.000828	2710	2.243446	0.44	0	0	0.8

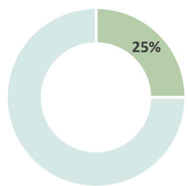
Facade Specification	Recycling Efficiency		Virgin Stock		Unrecoverable Waste		
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	0.98	0.9	12.636840	2.938800	0.000000	1.861240	3.869420
Steel transom	0.98	0.9	1.576208	0.366560	0.000000	0.232155	0.482637
Glass	0.8	0.25	94.500000	12.600000	0.000000	94.500000	59.850000
Glazing Bead	0.7	0.7	1.234871	0.220513	0.000000	0.415824	0.428425
Polyamide Thermal Break	0.2	0.2	2.290579	1.018035	0.000000	1.018035	1.527053
EPDM Gaskets	0.1	0.1	0.999274	0.444122	0.000000	0.999274	0.943758
Aluminium cover cap	0.7	0.7	1.256330	0.897379	0.000000	0.423050	1.108904
Aluminium pressure plate	0.7	0.7	1.256330	0.448689	0.000000	0.423050	0.660214

15 + 15 years



Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.276456	75	30	0.40	2.250000	0.38
Steel transom	0.276456	75	30	0.40	2.250000	0.38
Glass	0.515789	30	30	1.00	0.900000	0.54
Glazing Bead	0.360164	35	30	0.86	1.050000	0.62
Polyamide Thermal Break	0.681818	40	30	0.75	1.200000	0.18
EPDM Gaskets	0.714286	30	30	1.00	0.900000	0.36
Aluminium cover cap	0.503411	75	30	0.40	2.250000	0.00
Aluminium pressure plate	0.407913	75	30	0.40	2.250000	0.08
	Total					0.32

30 years



30 years

Facade Specification								Material Inflow		Material Outflow	
Material	Source	Quantity	Cross section area (m2)	Length (m)	Volume (m3)	Density (kg/m3)	Mass (kg)	F_R	F_U	C_R	C_U
Steel mullion	Primary	2	0.0062	3	0.037200	7900	293.880000	0.57	0	0.95	0.1
Steel transom	Primary	2	0.00062	1.16	0.001438	7900	11.363360	0.57	0	0.95	0.1
Glass	Primary	1	3.0 x 1.2		0.050400	2500	126.000000	0.25	0	0.7	0
Glazing Bead	Primary	1	0.000103	7.9	0.000814	2710	2.205127	0.44	0	0.4	0
Polyamide Thermal Break	Primary	2	0.000266	4.16	0.002213	1150	2.545088	0.1	0	0.6	0
EPDM Gaskets	Primary	2	0.000157	4.16	0.001306	850	1.110304	0.1	0	0.8	0
Aluminium cover cap	Primary	2	0.0000995	4.16	0.000828	2710	2.243446	0.44	0	0.94	0
Aluminium pressure plate	Primary	2	0.0000995	4.16	0.000828	2710	2.243446	0.44	0	0.94	0

Facade Specification	Recycling Efficiency		Virgin Stock		Unrecoverable Waste		
Material	E_C	E_F	V	W_0	W_C	W_F	W
Steel mullion	0.98	0.9	126.368400	-14.694000	5.583720	18.612400	-2.595940
Steel transom	0.98	0.9	4.886245	-0.568168	0.215904	0.719679	-0.100376
Glass	0.8	0.25	94.500000	37.800000	17.640000	94.500000	93.870000
Glazing Bead	0.7	0.7	1.234871	1.323076	0.264615	0.415824	1.663296
Polyamide Thermal Break	0.2	0.2	2.290579	1.018035	1.221642	1.018035	2.137874
EPDM Gaskets	0.1	0.1	0.999274	0.222061	0.799419	0.999274	1.121407
Aluminium cover cap	0.7	0.7	1.256330	0.134607	0.632652	0.423050	0.662458
Aluminium pressure plate	0.7	0.7	1.256330	0.134607	0.632652	0.423050	0.662458

Facade Specification	Calculated results					
Material	LFI	L_{av}	L	X	F(X)	MCI
Steel mullion	0.208275	75	30	0.40	2.250000	0.53
Steel transom	0.208275	75	30	0.40	2.250000	0.53
Glass	0.648590	30	30	1.00	0.900000	0.42
Glazing Bead	0.646067	35	30	0.86	1.050000	0.32
Polyamide Thermal Break	0.887755	40	30	0.75	1.200000	0.00
EPDM Gaskets	0.913876	30	30	1.00	0.900000	0.18
Aluminium cover cap	0.437870	75	30	0.40	2.250000	0.01
Aluminium pressure plate	0.437870	75	30	0.40	2.250000	0.01
	Total					0.25

F_R	Fraction of mass from recycled
F_U	Fraction of mass from reuse
C_R	Fraction of mass for recycling
C_U	Fraction of mass for reuse
E_C	Efficiency of recycling process at EOL
E_F	Efficiency of recycling process used for production
V	Virgin Feedstock
W_0	Waste going to landfill or energy recovery
W_C	Waste generated in recycling process
W_F	Waste generated to produced recycled content
LFI	Linear Flow Index
L	Use Life span of material
L_{av}	Industry specified lifespan