FACADE REVERSE LOGISTICS

Achieving circularity by application of reverse logistics strategies for curtain walls & window façade constructions

MASTER THESIS
BUILDING TECHNOLOGY MASTER TRACK

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EXECUTIVE SUMMARY

If the Netherlands wants to achieve its goal of being completely circular by 2050 (Berkel, Delahaye, & Faasdreef, 2019), radical solutions must take place. Implementing a circular economy is a challenge, but it proves to be significant given the rate at which resources are being consumed. Designing is one of the most important tasks to achieve the circular agenda. Highlighted by Augusto, Ribeiro and Hotza "considering that design process determines 80% of the environmental impact generate by a product or service, it is important to develop production processes able to support companies in the development of environmentally friendly products or services in a fast, reliable and pragmatic manner" (Augusto, Ribeiro, & Hotza, 2019). The design process has a significant weight in the repercussions a project might have in the environment. Even though such design only refers to the architectonic or product design, the current research takes it a step further and also envisions strategic design. Reverse logistics is a vital component of the circular economy, as it would solve major loopholes and answer the questions that are currently being asked. Understanding the market and having a clearer picture of the behaviour of the materials is vital to assess the current situation and the solutions to be proposed. As mentioned by the Ellen MacArthur Foundation, "thinking of systems" (Ellen MacArtur, 2017) is one of the pillars of circularity, which is what reverse logistics might address. The current research analyses the existing conditions, applied to a specific product, and then proposes a product and strategy redesign to facilitate a reverse logistics process.

The general objective is: to develop a framework that is useful to analyse current construction practices and that also helps identifying possible solutions, both at product and system level, facilitating the implementation of reverse logistics in the façade industry. At the end, a framework that organizes RL is proposed as well as a theoretical basis for DfRL, Design for Reverse Logistics, considering the steps needed to facilitate RL. An application of both formats is performed in a specific case, the CITG building facade panel, and an eventual design exercise is made. Universal panel solutions are proposed, a configuration that will allow interchangeability between products.

ACKNOWLEDGMENTS

Through the development of the current research I had several mentors that helped me. I must start with my two main tutors, Tillmann Klein and Bob Geldermans. Tillmann was of great help to understand circularity applied to the built environment, especially when thinking of products. His questionings and conversations guided the research into interesting territories. His reminders of the relevance of the topic also helped to motivate me and the continuous search for new inspiration. Bob was incredibly thoughtful as well. His critical thinking and relations to bigger contexts challenged me to go beyond my own reasoning. The support he gave and his advice on keeping things simple were extremely helpful to make the research interesting yet complex enough. Complementing the advice given by them, I also had the guidance from Juan Azcarate, involved in the circular business side. However, his interest also permeated into other dimensions of the research, enriching the work. His fresh ideas and current work inspired me in ways to organize the information and bring more clarity to the investigation. Thaleia Konstantinou was also part of the set-up of the research. She helped me during the initial steps of the thesis by setting a good foundation. Other teachers and mentors who were also briefly consulted during the process were: Fred Veer for glass consultation, Rusné Šileryté for the material flow analysis, and Pieter Stoutjesdijk for circularity and future practices. Luisa Calabarese, my external advisor, also helped to bring cohesion to my work, making editorial notes.

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To all of my good friends in TU Delft, I thank them for supporting me and giving me the back up I needed. Even when a pandemic emerged during the research process, they were my family. I highly appreciated getting the chance to share my ideas and getting their feedback. The dialogue I had with them inspired me and continue to do so.

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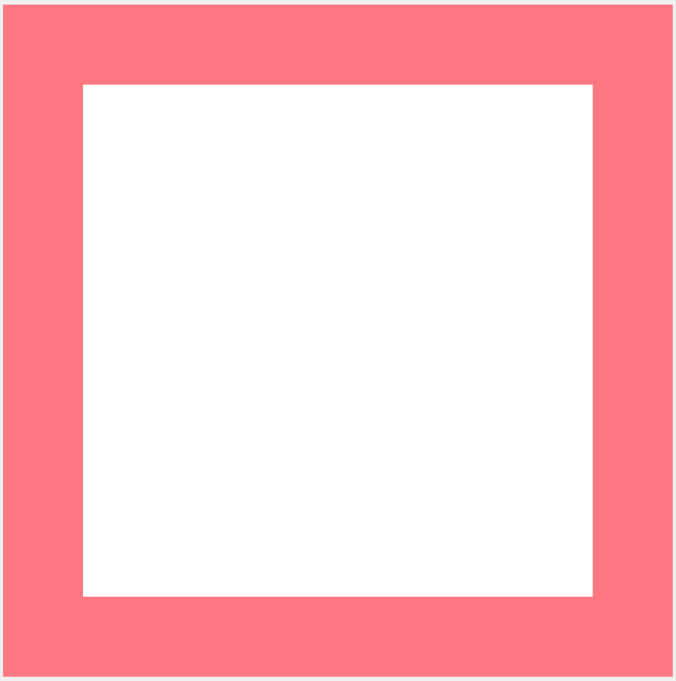
LIST OF ABBREVIATIONS

- BIM: Building Information Modelling
- BM: Business Model
- C2C: Cradle to Cradle®
- CBM: Circular Business Models
- CDW: Demolition and Construction Waste
- CE: Circular economy
- CLSC: Closed-loop supply chain
- DfD: Design for Disassembly
- DfRL: Design for Reverse Logistics
- EMF: Ellen MacArthur Foundation
- EoL: End of Life
- HoI: Harvesting of Information
- LFI Linear Flow Index
- MCI Material Circularity Indicator
- PSS Product Service System
- RL: Reverse Logistics
- SCM Supply Chain Management
- WM: Waste Management

REPORT FORMATS



This work proposes various formats throughout its development. To be able to identify them more easily, this format can be identified. The coloured frame will indicate a format that is new and that can be developed for future use.

They will also have a title, suggesting a name, and define who is the target audience of such format.

When one of the previously mentioned formats is being applied, the frame is gray. It is using the structure proposed by the format and it is being filled with information, either found in the literature research or generated from the specific case being analysed.

1. RESEARCH OUTLINE

Design outline of the current research, including the background, problem statement, objectives, research questions, design questions, methodology, relevance, and a preliminary reflection. Schemes on the overall planning followed throughout this project are also shown, giving an overview of the process.

1.1 BACKGROUND

"Leading analysts of all the major resource domains – water, food, material resources and energy – tell us that our global industrial and financial models, based largely on the assumption of endless growth, are taking human societies to the brink of a series of shortages and insecurities." (Goodbun, Till, & Iossifova, 2012).

Last century was marked by one of the most defining moments in humankind: a second Industrial Revolution in which innovative manufacturing processes made it easier to produce goods. From that point, resource consumption has reached unmatched levels, leading to scarcity and worldwide environmental issues. In their controversial book from the seventies "Limits to Growth", Meadows, Randers and Meadows predict that humanity is heading towards a critical state of scarcity and continue by saying "there are limits, however, to the rates at which sources can produce these materials and energy without harm to people, the economy, or the earth's processes of regeneration and regulation" (Meadows, Randers, & Meadows, 1972). The computer simulations they ran to predict this critical state took into account the economic system currently employed: a linear economy that treats resources like if such limits were non-existent. The "take-make-consume and dispose pattern of growth" (EEA, 2016) is still mostly used throughout the world economies, defined by a capitalist economy in which growing equals progress. Reacting towards this unsustainable approach, a new model is emerging: the circular economy. It aims to design out waste by keeping products and materials inside the economic and productive loops (Ellen MacArtur, 2017). Redefining growth and ways of consuming are key to answer the current scarcity issues.

It is widely known the construction industry generates 35% of the waste in Europe and is responsible for 30% of the resource consumption (Delft, 2014). Moreover, the façade of a building is becoming highly specialized and represents 25-30% of the embodied energy of a building. (Michael, 2016). There is an urgent need of rethinking the ways of designing and collaborating with other disciplines during the complex process of design-construction. Like stated in "la problematique" by Peccei, founder of the Club of Rome, viewing the problems of mankind individually, in isolation or as problems capable of being solved in their own terms is doomed to failure (Braillard, 2019). Design in a circular built environment is the first step towards major solutions, an approach that demands collaboration and connections between agents resulting in highly efficient products. It is not only about design but strategic factors involving the rest of the stakeholders need to align, rendering the new economy even more feasible.

1.2 PROBLEM STATEMENT

Sustainable solutions are on their way. Regarding the built environment, the current efforts of companies are reduced to the recycling of materials. VMRG, the Dutch Metal Façade Industry Branch Organisation, is doing the first tests in circularity by dismantling curtain walls, collecting the materials, and recycling them to be reused in different applications. However, this is the most resource-consuming way of recovering an already used element. Answering this problematic, design for disassembly is also being explored. In the Netherlands, the circular term has become widely popular and architects are incorporating a way of adaptable design. However, the main problem does not lie there: designing with adaptability in mind is useless if there is not a clear vision of the process behind. Circularity demands an understanding on what happens to a product once it has reached its end of life. The term for this process is "reverse logistics" in which the flow of an element from its "use" location to the respective restoring facility happens. The issue then to tackle is the lack of guidelines necessary for a reverse logistics to be feasible. Apart from the design solutions being addressed, there is a need for a framework in which strategies are developed, involving the relevant stakeholders and creating awareness to bring a full circle to the cycle. Before the design and construction process even begin, there must be a clear map and foundations for the cycle to work properly. Even though a strategy might be drawn , external barriers are also likely to appear. These will be also highlighted so attention can be put into those aspects as well for future elaboration.

1.3 OBJECTIVES

The general objective is: to develop a framework that is useful to analyse current construction practices and that also helps identifying possible solutions, both at product and system level, facilitating the implementation of reverse logistics in the façade industry.

The sub-objectives will be:

- Understand the relationship between circularity in the built environment and reverse logistics, especially in a system level.
- Define the best method to assess circularity in a product and process, taking into account previous research and defined methodology.
- Understand the basics of legislation in Europe and The Netherlands addressing waste from Demolition and Construction, to assess how "good" or "bad" the situation is.
- Analyse the CITG building and its east façade, to understand how the proposed design and strategy currently work.
- Propose conceptual design solutions to facilitate reverse logistics, opening the dialogue in the topic. Solutions might come in the form of a product redesign, design guidelines or a shift in the current strategies.
- Evaluate the bigger picture by means of flows and pose the right questions for further research addressing facade circularity.

The final products, as shown in Figure 1, will be:

- Façade criteria that elaborates in the DfRL Design for Reverse Logistics theory.
- The framework that helps organizing the Façade Reverse Logistics process.
- Application of the framework, using the analysed case study and identifying weak links.
- Design solutions at product and system level, applied in the framework context for evaluation.
- A reflection of the bigger picture and how the future vision would look like

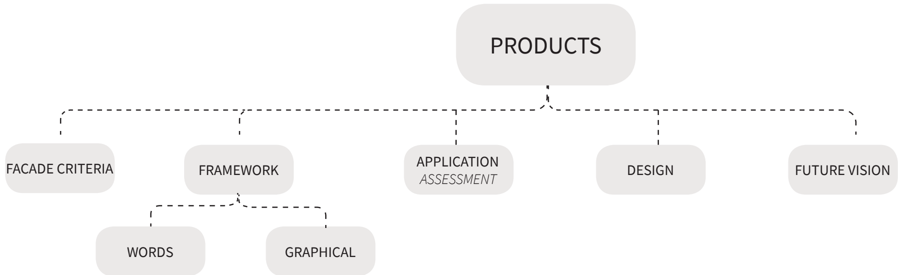


Figure 1 *Products generated*

As for the boundary conditions:

- An integral material flow analysis would be the best way of visualizing the current and proposed scenarios. However, the lack of information is the main barrier to render a complete report of the flows. A case by case study is needed to get such amount of information, so time and resources are required to perform such analysis. The current research will represent a schematic supply chain of the products going into a façade, without going into detail of quantities and prices.
- The strategy design is part of a roadmap to get to a functional reverse logistics process. As already mentioned, there are barriers and other important stakeholders involved who need to be willing to cooperate. Aligning the necessities and mentalities is necessary in all other realms (political, for instance) for a proper application. The roles of these stakeholders will be highlighted.
- The economic factor won't be included in the current project. The research will only have a general overview of the values of a product as the main scope lies within the design and management strategy disciplines.
- As it is comprehensible, the author will only focus in a specific case study (company and given product) to apply the solutions to. It is understood the solution can be replicated or taken as a base for further research.

1.4 RESEARCH QUESTIONS

The main research question is:

- RQ: How can the construction industry be ready to implement a reverse logistics for façade products and what factors need to align for a smooth transition?

The sub-questions are:

- SRQ1: What is the relationship between circularity in the built environment and reverse logistics?
- SRQ2: Which products assessments are there to evaluate their circularity potential or , in this case, their reverse logistics potential?
- SRQ3: What does the current Dutch legislation state over Demolition and Construction Waste, and does it support reverse logistics?
- SRQ4: What aspects should the framework include to address the reverse logistics process in a holistic way?
- SRQ5: What stages are the most critical during the reverse logistics implementation and how do geographical locations influence the process?
- SRQ6: At the end, how does the design & construction process look once a reverse logistics is applied?

The background questions are:

- What is the current material flow of the main façade materials?
- Which business models are the most suitable for a reverse logistics implementation?

1.5 DESIGN QUESTIONS

The main design question is:

- DQ: How can the CITG window-wall façade panel proposed by Alkondor and TU Delft be improved to accommodate a reverse logistic process that assures a second use in a different building?

The sub-questions are:

- SDQ1: What façade criteria must be contemplated when designing and evaluating the "reverse logistics" potential of a product?
- SDQ2: How must the framework be formulated to organize the reverse logistics process, for it to serve as a canvas to analyse other cases?
- SDQ3: What design solutions (if proven necessary) can be applied to the CITG façade panel and how are they improving the overall efficiency?
- SDQ4: How does geographical locations inform the reverse logistics process?
- SDQ5: How can the CITG scenario and proposed solutions be extrapolated to other cases, drawing the bigger picture and the steps that can be further taken?
- SDQ6: How does the future vision look like for reverse logistics and the closing of resource loops?

1.6 METHODOLOGY AND APPROACH

The research relied on three different methods: (1) Literature Reviews, (2) Interviews, and (3) Research through Design, as shown in Figure 2. As most of the topic is reflected in papers and theories developed by researchers, a literature review was an ongoing process throughout the whole project. Different topics were analysed: circular economy, circular business models, reverse logistics, circularity in the built environment, critical façade components and materials, design strategies for disassembly, and integration in the supply chain. Reverse logistics, being the main focus of the current research, was highlighted. Little literature has been published on such topic, especially when applied to the construction sector. Lessons from the manufacturing industry were drawn, which complemented and filled the existing literature gap. The first 7 chapters, corresponding to the literature research, touch upon these basic subjects : 2 Circular economy, 3 Circular business models, 4 Reverse logistics, 5 Circular built environment, 6 Materials, 7 Products / Facades, and 8 Assessments. Chapter 9 addresses Dutch legislation of Construction & Demolition Waste, to complement the overall thematic picture, as well as a chapter 10 to Integrate and bring a conclusion to the Literature section.

The research has partners involved, namely VMRG, a façade branch association. It is a network connecting different stakeholders in the façade profession, and it has valuable connections to the industry. Taking the opportunity this offers, interviews were conducted with the relevant actors to understand from a primary source the current situation of the industry. The real players revealed what the areas of opportunity were and what has already been done to contribute to the circular economy. The material synthesized from the interviews will be applied throughout the chapters following the literature review.

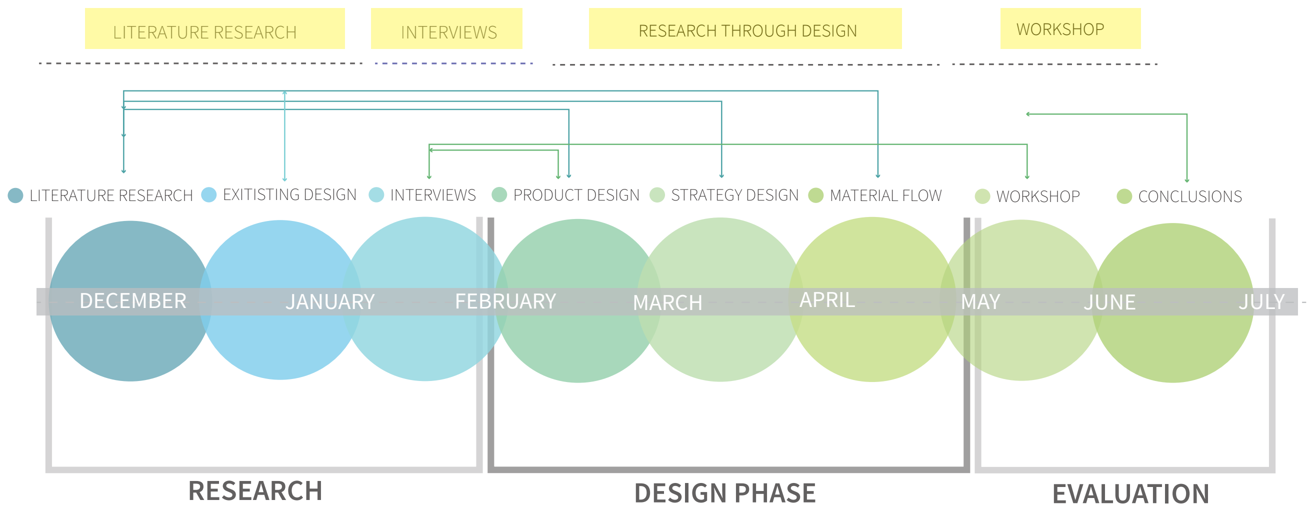


Figure 2 *Methodology followed*

Research through design tied everything together. It is the literature review and the interviews that informed the eventual designs, the framework being part of them. First, a framework organizing the reverse logistics topic was generated, covering the most relevant aspects to be tackled. A façade criteria was also developed to help on the evaluation process. Both products helped on the analysis of the existing solution for the CITG building panel. After such evaluation, a redesign of such product will be done if proven necessary, with the primary objective to facilitate the reverse logistics process. Feedback from the partners and tutors will be used to assess the different design proposals. In this case, a mock up would have been suggestible but due to the time constraints and other products to be delivered, it wasn't part of the final deliverables. Also, the design of the strategy will wrap the solutions given, by providing guidelines to the reverse logistics process. The next chapters will then focus on the analysis and design development: 11 Framework and criteria, 12 Application and 13 Conceptual Design. The last chapters will evaluate and conclude the whole research, highlighting any further development or areas to focus: 14 Discussion, 15 Bigger picture, and 16 Conclusions.

It must be highlighted the Application Workshops were a fourth research method to validate the outcome of the research, as part of the programme envisioned for the Façade Relog research conducted by TU Delft and other institutions. However, due to the current circumstance, such event was cancelled and therefore also preventing the workshops to be applied. It will be a good exercise to share the outcome with stakeholders to receive feedback from them and adjust according to their expertise.

1.7 PLANNING AND ORGANIZATION

The scheme (Figure 3) shows the thematic organization of the current research and the last diagram (Figure 4) shows the graduation plan in a simplified format.

The research team is composed of the following.
• **Supervision as first tutor**: Tillmann Klein
• **Supervision as second tutor**: Bob Geldermans
• **Supervision as third tutor**: Juan Azcarrate
• **Execution partner**: VMRG
• **Advisory Board**: Luisa Calabrese
No financial framework was needed.

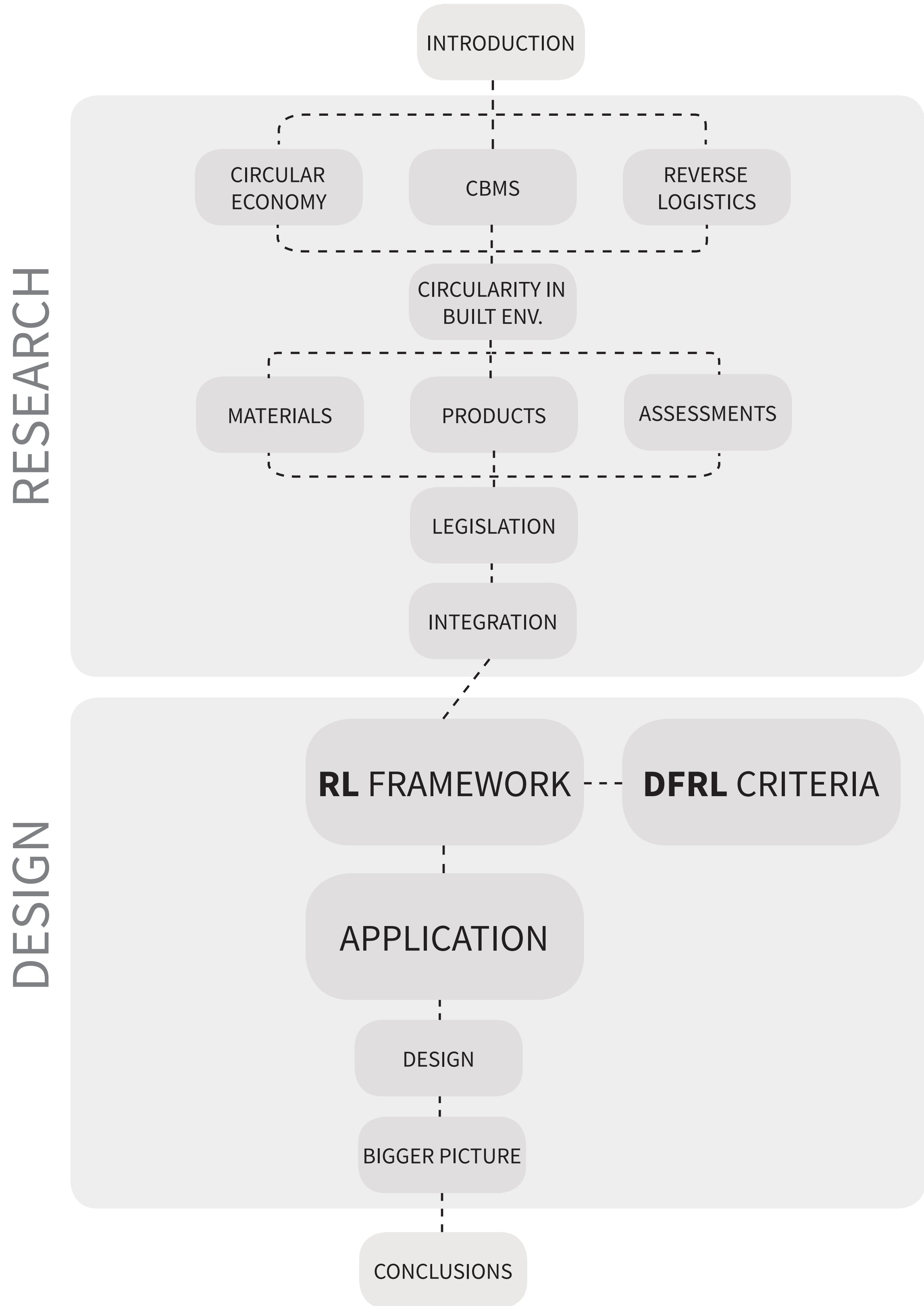


Figure 3 *Thematic organization*

1.8 RELEVANCE

If the Netherlands want to achieve its goal of being completely circular by 2050 (Berkel, Delahaye, & Faasdreef, 2019), radical solutions must take place. Implementing a circular economy is a challenge, but it proves to be significant given the rate at which resources are being consumed. Designing is one of the most important tasks to achieve the circular agenda. Highlighted by Augusto, Ribeiro and Hotza “considering that design process determines 80% of the environmental impact generate by a product or service, it is important to develop production processes able to support companies in the development of environmentally friendly products or services in a fast, reliable and pragmatic manner” (Augusto, Ribeiro, & Hotza, 2019). The design process has a significant weight in the repercussions a project might have in the environment. Even though such design only refers to the architectonic or product design, the current research takes it a step further and also envisions strategic design. Reverse logistics is a vital component of the circular economy, as it would solve major loopholes and answer the questions that are currently being asked. Understanding the market and having a clearer picture of the behaviour of the materials is vital to assess the current situation and the solutions to be proposed. As mentioned by the Ellen MacArthur Foundation, “thinking of systems” (Ellen MacArtur, 2017) is one of the pillars of circularity, which is what reverse logistics might address. The current research analyses the existing conditions, applied to a specific product, and then proposes a product and strategy redesign to facilitate a reverse logistics process.

1.9 REFERENCES

The list of the current bibliography can be found in the bibliography section.

1.10 REFLECTION

The circularity topic is now becoming familiar and a common goal. The concept itself is easy to grasp: get rid of as much waste as possible by keeping the products and their value in the productive loops. Closing the loops is the final objective of circularity. However, what this implies is the real challenge. Developing a reverse logistics is necessary for circularity to happen in the current market. It will mean a common collaboration effort from various stakeholders. Architects, planners and designers can all do their parts, but it is necessary for the rest to align. Policy-makers, politicians, and business owners must all change their mentality so a closed loop is achieved. When scarcity of resources is realized and taken as the current reality, all the actors involved will stimulate a resource-conscious culture.

If there is a topic that is relevant for society, it is circularity. Even if the term is getting too familiar in theory, it is not the same case in practice. The current efforts from the pioneer companies are reduced to the lowest levels of re-life options, spending more resources than needed and reducing the value of the products. It is necessary to come up with guidelines and frameworks to incentive the participation of all agents in society. Changing the perception of the people is one of the major challenges up to date, and it is researches in circularity that might help on facing such misconceptions.

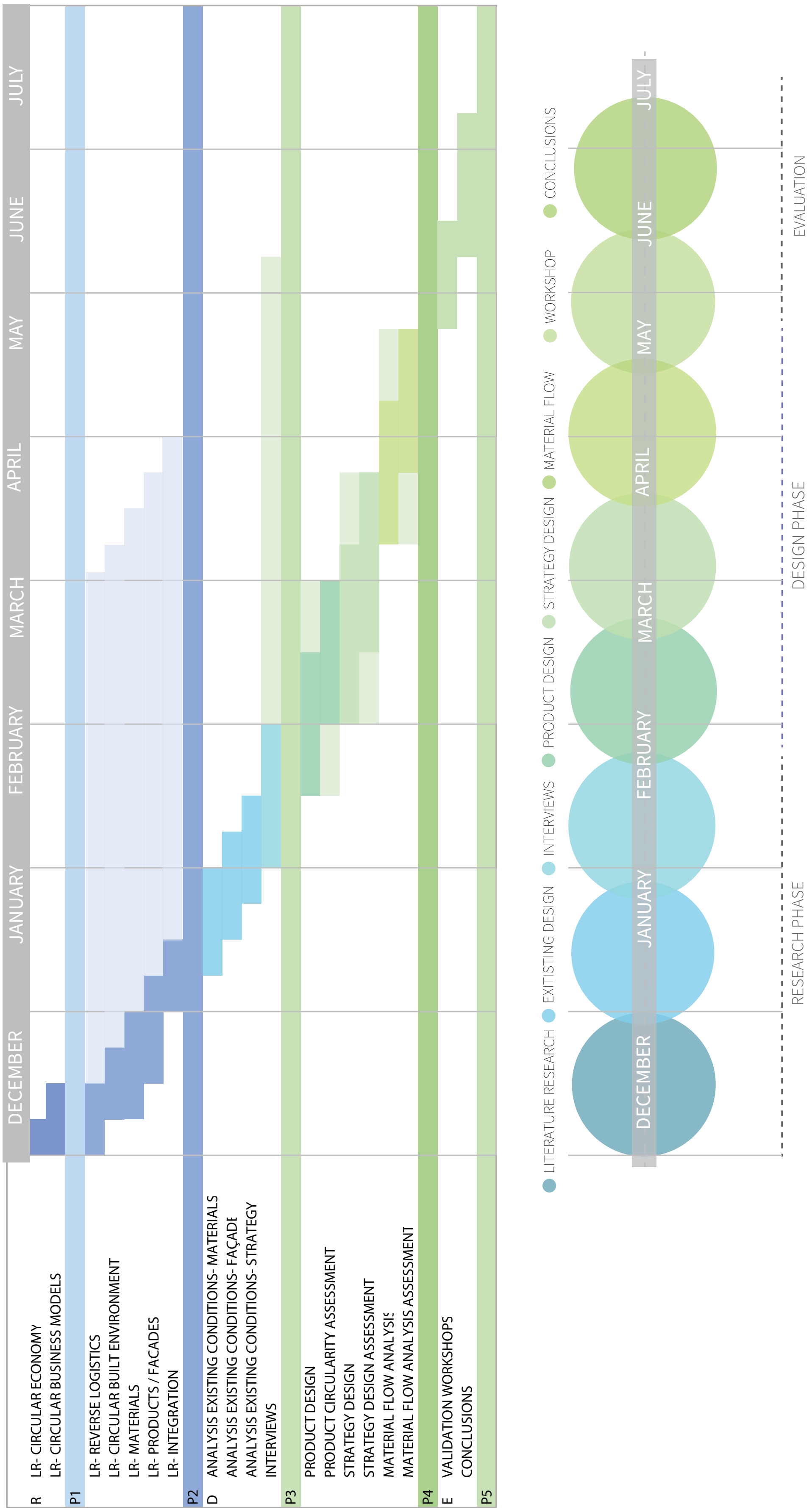


Figure 4 *Graduation plan*

2-10. LITERATURE RESEARCH

The literature research encompasses the various topics investigated, starting form the most general to the most particular. The Circular Economy concept is revised, as well as the Circular Business Models directly linked. Reverse Logistics is evidently a concept that needs extensive explanation, and the fourth chapter elaborates on it. After, applying Circularity in the Built Environment is next, and two levels are explored, Materials and Products. Assessments on Circularity and reviewed and finally a Legislation chapter is also included, to contemplate the legal context in which the research is situated. Integration is the last chapter on this first half, bringing everything together.

2 CIRCULAR ECONOMY

2.1 FOUNDATIONS & HISTORY

The Circular Economy (CE) concept emerged as an alternative to the linear economic model (Figure 5), addressing the environmental and sustainability issues. Although the term seems to be relatively new, it has been around for centuries in previous ways of life, when human societies lived in full synergy with nature (Sillanpää & Ncibi, 2018). The common term has been attributed solely to the Ellen MacArthur Foundation, but there have been other scientists, environmental activists, architects and politicians that have been developing and laying the foundations of the term currently known.

Some of the founding fathers of the CE concept are listed by Sillanpää and Ncibi in their book "The Circular Economy: Case Studies about the Transition from the Linear Economy". The first incubator of the CE concept was the science of Environmental Economics, developed in 1974 by Karl-Göran Mäler in his book of the same name (Sillanpää & Ncibi, 2018). This subdiscipline of economics combines the conventional economic topics and the economic growth theory with the sustainable development philosophy (Pearce, 2002). It deals with different alternatives of waste disposal, quality of air, water and soil resulting from industrial activities, and the promotion of sustainability. "Environmentalism", published in 1981 by Timothy O'Riordan gave significant references to policy and decision makers on resource and environmental management (O'Riordan, 1981). Walter Stahel also contributed with his 1986 book "Product life as a variable: the notion of utilization", in which he proposes spiral-loops that minimize matter and energy flow, through specific design strategies for the service-life extension of goods, such as reuse, remanufacture, refurbishment and repair (Stahel, 1986). The rest of the list of contributors is extensive, passing also through McDonough's and Braungart's "cradle-to-cradle" concept (explained later in this chapter), until the recent concept by Ellen MacArthur is defined. Even though she is not considered one of the founders of the concept, her contribution is highly responsible of popularizing and accelerating the transition towards a circular economy. They also provided the now renown butterfly diagram that illustrates the loops of technical and biological materials.

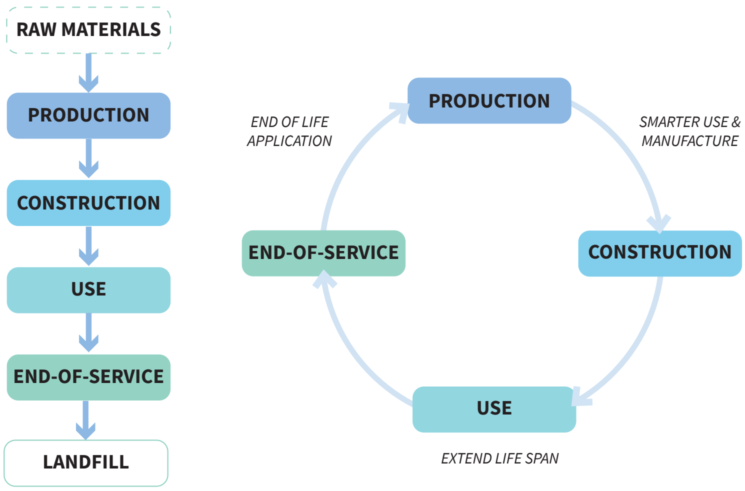


Figure 5 *Linear vs Circular Economy*

2.2 CE CONCEPT

Institutions, scientists and professionals have developed their own definition for the CE concept. Each one reflects a similar backbone concept but varies according to the focus of each entity. One of the most comprehensive definitions is given by the KTH Royal Institute of Technology:

"a sustainable development initiative with the objective of reducing the societal production-consumption systems linear and material energy throughout flows by applying material cycle, renewable and cascade-type energy flows to the linear system. CE promotes high value material cycles alongside more traditional recycling and develop systems approaches to the cooperation of producers, consumers and other societal actors in sustainable development work." (Korhonen, Nuur, Feldmann, & Birkie, 2018)

Taking the definition by KTH, and matching it with the one developed by the Ellen MacArthur Foundation, basic principles can be noticed: design out waste and pollution, keep materials and products in use, and regenerate natural systems (Ellen MacArtur, 2017). There is also a distinction between biological and technical cycles as highlighted in the butterfly diagram in Figure 6: biologically-based materials are designed to feed back into the processes regenerating living systems, while the technical cycles make sure products are recovered and re-looped in the same value circles by means of different strategies. Such strategies (maintenance, repair, reuse, redistribute, refurbish, remanufacture, recycle, and energy recovery) are addressed in the following chapters.

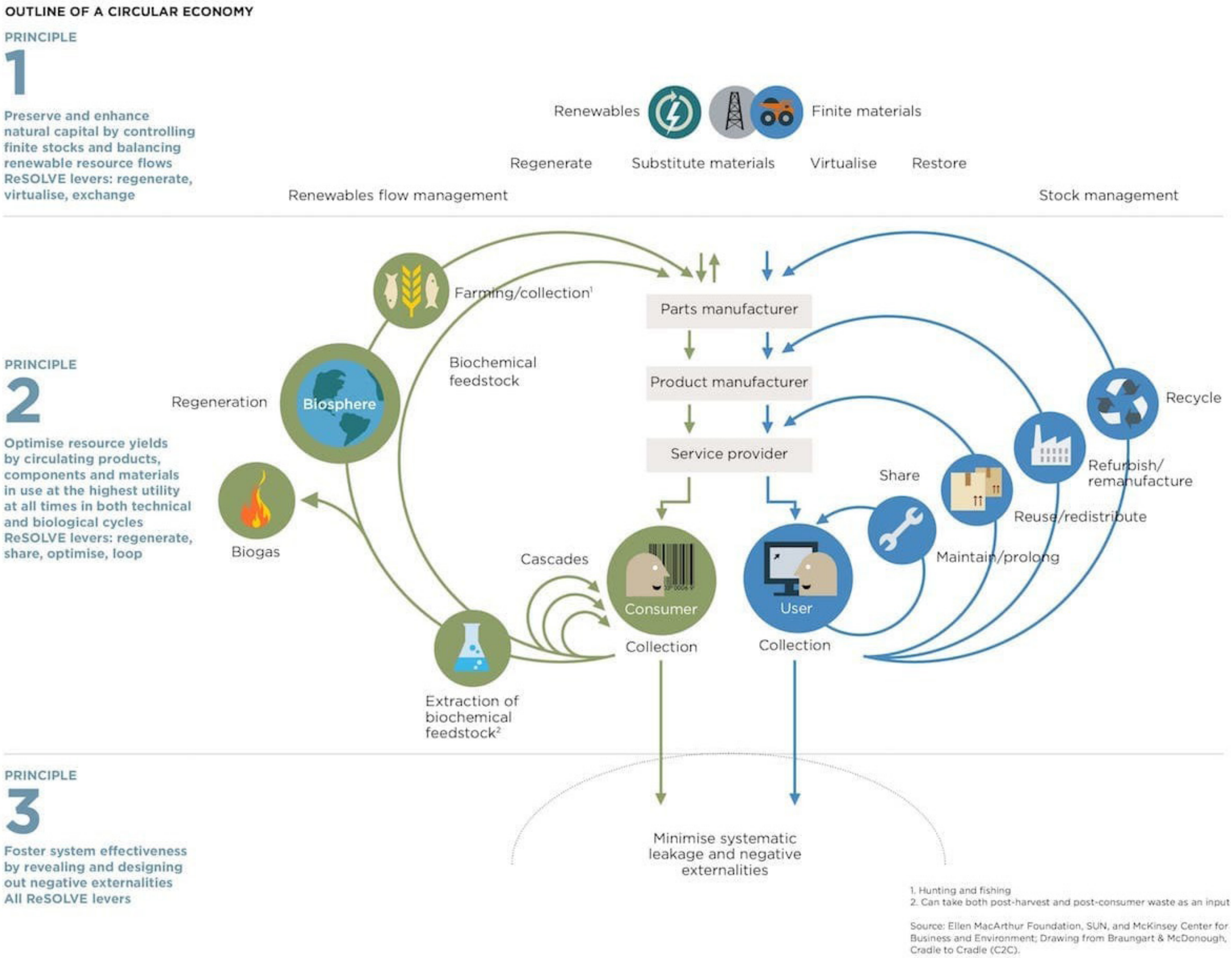


Figure 6 *Butterfly Diagram, by EMF (2017)*

2.3 MAIN PRINCIPLES

There are fundamental principles revolving the concept and might clarify the circular approach, some of them are (EMF, 2015): waste is "designed out", diversity builds strength, renewable energy sources power the economy, thinking in cascades and thinking in systems. From the five, the most important and relevant ones for the current research are the first and last.

• **Waste is "designed out"**. The most relevant principle in which the waste of one process is the food for another. It is imperative to optimise resources by circulating products, components, and materials at the highest utility in both technical and biological cycles.

• **Think in systems**. System-thinking must be applied broadly. Understanding the parts, links, and functions of the respective systems is necessary for a meaningful intervention. Circular economy has proved to be a highly complex system; the links have to be taken into account.

Both principles refer to the idea of resources in a continuous loop, a key component in the circular schemes. Their shape and their destination reveal essential properties in the process, as shown in figure 7. The power of the inner circle (1) lies on the stronger value of the strategy when compared to outer circles: more preservation of the product's value, embedded labour and energy (EMF, 2015). The power of circling longer (2) has to do with the extension of the life span of a product by reusing it, avoiding the material, energy and labour that a new product would need (EMF, 2015). The power of cascade use (3) diversifies the reuse applications across the value chain, preventing the inflow of virgin material and conserving the additional value of products. Finally, the power of pure inputs (4) is their potential to increase collection and redistribution efficiency due to the unpolluted quality of the material (EMF, 2015). They all help on keeping the quality, extend the life span and enhance the material productivity.

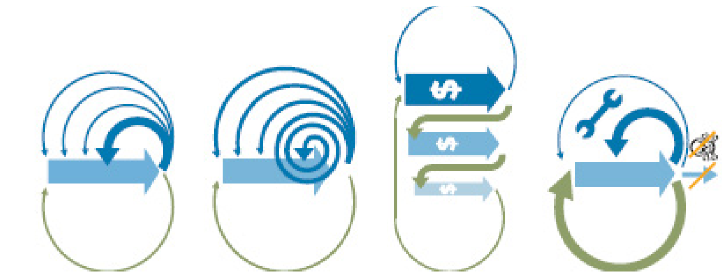


Figure 7 *Power of the circles by EMF (2017)*

2.4 RELATED GREEN CONCEPTS

Other concepts valuable to revise because of their similar principles may enrich the overall research:

Green economy	Concept that "results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UN Environment, 2008)
Industrial ecology	Studies the impact of "the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and on the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" (White, 1994)
Cradle-to-Cradle	"The waste of one production system is the food for another system (everything can be designed, produced, used, and disassembled to be safely returned to the soil as biological nutrients, or reintroduced to the production cycles as technical nutrients)… there is a capitalizing on the abundant, clean, and renewable energy sources… and inspiration is drawn from the diversity of nature through highly yielding and efficient phenomena" (McDonough, 2002)
Natural capitalism	Envisions an "increase in the productivity of natural resources… shifting to closed-loop production models… 'service-and-flow' business models… and reinvesting in natural capital by promoting initiatives and aiming activities at restoring and regenerating natural resources" (Lovins & Lovins, 2001)
Regenerative design	"Based on process-oriented and self-regenerative systems, designed to enable the valorization of the full potential of resources, thus eliminating the notion of waste" (De Plessis, 2012)

2.5 CONCLUSIONS

The Circular Economy concept has been studied already by numerous researchers in the past. Recently, there is not an official definition to the concept, but general principles can be drawn from the literature available. Diversity in design to accommodate the future changes, shifting to renewable resources, thinking in systems and cascades, and avoiding waste are the core ideas behind the model. The butterfly diagram is a good starting point to grasp the concept, as it applies to any activity or industry. The current research will be situated in this context, taking the basic principles and core ideas to develop a system that responds to a bigger picture and can be used for further analysis.

3 CIRCULAR BUSINESS MODELS

3.1 CONCEPTS

The development of new business models is necessary to materialize the transition towards a circular economy, which represents a radical change from the current linear economy (Vergara, 2019). Circular business models or CBMs are those that involve the creation of value by exploring the value retained in old products that can be reused to generate new offers (Sehnem, 2019). These business models involve activities such as regeneration, sharing, reintroduction of resources into the product chain, optimization, virtualization, and exchange. The model also involves repair, reuse, remodelling, remanufacture, recycling, sharing and reverse logistics, explored in the following chapters.

CBMs can translate into different propositions, however there is one category that has been explored extensively, based on services rather than goods. Product-service systems shift the value proposition of a traditional product-based transaction, based on the ongoing delivery of performance services. They combine tangible products and intangible services capable of fulfilling specific needs of customers (Tukker, 2004). The following section elaborates more on the types of models and some of their characteristics.

3.2 MODELS

A first classification explored by Tukker in 2004, classifies the product service systems in three as shown in Figure 8: product-oriented, use-oriented and result-oriented. The first is still focused in product sales, with some extra services; the product-related service (1) offers assistance during the use phase of the product and in the advice & consultancy (2) the provider gives advice on most efficient uses. The second one mainly consists on retained ownership of a product by the provider; in the product lease (3) scheme the provider is responsible for maintenance, repair and control, in the product renting & sharing (4) the user does not have unlimited and individual access as other can use the product, and the product pooling (5) allows a simultaneous use of the product. The third and last classification is the result-oriented, in which the client and provider agree on a result with no pre-determined product involved; the activity management/outsourcing (6) keeps some activities outsourced to a third party, the pay per service unit (7) makes the user only pay for the output of the product according to use level, and the functional result (8) is a model in which the provider agrees on a specific result with the client (Tukker, 2004). The reliance on the product decreases from model to model, in order of appearance, as well as the freedom from the provider to fulfill the client's needs.

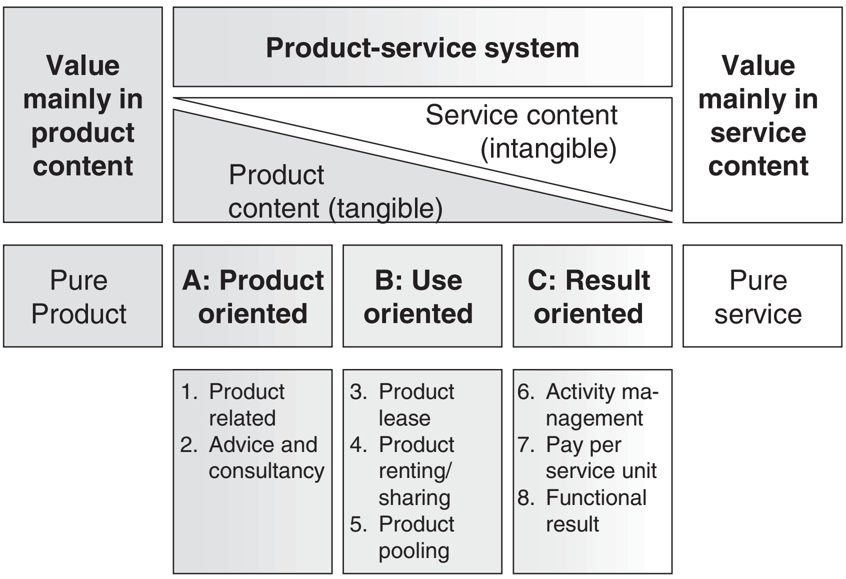


Figure 8 *Main and subcategories of PSS by Tukken (2004)*

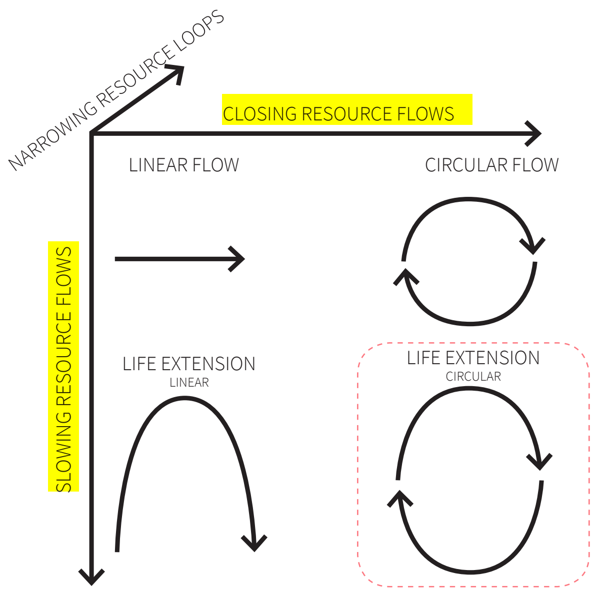


Figure 9 *Categories of CBMS by Bocken (2016)*

Narrowing the scope to CBMs, different authors and sources have been addressing the categorization of models in order to understand and operationalize the business model innovations to achieve circularity. The framework of slowing, closing, and narrowing resources developed by N.M.P. Bocken presents a clear and comprehensive categorization of business models strategies, focusing on how the resources flow through a system (Bocken et al., 2016). It is noticed that such models come from the industrial design field, as the construction industry still lacks development of theories. It specifies actions needed to achieve circularity for circular product design by defining circular approaches (slowing, closing and narrowing) and respective business models and design strategies. According to Bocken, there are two main types of approaches: slowing loops and closing loops. The first focuses in extensive use of products due to their design and product life extension. The second is about reuse of materials through various strategies, explained in the latter chapters. Narrowing loops is not considered as a circular model, but a sustainable one, as it aims at reducing the resource use in the product and its process. Figure 9 illustrates Bocken's models.

Describing each one briefly (Figure 10), and using Vergara's recent findings for the Façade Leasing project (Vergara, 2019) the Access and Performance Model (1) transfers the maintenance responsibilities of the product to the manufacturer, for which the customer must pay a customized service. The Extending Product Value uses take-back guarantees to ensure the return of the product to the manufacturer to exploit the residual value. The Classic Long-Life Model (3) delivers long-lasting products that can be easily repaired and maintenance through a system of services. The Encourage Sufficiency strategy (4) is the least explored in the Slowing Down approach, in which companies encourage a low consumption from the end-users. For the Closing Loops schemes, Extending Resource Value (5) makes sure to exploit the residual value of resources by incorporating new collaborations or take-back systems to collect materials and turning them into new forms of value (Bocken et al., 2016). The last one is Industrial Symbiosis (6), in which a process-orientated strategy is conducted by turning waste outputs from one process into "food" for another process. This last strategy was the least explored of all the strategies when analysing the thesis work conducted in the past years in TU Delft. The current research takes these last two strategies to develop a new solution in the design phase, having as a goal to make products loop back into the productive cycles.

	Approach	**Strategy**	**Description (bocken et al., 2016)**
Sustainable BMs	Narrowing loops	Resource Efficiency	Reducing resource use associated with the product and the production process, it does not address the time dimension.
Circular BMs	Slowing loops	Access and performance model	Providing the capability or services to satisfy user needs without needing to own physical products
		Extending product value	Exploiting residual value of products- from manufacture, to consumers, and then back to manufacturing - or collection of products between distinct business entities
		Classic long-life model	Business models focused on delivering long-product life, supported by design for durability and repair for instance
		Encourage sufficiency	Solutions that actively seek to reduce end-user consumption through principled such as durability, upgradability, service, warrantees and reparability and non-consumerist approach to marketing and sales
	Closing loops	Extending resource value	Exploiting the residual value of resources: collection and sourcing of otherwise wasted materials or resources to turn these into new forms of value
		Industrial Symbiosis	A process-orientated solution, concerned with using residual outputs from one process as feedstock for another process, which benefits from geographical proximity of business

Figure 10 *Circular Business Models by Bocken (2016)*

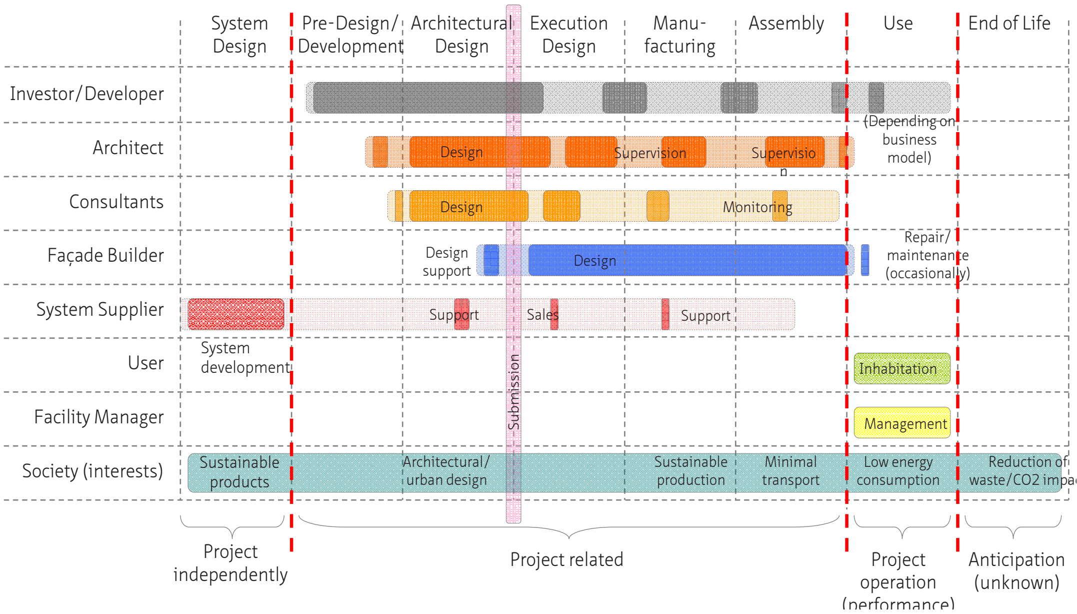


Figure 11 *Stakeholders in the different phases of a construction project by Klein (2013)*

3.3 STAKEHOLDERS

The models are inserted in a complex process involving various stakeholders. Tillmann shows in a timeline scheme (shown in figure 11) the involvement of the different actors and the different stages in which they intervene. It all begins with the client or investor, who looks for investment in the form of a building with high profit potential. The architect then designs the project with the help of consultants from other disciplines, defending the architectural and innovative features a project might have. The general contractor takes on the risk of executing the project, relying in subcontractors to get the job done. His profit comes largely from the set price with the client and the real cost of construction. One of the subcontractors is the façade builder, responsible of translating the architectural expression into feasible specifications and a tangible product. Innovations in his own work method and façade construction are common recurring strategies. The time constraints and financial pressure are high for the façade provider, and a close relationship is needed with the system supplier (Klein, 2019). The latter is the fundamental actor with a bifold intervention: the architects decide in the application of their products based on their flexibility but is the façade supplier the buyer of such products based on their simplicity. His role, that one of the system supplier, then begins even before the project has been designed. The facility manager is in charge of the maintenance of the building once it is in operation. The users then inhabits or make use of the building, with an interest on high comfort, little maintenance, and long-lasting products.

3.4 APPLICATION IN DIFFERENT SECTORS

In Vergara's report, applications of the six CBMs are illustrated; figure 12 shows the 29 cases the author found in the construction sector and the strategy which they belong to. She mentions cases ranging from Mitsubishi's Elevators offering longer product life and quality, to Kyocera's printing service solutions which includes paper management consultation and real time monitoring (Vergara, 2019). She concludes most of the examples studied in real life do not pertain to the construction industry, but to other fields. The complexity of the built environment might be one of the main reasons behind such lack of real-life case studies. Also, most of the "built" examples are tested and occurring in test labs, meaning highly controlled environments might miss factors offered during a real implementation. From these few cases, the outcomes are still to be seen as most of the projects haven't reached their end of life, meaning the loop has not been yet closed.

One of the current projects being developed is the Façade Leasing project in TU Delft. Choosing a façade as target for such business models comes from its high initial investment: it represents from 30-40% of the initial investment of a new

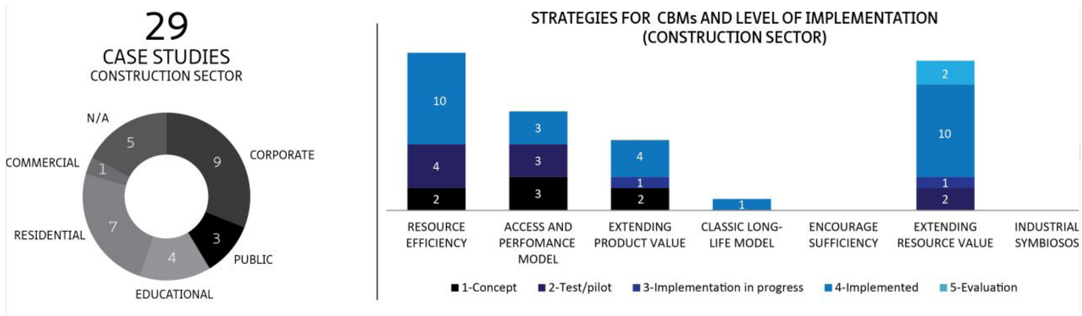


Figure 12 *Case studies of CBM by Vergara (2019)*

building project and up to 50-90% for a deep energy renovation (Dall'O, 2013; Parker & Wood, 2013).The project is based on new roles and functions for the stakeholders involved in design, engineering, construction, financing, management and end-of-life reprocessing of the products (Azcarate, Heijer, & Klein, 2017). Suppliers of façade systems increase the value of their product-service offerings by having a competitive advantage, assuring financial stability and higher profit margins. They are responsible of meeting long-term demands of the building owner, as well as managing expenses and meeting long-term Total Cost of Ownership. For clients, it means a better quality for their building in terms of energetic and technical performance without a large initial investment. Periodical service fees are more easily balanced by the profit of energy savings, rental increase or occupancy stability (Azcarate et al., 2017). By spreading the total cost of a façade system, the usual financial burdens might be alleviated. There are still questions about feasibility of the application of such model, such as the inability of medium enterprises to pre-finance an entire façade, requiring an investor and a financial institution to remove this load and in exchange for a periodic financing fee (Azcarate et al., 2017). The scheme of the project is shown in figure 13 and it will be used for further exploration in the design phase.

3.5 CONCLUSION

Establishing the relevance of business models in the circular economy is vital to have solid foundations in the current research. There are several alternatives to approach CBMs, but the focus here will lie on the strategies that attempt to close the resource flows. Slowing the flows, even if it is important as well, is being already addressed in the industry and in overall research work. Offering long-lasting products and giving good maintenance are policies extensively explored nowadays, as explained in the Application chapters. Calling for a more holistic approach, closing the loop requires cooperation between stakeholders and simplification of the processes, explored in the second half of the report.

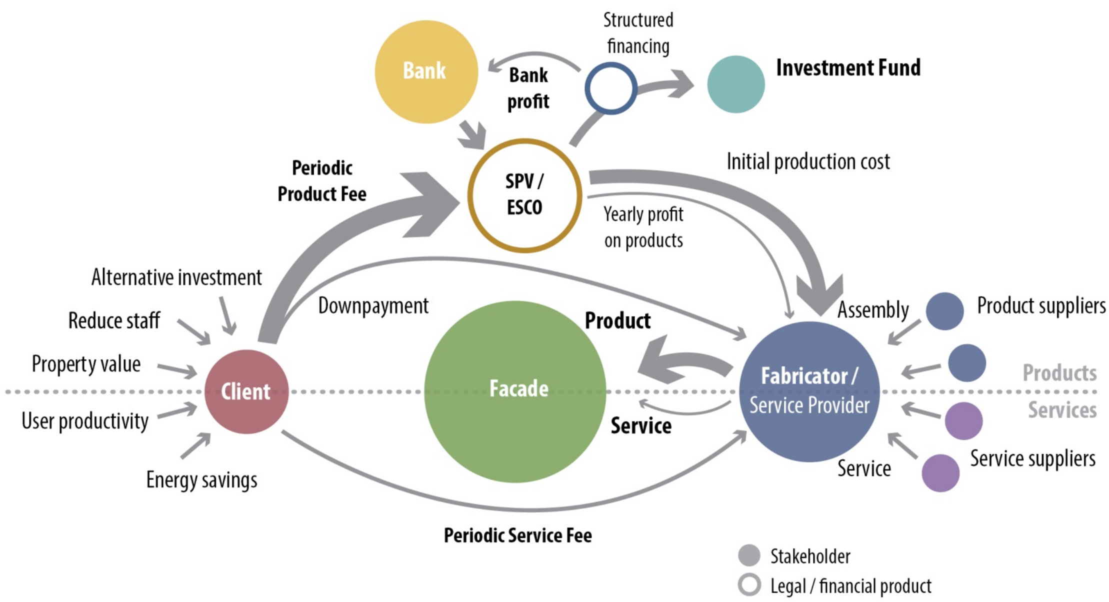


Figure 13 *Facade leasing scheme by Azcarate (2017)*

4 REVERSE LOGISTICS

4.1 SUPPLY CHAIN

The definition of supply chain given by Robert Handfield and Ernest Nichols in their 1999 book “Introduction to Supply Chain Management states it “encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end-user, as well as the associated information flows. Material and information both flow up and down the supply chain. Supply chain management (SCM) is the integration of these activities through improved supply chain relationships, to achieve a sustainable competitive advantage” (Handfield & Nichols, 1999). If CE is to be implemented, securing a sustainable supply chain of raw materials, products, energy, finances and information is vital. The correct management of flows of the different resources would assure an optimal use of resources, save material cost, minimize energy consumption and promote new business models, engaging both manufacturers and consumers in the supply chain. A well-planned SCM strategy would reinforce the competitive strategy of any company. Such reforms in the business fields is referred to as green or sustainable SCM. Business models and strategies like the ones explained in the previous chapter as well as focus on product design, manufacturing by-products, product life extension, recovery processes, and reverse logistics are a few that can be implemented.

4.2 REVERSE LOGISTICS

Relating to circularity, a closed-loop supply chain (CLSC) is key. Guide and Van Wassenhove defined CLSC as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time.” (Guide & Wassenhove, 2009). It relies in fresh technologies and practices that enable products to re-enter the value circles, through recovering operations carried by manufacturers or partnerships within an extended supply chain network. Such network could include “trading partners, sponsored start-ups, firms involved in other activities (networks in eco-industrial parks), and also with consumers” (Sillanpää & Ncibi, 2018). CLSC is then one if not the main backbones for a successful CE model.

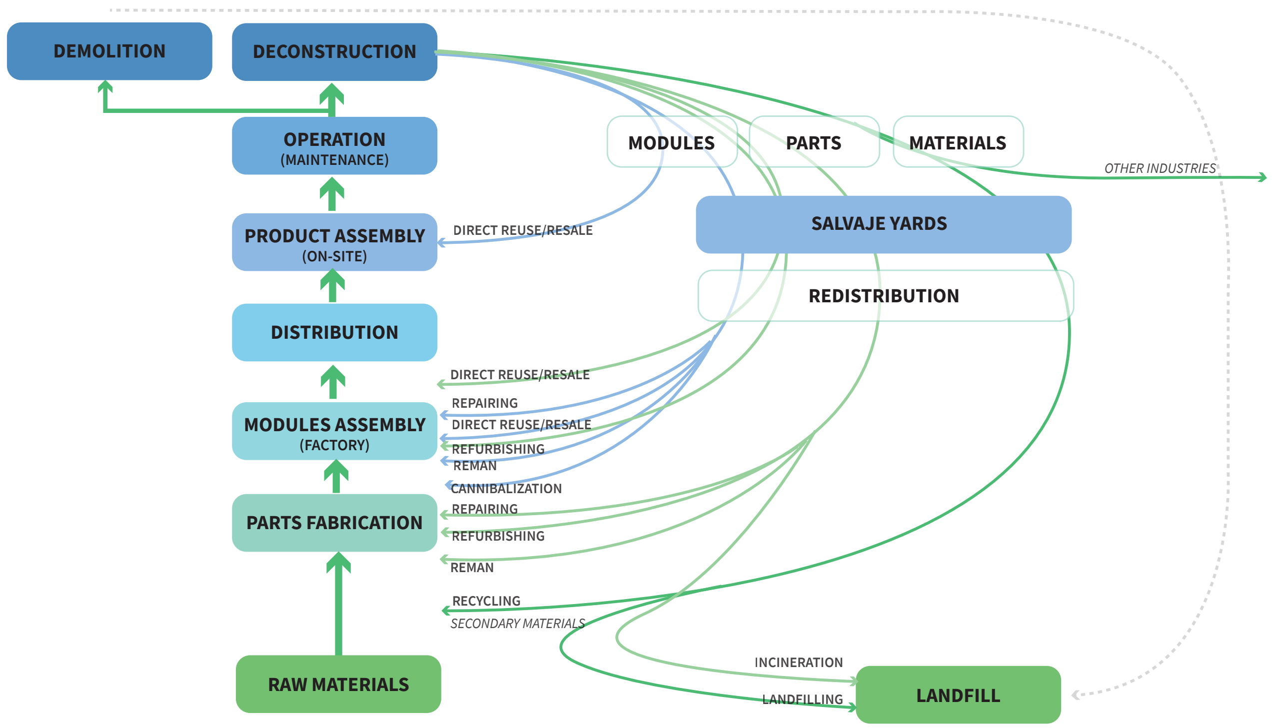


Figure 14 *Facade reverse logistics, based from Butterfly diagram*

Fundamental of closed-loop supply chain management is reverse logistics, a basic idea of "enabling and facilitating the flow of used products back to the original point of manufacturing or to the other outlets able to reincorporate those products into related or completely different production systems" (Sillanpää & Ncibi, 2018). It basically concentrates on movement of materials from the points of consumption back to the manufacturing points. The circular supply chain then involves forward and reverse logistics, and it could be represented using different schemes (see figure 14). There are various factors that need to be taken into account for a strategic network design featuring reverse logistics, such as "collection platforms, recovery methods, available infrastructure, the proper time and state to recover the product at the end of its useful life, and for what new life this product (or parts of it) is being upgraded or transformed" (Sillanpää & Ncibi, 2018). Those are the main differences with Waste Management WM, as the latter deals with products at the end of their life whilst RL attempts to extend the life of the materials and products before they reach the end of life point.

According to Schultmann and Sunke, the stages of reverse logistics can be distinguished into: collection, inspection/selecting/sorting, reprocessing, and redistribution. (Schultmann & Sunke, 2005) The diagrams below (figure 11) show a comparison between a forward logistics and one with recovery options. The complexity lies on the long-life cycles of buildings and the immobile condition of civil objects. Their recovery usually takes place on-site and the high number of actors (contractor, supplier and sub-supplier) and materials of different compositions, degrees of deterioration and use pattern ads to the complexity of the process. The authors also differentiate the return stages of a product: manufacturing returns (material surplus, returns from quality controls or production leftovers), distribution returns (product recalls, B2B commercial returns, functional returns) and customer returns (reimbursement guarantees, B2C commercial returns, warranty or service returns, end-of-use and end-of-life returns). After return, the value of the return can be recovered by various actions such as reuse, repair, refurbishing, remanufacture or recycling (Schultmann & Sunke, 2005), explored in the next chapter. It is interesting to see how Hosseini et al. schematize the RL process and put at the centre the salvage yards and secondary markets' agents, highlighting their central role in the hole process. Their participation will be explored in the elaboration phase.

4.3 MAJOR OPPORTUNITIES AND CHALLENGES

4.3.1 OPPORTUNITIES

Advantages of adopting RL can be put into three different categories: economic, environmental, and social aspects. The economic drivers include cost savings from using less material and energy, lower inventory, less equipment maintenance, lower transportation, procurement, labour and disposal costs, as well as revenues from selling recovered items. The environmental drivers translate into a reduced use of raw materials, less energy consumption for producing products, generating less waste, lower levels of pollution, and meeting environmental regulatory requirements. Social drivers from RL implementation are the generation of a large number of jobs and improving the green image and reputation of the business (Hosseini, Rameezdeen, & Chileshe, 2015). A complete matrix of the advantages of RL is included in the appendix, according to the classification and author. Table 1 & Figure 15 show a summary of the potential advantages. Further exploration of Reverse Logistics will provide and give evidence to other major opportunities, as its application is still starting in the construction industry.

Economic
- Cost savings (less material & energy)*
- Lower inventory
- Less equipment maintenance
- Lower transportation*
- Lower labour and disposal costs*
- Revenues from selling recovered items

Environmental
- Reduced use of raw materials
-Less energy consumption
-Generation of less waste
-Lower pollution levels
-Pushing environmental regulations

Social
- Generation of jobs
-Better image for businesses

Table 1 *RL implementation opportunities*

The opportunities marked with an asterisk are still debatable if they truly represent a positive aspect in the RL contest. Discussions and a real application of such practices will define the advantages in the construction industry. Elaboration on that will be addressed on the second half of the report.

Figure 15 *Main RL implementation opportunities*

4.3.2 BARRIERS

Barriers to adopt RL can be grouped into two: industry-specific and organisational barriers. Organisational barriers include the extra time, resources and effort necessary for the management of collection points and a correct timing. Also, the high initial costs of the labour required for sorting and separating the salvaged materials is a challenge, which is carried out manually. According to a study in Massachusetts, Dantata et al. (2005) found the cost of deconstruction to be 19-25% higher than conventional demolition. The situation is also worsened when construction companies are able to send the extracted materials to easier and cheaper destinations, namely landfills (Hosseini et al., 2015). Another relevant factor is the lack of government incentives, highlighted as one of the major barriers. Lack of standards and technical guidelines makes the use of salvaged items a source of liability.

For the industry-specific barriers, the impact of a large number of stakeholders in deciding the fate of an existing building is one of the main challenges, as well as the fragmented structure of the construction supply chain. There's a lack of cooperation among these and treating construction as a linear process entailing sequential relationships between design, construction and operation phases is a problem (Hosseini et al., 2015). Long lifespan of buildings with changing ownership is another barrier pertaining to the construction industry in specific. As asserted by Schultmann, the composition of buildings at the end of their life are generally not known. RL stakeholders are forced to deal with a variety of product qualities after deconstruction (Schultmann & Sunke, 2005). Lack of infrastructure, specially recovery facilities, infrastructure, technology and the immaturity of markets for salvaged items have been also highlighted (Hosseini et al., 2015). A synthesis of the barriers is presented in table 2 & figure 16, and a more exhaustive matrix has been included in the appendix III, classified by type and author who addressed each argument.

According to Schultmann and Sunke, the main structural difference between the construction industry and the manufacturing industry is not the recovery process, but the organization of the collection and the design of logistic processes from the building site to the recovery facilities (Schultmann & Sunke, 2005). Product recovery not only reverses the product flow with the consequence that there are many supply sources (collection points, retailers) and few demand points (recovery facilities, disposal sites), but that design is complicated by the high uncertainty in many factors. Even the products themselves might have barriers, such as the immobility, the size, the existence of hazardous materials, their design not contemplating easy disassembly, and the wide variety and uncertainty of the location of origin points. Obstacles can be also found in common problems such as the transportation activities, inefficient route planning and empty truck loads, called deadheads. Deadheads cannot be avoided due to the missing planning certainty from the construction sites and usually different role of the actor (Schultmann & Sunke, 2005). The negative perception of the industry and general public must be highlighted, as construction organisations consider environmental management as a non-profit activity. Customer preferences and perceptions that the salvaged materials are inferior in quality, could also affect its use in new buildings.

Figure 16 *Main RL implementation barriers*

Organisational	- Extra time and resources to coordinate operations
	- High costs for specialized labour
	- High costs for selective deconstruction
	- High coordination demand for transportation
	- Easier alternatives for disposing waste
	- Lack of government incentives
	- No standards or guidelines
Industry specific	- Large number of stakeholders
	- Fragmented structure of industry
	- No cooperation between stakeholders
	- Linear process practices
	- Unknown composition of materials/ buildings
	- Lack of infrastructure
	- Immaturity of secondary markets
	- Products not designed for easy recovery

Table 2 *Main RL implementation barriers*

4.4 ACCELERATION OF RL

RL needs close collaboration and an integrated approach of all stakeholders by building partnerships. The construction industry suffers from disconnection of design, construction and operation, as well as poor communication and lack of coordination among the parties involved. There's a need of motivation for the enterprises to take action in reverse logistics; according to Schultmann and Sunk it can be classified in three types of motivation: profit-oriented, legislative, and corporate citizenship drivers. The first has to do with cost reduction for disposal and substitution for new input materials; cost and profit are the most important for construction practitioners. If the savings are shown, one of the main economic barriers would be avoided. The second motivation is related with extended producer responsibility EPR which can translate into profits and more economic security, and the third with the "license to operate" granted by the stakeholders (Schultmann & Sunke, 2005). This last one, even if it is the most subjective, can have a great impact in companies, as activities might be discouraged because of the negative perception from the stakeholders.

More specific factors would need to be taken into account. One of the differences between successful RL in the manufacturing industry and the still experimental one in the construction field is the need of salvage yards or used building material retail operations, UBMROs (NAHB, 2001). These are businesses active in buying and selling recovered materials. Normally, salvaged materials are delivered by a deconstruction agent to a salvage yard. A deconstruction agent could be a demolition, deconstruction or a renovation contractor who delivers extracted materials from demolished or renovated building or maintenance, renovation or adaptive use projects (NAHB, 2001). Materials can either be purchased through on-site sales or recovered directly from the building slated for demolition or renovation, according to the mentioned report by the NAHB. Elaboration on whether this factor is decisive or not for an optimal strategy will be done in the Application chapter.
The characterisation of returned products is also vital: composition (presence of hazardous materials, material heterogeneity of product, and the size of the product), deterioration (aging during its use), and use pattern (issues like location, intensity and duration of use). Hosseini et al. address two related concepts Harvesting of Information (HoI) and Design for RL (DfRL). There is a major positive influence if adequate information and knowledge are provided. HoI is an integrated set of processes in a RL system geared towards on-time capturing of any internal and external organisational information regarding the nature, quality, amount, flow, locations, and relevant aspects of logistics of returned products from main performers and convert this knowledge into actionable awareness that can be shared with others within the RL network (Hosseini, Chileshe, Rameezdeen, & Lehmann, 2014). DfRL, on the other hand, concerns designing the products in order to enhance the ease and the potential of value recovery of returned items. It is built on the premise that products should deliver some value to end-users alongside maintaining a return value that must be obtained from returned items with minimal costs, risks, uncertainties and effort.

Designers could also play a significant role in promoting RL as they are key decision makers with regard to the use of salvaged materials in new buildings. Regulation should eliminate some of the risks perceived by designers and builders, both at the deconstruction stage and for the use of salvaged materials in new construction (Hosseini et al., 2015). Designers should practice the principles of design for deconstruction and take leadership in promoting the use of salvaged materials, both to clients and to the other players in the design and construction team. Builders should use salvaged materials and deploy construction methods that make reverse logistics an easy process. Actually, RL is assured if on-site sorting is possible, or "yard installation" as coined by Hosseini (Hosseini et al., 2015). For the demolition subcontractors and salvaging companies, deconstruction (addressed in the Framework chapter) and dismantling should be the common practice as opposed to mechanical demolition, enhancing the productivity of the process by training the workmen. They should also share and manage the knowledge when it comes to the benefits of reverse logistics to reduce the overall risk levels.

As for the theoretical level, little is known about the application of reverse logistics in the construction industry. Theories and innovation diffusion are key to make the concept widely accepted. Regarding the hierarchy of practices in which reuse and reduction are of the highest priorities, RL should be considered the policy needed to accelerate such practices. Explorations on the economic and financial benefits must also be done, as well as the link between RL and the reduction of greenhouse gas emissions. The implementation of integral virtual networks as BIM needs further development, and more practical matters such as health and safety when it comes to the recovery process. A synthesis table of the major accelerators identified in the literature research is presented below as well as the casual loop diagram found in the appendix IV, representing the major elements for RL to work.

ACCELERATORS
- Focus on the savings, specially economic
- License to operate by stakeholders
- Proper infrastructure (salvage yards)
- Harvesting of information (HoI)
- Design for reverse logistics
- Eliminate regulation risks of used products
- Change designers' perspectives on used products
- Yard installation
- Choose deconstruction over demolition
- More research

Table 3 *Main RL accelerators*

Figure 17 *Lessons from other industries*

4.5 LESSONS FROM OTHER INDUSTRIES

Case studies regarding reverse logistics tasks concentrate in the automotive industry, the industry of electrical and electronic equipment, and the publishing industry (Schultmann & Sunke, 2005). In the conference proceedings “Challenges and opportunities for reverse logistics initiatives in the automotive industry” Nunes, Bennett and Shaw study how some automotive companies handle reverse logistics. Their findings show that companies are trying to respond to the end-of-life legislation based on cost-effective approaches as well as corporate environmental responsibility. They use outsourcing when expertise is found to extract value from scrap and there is cooperation with suppliers and vendors to facilitate the dismantling of cars and recycling of parts (Nunes, Bennett, & Shaw, 2011). The automotive entities also encourage their Waste Management Companies with not only their normal service revenue, but an extra incentive for assuring a proper waste treatment. Another valuable example is explained in the Toyota Supply Chain Management book from Ananth Iyer, in which a 4VL model was developed, highlighting the importance of variety, velocity, variability, and visibility in their production line (Iyer, Seshadri, & Vasher, 2009). Visibility, for example, refers to the transparency in the processes that enables a continuous learning and improvement. It is this continuous capacity to learn and the balance Toyota achieves in their supply chain that has been emulated by other companies. This much-needed level of coordination is the goal to be applied into the construction industry.

4.6 CONCLUSIONS

Even if Reverse Logistics in the industry has not been adopted and the amount of research has been minimal, the findings here shown are a good basis for the eventual development of the topic. The opportunities it offers as well as the barriers, will be mapped in a holistic framework to bring together the different theories and sources in a single platform. As highlighted by some of the authors, there are already some identified strategies that can be incorporated to accelerate the implementation of Reverse logistics. They will be taken into consideration in the Design phase of the current research. Such accelerators will not just inform but provide food for thought in the development of new systems that make RL more feasible.

5 CIRCULARITY IN THE BUILT ENVIRONMENT

5.1 THEORY OF LEVELS

Circularity when applied to the Built Environment can be digested in different levels, according to Klein: it starts form the material level and goes into products, buildings, cities and regions. Circularity is present at the different scales and to complement the process technology, design, flows and resources, society and stakeholders, economy and management are always present (Klein, 2019), as shown in figure 18. Time is a major factor to take into account, as highlighted in the Circular business models section.

The relationship between time and a building was already addressed by Stewart Brand, in which he developed a temporal theory to understand buildings. Instead of focusing in the spatial aspects of the building, he addresses each layer of the building and assigns a lifespan according to its characteristics with the intention of developing a long-term adaptability, allowing the building to evolve and age adequately (Brand, 1994). Shown in figure 19, he identifies 6 different layers: the site (eternal), structure (60-200 years), skin (30-60 years), services (5-30 years), space plan (5-20 years), and stuff (5-15 years). Each layer should have their natural cycle and be adaptable according to their life cycle.

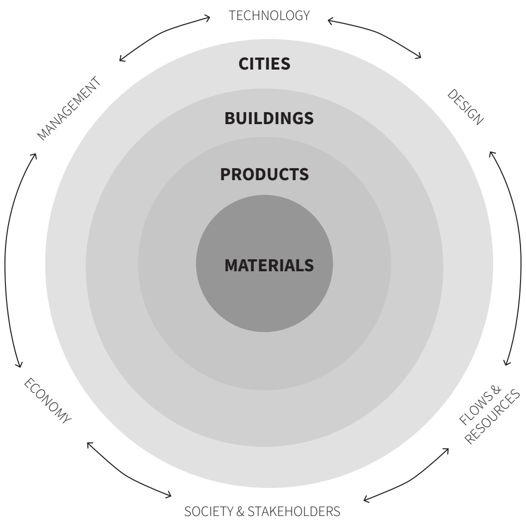


Figure 18 *Circularity levels by Klein (2019)*

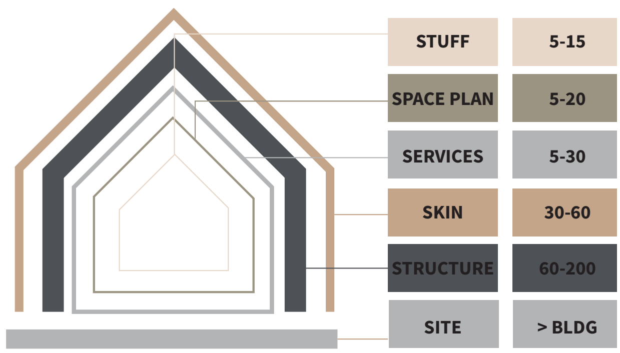


Figure 19 *Building layers by Brand (1994)*

A more detailed classification of levels is developed by Eeckhout, focusing in industrial building products, starting from raw materials and arriving at the building complex. His original system is simplified to the field of facades in Figure 20. The product levels he identifies are the following (Eeckhout, 2008):

- **Materials**: as the base ingredients without any further shaping or treatment. Composite materials fall also into this category.
- **Standard materials:** they are intermediate goods, available in standardized forms, I-beams for instance
- **Commercial material**: shaped for the purpose of a special product or project, such as extruded aluminium profiles for window frames or rubber gaskets
- **Elements:** assemblies of different commercial materials. An IGU for instance
- **Subcomponent**: closed assembly of elements with a functional purpose, like a window frame
- **Component**: independent functional building unit, assembled off-site and transported to site. Unitised façade part
- **Building part**: collection of elements and components with identical technical function, like a curtain wall.
- **Building** is the whole collection of elements that make up a building.

Relating both concepts, the shearing layers of Brand and the classification made by Eeckhout, a visual classification can be made. As shown in the Figure 21 by Beurskens and Bakx, they relate the building systems as the first four layers of Brand (except site): structure, skin, service and space plan (Beurskens & Bakx, 2015). The rest is divided into systems, subsystems, components, elements, and materials. Starting from the system level and until the most detailed one, they also highlight some principles that must be taken into account for a correct application of circularity, namely design for disassembly and design for adaptability, as well as the election of sustainable materials. The first two will be explored in the Assessments chapter.

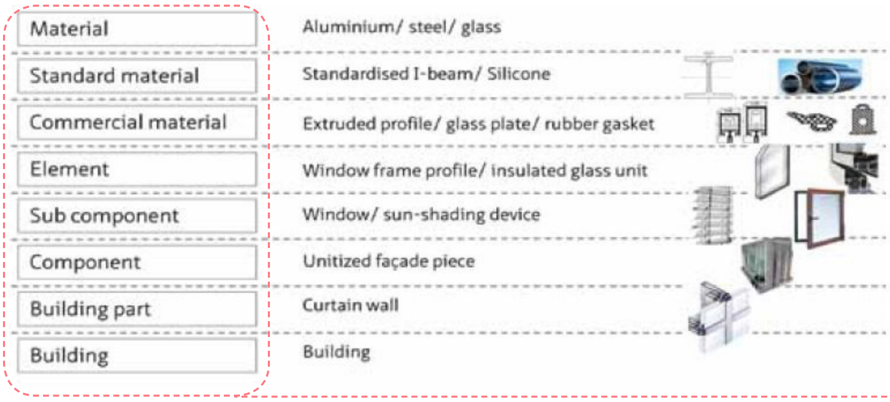


Figure 20 *Product levels for facades by Eeckhout (2008)*

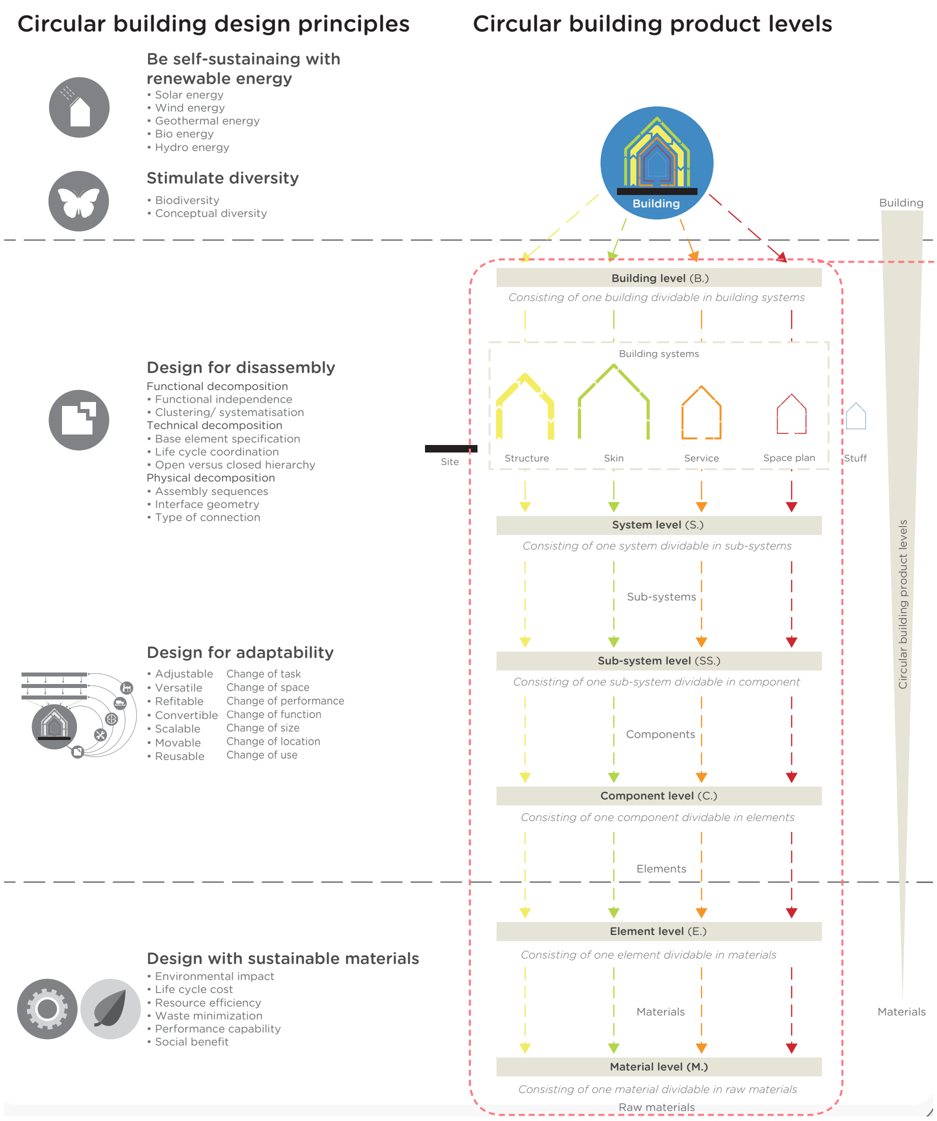


Figure 21 *Construction domain by Beurskens & Bakx (2015)*

5.2 RE-LIFE OPTIONS

There have been several articles addressing the different re-life options that might reintroduce materials into the productive loops of the construction process. There have been classifications of 3, 4 , 5, until 10 R-imperatives for circular economy in academic literature. For the current research, the system of 10 R's shown in Figure 22 is reviewed, explained by Reike, Vermeulen and Witjes. The strategies are then inserted in the supply chain process in Figure 23. They are comprised of 2 preventive options or R0, denoting zero use and impact and 8 reutilization options (Reike, Vermeulen, & Witjes, 2018):

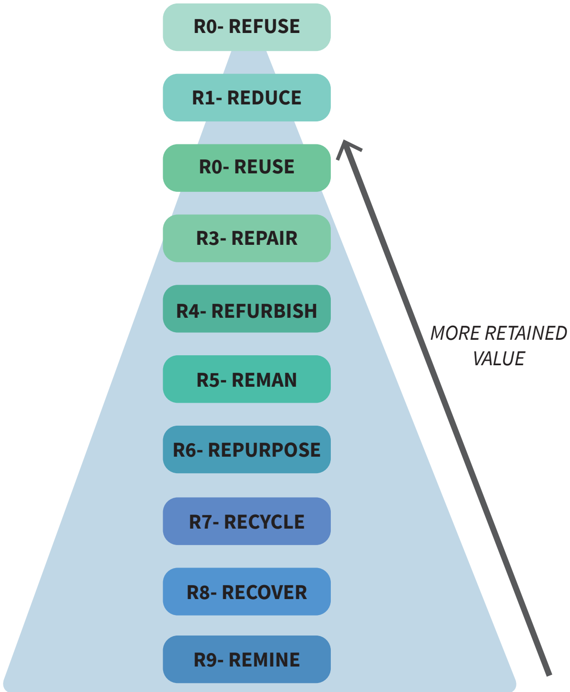


Figure 22 *Re-life options*

- **Short loops:** products remain close to its user and function
  - **o Refuse/R0:** for consumers, it means buying and using less, shifting to a post-material lifestyle. Producers can also refuse the use of hazardous materials or virgin materials.
  - **o Reduce/R1:** instead of disposing waste after it is created, eliminate the production of waste. It can also be understood as using products less and sharing for consumers. For producers, it means using less material per unit of production.
  - **o Resell/Reuse/R2**: it applies to second consumer who does not need significant adaption to use a product, and it works as new and with the same purpose. Minor maintenance and small repairs are common here. Reuse has been regarded as the most preferred method for keeping a component or material back in the construction loop. This requires less energy, raw materials and generates less pollution compared with the other 8 reutilization strategies (Guy and Gibeau, 2003).

- **Medium long loops:** products are upgraded and producers are involved
  - **o Repair/R3:** bringing back to working order a product to extend its lifetime and making it as good as new. It can be done by different actors and with or without changing ownership.
  - **o Refurbish/R4:** it applies when overall structure of a large multi-component product remains untouched, while many components are repaired or replaced.
  - **o Remanufacture/R5:** it applies when full structure of multi-component product is disassembled, checked, cleaned and repaired, resulting in a product with a quality comparable to its original state.
  - **o Repurpose/R6**: the products get a distinct new life cycle and it is adapted to another function.

- **Long loops:** products losing their original function
  - **o Recycle/R7:** processing of mixed streams of post-consumer or post-producer products to capture nearly pure materials, by means of expensive technological equipment. The products lose their original structure and their function, and can be applied anywhere, becoming secondary materials.
  - **o Recover/R8:** extraction of elements from end-of-lie composites. It is also understood as capturing the embodied energy of waste, linked to incineration and biomass.
  - **o Re-mine/R9:** retrieval of materials after the landfilling phase, extracting the valuable parts from disposed products.

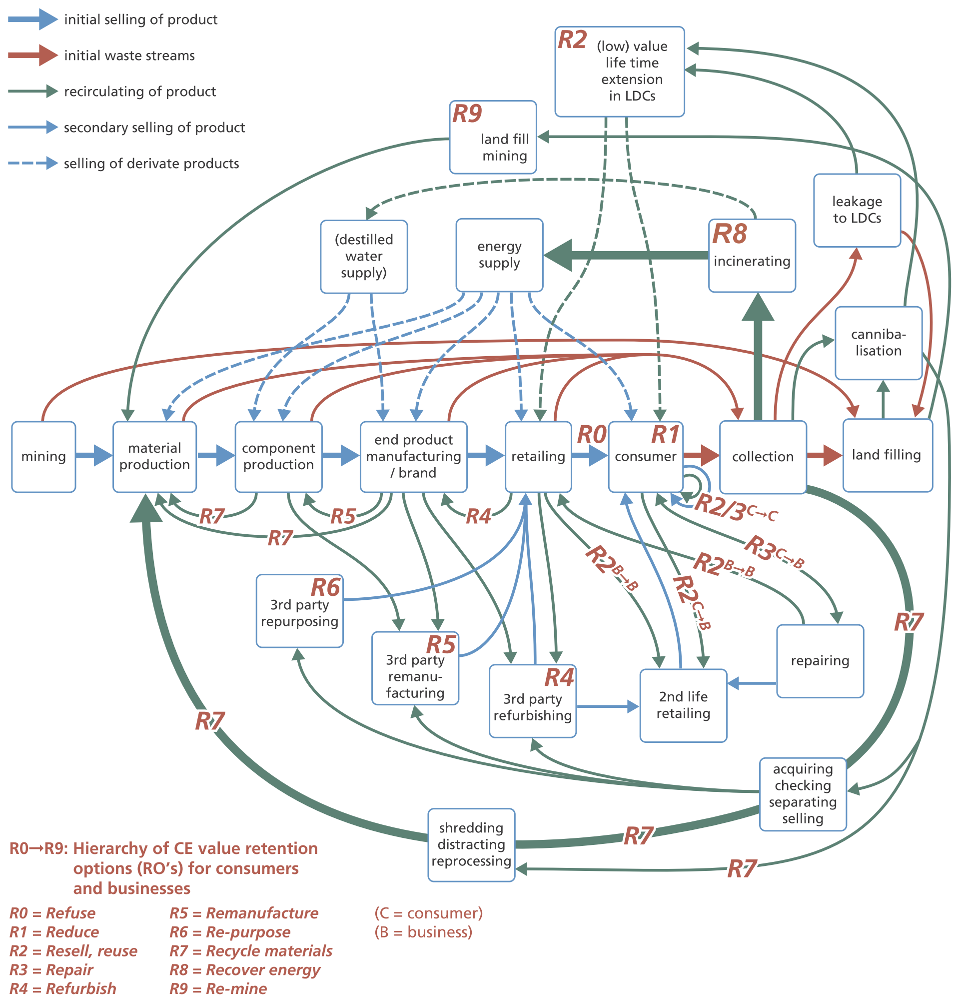


Figure 23 *Re-life options inserted in circular scheme by* Reike, Vermeulen, & Witjes (2018)

5.3 DESIGN STRATEGIES

Parallel to the distinction made between possible treatments for re-life of products, there are some basic strategies that promote circularity in the construction industry. They are several, but a summary is presented in the table below (Ellen MacArtur Foundation & Granta, 2015).

The described strategies will be reprised in the second half of the research, when the design stage is conducted.

Modularity in buildings	Designing with a kit-of-parts logic is highly valuable, as it allows to interchange parts and rely on existing resources to complete a building. It also refers to prefabricated elements, which streamline the construction process and prevent material losses on site.
Standard dimensions	Designing with standards dimensions allows for major compatibility between elements and assures higher residual values.
Extending life of products	Designing products that endure and have long lifespans is vital, as well as detailing a building that is protected from extreme weathering. Having protected building systems and subsystems ensures major durability and less need of maintenance.
Dismountable components	Highlighted throughout the current research, designing products that are easily recovered is a must. When products enable dismounting, the whole process is improved and stakeholders have less burdens in the loop closing.

Table 4 *Design strategies*

5.4 INTEGRATION

Both of the previous sections could be visualized in a similar scheme to the butterfly diagram as seen in Figure 24, applying it to the construction industry. Beurskens and Bakx did a “Circular building construction model” in which the usual linear economy is depicted in a straight line, going downwards, starting from the resource extraction and reaching the landfill. The building layers are also shown in this process. After extraction, the material manufacturer is responsible of the transformation of virgin feedstock into valuable and useful material. The product manufacturer then transforms the material into products, easy to assemble. The service provider is the connection between product manufacturer and the user, offering product-service systems; they should be linked with re-assembler who is in charge of disassembly and reassembly of the building systems (Beurskens & Bakx, 2015). Communication and coordination between designers, contractors and manufacturer is vital at this point. After (re)use, the re-life options take place, not before the proper disassembly is conducted. The re-life options should be tight circles, as it would mean products remain closer to their function and user, therefore retaining their value. Service is also another thing to take into account, which mainly consists of maintenance, repair and monitoring. Lastly, the cascading concept refers to the possibility of materials flowing to other function within the same section (closed loops) or going directly to other sector, or open loops.

5.5 CONCLUSIONS

Circularity in the Built environment is translated into different layers, from the most general to the most particular. In this case, focus will be put on the product and material level, reviewed in the following two sections. Besides, even if there are several options when it comes to re-life and possible treatments given to products, just reuse and remanufacture will be further developed due to the extensive literature found. Recycling will also be used as a counterpoint to compare the other two “preferable” options. At the end, the layering helps to organize the application of circularity and aligns the design strategies for an easier recovery and a potential second use. Having such principles are key to enable the rest of the process to flow properly.

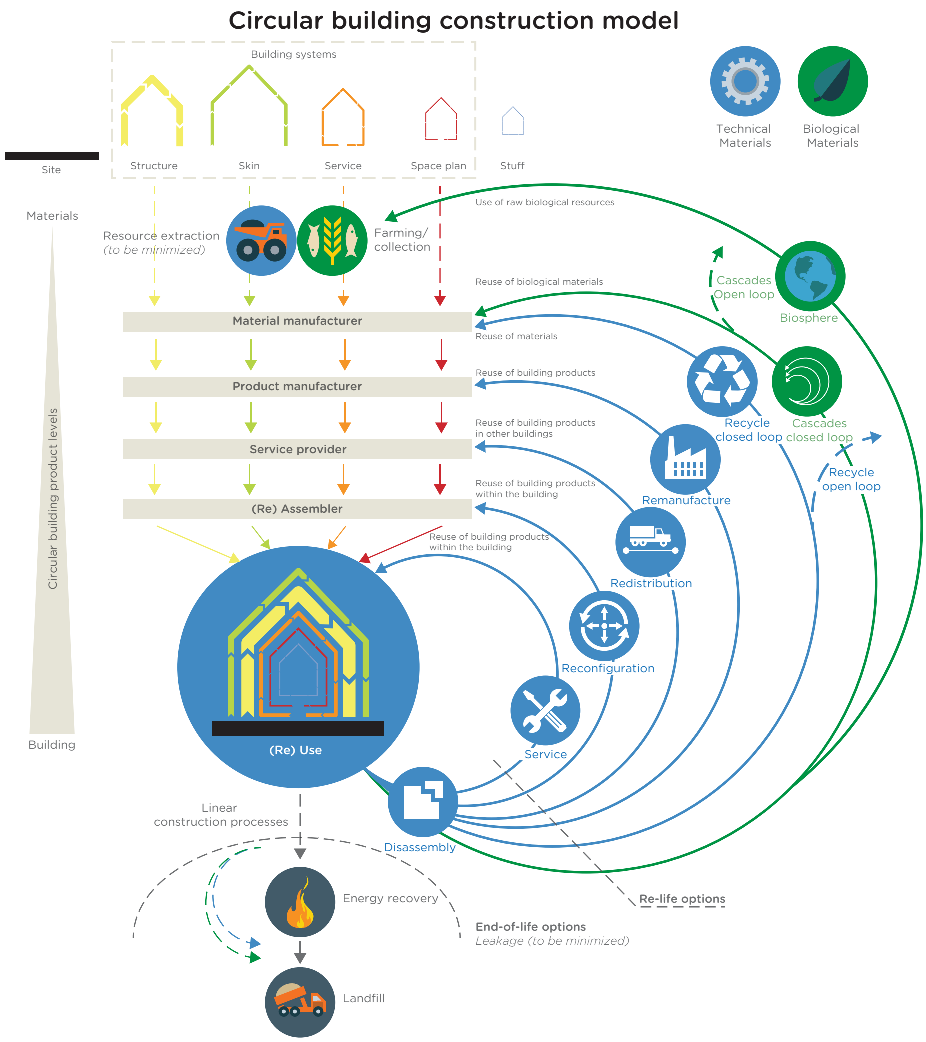


Figure 24 *Circular building construction model by Beurskens & Bakx (2015)*

6 MATERIALS

6.1 OVERALL VIEW

According to a report by OECD, the world's consumption of raw materials is predicted to double by 2060, caused by the global economy expansion and the increase of living standards (OECD, 2018). Double the pressure on the environment would mean 167 Gigatons of global materials by 2060, almost double of today's 90 Gigatons. The extraction and processing of fossil fuels, metals, and non-metallic minerals will also translate to a worsening of air, water and soil pollution. Even though measures have been taken already, shifting to a service industry and more effective manufacturing processes, the increase in resource consumption is prevalent. The report, presented by Masamichi Kono, states the most dramatic rises are minerals, which includes construction materials and metals, especially in high-developing economies, the figure below shows the projections to 2060 (OECD, 2018).

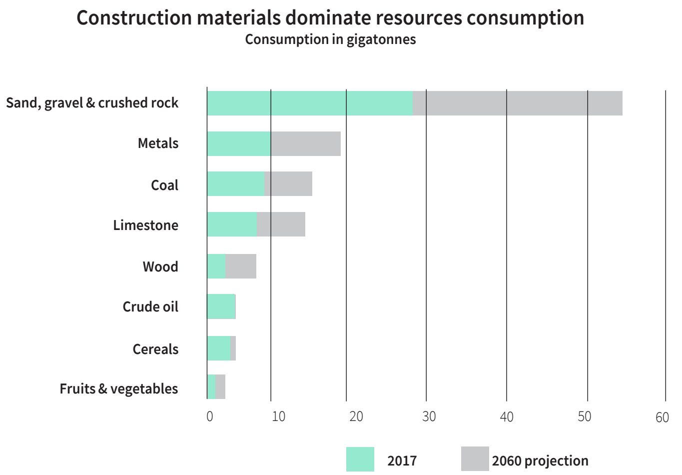


Figure 25 *Resource consumption in Gigatonnes by OECD (2018)*

The report also explains the recycling industry is a tenth of the size of the mining industry (in GDP share terms) and it is most likely to grow, but it won't be enough to compete with the primary material extraction. The global environmental impact analysis of the extraction and production of seven metals, including aluminium and some other building materials like concrete, show sever impacts as acidification, climate change, energy demand, human health and toxicity of water and land (OECD, 2018). An interesting observation in the "Global Material Flows and Resource Productivity" report by Schandll, links the major material footprint and domestic material consumption per capita in countries with very high Human Development Index (Schandl et al., 2016). The Netherlands and most of the European countries form part of this group. Making a shift in the economy is then a vital strategy. These indicators can be visualized in the graphs below.

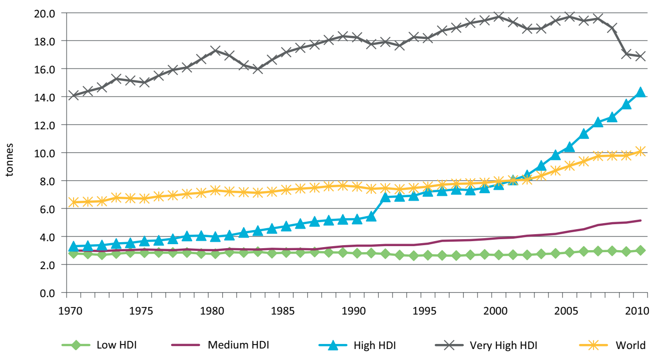


Figure 26 *Major material footprint by HDI, Schandl et al. (2016)*

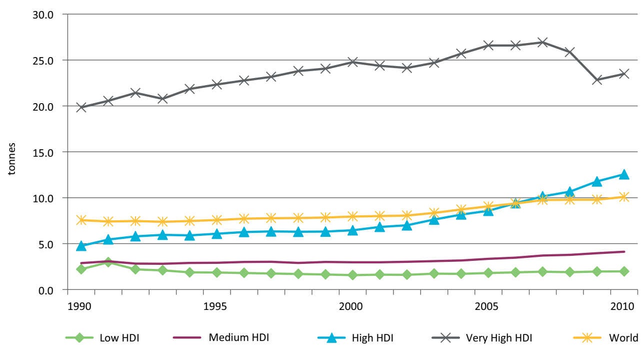


Figure 27 *Domestic material consumption by HDI, Schandl et al. (2016)*

Finally, according to the European environment state and outlook 2020, between 30 and 60% of the environmental pressures associated with European consumption are on countries abroad where many goods are produced – this footprint on resources such as land, water and energy showed an upward trend in the period studied, while reductions on certain environmental pressures were seen within Europe (Pantzar & Suljada, 2020). This poses ethical issues as well, as the negative side effects are not even felt in the consuming countries, but on the producing ones. A shift in consumption and production methods is necessary.

6.2 MATERIAL FLOWS

The REPAiR project, standing for Resource Management in Peri-urban Areas, studies the potential reuse of secondary material. The project analyses and models specific areas with their subsystems to define the metabolic patterns, focusing in the flow of waste from its production point to the management location. An interrelation is made between several factors, answering the spatial dimensions, as well as the actors involved, and at what stages is their involvement related. Among their tasks is the Material Flow Analysis, or MFA, which addresses the material flows and stocks, taking into account the patterns of consumption and production of waste (Geldermans et al., 2017). Instead of using a standard MFA, the authors develop a unique method called the AS-MFA, or Activity-based Spatial Material Flow Analysis, which basically links the flows and stocks to their involved actors and locations, including specific quantities and quality.

The goals of the AS-MFA are various: to determine the qualitative and quantitative waste flow specifications in space and time, identify specific activities relating to material flows and stocks, identify the area's major physical and human processes, find out how and where such processes are interlinked, and illustrate the magnitude of stocks and flows on a map (Geldermans et al., 2017). They follow a specific procedure to achieve these goals, which consists in six steps:

1. Define material scope: by determining challenges with local stakeholders, materials are chosen. The availability of information is vital, as well as traceability and justifiable reasons for the selection of a specific material.

2. Define supply chain of material: it should be conceptually defined per waste material /key flow. By understanding the whole chain and the activities and actors involved, a systems perspective is taken. The waste material flows and by-products from all the activities should be identified.

3. Select geographical area and the spatial scale: the smaller the area to be studied the more detailed the analysis. This is closely related to the actors to be analysed.

4. Define case specific supply chain: the specific activities from the elected region are identified as well as the actors. NACE codification (translating the activities to a system

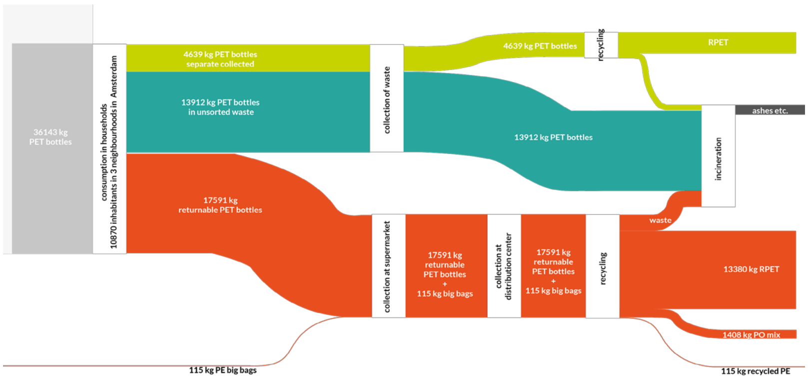


Figure 28 *Sankey diagram by Geldermans et al. (2017)*

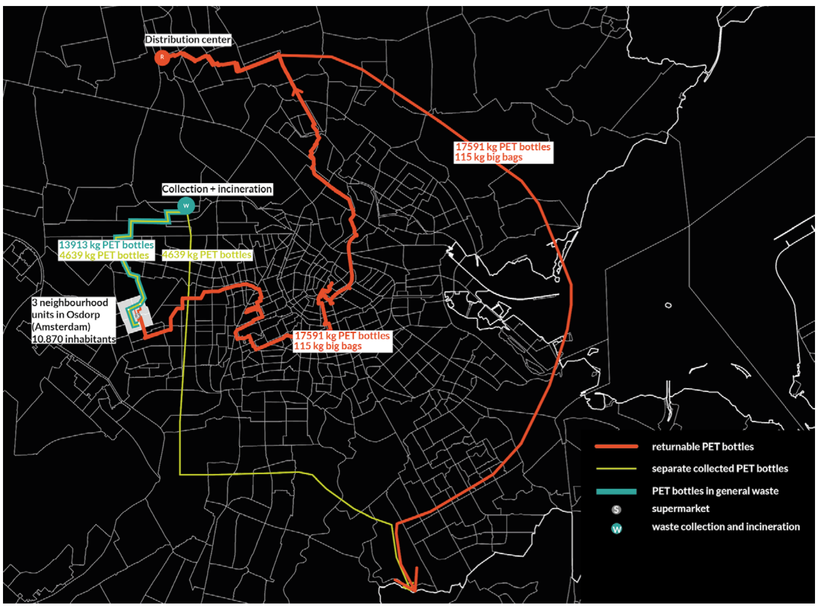


Figure 29 *Spatial representation by Geldermans et al. (2017)*

of codification) is conducted and dent to experts to manage the information and determine how many actors are registered with such code.

5. Mass-balance: the data on quantities and quality of the material is collected. The mass balance per actor is simple, the inputs should equal the final sum of stock and outputs. It is measured in mass unit, either kilograms or tonnes. In this step, more data is collected, such as quality of the material input, stock and output.

6. Map and visualize the results: the final outcome is to visualize the previous steps in a physical map, showing with lines and widths the quantities of materials and their flows, according to the activities performed by every actor. A Sankey diagram is first schematized (Figure 28) and a regional map is produced (Figure 29).

These types of tools are supposed to be highly useful for decision-makers in the resource, waste and environmental management fields. Even though the project does present a valuable tool and analysis, their results cannot be used as references for the current research as their focus only lies in food waste. Gelderman explain their initial intention was to also describe the flows of Construction & Demolition Waste, however, the time and resources in hand were not enough to provide a proper study. The next section elaborates in a potential way of studying such materials, in a way that an approximate result is rendered at the end of the procedure.

6.3 CONCLUSION

For the current research, the author is aware of the barriers to implement the same process as the REPAIR project. Even the researches of REPAIR highlighted the amount of labour their own methodology must undergo, as material flows are complex and involve numerous actors and activities. Besides, getting a hold of the information to map an accurate flow of materials is a task that deserves its own research. Companies won't disclose information if it is compromising, and some may not even possess such data. Under such circumstances, a simplified version of the methodology is devised to understand the broader flows of specific façade materials. Given the collaboration with VMRG, focus in metallic components, namely aluminium, will be done. The following steps, summarized in Figure 30, will be conducted:

1. Define material: a specific material will be chosen as well as the components that make it up. This is aligning with the façade component to be analysed. For example, for a common curtain wall mullion, aluminium would then be chosen.
2. Supply chain scheme: a generic supply chain will be schematized to understand the general steps in the manufacturing of the façade component.
3. Identify specific author: the project will study a product from a façade. The façade and system provider will then be the main authors to be studied, as well as the providers and the post-consumer agents.
4. Location definition: in this case, because of the collaboration with VMRG, the Netherlands will be studied. In the Design phase, having identified the actors of the existing façade and other involved in its manufacturing, a specific location will be defined.
5. Mapping: all the previous information is mapped into a physical regional map, identifying the actors, their location, and type of material flowing. The width of the material will represent the quantities broadly, and if information of the quality is obtained, it will also be represented. The previous step of mass balancing is not taken into account, as quantifying the materials going in and out require highly specific information that most probably won't be available. If possible, it will be carried out before the mapping step.

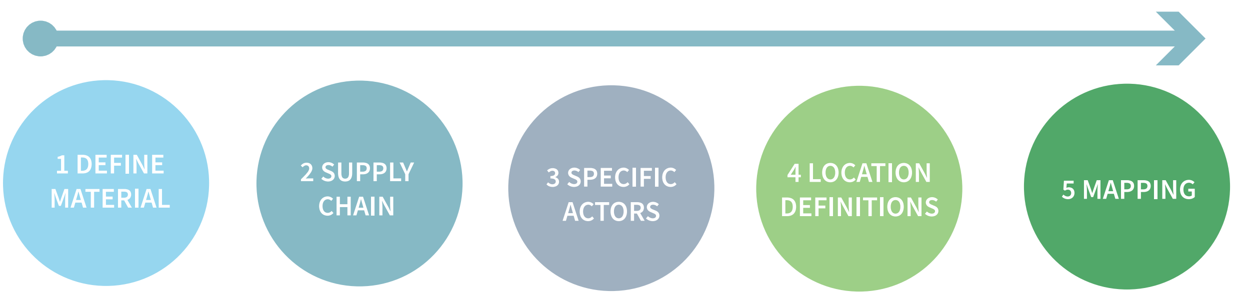


Figure 30 *Proposed material flow methodology*

7 PRODUCTS / FACADES

7.1 CONTEXT

Following the levels in which circularity is inserted, products are the next level after materials. To target the façade as a product is logical as it represents from 30-40% of the initial investment of a new building project and up to 50-90% for a deep energy renovation (Dall'O, 2013; Parker & Wood, 2013) as shown in Figure 31. Moreover, the façade of a building is becoming highly specialized and represents 25-30% of the embodied energy of a building (Michael, 2016). Facades require a special focus as more services go into them, meaning more material, resources and labour are put into such products.

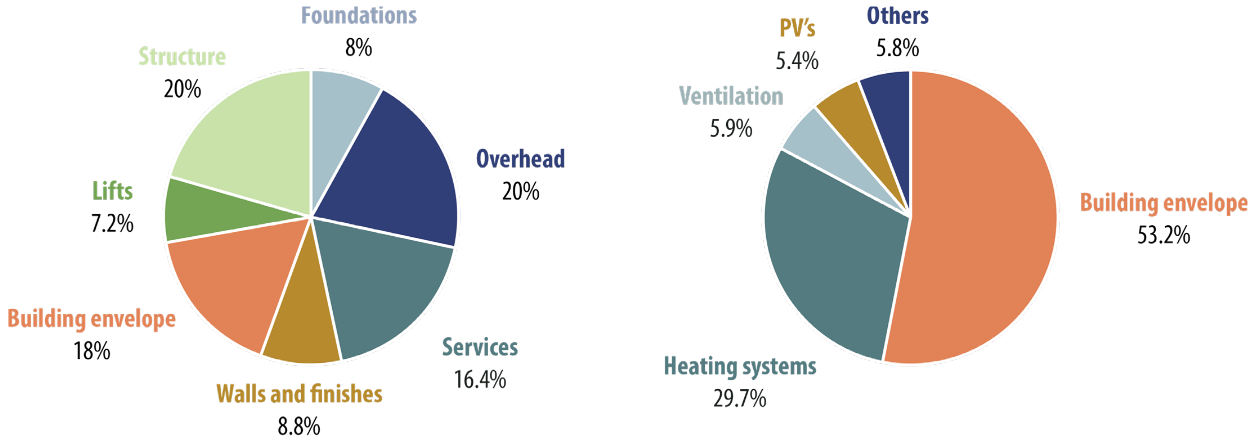


Figure 31 *Share of common building systems in overall cost (Dall'O, 2013; Parker & Wood, 2013)*

7.2 TYPES

Facades can be essentially defined as the envelope of buildings. With time, their complexity and functions have increased dramatically, resulting in different types. A matrix of functions was developed by Knaack, in which the overall roles of a façade are identified (Appendix VI). The main ones described are: insulation against hot, cold and noise, waterproofing, providing natural light for interior, protection against light, resistance against loads (wind, interior, and self-weight), vapour management, visual contact to outside and inside as well as the architectural appearance. Adaptability is a recent topic, as discussed in the next chapter, in the list of requirements.

When it comes to types, not a single definite classification system has emerged, making it difficult to come up with an overall scheme. From the types, two are highlighted because of their extensive use: curtain walls and window walls. Curtain wall systems are generally composed of a lightweight aluminium frame onto which glazed or opaque infill panels can be fixed, forming a water and air-tight barrier from external conditions (Klein, 2013). They hang from the main structure and act as an independent system. Window walls, on the other hand, are compartmentalized within the structure and slabs of the building, interacting closer with the building systems. They can come in several shapes and forms, and usually follow a panel configuration like the curtain walling system. Their main characteristics are described in Table 5 (Corp., 2017), as well as some of their major advantages and disadvantages.

Even though curtain walls are more labour- and cost-intensive, some features are safer when compared to window walls regarding structural integrity and resistance to moisture, wind, earthquakes, and heat. A graphical representation of the various design alternatives are schematized in Figure 32, presented by Knaack and Tillmann (Knaack et al., 2014).

Curtain wall systems	
Stick systems	First vertical mullions are installed and anchored to the floor slabs. Most of the times the glazing occurs in situ and additional components like horizontal mullions and spandrel panels are fixed once the vertical mullions have been placed.
Panel system	A less cost-intensive option than stick systems, they consist of large panels that are prefabricated off-site and then attached to anchors within the building structure, specifically the slab.
Unit-and-mullion system	First mullions are anchored to the structure, and then prefabricated units are attached to the mullions.
Window walls	
	Most commonly manufactured and glazed off-site, placed in between the slabs and sealed with caulking and tape
	Cost-effective option when compared to curtain walls (one half the cost of a curtain wall), eliminating the need for time-intensive construction of the mullion system and on-site glazing walls.
	Risk of sound transmittance is greatly reduced, as noise cannot reverberate across the entire system when window walls is compartmentalized between floors.
	Pre-certification by manufacturer helps on reducing costs as well as project cycle times due to an optimized installation.

Table 5 *Facade types*

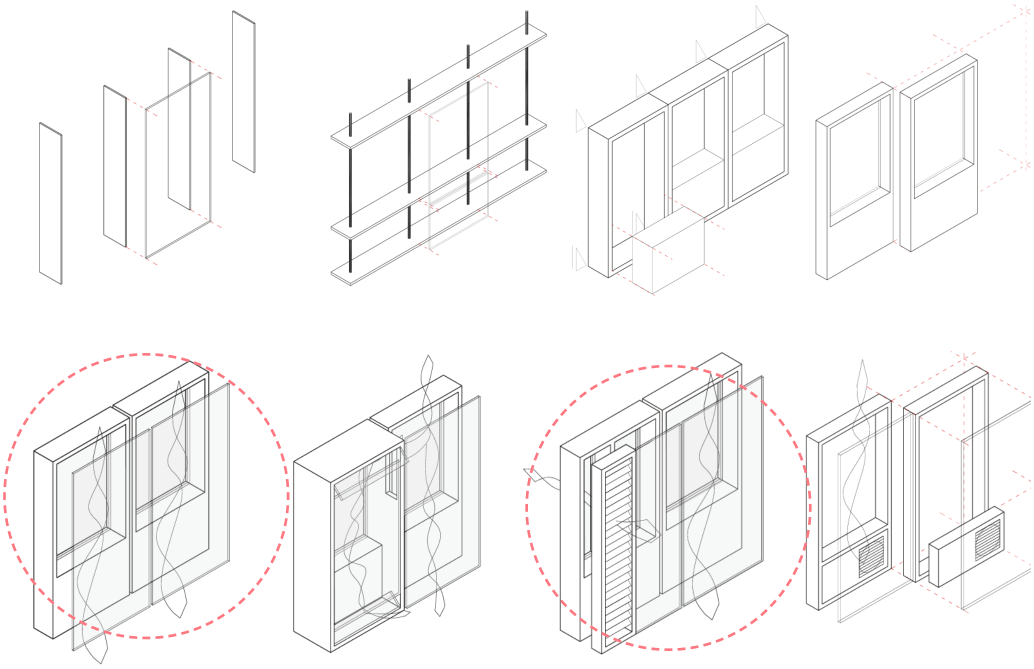


Figure 32 *Facade functions by Knaack, Klein et al.(2014)*

7.3 PROCESS

Even if it is a part of an entire building, the production of a façade is a complex process on its own. Different stakeholders must come into place to finally install the façade in place, having a whole manufacturing and assembly process behind. Klein schematizes such process in Figure 33, in which the actors and phases are identified. Architects and engineers are in constant contact with the client to develop de project, different from the involvement of a façade supplier who is not related in the initial stages. They are however, interested in making long-term relationships with clients and consultants for further projects. The systems must be developed beforehand, serving the façade supplier for the overall façade panel assembly.

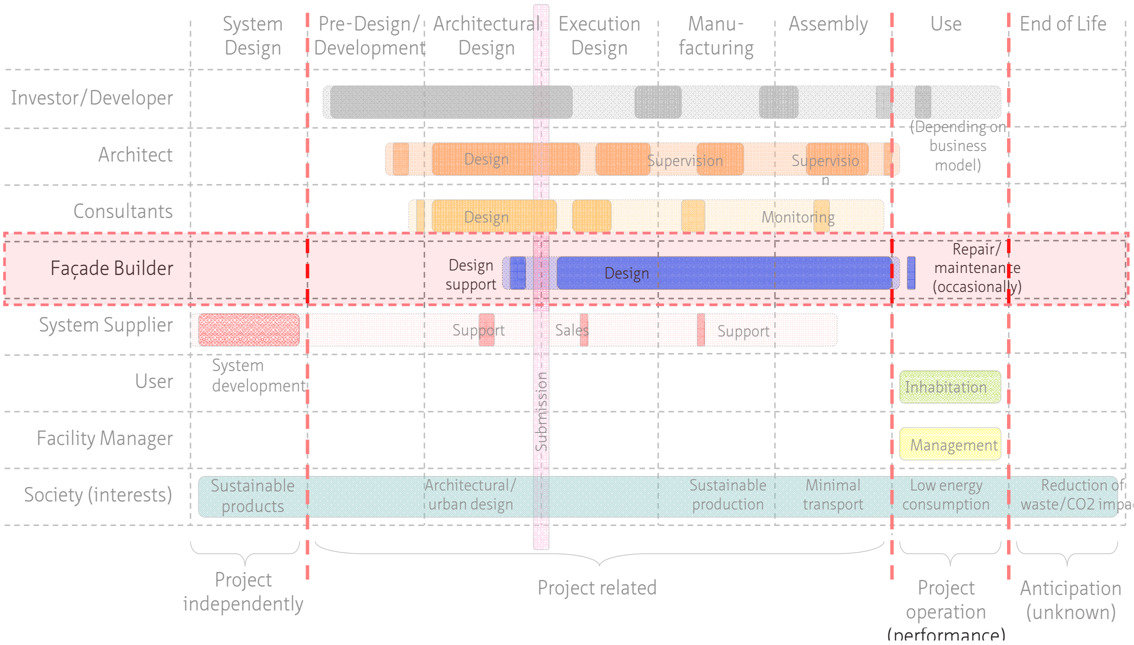


Figure 33 *Different phases of a construction project by Klein (2013)*

7.4 LEVELS

Based on the levels already explained in chapter 5, a façade can be understood in such terms as illustrated in figures 34-35. For a typical curtain wall, the glass, aluminium, and rubber are the main materials. Commercial materials would then be the extruded aluminium profiles for the mullion structure and the rubber gaskets for airtightness. The next level would be the elements, in this case the assemblies of different commercial materials. The union of these make up the sub-components, such as the insulated glass unit and the window frames with the spacers and glazing gaskets. A level up, components, can include the full window, a sun-shading system or a building service component. Finally, the sub-system is the independent functioning building unit as described by Eeckhout. It is assembled off-site and installed directly, such as a unitized façade panel. The previous components form a building system, which is the total curtain wall of a building.

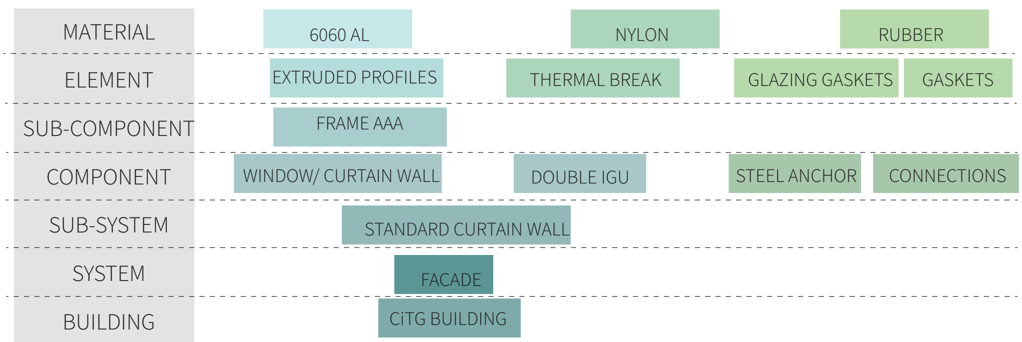


Figure 34 *Typical curtain wall divided in product levels*

7.4.1 GENERAL COMPONENTS

A common detail of a curtain wall, specifically where the IGU units meet and the mullion is placed, has become the base to study such systems. The detail and the main functions performed by each component are shown in figure 36, as an exercise to identify the circular levels previously described. Variations of the detail are made according to the situation and application, but the basics elements remain the same. An exploration of the optimization of such components will be made in the design phase if relevant, with the goal of developing an alternative to the traditional configurations.

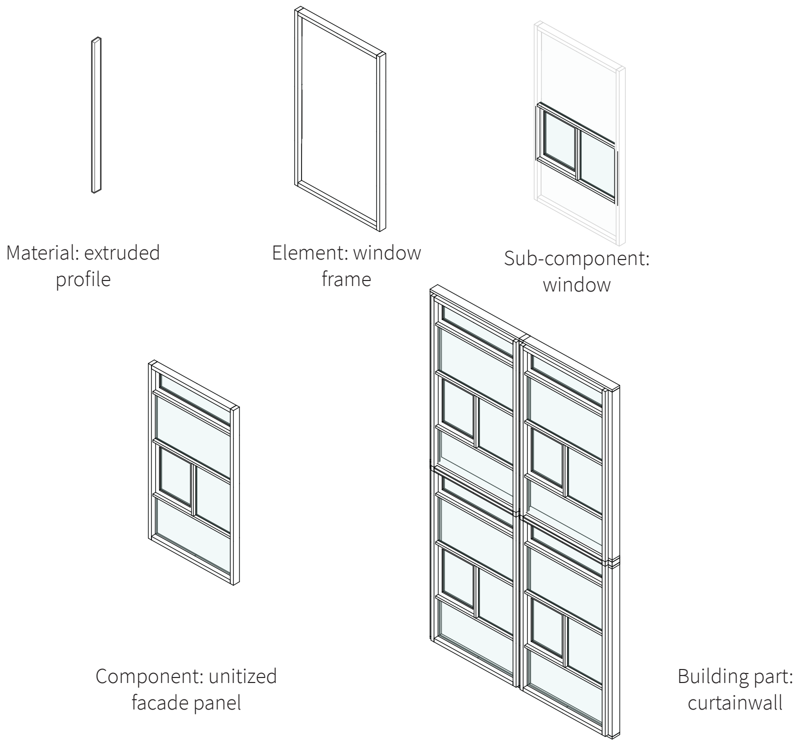


Figure 35 *Typical curtain wall divided in product levels*

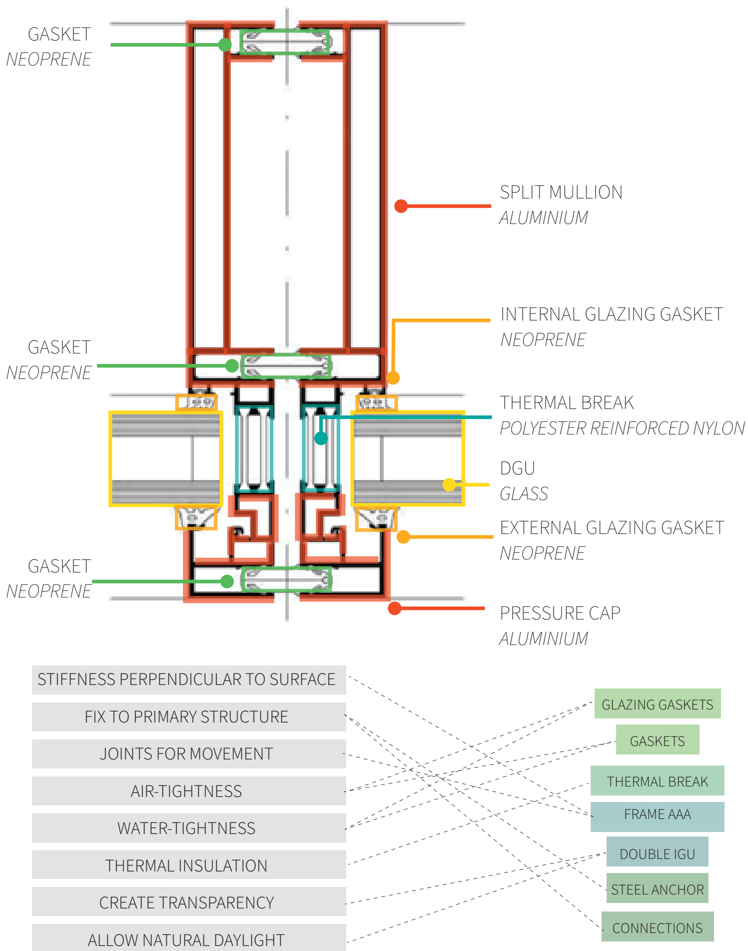


Figure 36 *Typical curtain wall mullion in components | Functions of each component*

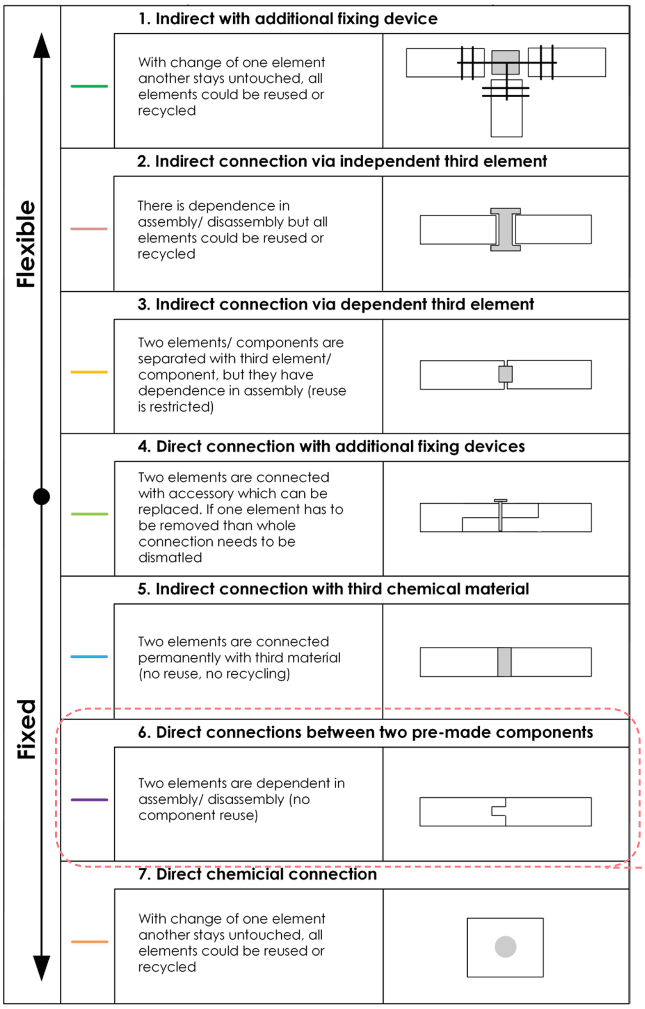


Figure 37 *Types of connections Durmisevic & Brouwer (2006)*

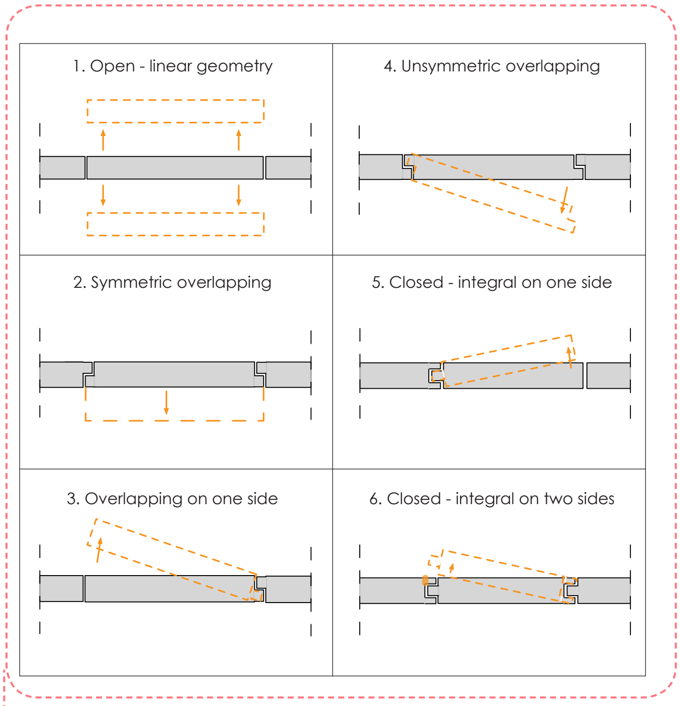


Figure 38 *Types of product edge by Durmisevic & Brouwer (2006)*

7.5 CONNECTIONS & INTERFACES

Another important aspect and of the major focus points in the present research, is the connection between each other and to the building which they are attached to. This is related to the level disassembly and overall circularity indicator, addressed in the next chapter. According to the classification made by Durmisevic and Brouwer, there are seven types of connections, ranging from the most permanent to the most flexible. The most permanent one is a direct chemical connection, followed by direct connections between two pre-made components, indirect connection with a third chemical material (like welding), and direct connections with additional fixing device. The most flexible are indirect connections, the least flexible being via dependent third components followed by independent third components, and finally with additional fixing device, being the most adaptable of the solutions. In summary, it is more recommendable to have additional components connecting two other components, as they allow for independency and easier handling when assembling and disassembling. The diagram in Figure 37 shows the seven types graphically, as well as the categories of product edges (Figure 38), closely related to such connections.

7.6 CONCLUSIONS

The product level, the focus of the current research, presents various complexities that make it relevant to address. Its high specialization justifies the recent exploration given to the topic, as demands on efficiency and user comfort have made the product a system in itself. Such context will be the reprised in the elaboration phase and a conciliation between the process it entails. Taking into consideration the levels and functions present in such a product is vital on the proposal of new strategies that can facilitate their reuse.

8 ASSESSMENTS

8.1 GENERAL CIRCULARITY ASSESSMENTS

There are several assessments for several properties. Most of the latest evaluations are concerned with the Life Cycle Assessment and the environmental impact a material or product has, translated to carbon emissions. They touch upon the energy and resources involved in the production and use of such product. Because this assessment has already been explored, it is not the focus of this research to assess products or their components by this mean. Instead, the potential for circularity is in question. A considerably fewer amount of authors have addressed such assessment, as it poses challenges on what's the most efficient and accurate way of performing it.

From the literature review, the following assessment methodologies were found:

Design for Manufacture	It is the integration of product design and process planning into one common activity. The goal is to design a product that is easily and economically manufactured.
Design for Disassembly	Proposed by Durmisevic, it categorizes a product's potential to be dismantled. There are eight categories divided into technical, physical and functional decomposition.
Design for Adaptability	Design theory a product should follow if it is to adapt and fit into new scenarios. Geraedts et al. propose 6 different strategies when it comes to adaptability: adjustability, versatility, refitability, convertibility, scalability, and movability.
Metabolic Criteria by MAT3	Addresses the information that a product should have in order to re-insert it in the productive loops.
Cradle to Cradle product certification	It rates products based on five quality categories, which are material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness. They are scored accordingly and a maximum platinum level is the goal to achieve. The ambiguity of the scoring and profit-oriented approach didn't suit the current research.

Table 6 *Assessment methodologies*

The following methods were further explored:

- The **MCI by the Ellen MacArthur Foundation** for the material level, as it evaluates a material according to its lifespan and how reusable it has been. It is a broad indicative for a material or product, relying majorly in available information. It will just provide an approximate value to have notions of given materials/products.
- The **Disassembly Potential by Durmisevic**, as it addresses the product levels, connections between elements and how it is composed. By keeping it in an intuitive level, it might provide a simple take on products.

8.2 MATERIAL CIRCULARITY ASSESSMENT

In his thesis about circularity indicators, Verberne develops a system to evaluate the level of circularity of a Building (BCI). However, this is a scaled-up version of the Material Circularity Indicator, developed by the Ellen MacArthur Foundation shown in figure 26. The MCI for a product measures the extent to which linear flow has been minimalized and restorative flow maximised for its component materials and how long and intensively it is used compared to a similar industry-average product. It is constructed from several product characteristics shown in the picture below, but the most important ones are: the mass of virgin raw materials used in manufacture (V), the mass of unrecoverable waste that is attributed to the product (W), and a utility factor that measures the length and intensity of the product's use (X) (Ellen MacArtur Foundation & Granta, 2015). The overall process is described below, which will assist in the process of assessment of specific materials (Verberne, 2016):

•Determine the material input, distinguishing between virgin materials and non-virgin, put into a single category even if they are reused, refurbished, remanufactured or recycled. The fraction of feedstock from virgin source is obtained with the following equation. If it's 0, then the inputs are fully circular.

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

•Determine the material output, the amount of waste is obtained as well as the products reusable fraction (the amount of materials that finds a 2, 3 or more lifetimes). The amount of waste going to the landfill or used for energy recovery (also considered waste) is:

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

•Determine the utility factor, or the lifetime of a product and the lifetime of a system. It is measured with the length of the product's use phase Lp divided by the lifetime of the specific building system Lsys.

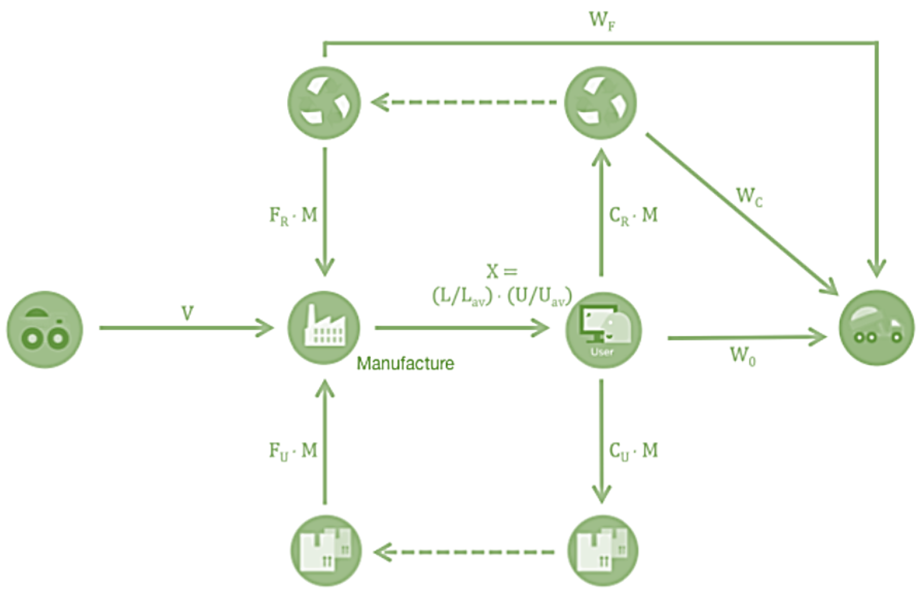
$$X = \frac{L_p}{L_{sys}}$$

•Determination of linear flow index LFI, which measures the proportion of material flowing in a linear way, considering 100% virgin feedstock and 100% waste. If the index is 1, the it is completely linear.

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

•Finally, determination of material circularity index, considering input, utility and output. The last variable is the function of the utility factor Xpa, with a constant a=0.9 established by EMA. To prevent the negative sign of a fully linear product with shorter lifetime than its system, a max is applied.

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



V = Mass of virgin feedstock used in a product
FR = Fraction of mass of a product's feedstock from recycled sources
FU = 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
Lav = 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
Uav = Actual average number of functional units achieved ruing the use phase of an industry-average product of the same type
CR = Fraction of mass of a product being collected to go into a recycling process
CU = Fraction of mass of a product going into component reuse
W0 = 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

Figure 39 *Diagrammatic representation of material flows by EMF (2015)*

8.3 PRODUCT CIRCULARITY ASSESSMENT

8.3.1 DESIGN FOR DISASSEMBLY

Once the end of life is reached, it is normal for the building systems and components to go to waste, as demolition processes do not contemplate the possibility of taking apart the elements from the construction. One of the main solutions for such problem is design for disassembly which allows the building components to have multiple lives and extend their life cycle. The 8 categories proposed by Durmisevic, explained briefly in the following table, encompass functional, technical and physical decomposition of elements (Durmisevic 2002).

Functional decomposition	
Functional independence	Measure level of autonomy of independent function and the level of separation. Distinction is made between integrated, incorporated or separated functions.
Systematization	Formation of single parts into sub-assemblies. Functional clusters are defined, which help on the assembly and disassembly processes.
Technical decomposition	
Relational patterns	Integration of building elements, in open or closed relational diagrams. Open hierarchies are independent and allow for disassembly, while closed lacks a systematization that prevents deconstruction.
Base element specification	They are the intermediaries within clusters and connect elements within a same cluster. Identifying it assures independence from cluster to cluster.
Physical decomposition	
Geometry of product edges	Connection type and interface of design, either open or interpenetrating. The last is to be prevented, as demolition is necessary to separate elements.
Assembly sequences	Five types of sequences, starting from the most convenient: parallel, sequential, interlocking, closed, and star. Variables such as geometry of product edges and connection types define such sequences.
Type of connections	Three types of connections: direct, indirect, and filled; they are also named integral, accessory and chemical, respectively. Indirect connections, or intermediaries, allow disassembly without compromising the main components.
Life cycle coordination	Elements with long life cycles should be assembled first and disassembled last, and the contrary for elements withe short life cycles.

Table 7 *Decomposition categories and systematization*

Stating the independent subsystems approach taken in the Design for Disassembly theory, relations can be drawn to the relevance facades have in this matter. Facades, being part of a system of different layers as described by Brand, have high potential to become reusable if the proper treatment is given. Their high embodied energy and their life cycle (long if installed in a building to be demolished, short of the building is new and intended to last for more than 100 years) make them suitable for study.

8.3.2 DESIGN FOR ADAPTABILITY

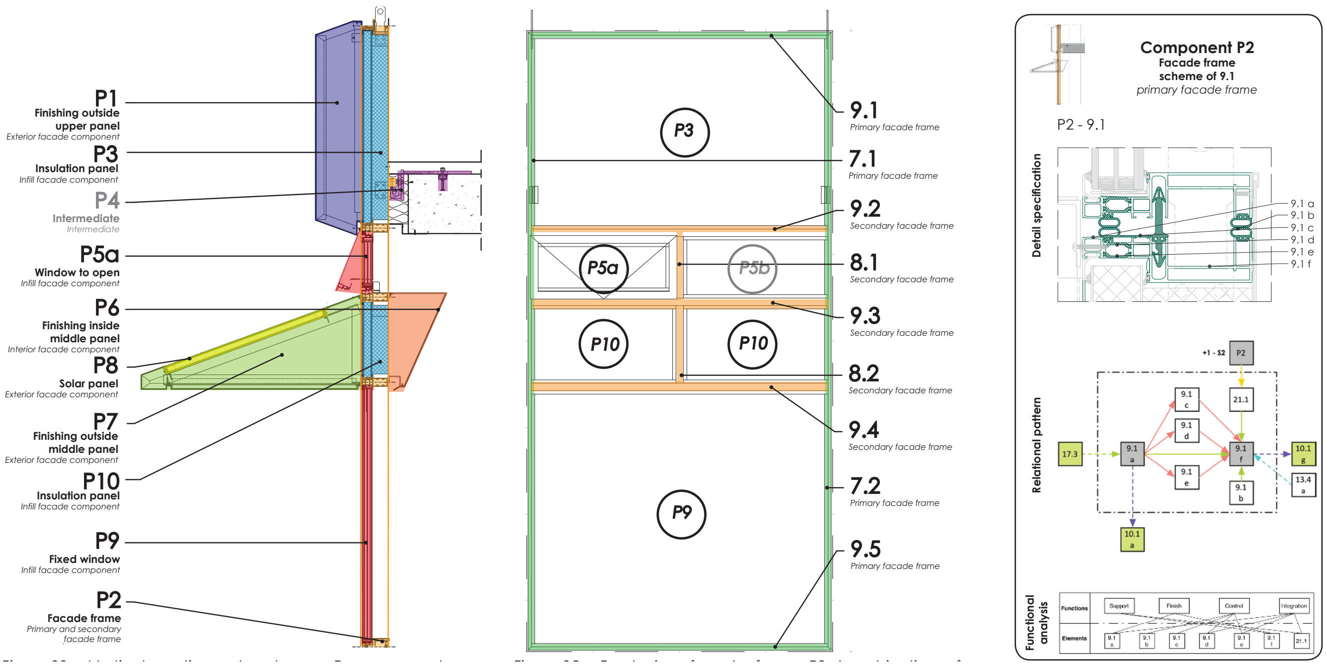
Constant changes call for adaptability, considering buildings as living systems that are able to adapt. The current crises in materials and economics demand buildings that are flexible and are able to change. This has been an ongoing topic since the last century and it is still in progress. Geraedts et al. propose 6 different strategies when it comes to adaptability: adjustability or changing tasks, versatility or changing space, refitability or changing performance of buildings, convertibility or changing the function, scalability or changing size, and movability or changing location (Geraedts, Hermans, Groep, & Rijn, 2014). An element can possess one or more of these characteristics, and still be called adaptable. A kit-of-parts approach is a good example of adaptable design, as it can be movable and a versatile system that adjusts to different configurations, as the ways of joining allow major compatibility.

8.3.3 MORPHOLOGICAL MATRIX

Developed by Beurskens & Bakx and based in Durmisevic, a method to visualize the circularity of a façade is done by means of the two design principles established in the first chapters: design for disassembly and design for adaptability. The ways in which they categorize the disassembly process gives indicators on how laborious is the process of recovering a façade (Beurskens & Bakx, 2015), used as indicator of circularity in design. Figure 40 shows the overall process.

- They first classify the façade with a coding system. They divide the façade into sub-systems and components, which will be later used for a more specific categorization.
- Every component is further dissected, and specific disassembly schemes are developed. It includes the component/ element name, the product levels and clustering, as well as the type of connection. If there are determining factors that result in a disassembly issue, then it is filled in an issues table.
- The different design for disassembly determining factors are analysed through diagrams. Following the graphical analysis, an overall disassembly scheme is produced, indicating how the façade components are linked to each other and to other products in the building. It also shows how the components are clustered in sub-systems. The types of connections are also addressed in this step.
- Finally, an assembly and disassembly sequence scheme is also produced. The façade is analysed in sequences , for both assembly and disassembly. Even though theoretically, the scheme should be a perfect mirror, it is rarely an equal process. The amount of steps in the sequence is an indicator of the dependence between different components and elements.
- The issues are lastly filled in a table, where there is a link between the elements and the scheme that pointed such issue.

They conclude with the morphological design and evaluation model shown in Figure 41, with the intention to provide guidance in the design and evaluation of a circular façade, in this case is specific for a unitised and stick system curtain wall. It follows the same top-down approach by levels, as the circular building product levels state (Beurskens & Bakx, 2015). Divided by properties and subcategories resulting in 28 parameters, the final output is the evaluation of the façade by linking the level achieved in each parameter (the most circular is in left, and the most linear to the right). If the line is a straight in the left side, then it is fully circular.



Coding of facade components | *Coding of facade sub-components* | *Relation of codes*

Figure 40 *Design for disassembly schemes by Beurskens & Bakx (2015)*

8.4 CONCLUSION

From the various assessments, just the most relevant and fitting will be selected and used in the elaboration phase of the project. From the overview in the chapter, the MCI is a simple method to have a notion of how circular a material/product is, and it can be complemented with a Morphological approach like the one developed by Beurskens and Baks. A simplification of it will be explored, as their work still lies in a highly theoretical field. CO2 emissions, even if they are not described here, will also serve as a sustainability indicator, if necessary. The final objective is for the assessments to inform the design and serve as reference when evaluating better alternatives. Most importantly, they should stay friendly to the reader or designer using them, as the main objective is to apply the generated content.

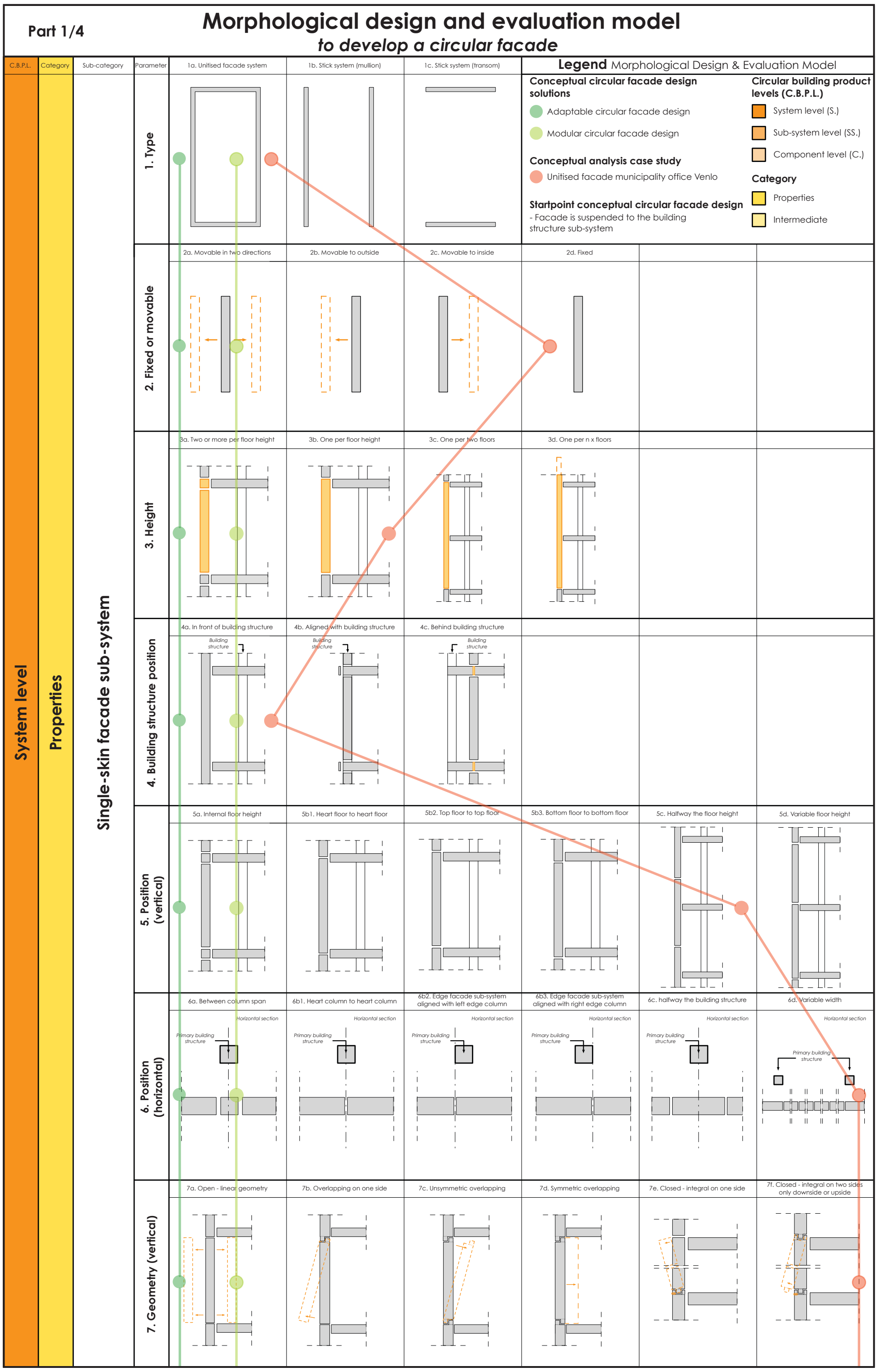


Figure 41 *Morphological design and evaluation model by Beurskens & Bakx (2015). A tool to assess circularity.*

9 LEGISLATION ON CDW

9.1 CONTEXT

Published by the Institute of European Environmental Policy, a report on the New Circular Economy Action Plan states that the EU has an ecological footprint of 4.7 global hectares (gha) per person, almost triple the global biocapacity of 1.7 gha per person (Pantzar & Suljada, 2020). In other words, three earths are needed to satisfy people's needs, Europeans at least. It has been realized that small adjustments to current production policies are not enough to achieve the required change. Actually, "between 30 and 60% of the environmental pressures associated with European consumption are on countries abroad where many goods are produced" (Pantzar & Suljada, 2020). The burdens are not only felt in the consuming countries, but also in the sourcing countries, compromising the environment's equilibrium. Efforts have been done to decouple economic growth and prosperity from consumption of finite resources, but is it enough? Given this, it is valuable to assess the current legislation status and what are the recent ideas surrounding the circular economy concept.

9.2 CDW

CDW stands for Construction and Demolition Waste, that is the waste resulting from any demolition work from a building. The key legislation in the context of CDW recycling is the EU Waste Framework Directive (2008/98/EC) which sets the basic concepts and definitions related to waste management and prescribes Member States to achieve the target of 70% of CDW being recovered by 2020. The recent and ambitious Circular Economy Package 2.0 (an update from a previous package), which includes revised legislative proposals on waste as well as an ambitious Circular Economy Action Plan or CEAP to stimulate Europe's transition towards a circular economy (Stoycheva & Loonela, n.d.). The CEAP targets "closing the loop", moving from a linear to a circular economy. It also highlights the importance of secondary raw materials and recurring to reuse and recycling to help maintain the value of waste at the end of life.

9.3 CURRENT LEGISLATION & DISCUSSIONS

Firstly, many of the existing policies and instruments have been developed from a linear viewpoint, which does not take into consideration a potential circular built environment. Legal issues might also hinder the adoption of circular business models in the construction industry, as under Dutch property law the delegated ownership of individual components that are part of a larger construction is principally prevented (van den Brink, Prins, Straub & Ploeger, 2017). In other words, the law states there should be only one owner, making it difficult to transfer products to others, which is one of the core ideas of circularity when the reusing concepts are applied.

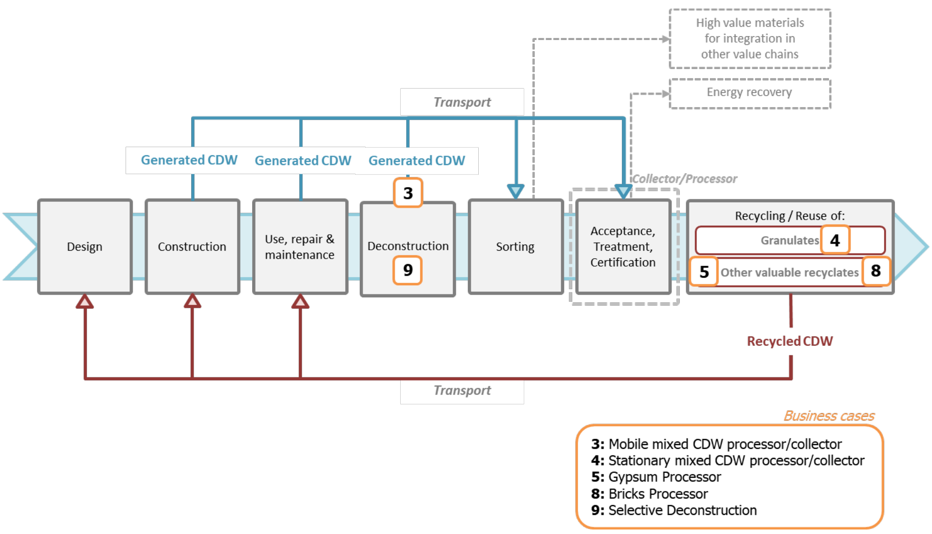


Figure 42 *General process and business model cases applied*

During a collaborative session organized by the European Comission, stakeholders united to evaluate five different business cases (Figure 42) that would push circularity into the construction industry: gypsum processor, brick processor, stationary mixed CDW processor, mobile mixed CDW processor, and selective deconstruction. From the session, selective deconstruction was evaluated as the most feasible and the most important to put into practice if circularity is to be achieved

(Bilsen et al., 2018). As explained in the next chapter, this is a cornerstone of reverse logistics as the initial step that allows for a smooth recovery process. Regarding the other two important business cases, mobile and stationary mixed CDW processor/collectors, they are also relevant in the supply chain process as they process the materials to be reused or recycled as is the case highlighted during the session. Each of them has their advantages or disadvantages, but either is necessary for reverse logistics. Mobile facilities create less transport costs and are flexible towards the needs of the market as they can move, however suffer from lower legal compliance as materials are typically re-integrated on-site, resulting in lower quality materials. Stationary facilities benefit from urban centres with high amounts of CDW, with generally better quality materials and improved legal compliance, however at the same time are limited to specific urban areas (Bilsen et al., 2018). However, an important distinction needs to be made, as such processors are only focused on mineral construction materials, which calls for an inclusion of metallic components.

9.4 LEGISLATION IN THE NETHERLANDS

Wealthier countries are more wasteful. The trend for the KPI to be higher in Western Europe reinforces this conclusion (Wolff, Prat, & Monier, 2017). The Netherlands is part of this group. Even if it scores the highest when it comes to recovery rates in the EU members (as shown in the bar graph in Figure 44-45), there is no distinction between the re-life options employed to recover a material or product. It is common practice to recycle, and it is mostly what the recovery category refers to. Countries with high recovery rates are likely the countries with best practices in terms of CDW treatment, in this case recycling. For instance, the Netherlands, as well as Luxembourg and Belgium, are densely populated areas, where great efforts have been put in reducing the disposal of mineral waste from construction and demolition. The Netherlands has landfill bans or recyclables as well, and a good spread of recovery facilities (Wolff et al., 2017). Figure 43 shows the progress on waste legislation in the European Union. It is assumed countries that are in higher levels, are more prone to adapt new strategies that push the current boundaries into more ambitious practices.

In 2012, according to the statistics published by Deloitte, over 93% of the CDW is recovered (recycling, energy recovery and other recovery), of which 95% is recycled. These figures exclude soil (241 Ktonnes in 2012) and also hazardous waste (Deloitte, 2015). However, they do include backfilling, a practice consisting of putting waste back on the land but without it being considered waste, which is alarming as the value of the material is practically lost and it is far apart from the reusing concept the circular economy refers to.

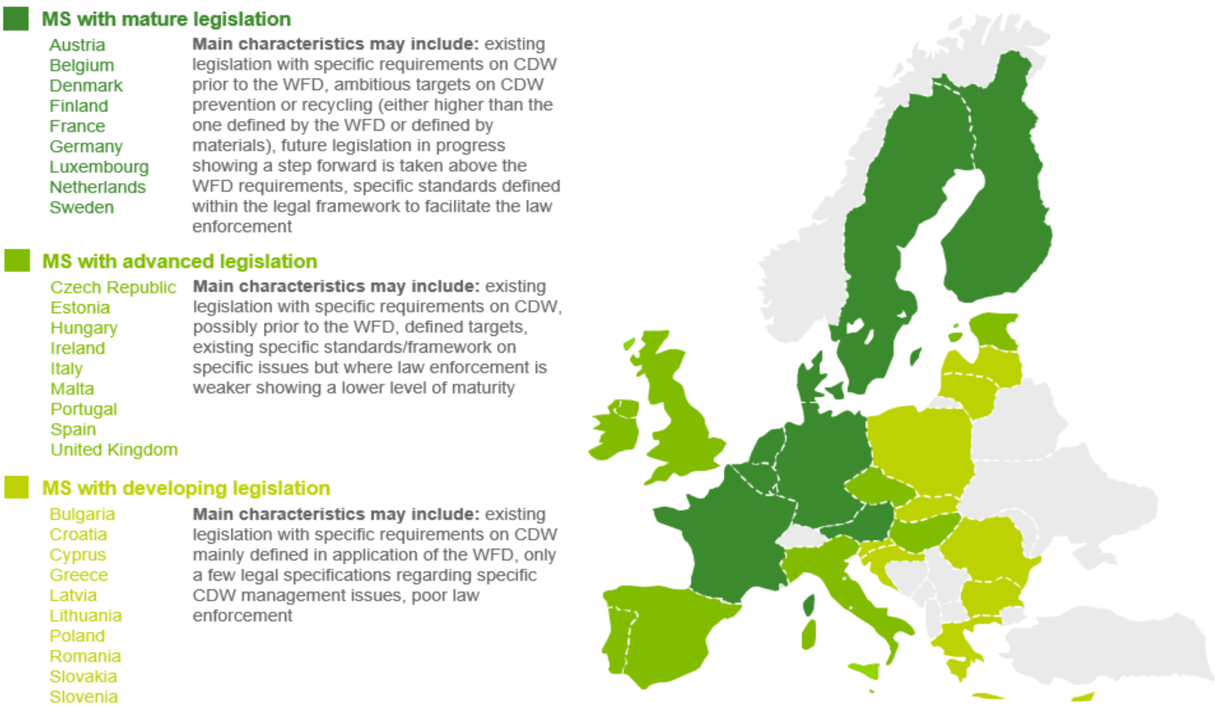


Figure 43 *Legislation maturity in the EU states*

Dutch legislation on waste can be found primarily in chapter 10 of the Environmental Management Act (Wet Milieubeheer; Wm). Without going into detail, some of the most important parts of legislation include (Deloitte, 2015) :

• Ensure no adverse effects on the environment because of waste (Article 10.1)
• Landfill ban. According to Article 10.2, there shouldn't be disposal on soil or any burn of waste. A typical market price including tax is € 186.34 per tonne if waste that can be reused is landfilled instead. However, there are exceptions in the Decision Exemptions Ban on Duping Outside Establishments document.
• Temporary removal. In general, it is prohibited to ship landfill material out of the Netherlands or into the country, as recycling is a viable option.
• Temporal recovery. It is allowed to receive shipments to the Netherlands for recycling unless much of the transferred material is landfilled later.
• A National Waste Management Plan must be established (Article 10.3 and 10.4).
• Rules for delivery, receipt, transportation and collection of industrial waste (Articles 10.36-10.55).
• Environmental Protection Act there should be an arrangement between collectors, transporters, dealers and brokers of waste. It states waste must be issued only by companies that have a license to take over this waste or companies authorized to collect waste. In other words, collectors must be registered, preventing any other contractor to act as disposer of the material.
• Makes reference to The National Waste Plan (Landelijk Afval Plan; LAP) which is related to the Waste Framework directive, the main document on treating waste. It sets goal on recovery rates (at least maintain current numbers) and use the Cradle to Cradle protocols.
• Makes reference to document From Waste to Resource (Van Afval Naar Grondstof, VANG), which addresses the waste prevention plan. It has eight operational objectives: sustainability at the front of the chain, improving waste separation and collection, directing existing waste policy to a circular economy and addressing specific chains and waste streams.

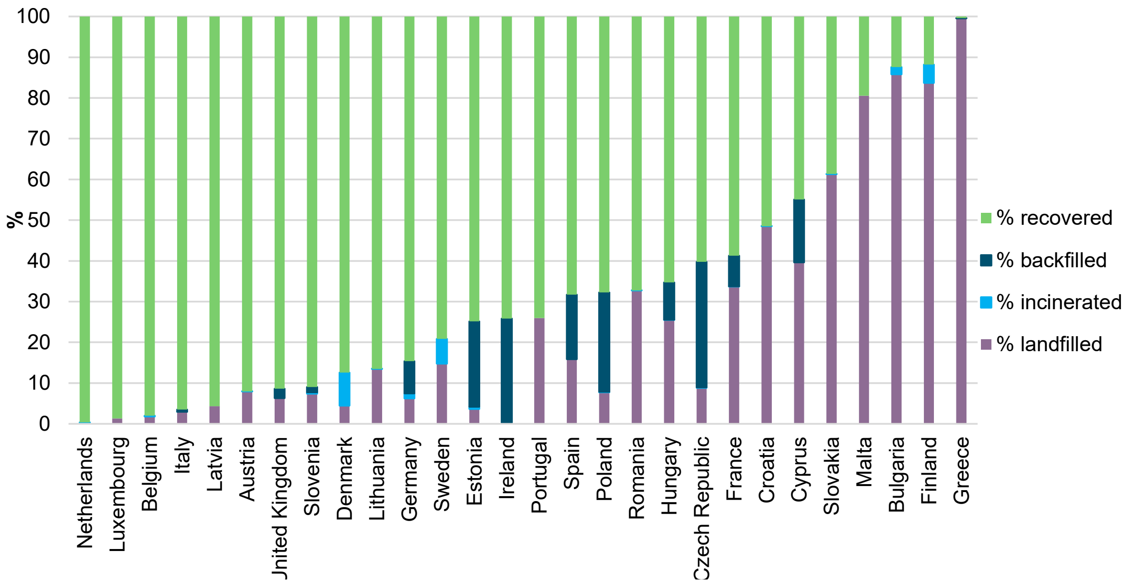


Figure 44 *Waste management strategies by country*

CDW treatment (2012)	Recycling	Energy recovery	Other recovery (includes backfilling)	Incineration	Landfill	Disposal and unkown	Other removal	Total
Hazardous waste (Kt)	1,187	16.70	0.72	4.72	262	7.61	0.001	1,479
Non-hazardous waste (Kt)	23,062	927	2.54	11.70	215	8.26	0	24,226
Grand Total (Kt)	24,249	944	3.27	16.42	477	15.87	0.001	25,705

Figure 45 *Dutch factsheet*

Country	Classification	Maturity matrix	Collection (tonnes)	Collection kg/capita	Treatment Score	Estimated market (tonnes)	Estimated market Score	Collection / Estimated market ratio	Collection / Estimated market score	Total score
United Kingdom	**Good** CDW recycling collection & treatment; relatively **large** market	4	55,544,858	863	4	69,401,844	4	80%	4	12
Netherlands		4	20,509,439	1219	4	20,509,439	1	100%	4	9
Sweden		4	1,841,884	191	2	16,366,965	1	*11%*	1	4
Denmark		4	3,309,996	588	4	7,324,648	1	45%	2	7
Luxembourg		4	543,775	989	4	1,781,717	1	31%	2	7
Germany		3	79,603,592	986	4	62,392,390	4	100%	4	12
Belgium		3	5,289,475	472	4	16,087,809	1	33%	2	7
Austria		3	9,174,000	1078	4	11,211,320	2	82%	4	10
Finland	**High**/*Low* collection ratio; *high*/**low** treatment score	3	1,104,925	203	4	7,501,115	1	15%	1	6
Ireland		3	148,402	32	3	3,675,284	1	*4%*	1	5
France		2	65,554,846	995	2	74,658,523	4	88%	4	10
Italy	**Large** CDW market; **low** recycling score; **low** collection / market size ratio	2	34,225,640	563	4	44,132,685	4	78%	4	12
Spain		2	7,212,433	155	2	25,491,282	3	28%	2	7
Poland		2	4,421,283	116	3	15,501,056	2	29%	2	7
Czech Republic	**Small** to medium CDW market, **low** recycling and reuse activities	2	2,959,902	282	2	6,567,847	1	45%	2	5
Portugal		2	960,585	92	4	4,690,887	1	20%	1	6
Hungary		2	2,698,023	273	3	3,374,136	1	80%	4	8
Slovakia		2	551,768	102	1	2,077,354	1	27%	2	4
Slovenia		2	229,595	111	4	1,238,425	1	19%	1	6
Estonia		2	626,139	476	3	1,011,491	1	62%	3	7
Romania		1	1,324,411	66	2	3,974,620	1	33%	2	5
Greece		1	367,018	34	1	2,866,515	1	13%	1	3
Bulgaria		1	682,074	94	4	2,049,857	1	33%	2	7
Croatia		1	289,090	68	2	1,309,508	1	22%	1	4
Lithuania		1	647,663	220	3	1,272,777	1	51%	3	7
Latvia		1	571,132	285	3	1,080,531	1	53%	3	7
Cyprus		1	152,201	177	1	462,870	1	33%	2	4
Malta		1	994,639	2338	1	245,145	1	*100%*	4	6
USA		n.a.			-	-	-	-	-	
Japan		n.a.			-	-	-	-	-	

Figure 46 *Countries evaluated in their recovery practices*

There is however no national or regional obligation for selective deconstruction, as well as on-site sorting facilities (Deloitte, 2015). Moreover, collection of different materials like glass and some metals is also not forced, nor the separation of hazardous waste from C&D operations.

9.5 IDEAS FOR BETTER CDW MANAGEMENT

From the report created by IDEA Consult, requirements are highlighted to implement a proper CDW treatment: a selective sorting at the source, selective demolition practices, and the presence of technologies that process the selectively demolished material fractions into suitable resources. The current treatment processes of CDW fractions are driven by economic incentives and legislative obligations on the supply side (e.g. achieving certain quality standards in metallic products) and on the demand side (e.g. a demand for highly processed materials) (Bilsen et al., 2018). The new business models will have to also consider financial incentives for demolition companies to selectively collect the required material stream, the possibility to produce a resource with the required specifications in an economically viable way, and having good prospects that assure demand for the produced material (Bilsen et al., 2018). Many interviewees also stressed the importance of a favourable and stable regulatory context for the economic viability of CDW recycling, such as land fill bans on CDW or landfill taxes that are substantial enough to enable CDW recycling, appropriate certification mechanisms for recycled products, selective deconstruction facilitation, among others.

Currently, there are initial investments going to the development of the waste processing industry. Through EFSI and InnovFin, the EIB presents clear opportunities to address the finance gap faced by CDW recycling infrastructure to achieve the goals set in the Circular Economy Plan.

9.6 CONCLUSIONS

Even though legislation is a complex and deep topic to fully address in the present research, the overall picture revealed some essential truths. The Netherlands is in the most privileged position when it comes to management of waste (Figure 46), which is an advantage but also a drawback as its existing infrastructure might pose a barrier to implement alternative recovery options. It will be assumed such position is of benefit and helps the country to be ready to apply new solutions. Besides, landfill and incineration bans make it easier (or leave no better option) for companies than to recover. It is important to highlight how recycling is the most common practice and it is definitely not the most advisable solution, as explained in the circularity concepts chapter. It is therefore the intention to push the boundaries and promote more valuable re-life options, keeping the most residual value of products.

10 INTEGRATION & CONCLUSIONS

10.1 KEY POINTS

A circular economy is necessary to face the current resource consumption challenges. As shown before, the trend shows a doubling of material extraction in 40 years, representing a major threat for the environment. By reusing products and retaining their value, by any of the means already explained, the scarcity issues can be alleviated. From the five principles stated of a circular economy, thinking in systems is vital, as everything regarding resources has links and agents that are involved, affecting one another. The construction industry now focused in a linear and forward logistics, when shifting to circularity, must incorporate reverse logistics into their agendas. To do this, the correct information and cooperation must be available. Design also plays an important role in the whole process, as it can make the deconstruction feasible or not, the first step to a complex process that gets products from their consumption point to the manufacturing one. It is then necessary to focus on design for disassembly and adaptability like mentioned in chapter 8, following a careful re-life option scheme that will bring a new life to the construction elements. However, this is a small part of the process. Strategies marrying all or most of the relevant stakeholders are necessary. The CBMs described in chapter 3 will be addressed in the elaboration phase, making emphasis on the supply chain and the actors that must intervene for the reverse logistics, as well as when and how. By highlighting roles and responsibilities, a clear picture will be obtained at the end. The material flow analysis, addressed in chapter 6, will help visualizing the shift from the current form of linear economy to a more circular one.

10.2 OBSTACLES

First of all, several assumptions need to be made in order for the reverse logistics to be implemented, such as design for disassembly and adaptability. When it comes to the implementation of RL there are important challenges. The four main barriers are the inaccessibility of products that have reached their end of life, as well as their deterioration, followed by the technical and economic costs for reprocessing such products. The fourth has to do with the cultural perceptions of secondary products, which might not be requested due to the misconception of a lower quality. Other obstacle that need addressing is the usual tight scheduling of the construction projects, the wide variety of origin points from which products are obtained and the lack of facilities, infrastructure and technology for reprocessing. There is a large number of actors involved in the process, making it more difficult to keep close cooperation among stakeholders. Besides, there are no guidelines or codes that can assist in the RL process and the specificity of each case would make such guidelines more abstract. The list can go on, but there is no option whether reverse logistics cannot be applied, as it is the only way of assuring a more sustainable future. Design can begin pushing the market towards it, as well as policies by decision-makers and governments.

A common topic of discussion that has not been addressed yet, as it is not in the scope of the current research is aesthetics. When it comes to the design, a concern over the appearance is always posed: is circularity and designing with re-life options in mind, always translate into an unappealing result that must be rectangular? Peter Stoutjesdijk from New Makers says this is normal as the circularity model is still in an early stage, and it only makes sense to develop designs that are regular and simple so a focus in the circular models is done. Once the process is mastered, experimentations in shapes and expressions might take place. In a world dealing with severe scarcity of resources, it is more important to focus on efficiency.

However, that is not all. The advantages already explained in Chapter 4, can surmount the obstacles posed of RL implementation. Costs savings are possible, due to the reduction of material and energy consumption as well as the resale of recovered items. The good reputation that comes from generating less waste and using less raw materials can help on the operation of companies or they can be even incentivized by the authorities to keep on manufacturing in a circular way. The objective is to start with pilot projects showing the positive impact RL and circularity will have in the economy and environment.

10.3 CONCLUSIONS

The theory already described forms a solid base to the research to come, schematized in Figure 47. They will be used in the second half of the project, where a framework is first proposed and it is applied to a specific case. Design will respond to the weak links identified in such application and system thinking will also be featured, as reverse logistics demands a holistic approach. Given the broadness of the project, it is reminded that a superficial but illustrative analysis is conducted. Posing the right questions, not answering them, is the main objective. Topics such as financial feasibility and time won't be covered, as well as aesthetic exploration. They will instead encourage further research and exploration, so the literature gaps on RL application are filled progressively.

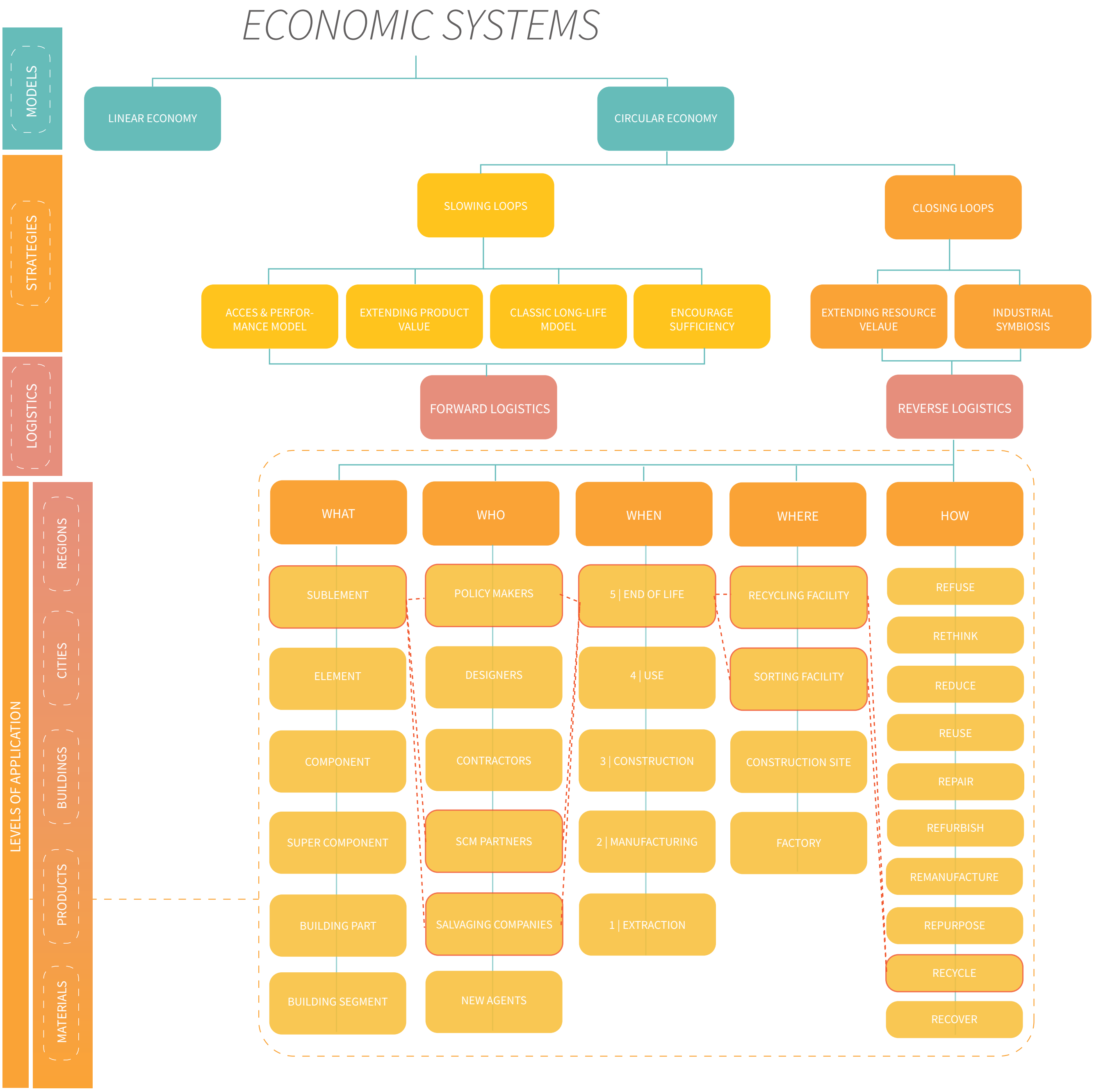


Figure 47 *Reverse Logistics Scheme by Topics*

11 FRAMEWORK & DfRL

The Framework and DfRL criteria are two of the most important products of this work. The RL Framework is a scheme that integrates the basic steps towards Reverse Logistics. The first steps are taken, by filling the canvas with findings from literature research and interviews. It has the intention to serve as a format for further development and use in the industry. The DfRL criteria develops the Design for Reverse Logistics concept proposed by Hosseini. It takes elements from previous assessments to bring together a cohesive and relevant criteria that will serve as guideline to take decisions regarding design.

11 FRAMEWORK

11.1 STRUCTURE

To have a clear vision of the current topic, a general framework is proposed where the essential aspects are covered. It is colour coded so it is easier to identify each one of the information boxes, as shown in Figure 48. The fundamental components are: the Supply Chain Process in gray that follows a specific Re-life scenario in yellow. The green box on the left showcases the main Stakeholders to be involved while the red box below it mentions the Façade Criteria that is relevant on the given stage. For example, Accessibility and Connections in the Collection phase are musts to facilitate moving the façade form one place to the another. The blue and purple boxes have to do with the logistics of each step: the left one are Key Points, or basic actions necessary to bring the supply chain process into its successful completion; the middle one is the Application box, which highlights variables that each re-life scenario would involve (for example, Deconstruction requires more resources or work than a conventional Demolition; in this case the Work variable is being compared). Also, the Technology box in purple addresses how a tag system could be used in each one of such phases, given VMRG is developing a platform called Cirlinq in which products have a link to a digital twin with essential information concerning the quality and status of the element (VMRG, 2020). Finally, the box in turquoise is one of the most relevant, as it mentions the main Barriers that are preventing a "better" re-life option being applied in the industry.

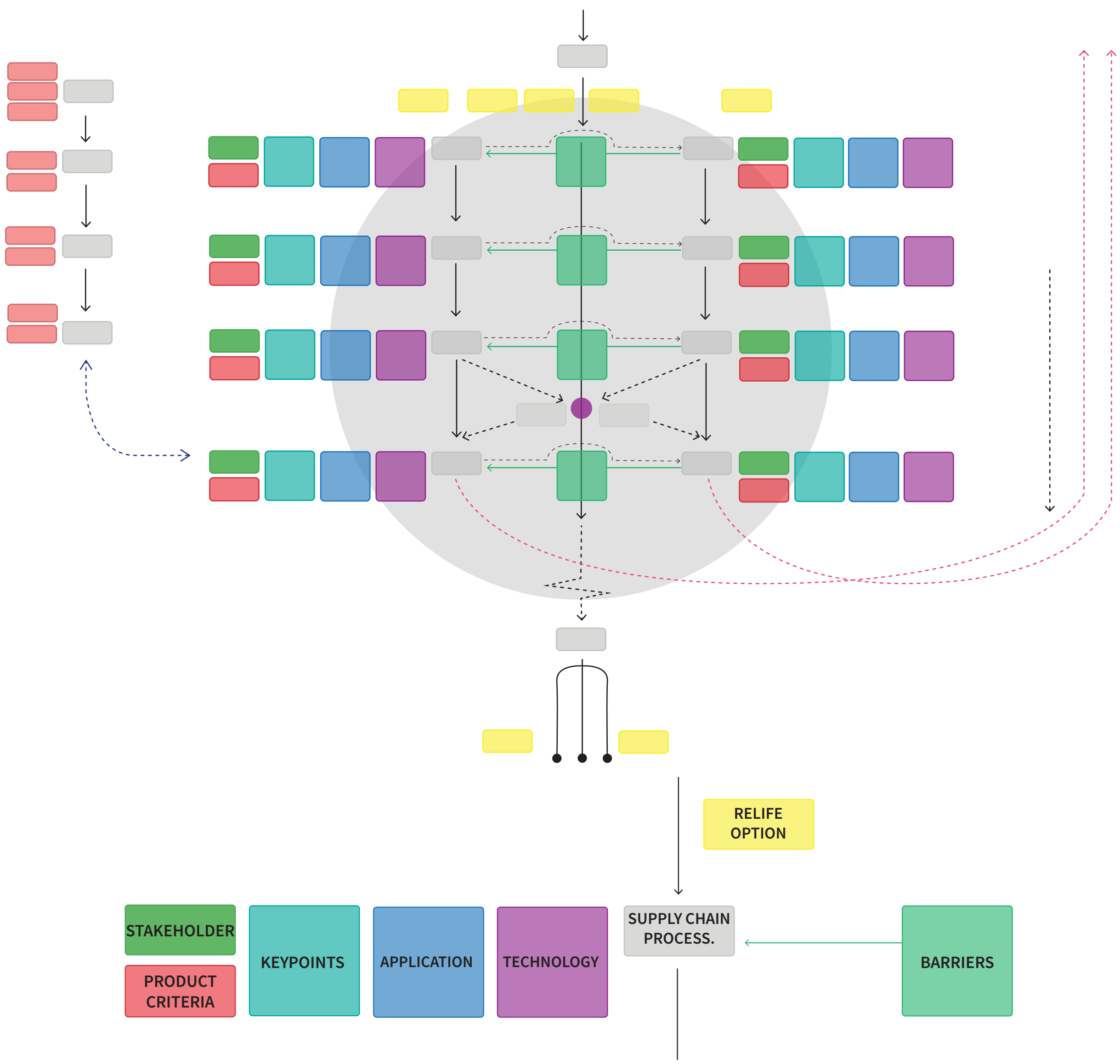


Figure 48 *Framework: overall structure*

When going into the overall framework it is important to notice how it showcases two different re-life scenarios: remanufacturing and recycling. It was a decision taken for this specific project, but it can also showcase the 10 different re-life options mentioned in the literature research. For simplification purposes, the supply chain process is then showing these two scenarios, focusing in the stages after the end of service of the product. Initially, the whole process was envisioned but the framework became too saturated with information. In the appendix, the original framework exercise can be found, in case it is of utility in future researches. After this, the different information boxes explained in the previous paragraph are present in each of the supply chain steps. The barriers are between the two parallel re-life scenarios, portraying the main aspects that prevent moving from a Recycling scenario to a Remanufacturing one. Finally, on the far left, the design phase complements the framework, as it is being informed by every stage of the supply chain process and the design necessities it involves.

11.2 SUPPLY CHAIN PROCESS

The supply chain process organizing the whole scheme can be separated in two: forward logistics and reverse logistics. Forward logistics is the common scheme a product undergoes for its manufacturing, several authors have addressed such phases. Tillmann, Beurskens and Bakx, and several others have defined the steps beginning from the material extraction to the eventual end-of-life of a product, where most commonly demolition occurs, resulting in materials going into recycling or as landfill (Klein, 2013) (Beurskens & Bakx, 2015). The most interesting part and the focus of this research is what happens after the product is no longer useful, the reverse logistics. The chosen scenario envisions a building at its end of life, a 60-year-old building that has just 15 more years to go. The owner decides either to repurpose or demolish it. However, the facade is one of the systems that still can be reused, as it was just installed and has a life expectancy of 30 years. This case, a real one described in the next chapter, serves as an example of how reverse logistics is valuable, as cases of old buildings from the ‘60s-‘70s no longer requiring useful products are becoming common. This is one of the many scenarios that can render a façade unusable. In any of the cases, Schultmann identifies the four major steps that need to happen for reverse logistics to be applied: collection, inspection & sorting, re-life treatment, and redistribution (Schultmann & Sunke, 2005). The present research doesn’t take “redistribution” itself as a step, as it is involved as an intermediate step between every major activity (between Collection and Inspection & Sorting, and between Inspection & Sorting and Remanufacture, as well as after Remanufacture to its new destination). Besides, a previous step is added as it is key for the process to properly start: selective deconstruction. Compared to demolition, selective deconstruction recovers the valuable elements that can have a new life, after the proper treatment is given to them. The following subsection describes briefly each one of this steps, including the definition of End of service, as it can be confused with the End of life term. It must be noticed these are the definitions that will be used throughout the present work.

11.2.1 END OF SERVICE

The end of service of a product is reached when it can no longer provide utility to the user/client due to certain factors. One of them is the building in which it is installed is no longer to be used. Not to be confused with end of life, which technically means a product is no longer usable due to its longevity.

11.2.2 SELECTIVE DECONSTRUCTION

Contrary to demolition, deconstruction is the process in which products and elements from a building site are integrally recovered without compromising the overall state of the product. In the report “Development and implementation of initiatives fostering investment and innovation in C&D waste recycling infrastructure” by the European Commission and conducted by IDEA Consult , the term is “focused on obtaining homogeneous and separable CDW streams from demolition activities as to augment the value of secondary material streams.” (Bilsen et al., 2018). It can be simply described as the reversing step of a construction. The process requires a careful initial deconstruction plan and an auditing process by a certified auditor. According to the mentioned report by IDEA, it has been identified as the most important strategy to shift into a circular economy, as it saves the quality of the material.

Figure 49 *RIM (Resource Information Modelling) digital modelling tool*

11.2.3 COLLECTION

Collection is the process in which the recovered products from a construction site are put into certain classifications —physical containers —to be then transported into facilities for inspection, sorting and an eventual re-life option. According to the report by Idea consult, it can be stationary —happens off-site —or mobile —in-situ (Bilsen et al., 2018). Either must be the most careful and the destructive-less possible. The report also mentions some of the advantages and disadvantages from both options: mobile collection is flexible and needs less transport but lacks on legal compliances due to lower quality products; stationary has more capacity and is in contact with better quality materials (Bilsen et al., 2018). Attention to mobile collection is put here.

Figure 50 *Collection of materials*

11.2.4 INSPECTION & SORTING

Inspection is the process of information extraction from a product. It is a process that "primarily focuses on checking the appearance, construction and basic function of a product." (AQF, 2017). In this case, it is achieved by a tag system which is linked to a platform that contains the relevant data of the product, such as its quality, material composition, whether it has been maintained or not, among others. A minor disassembly process might be necessary to obtain such information, on specific components. Sorting uses such information to put the products in the right productive loop or re-life option.

Figure 51 *Inspection and sorting*

11.2.5 STORAGE & SECONDARY MARKETS

Not all products will directly end up in a facility for a re-life treatment. The products that still have no destination or client, will then be stored or offered in secondary markets. Those markets will make the products reachable, making information availability vital. In the context of waste markets or secondary materials, a report by the Danish Environmental Protection Agency explains "a key element is the extent to which re-use or recycling can be done at "higher" quality levels of the circular flows." (Bendsen, Førby, Bakas, Kampmann, & Andersen, 2019) In other words, it is vital to retain the higher value of the products, as they were already subject to resource and energy investments.

Figure 52 *Storage and secondary market*

11.2.6 RE-LIFE OPTION: REMANUFACTURING

As explained in the literature research, there are several re-life options. The exercise being conducted envisions remanufacturing as a more desirable relief option, when compared to recycling. Remanufacturing according to Boorsma is the process of returning a used product to its original performance specification by performing manufacturing steps on an end-of-life component or product (Boormsa, 2016). In order words, its residual value is increased as the result is a product with the same quality it had after its initial manufacturing. Minor resources and work were put into the product to render it "as new", when compared to recycling for instance. Giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent is also part of the process.

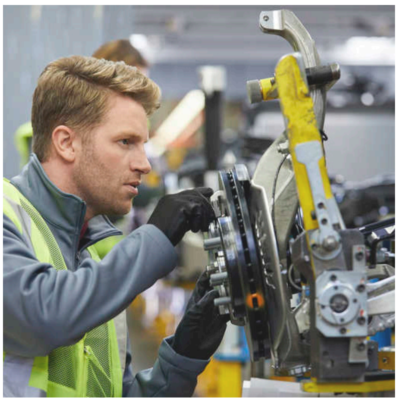
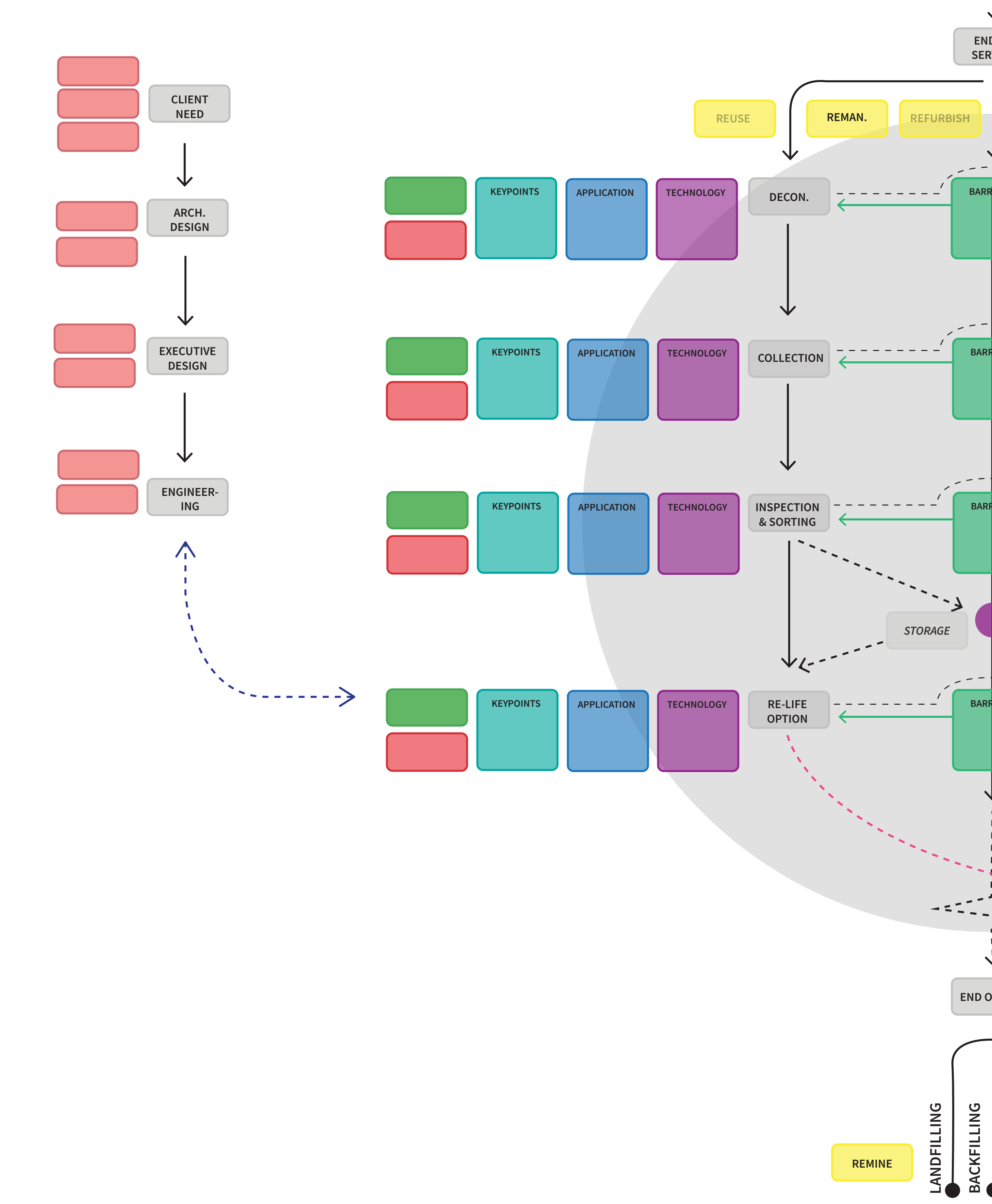


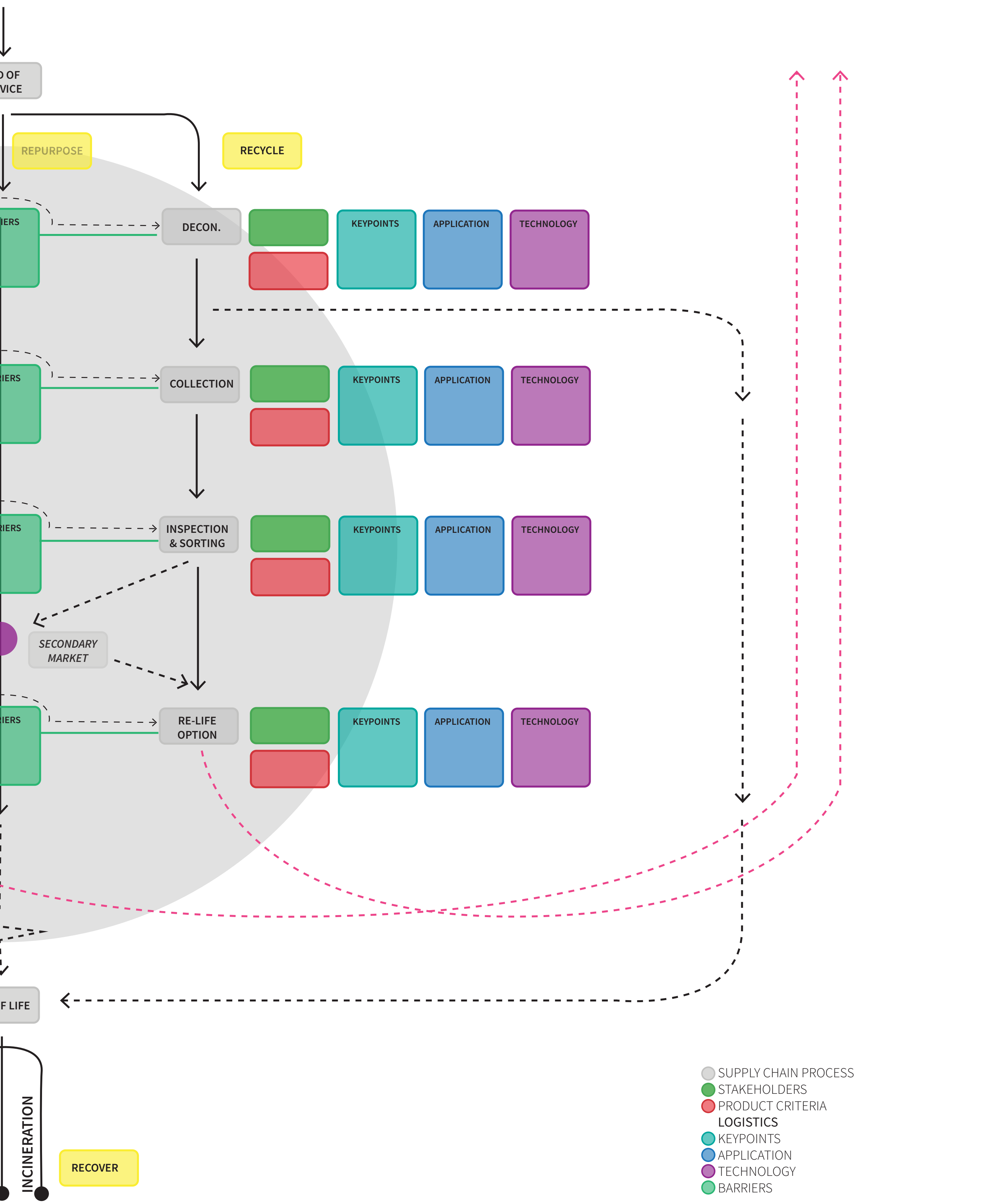
Figure 53 *Remanufacturing process*

Format 1 showcases the main steps just described, utilizing the format previously described.

FORMAT: RL FRAMEWORK



DESTINED TO:
Industry actors, facade providers, OER, OEM, demolition contractors



Format 1 *RL Framework*

11.3 LOGISTICS

The objective of the framework is to be filled with valuable information that will inform the reverse logistics process and will contribute to its application. From literature research and interviews with stakeholders, the boxes are starting to be filled with basic information. The intention at this stage is not to be exhaustive, but to highlight the main factors to be considered. The information boxes will then grow and adapt to the input given by others. A special emphasis was put on the stakeholders involved, located on the left side of each of the supply chain steps. Because there are still questions on who is in charge of recovering the façade and all the process involved in the reverse logistics, it was vital to make such distinction.

Each one of the four main steps are explained in this chapter in a table format (Table 8), as the framework only allows for the most vital keywords.

DECONSTRUCTION / DEMOLITION	
REMANUFACTURING	**RECYCLING**
STAKEHOLDERS	
-Façade providers in case of a closed system (they retain the ownership of the facades along with an SPV) -An SPV, or Special Purpose Vehicle that owns the product and wants to recover it for a next use and different client (Azcarate, Klein, & Heijer, 2019) -A specialized deconstruction company when specialized labour is needed (Bilsen et al., 2018) -An auditing office that evaluates the project and elements to recover, prior to the deconstruction itself (EU Construction and Demolition Waste Management, 2018)	-A demolition company conducting a conventional process of tearing down a building or specific products (Wolff et al., 2017)
KEYPOINTS	
-A deconstruction plan must be developed since the planning phase, by the architecture office or by a specialised construction engineer (Bilsen et al., 2018) -An auditing process is vital as it will provide feasibility notions of the deconstruction process. Verified experts are required. (EU Construction and Demolition Waste Management, 2018) -Recovering the facades integrally. The whole panels are removed and demounted from the main structure. Technology might help in the process. *Check TRACIMAT and BRL SVMS_007, they propose tracing the routes for material recovery and inventories (EU Construction and Demolition Waste Management, 2018)	-For demolition, no prior processes are needed. Conventional equipment and labour result in a tearing down of construction elements and a fast processing (cutting aluminium frames to detach them more easily and make transportation more effective). *Check Waste Framework Directive (2008/98/ec), comitology in Art -29(2) *Check C&W Waste Management Protocol, guidelines to handle waste streams *Other documents: “Development & implementation at initiatives fostering investment & Innovation in C&D recycling infrastructure”, “Resource Efficient Use of Mixed Waste” where obstacles are identified, Dutch “ National Waste Plan”.
APPLICATION	
-Consider extra cost and labour of deconstruction plan -Consider extra cost, labour and time of auditing process -Consider extra cost, labour and time of deconstruction process -Consider specialized labour for workers -Consider the creation of an incentive for deconstruction processes	-Consider the cost and labour of conventional demolition -Consider the conventional labour of workers -Consider the creation of a demolition tax

TECHNOLOGY	
-Tag system helps on identifying products to recovery and their overall status. (VMRG, 2020) -Tag is update with the "recovered" status and a brief explanation of how it was made can be included (to record the whole process) -Unrecoverable materials discarded must also be taken into account, for a future environmental impact calculation	- Tag helps identifying products to be teared-down
BARRIERS	
-Higher costs when compared to recycling -Extra logistics involved to deconstruct as well as the extra labour highlighted in Application -Lack of government incentives for deconstruction (Hosseini et al., 2015) -Strict regulations involving safety practices during deconstruction process (Hosseini et al., 2015) -Variety of product quality and lifespan are unknown variables in most of the cases	

COLLECTION	
REMANUFACTURING	**RECYCLING**
STAKEHOLDERS	
-Façade providers in case of a closed system (they retain the ownership of the facades along with an SPV) -An SPV, or Special Purpose Vehicle that owns the product and wants to recover it for a next use and different client (Azcarate et al., 2019) -A specialized deconstruction company when specialized labour is needed	-A demolition company conducting a conventional process of collection of specific products
KEYPOINTS	
-After being dismounted from its installation place, the product is moved within the same construction site via cranes or special equipment, and it is pre-sorted to its next destination -Coordination and excellent communication is needed to organize the transportation to the various inspection & sorting facilities. (Schultmann & Sunke, 2005) -In an open system, the network of facilities is most likely to be broad and intricate as the owner of the façade is changing -In a closed system, the process is simplified as the same owner remains throughout the whole process -After the pre-sorting, the products are transported to the next destination	- After being teared down and cut into more manageable pieces, the elements are put in a specific site or container from which transportation will pick them up (VMRG, 2018) -Coordination to know the destination is needed
APPLICATION	
-Consider extra costs and labour of detailed collection -Consider extra costs and labour of pre-sorting -Consider extra labour and coordination of transportation logistics	-Consider labour of collection -Consider coordination of transportation logistics
TECHNOLOGY	
-Tag system to help on pre-sorting process and the coordination for transportation(VMRG, 2020) -Tag can be updated with "on route" status of the product, specifying the destination where the inspection and sorting will take place	-Tag can be updated with "on route" status of the product, specifying the destination where the inspection and sorting will take place

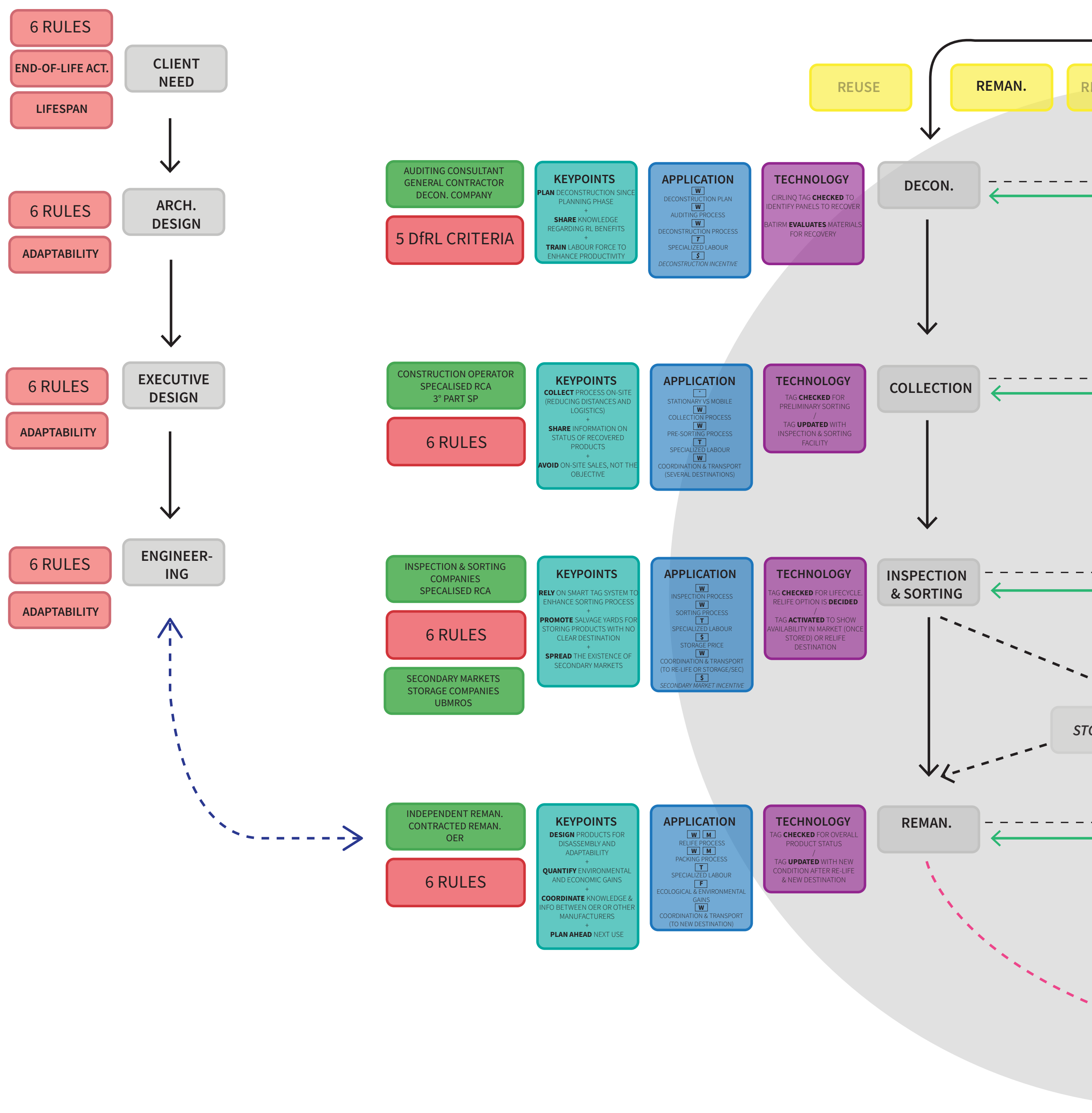
BARRIERS	
-Large size of products might complicate a seamless collection process -Transportation logistics and coordination require extra labour (Hosseini et al., 2015) -Making efficient use of transportation and no waste of space is a challenge to be considered (Hosseini et al., 2015)	

INSPECTION / SORTING	
REMANUFACTURING	**RECYCLING**
STAKEHOLDERS	
-Inspection and sorting companies -Specialised Reverse Chain Actors (New actor)	-Recycling companies
KEYPOINTS	
-Inspection routines should be quick and efficient and should provide enough information about the product to determine the best productive loop at which it can be inserted (Schultmann & Sunke, 2005) -Tag system might help on getting such information, as it will include an overview of its lifespan, use and whether the proper maintenance has been given to it -Sorting processes will require advanced coordination to direct the products to the proper facilities -Another step in the process could proceed after this: not all products are expected to have owners and a defined destination or building to be applied to. Some of them would need to be directed to a storage and secondary market where they will be available to others. More research on this needs to be conducted. (Hosseini et al., 2014)	-Materials are weighted and put into containers (VMRG, 2018) -Materials are cut down even to smaller pieces, to make handling easier -Material is transported to the recycling/melting facility
APPLICATION	
-Consider extra cost and labour of detailed inspection -Consider extra cost and labour of detailed sorting -Consider extra cost of storage -Consider extra risk and coordination of secondary marketing -Consider government incentive on reused products	-Consider labour of weighting and cutting into easier-to-handle pieces
TECHNOLOGY	
-The tag system will speed up the inspection process, as it will provide straight-up information about the product -The tag will also help on the sorting process, as it will keep track of the destination after it has been sorted	- No tag system required in current system
BARRIERS	
-Lack of recovery facilities and the complex network that might be formed -Once in a secondary market, the lack of market demand is the major barrier: no demand justifies no supply (personal communication Joep Römgens, April 30, 2020) -Lack of market awareness about the quality and second life of products (personal communication Joep Römgens, April 30, 2020)	

RELIFE OPTION	
REMANUFACTURING	**RECYCLING**
STAKEHOLDERS	
-Independent remanufacturer -Contracted remanufacturer -OER: Original Equipment Remanufacturer -OEM: Original Equipment Manufacturer or Façade provider in this case	-Recycling company
KEYPOINTS	
-An initial disassembly is done, where the façade components are to be identified and sorted to their right remanufacturing treatment -The repair takes place for each of the necessary components (not all of them are to be fully remanufactured, identified with the tagging system) -Cleaning of the components -The product is re-assembled -The tag system is updated -Packaging of the product is done -Transportation to the next end product manufacturing facility or construction site, given the case **Check Circular Economic Package which override the WFD Directive 2008/98/EC*	-Aluminium pieces are put into the smelting furnaces -Aluminium billets result from extrusion processes
APPLICATION	
-Consider extra cost and labour of overall remanufacturing process -Consider extra material for replacing any element inside the component during remanufacturing process -Consider extra cost and labour of packaging -Consider the economic and environmental gains from this scenario versus the recycling one -Consider an incentive from government promoting remanufacturing processes	- Consider cost and labour of melting -Consider cost and labour of extrusion process -Consider environmental and economic burdens from such processes
TECHNOLOGY	
-Tag system is checked to identify the components to be remanufactured -Tag system is updated once the product is remanufactured -Tag system is updated with the next destination	-No tag system required
BARRIERS	
-Lack of incentives from government for remanufactured products -Reuse/remanufacture or any other relief options that are nor recycling, are not taken into account when it comes to CD waste treatment, making it harder to estimate their benefits.	

Table 8 *Logistics information and findings*

As stated before, the table explained here is shown in the framework developed, shown in Figure 54. Sources to the statements can be found in the table above and some external references that were consulted and can be used to find out more about the corresponding topics.



NOTES

OER	(ORIGINAL EQUIPMENT REMANUFACTURER)
OEM	(ORIGINAL EQUIPMENT MANUFACTURER)
UBMROS	(USED BUILDING MATERIAL RETAIL OPERATOR)
RCA	(REVERSE CHAIN ACTOR)
SP	(SERVICE PROVIDER)
DECON	(DECONSTRUCTION)

T: TIME
W: WORK
M: MATERIAL
$: COST
F: FOOTPRINT
**ALL WORK INVOLVES EXTRA COST*

REMINE

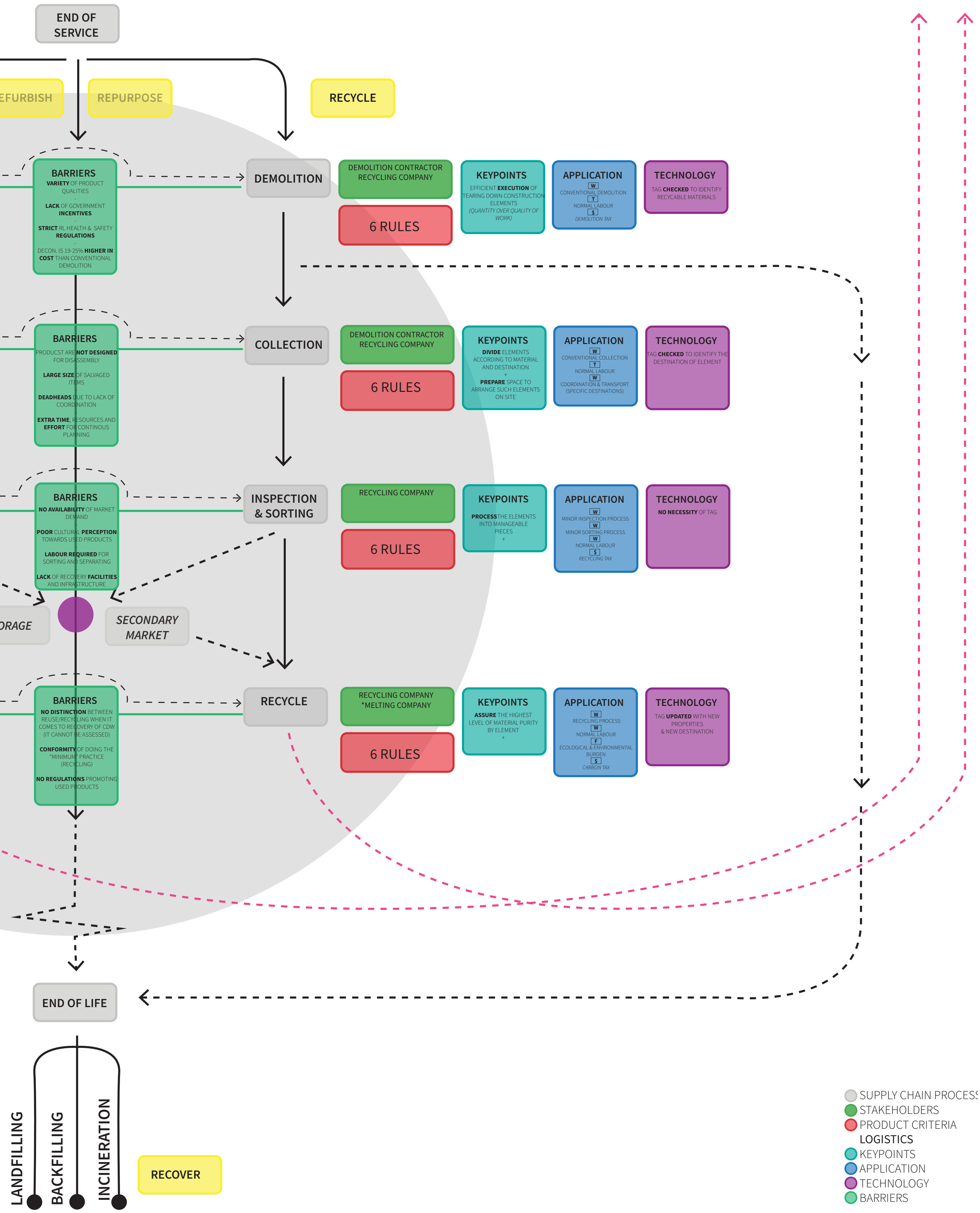


Figure 54 *Framework filled*

11.4 DfRL CRITERIA

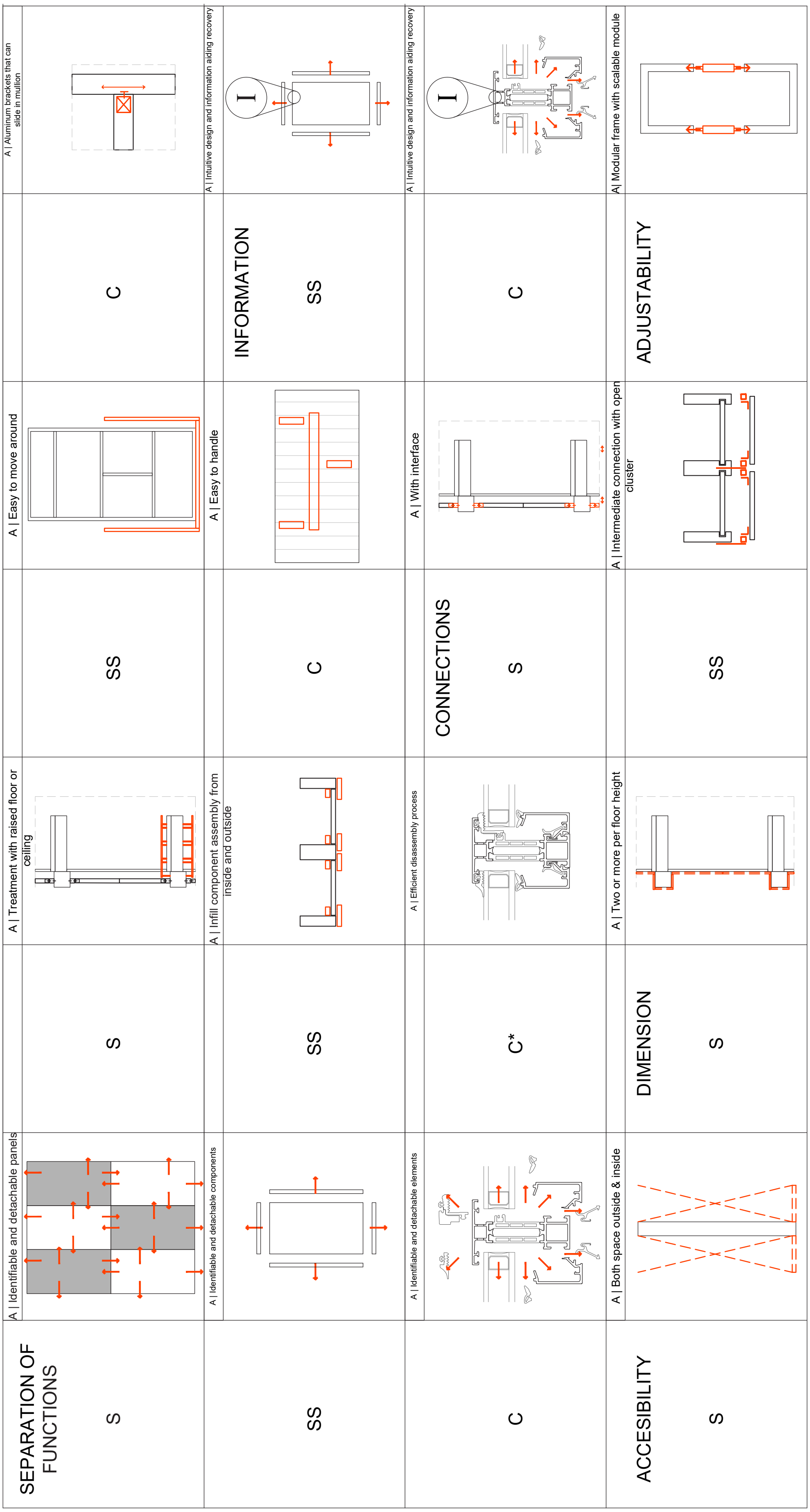
One of the main sub-products of the current thesis is the evaluation criteria of a product having as main focus the facilitation of reverse logistics. How can the façade be designed so it is the easiest to recover? For this, various sources were consulted, resulting in a hopefully intuitive and graphical evaluation model. It is based on the theories revised in the Assessments section—Design for Disassembly and Design for Adaptability— but it is simplified to 6 major criteria.

The six DfRL rules proposed are the following: Separation of elements, Accessibility, Dimensions or Size, Interfaces & Connections, Information Availability and Adjustability. They are the result of a synthesis from previous researches and adjusted to fit the Reverse Logistics framework. Some of the references used to develop the rules were: Jeroen van Veen's thesis on the PD Lab cladding system (Veen, 2016), Beurksens and Baxk's morphological approach (Beurskens & Bakx, 2015), and the mentioned disassembly criteria from Durmisevic (Durmišević, 2016). Without going into detail, each step on the process was visualized on a 3D software or as simple sketches. Having identified the necessary recovery activities, relevant criteria was highlighted, criteria that would inform the design phase of the product, making the recovery activity easier. Application to the different product levels is also possible. Apart from the written rules, a morphological table is also developed (Format 2), showing graphically the rules described in Table 9.

It was considered more relevant to make the criteria simple and reduced, so the user can understand and apply it quickly. Explorations and tests on other proposed ways to assess circularity can be found in the appendix. Their methods, however, proved to be too subjective and useless, given their high level of subjectivity. The best option at the end was the set of rules. Feedback from experts is then key to keep on developing such rules, which won't directly give a formal assessment to a product but will act as guidelines to help make decisions.

	LEVELS	CRITERIA	STAGE
1		SEPARATION OF ELEMENTS	
	S,SS,C	The façade system, sub-system and components should be dividable according to their function and should allow for detachability from one another.	ALL
		INTEGRITY & PURITY	
	C, E	The separation of functions must ensure the integrity and purity of the component or element, so any future treatments are viable. *Applicable for the Re-life option stage (Remanufacture & Recycling).	RE-LIFE OPTION
2		ACCESSIBILITY	
	S,SS,C	The façade system, sub-systems and components themselves, as well as the connections between them, should be easily accessible.	ALL
3		DIMENSIONS	
	S,SS	The vertical and horizontal façade sub-system dimensions should allow for an easy and effortless disassembly, an efficient transportation, as well as a proper future treatment.	ALL
4		CONNECTIONS/INTERFACE	
	S,SS,C	The façade sub-systems, components, and elements should be connected with independent interfaces, be consistent and allow for non-destructive demountability.	ALL
		INTEGRITY & PURITY	
	C, E	Having independent interfaces must ensure the integrity and purity of the component or element, so any future treatments are viable. *Applicable for the Re-life option stage (Remanufacture & Recycling).	RE-LIFE OPTION
5		INFORMATION AVAILABILITY	
	SS, C	The façade sub-systems and components must include the proper information about its age, quality, journey, maintenance activities, as well as guidelines facilitating the recovery process. It must help on deciding the re-life option which the product should undergo. Check Material Passport	ALL
6		ADJUSTABILITY	
	C	The façade components should be adjustable in length, depth and function by reconfiguration, replacing, adding, removing and upgrading elements. *Applicable for the Re-life option stage (Reuse).	RE-LIFE OPTION

Table 9 *DfRL Criteria*



Format 2 *DfRL Criteria*

12 APPLICATION

The application takes the formats previously defined and puts them into the test, taking the CITG panel by Alkondor and TU Delft . The chapter begins by analysing the existing solution in terms of the existing documentation. After that, the RL Framework is filled with two different scenarios as well as the Graphical framework for a friendlier visualization of the process. The DfRL is also used, working as a conclusion. Weak links are identified to be reprised in the following chapter about Design.

12 APPLICATION

12.1 GENERAL CONTEXT

The first leasing project by TU Delft on the EWI building in 2016 brought stakeholders together in a common product, resulting in a close interaction between the different parties. The four panels installed on the façade served as a mock-up to understand a new business model, different from the usual product-oriented one. The second leasing project was applied to the Faculty of Civil Engineering and Geosciences of TU Delft, known as "CiTG" (Figure 55). It had an overall poor energy performance and the intention was to make an energy retrofit in the whole east façade, using the product-service model (Hollander, 2019). The project provided the perfect scenario to explore the new circular business model in a larger scale, redefining the new roles of the stakeholders involved and their contractual obligations (Azcarate et al., 2017).

A product-service system application was intended; however, it did not go through. But the fact that the facade was all designed with recovery in mind, makes the case worth studying. Exercises in compatibility are a must to prevent future issues when the re-life options take place. Other features that make this case attractive is the challenge of rendering a better performing envelope in the process. Besides, it is a convenient project to address as it is part of the university campus and the documentation is more accessible than other projects, assuring a better development and elaboration of the design.

Figure 55 *CiTG Building by Hollander (2019)*

12.2 DESCRIPTION

Designed by the architecture office Van Broek and Bakema in the 1960s, it features a brutalist exterior with solid and transparent patches in its façade. A window wall system is evident from simple inspection and the concrete structure is exposed to the outside, leaving the vertical structural elements inside.

The original façade consists of uninsulated steel frames with single glazing and manually operable windows. It mainly features panel-based components of about 1.80 x 3.10 meter inserted in between the concrete slab and the outer concrete ring beam. The panels are composed of spandrel parapet, double window with one fixed glazing and an operable part, a top fixed glazing unit at the top and an operable glazing unit for ventilation (Hollander, 2019). This system covers four regular stories and the top irregular one. As already mentioned, the panels are places outside the structure, namely the vertical elements of the load-bearing system. They are confined in between the slabs, yielding an average height of 3.10 meters. The connections between each 1.80-meter panel are aluminium mullions. Figure 56 shows the structure and original facade system.

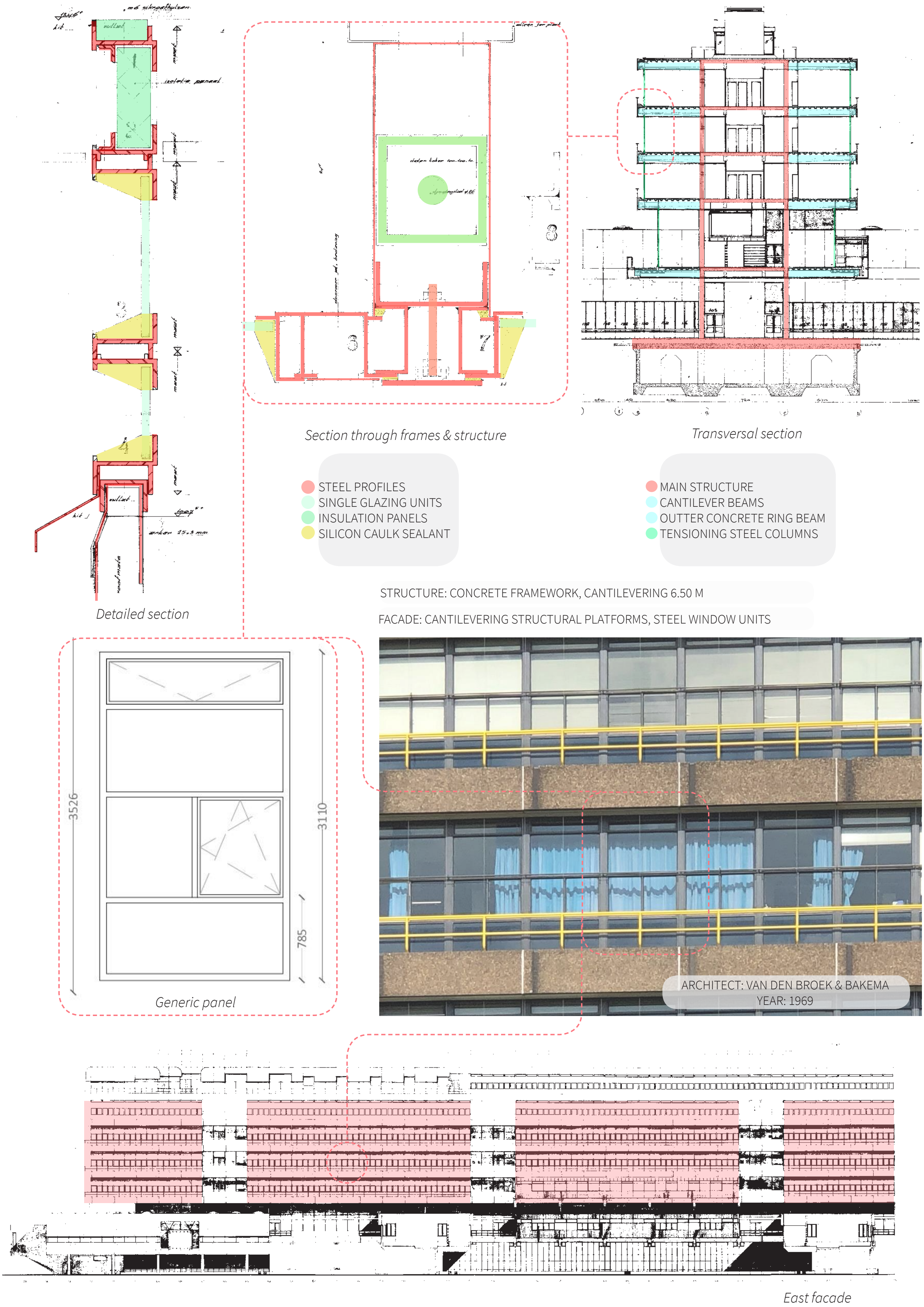


Figure 56 *Original facade analyisis of CiTG Building*

12.3 DESIGN SOLUTION FROM ALKONDOR

In recent years, the need of an overall refurbishment and energy retrofit was evident due to its poor performance. Being built during the post-second world war period, it reached its end of original service life recently, just like 50% of building across Europe (Azcarate et al., 2017). The image of the building is still a feature to be preserved, as defended by the university and municipality. Decided by TU Delft, the west façade only underwent minor maintenance activities that would assure an adequate environment for working inside ("Civil Engineering faculty building gets ten year lease of life.," 2017). Such "economical" maintenance comprised the removal of the old cladding, installation of new ceiling panels, new exterior blinds, painting the railings and replacing the casement window stays. These, however, are of no use for the overall performance of the building.

As opposed to the west, the east façade was subject to the leasing façade project, including a panel that could be easily recoverable. It was a result of a collaboration between TU Delft and Alkondor Hengelo. The new solution (Figure 57) features high performance framing and glazing, centrally operable windows including an upper window for night-cooling airflow, and external sun shading with high-velocity wind resistance. It also resembles the original design proposed by the architect. The high-performance aluminium block system based on Schuco AWS 75 BS HI and insulated triple glazing assure a U value of 0.8 W/m2K, improving 85% when compared to the original façade (5.4 W/m2K). More specifications are described in Table 10 and the products used are shown in Figures 58-60.

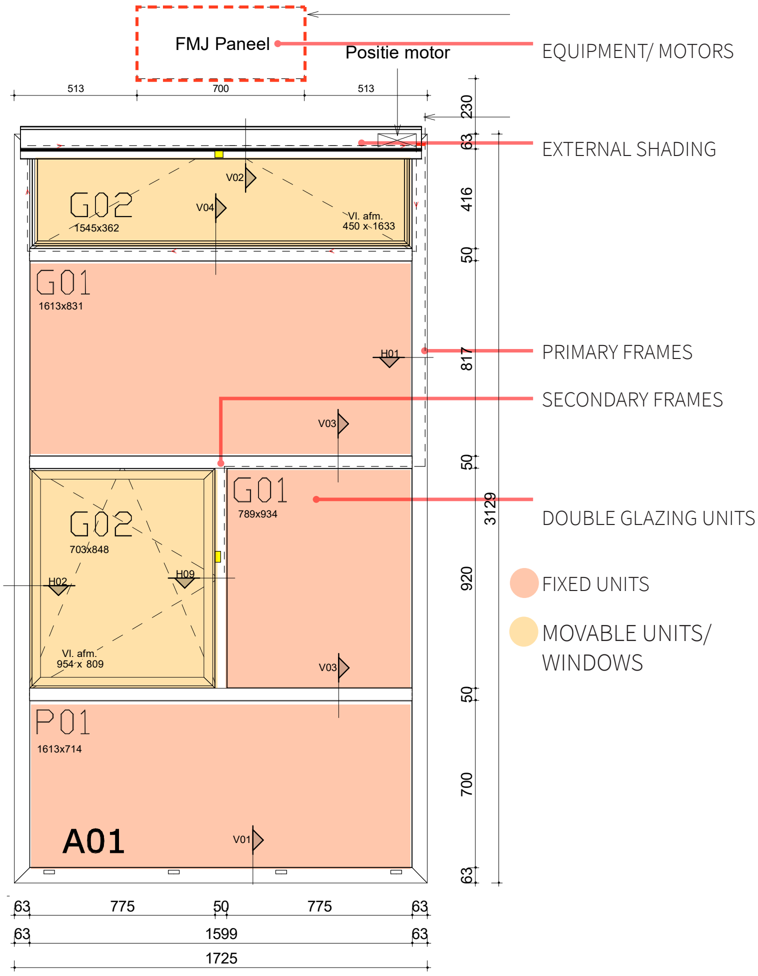


Figure 57 *Generic panel & components*

Curtain Wall System:	Schuco AWS 75 WF.SI
Material	Aluminium extruded profile
Alloy	EN AW 6060
Surface treatment	Powder coating, painted, duraflon
Colour	Antracite Gray
Uf-value	1,2 W/(m²K)
Frame depth	75 mm
Acoustic insulation	45 dB
Watertightness (DIN EN 12208)	Class 9A
Airtightness (DIN 12207)	Class 4
Wind resistance (DIN 12210)	Class C5/B5
*Window System 1:	Schuco Avantec Simply Smart
*Window System 2:	Schuco Tip Tronic

Table 10 *Specifications of systems used*

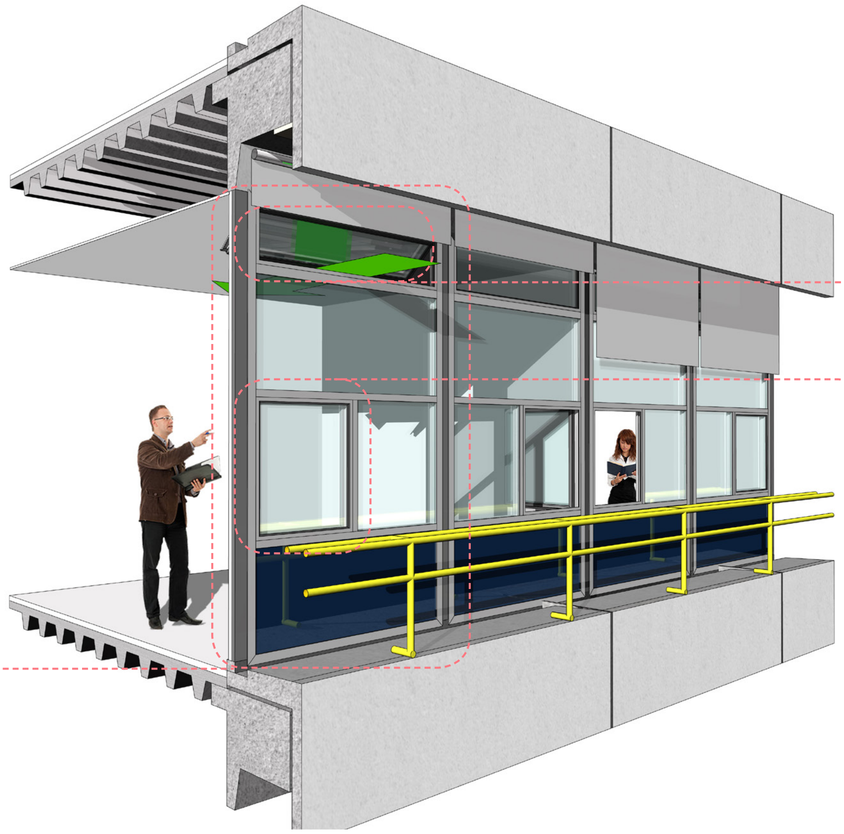


Figure 58 *CiTG Building Proposal by Azcarate et al. (2017)*

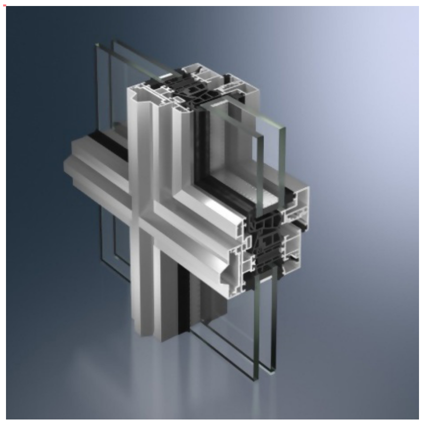


Figure 59 *Schuco* AWS 75 WF.SI | Avantec Simply Smart

Figure 60 *Schuco Tip Tronic*

12.4 DETAILS & DOCUMENTATION

The following drawings (Figures 61-63) provided by Alkondor Hengelo show the system used for the refurbishment of the CITG building. The most relevant feature is the wooden substructure that allows for an easy installation and eventual removal. It also allows the panels to move, providing more tolerance when compared to a conventional installation without such intermediary.

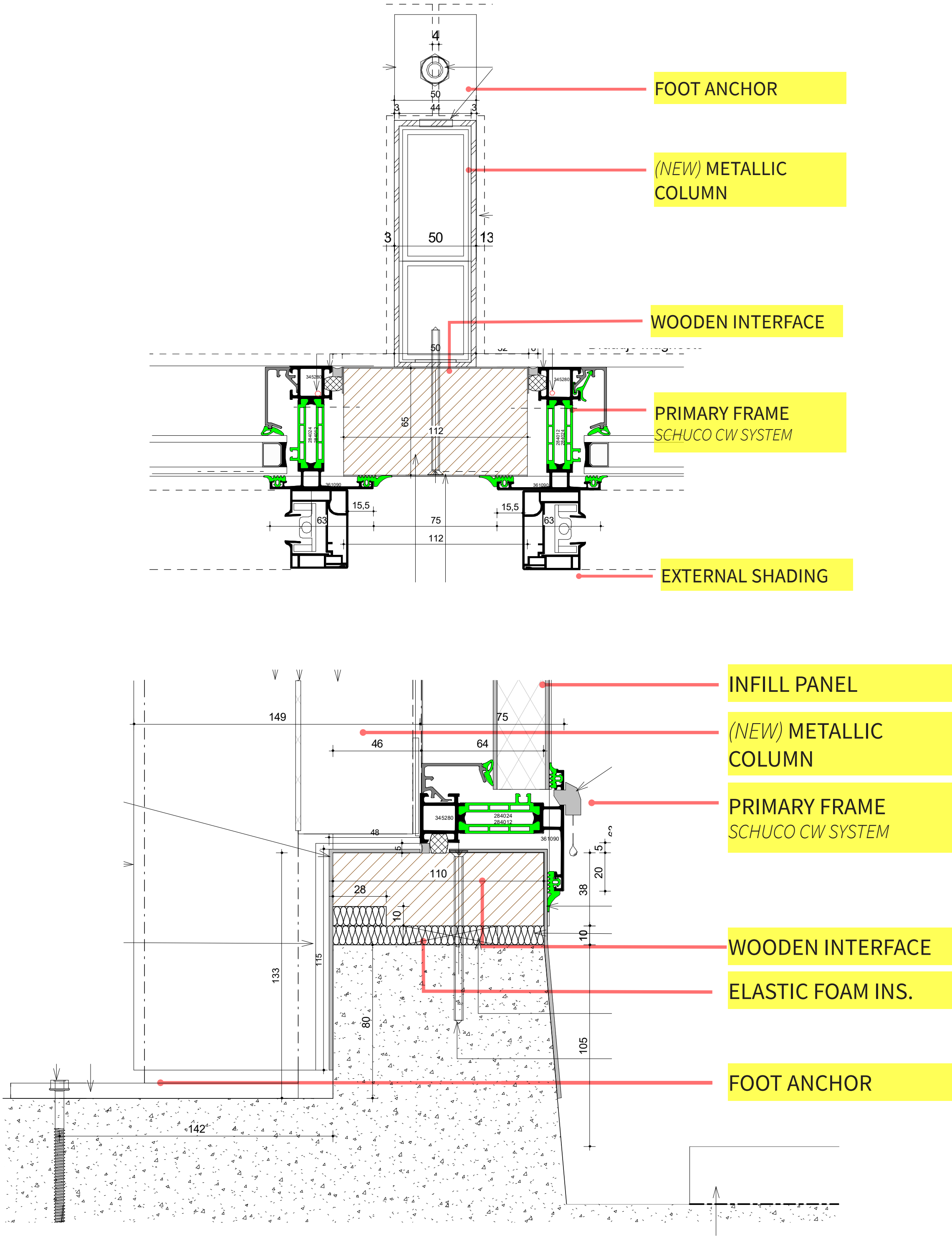


Figure 61 *Horizontal section and vertical section details*

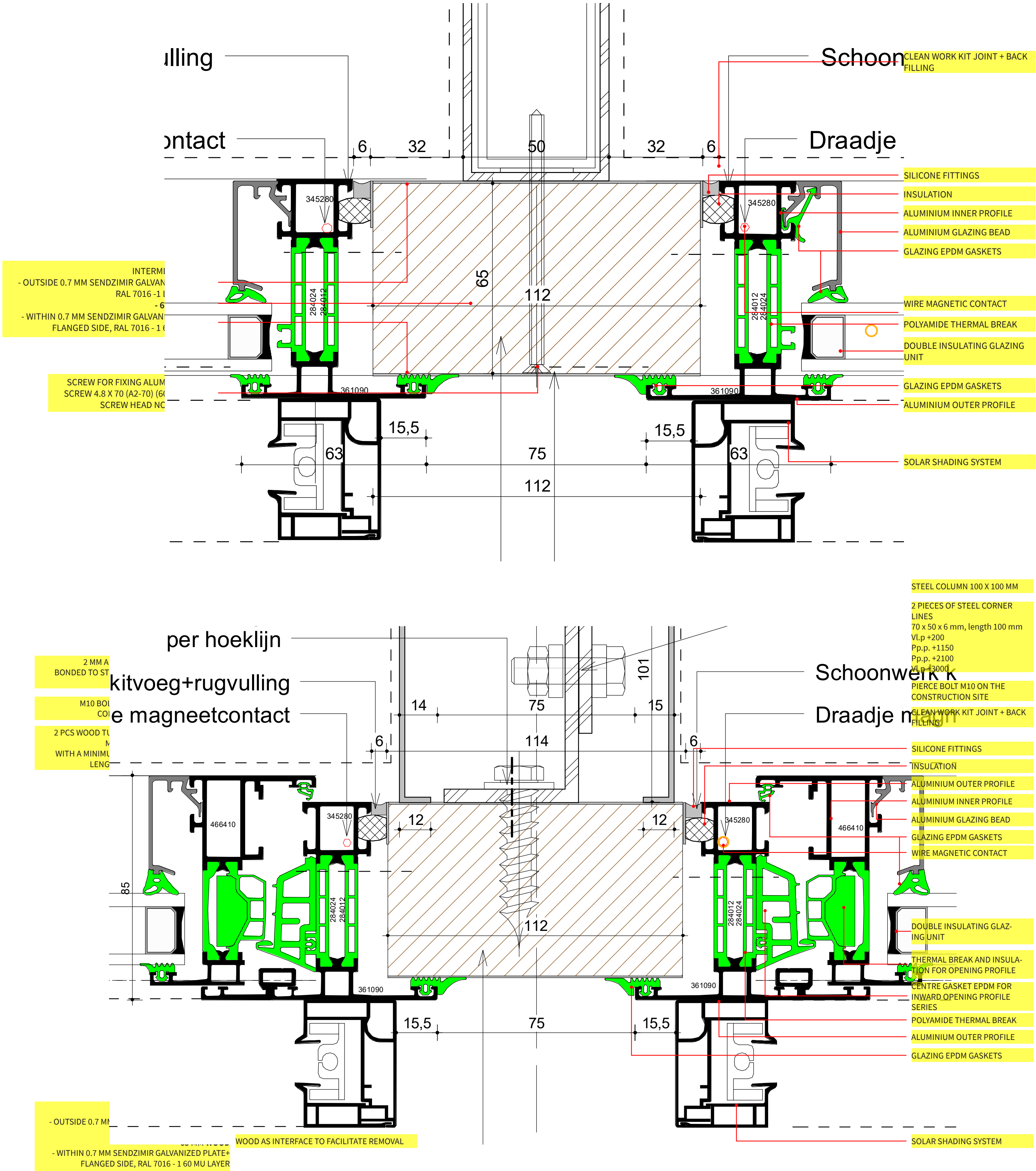


Figure 62 *Horizontal section details on connections to structure*

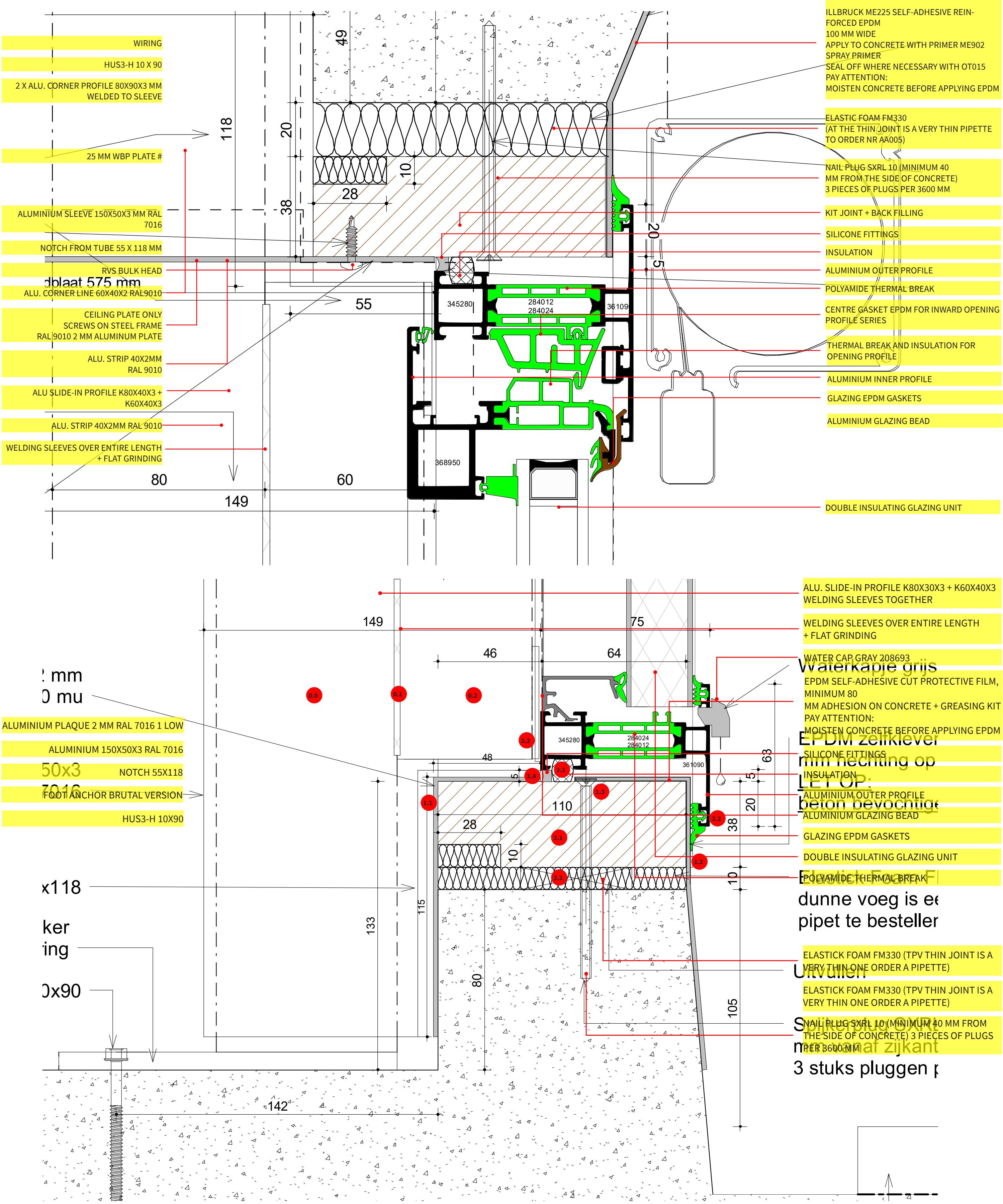


Figure 63 *Vertical section details on connections to structure*

12.5 MATERIALS USED

A scheme of the materials going into the described panel for the CITG is shown below (Figure 64), conceptualizing the supply chain process involved. It is informed from the interviews with Juan Azcarate and Tillmann Klein, and in a lesser degree Maritjn from Alkondor. The working map is shown in the appendix VII, used to link the input given at the various stages of the research. Even though the current work is not focused on different material alternatives and their properties (but more how they behave in the supply chain), it is important to have their lifespans present as they will inform on any necessity for any re-life treatment. Table 11 shows the lifespans of the main materials. The EoL scenarios are also relevant, to make the distinction between the current situation and the proposed/most desirable scenario.

	Element	Material	Expected lifetime (years)	Current EOL scenario	Potential
Façade panel	Extruded profiles	Aluminium (Powder coated)	75	Recycled	Reuse
	Thermal break	Polyamide (PA 66 - 30% glass fibre)	Approx. 40	Incinerated	Reuse
	Rubber gaskets	EPDM	30	Incinerated	-
	Glazing beads	Aluminium (Powder coated)	75	Recycled	Reuse
	Corner brakets	Aluminium	30-50	Recycled	Reuse
Interfaces	Watertight barrier	EPDM	30	Incinerated	-
	Rigid Insulation	XPS foam (extruded polyestyrene)	Unknown (Approx. 30)	Incinerated	-
	Wooden interface	Wood (not specified in details)	20-40	Recycled	Recycle
Other systems	Aluminum window system		43.6	*Low maintenance	Reuse
	PVC window system		24.1	*Low maintenance, difficult to repair	Recycle
	Timber window system		39.6	*High maintenance, easy to repair	Recyle
	Al-clad timber window system		46.7	*Low maintenance, easy to repair	Recycle
	*The glass and its insulation system are not included in the material analysis				
	**Potential refers to highest level of re-life option possibly applied				

Table 11 *Materials used on facade system & lifespans*

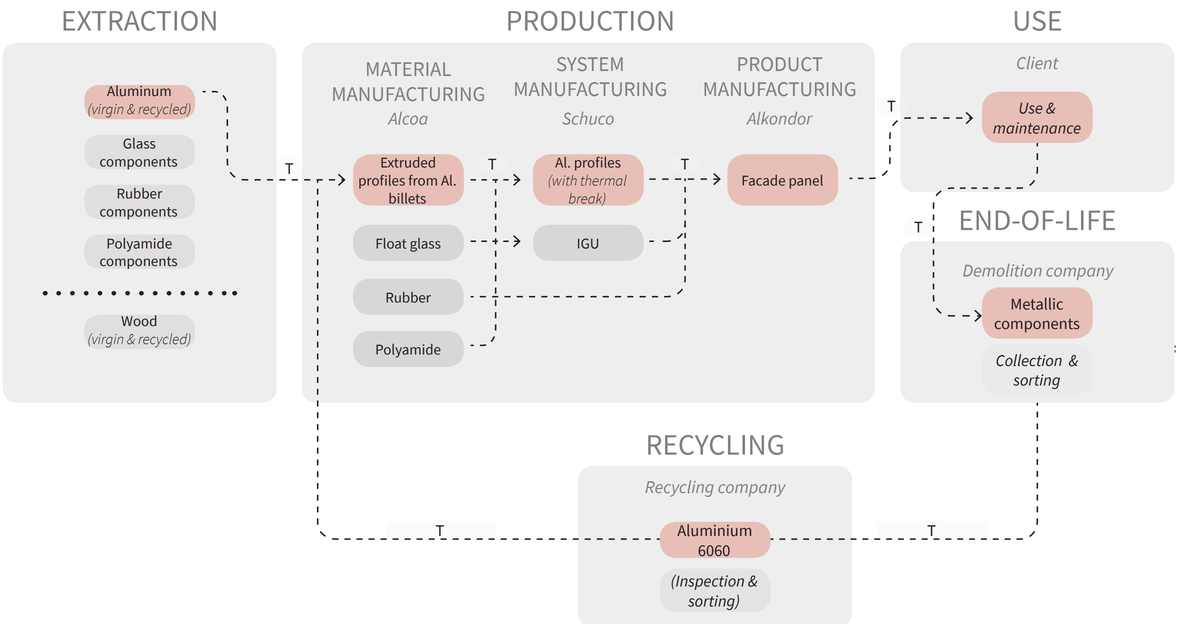


Figure 64 *Scheme of current supply chain for the CITG facade subsystem*

12.6 ASSESSMENTS

To assess the CITG design solution, a hypothetical scenario of remanufacturing the façade for a second life is assumed. From interviews with the designers in charge—Juan Azcarate, Tillmann Klein, Martijn Veerman—it is known the façade was designed to be fully recovered. It is assumed the façade—with a lifespan of 30 years—will be recovered to be used in a different building that is not the CITG—a 60-year-old building with 15 years more to go. This is compared to the recycling scenario, the common practice currently. The comparison will then provide a clearer view of the remanufacturing requirements and overall differences versus recycling. The schemes presented are both in the "Descriptive" Framework Format and also in the "Graphical" Framework Format, friendlier to the reader (see figure 65). Both assessments are based on the framework, on the four basic steps defined in the previous chapters. The "Descriptive" Framework highlights the logistic dimension (addressed in the information boxes), identifying Stakeholders, Places, Key Points, Application requirements and Barriers. The "Graphical" Framework Format highlights the product dimension (addressed graphically, with disassembly diagrams when needed). Using the rules defined in the Product Criteria, the product is evaluated in the "Graphical" Framework Format. At the end, it is intended for this assessment to reveal the weak links that will be tackled in the design stage.

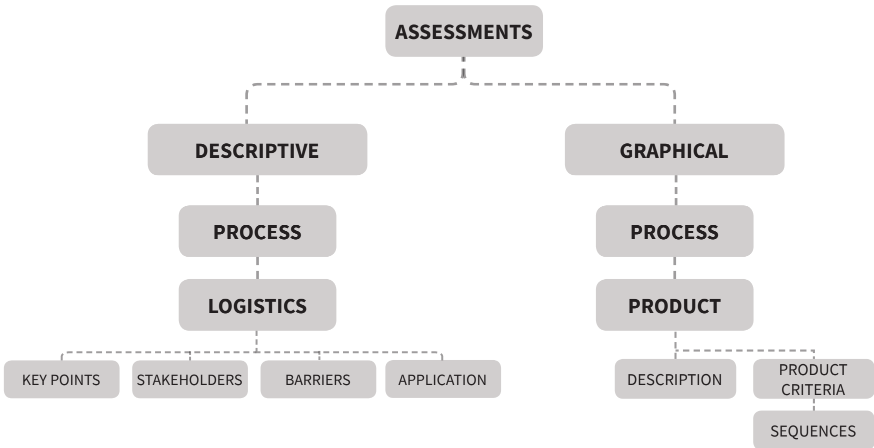
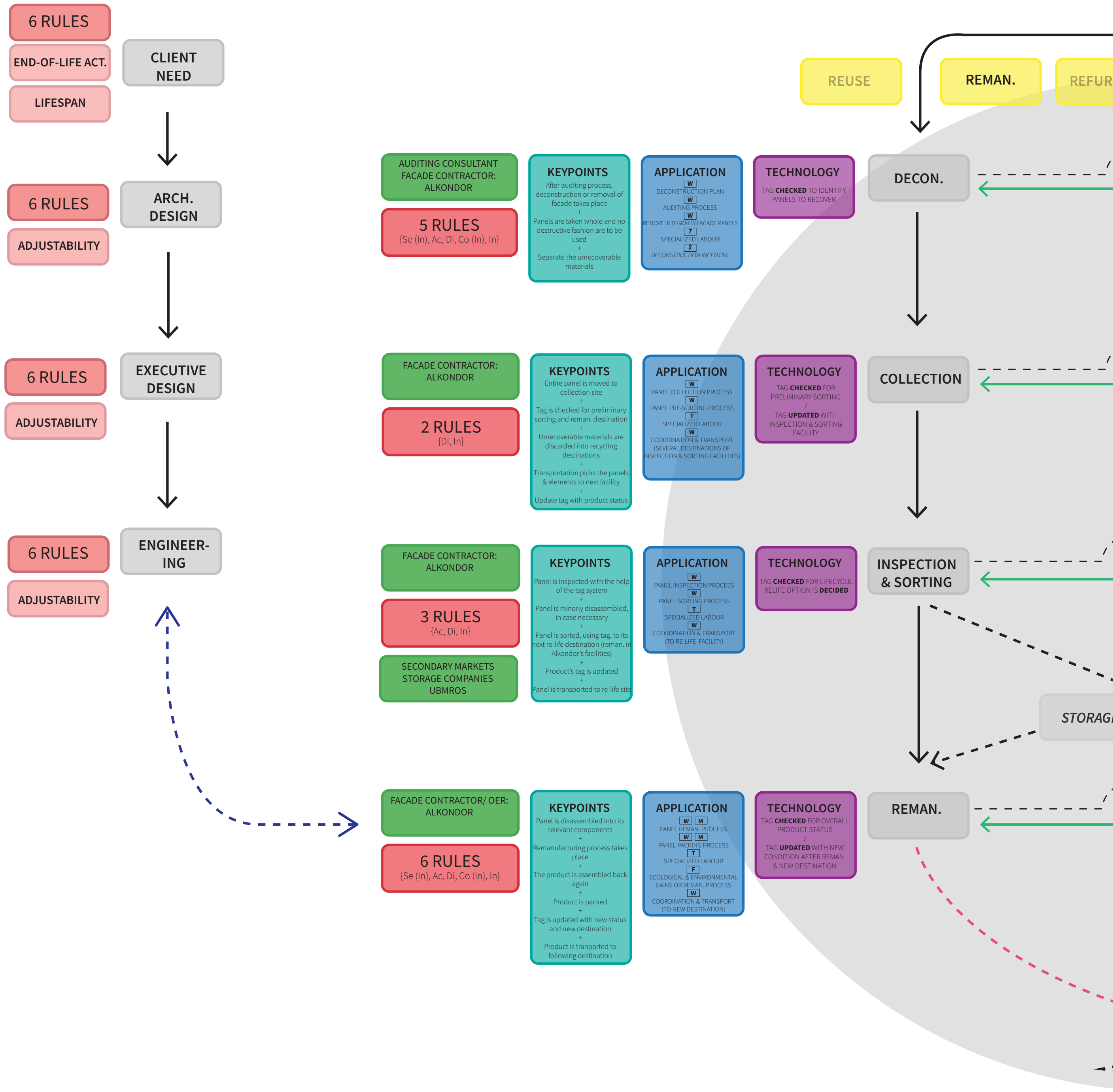


Figure 65 *Scheme of application*

12.6.1 DESCRIPTIVE ASSESSMENT

As explained in the framework, each step is filled with relevant information that might be of use in next research, especially the Application Information box. In the current framework, the CITG case is being analysed. The four basic steps are filled with the process to be followed and the unknowns that are presented along such process. There is an important distinction between the two schemes: two different scenarios are identified. The first is classified as a Closed System (Figure 66) and the second an Open System (Figure 67). A Closed system here refers to the RL process remaining within the responsibility of the original façade supplier, Alkondor. They are the façade technicians who will be in charge of conducting the deconstruction, collection, inspection & sorting, and remanufacturing, with the goal of having their own product installed in a new building, for a second life. The SPV or façade investor is also behind, as they are the owners of the façade and they will take responsibility for it once Alkondor loses interest on the product and decides to "sell" it. The second scenario, the Open System, assumes Alkondor or the façade supplier, is no longer responsible for its products after its first use/installation. So once deconstruction happens, the façade investor is totally in charge of organizing which company will recover the façade and collect it, which company will inspect and sort it, and which will remanufacture it. The costs of the whole operation will be then absorbed by the next client, who while lease the façade for a price that contemplates the previous steps. Besides, secondary markets are also a highlight in this case, as the possibility of used products having no owner is high. Such markets are key to make second-hand products available to others, an underdeveloped business sector nowadays.

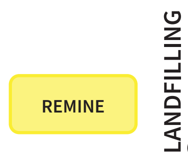
In conclusion, the Closed System accounts for a simplified version in logistics and stakeholders: only one main actor is involved during the four steps. However, from interviews with VMRG and Schuco, the roles and responsibilities described in the Closed System are far from being currently applied. There is a need of new actors that absorb the tasks and risks involved in the overall process, for it to be implemented in the industry.



NOTES

OER	(ORIGINAL EQUIPMENT REMANUFACTURER)
OEM	(ORIGINAL EQUIPMENT MANUFACTURER)
UBMROS	(USED BUILDING MATERIAL RETAIL OPERATOR)
RCA	(REVERSE CHAIN ACTOR)
SP	(SERVICE PROVIDER)
DECON	(DECONSTRUCTION)

T: TIME
W: WORK
M: MATERIAL
$: COST
F: FOOTPRINT
ALL WORK INVOLVES EXTRA COST



DESCRIPTIVE ASSESSMENT: Closed system

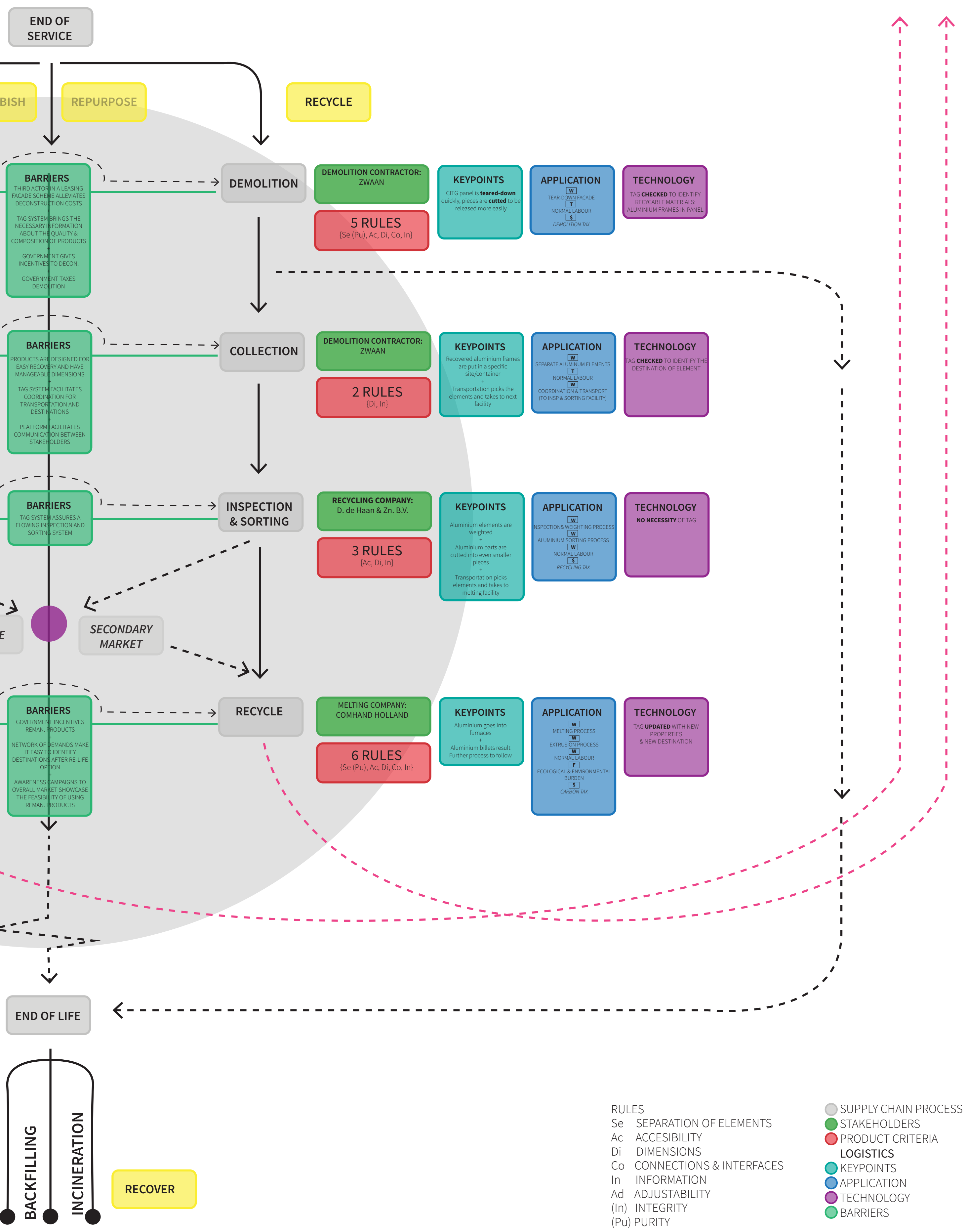
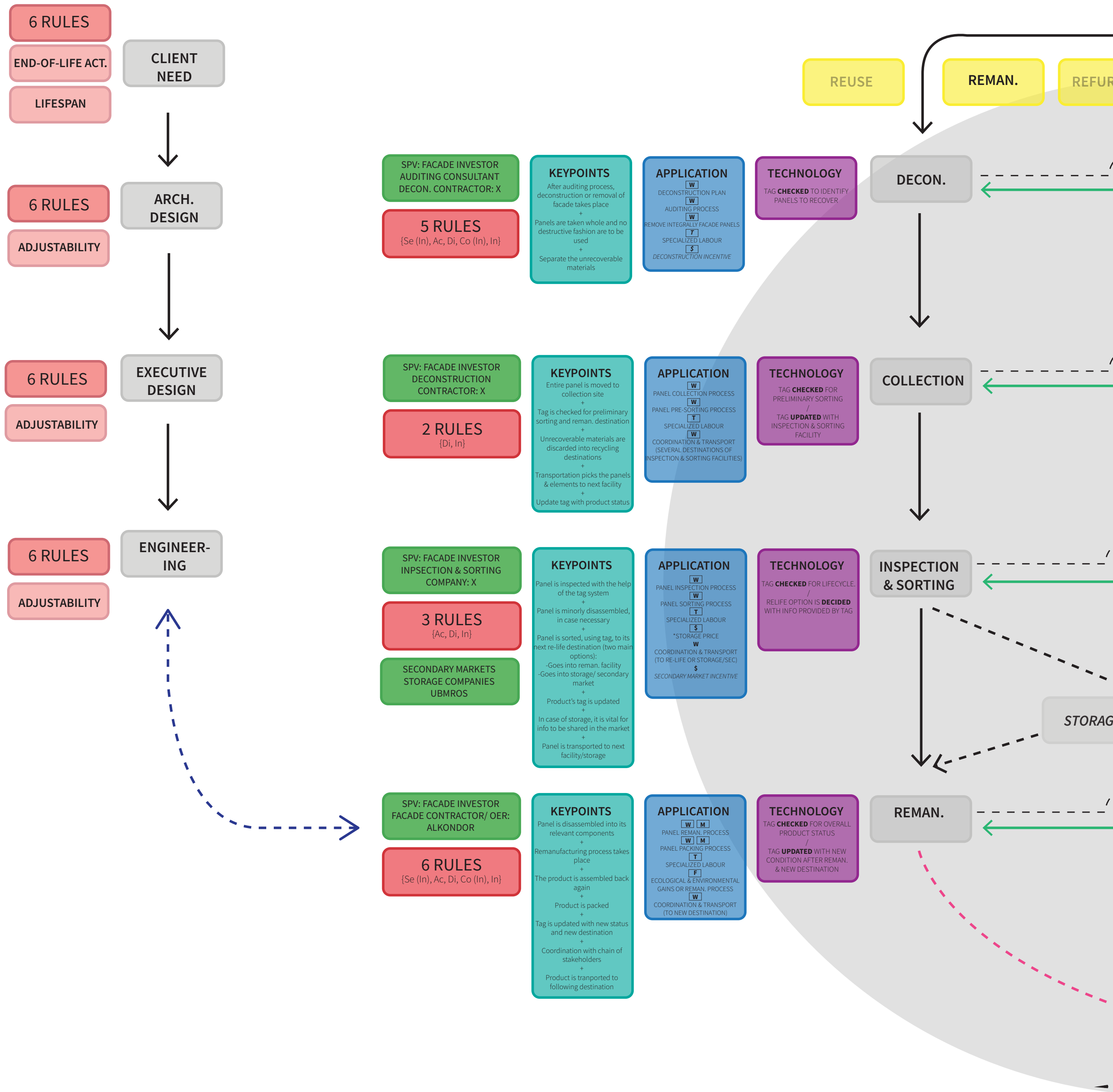


Figure 66 *Closed system, CiTG facade case study*



NOTES

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OEM (ORIGINAL EQUIPMENT MANUFACTURER)
UBMROS (USED BUILDING MATERIAL RETAIL OPERATOR)
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SP (SERVICE PROVIDER)
DECON (DECONSTRUCTION)

T: TIME
W: WORK
M: MATERIAL
$: COST
F: FOOTPRINT
ALL WORK INVOLVES EXTRA COST

REMINE

LANDFILLING

DESCRIPTIVE ASSESSMENT: Open system

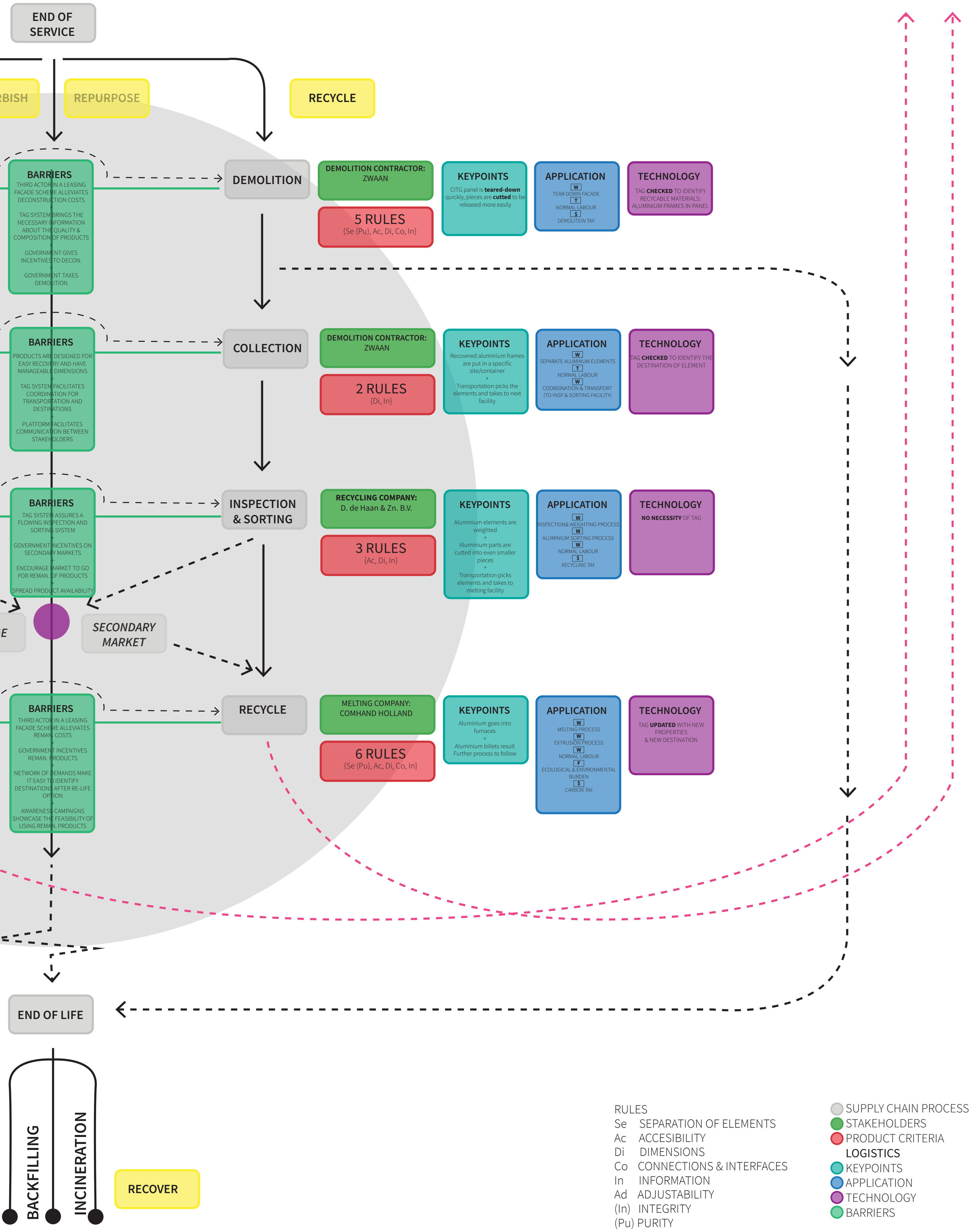


Figure 67 *Open system, CiTG facade case study*

12.6.2 GRAPHICAL ASSESSMENT

The Open System is illustrated in the diagram in Figure 68. Just to give an overview of the process, as it has been mentioned in the previous sections, the four main steps are represented. Assuming the CITG has been in use for 15 years after its installation in 2019 and the CITG is to be repurposed/demolished, the first stage is the deconstruction. The deconstruction plan is necessary beforehand as well as the auditing process to make an efficient overall deconstruction. Such process would address the overall building. A deconstruction company is hired by the façade investor to recover the façade. It is then collected and pre-sorted on site, using the tag system to define the next destination. During the inspection and sorting phase the façade is evaluated, using the tag as well to get relevant information on its use, maintenance and overall quality. Once the product's information is disclosed, two different routes can be identified: it going directly into a remanufacturing facility where it can have the proper treatment for a second use (in this case, a client has already bought/leased the façade for a specific project), or it going into storage and a secondary market where the next client would acquire it (in this case, a client is missing). After a client leases or buys the product from the secondary market, then remanufacturing takes place. Finally, after the re-life process, the product will reach the next corresponding facility or building for installation.

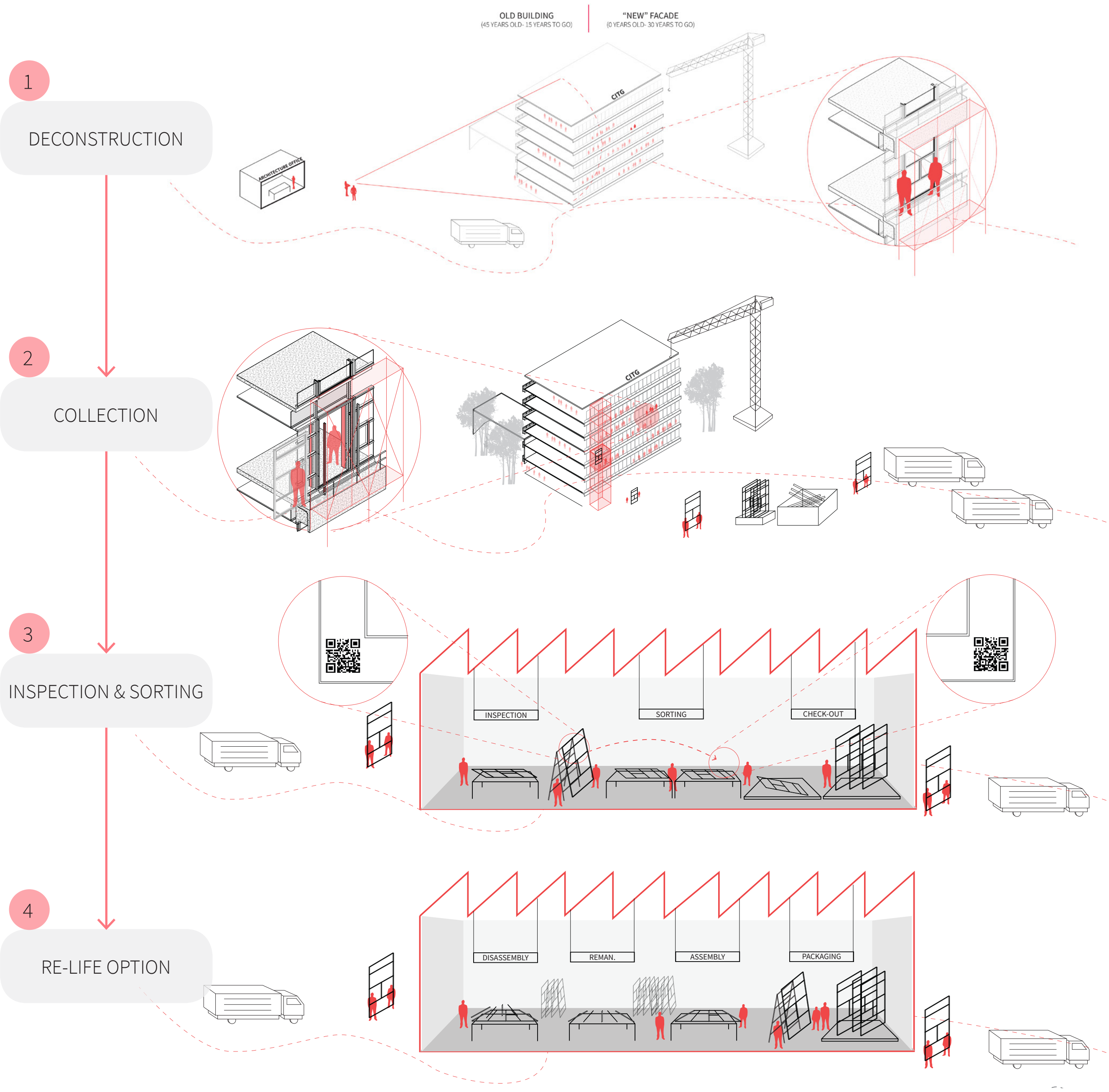


Figure 68 *Overall view of Graphical Assessment*

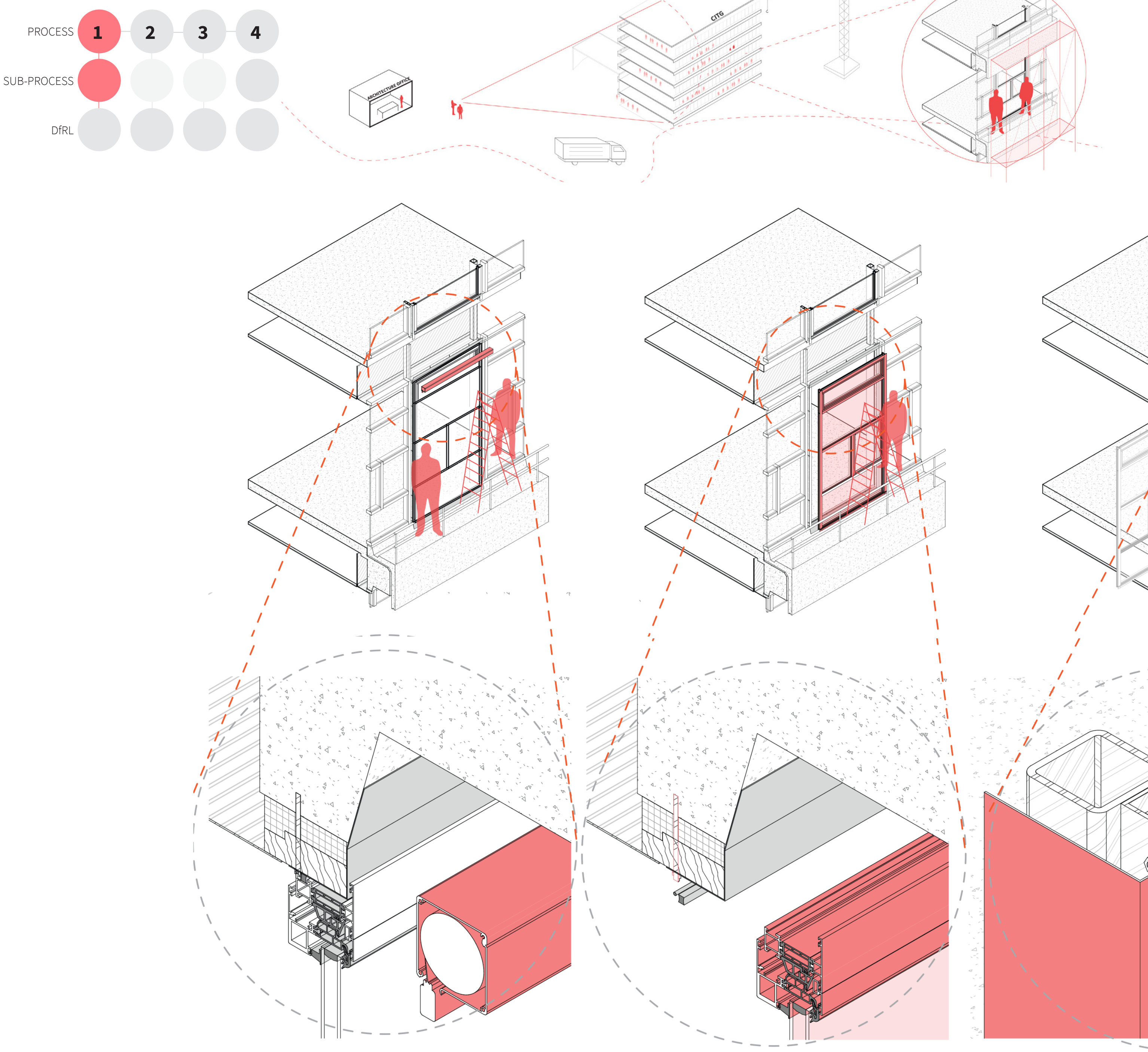
(The following descriptions correspond to the figures shown in the next pages. The numbers indicate which diagram they are referring to.)

1 For the **Deconstruction** process, the correct removal of the façade is key for the rest of the process. According to Alkondor and the designer from TU Delft, the façade is designed for an easy recovery. The construction sequence can be seen in the diagram below. The process starts with the extraction of the external sun shading, screwed to the wooden interface, located at 3.13 m above the floor level. The panel is then dismounted from the wooden interface, having screws as the connection. Such frame acts as intermediary between the façade panel and the main structure. Even though the panel is considerably smaller than most of the curtain wall panels in the market for conventional office buildings, the height of the CITG panel has a total of 3.13 meters, which does pose a harder task considering the initial design intention was to facilitate recovery. After the panel is removed, the aluminium covers that wrap the wooden interface and the structural columns are teared off. Next are the functional layers that bring thermal protection and tightness to the whole system: the EPDM membrane , the wooden interface beneath, the rigid insulation and the silicone sealings. They are all discarded and go into landfilling. The last element would then be the additional steel column added for the installation of the panel, which is connected with a bracket to the concrete slab.

2 **Collection**, which encompasses taking the panel from its dismounting point to its collection point, informs also the design. Given its dimensions, the panel would be laborious to move through the scaffolding system and elevators. Pre-sorting on site is also a task made more difficult due to the size of the panel; as for information, the panel possesses a tag system that will allow an efficient coordination with the transportation actor, in charge of delivering the façade to the next location. Besides this, the unrecoverable materials are also sorted to the landfill, inevitable components according to current façade practice.

3 The **Inspection and Sorting** process is vital for various reasons, one of them being the definition of the right re-life option to be applied to the product. It begins with the product reaching the Inspection & Sorting Facility, where it is checked and evaluated. A minor disassembly might be conducted if necessary, to reach an adequate level of information. The tag system is also consulted here to determine the overall quality of the product, its use in the building (e.g. how many times a door or window has been opened), how many times and which maintenance has been given, and who is the owner of the product at the time. To have a better idea of the information that such code might provide, consult the appendix X where a typical material passport is described. In fact, VMRG'S Cirlinq is also addressing such task, by giving products relevant recovery information. All of these resources help on sorting the product to the right location, to the right productive loop. Two destinations might be available at this point: the remanufacturing facility where it can have the proper treatment for a second use (in this case, a client has already bought/leased the façade for a specific project), or it going into storage and a secondary market where the next client would acquire it. After a client leases or buys the product from the secondary market, then remanufacturing takes place.

4 The last step in the framework is the **Remanufacturing** of the panel. When reaching the facility, the first step consists on disassembling the product and take apart the pieces to give them the proper treatment. The construction sequence can be seen below. In this case, the window systems are first dismounted from the main frame. The two windows used in the panel are from Schuco: the AvanTec SimplySmart and the TipTronic. They are screwed to the primary and secondary frames, so unscrewing them allows to dismount both systems in a non-destructive way. Then, the glazing beads are unplugged. Force was applied in the first place to install them, which doesn't assure a wholesome recovery. After they are removed, the gaskets and the glass units are dismounted, both of them being pressured in place. A total disassembly would mean secondary frames being separated from each other and from the main frame. However, according to Joep Römgens from Shuco, frames in a window system are the last thing to be remanufactured and it is not a common activity to do in real practice. In any case, it is worth highlighting wet connections are used to unite the frame, using T- or corner cleats filled with an adhesive. Even if they are not separated for the remanufacturing process, it might be an interesting point to research in the future. After disassembly, remanufacturing of the separate components is done, it is re-assembled and shipped to its next location. In this case, a new client leases the façade, owned by the façade investor. Transportation is involved and the tag system is used for an effective coordination.



SUN SHADING IS DISMOUNTED

- -Sun shading screwed directly to wooden interface
- -Need of ladder to reach the equipment
- -Scaffolding needed for protection

UNKOWNS

- -Cost of removal
- -Work (time) of removal

WHOLE PANEL IS DISMOUNTED

- -Panel is unscrewed from the wooden interface
- -Dimension of panel requires use of scaf-folding and elevators/crane
- -Need of ladder to reach the whole panel
- -Scaffolding needed for protection

UNKOWNS

- -Cost of dismounting
- -Work (time) of dismounting

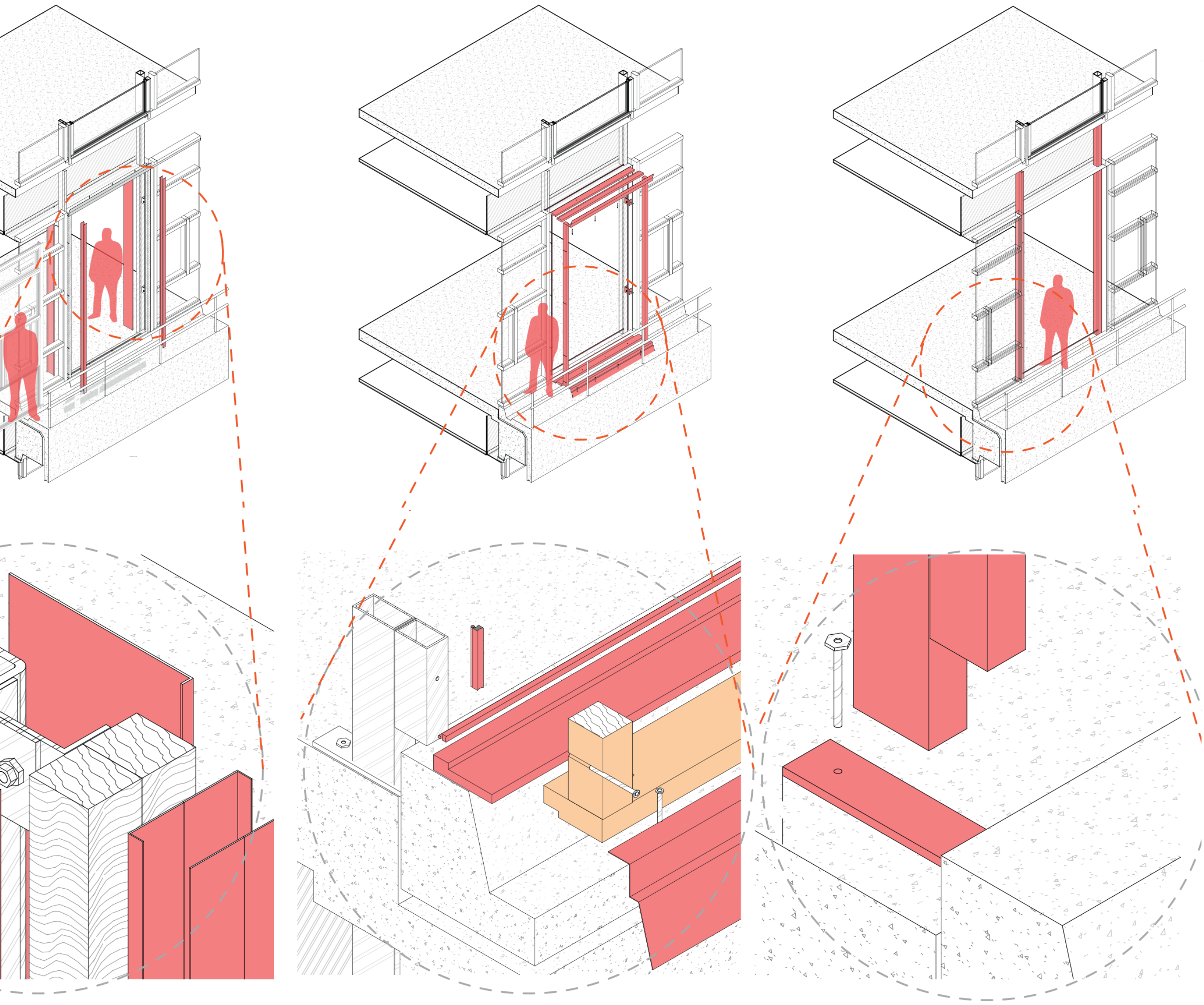
INTERFACE (

- -Caps are naile
- - Caps are teare
destructive way
-Aluminium cap
remanufacturin

-Environement

Format 3 *Graphical Assessment* | **In this case it is filled, but the way of formatting is suggested*

GRAPHICAL ASSESSMENT: Deconstruction



CAPS ARE TEARED DOWN

d to the wooden interface
ed down from interface in
y
os cannot be recovered for
ng but for recycling

UNKOWNS

al cost of recycling

UNRECOVERABLES ARE TEARED DOWN

-The wooden interface and functional layers are teared down
-The unrecoverables (wooden interface, the EPDM membrane, the silicone sealing, and the rigid insulation) go to landfill
-Wooden interface can only be recycled

UNKOWNS

-Environemental cost of landfilling
-Environemental cost of recycling

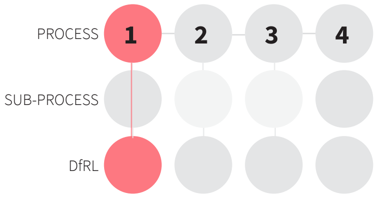
STRUCTURE IS DISMOUNTED

-Structure (steel columns added for facade installation) is dismounted
-Destination of column unclear, most likely recycling
-The bracket and concrete wegde anchor (or bolt) are recycled

UNKOWNS

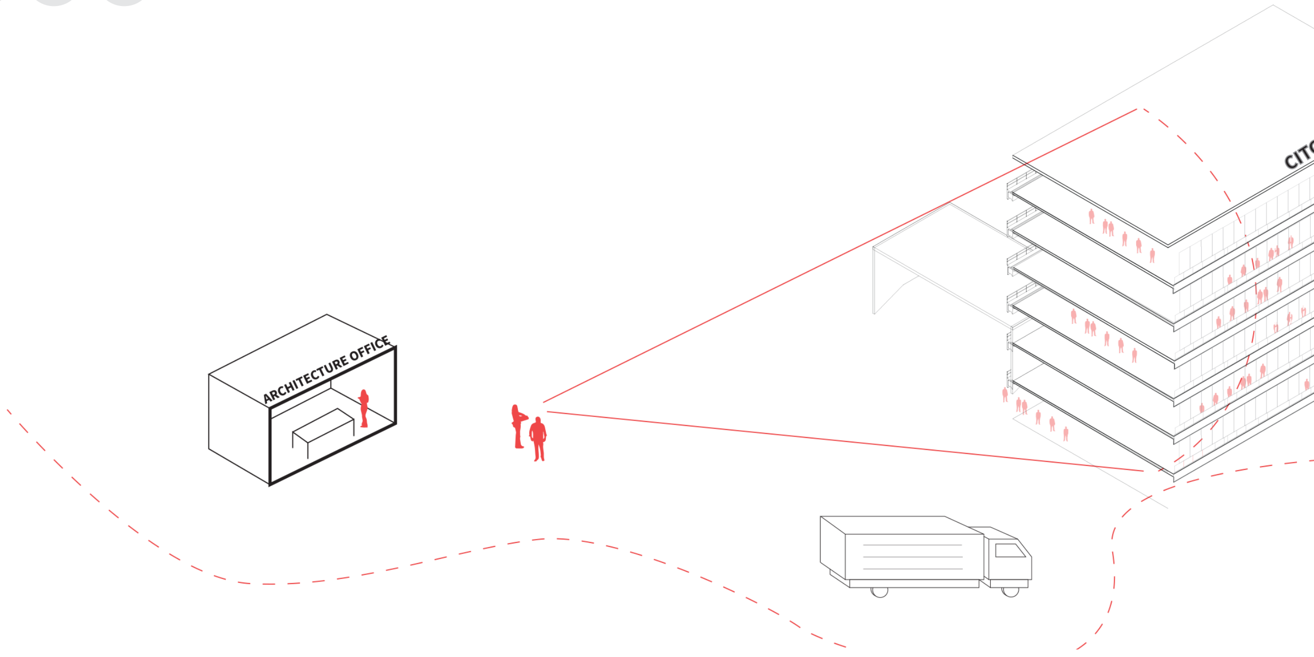
-Environemental cost of recycling

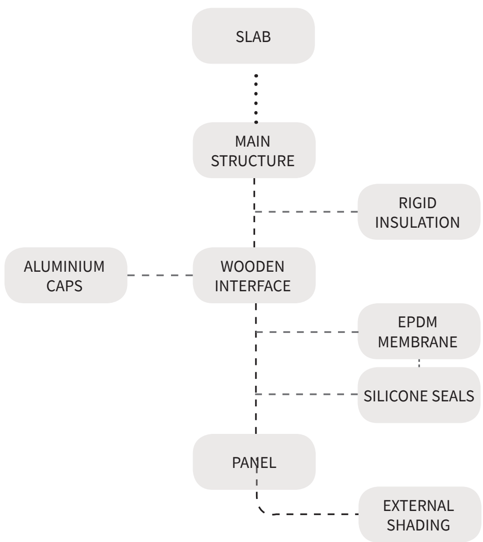
Figure 69 *Graphical Assessment: Deconstruction*

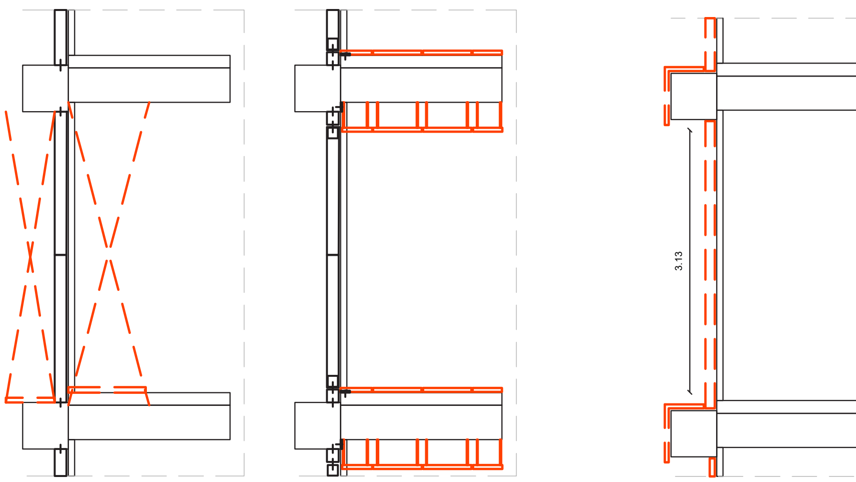


OLD BUILDING
(45 YEARS OLD- 15 YEARS TO GO)

(0 YEA







SEPARATION OF ELEMENTS

Consult diagram of relations (sequence) in appendix

SS: Panel can be dismounted completely (screwed)

SS/C: Sun shading can be dismounted completely (screwed)
-Different functional layers are indeed separate, but connected via destructive media

ACCESIBILITY

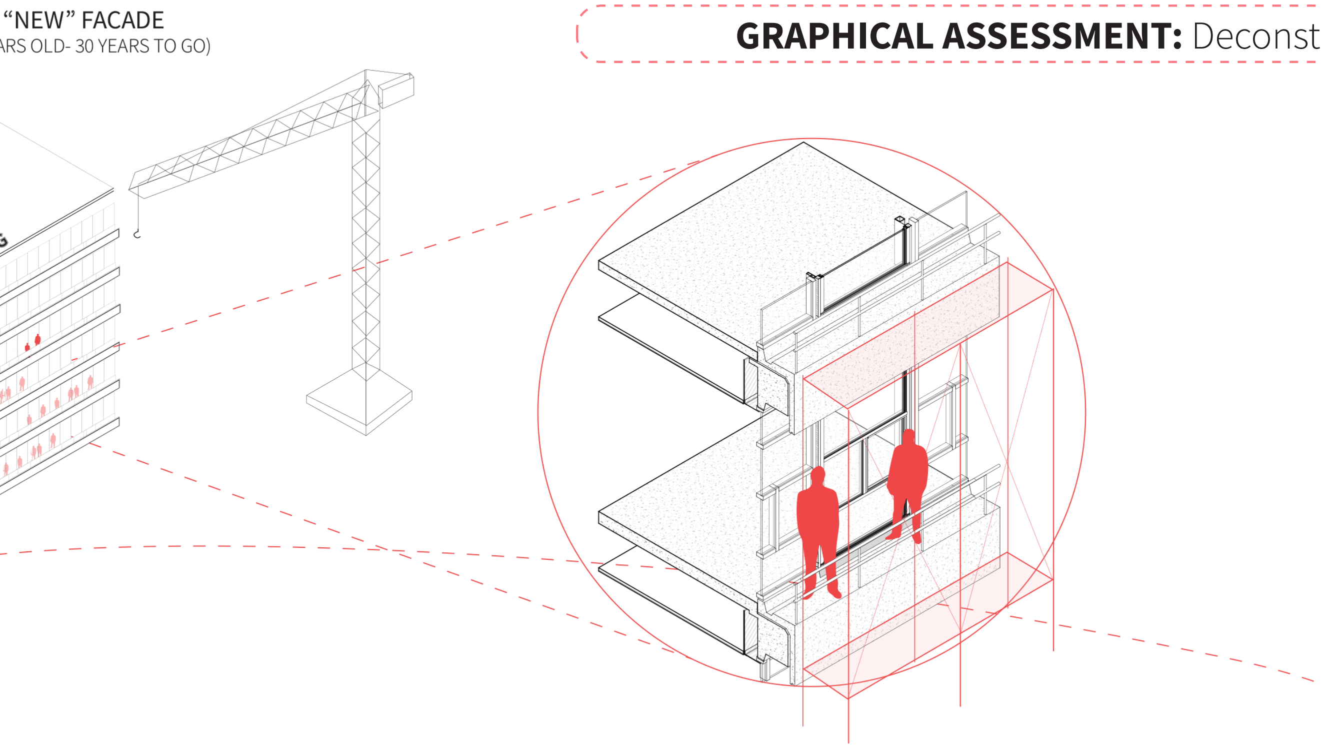
S: Accesible from outside, from service corridor (but reduced). If necessary, also easily accesible from inside.

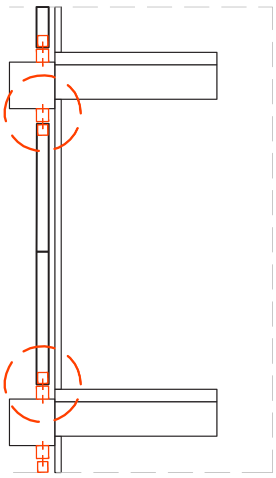
SS: Structural connection to inside of the slab. Hidden above the ceiling and floor, but easily accesible.

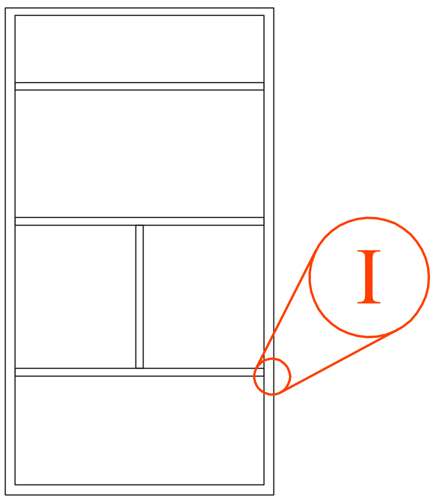
DIMENSIONS

SS: Panel too big to handle eas
eters high by 1.65 meters wide

GRAPHICAL ASSESSMENT: Deconstruction







sily (3.10 m
)

CONNECTIONS/INTERFACES

Consult diagram of relations (sequence) in appendix

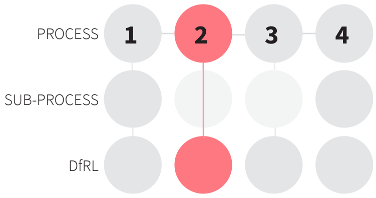
S: Panel connected to structure with inter-face
-Unrecoverable components (including interface) nailed, fixed to structure

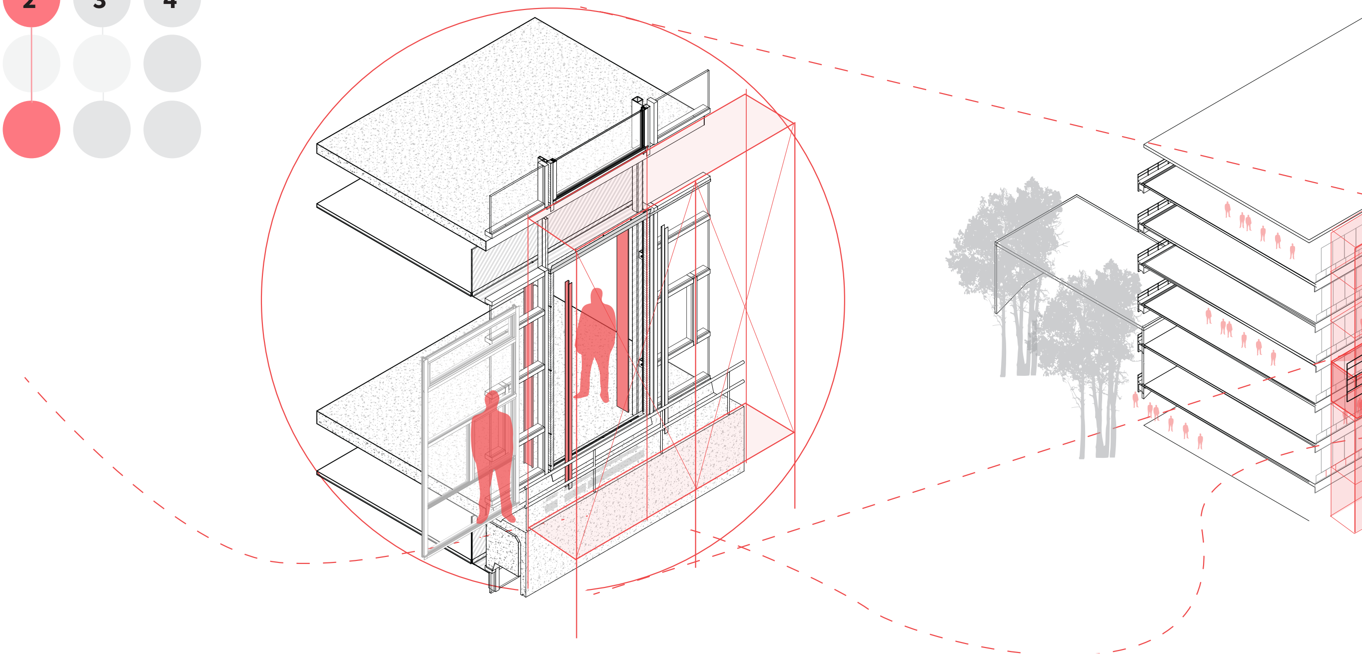
SS/C: Sun shading connected with screws to interface

INFORMATION

SS: Tag available, makes identification of products easier and quicker

Figure 70 *Graphical Assessment: Deconstruction*





PANEL IS MOVED TO COLLECTION ZONE

-Whole panel is maneuvered by at least 2 workers, using cranes and construction elevator

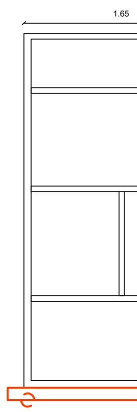
UNKOWNS

-Work (time) of moving

PANEL IS PRE-SORTED

-Panel is pre-sorted to its next destination
-Tag system is used to define destination and the owner of the facade

UNKOWNS



SEPARATION OF ELEMENTS

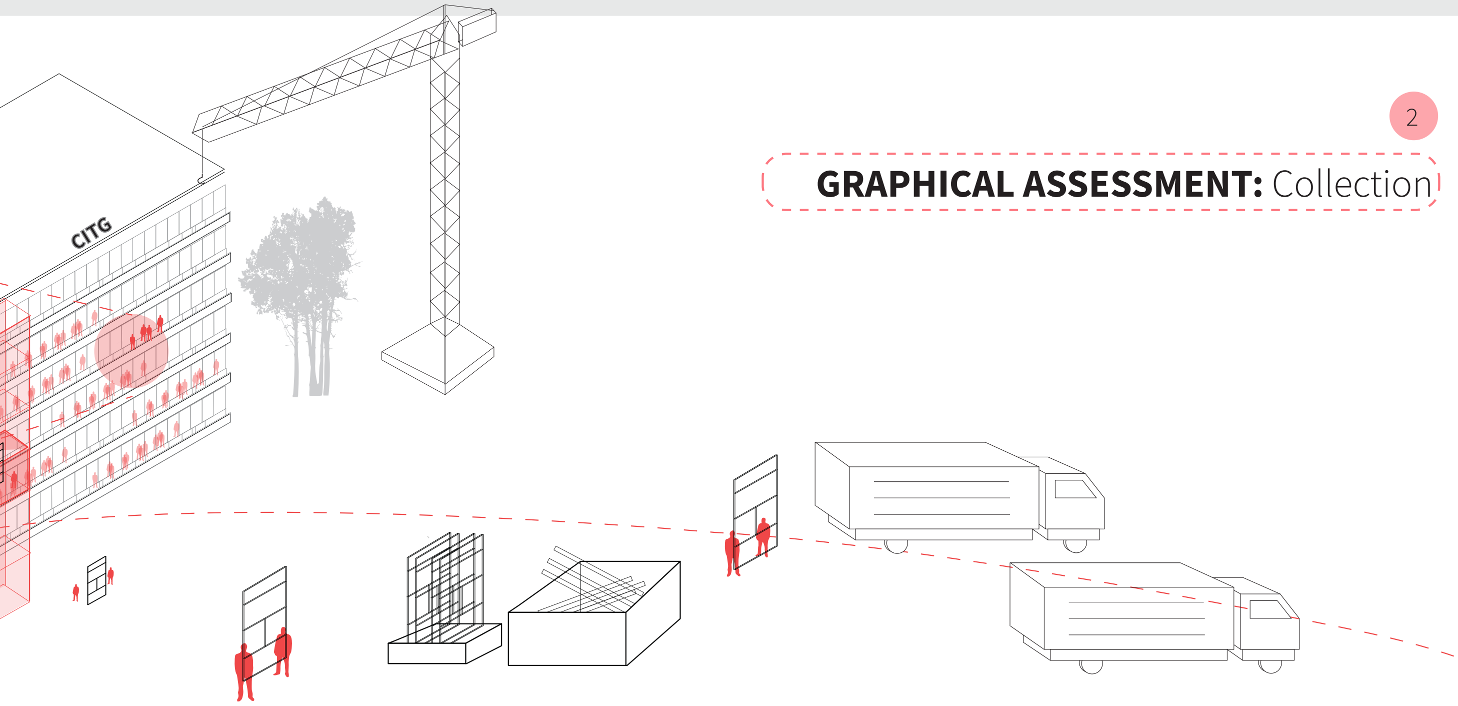
ACCESIBILITY

DIMENSI

SS: Panel too big to hand
eters high by 1.65 meter
to be moved horizontally
scaffolding or service co
vertically through the el

2

GRAPHICAL ASSESSMENT: Collection



UNRECOVERABLES ARE DISCARDED

-Unrecoverables are put into landfilling containers (EPDM membranes, rigid insulations, silicone fittings)
-Some of them are put into recycling containers (woden interface)

UNKOWNS

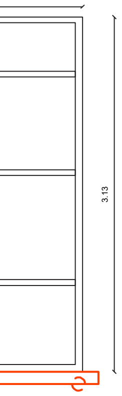
-Environemental cost of landfilling

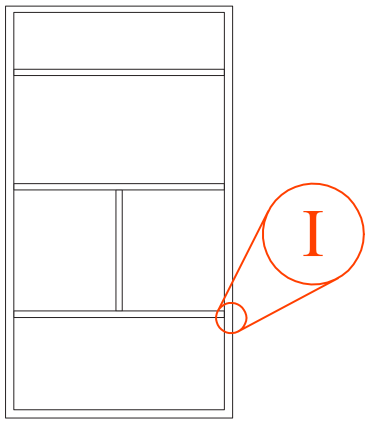
PANELS ARE TRANSPORTED

-Panels are transported to their inspection & sorting destination

UNKOWNS

-Cost of transportation
-Work (time) of (organizing) transportation





ONS

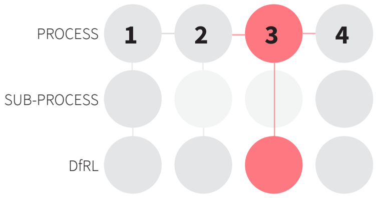
dle easily (3.10 m
s wide). It needs
y through the
rridor, and then
evator.

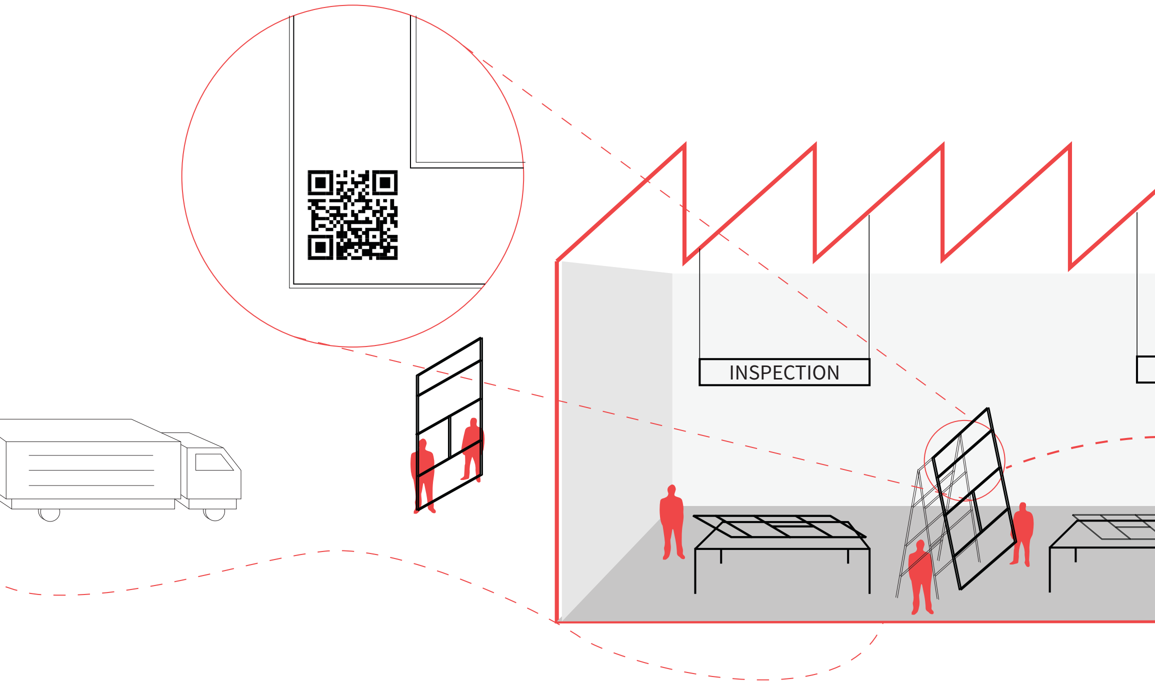
CONNECTIONS/INTERFACES

INFORMATION

SS: Tag available for destination identification. It facilitates coordination with next entity in charge.

Figure 71 *Graphical Assessment: Collection*





PANEL IS INSPECTED

-Panel is inspected
-It is disassembled if necessary, to obtain the right information

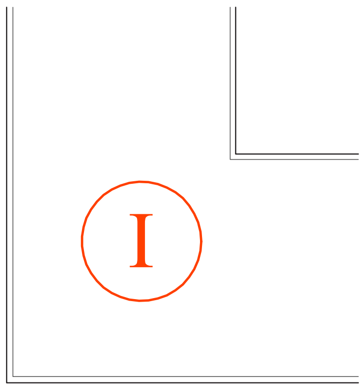
UNKOWNS

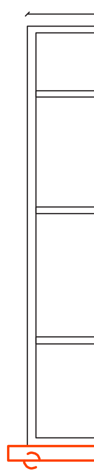
-Cost of inspecting
-Work (time) of inspecting

TAG SYSTEM IS CHECKED

-Tag of panel is checked and revised, to make informed decision of next stage
-A report or a document from such tag system is generated from which the decision maker will depend on

UNKOWNS





SEPARATION OF ELEMENTS

-SS: In this case, being a "whole piece", panel does not have necessary pieces that require extra examination

ACCESIBILITY

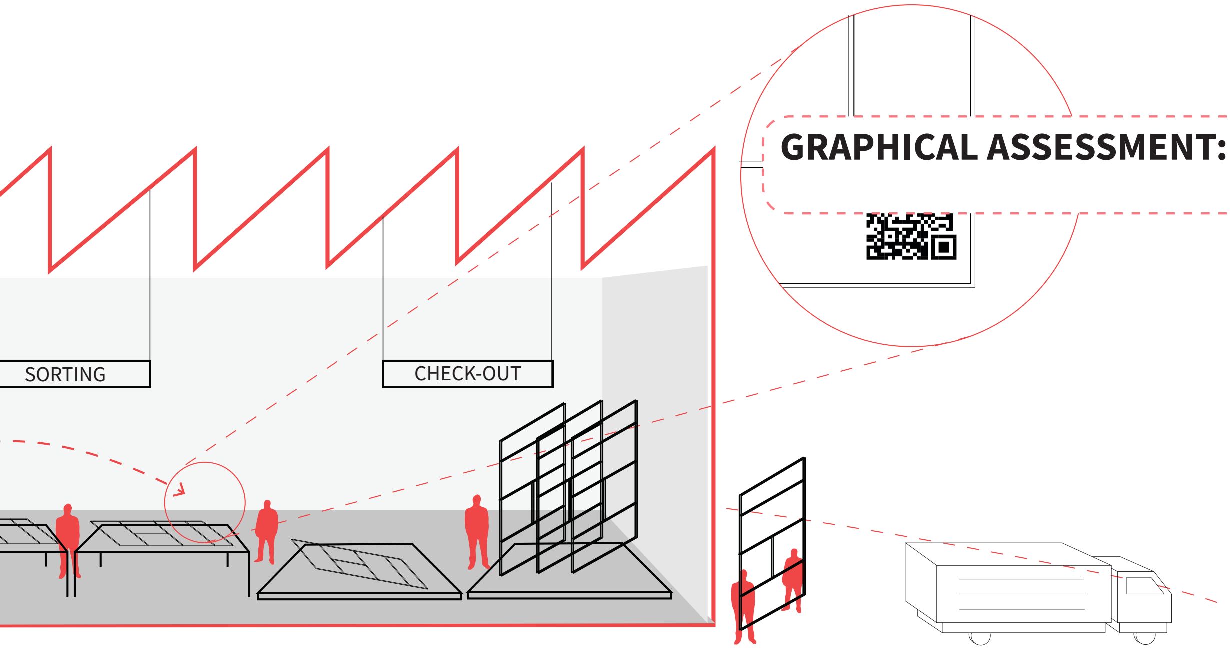
-SS: No necessary pieces require to be accessible.
*Accesibility to tag is easy and reachable (located on the outside of the main frame.

DIMEN

SS: Panel too big to ha
eters high by 1.65 met
be moved horizontally
during the various ins
processes.

3

GRAPHICAL ASSESSMENT: Inspection & sorting



PANEL IS SORTED

-Panel is sorted to the right facility
-Panel can have different destinations:
*Storage /secondary market when no clients are defined
*Remanufacturing facility for a relife treatment

UNKOWNS

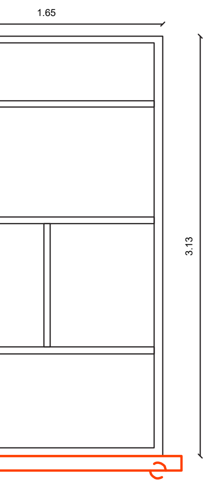
-Cost of sorting
-Work (time) of sorting

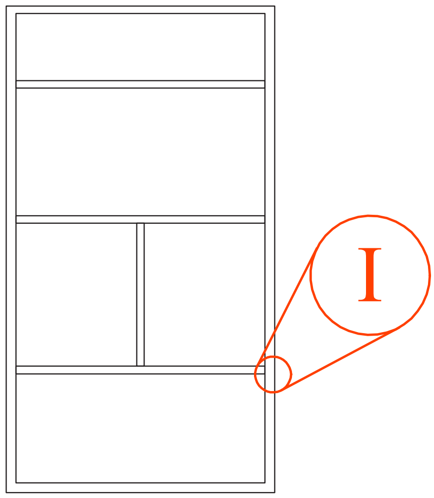
PANELS GOES INTO STORAGE/ SECONDARY MARKET

In case there is no owner:
-Panel is stored and offered in secondary markets
-Spreading the availability of the panel is key to assure panel's next life

UNKOWNS

-Cost of storing
-Work (time) of storing (logistic)
-Work (time) making it available to market





SIONS

andle easily (3.10 m
ers wide). It needs to
y through the facility
pection/sorting

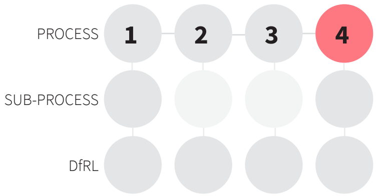
CONNECTIONS/INTERFACES

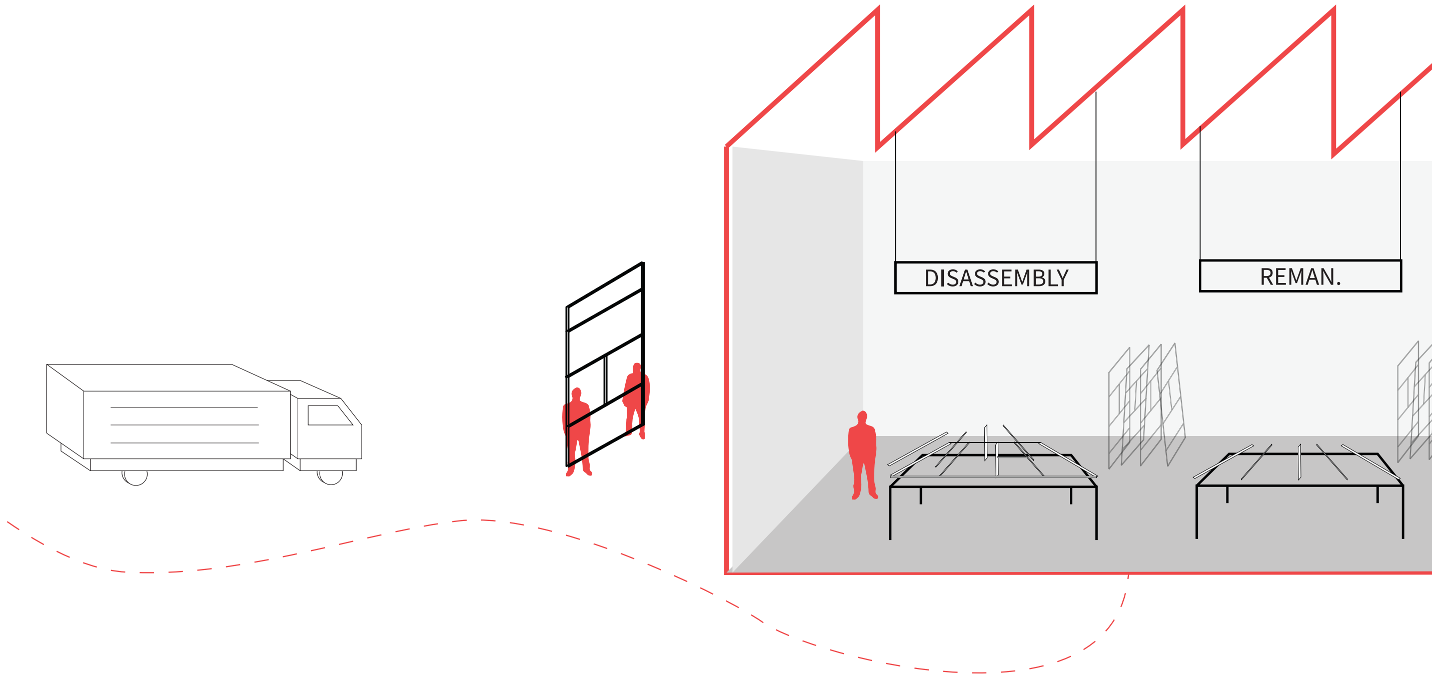
-Connections are not relevant during inspection&sorting processes, as there are not elements to be separated (see separation of elements).

INFORMATION

SS: Tag available for destination identification. It will inform if the product has a owner and which re-life option is to be applied, according to overall quality and maintenance status.

Figure 72 *Graphical Assessment: Inspection & Sorting*





PANEL IS DISASSEMBLED

NEXT PAGE

UNKOWNS

COMPONENTS ARE REMAN.

-The components resulting from the disassembly process are given the proper treatment, if necessary.
*This will depend on the information collected in previous stages from the tag system

UNKOWNS

-Cost of remanufacturing
-Work (time) of remanufacturing components

PANEL IS R

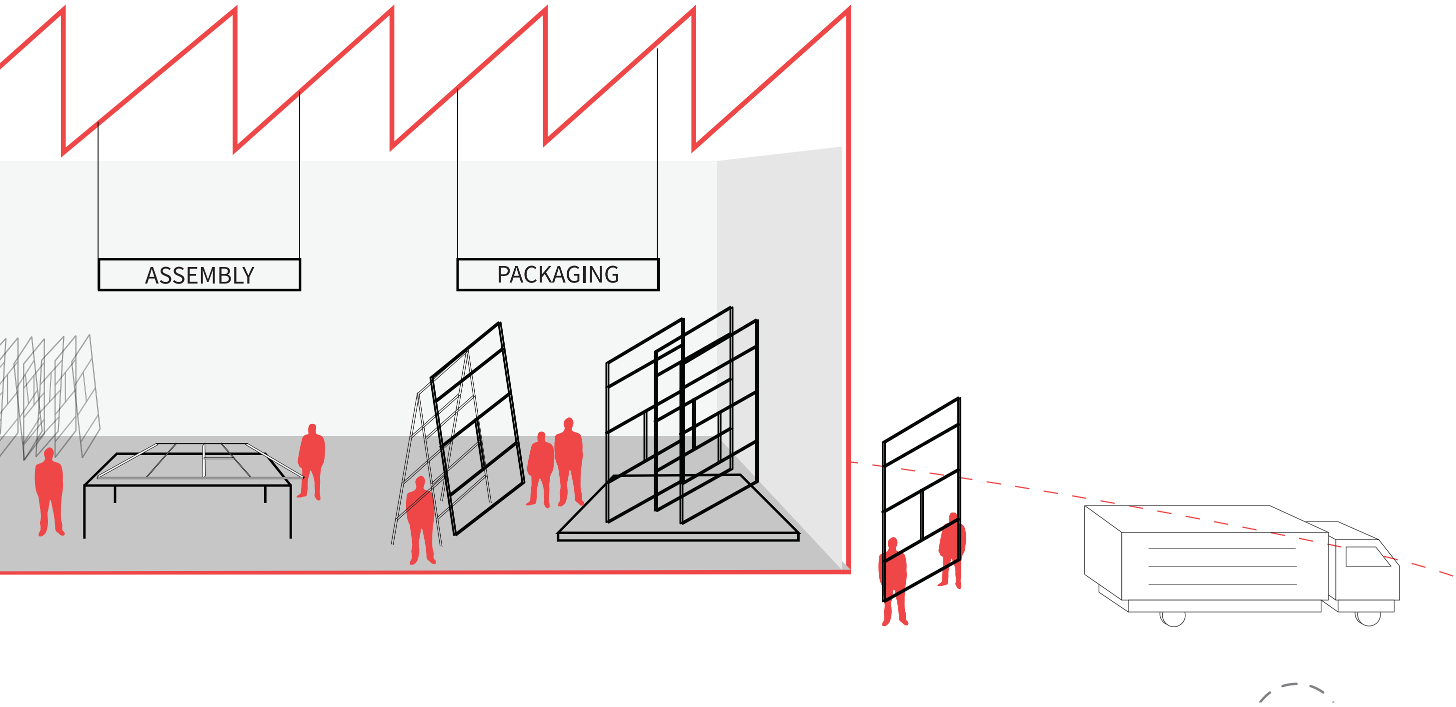
-The components ar
their original arrang
quality is achieved w

UNK

-Work (time) of re-as

4

GRAPHICAL ASSESSMENT: Reman.



E-ASSEMBLED

e re-assmbled into
ement. The " as new"
with the reman process.

KOWNS

ssembly

PANEL IS PACKAGED

-The panel is packaged to be shipped to its next destination
*Research on sustainable ways for packaging materials or methods is necessary to address the environmental cost of repackaging.

UNKOWNS

-Cost of packaging
-Work (time) of pagacking
-Environmental cost of pagacking

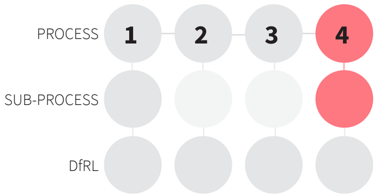
PANELS ARE TRANSPORTED

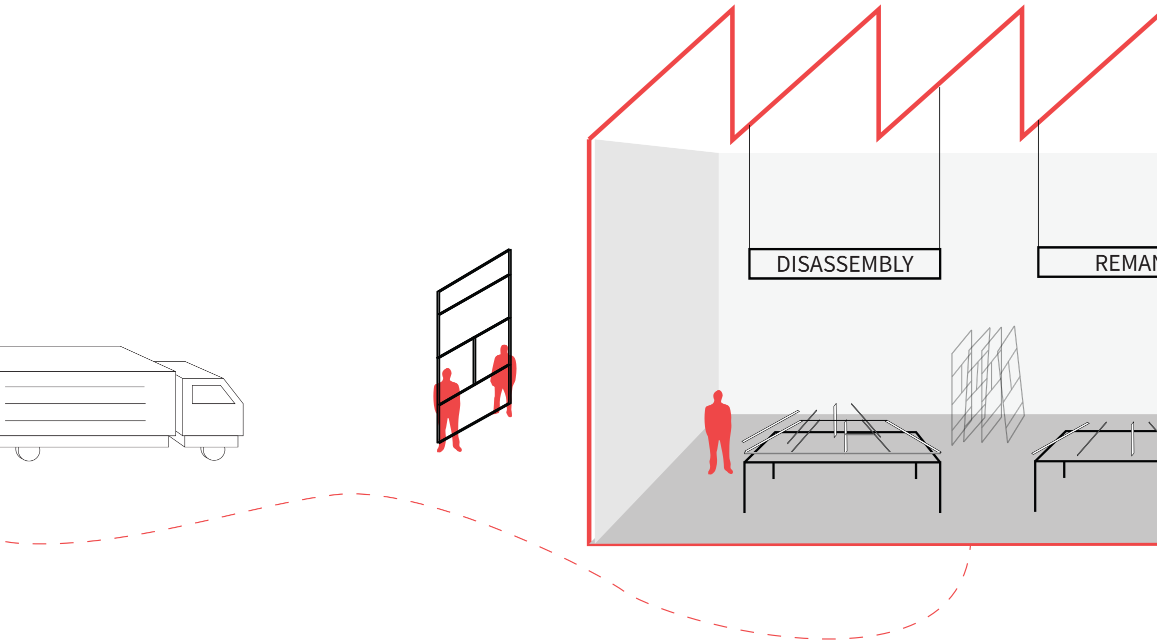
-Panels are transported to their next destination. In this case, they will be shipped to a new buidling, where a new client leases the facade as a service (facade investor is still the owner)

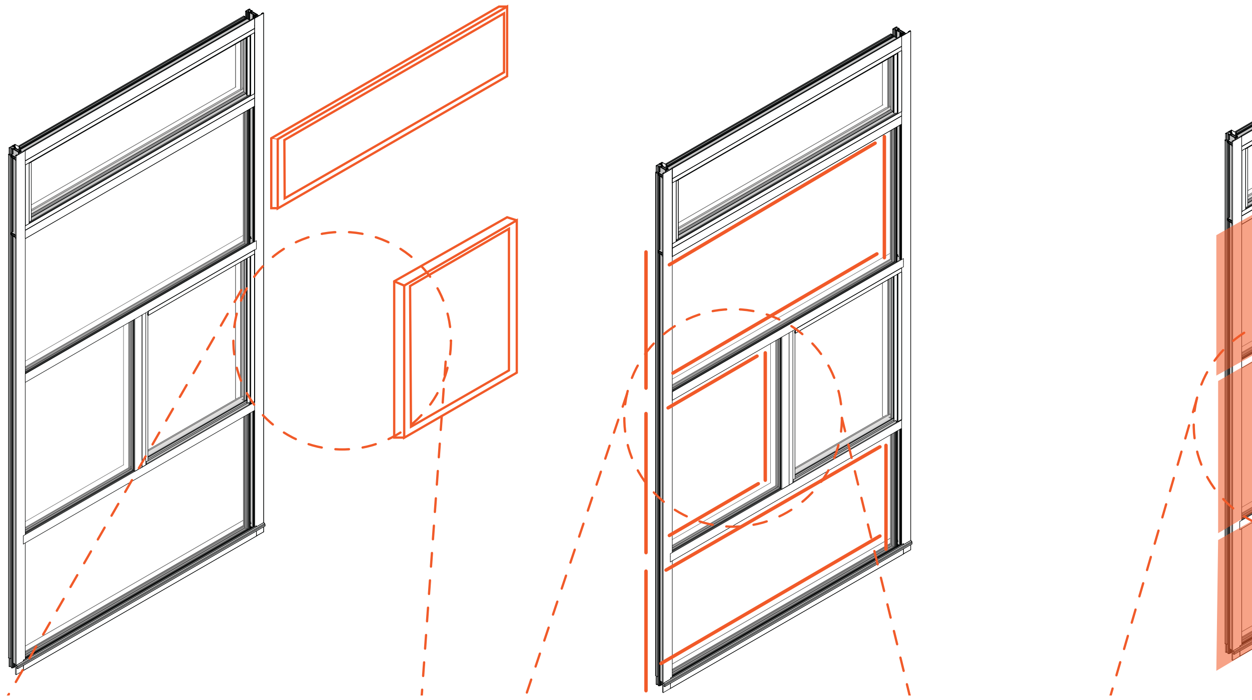
UNKOWNS

-Cost of transportation
-Work (time) of (organizing) transportation

Figure 73 *Graphical Assessment: Remanufacturing*







WINDOWS ARE REMOVED

-Two windows in sub-system are removed
-Windows are screwed to frames

UNKOWNS

-Cost of removal
-Work (time) of removal

GLAZING BEADS ARE REMOVED

-Glazing beads are removed using knife/ tool
-They are not screwed but plugged in, so force and a basic tool must be used to unplug them

UNKOWNS

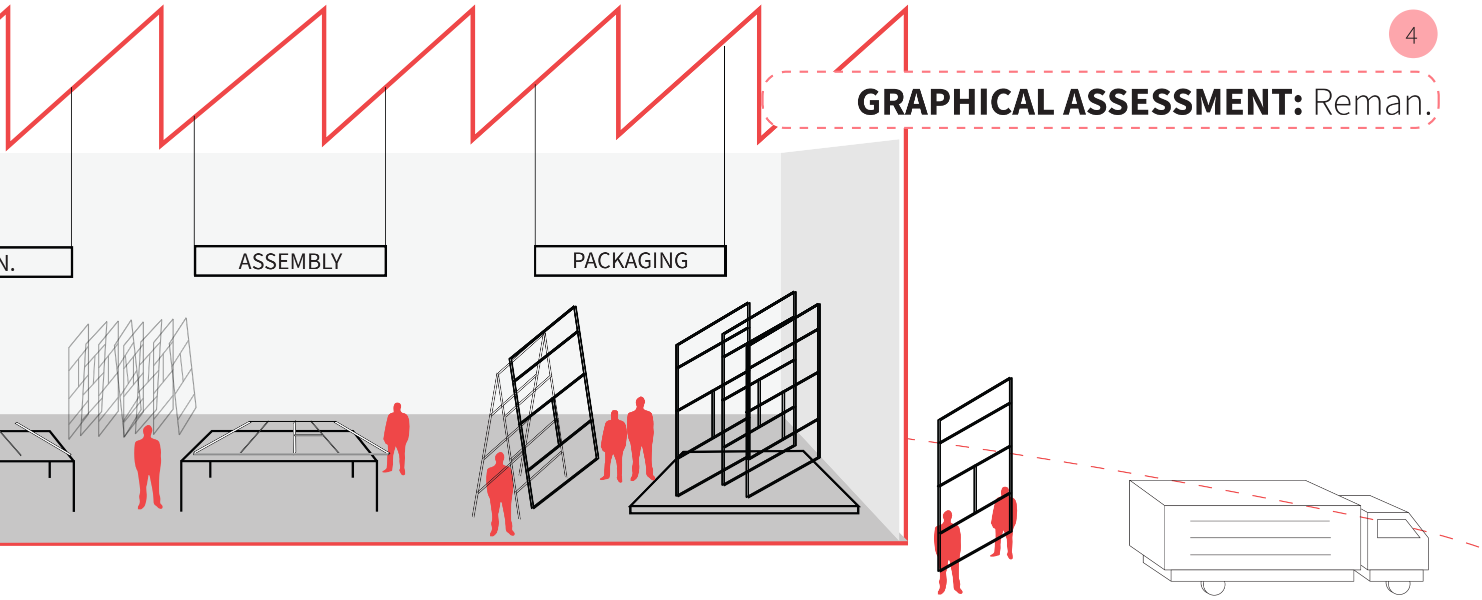
-Cost of removal
-Work (time) of removal

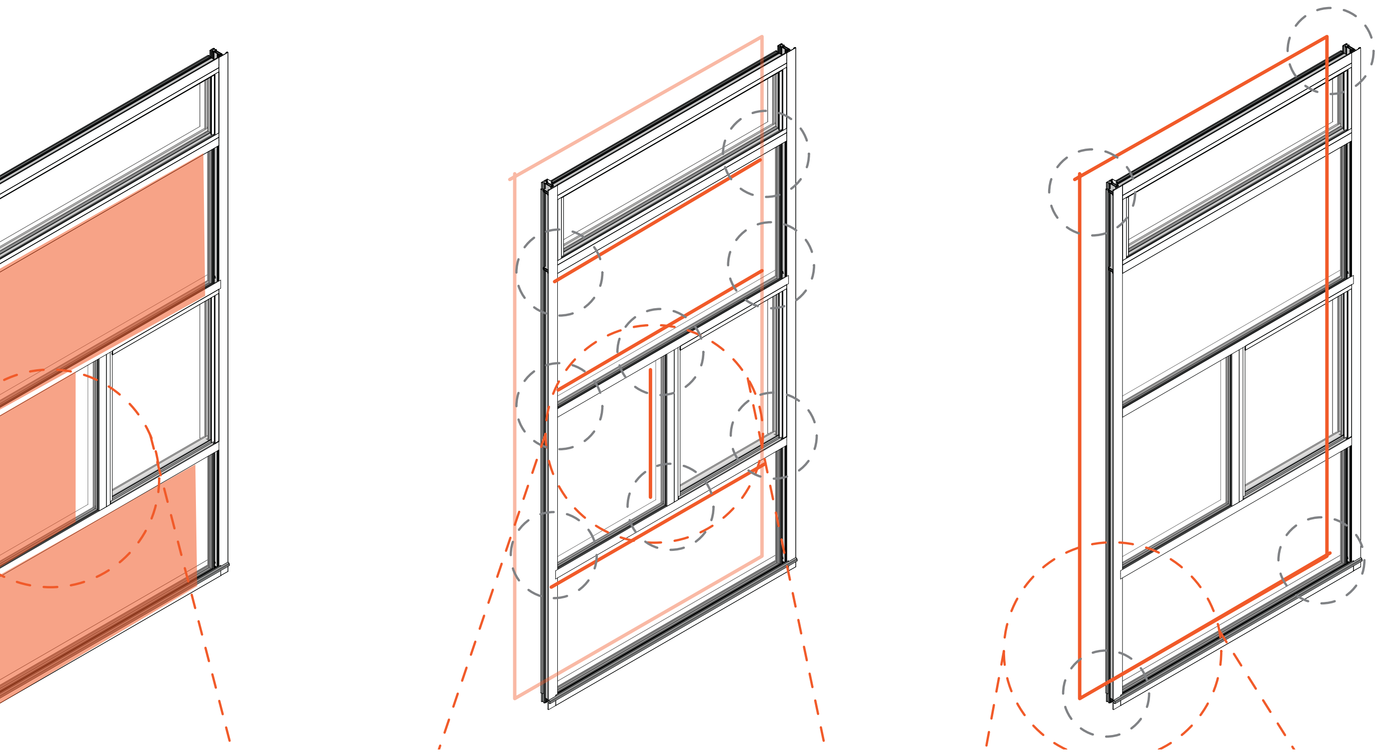
GLASSES

-Glass units are
frames
-Rubber gaskets
are discarded (la

-Cost of dismou
-Work (time) of

GRAPHICAL ASSESSMENT: Reman.





S ARE DISMOUNTED

dismounted from the

are also removed, ane they
andfilling)

UNKOWNS

nting
dismounting

SECONDARY FRAMES REMOVED

- -Secondary frames (mullions and transoms) are connected to each other and to the main frame orthogonally, using wet connections to achieve a fixed union .

**Rare in common practice to separate frames*

UNKOWNS

-Cost of removal
-Work (time) of removal

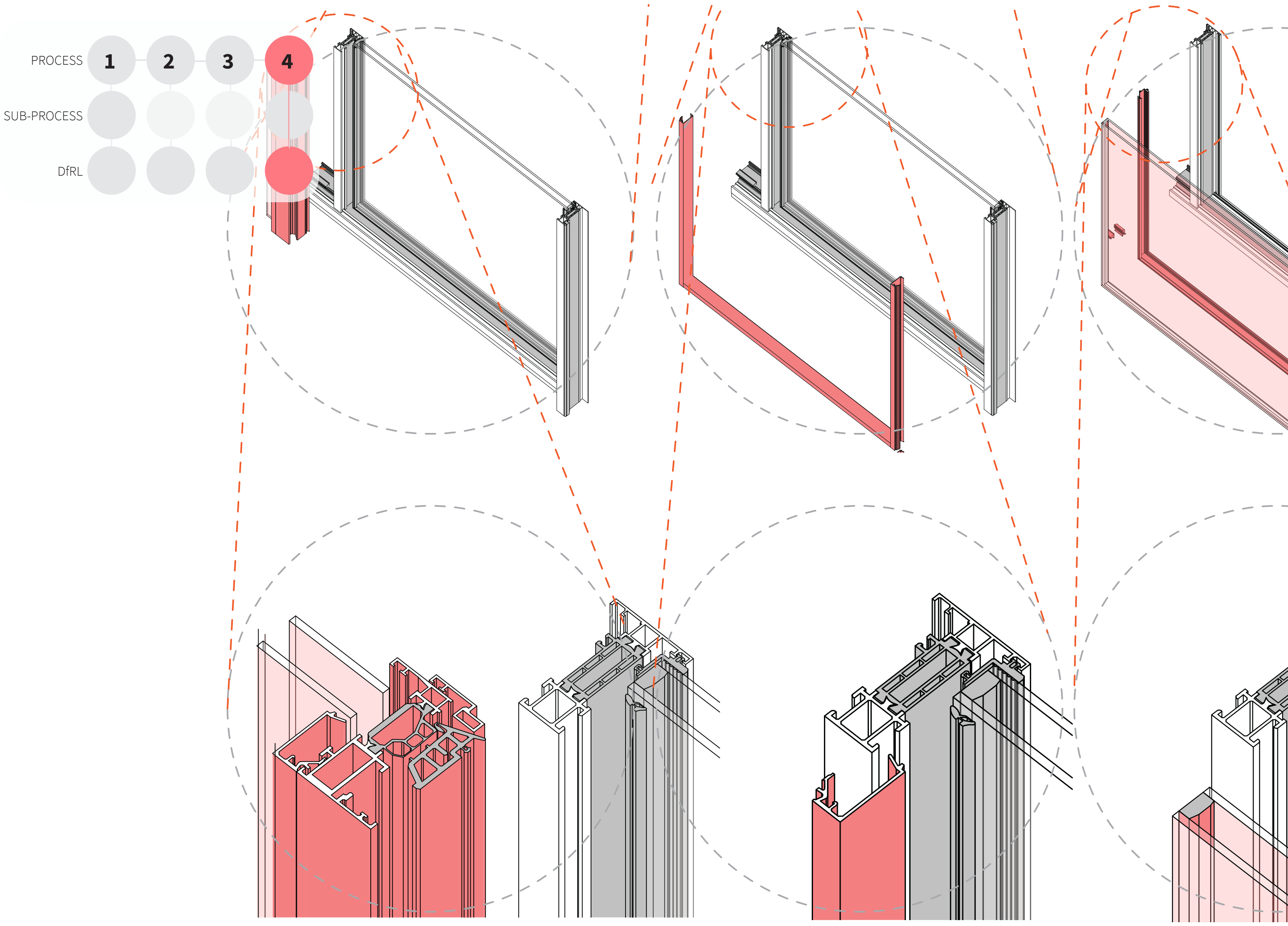
MAIN FRAME DISASSEMBLED

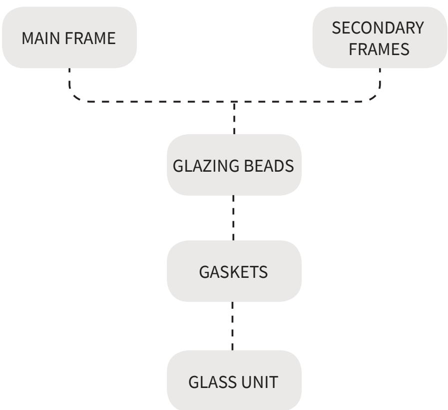
- -The primary frame is connected diagonally, connecting transoms and mullions with corner cleats to form a fixed union. The corner cleats use wet connection method
- -Main frame is fixed in dimension and does not allow for adjusting in length

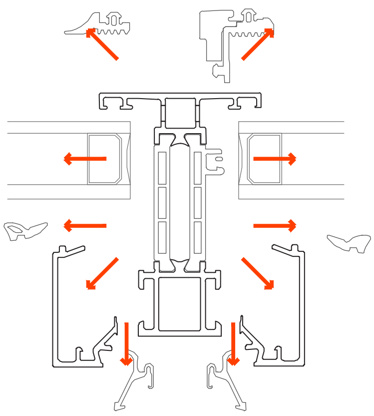
UNKOWNS

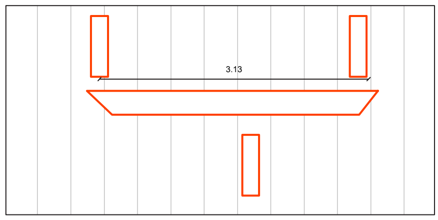
-Cost of removal
-Work (time) of removal

Figure 74 *Graphical Assessment: Remanufacturing*









SEPARATION OF ELEMENTS

Consult diagram of relations (sequence) in appendix

-C: Windows are screwed to frames

-Glazing beads are plugged in to frame/glass

-Gaskets are pressured in to glass

-Glass are resting on frames

-Secondary frames are fixed to main frames with wet connections

-Main frames are connected with corner cleats & wet connection

-Frames have thermal break that is virtually impossible to separate (rolled, pressed)

ACCESIBILITY

-C: The windows, glazing beads, glass are easily accesible

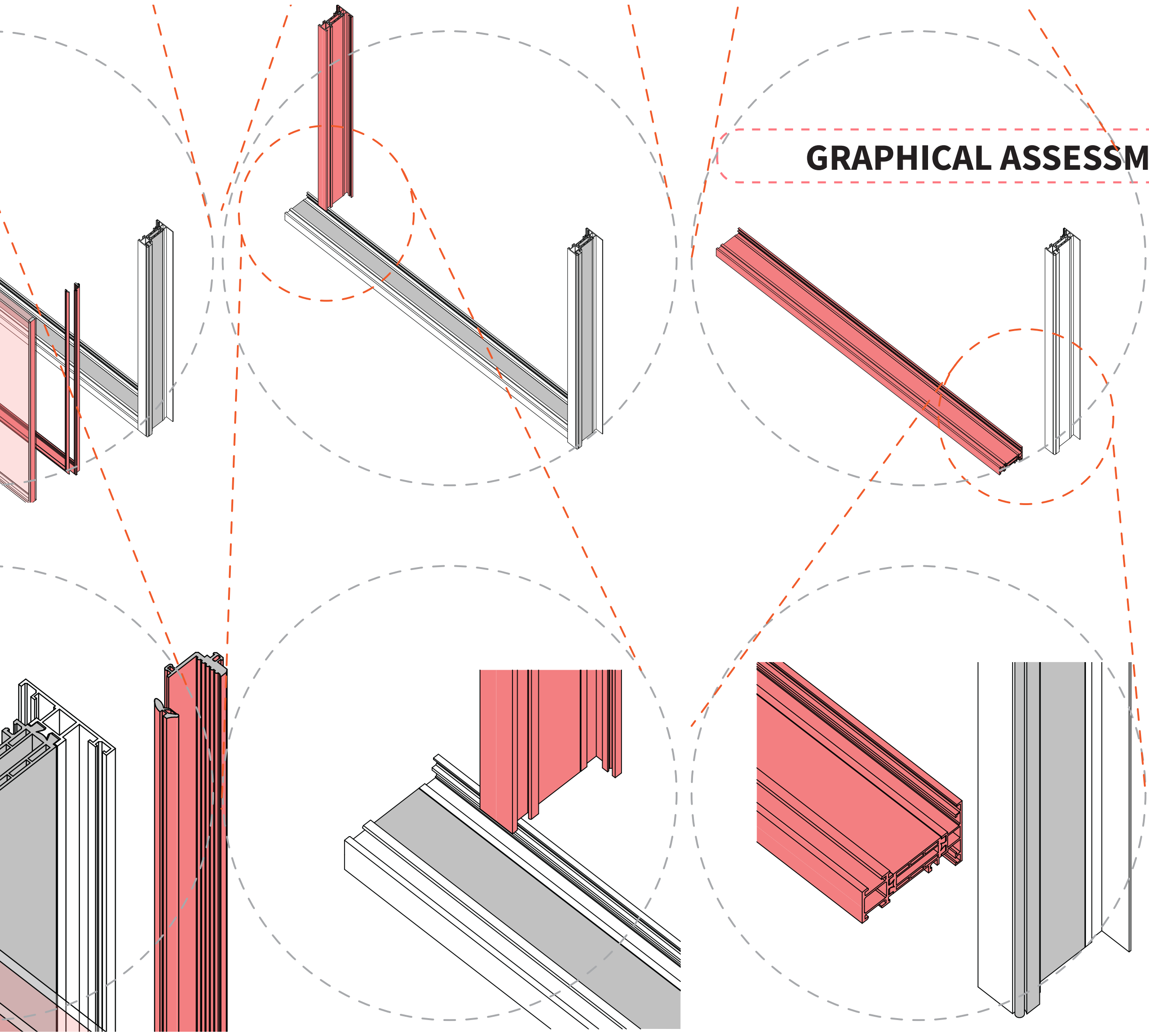
-The secondary frames and primary frames are accesible but diffcult to separate (check separation of elements)

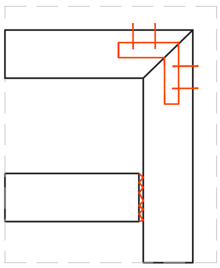
DIMENSIONS

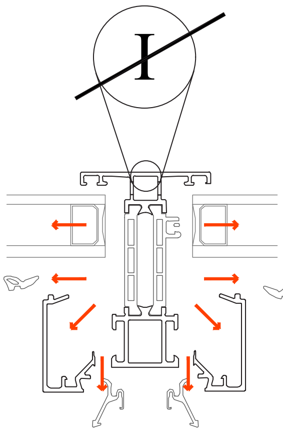
SS: Panel too big to handle smoothly (3.10 m high) in the first stage.

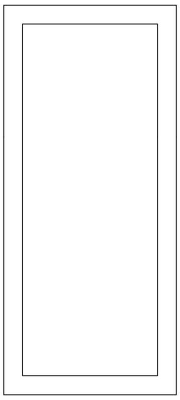
C: Main frame is big, but still can be remanufactured. Rest of the frames and glazing beads have easily procesable sizes.

GRAPHICAL ASSESSMENT: Reman.









CONNECTIONS/INTERFACES

Consult diagram of relations (sequence) in appendix

-Window to frame: Screws
-Glazing bead to frame/glass: Plugged-in/pushed
-Gaskets to glass/frame: Pressured
-Secondary frame to main frame: Wet connection (or cleats*)
-Between main frames: corner Cleats, riveted

INFORMATION

SS: Tag available for maintenance information and overall quality.
**Important: not every component has a tag in current practice, it is the overall system that has it, as it would make operations more complex.*

ADJUSTABILITY

C: The frames are fixed and do not allow for any dimension adjustability.

Figure 75 *Graphical Assessment: Remanufacturing*

A geographical assessment was also conducted along the graphical one, shown in Figure 76. It illustrates the flow of the product, starting from Schuco, where the system is manufactured, until its next use. It must be clarified it represent a highly hypothetical scenario and the intention is only to show how the differences between re-life options would look like. For recycling facilities, the locations Kawneer disclosed to Cortes in her thesis work (Cortés, 2019) were used and for the remanufacturing facilities, a desktop research into warehouse facilities and companies was conducted. As for the next use where the panel would be used, a building suggested by Alkondor to Hollander was used, as it somewhat compatible to the panel being recovered (Hollander, 2019). The tables generated in the appendix XII display the locations considered and other remarks. This geographical evaluation is part of the graphical assessment shown in the previous pages, but due to formatting reasons, it did not fit in such layouts to show the desired level of detail.

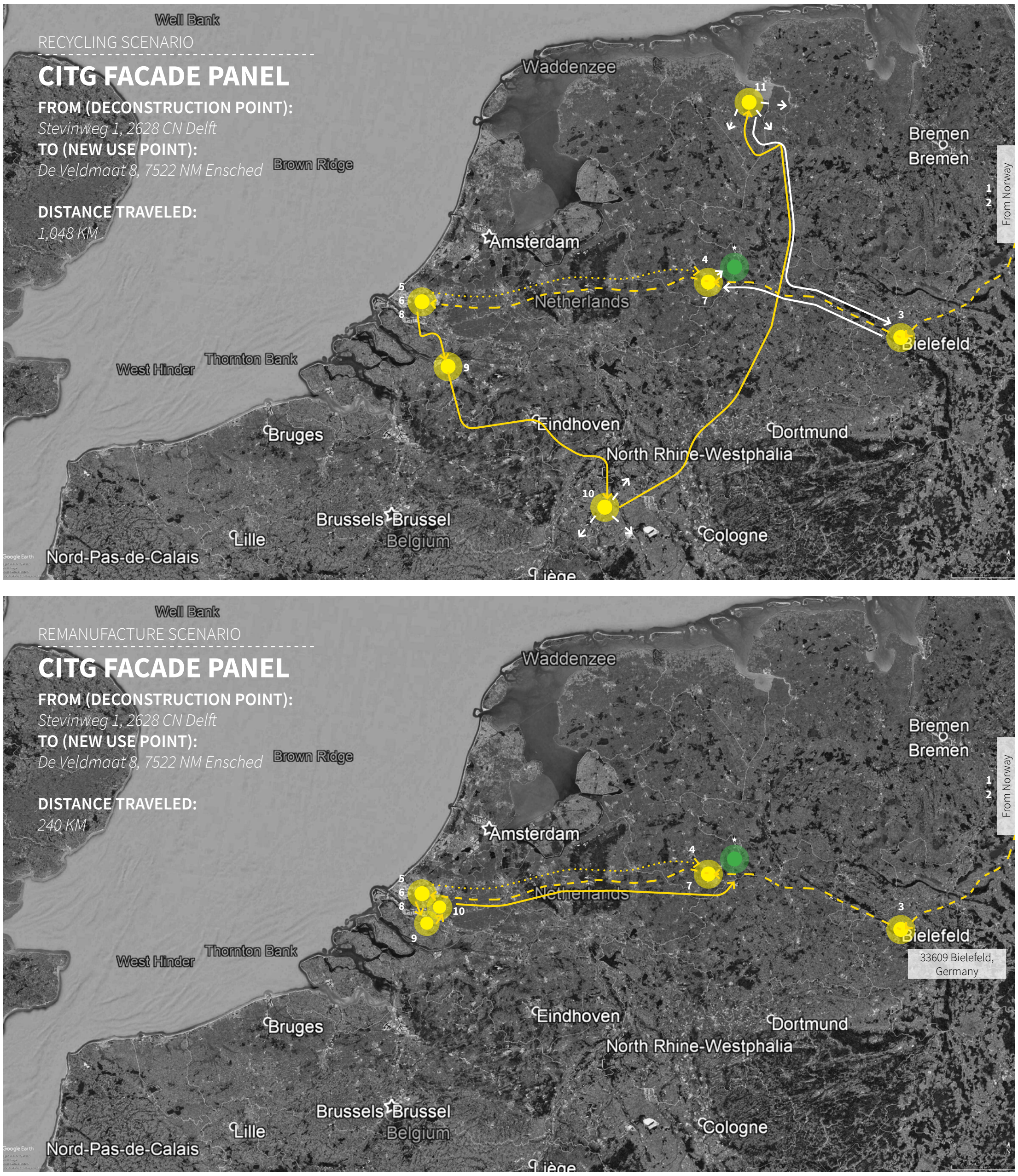


Figure 76 *Graphical Assessment: Geographical Evaluation*

12.7 CONCLUSIONS

With the framework application, an overall analysis of the RL process was visualized for the CITG façade. The diagrammatic exercise, especially in the first and last steps of the process, revealed some of the weak links that block the flow of RL. As a form of summary, a Factsheet format (Format 4) is generated. Having identified such spots, the next chapter will focus on design ideas that might solve these areas of opportunity. In this way, the framework proposed, the façade criteria and their application come together and round-up a methodology that informs RL and gives basic guidelines.

FORMAT: Factsheet

DESTINED TO:
Facade and system providers, designers, engineers

FACTSHEET

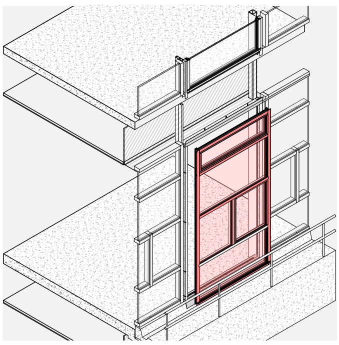
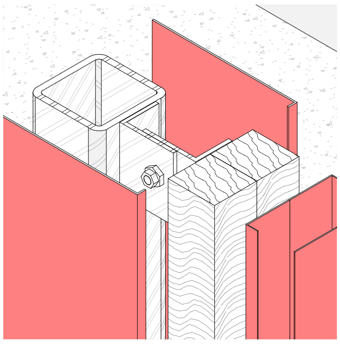
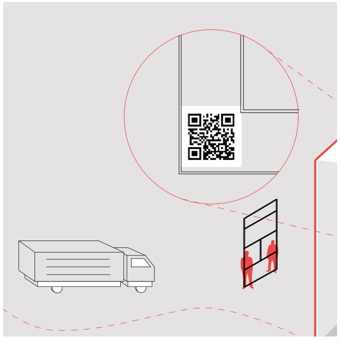
PRODUCT DESCRIPTION

Facade panel for the CiTG building
Window wall construction
Facade provider: Alkondor Hengelo
System provider: Shuco
Location: Stevinweg 1, 2628 CN Delft

MCI & CIRCULARITY INDEXES

GRAPHICAL ASSESSMENT: HIGHLIGHTS

**Consult the Descriptive Assessment*

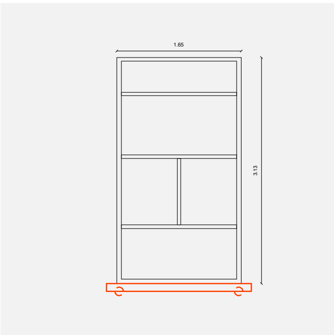
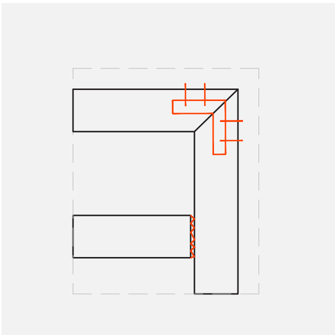
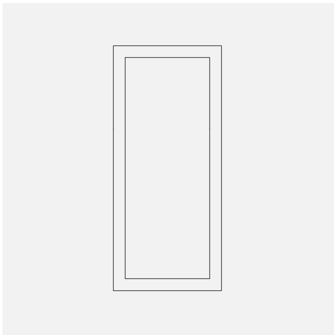
COMMENTS

- Panel dimension too big for logistics

- Al. covers screwed to interfaces

* Transportation/ coordination as main barrier

DFRL CRITERIA: HIGHLIGHTS

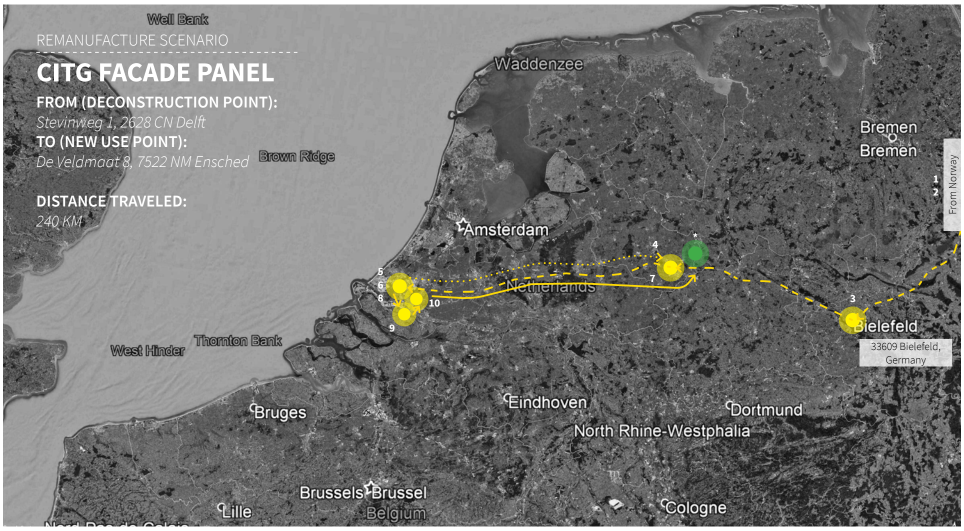




COMMENTS

- Panel dimension too specific

- Wet connection in frame unions

-Non-adjustable mullions & transoms



GEOGRAPHICAL ASSESSMENT

LEGEND

1 Material extraction
2 Material manufacturing
3 System manufacturing
4 End-product manufacturing
5 Installation
6 Use
7 Maintenance
8 Deconstruction | Collection
9 Inspection & sorting
10 Remanufacturing
Next use

Forward logistics
Reverse logistics

Format 4 *Factsheet, summary of the assessments*

13 DESIGN CONCEPTS

In the Design Concepts, the evaluation is used to generate conceptual design ideas, responding to the weak links identified. A conceptual design and exercise are developed to illustrate how the research on RL and its results inform a design process and the way of approach design tasks. A generic building & facade system based on modularity is taken as the context to apply such exercise.

13 DESIGN CONCEPTS

13.1 PROGRAM OF REQUIREMENTS

The requirements would be then to:

- Propose conceptual design solutions that respond to the weak links identified in the framework application (see previous chapter)
    - o Propose conceptual ideas that are both product and system oriented
    - o Design according to the process and to facilitation of RL
    - o Take into consideration stakeholder's roles and the logistics behind the product
- Reflect the lessons learned from the CITG case to apply them into a wider generic context
- Evaluate the main design solutions and have conclusions
    - o Materials and products are mapped in their hypothetical scenarios to have a clear picture of their flows after their first end-of-service

13.2 REFERENCE PROJECTS

Cepezed's projects are a good example of a kit-of-parts approach. One of their most recent ones is the Amsterdam Courthouse, a fully circular building that is planned to be moved in the future to another building site. From an interview with Ronald Schleurholts, some design strategies were explained, such as the use of light textile materials that give the impression heavier & conventional ones, the use of magnets to connect different elements, a strong modular design, among others (personal communication, October 25, 2019). However, it was also explained there was a lack of experience on how the reverse logistics would work after the end of life of the building simple because that stage hasn't been reached. An overall plan is set since the beginning, but a major difference lies between theory and practice. Their details, nonetheless, reveal some of their circularity-oriented design. Figure 77 shows their demountable office conept and Figure 78 complements with other references.

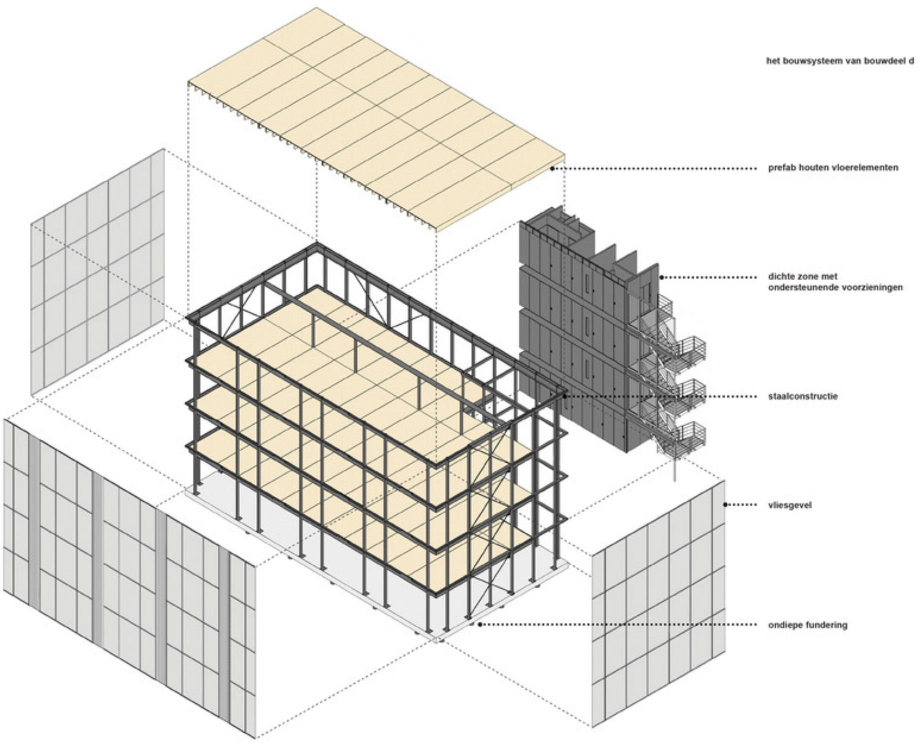
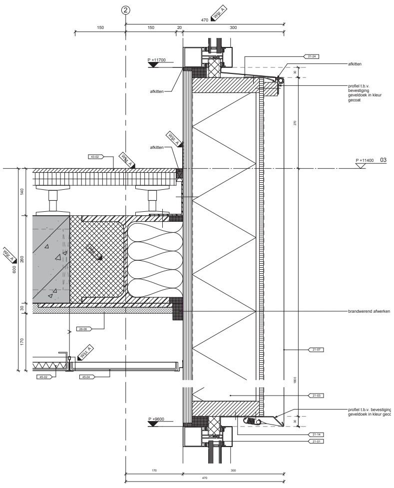
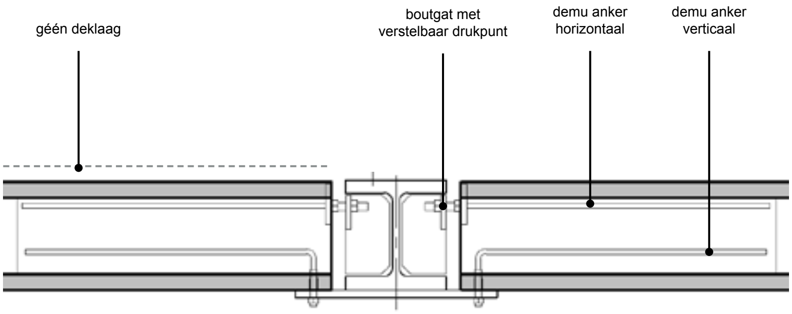
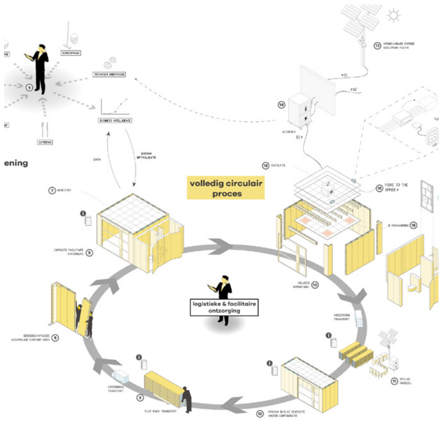
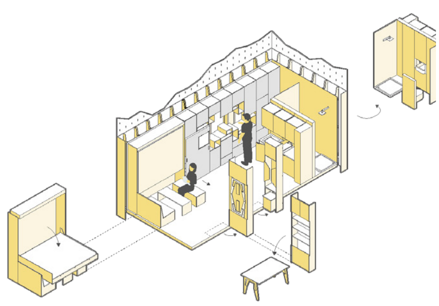


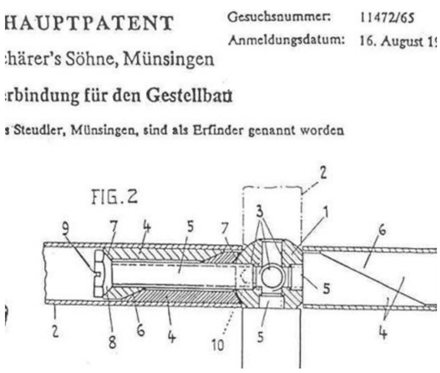
Figure 77 *Demountable office by Cepezed*

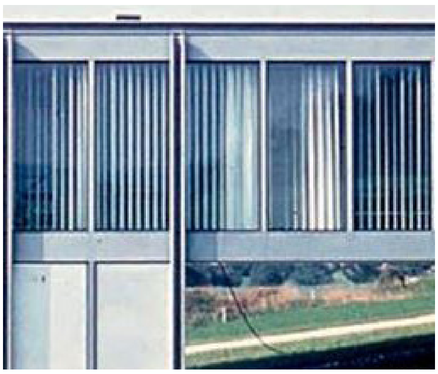


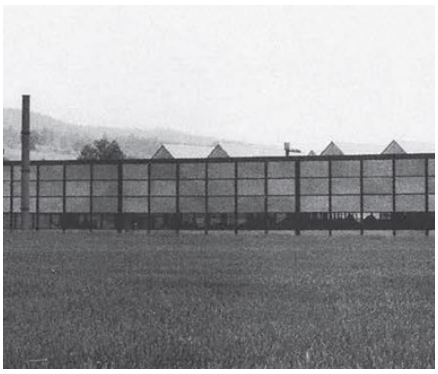


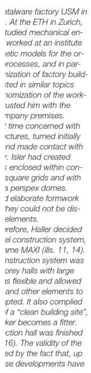





HAUPTPATENT Gesuchsnummer: 11472/65
Anmeldungsdatum: 16. August 1!
:härer's Söhne, Münsingen
:rbindung für den Gestellbau
: Steudler, Münsingen, sind als Erfinder genannt worden



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nomization of the work-
usted him with the
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square grids and with
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d elaborate formwork
hey could not be dis-
elements.
:refore, Haller decided
el construction system,
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nstruction system was
orey halls with large
is flexible and allowed
and other elements to
ipted. It also complied
f a "clean building site",
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ction hall was finished
16). The validity of the
ed by the fact that, up
se developments have

Figure 78 *Amsterdam Courthouse by Cepezed | New Makers Circular Model | USM Haller system | Mini, Midi and Maxi by Fritz Haller*

For more reference projects and initiatives that served for inspiration, refer to Appendix XI.

13.3 BRAINSTORMING

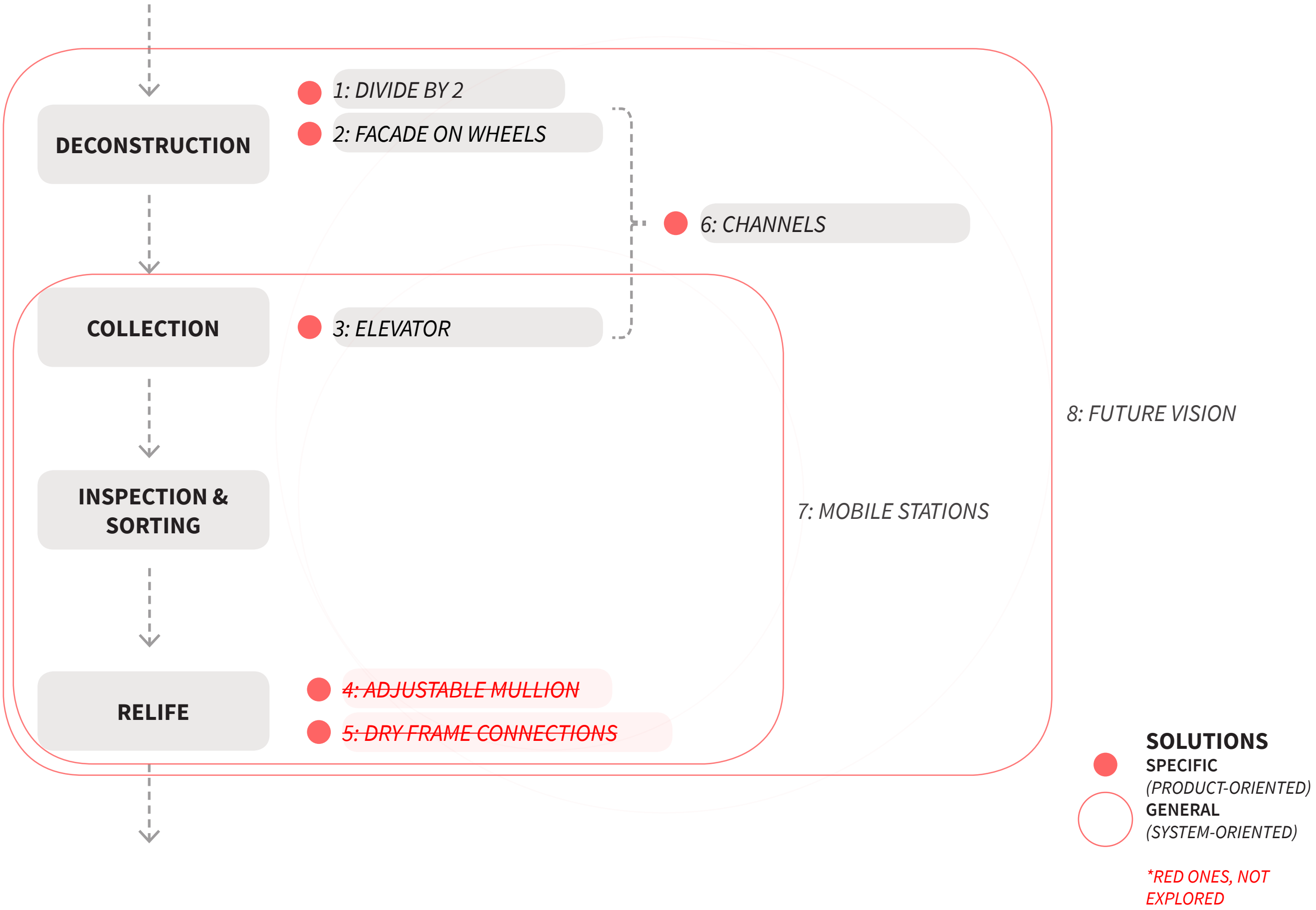
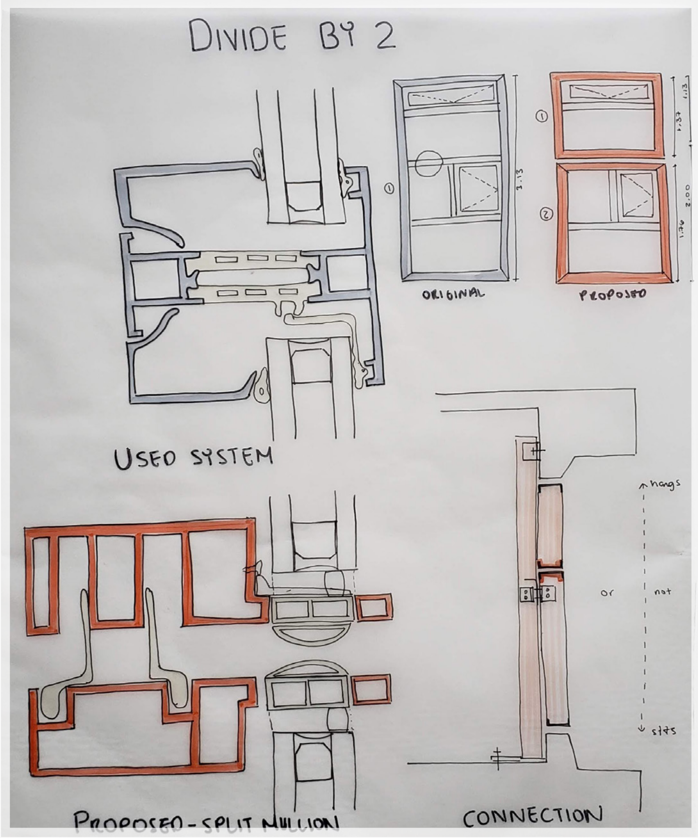


Figure 79 *Design ideas in levels*

From the weak links identified in the application chapter, conceptual ideas were proposed. As shown in Figure 79, they can be product-oriented or system-oriented. The product-oriented ones respond to specific stages of the process and address the design of the physical product. The system-oriented, on the other hand, address the process and encompass one or more stages. The brainstorm helped on proposing a series of ideas to facilitate RL, without focusing on one in particular. In fact, the current project does not intend to develop a single idea and elaborate on that to detail level but leave the discussion open and let the experts —or anyone interested— make their contributions. The ideas shown in Figures 80-82 here will inform the next section, in which the lessons learned will summarize the main findings based on the CITG case.

According to Schultmann and Sunke, the main structural difference between the construction industry and the manufacturing industry is not the recovery process, but the organization of the collection and the design of logistic processes from the building site to the recovery facilities (Schultmann & Sunke, 2005). So, what would happen if the inspection and sorting is conducted also on-site? Assuming there is enough space and it is possible, costs and coordination for transportation will be reduced. Transportation was mentioned by Römgens to be one of the major barriers to bring RL into reality (personal communication, April 30, 2019). Actually, according to Hosseini, RL is assured if on-site sorting is possible, or "yard installation" (Hosseini et al., 2015). This made the "Mobile stations" idea come into place.



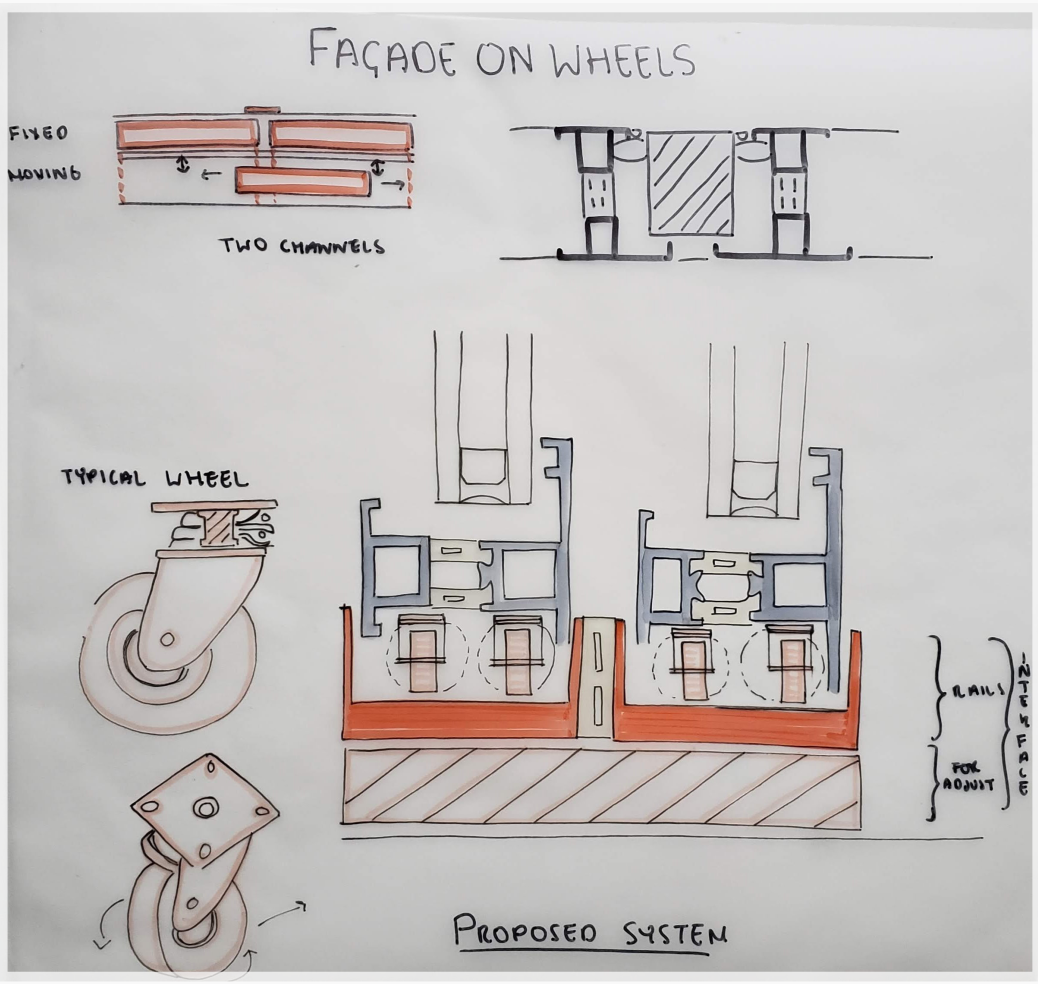


Figure 80 *Design ideas: Divide by 2 | Facade on wheels*

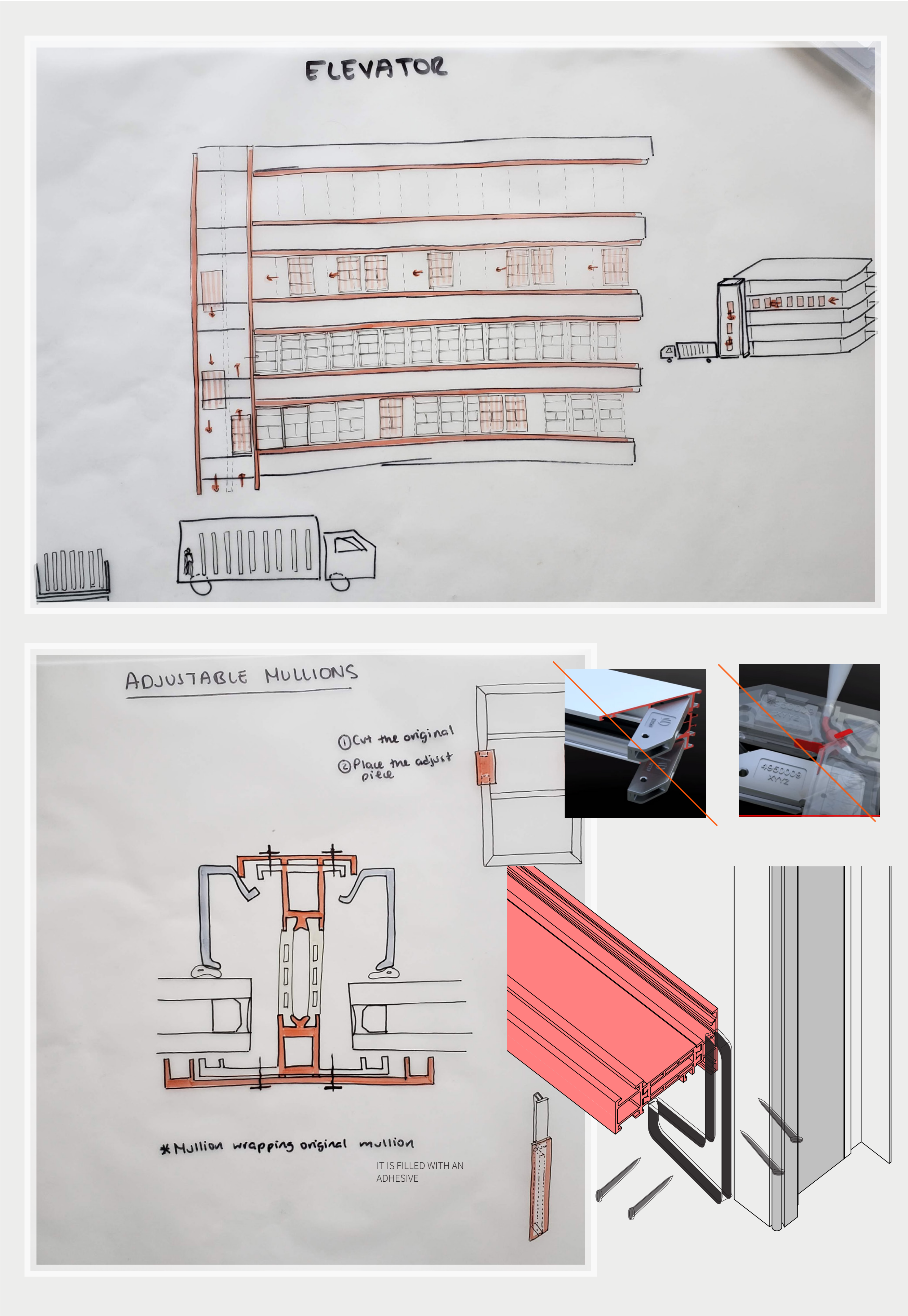
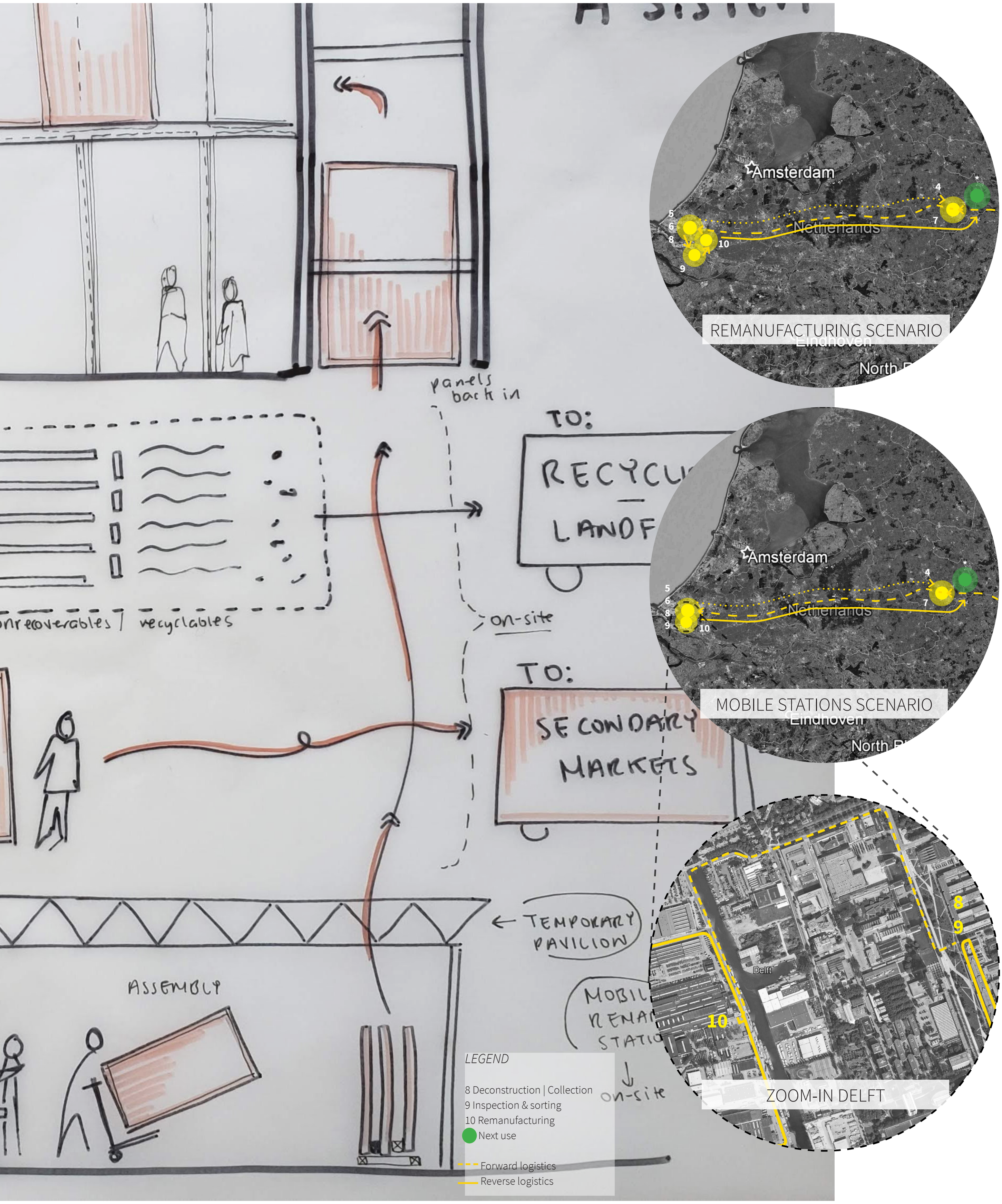


Figure 81 *Design ideas: Elevator | Adjustable mullions | Dry connections*

Figure 82 *Design ideas: Mobile stations*



*Having mobile stations near the deconstruction sites would imply a different dynamics in the local site. How is the enviornment affected by transfering the re-life process to a nearby location?

13.4 LESSONS LEARNED

From both the assessment in the previous chapter and the brainstorm of conceptual ideas applied to the specific CITG case, some lessons learned can be drawn. A synthesis of the ideas is shown in Figure 83.

• From the **design dimension**, the CITG panel does some key things right. The wooden interface does facilitate recovery and prevents any damage to the highly valuable façade components, namely the panel containing the whole window wall system. This highlights the importance of having intermediaries (preferably with short life spans, and in the case of the CITG, biodegradable in the form of wood) when connecting elements, as they reduce the chance of affecting the integrity and the longer lifespan of a core facade components. Another feature that assures better decision taking in the CITG case is the information availability from the sensors by Alkondor, which will inform stakeholders on when and how maintenance should be given. However, the major barrier identified and addressed in the brainstorm was the dimensioning aspect. The panels are too big to facilitate a reverse logistics process. By considering alternatives in sizes, an improvement in the design could be achieved.

• From **literature research** and previous authors addressing the topic, it was identified Inspection and Sorting should be carried on site, as it assures a successful RL process. By simplifying the logistics and stakeholder involvement, the process can benefit. As envisioned in the last idea in the brainstorm, a concentration of activities on site is preferable, reducing transportation efforts as well. Besides, Hosseini et al also mention market demand to be a key factor to assure CE practices. If society doesn't ask for these products, implementation is impossible.

• Finally, from the **interviews** conducted to the experts in the field, two main aspects were identified. Regarding also dimensions, the specificity that panels (like the CITG) present in dimension totally prevent reusability in other buildings. This is one of the biggest barriers there is, concerning design. If panels are not compatible, a second life won't be assured. The last remark concerns transportation considered to be the most important barrier when it comes to the logistics and the main obstacle that does not allow RL to be a common practice. Too much effort is taken to organize and get the products from one place to another.

Figure 83 *Main lessons learned*

Having identified the lessons lessons, solutions can be formulated if the design were to be replicated in a larger or more generic context. The same synthesis is shown in Figure 84, with respective solutions. Using the same thematic division:

• **Design**: Interfaces should always be included to make installation of façade systems easier as well as their recovery. Interfaces allow adjustability on site and prevent direct connections between elements that might suffer damage once they are to be dismounted. Panels should be smaller; their dimensioning should facilitate RL. A general rule would be to design panels that are not more than a single story, even better if there are various panels per story. However, the installation process then becomes more complicated. A balance must be met between those two: having the best dimensioning versus the most optimal number of pieces composing a façade system.

• **Literature research:** To assure Inspection & Sorting activities on site, the right information must be available. The QR code system- explored in the explained applications like CirlLinq and BatiRIM- should provide basic information on materials in the products, the quality, maintenance given, the expected lifespan and the current age of the product, who manufactured the product, expected remanufacturer, among other. The material passport is a good example of data compilation that can be used to make informed decisions about sorting and the destination a product has. The material passport data tree can be found in the appendix. Besides, to assure a market demand it is vital to offer attractive products that society values and ultimately requests. Even if reused, products should be designed in a way that they facilitate recovery but are still appealing. There is a considerable amount of subjectiveness to such solution, as making a product "attractive" might have several definitions. Aesthetic expression and functionality are two of the main categories in a product that could be explored. Interfaces that have several functions and that are a visible part of the façade could be examples of application. Making products identifiable is also a strategy for a successful implementation. In the appendix, an example from a whole different discipline is shown, addressing how important branding is on products to make products more desirable.

• **Interviews:** Given specific dimensions in products doesn't allow for interchangeability, products should be designed using a universal grid system. If taking the office as typology example, a module of 1.20 or 1.50 meter could be used (Commission, 2011). An auxiliary sub research on offices can be found in the appendix, which helped in getting basic notions on what a standard office should take into account. Products could then be thought with a grid system in mind, assuring compatibility between buildings. A light standardization would be a sufficient first step, meaning products would not be limited to specific dimensions (1.20, 2.40, 3.60…) but rounded dimensions (1.20, 1.30, 1.40, 1.50…) that can assure a second life. As for the obstacle of transportation mentioned in the interviews, the idea of concentrating activities in-situ or nearby the site is taken to an extreme, envisioning mobile workshops with the necessary equipment to remanufacture products. If mobile workshops could be allocated near the recovery site or the new installation, coordination efforts are to be minimised. The environmental effects, however, should be taken into account, as the site hosting such workshops must accommodate new spatial and energetic demands to fulfil the remanufacturing tasks, or any of the re-life options to be applied.

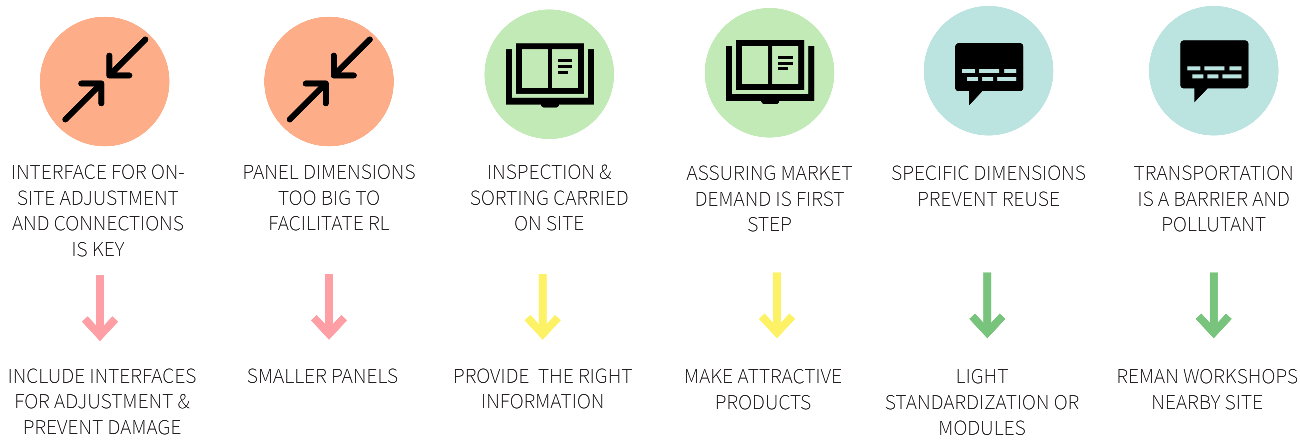
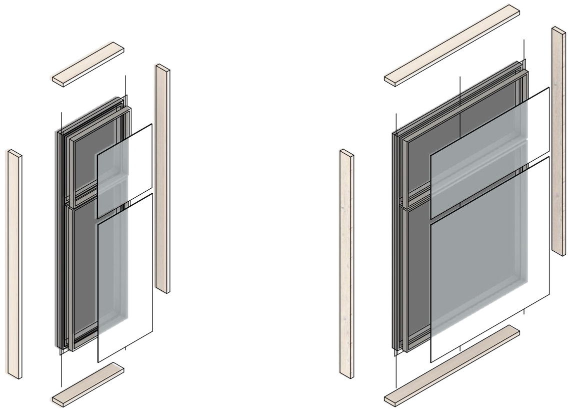


Figure 84 *Main lessons learned and their possible solutions*

13.5 DESIGN REPLICATION

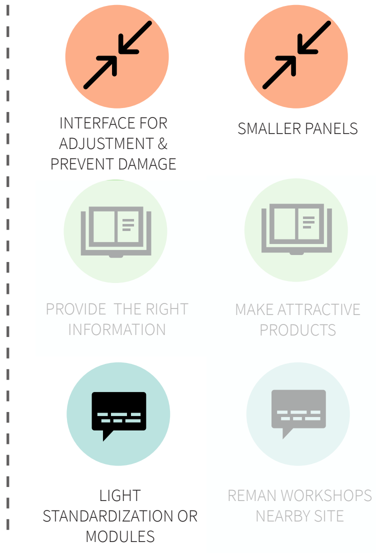
From the lessons learned from the CITG and the proposed solutions, conceptual ideas are formulated. The main objective of this final exercise is to represent in a physical product all of the findings from the research process, reflected theoretically on the previous section. The illustrations presented down below attempt to portray such solutions. Alternatives might be endless, but the design exercise serves as food for thought for further research. It must be noted the presented exercise is highly conceptual and the intention is not to develop detailed schemes, as that requires another research in itself to bring concrete solutions. Instead, the current research comes to a close with a physical portrayal of the findings and ideas to make a clear statement on how a generic building would look like if RL, and therefore CE practices, are at the core of the design & construction process.

The base module is based on the grid of 1.20 m, a common module for the office typology in Europe. Auxiliary research on grids and modules can be found in the Appendix XI. The module is 2.40 wide x 3.60 meter high. This responds to the "light standardization" solution. There is also the option of having smaller modules, by considering half-modules that are 1.20 wide x 3.60 meter high. This responds to the "smaller panels" solution. Both consider a wooden interface for easy installation and recovery. Figure 85 shows the installation process.



Base Module
1.20 x 3.60 m

Double Module
2.40 x 3.60 m



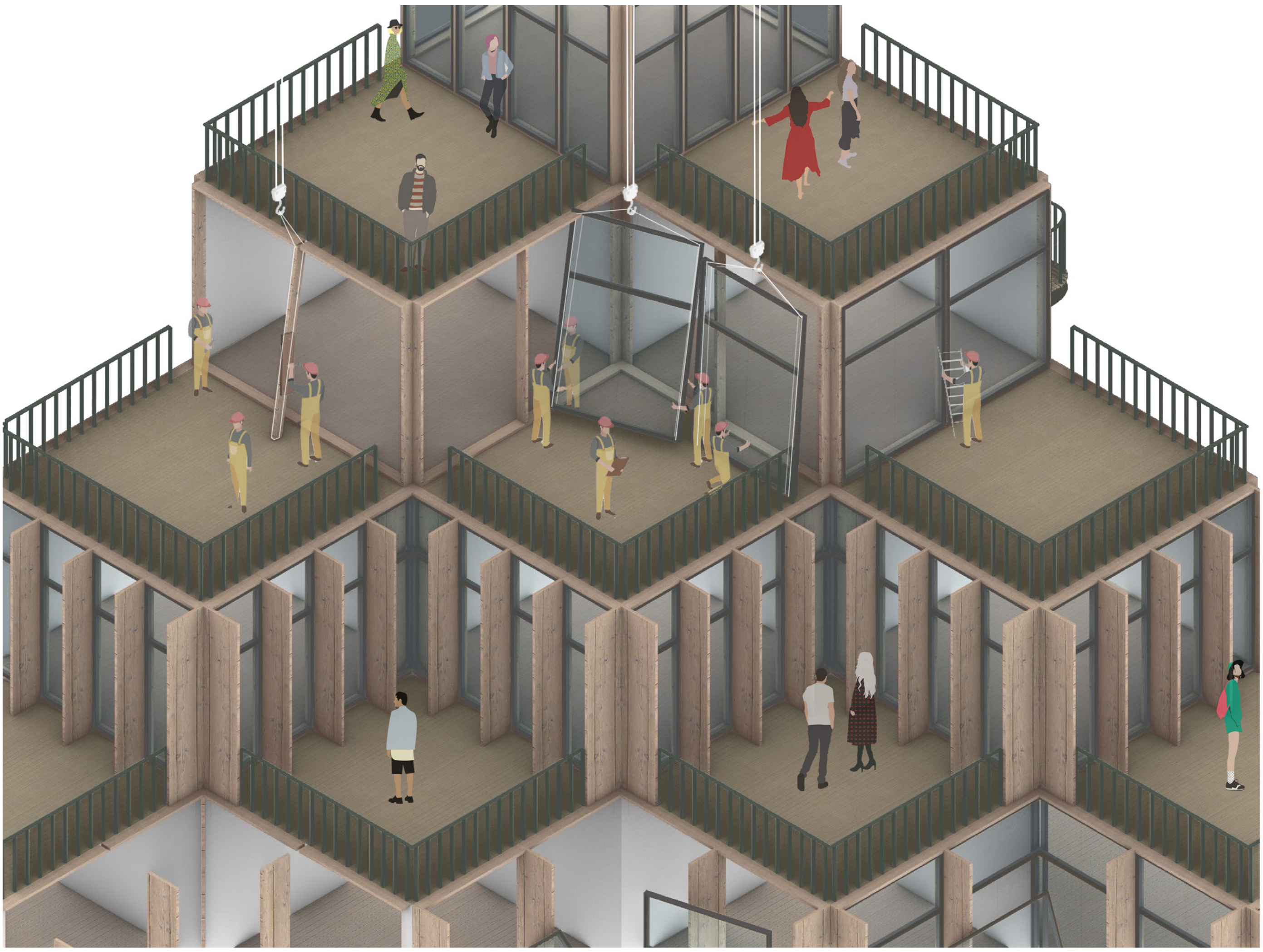
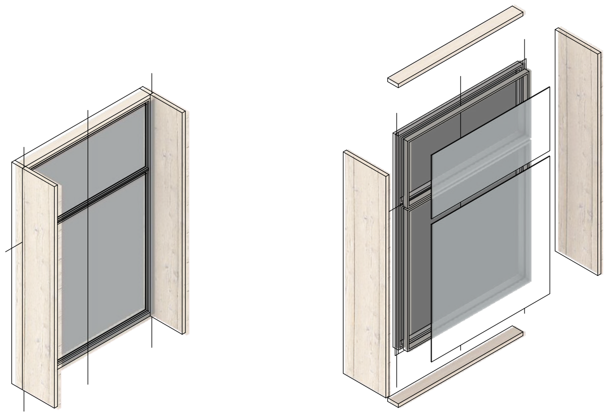


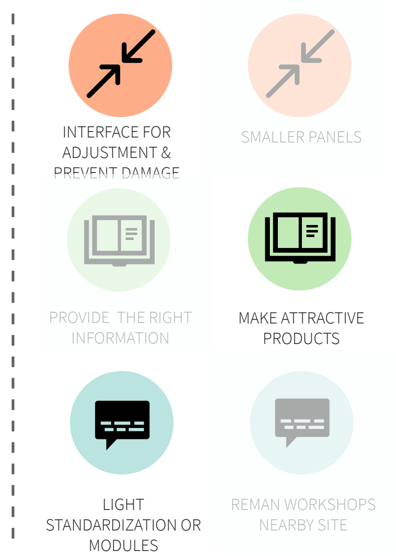
Figure 85 *Basic & Double Module Installation Process*

Responding to the “interfaces inclusion” as well as the “attractive products” solutions, the interfaces are designed as expressive façade elements that are no longer hidden. They might also incorporate other functions (their surface could provide area for PV, for example, or their interiors could host installations, if the interfaces were to be made hollow). Figure 86 shows the panels in the buidling context.



Double Module
+ external interface

Exploded view



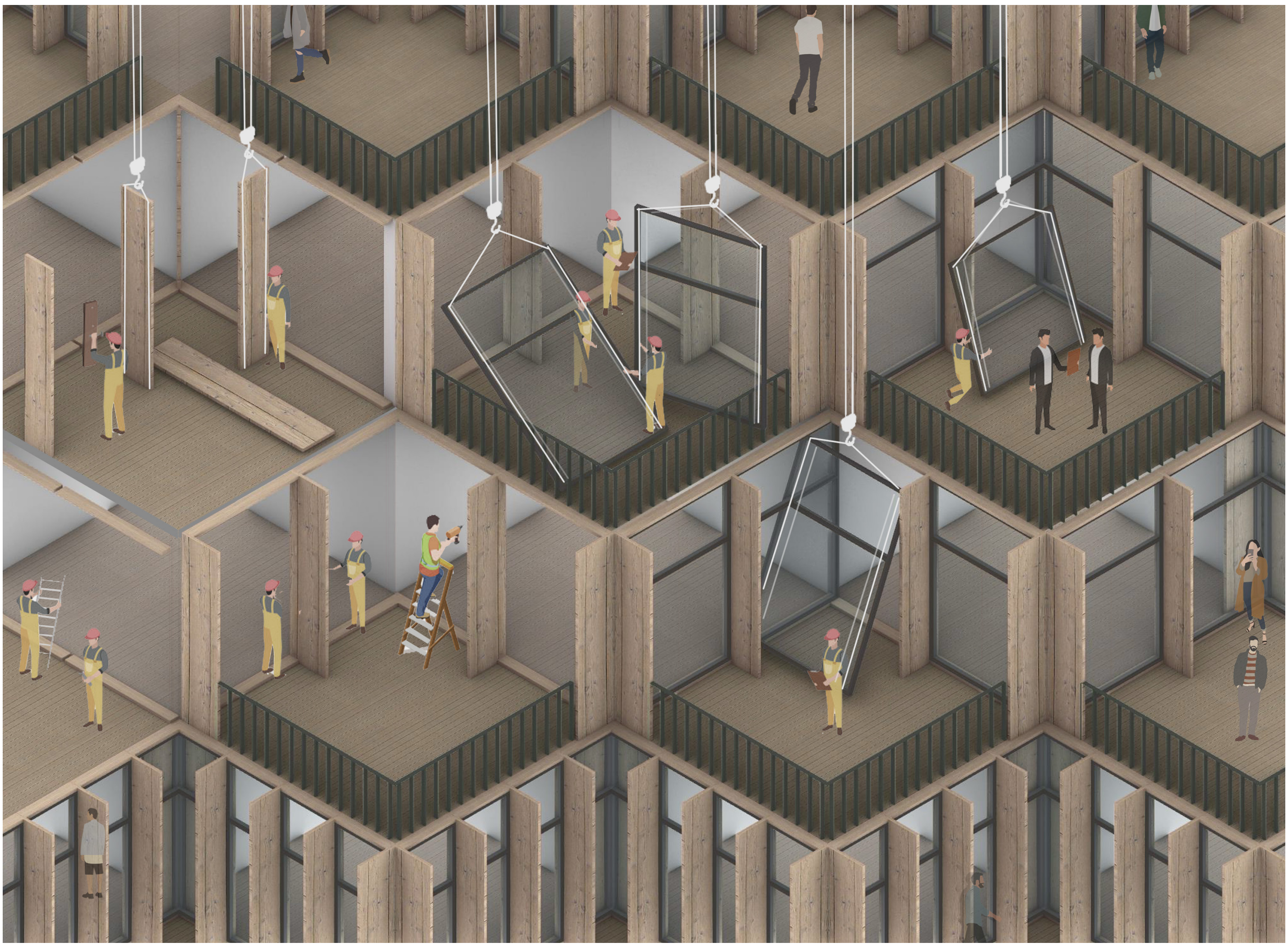


Figure 86 *Double Module + External Interface Installation Process*

The same logic applies to the next design idea, but adding the solution of having “smaller panels”. Interfaces become part of the façade, making the products identifiable even if they are reused. Besides, if the “right information” solution is added to the previous ideas, the functionality aspect of interfaces could allow for a rapid visualization of the quality of a product. Y using the QR code system, a light might pop on the side of the interface to reveal if maintenance is needed or not, or if the products is to go to its next destination. Figure 87 shows the idea.

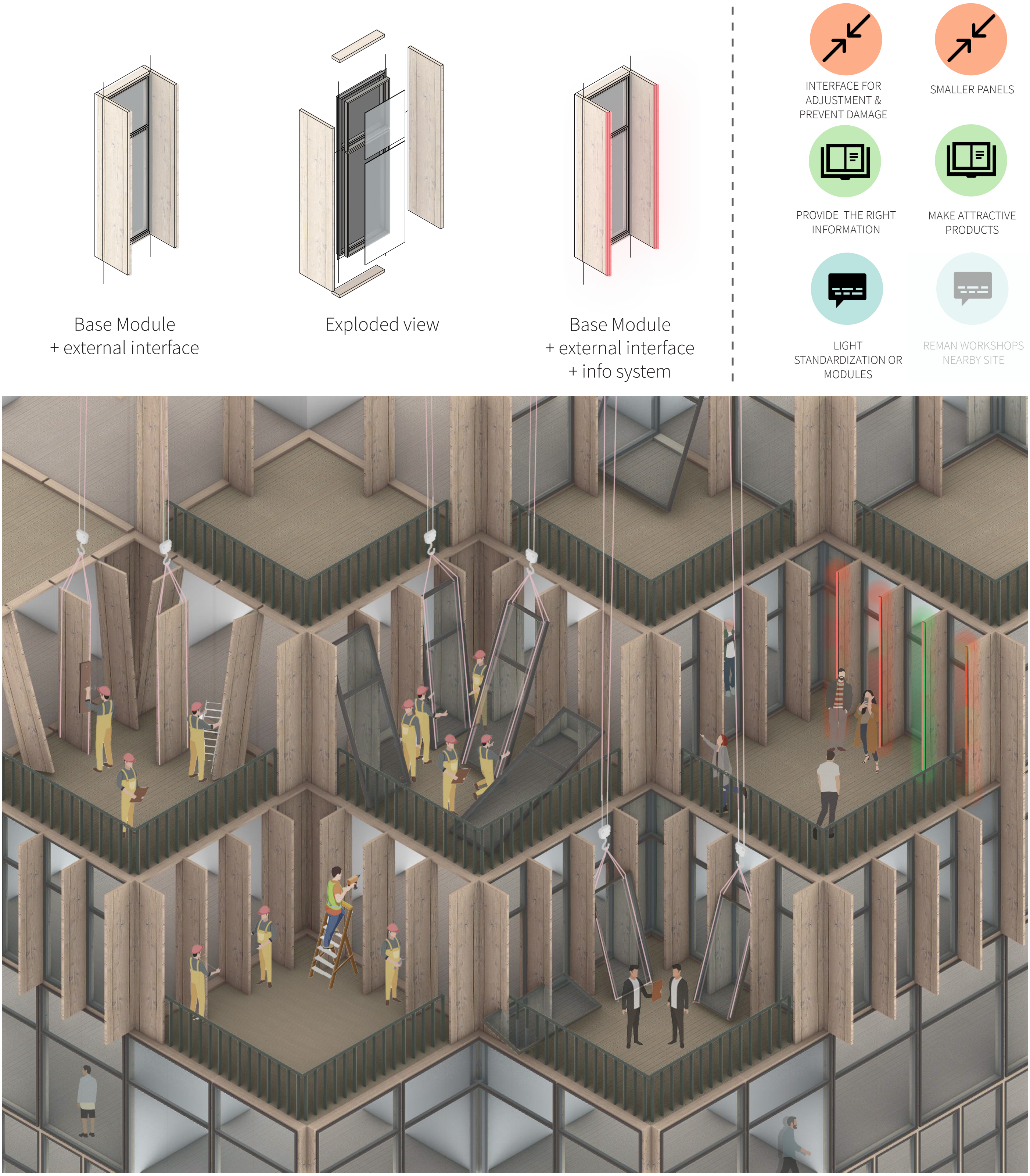


Figure 87 *Definition of modules*

Finally, by playing with the idea of making attractive products, versatility and adjustability are factors to be considered. For this, unitized balconies are proposed to have as an addition to the main module. They can be plugged in or unplugged if recovery is necessary. Also shading can be added, either on the interiors or exteriors. The concept is shown in Figure 88.

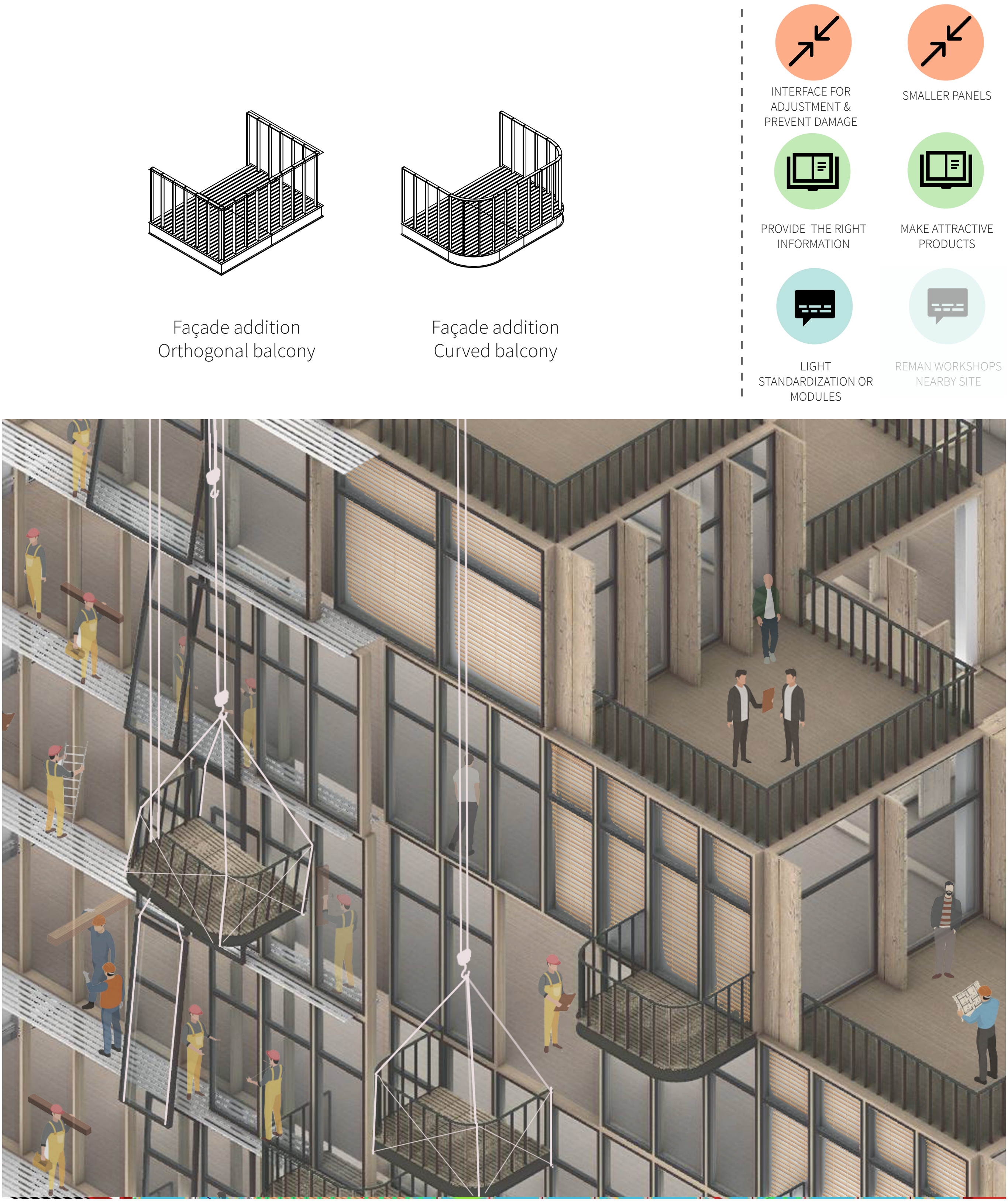
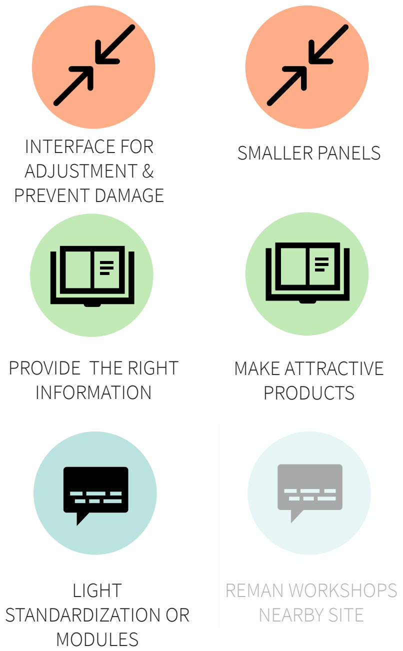


Figure 88 *Logic behind the skin & intermediary layering*



At the end, even if a simple base module is to be considered, several options and iterations could result. The final image (Figure 89) shows the versatility of the system by only varying the module in dimensions and infills, as well as the interface. The interface itself can be a protagonist of the system, being an expressive element that has more than one function (the intended one of making installation & recovery easy): it can produce energy, inform about the products quality, protect from sun exposure, host secondary substructures for an external skin, among others.

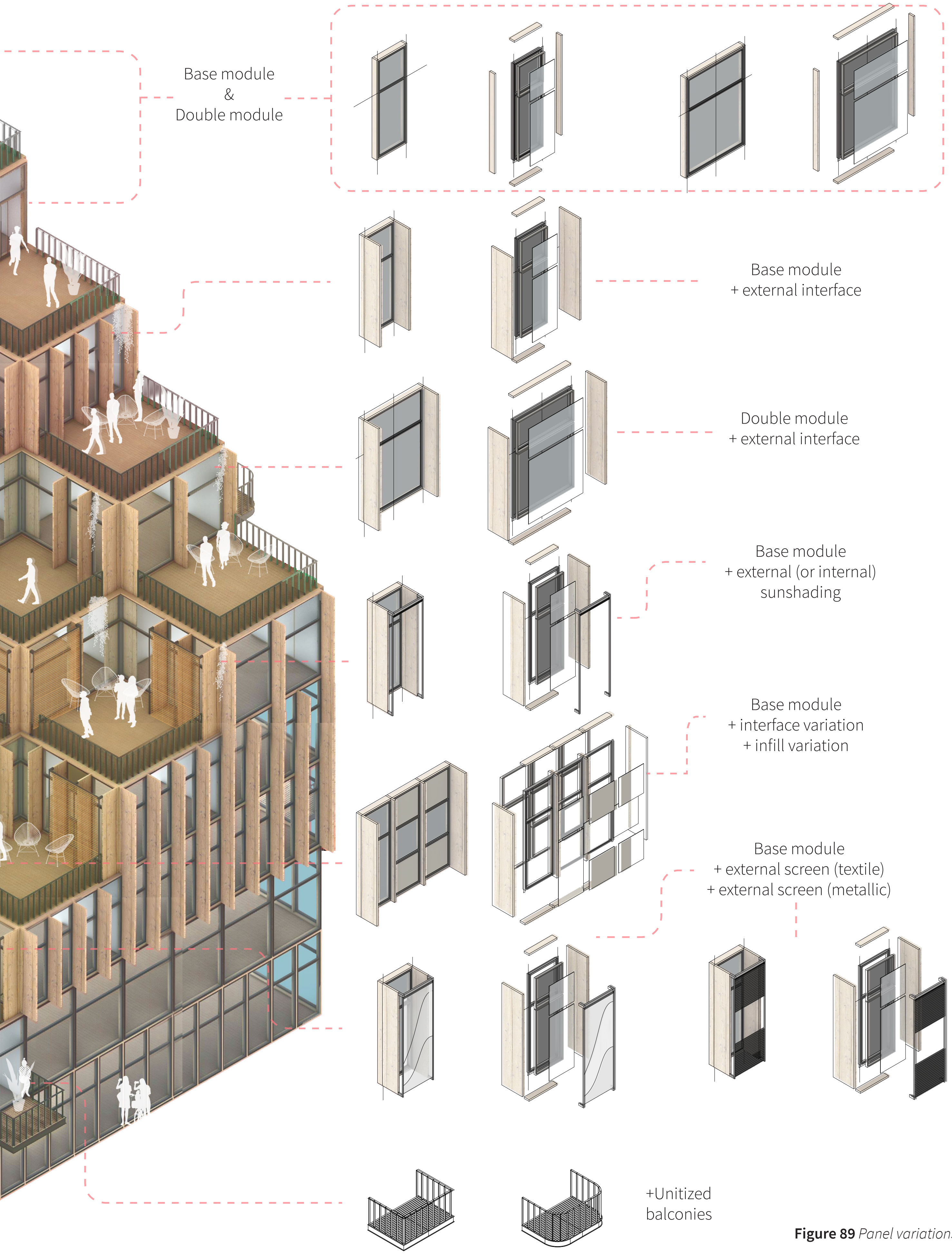


Figure 89 *Panel variations*

13.6 ASSESSMENTS

To employ the same assessments method, a simplified application is used. To perform the assessments, the idea that the façade panel were to be compatible with other buildings is assumed, given its dimensions and interfaces allow for it as well as a market that demands such products. First, the Descriptive assessment is filled, comparing both the Reusing and the Remanufacturing scenarios. Then, a summary of the Graphical assessment is also formulated, showing the four main steps of RL. At the end, the Graphic assessment is complemented with the Geographical analysis, which takes the two already addressed scenarios (Recycle and Remanufacture) and a comparison is made with the Reusing case.

Descriptive Assessment

The first noticeable aspect when comparing Remanufacturing and Reusing in Figure 90 is their similarities. The first two stages practically remain the same, as deconstruction and collection require the same level of coordination. The difference in these initial phases might only lie in the necessity of having more intricate ways of recovering the façade panel from its installation point, as reusing implies the product has an excellent quality and its integrity has not been compromised. It is highlighted how an efficient design could help to make the shift from a remanufacturing to a reuse situation. The same initiatives and incentives apply in this case, urging governments and regulations to be aligned with deconstruction and collection practices. From there, the logistic changes. For inspection and sorting, the products would be processed on site in the reusing scenario, a commentary made by Coelho and Brito stating RL can only be assured if “on-yard installation” or on-site sorting is conducted (Coelho & Brito, 2011). A spatial feasibility study would be needed to confirm if such activity can be performed on site. If it is possible, saving in logistics efforts and transportation will be made. Taking the concentration of activities even further, the Reusing scenario envisions mobile workshops nearby the deconstruction site- or even near the new installation site- that also reduce the coordination efforts between stakeholders. The workshop, in this case, would be dedicated to give quick maintenance to the products, in case they are necessary. It is assumed the panels were designed for an integral recovery and they are compatible with the next destination, reducing the necessity of intensive labour going into the product. The final outcome is the same for both cases: a product that has a second life, but with less resources invested to render it usable again.

Graphical Assessment

The Graphic Assessment (Figure 91) depicts the same process as the Descriptive one. Deconstruction and Collection are conducted on site, being the result of an auditing process done by a third party. After the products are recovered, the Inspection & Sorting is carried out on site, if enough space is provided and the stakeholder in charge (in this case the façade provider in a closed system, or an external façade contractor in an open system). This is followed by the “Reuse” phase, which consists on giving a light maintenance to the product, in case it is necessary, before transporting and installing it in its next destination. The mobile workshop idea is a conceptual proposal that must be explored further, but it is promising as it encourages an efficient process that optimizes the flow of products. This conceptual phase would only work if the products to be treated are designed properly, requiring the least amount of work to render them functional again. Product design should assure a decent quality and integrity, even after being used for the first time and being recovered.

Geographical Assessment

The geographical comparison done in the previous chapter between recycling and remanufacturing showed contrasting results between the two scenarios. Transportation was reduced considerably, minimizing the coordination efforts between each stage of the process. When mapping the Reuse scenario (Figure 92), the same observation can be made as in the previous two assessments. The distances do not reduce that much and the destination points seem to be equal. However, the difference does lie in the mentioned two last steps, in which Inspection and Sorting remain in the CITG site and the Relife Option phase is moved to the same city, Delft (for Remanufacturing, workshops in the south of Rotterdam were assumed as the remanufacturing facility).

GRAPHIC ASSESSMENT: Reuse

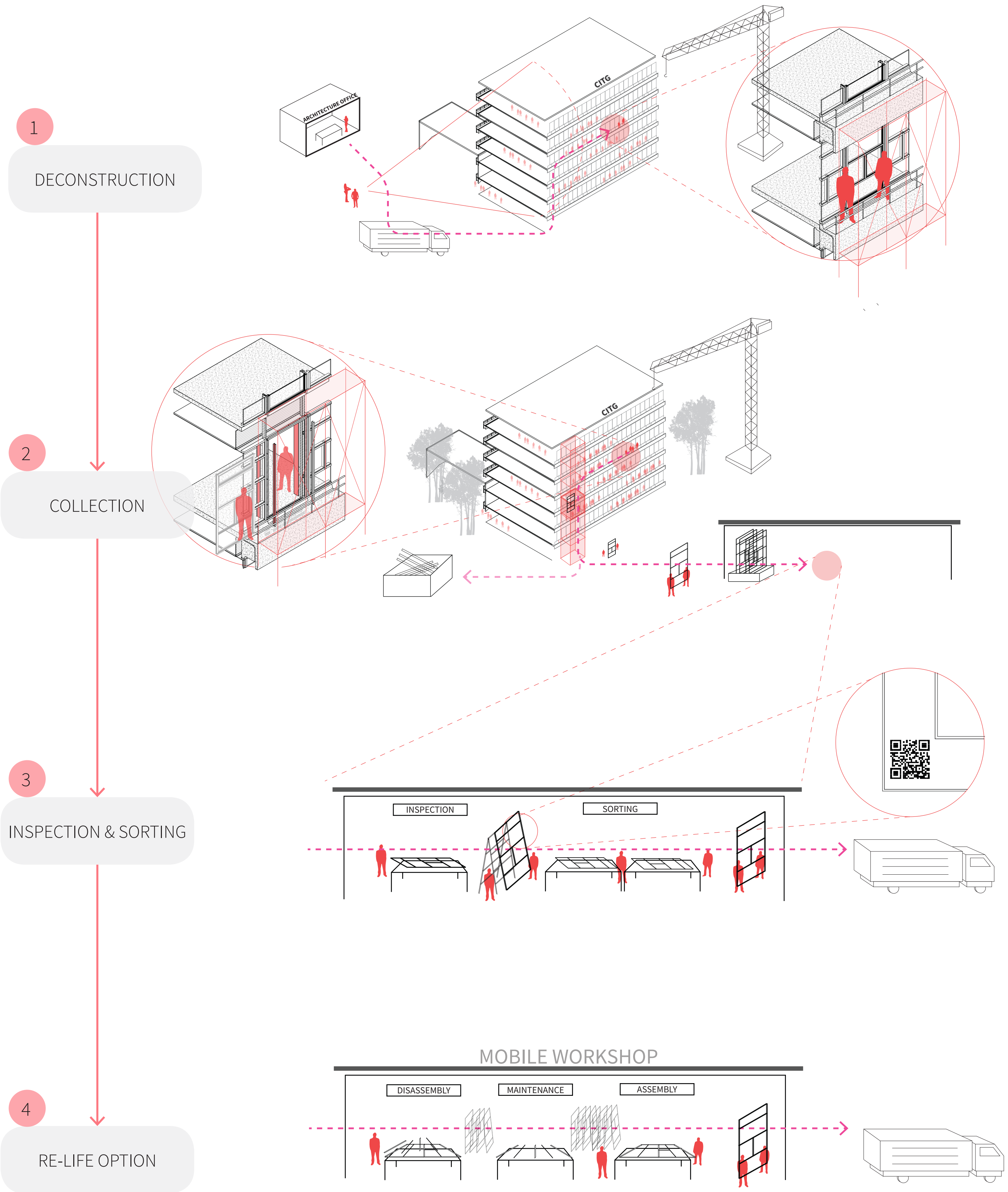
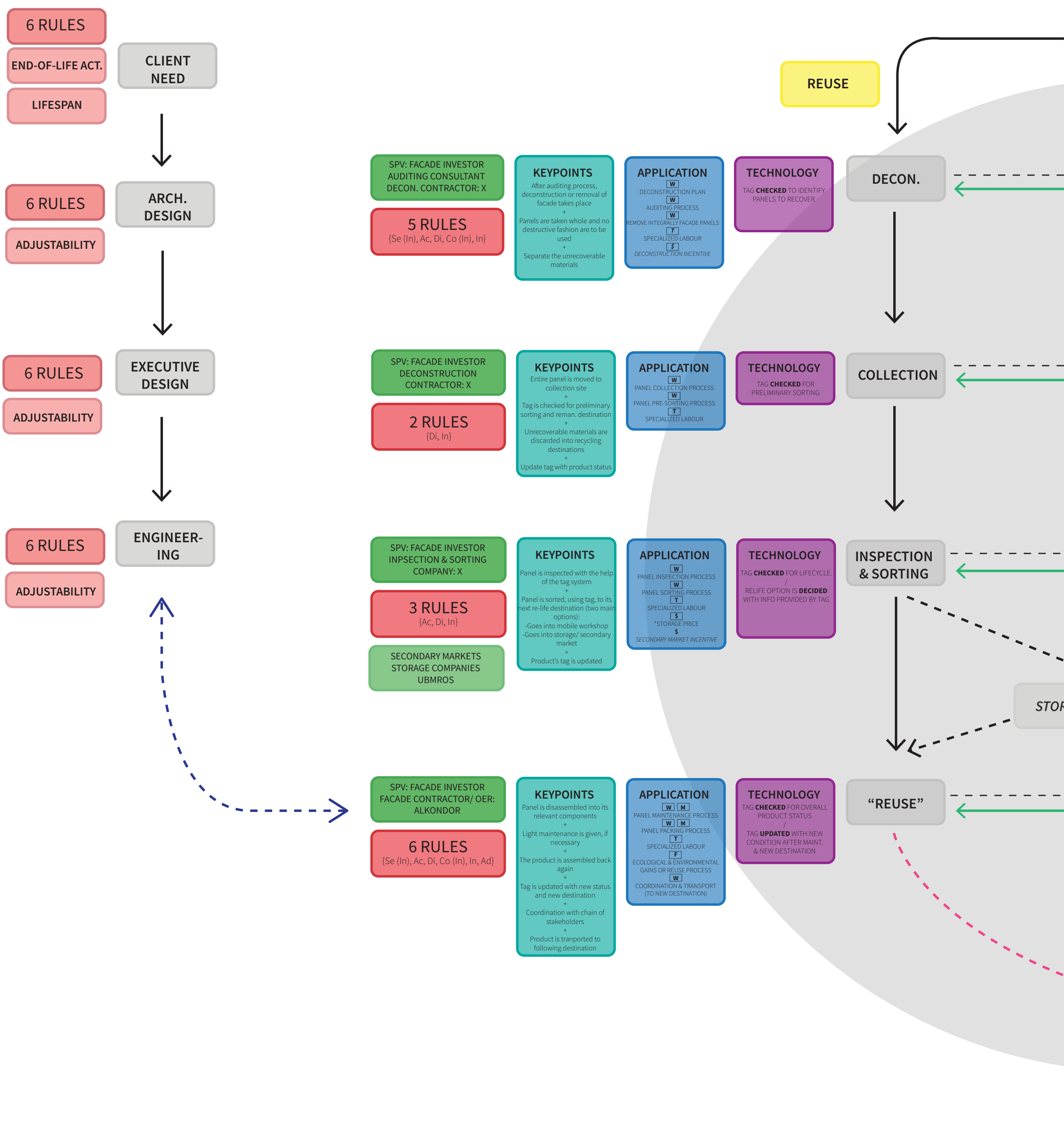


Figure 90 *Graphical assessment for reuse*



NOTES

OER	(ORIGINAL EQUIPMENT REMANUFACTURER)
OEM	(ORIGINAL EQUIPMENT MANUFACTURER)
UBMROS	(USED BUILDING MATERIAL RETAIL OPERATOR)
RCA	(REVERSE CHAIN ACTOR)
SP	(SERVICE PROVIDER)
DECON	(DECONSTRUCTION)

T: TIME
W: WORK
M: MATERIAL
$: COST
F: FOOTPRINT
ALL WORK INVOLVES EXTRA COST

REMINE

DESCRIPTIVE ASSESSMENT: Reuse vs reman.

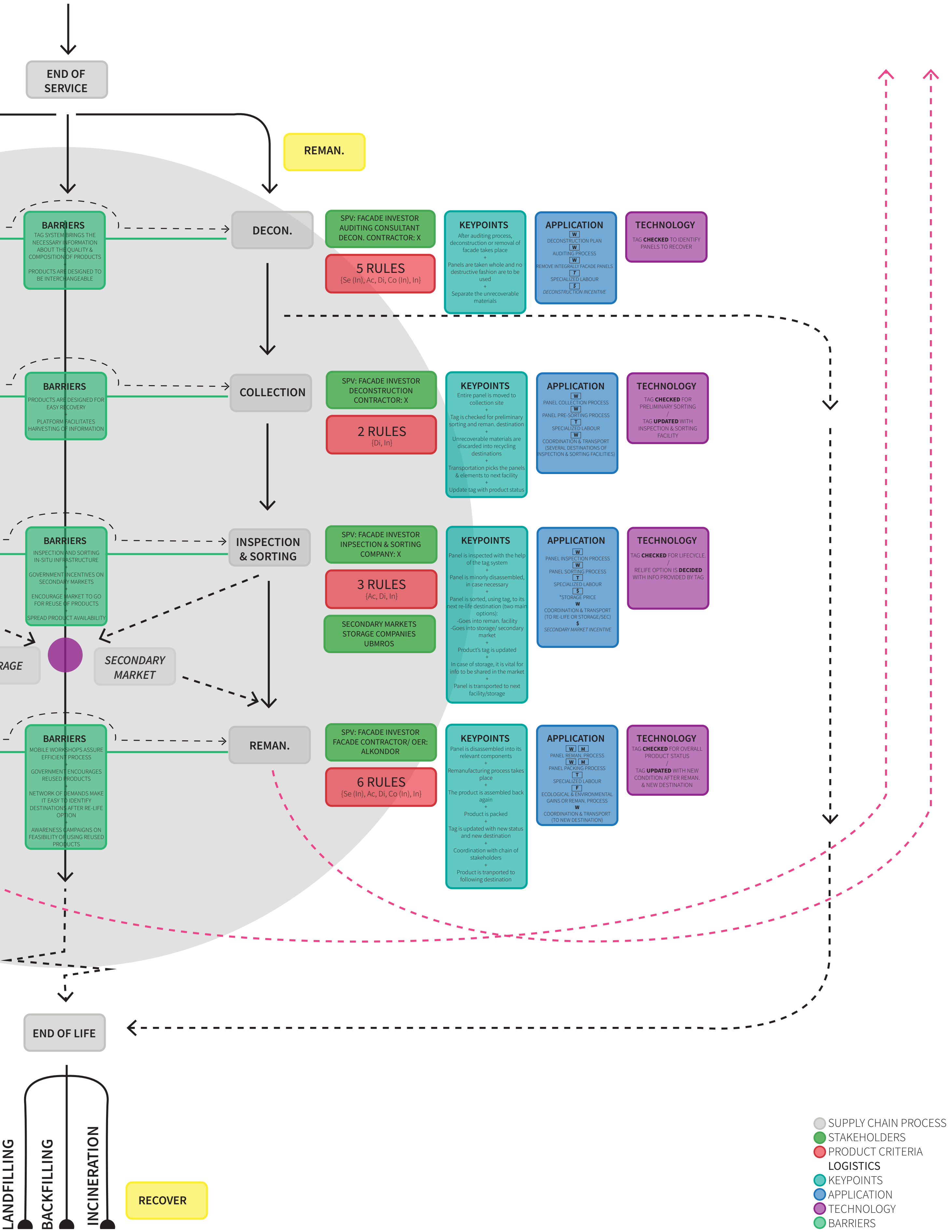
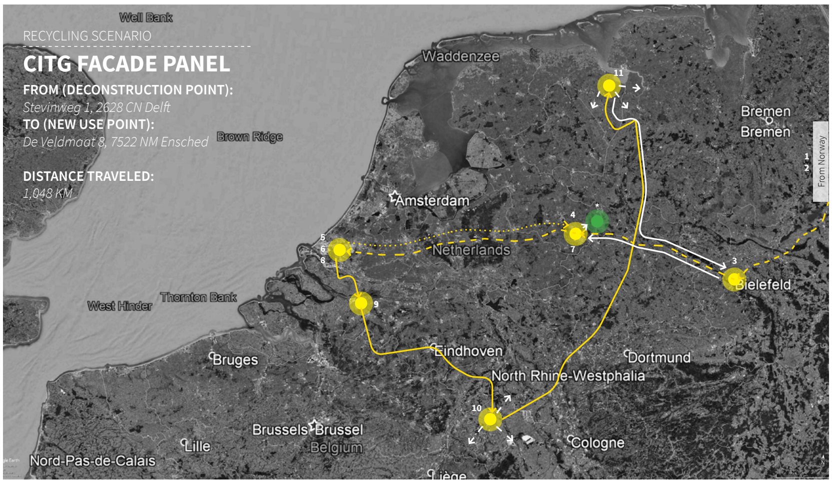
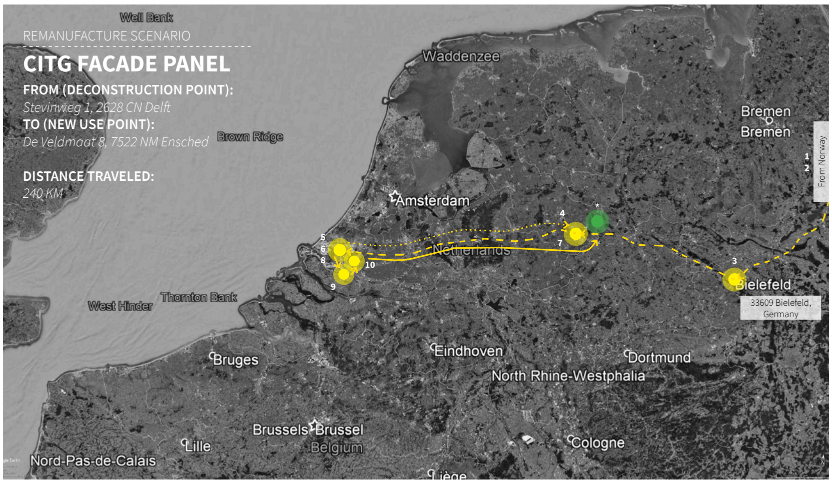


Figure 91 *Descriptive assessment: Reuse vs Reman.*

GEOGRAPHIC ASSESSMENT: Recycle vs Reman. vs. Reuse





GENERAL LEGEND
1 Material extraction
2 Material manufacturing
3 System manufacturing
4 End-product manufacturing
5 Installation
6 Use
7 Maintenance

Forward logistics
Reverse logistics

RECYCLING
8 Deconstruction | Collection
9 Inspection & sorting
10 Processing
11 Recycling (melting & extruding)
Next use

REMAN
8 Deconstruction | Collection
9 Inspection & sorting
10 Remanufacturing
Next use

REUSE
8 Deconstruction | Collection
9 Inspection & sorting (in situ)
10 Reuse (mobile workshop)
Next use

**The locations used for this exercise can be found in the appendix.*

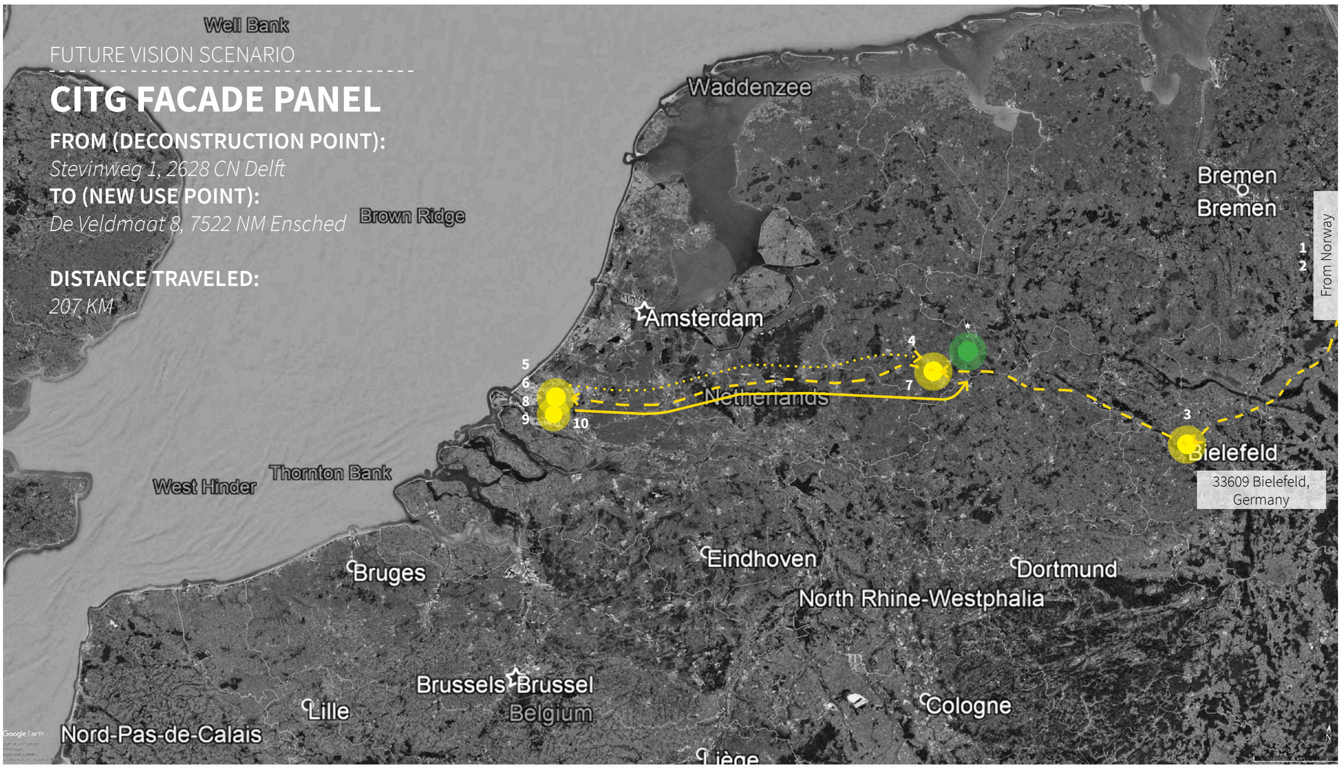


Figure 92 *Geographical assessment for reuse*

13.7 CONCLUSIONS

The design exercise showed important findings. Even though the initial intention was to largely intervene the CiTG- as the subject of the research- it was found there was no case in doing so because of its specificity. The measures taken by TU Delft and Alkondor are indeed big steps towards circularity, especially the addition of the wooden interface that helps on the recovery of the façade. However, its large height poses problems in the operation. Even though it hasn't reached the point where dismounting is necessary, its size can be identified as a source of problems. With this in mind, it was concluded a better exercise consisted on applying the RL knowledge and lessons learned into a generic building, reflected in a panel that could be interchanged. The exercise helped on relating the DfRL guidelines and to tangibly apply those foundations in a product. Even if the design exercise is purely conceptual, the intention is to trigger the minds of others to come up with new ideas. Aspects such as aesthetics are left for further development. Such aspect, even if initially considered of less relevance given the current context of material scarcity, proved to be one of the main drivers to assure a demanding market.

14 DISCUSSION

The Discussion Chapter relates the findings from the literature research and the most important theory from experts in the field, with the findings made throughout the research process. The assessments and the conclusions that resulted are linked to established arguments, rounding up or highlighting discrepancies between the two. As part of the discussion, a quantitative assessment is also introduced in this section, as a way contextualizing the findings in solid numerical data. The result shown, being quantifiable, can be used to compare with other products or scenarios. Further research is encouraged, as the industry and clients are interested in hard data to shift into a circular economy.

14 DISCUSSION

14.1 MAIN RELATIONS

The main reason that initiated the current research was the knowledge gap and lack of application of Reverse Logistics in the Built Environment. From the literature research at the beginning the main concepts and principles were reviewed and a clear outcome resulted: there is no general agreement on what circularity means. Having an ambiguous definition does not help on the definition of future goals that will shape the way of constructing. Reverse logistics, being identified as one of the subprocesses happening inside the CE practices, was basically defined as the dynamics and flow of products form the consumption point back to the manufacturing point. Hosseini et al listed the opportunities and barriers that RL implementation presents, giving a reason why it has not been yet implemented. Aspects such as lack of proper information, facilities and coordination of stakeholders, as well as uncertainties in building products were mentioned as obstacles (Hosseini et al., 2015). Such barriers were addressed in later stages to complete a larger picture of the topic.

Understanding the different levels of circularity was also key, and TU Delft had already addressed such topic in recent years, promoting research to understand circularity in the construction context. For the material side, the flow analysis was intended to be used for analysis or material behaviour. Even if it didn't reach the same level as the Repair project by Geldermans et al. (Geldermans et al., 2018), the basic idea is portrayed along the research to reflect the hypothetical scenarios proposed. The product level was also analysed, being the main focus of the research, and the CITG case proved to be highly valuable to extract lessons learned. Various assessments were used. As explained in the Assessment section, there are various existing assessments that have been addressing the impact of products. The intention however, was to design a way to practically assess a product regarding its process and how it can be recovered and what factors must align. The framework is then proposed, an assessment method that did not had any forerunner but instead it is a result from the various theories and authors lately developed. Its intention is to organize the topic in a logic way and leave a blank space that can be filled as a canvas by later work. The four major steps developed by Schultmann (Schultmann & Sunke, 2005) served as a basis to develop such framework, as it was one of the only authors that brought concrete steps to implement RL into the built environment.

After the development and initial filling of the framework, the façade criteria was also addressed, based on the concept established by Hosseini DfRL, or Design for Reverse Logistics (Hosseini et al., 2015). Defining which aspects such design theory would have to address was also proposed in the current research, based on previous existing assessments like Design for Disassembly by Durmisevic or the Morphological Matrix by Beurskesn and Bakz. Both formats were applied to evaluate the CITG case, assessing its successes and areas of opportunities. The assessment allowed to practically identify the essential steps on the process, namely the technical steps involved to actively recover the façade and take it to the next stage. The conclusions from the assessments were consistent with the results from the interviews. First, the design does play a role in the recovery and interfaces are vital to facilitate the process. Having biodegradable or less valuable components as interfaces ties in a coherent logic, as such elements might be lost during the dismounting process, but assures integrity of the main systems composing the façade. Dimensioning is also an important topic: even though several authors have been already addressed standardization and system building since the seventies, having compatible systems based on universal grid systems is encouraged. The difference, however, lies in the reason why it is relevant to employ such grid: before it was out f experimentation and a new efficient architecture. Nowadays, it would be because of scarcity of materials and the need of prevent unnecessary waste in the industry. The other lessons learned also align with the Harvesting of Information highlighted by several authors (Nunes et al., 2011) as well as the strategies that demand a concentration of activities nearby the site. The design ideas the resulted from the lessons learned were shown conceptually in illustrations, as concepts that might be developed even further.

14.2 CONTEXTUALIZATION- QUANTITATIVE ASSESSMENTS

The qualitative assessment developed in the previous chapter was the main focus of the research. It gives practical notions on how a product could accommodate RL practices, and who's and when's. However, another way to assess the products, specially when envisioning different scenarios that a product can undergo, is in a quantitative fashion. For the quantitative assessment , the intention was to complement the qualitative one and provide a more concrete and measurable result. As mentioned in the assessment criteria chapter, the MCI and the Energy & Carbon footprint were used. The first, a method developed by Ellen MacArthur and Granta Design, provides notions of the circularity of a product. Some limitations are mentioned at the end of the assessment. The second is a result from a CES analysis, in which the products and their properties were input, and the resulting output informs about the life cycle of the building according to the processes involved. It must be noted that only three components of the whole façade were analysed, as it is assumed some of them will have to be replaced due to their shorter lifespans and durability (namely the glazing beads, gaskets, silicones fittings and the glass panel itself). In short, the replaceable elements were not analysed, only the ones with the potential to be reused- the frames, the solid infill panel and the steel column. The following (Figures 93-95) are the summary sheets of each of the three evaluated scenarios, taking into account the same CITG panel as reference.

Starting with the MCI, the differences between the first two scenarios- Recycling and Remanufacturing- are not evident. There is a small increment in the circularity indicator (from 31% to 36%, respectively) even if the strategies differ considerably in their processes. However, it is understandable the difference obtained is only 5% as the MCI calculation does not consider remanufacturing and its specificities in the formulas. Important variables are not included as input, like transportation or remanufacturing work, which renders the indicator only as a notion of circularity. On the other hand, because the MCI does focus on recycling and reusing (those are initial inputs) the obtained difference when comparing these two scenarios is a larger 17%. The result in this case reflects the use of completely reused components, which is partially unrealistic as they might undergo light maintenance to have a new life. It must be noted that, even if some components are to be reused, it is assumed particular materials inside the component would need replacement. For example, the solid infill panel can be reused, but its insulation fill would need to be replaced after 30 years, approximately. The glass, a whole other topic, might also have the potential to be recycled, but it is left out of the scope of this research.

For the Energy and CO2 Footprint, a CES analysis was conducted. The software by Granta uses materials, their quantities, and the processes to show a lifecycle assessment. As mentioned before, only three main components of the façade were analysed, those that are more likely to be reused. The aluminium-polyamide frame, the solid infill panel, and the additional steel column were then studied. A particularity in the frame must be highlighted, as it possesses sensors and motors that allow it to open and close automatically. This is reflected in the Use phase, which overshadows the rest of the phases due to the energy it requires to perform such task. However, it is not taken into account for the purposes of this research, as the main focus lies in the material and energy put into the creation process.

As highlighted in the limitations of each summary sheet, both methods of assessment only provide rough numbers of the corresponding indicators, as they are not calibrated with the subtle differences between the different re-life scenarios. However, major conclusions could be drawn from the calculations, as highlighted in Figure 96. It is interesting how the most consuming phase (apart from the exceptional Use phase in the frame, as it has sensors and motors that open-close the windows) is the Material phase. This states the importance of better re-life options, which would reduce considerably the footprint of the Material step. Also, it is relevant to notice how transportation is one of the lowest in all cases. This contradicts the opinions from experts, who state transportation is one of the worst stages and main barrier to shift to CE practices. Such discrepancy might be due to the fact the calculation only envisioned a short route. As highlighted in the maps , a very light distance is considered- even in the worst case, recycling- exploring only in-land transportation in the form 14 tonne (2 axle) trucks. Transportation logistics, on the other hand, might as well pose an important logistic barrier, as the organization effort that takes to organize the transportation is not in the usual routine of the consulted stakeholders. Even if it is a factor that cannot be measured, it must be included in the equation to assess the complexity of shifting from one strategy to another.

QUANTITATIVE ASSESSMENT: RECYCLING SCENARIO

MCI

The recycling scenario reflects a 31% of Circularity Index for the whole facade product, including the interface used and the additional steel column.

Highlights:

-The highest potential is in the frame, due to its durability (considered 75 years), followed by the steel column and infill panel.

-The lowest are the unrecoverable items (EPDM and wood) as well as items that need replacement after 15 years (gaskets).

-Having an interface that will be waste has the trade-off of assuring recovery of more important components, life the frame.

Limitations:

MCI just provides basic notions as it does not take into account the subtleties of the process (e.g. if assessing for reuse, it doesn't take into account the energy/ resources that went into it to make it a reusable product again). Besides, it doesn't consider other relife options like remanufacturing or repurposing.

ENERGY & CO2 FOOTPRINT

*As explained, only the three main components of the facade that had the largest lifespan and reusability where assessed.

Highlights:

-The frame has the particularity of having the highest percentage in Use, as the frame has motors to operate it, which asks for attention in maintenance to keep such percentage low.

-The infill panel as well as the steel column have their highest energy and CO_2 percentages in the Material phase, making reuse (or other Re-life option) relevant to explore as less material is required.

-It must be noted that for Material the normal recycling rate was used as input (eg. 50% for aluminium), meaning the percentage could have been higher if virgin feedstock would have been used as input in the cases of the metallic components.

-Transport and manufacturing are the lowest overall.

-Disposal represents also a low percentage of consumption, which is contradictory with the statement of recycling being one of the most intensive of the Re-life options.

Limitations:

-It is uncertain what does CES take into account to make calculations, especially in the disposal & manufacturing calculation which are in the lower side (and expected to be higher).

-When comparing with other scenarios / relife options, it is important to realize that a single category does not represent the steps defined in the framework. Adding them provide a better idea of the consumption per step.

--For example, when addressing the recycling process, Disposal only does not represent the resources needed to recycle an object, but the addition of the Material process might result in a more realistic number.

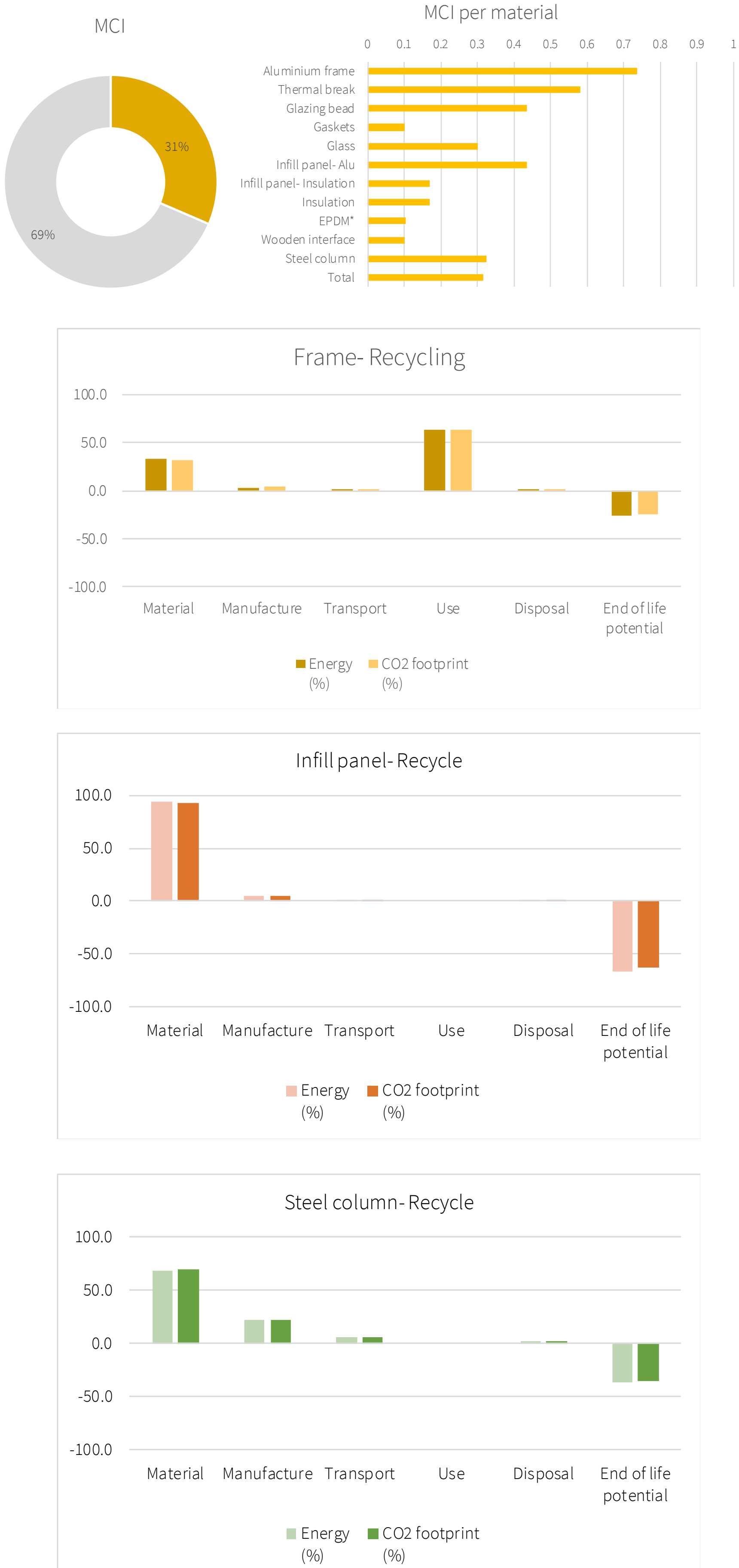


Figure 93 *Quantitative assessment: Recycling*

QUANTITATIVE ASSESSMENT: REMANUFACTURING SCENARIO

MCI

The remanufacturing scenario reflects a 36% of Circularity Index for the whole facade product, including the interface used and the additional steel column.

Highlights:

-The evident shifts in MCI are in the frame and infill panel, as they could be remanufactured for another use.

-However, there is not a considerable difference between the recycling and remanufacturing scenarios, as such distinction is not truly given in the MCI. This diminishes its value.

Limitations:

MCI just provides basic notions as it does not take into account the subtleties of the process. Besides, remanufacturing cannot be truly assessed as there is not an option to evaluate its efficiency, only through a combination of recycling/reusing it can be somewhat reflected.

ENERGY & CO_2 FOOTPRINT

**As explained, only the three main components of the facade that had the largest lifespan and reusability where assessed.*

*To see a direct comparison between the actual quantities of each scenarios, go to page X.

Highlights:

-The frame has the particularity of having the highest percentage in Use, as the frame has motors to operate it, which asks for attention in maintenance to keep such percentage low.

-The infill panel as well as the steel column have their highest energy and CO_2 percentages in the Material phase.

-It must be noted that for Material, the normal recycling rate was used as input, meaning the percentage could have been higher in the cases of the metallic components.

-Transport and manufacturing are the lowest overall.

-Little to no difference between disposal percentage between recycling and remanufacturing.

-The only significant difference between recycling and remanufacturing is the End of life potential (higher in the latter).

Limitations:

-It is uncertain what does CES take into account to make calculations, especially in the disposal & manufacturing calculation which are in the lower side.

-When comparing with other scenarios / relife options, it is important to realize that a single category does not represent the steps defined in the framework. Adding them provide a better idea of the consumption per step.

--For example, when taking about recycling, disposal only does not represent the resources needed to recycle an object, but the addition of the material process might result in a more realistic number.

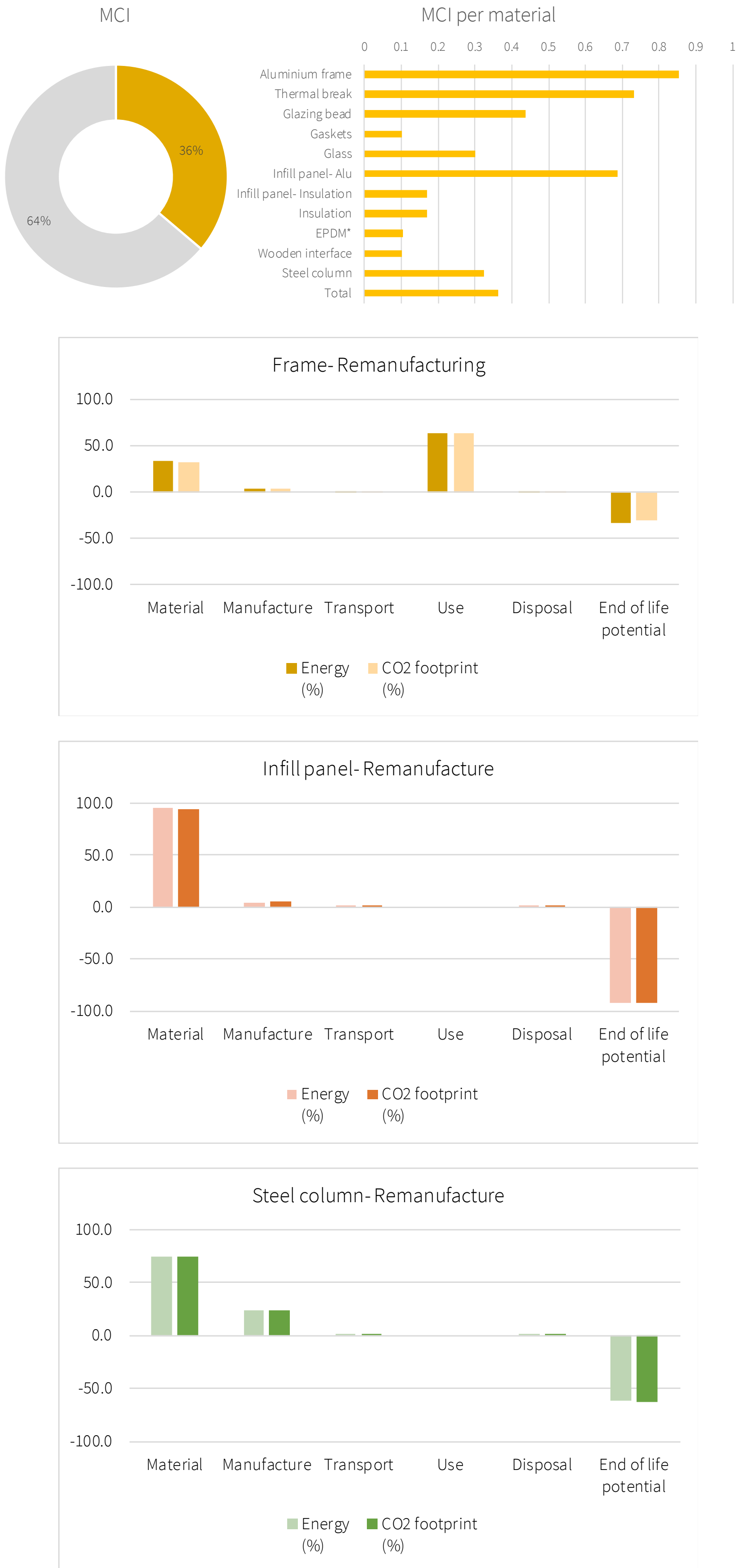


Figure 94 *Quantitative assessment: Reman.*

QUANTITATIVE ASSESSMENT: REUSING SCENARIO

MCI

The recycling scenario reflects a 48% of Circularity Index for the whole facade product, including the interface used and the additional steel column.

Highlights:

-The main difference between Reman and Reuse is that input products in Reuse are also defined as reused parts, which yields a higher MCI.
-If the frame, infill panel and steel column are reused, then the MCI is realistic.

Limitations:

MCI just provides basic notions as it does not take into account the subtleties of the process (e.g. if assessing for reuse, it doesn't take into account the energy/ resources that went into it to make it a reusable product again).

ENERGY & CO2 FOOTPRINT

**As explained, only the three main components of the facade that had the largest lifespan and reusability where assessed.*
*To see a direct comparison between the actual quantities of each scenarios, go to page X.

Highlights:

-The frame has the particularity of having the highest percentage in Use, as the frame has motors to operate it, which asks for attention in maintenance to keep such percentage low.
-CES reflects a very idealistic reuse scenario, as it minimizes considerably the material, manufacturing and disposal categories (there is no possibility to input light repair work before reusing a product).
-Even if reuse is assessed, the infill panel considers the insulation in between the sandwich panel to be replaced.
-The end of life percentage is misleading, as the calculation reflects a very low potential (expected to be high, as reusing retains the most value).
-Consult page X (and the appendix with the calculation input), to see the real quantities and comparisons. They reveal how the EoL for reuse is significantly lower than the rest of the cases.
-If the steel column is completely reused, then the bar chart is realistic (but its measures are too specific for it to be feasible).

Limitations:

-It is uncertain what does CES take into account to make calculations. In this scenario, EoL is questionable.
-When comparing with other scenarios / relife options, it is important to realize that a single category does not represent the steps defined in the framework. Adding them provide a better idea of the consumption per step.
--For example, when taking about recycling, disposal only does not represent the resources needed to recycle an object, but the addition of the material process might result in a more realistic number.

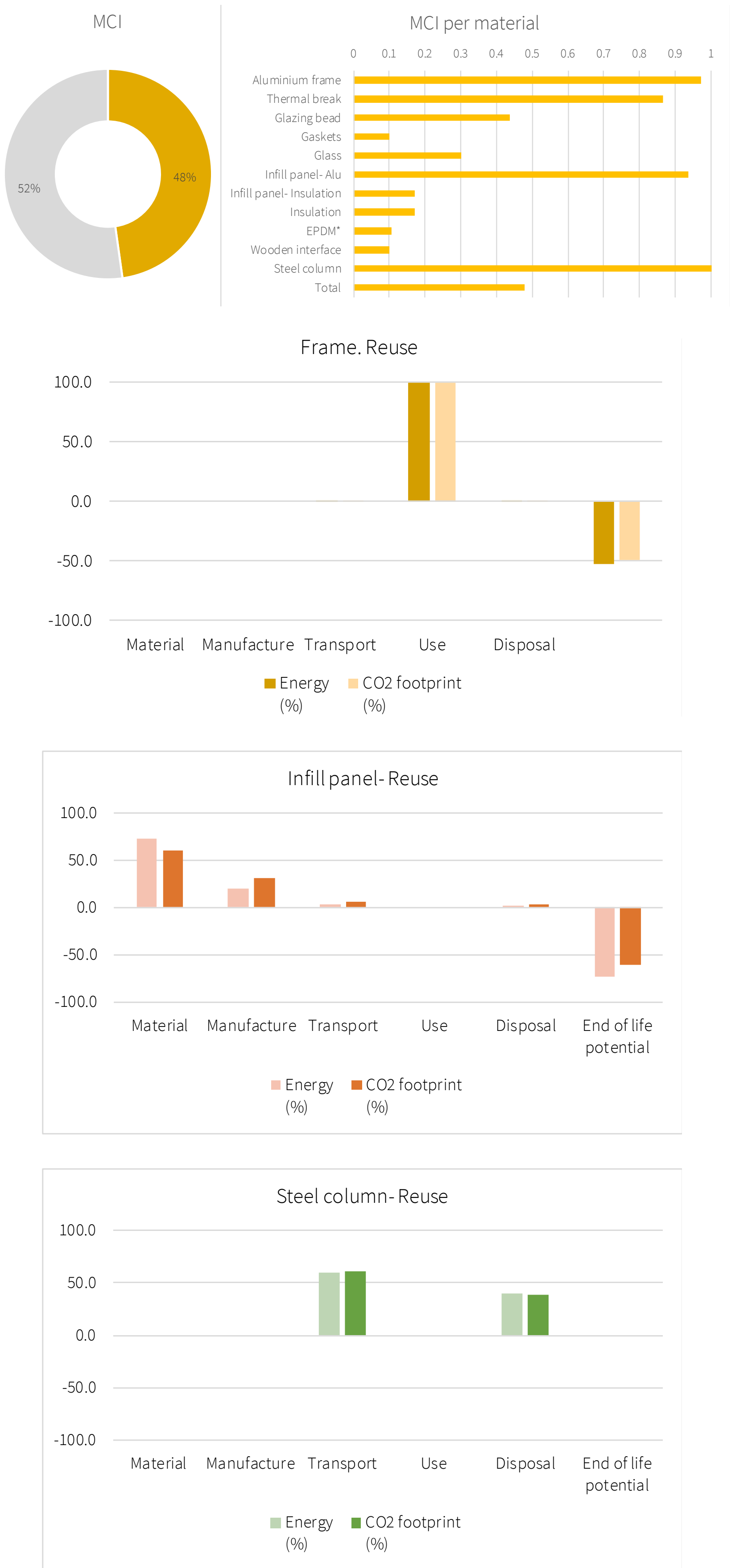


Figure 95 *Quantitative assessment: Reuse*

QUANTITATIVE ASSESSMENT: FINAL COMPARISON BETWEEN THE 3 SCENARIOS

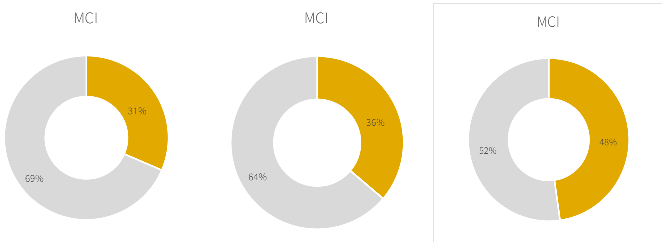
MCI

Highlights:

-The MCI difference is only evident in the reusing scenario.

Limitations:

MCI just provides basic notions as it does not take into account the subtleties of each process.



ENERGY & CO_2 FOOTPRINT

Highlights:

-When comparing the frame, Recycle and Reman have similar quantities. Reuse drastically reduces material and manufacturing processes, as expected.
-When comparing the infill panel, even if the insulation is replaced, the Reuse scenarios shows a drastic reduction to almost 0 in its Total quantity. However the EoL is also reduced to almost 0, questionable due to the lower quantities in the previous stages.
-When comparing the steel column, the same conclusion of the infill panel apply.
-Generally, it is interesting to note how the highest (apart from the exceptional Use phase in the frame) is the material phase. This states the importance of better relife options, which would reduce considerably the footprint of the Material step.
-Also, it is interesting to notice how transportation is one of the lowest in all cases. This contradicts the opinions from experts, who state transportation is one of the worst stages. However, the calculation only envisioned the route in the maps (which a very light route, only using in-land transportation, trucks) and the logistics is another factor that cannot be measured (and it might be the aspect the experts were also referring to).

Limitations:

-It is uncertain what does CES take into account to make calculations.

Figure 96 *Quantitative assessment: Comparisons*

14.3 QUALITATIVE ASSESSMENTS SYNTHESIS

From all of the assessments applied along the research and the various scenarios assumed, the graphic below can serve as a general overview of the results. The three main scenarios are shown per row (recycling, remanufacturing and reusing) and the four basic steps are shown per column (deconstruction, collection, inspection & sorting, and re-life option). Recycling depicts the common practice followed by the industry in the Netherlands. Products are teared down from their installation site, normally cut into pieces and collected into containers that are latter shipped to a place where the recoverable materials can be weighted. Aluminium, one of the focus materials of the research, is cut and processed even further to get pieces that can be transported and put into furnaces to melt the metal back into a pure state. Aluminium billets result and these go again into the system manufacturing to be converted into profiles for window systems or many other uses. When comparing with remanufacturing, design would facilitate the process by creating products that can be fully recovered. After being collected, they go into inspection and sorting in which a tag/data system could be used to identify the most suitable re-life scenario. If there is a client and next destination, the product is remanufactured and brought into its original quality state. After that, it is transported into its new destination. For the final scenario, reusing, the two initial stages repeat, with the design premise being compatible products, with similar dimensions. Reuse would then imply a seamless process, as the inspection and sorting would also happen on site, and the maintenance shifting to a nearby mobile workshop. This would suggest products are robust and based on an universal grid, which reduces the need of specialized machines and equipment. At the end, it all reduces to less stakeholders involved in the reuse of a product, by minimizing distances, efforts and coordination, through design and planning. As mentioned before, regulations and the market must also align, allowing products to flow from building to building.

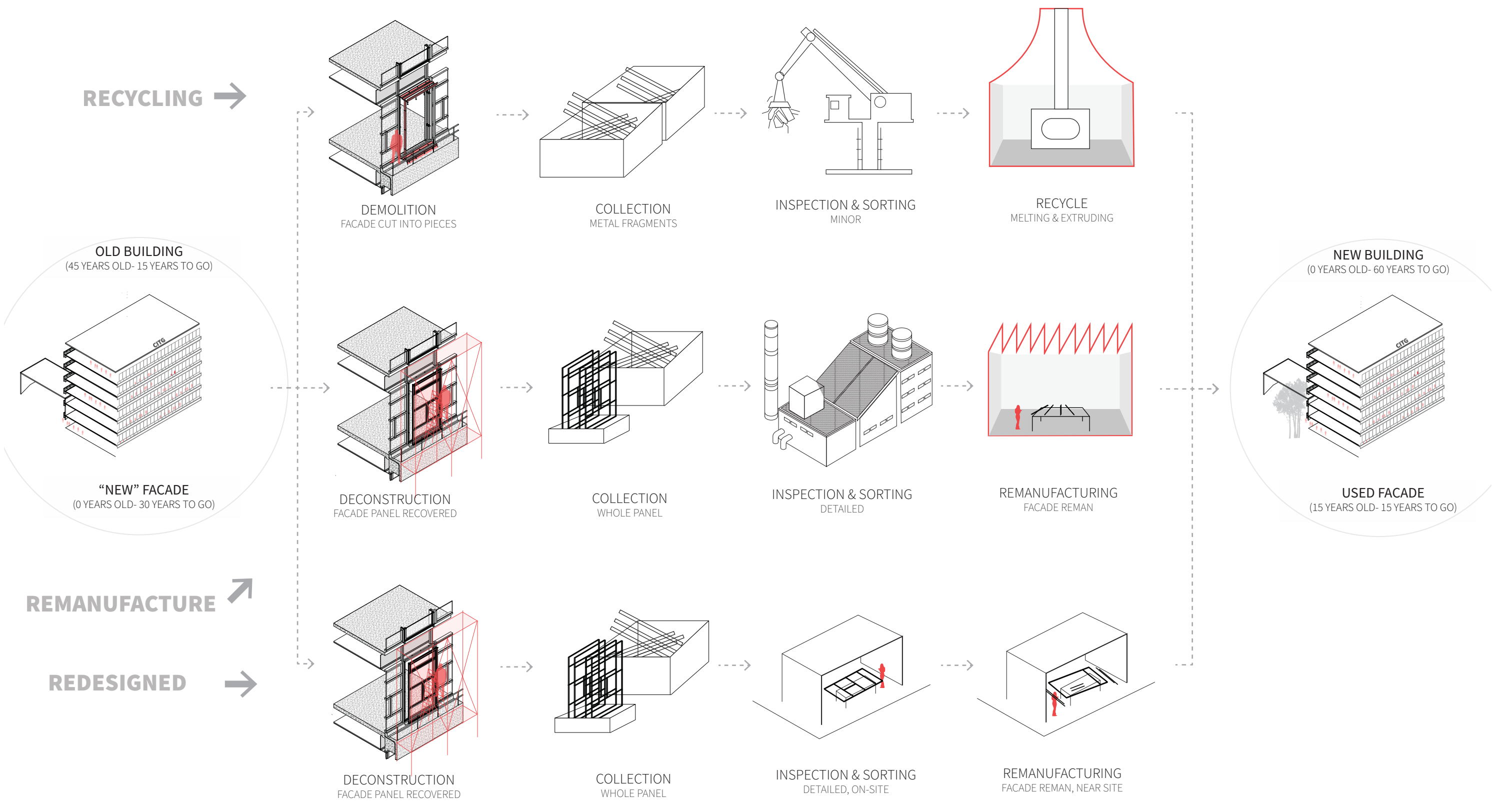


Figure 97 *Summary of qualitative assessments*

14.4 CONCLUSIONS

When relating the theory findings during the literature research and the findings during the interviews and the design parts, the result is a coherent conclusion. The reasons why RL has not been implemented in the construction industry have to do with the several amount of variable, unknowns and stakeholders in the same process. Commodity on doing the “least” wrong practice has left the built environment feeling satisfied, but such ways are the ones leading to the several material scarcity scenario explained in the previous chapters. The next big step is having the commitment by the industry to invest in efforts and design that is durable and recoverable. Even if initial investments are high (consult the next section for specific numbers) and circularity is just considered to have ecological impacts, the payback does not only come as economical retribution but also as environmental relief. As previously highlighted, designers have a huge responsibility in the facilitation of such process. Using the current research as a solid background and the current environmental necessities, design ideas can begin to be more speculative (Figure 98). What if system building thinking is brought back? What if construction, apart from being highly functional, eradicates waste, while still being desirable and attractive?

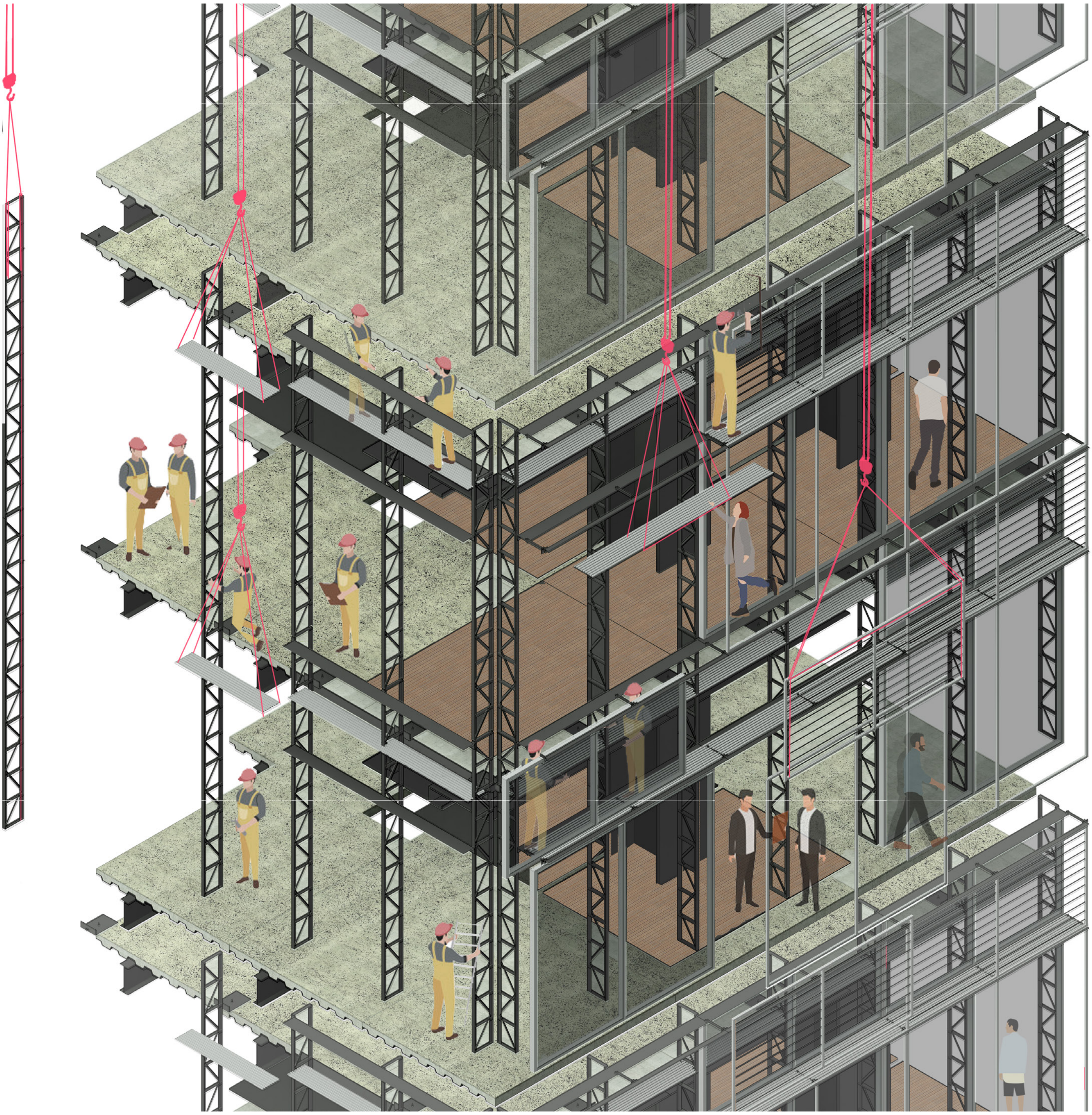


Figure 98 *The renaissance of system building*

15 BIGGER PICTURE

The Bigger picture zooms out and evaluate the situation of the industry and also addresses aluminium in specific, to state some connections to the larger context. The main barriers to tackle next are mentioned, as well as some facts in case RL application is still a questionable task to consider in the construction industry.

15 BIGGER PICTURE

15.1 CURRENT CONTEXT

According to Eurostat, the construction industry in Europe in recent years has been at a steady annual percentage growth from 2013 until now, as shown in Figure 99. This would normally imply the industry will continue production processes at a steady rate, demanding a familiar consumption of materials and products. As mentioned in the material section, if demand were to continue the same current trends, the world's consumption of raw materials is predicted to double by 2060 (OECD, 2018). Double the pressure on the environment would mean 167 Gigatons of global materials by 2060 (today is less than 90 Gigatons), leading to severe environmental consequences. In this context, it is valuable to rethink consumption and be open to the opportunities that circularity offers: to reuse as much as possible, remanufacture, or have any strategy that doesn't take away the value of products. With unexpected scenarios like the current ceasing of activities (referring to the Corona outbreak in 2020), it is even more interesting to think in the effects on the Built Environment. Even if there are no updated graphs showing construction activity, it can be assumed a lower percentage is a result of such circumstances. It might be even more feasible to think of circularity and RL solutions in those contexts as well, having as main argument saving of costs and an industry less dependent on new feedstock.

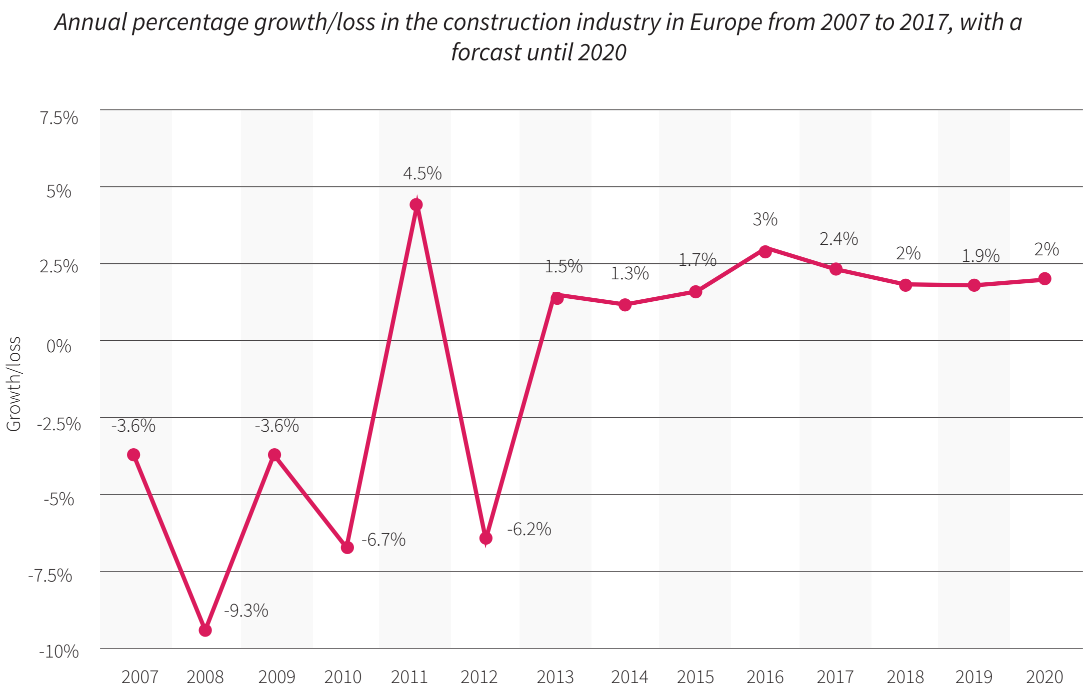
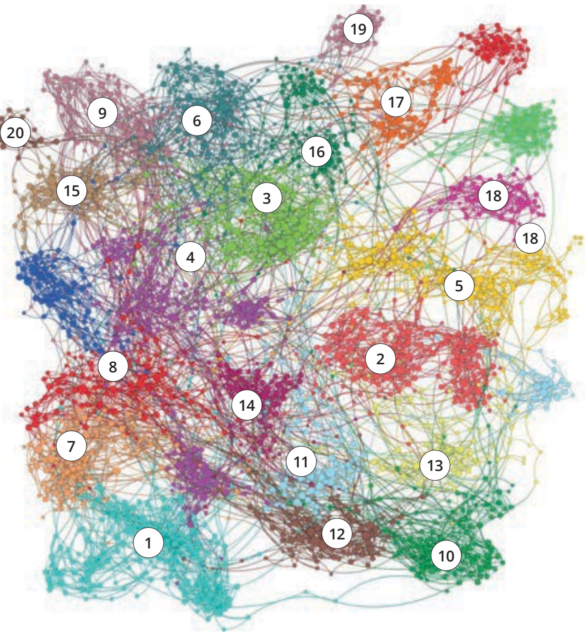


Figure 99 *Construction industry growth (Statista 2020)*

Actually, from a report from Deloitte, the growing construction industry shows its commitment with new practices. In the past, construction had been always related to a lack of innovation and a general lag in technology updates. It has been revealed BIM started to challenge this idea in 2003. Having models full of information that would help on the management and assessment of construction during the process enabled professionals to be more in control. Moreover, over the past five years, robotics, IoT, smart buildings and 3D printing have been moulding the industry and shifting perspectives on how things should be done (Deloitte, 2019). The graph below (Figure 100) shows the companies that have been applying these methods and many other, and their interconnectedness. Having digitization shaping the industry is one of the most valuable drivers for practices such as RL to come into a real application. As already discussed, RL would rely mainly on coordination, logistics and information availability; with the application of these technologies, its feasibility becomes higher.

ConTech ecosystem



	Cluster	Share
1	Machinery, components & assembly	8%
2	General contracting	7%
3	Construction management software	7%
4	Robotics & 3D printing	6%
5	Building Information Modelling	6%
6	Consulting	6%
7	Construction materials and technologies	6%
8	Trading & investments	5%
9	Networks, cable & fiber	5%
10	Landscape construction, environment, waste & water	5%
11	Oil & gas	4%
12	Engineering & technology	4%
13	Road & railway, structural engineering	4%
14	Solar energy	3%
15	Artificial Intelligence, IoT, smart	3%

Figure 100 *Construction & Technology ecosystem (Deloitte 2019)*

If aluminium is taken as example, its flows might behave differently. Its production has been increasing exponentially over the years, but major production occurs in different parts of the world. The map below (Figure 101) shows how China is one of the major aluminium producers, with 3,100 metric tonnes of aluminium. From the Sankey diagram (Figure 102), it is shown how Europe doesn't mine bauxite at all, and for its production 20% comes from South America. Even though 47% of the aluminium going for production comes from recycling of their its aluminium, Europe showcases a dependence on other countries to satisfy its needs of production. Besides, recycling aluminium does not mean it goes into the construction industry; it mostly goes into the packaging and transportation fields. If a circular economy is applied, the loop will be a continuous circuit staying flowing through the same place, saving on material extraction in other locations and therefore less need of transportation. It will also mean products are not being downcycled into other uses but remain in a compatible use.

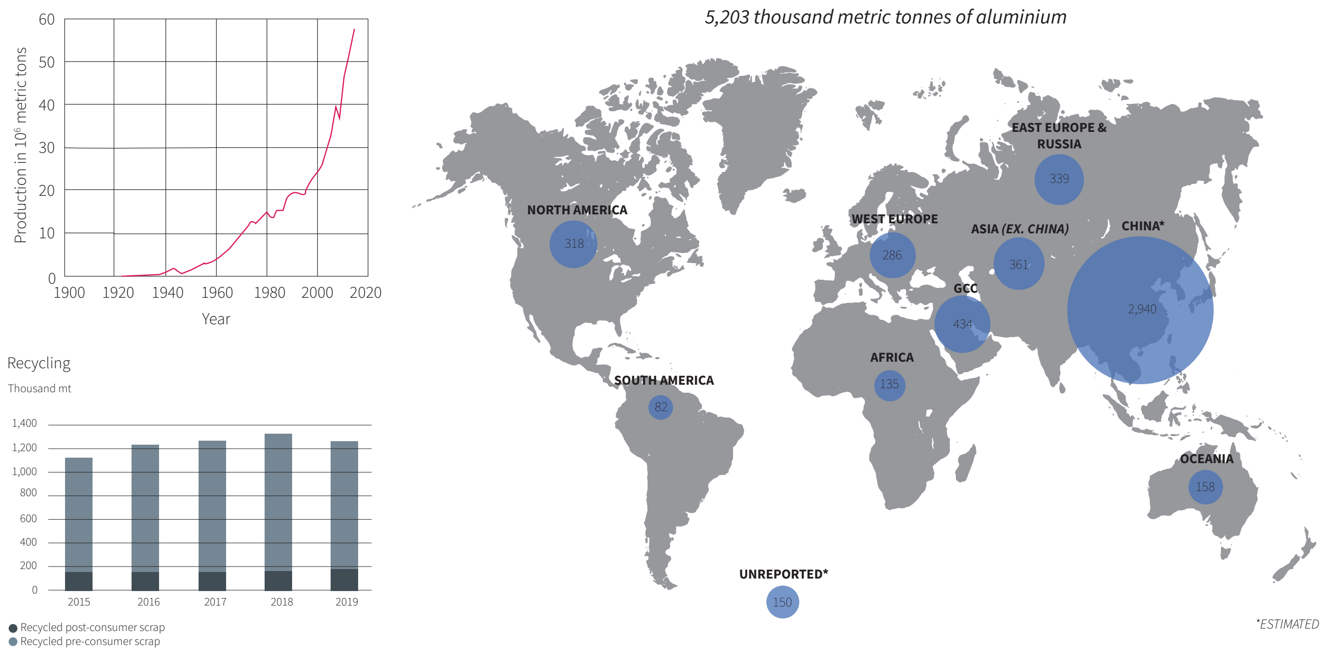
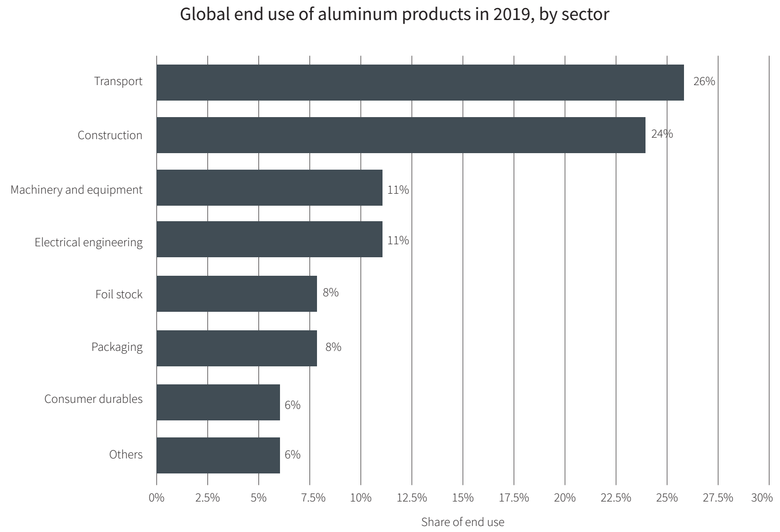
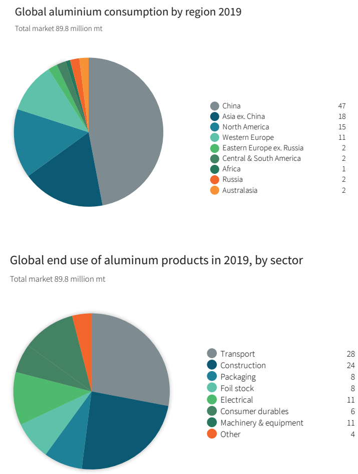
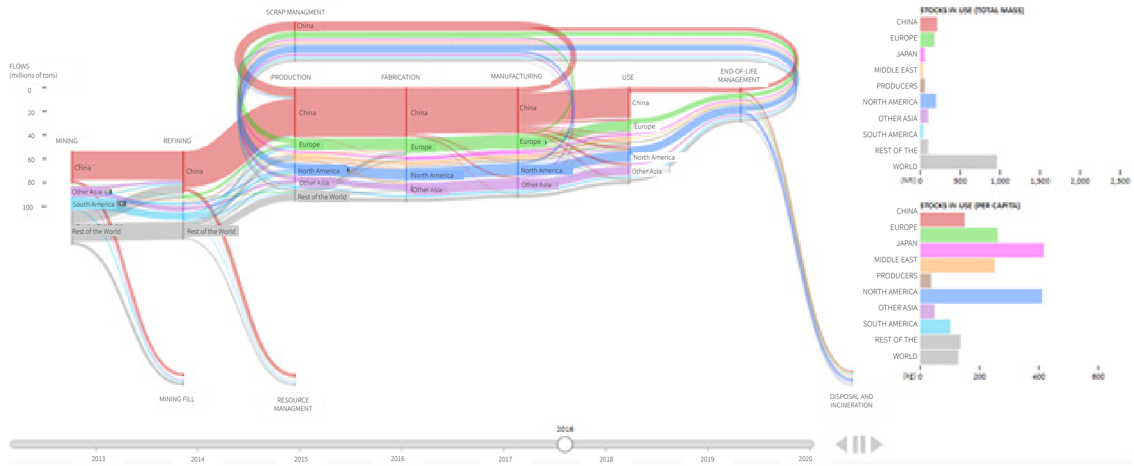


Figure 101 *Aluminum production through the years | Aluminum recycling rates | Aluminium production by location*







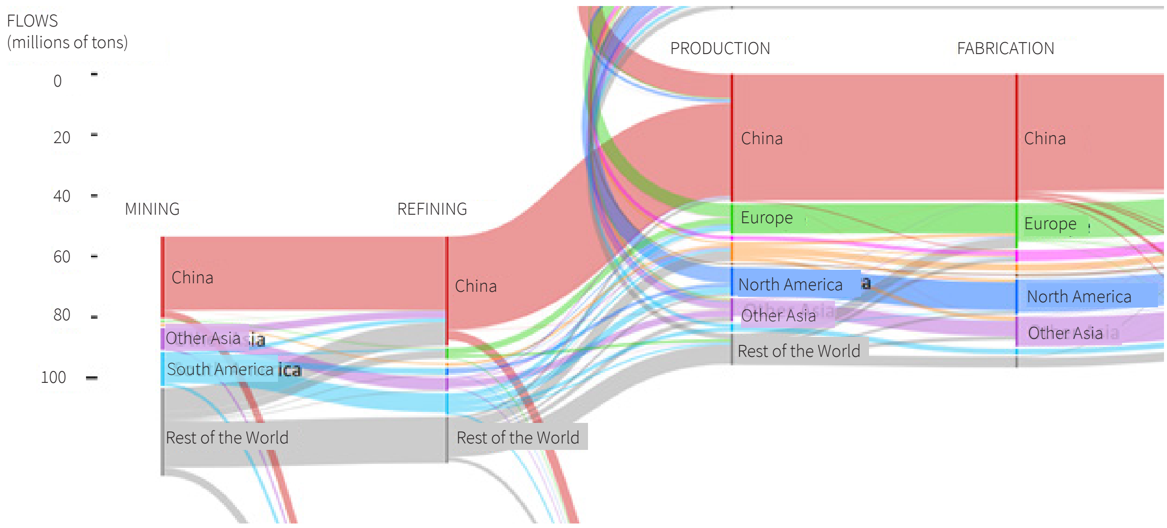


Figure 102 *Aluminum consumption by sectors | Sankey diagams of aluminum through its lifecycle*

15.2 FUTURE VISION

From all the brainstorm and design ideas presented in the previous section, a future vision is created. How could an optimal process of RL look like at end? It would all start with the client's request, a client aware of the products available in the market (e.g. panels being left unused due to certain reason) and having no prejudgements towards them. Reuse products are as good as new ones, is the mindset to be encouraged. When working along the architects and engineers, the awareness of the client will allow the architect to design with those products in mind, which will have standard dimensions, facilitating the compatibility between buildings. This would mean buildings being designed and constructed in consistent ways, assuring a proper reuse of components. A few centimetres specified in the design are the difference between a panel that can be reused and a panel that cannot. At the same time, managers will think ahead of the Reverse Logistics process: mobile stations shall be used as well as he maximum amount of operations on site. This is a paradigm and contraposes the current idea of having the most operations off-site. But a clear distinction has to be made: for forward logistics, off-site assembly is the most recommendable always; for reverse logistics, on-site operations would facilitate the whole process, saving time and costs for coordination and transportation. Finally, legislation must also align with circular strategies on products and, most importantly, society must shift their perception and accept the new way of constructing. Figure 103 portrays the vision using the different identified layers.

Figure 103 *Future Vision*

15.3 HOW TO GET THERE

All of the previous chapters, starting from the Framework and ending in the Design, have the intention to facilitate RL and close loops. The Framework Formats give a clear view of the process, highlighting who would be involved and what needs to be done. But the most important is that they are dynamic and their goal is to act as a canvas to be filled with different perspectives and experiences from others. The Application of the Framework, in which a specific case was evaluated, helps on the creation of guidelines and awareness to the design of products and strategies. Finally, the Design Exercise intends to open the discussion on the best ideas to implement RL in a bigger scale, going from product solutions to system solutions. So, reprising the Accelerator table presented in Chapter 5, the following aspects could be added.

ACCELERATORS
- Focus on the savings, specially economic
- License to operate by stakeholders
- Proper infrastructure (salvage yards)
- Harvesting of information (HoI)
- Design for reverse logistics
- Eliminate regulation risks of used products
- Change designers' perspectives on used products
- Yard installation
- Choose deconstruction over demolition
- More research on the four main steps and their impacts
- Design facades that can be dismounted and moved easily
- Design with standardization in mind
- Concentrate reverse logistics operation on-site or nearby
- Reduce transportation and coordination to the minimum

Table 12 *RL accelerators*

15.4 NEXT BARRIERS TO TACKLE

To bring a conclusion to the barriers, especially the ones needed to be tackled next, the following referenced list can be taken into consideration. They were found throughout the literature research on regulations.

BARRIERS
-Ban landfilling of recyclable plastics, glass, paper, cardboard, metals and biodegradable waste by 2025, while Member States should endeavour to virtually eliminate landfill by 2030 (European Comission, 2014).
- Clarify the calculation method for recycling/reusing materials in order to ensure a high recycling/reusing quality level (European Comission, 2014).
- According to Article 25 of the Directive 2008/98/EC on Waste and Repealing Certain Directives: "it is appropriate that costs be allocated in such way as to reflect costs to the environment of the generation and management of waste" (European Parliament, 2008). This should be enforced.
- According to Article 26 of the Directive 2008/98/EC on Waste and Repealing Certain Directives: "the polluter-pays principle is a guiding principle… The waste producer and the waste holder manage the waste in a way that guarantees a high level of protection of the environment" (European Parliament, 2008). This should be enforced.

Table 13 *RL Barriers*

15.5 FACTS

The following are facts found throughout the literature research that are encouraging for RL application. They are presented here in case there are still doubts on why RL practices should be taken seriously:

FACTS
-It is estimated that improvements in resource efficiency all along the value chains could reduce material input needs by 17-24% by 2030 (European Comission, 2014).
-A better use of resources could represent an overall saving potential of 630 billion per year for European industry (European Comission, 2014).
- Circular economy approaches have the potential of boosting the EU GDP up by 3.9%, creating new markets and new products (European Comission, 2014).
- “Waste prevention, eco-design, reuse and similar measures could bring net savings of € 600 billion, or 8% of annual turnover for businesses in the EU” (European Comission, 2014).
- Applying circular strategies would reduce annual greenhouse gas emissions by 2-4%, helping achieve the reduction goal by 40%. This means 62 Mt of CO2eq per year would be avoided in 2030 (European Comission, 2014).
- 180 000 directs jobs in the EU will be created by 2030 after a successful implementation, in addition to 400 000 jobs created for proper waste legislation (European Comission, 2014).
- To create a fully efficient reuse & recycling system 14 billion euros would be required only for Britain, and 108 billion euros for the entire Europe. If these quantities are compared to the 760 billion euros Europe has as revenue from being the world’s largest net importer of resources, the implementation of a functional reuse &recycling system seems feasible (McKinsey Center for Business and Environment, 2015)
- There are also funding creation from various sources to get projects related to proper management and second life of products. Examples are the EFSI & Innovation programs.
- Mobile collection/processing is one third of the cost of stationary collection/processing. Mobile would have a capacity of 115 tonnes per year and require a total cost of 1,170,000 for equipment, land and building. Stationary would have a capacity of 200,000 tonnes per year and would cost 3,000,000 for equipment, land, infrastructure and building (Bilsen et al., 2018).
- When considering recycling, the lowest re-life option, 7,940 kg CO2 per tonne aluminium are saved, which is 34% of the CO2 emissions. When production from aluminium scrap is done, it saves 97% of CO2 when compared to primary aluminium production. (Classes, 2016)

Table 14 *Facts*

15.6 CONCLUSIONS

The industry has been showing trends that point in a promising direction, namely to a more intelligent approach where information and coordination is key. It seems the way is being paved to a more responsible industry. Analysing the production of aluminium and overall construction production, numbers show steady growth. If this growth is to be made sustainably, circularity practices need to be applied. If not applied, resource scarcity will be an issue sooner than expected. As addressed here and in the initial chapters, there are barriers that have prevented the industry from taking the better solutions. Stating the facts and advantages, as well as having pilot projects implementing a RL process, are key to a circular transition. The current research provides insights into RL and ways of assessing the technical process, in the hopes of providing a solid foundation to tackle the topic from different perspectives.

16 CONCLUSIONS

Answers to the proposed questions form the Design outline are given, as well as general remarks. Further research and limitations are presented. A final reflection is also included.

16 CONCLUSIONS

16.1 INITIAL QUESTIONS

The main **research question** is:

• *RQ: How can the construction industry be ready to implement a reverse logistics for façade products and what factors need to align for a smooth transition?*

• RL practices have not reached the construction industry because of its complexity. Several authors have addressed that the various stakeholders involved, a fragmented communication, and lack coordination haven't allowed for circularity to happen (Hosseini et al., 2014). Besides, products are not designed to be recovered, and it gets even more difficult due to their stationary nature and the different lifespans found in components. In order to tackle this, some accelerators need to put in place, such as information availability (being explored by associations already, like Cirlinq by VMRG), major coordination through connecting platforms, and designing for disassembly. In this case, the framework highlights the roles in each part of the process and what are key activities to fulfil such steps. Having a methodology can help on having a clear overview of the topic and begin bringing awareness to the industry. Because the question and answers are so broad, the following sub-questions help to breakdown the answers.

The sub-questions are:

• *SRQ1: What is the relationship between circularity in the built environment and reverse logistics?*

• Circularity is understood as an economic system where material loops are closed, keeping the most value in the products at every turn. When applied to the built environment, the concept can be translated into different layers, assuming they have different lifespans and ways of separating them. Reverse logistics, as explained in Chapter 5, is what happens when these layers (systems, subsystems, components…) leave their consumption point and go back to their manufacturing points, in order to have a re-life option. This allows them to keep their values and have a good quality for a second, third or any number of uses. Four major steps are involved in reverse logistics: deconstruction, collection, inspection & sorting, and the re-life option. The detailed explanations of each of these steps is given in Chapter 11. A variation is made from the theory developed by Schultmann and Sunke, in which he describes transportation as an extra step at the end of the process (Schultmann & Sunke, 2005). For the purposes of this research, transportation was assumed to be a sub-activity that takes place in between every stage.

Figure 104 *Basic RL concept*

• *SRQ2: Which products assessments are there to evaluate their circularity potential or, in this case, their reverse logistics potential?*

• Circularity assessments have been a recent topic in the academic field. It is a complex topic to evaluate, as circularity in design mainly assesses geometry and the ways products are configured. This yields subjective results that will vary according to the expertise of the evaluator. As analysed in Chapter 8 some examples are the Disassembly Potential by Durmsevic (Durmišević, 2016), the Design for Adaptability by Geraedts (Geraedts et al., 2014) and the Morphological Matrix by Beurskens and Bakx (Beurskens & Bakx, 2015). The first two intend to give scores to physical solutions, which might result arbitrary as they are highly dependent on the criteria and expertise of the evaluator. The third is more convenient as it more descriptive and shows graphically alternatives for a circular approach. A similar method was followed to develop the criteria in this work, but in a simplified and less theoretical version. The previously mentioned assessments correspond to a qualitative assessment. Apart from these, quantitative assessment as the MCI developed by the Ellen MacArthur and Granta, and the Energy and CO2 Footprint calculation from the CES software were used to contextualize the findings in numerical indictors. They are, however, quick calculations that can only be used as rough references, due to the limitations mentioned in the Discussion Chapter (Chapter 15).

• *SRQ3: What does the current Dutch legislation state over Demolition and Construction Waste, and does it support reverse logistics?*

• Dutch legislation is one of the most forward-thinking currently regarding WM, Waste Management. It has rules that are paving the way to a more sustainable and circular future. It is also complemented with the Circular Economy Plan (Pantzar & Suljada, 2020), set for the EU. Landfill bans are a major step towards circularity, as well as incineration taxes. Removal of landfill material to other countries and accepting recycling from other countries are also good initiatives. However, there is still some legal barriers preventing reverse logistics to be implemented. For example: selective deconstruction is not necessary nor selective processes on site. These are two of the major steps to assure reverse logistics. Also, the fact the waste can only be treated by the original owner prevents others from being involved in the management of such material. A more detailed explanation on regulations and barriers can be found in chapter 9, as well as in Chapter 11, where the framework serves as a basis to situate these findings.

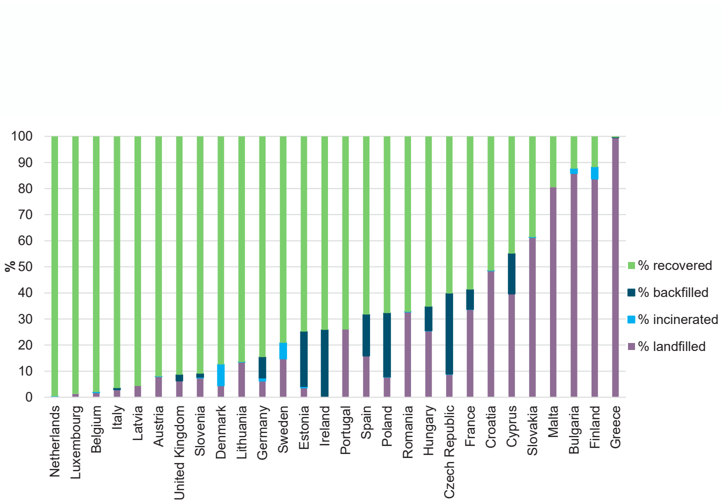


Figure 105 *Netherlands as country with best WM*

• *SRQ4: What aspects should the framework include to address the reverse logistics process in a holistic way?*

• The framework idea originated from the necessity of having a clear view of the topic, as it has not been explored in the past. Certain categories were defined to describe each step, thoroughly explained in Chapter 11 and applied in Chapter 12. The main backbone was setting the right steps in the Supply Chain after the end of service of a product was reached: deconstruction, collection, inspection & sorting, and re-life option. The next was identifying Stakeholders, or who is involved in the process, as there is still a lack of coordination between the responsible parties. After that, Key Points in every step where highlighted; they are the main activities that need to be addressed. The Application requirements enlist the variables that might differ in each scenario. They refer to the work or costs needed to conduct the activities described, left as unknowns for future research. Technology is also mentioned throughout the framework, being an important ally for RL. Finally, the Barriers are described as well, as they account for decisive factors that will determine the implementation of RL or not.

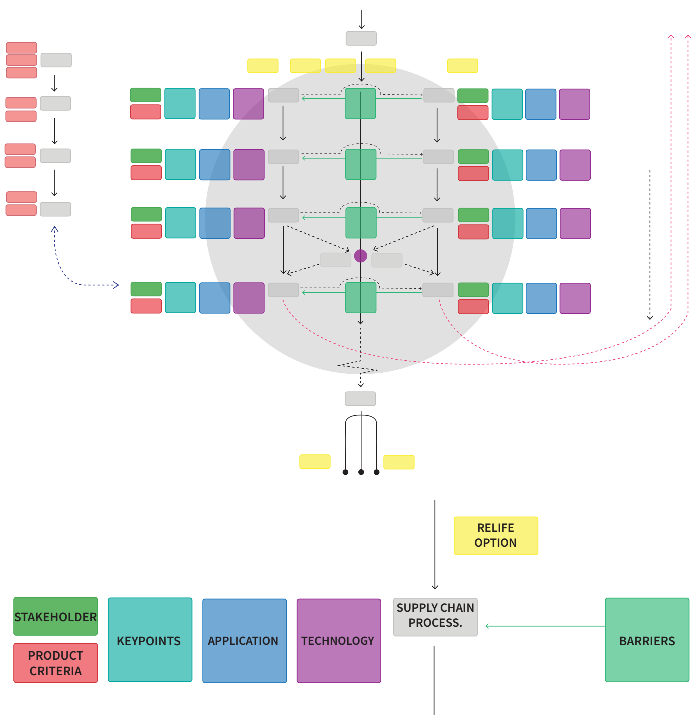


Figure 106 *Framework components*

• *SRQ5: What stages are the most critical during the reverse logistics implementation and how do geographical locations influence the process?*
• The four steps according to Schultmann are: collection, inspection and sorting, re-life option, and redistribution (Schultmann & Sunke, 2005). Chapter 11 elaborates in each of the steps. In the current research, selective deconstruction is added at the beginning as one of the fundamental steps to properly start the process. It enables an integral recovery of products and assures the value is not lost in the dismounting process. Collection here means the movement of the façade to its pick-up point, namely the horizontal and vertical translation of the product within the site. Inspection and sorting are transcendental as they will define the productive loop to which the product will be directed, and technology can give answers to this with a tag system like Cirlinq, revealing the quality of the product. The scheme and data proposed by the Material Passport can also serve as a basis to develop such information system. It was discussed if such stage should be onsite or offsite and it was concluded that RL will be more feasible if operations are to be done in situ. Finally, the re-life option takes the product and gives it the proper treatment to bring it to the desired status for a new use. It was also discussed whether this stage should be in the nearest location to the actual collection point, as it will minimize coordination efforts. In this sense, geographical location is a whole topic to discuss separately because having less distance to travel means less coordination effort, less wasted time, less C02 emissions, and less pollution overall. However, it would also imply an environmental burden to the site hosting the new re-life activities. As explained in Chapter 14, it was concluded keeping the stages closer to the locations will facilitate RL, but further analysis would be required to bring a more grounded answer.

• *SRQ6: At the end, how does the design & construction process look once a reverse logistics is applied?*
• The design process and construction will be informing themselves continuously and simultaneously. It must start with architects and engineers designing with disassembly in mind and considering standard dimensions since the beginning of the schematic design. Even though this is a radical idea proposed in the design elaboration (Chapter 13) of this work, it seems like one of the most obvious and yet effective practices to ensure compatibility between buildings and products. The client must also be aware of this new approach and ask for a design that can have a better outcome than simple demolition and landfill, or recycling at the most. When construction is conducted, a simple installation and dismounting must be envisioned, in which the least amount of effort is applied. Operations for RL must be carried on site, as much as possible. As proposed in Chapter 13, deconstruction and collection are obviously site-based activities, but also inspection and sorting can be conducted on site and even the re-life option can be thought to be performed nearby. After that, products will flow to other building, to new clients, who will repeat the process and ensure closed loops. A new market that enables products to be reused will be created, requiring less efforts to achieve circularity and eliminating/minimizing waste from the construction process.

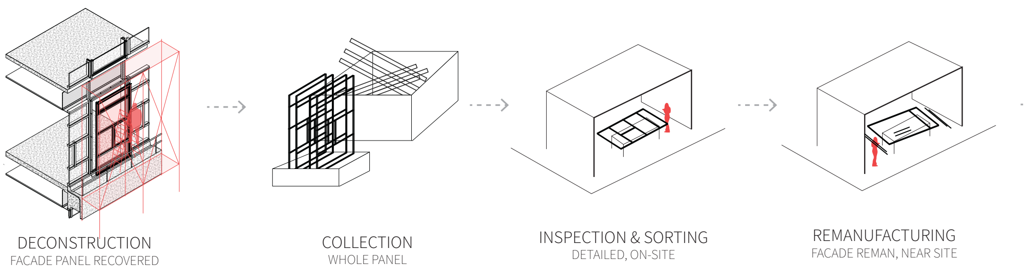


Figure 107 *RL practices complement the circular vision*

The main **design question** is:

• *DQ: How can the CITG window-wall façade panel proposed by Alkondor and TU Delft be improved to accommodate a reverse logistic process that assures a second use in a different building?*
• After analysing the current design, design ideas were generated to facilitate RL, as identified in the previous assessment chapters. The exercise in Chapter 13 consisted on putting a variety of ideas, in a brainstorm fashion, that responded to the weak links from the Application of the Framework in Chapter 12. Therefore, the CITG could be improved in many ways, not only on the product level but also on the system level. As showed in the Design Concepts, the façade could be divided in 2 to make it more manageable, a channel system could be incorporated to move the façade more effortlessly, an elevator system could be incorporated, or even the window system itself can allow for adjustable mullions. These are all ideas that would

need further elaboration to revise their feasibility. Also, on the system level, mobile stations could be incorporated into the process to speed up the process, but that also raises the question of impacts at local level. After the brainstorm, the lessons learned were enlisted, highlighting how the CITG building would not be possible to be reused due to its dimensions: they are too specific. This and other 5 key points served to inform a generic panel design, which physically reflects the major findings of the research. The following sub-questions help breaking down the answers.

The sub-questions are:

- *SDQ1: What façade criteria must be contemplated when designing and evaluating the "reverse logistics" potential of a product?*
- Design for Reverse Logistics or DfRL is a concept mentioned by Hosseini, referring to a specific way of designing that facilitates reverse logistics operations (Hosseini et al., 2015). Taking into account the existing circular theories and assessments, as well as the framework created in this work, a DfRL scheme is proposed. As explained at the end of Chapter 11, it comprises six main rules that respond to the 4 major steps of RL. The six DfRL guides are: Separation of Elements, Accessibility, Dimensions, Connections & Interfaces, Information Availability, and Adjustability. It can be noticed how some of them were already addressed in previous theories, but the objective was to bring together the most relevant terms into a simple proposition. They should be taken as guidelines to consider during the design phase to facilitate RL. In this case, they were also used to evaluate the specific CITG product and its recovery process, to identify the weak spots that can be addressed in future design decisions.

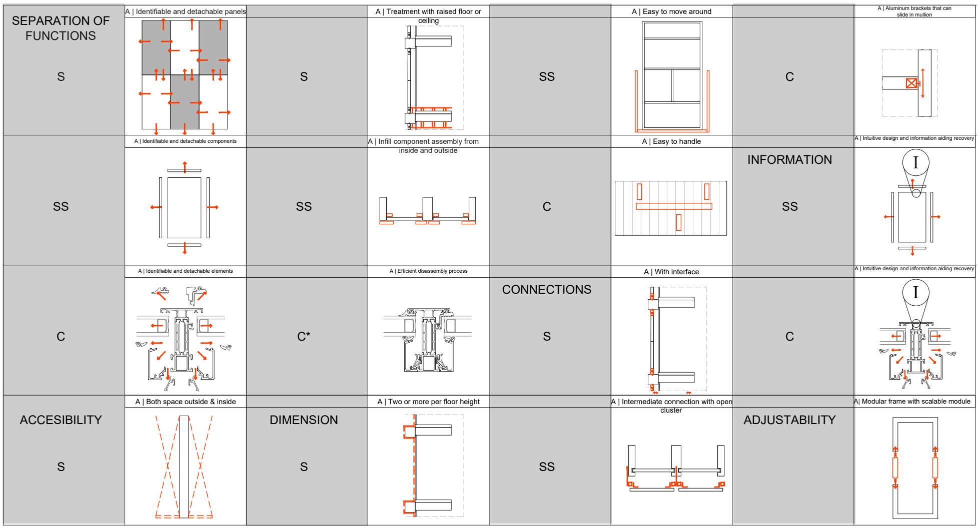


Figure 108 *DfRL synthesis*

- *SDQ2: How must the framework be formulated to organize the reverse logistics process, for it to serve as a canvas to analyse other cases?*
- The categories described in question SRQ4, which compose the information going into the designed RL framework, were thought to be showcased in two different formats. The first, shown in chapter 11, is the Descriptive Framework Format; it provides an overview of the main Stakeholders, Key points, Application requirements, Technology, and Barriers involved in the process. Each one of the information boxes gives basic terms and points to consider, according to research and the interviews conducted. In other words, it has a more theoretical approach focused on the system and process. The second format is the Graphical Framework Format, a document based on diagrams. It is focused on the product and its journey through the process, shown in Chapter 12. Diagrams are used to describe such process, making it friendlier to the user. Instead of only describing the categories mentioned above, emphasis is made on the product and, for this, the DfRL guides are applied to bring clear conclusions about the physical product being analysed. Both formats are filled in this work, however the idea is for them to act as a canvas for future application and assessment.

• *SDQ3: What design solutions (if proven necessary) can be applied to the CITG façade panel and how are they improving the overall efficiency?*

• Design solutions for the CITG building were thought in scales, as illustrated in Chapter 13. Solutions for specific stages of RL were formulated, addressing the product, and others encompassed more stages and focused on adjusting the process. Even though the panel does facilitate a smooth recovery during the deconstruction process, there are some alternatives in design that could be applied. As mentioned in the main design question, the panel could be divided in 2, changing the profile system as they both would create an additional horizontal joint. As for the system, the inspection & sorting is envisioned to be conducted on-site. This could save on coordination and transportation costs. Taking it even further, remanufacturing or any re-life option could also be performed near the site, which would simplify the whole process. Evaluation on local impacts due to these activities would need to be considered. After the brainstorm, the lessons learned were enlisted, highlighting how the CITG building would not be possible to be reused due to its dimensions: they are too specific. At the end, the main solutions (interface inclusion, smaller panel dimensions, pertinent information, attractive products, light standardization, and concentration of activities) are reflected in a series of panels that originate from a base module. The 1.20 m grid system is used to formulate the design and then explorations in the interfaces and infills are made. Variations in the elements answer to some of the solutions previously mentioned: interfaces that make recovery easier, expressive interfaces that make panels more attractive and functional, lights that reveal important information about the façade system, additional balconies that would bring more versatility, among others.

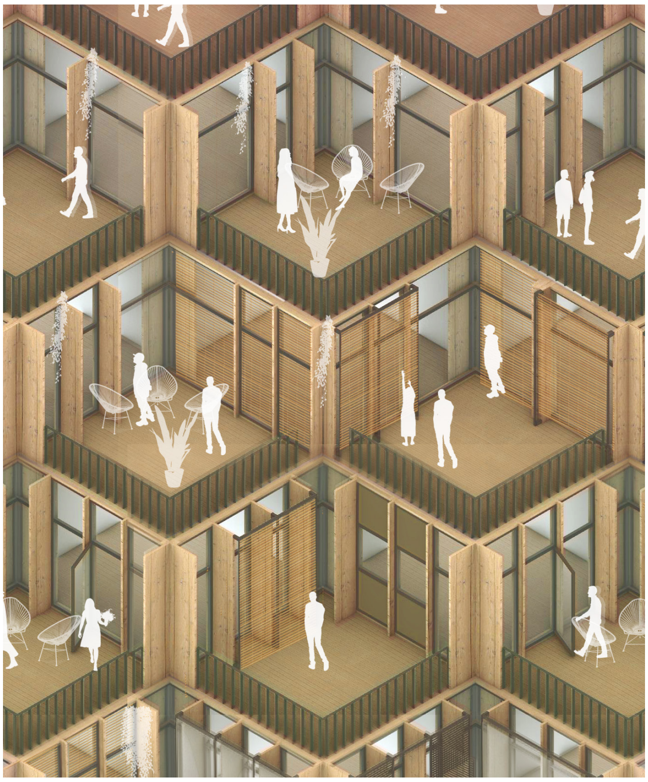


Figure 109 *Design exploration*

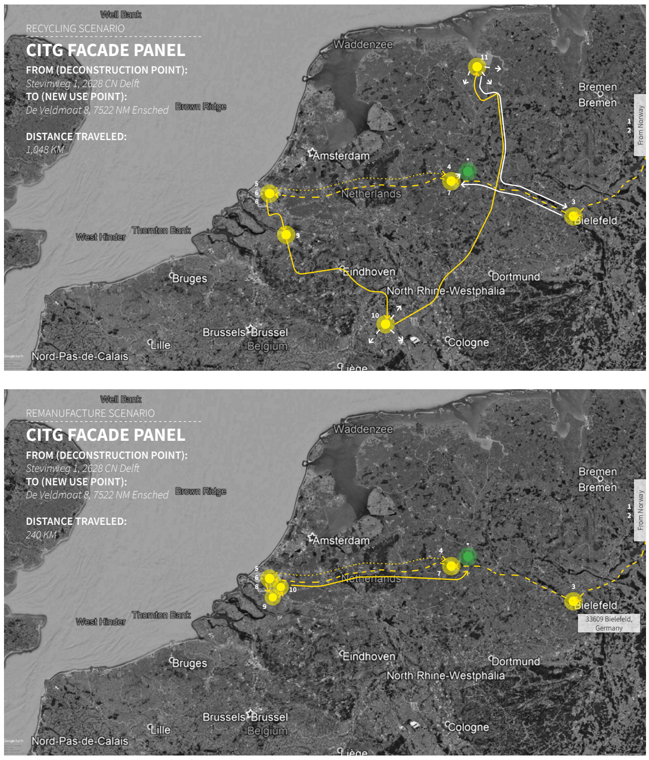


Figure 110 *Geographical assessment*

• *SDQ4: How does geographical locations inform the reverse logistics process?*

• If a normal recycling process is mapped geographically, the flow of a product seems to encompass a large area. From pure logic, it is known a product, as it is cut down and turned into pieces, might end up in any recycling facility to be melted and extruded into its next destination. This means transportation and considerable energy is going into a product to break it down and to manufacture it again into a usable new product. Remanufacturing, in the other hand, requires less transport and hopefully a more localized sorting facility, as well as re-life location. This translates into less distances to be travelled and less energy spent on the product. From the visualizations of the CITG building, which were hypothetical scenarios, recycling requires almost 1000 km more than remanufacturing. Even if the exercise doesn't portray reality, it shows how such differences could look like. Taken even further, if mobile stations were to be applied, distances can decrease even more and simplify coordination efforts. Impact on the environment would still need to be assessed, as mobile stations would pose an influence on its surroundings. In the Discussion Chapter, a preliminary quantitative assessment is made, in which recycling, remanufacturing and reusing are compared. It is concluded there are considerable differences in their energy and CO2 footprints. However, it is not conclusive if transportation represents a major portion of the impact of a product. From the analysis, transportation impact is almost not noticeable when compared to the Material or Dispose phases, but it most be highlighted a short route was used to simulate the results. Further research might reveal different results.

- *SDQ5: How can the CITG scenario and proposed solutions be extrapolated to other cases, drawing the bigger picture and the steps that can be further taken?*
- The CITG case served as a starting point to identify some of the weak links to address in similar cases. Ideas on dimensioning and standardization were evidenced throughout the facade criteria evaluation. This gave idea of going back into the modularization of a building, specifically the idea of system building. Making sure a universal understanding and design is thought since the beginning, a market in itself could be developed and products could flow between buildings. Developing on these ideas, office buildings could respond to design guidelines that facilitate circularity, without compromising their image. Even if aesthetics was not the focal point of the current research, further exploration can reveal new concepts that defy the idea of standard buildings, making them attractive to the market. By appealing to people, and therefore clients, such buildings can assure a future and a demand.

- *SDQ6: How does the future vision look like for reverse logistics and the closing of resource loops?*
- As explained in Chapter 15, it would all start with the client's request, a client aware of the products available in the market (e.g. panels being left unused due to certain reason) and having no prejudgements towards them. Reuse products are as good as new ones, is the mindset to be encouraged. When working along the architects and engineers, the awareness of the client will allow the architect to design with those products in mind, which will have standard dimensions, facilitating the compatibility between buildings. This would mean buildings being designed and constructed in consistent ways, assuring a proper reuse of components. A few centimetres specified in the design are the difference between a panel that can be reused and a panel that cannot. At the same time, managers will think ahead of the Reverse Logistics process: mobile stations shall be used as well as he maximum amount of operations on site. This is a paradigm and contraposes the current idea of having the most operations off-site. But a clear distinction has to be made: for forward logistics, off-site assembly is the most recommendable always; for reverse logistics, on-site operations would facilitate the whole process, saving time and costs for coordination and transportation. Finally, legislation must also align with circular strategies on products and, most importantly, society must shift their perception and accept the new way of constructing.

Figure 111 *Future vision*

16.2 CONCLUSIONS

From the literature research and overall findings throughout the process, it was found the authors addressing reverse logistics are minimal. Circularity is a trending topic currently, but research focused on reverse logistics and how to apply it in the construction industry is rare. Some authors like Hosseini do mention in their articles how the several variables and stakeholders involved in construction have made it difficult and even an irrelevant topic to cover. Starting the conversation is the first step towards a future application.

When analysing the legal situation in present context, some interesting findings were obtained: there is no distinction when recovery waste is documented. It well can be recycling or reusing, but there is no specific data giving a notion of current practices. Recycling is understood to be the most common practice, as it is the most convenient and the only way in which products allow to be treated. Even though Europe in general is advanced in terms of waste management, there are still big steps to be taken if circularity is to be achieved. The goals set for 2050 are ambitious, but they are the least to lessen the environmental burden currently produced from the linear economy.

From the design exercise, the framework creation intends to be a valuable addition to the literature in Reverse Logistics when applied to the Built Environment. It being a canvas to be filled with expert views and experiences is the most valuable outcome. Applying the framework to the specific CITG case helped on understanding the framework itself, as well as the specific recovery process of the CITG. After having the assessments and the identification of the weak links, several conceptual ideas in the form of a brainstorm leaves spaces for future development. Ideas concerning only the product were envisioned, complementing with system-oriented solutions that would render a more efficient process. Such solutions start departing from the designer's responsibility and shift towards policy-makers and managers. At the end, the design exercise reflects the most relevant lessons learned into a generic panel, based on a modular system. The design is highly conceptual but invites the reader to think of new ideas and challenge their own thinking of facades. By stating the obvious, like relying on standard dimensions and sharing of information, the message is better transmitted. All of the research and findings point to the necessity of a transition: shift the current practices, economies, and ways of designing, to result in a construction industry that allows for reused products having more than one life.

16.3 LIMITATIONS

Reverse Logistics is a topic taking its first steps in the construction industry. It being part of circularity, will be explored further in the near future, especially in an era where digitalization is predominant. Due to time constraints, having a deeper understanding of the various topics surrounding RL was not possible. Topics like supply chain process, system-thinking, transportation optimization and stakeholder coordination might be among the relevant topics. The overview developed gives opportunities for others to study and analyse the unknowns highlighted throughout the research. The most relevant variables to focus-on are highlighted in the Descriptive Assessment Framework, in the Application Information Boxes. They are quantifiable factors that would be good points of reference when analysing the different re-life scenarios. For instance, defining how much more expensive is to deconstruct than to demolish or how much preparation it needs is highly relevant. Even though some of the mentioned aspects are more abstract than others, estimations are enough to serve as initial indicators.

Besides, experimenting with physical models was not possible: first, because of the time constraint and the extensive research work, and second because of the physical confinement everyone was subject of. Having physical models would take the research to the next level, by relating the actual design of a product and how it is assembled with the reverse logistics process behind. Having a partnering company would be useful to build such model. In the case of the current research, VMRG was more information-oriented, which enriched the theoretical research. A façade supplier would be the best match for the model exploration.

Finally, having the current circumstances (referring to the Corona outbreak in 2020), the validation workshops in which the framework would be put to the test were not conducted. This is considered a major step of the process: to have direct input from industry actors, who ultimately are the intended users . Their insights might confirm the thematic organization and the ways in which the ideas can contribute to an overall theory.

16.4 FURTHER EXPLORATION

As stated in the first chapter, the current research offers a more longitudinal than transversal vision of the topic. The research gave an overview of the Reverse Logistics when applied to facades, addressing the various stages and relevant points to consider. It is due to this broadness that several of the points mentioned could be taken into different research projects and be further developed. The industry now needs hard data and evidence to apply Reverse Logistics in their supply chain. An initial Quantitative Assessment was performed in the last chapters, to suggest a way of comparing different scenarios. Exploring new calculation methods that can take into account the subtleties of each scenario would be relevant and highly useful for the industry. Even the Qualitative Assessment, substantially explored in the current research, is also open to transformation and feedback from other perspectives. The format should be developed to be the friendliest and most understandable to be used in the practical world.

As highlighted in various occasions, money is one of the biggest variables and barriers. Understanding the differences in cost and how a façade being reused or remanufactured can be treated so it is still a convenient product to acquire, is vital. Analysis on financial feasibility is one of the most urgent aspects to explore, as showing the potential saving would directly speak to investors and clients. Also, calculating the environmental gains when reusing as well as the burdens that recycling represents is key to put forward the idea of closing loops more efficiently. Energy and carbon dioxide footprint are two of the indicators that can be used to bring clear references of environmental impact.

Finally, physical modelling of the developed concepts is also a subject to address, as having physical products always helps on concretizing theoretical concepts. The models should not only focus on panels that can be disassembled, but also interfaces that enable interchangeability. It is in the connections and intermediaries that recovery is assured, and such topic has not been addressed enough. Focus on who must be in charge of the coordination and creation of such interfaces must also be defined, as confusion is common in current practice when it comes to their responsibility.

16.5 FINAL REFLECTION

RELATIONSHIP RESEARCH-DESIGN

The reverse logistics topic in the construction industry has the particularity of being a relatively new subject in its first steps of exploration. Given this, the research part of the current thesis project has been predominant. The intention since the beginning is to use such material and apply it in a tangible methodology and eventual design exercise, as this has not been conducted in most of the previous research works. From the building technologist perspective, design can greatly facilitate the implementation of reverse logistics for facades. It is one step that makes circularity more achievable. It is my role to link the findings made in the first stages to the design dimension for a proper illustration of the theory.

I have realized during the research process that design is not the only barrier preventing a proper implementation of reverse logistics, it is mostly the economic and legal aspects that block the system. This is also a good reason for the thesis to include the logistics part, in which such aspects are highlighted, even if my area of studies does not address them. Just be laying everything on the table, a discussion can be encouraged, allowing other experts to bring their knowledge and experience. The following steps are directed to start this process, having interviews with façade industry actors that inform the overall topic.

RELATIONSHIP TOPIC-TRACKS

Even if not immediately evident, Façade Reverse Logistics is directly intertwined with the Building Technology Master Track a sit responds to one of the most urgent needs in the construction industry: less resource consumption. The built environment is known for consuming 40% of the resources on earth due to the linear economy model being followed since the industrial revolution. As comfortable and easy as it is to construct and manufacture our products in such ways, they are the most unsustainable and irresponsible. They are leading the planet to a delicate state, a point of no return where global warming and pollution would not allow to follow the common consumerist lifestyle we are used to have. It is logic then to pose the question from the Building Technology discipline, how can our processes and design have a less negative impact in the environment? Not even that, but how can we have no impact or even a positive one when building? By applying circularity strategies, the way we design and construct would allow to close loops and use the resources to the fullest, without having any waste or consuming unnecessary energy in the processes.

There is also the link "reverse logistics" has with the master program, Circular Built Environment (CBE). Circularity is a new economic model that prevents having any waste, by introducing a cradle-to-cradle approach to the current flows. Instead of having a normal forward logistics, a reverse one must be implemented to close such productive loops. The topic focuses on this specific part: what needs to happen during this stage and what strategies must be implemented to avoid products turning into waste or a downcycle process.

METHODS & PROCESS

To address this particular research, an extensive literature research was conducted as well as a series of interviews with experts from the façade industry. They gave input on how RL is perceived and how feasible it is to be applied in real practice. Such method was highly effective, as the thesis is a "one of its kind" — no previous examples were found that could serve as starting point— and it was necessary to set those foundations. The way to reflect the findings generated the idea of the framework creation. This marked the start of the design phase. Even if it is unconventional for a creative exercise to consist on more methodology creation, the proposed RL framework paved the way for a deeper understanding of the topic and its context. Such product was complemented with the proposal of the DfRL (Design for Reverse Logistics) criteria, a concept that still needs to be explored and put to the test. Both formats were used in the Application phase to evaluate a specific product. They proved to be of good use and gave basic notions on the considerations for RL implementation. Finally, the Design Phase turned the lessons learned from the previous chapters into conceptual ideas. Brainstorming and discussion with the mentors indicated that developing ideas for the specific product being addressed was less useful than if the exercise transferred the knowledge to bigger contexts. The final design speculates on the office of the future, having RL practices at its core. It translates— at least from the designer's point of view— the criteria and requirements RL suggests.

All of the process and methods employed in the research worked well and complemented each other to result in a coherent storyline. It must be noted, however, the initial intention was to validate the results— especially the framework— in the scheduled workshops in June. The current situation (referring to the Corona pandemic) didn't allow for those workshops to happen, part of the Façade Relog event that TU Delft is organizing along with other institutions and companies. The goal is to generate knowledge and awareness in the industry to bring Reverse Logistics into the picture. The project will run for two years, and even if it was not possible to apply the framework and validate it with experts, it will be valuable to use it in the future to have input form others. This will enhance the developed methodology and make it a more informed tool.

RELATIONSHIP SOCIAL AND BROADER CONTEXT

Reverse logistics is one of the most relevant construction topics when it comes to the social context. It isn't without the cooperation of society that a full implementation is possible, and if it is, it will benefit the environment and society equally. Apart from the benefits highlighted in the literature research, having a fully circular built environment will ensure a more responsible practice where society's future is respected. Professionally, the topic is relevant as it is still to be applied into real practice, and it is a top priority given the current situation of material scarcity.

Having in mind an eventual transferable model to the professional world, the current project develops a framework that can be filled with information from other cases or products. It is versatile as it allows any feedback coming from different experts inside or outside the industry. When having talks with the assigned mentors, a high value was given to the development of such framework, as it organizes the topic in a simple way and serves as canvas for future explorations and findings.

ISSUES ENCOUNTERED

Due to the recent exploration of the topics, the industry and governments are still having questions on how to implement reverse logistics, and if it even makes sense to do so. The main dilemma encountered was the lack of initiative taken by governments in their legislation or construction application form building offices. Because the current linear model is so comfortable, convenient, and especially economic, almost no one questions the way of doing things. The rest is considered an impassable challenge that simply cannot be faced. General education of society is also a major barrier for a proper implementation: no one wants used products; they are thought to be of less quality. Supply must be met by a corresponding demand: if remanufactured/reused products are to be produced, a market must also want to acquire them and use for a new life. Hopefully, at the end of the research, the physical design of the façade can reflect so well the reverse logistics requirements, that it can leave more than one wondering of its application in the real industry. Hopefully, the developed methodology can serve for future development of the topic and new research to come.

17 BIBLIOGRAPHY & 18 APPENDIX

17 BIBLIOGRAPHY

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Personal Communication with Stingo Huurdeman. Schuco International. April 3, 2020.
Personal Communication(2) with Joep Römgens. Schuco International. April 30, 2020.

18 APPENDIX

I. CONSTRUCTION PROCESS (FORWARD & REVERSE)

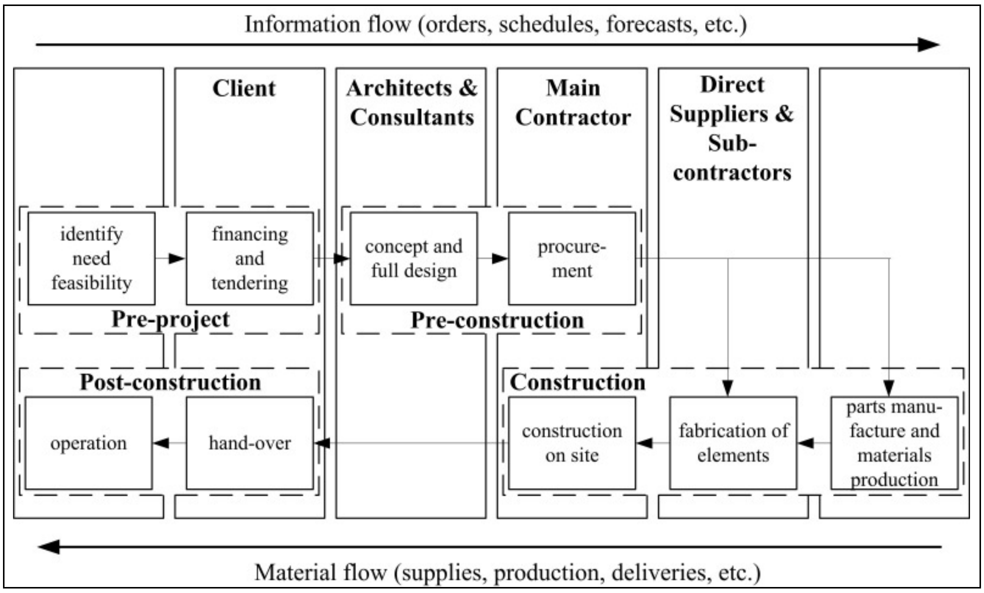


Figure 1. Forward construction supply chain (Lowe & Leiringer 2006).

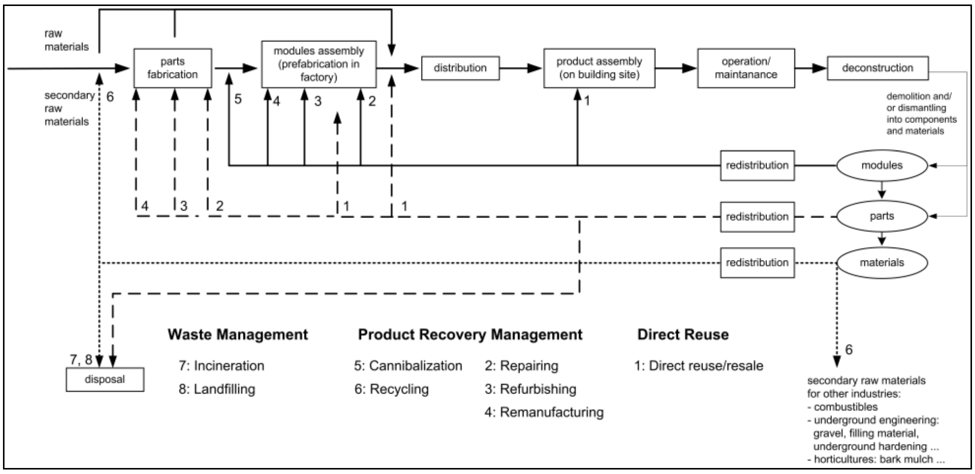


Figure 2. Recovery options for C&D waste (Schultmann & Sunke 2006).

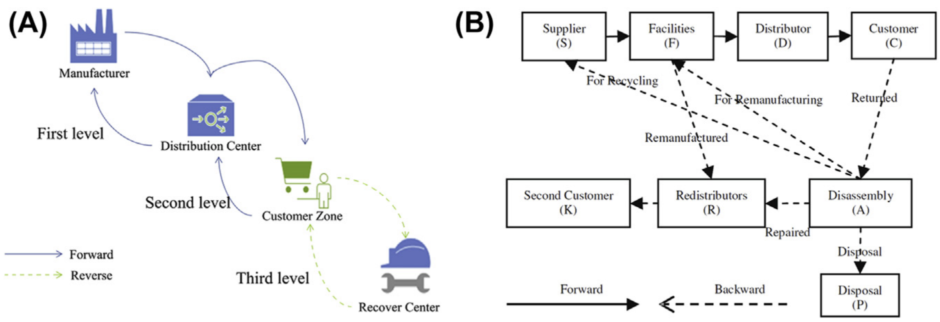


Figure 1.4 Forward–reverse logistics network: (A) three-leveled [143] and (B) multileveled configurations [144].

II. ADVANTAGES OF RL

Table 1. Advantages of RL for the construction context in previous studies.

Author (year)	Economic advantages				Social advantages				Environmental advantages			
	Eco1	Eco2	Eco3	Eco4	Soc1	Soc2	Soc3	Soc4	Env1	Env2	Env3	Env4*
Thormark (2000)									×	×	×	
NAHB (2001)							×		×	×	×	
Sassi (2002)									×	×	×	
Chini and Bruening (2003)		×				×	×		×	×	×	
Shakantu et al. (2003)	×			×				×				
Guy and Gibeau (2003)	×				×		×		×	×		
Greer (2004)		×					×					
Dantata et al. (2005)		×	×		×				×	×	×	
Addis (2006b)			×			×			×	×	×	×
Guy et al. (2006)			×	×					×	×	×	
Leigh and Patterson (2006)		×	×			×	×	×	×	×	×	
Mulder et al. (2007)	×								×	×	×	×
Schultmann and Sunke (2007a)									×	×	×	
Smith et al. (2007)		×					×		×	×	×	
Aidonis et al. (2008)		×	×			×	×		×	×	×	×
Gorgolewski (2008)	×					×	×	×	×	×	×	
Kralj and Markič (2008)				×				×	×	×	×	
Laefer and Manke (2008)	×		×	×				×	×	×	×	
Sassi (2008)	×							×	×	×	×	
Shakantu et al. (2008)				×					×	×	×	
da Rocha and Sattler (2009)									×	×	×	
Roussat et al. (2009)							×		×	×	×	
Denhart (2010)		×					×		×	×	×	
Sinha et al. (2010)									×	×	×	
Coelho and de Brito (2011)									×	×	×	
Hiete et al. (2011)			×									
Saghafi and Teshnizi (2011)	×					×						
Densley Tingley and Davison (2012)									×	×	×	
Shakantu et al. (2012)	×			×					×	×	×	
Shakantu and Emuze (2012)				×					×	×	×	
Guy (2014)			×									
Jaillon and Poon (2014)									×	×	×	
Storey and Pedersen (2014)		×	×									
Notes	**Eco1**: Cost saving owing to less use of material/energy				**Soc1**: Less impact on neighbours (sites with limited access in urban areas)				**Env1**: Generating less waste			
	Eco2: Revenue made through selling recovered items				**Soc2**: Improving the image and reputation of the businesses involved in RL				**Env2**: Using less raw materials in the production process			
	Eco3: Lower costs of waste disposal				**Soc3**: Generating large number of jobs				**Env3**: Less CO_2 emissions through less energy consumption for producing or transport of goods			
	Eco4: Lower costs of inventory, maintenance, transportation and procurement of new products				**Soc4**: Less pollution in terms of visual, soil, water, weather, sound, etc.				**Env4**: Meeting legislative requirements			

HOSSEINI ET AL. (2015)

III. BARRIERS TO RL IN THE CONSTRUCTION CONTEXT

Table 2. Barriers to RL in the construction context.

	Industry-specific barriers												Organisational barriers							
Authors (year)	Ind1	Ind2	Ind3	Ind4	Ind5	Ind6	Ind7	Ind8	Ind9	Ind10	Ind11	Ind12	Org1	Org2	Org3	Org4	Org5	Org6	Org7	Org8
Kibert et al. (2000)	×						×				×	×								
Catalli and Williams (2001)		×	×										×			×				×
Crowther (2001)	×										×									
Crowther (2002)	×																			
O'Brien et al. (2004)						×														
Sassi (2002)	×																			
Chen et al. (2003)														×	×			×		
Chini and Bruening (2003)	×	×	×		×					×			×		×				×	×
Pulaski et al. (2003)													×							
Greer (2004)		×	×		×								×							
Sassi (2004)	×	×			×					×	×		×	×		×		×	×	
Dantata et al. (2005)		×											×	×						
Pun et al. (2005)				×	×	×		×									×			
Addis (2006b)	×									×			×			×				×
Addis (2006a)		×				×	×			×						×				
Guy et al. (2006)						×	×													
Leigh and Patterson (2006)		×			×					×			×	×	×	×				
Schultmann and Sunke (2007a)							×				×	×	×					×	×	
Schultmann and Sunke (2007b)				×	×	×	×	×			×		×						×	
Smith et al. (2007)	×			×																
Gorgolewski (2008)	×	×						×				×	×				×			
Sassi (2008)		×	×												×					
Crowther (2009)	×																			
da Rocha and Sattler (2009)											×									×
Durmisevic and Yeang (2009)											×									
Nordby et al. (2009)			×										×							
Denhart (2010)			×													×			×	×
Razaz (2010)			×				×													
Sinha et al. (2010)				×	×															
Coelho and de Brito (2011)								×			×		×	×			×		×	
Hiete et al. (2011)					×															
Densley Tingley and Davison (2012)	×																			
Kibert (2012)	×					×	×				×	×								
Shakantu and Emuze (2012)						×														
Srour et al. (2012)		×						×						×		×			×	×
Vaughan (2013)		×			×															
Anggadjaja (2014)			×												×	×				×
Durmisevic and Binnemars (2014)	×															×				
Earle et al. (2014)													×							
Jaillon and Poon (2014)	×							×									×			
Kuehlen et al. (2014)	×																		×	
Nakajima (2014)	×															×				
Nakajima and Russell (2014)	×				×											×				

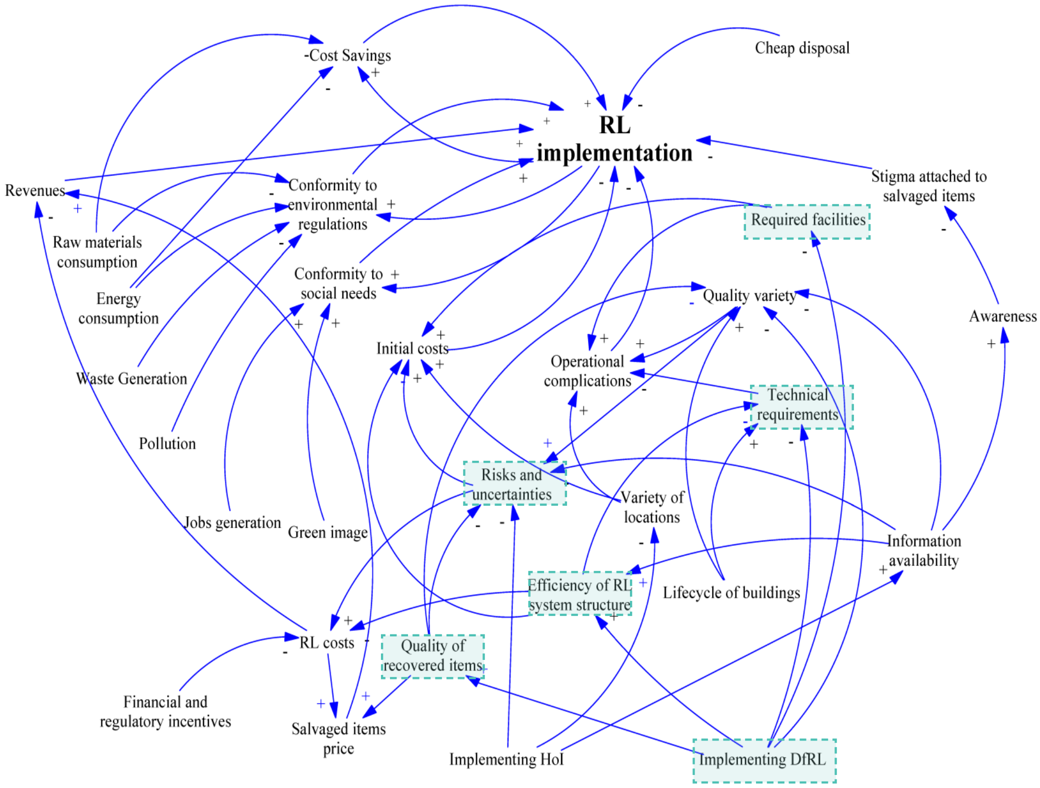
Notes

Ind1: Buildings are not designed for easy dismantling
Ind2: Tight scheduling of construction projects
Ind3: Lack of standards, codes and guidelines
Ind4: Wide variety of origin points in RL system
Ind5: Lack of recovery facilities, infrastructure, technology and markets
Ind6: Large number of parties and decision makers involved (mostly small and medium-sized enterprises (SMEs)
Ind7: Long lifecycle of buildings
Ind8: Immobility of buildings and huge size of building products
Ind9: Linear, sequential relationship between the design and construction phase
Ind10: Lack of awareness in the construction industry
Ind11: Vast variety in quality of extracted materials from buildings
Ind12: Uniqueness of each building for deconstruction

Org1: Excessive effort and time necessary
Org2: Higher initial costs
Org3: Low cost for disposal of materials
Org4: Lack of support from legislations and regulations
Org5: Necessity of having suitable storage area on-site
Org6: Cultural perspectives against RL
Org7: Existence of hazardous substances in buildings
Org8: Consumer preferences, taste, and perceptions

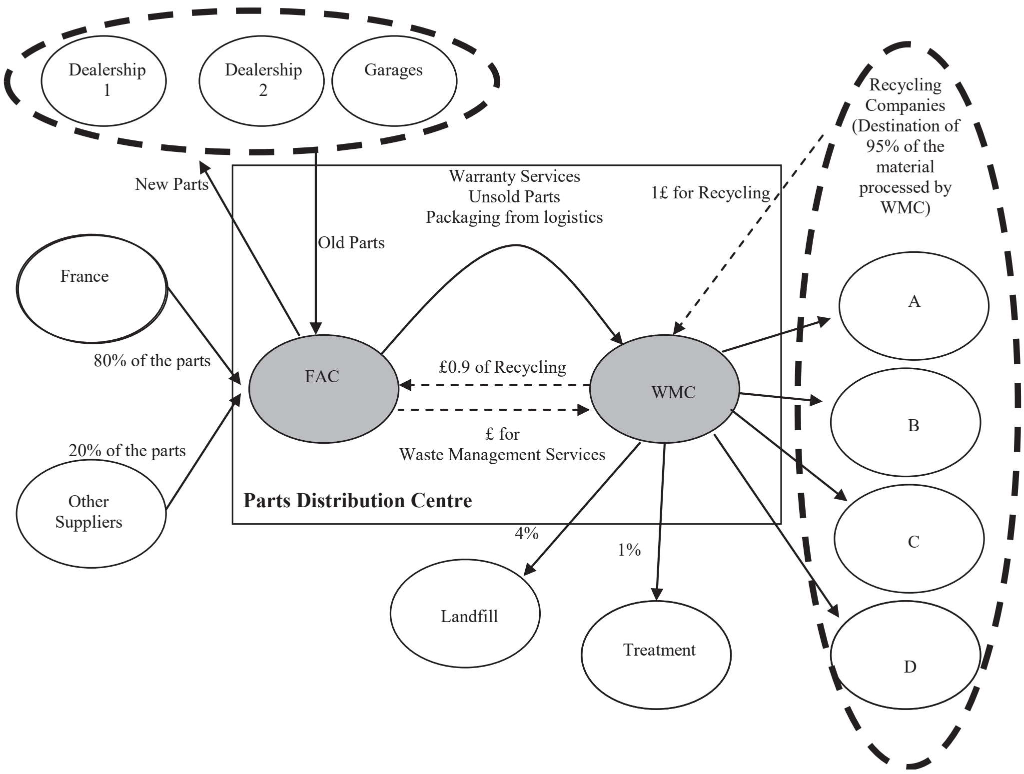
HOSSEINI ET AL. (2015)

IV. CASUAL LOOP DIAGRAM, MAJOR FACTORS FOR RL

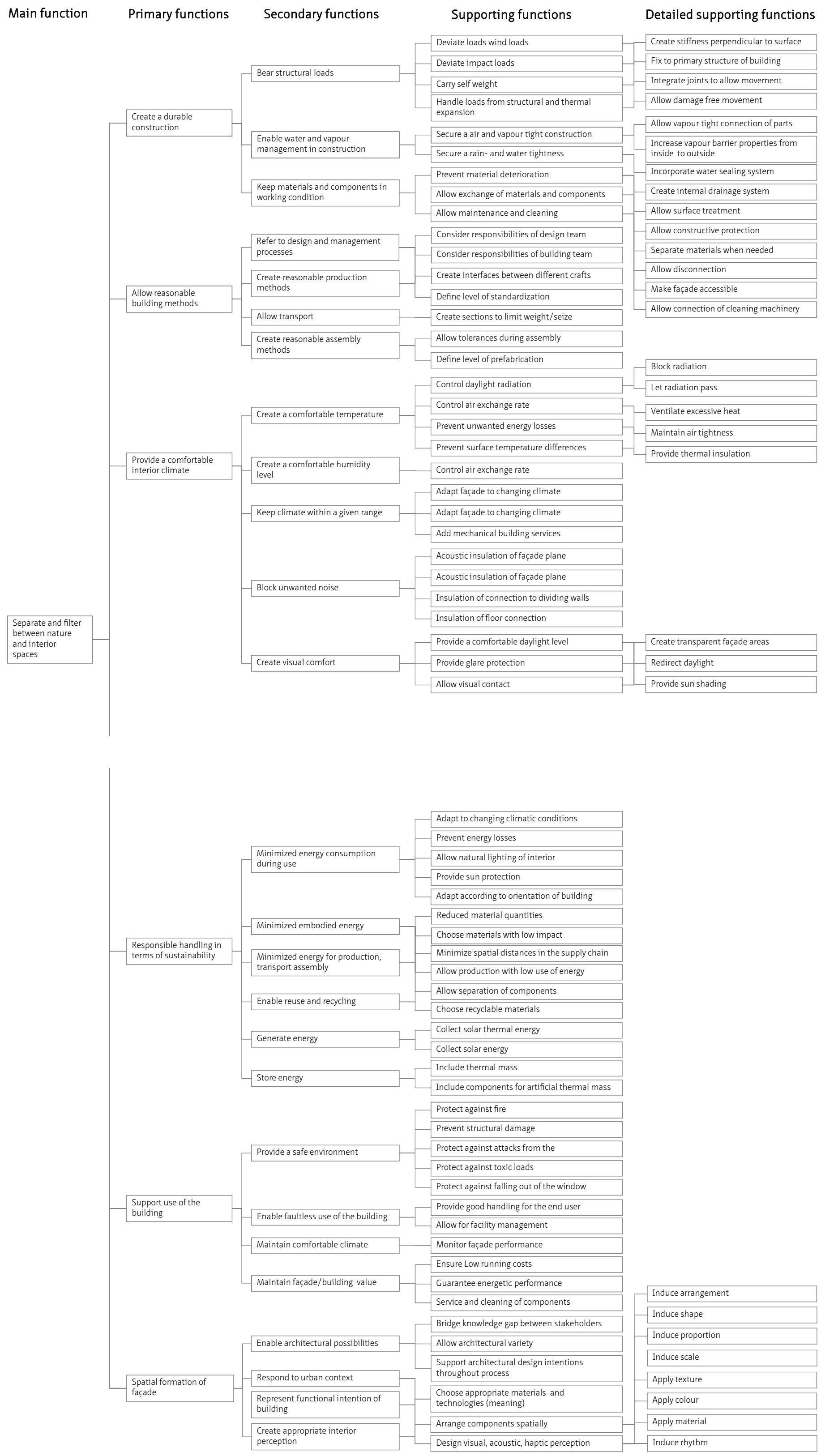


HOSSEINI ET AL. (2015)

V. REVERSE LOGISTICS IN AUTOMOTIVE INDUSTRY

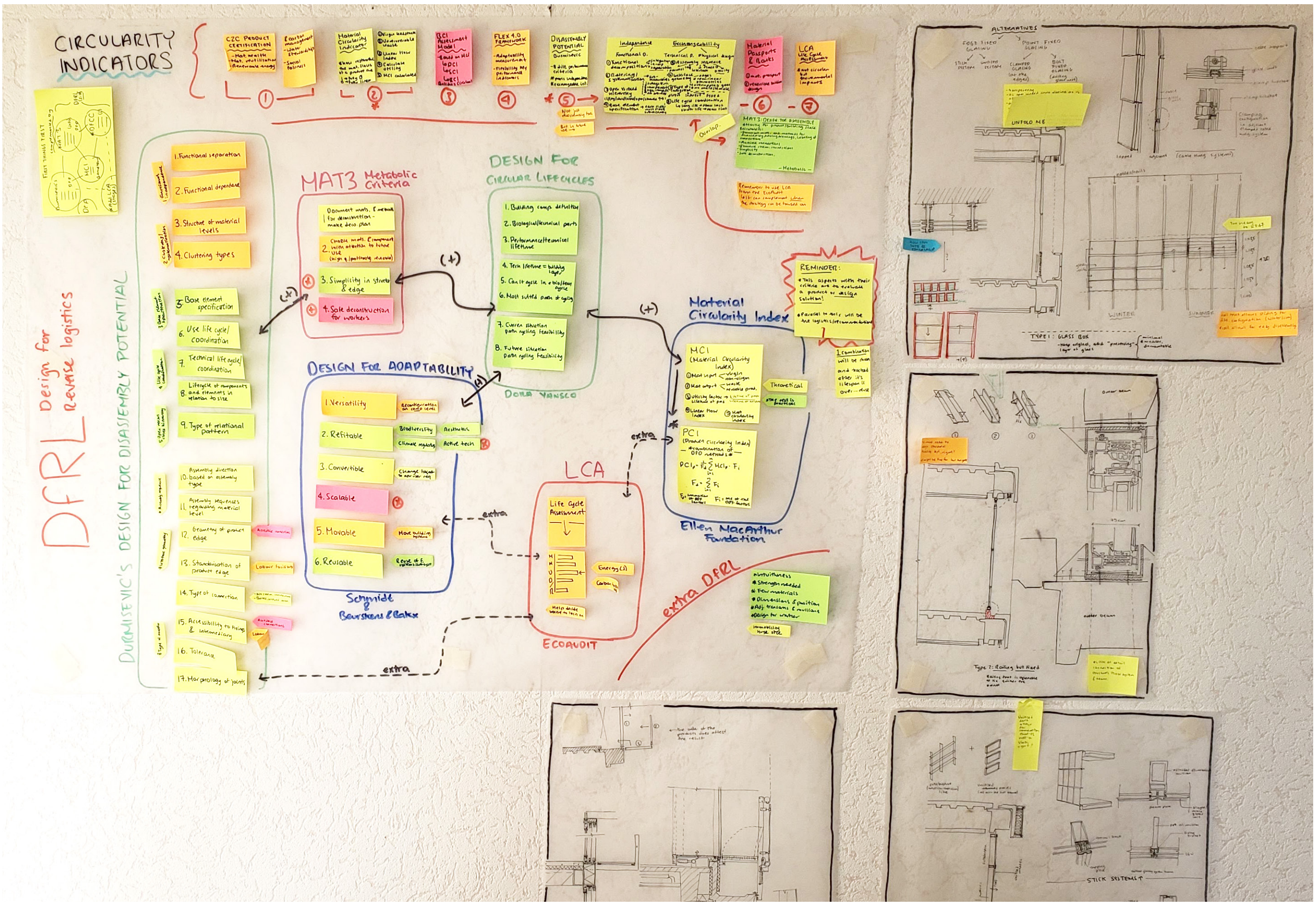


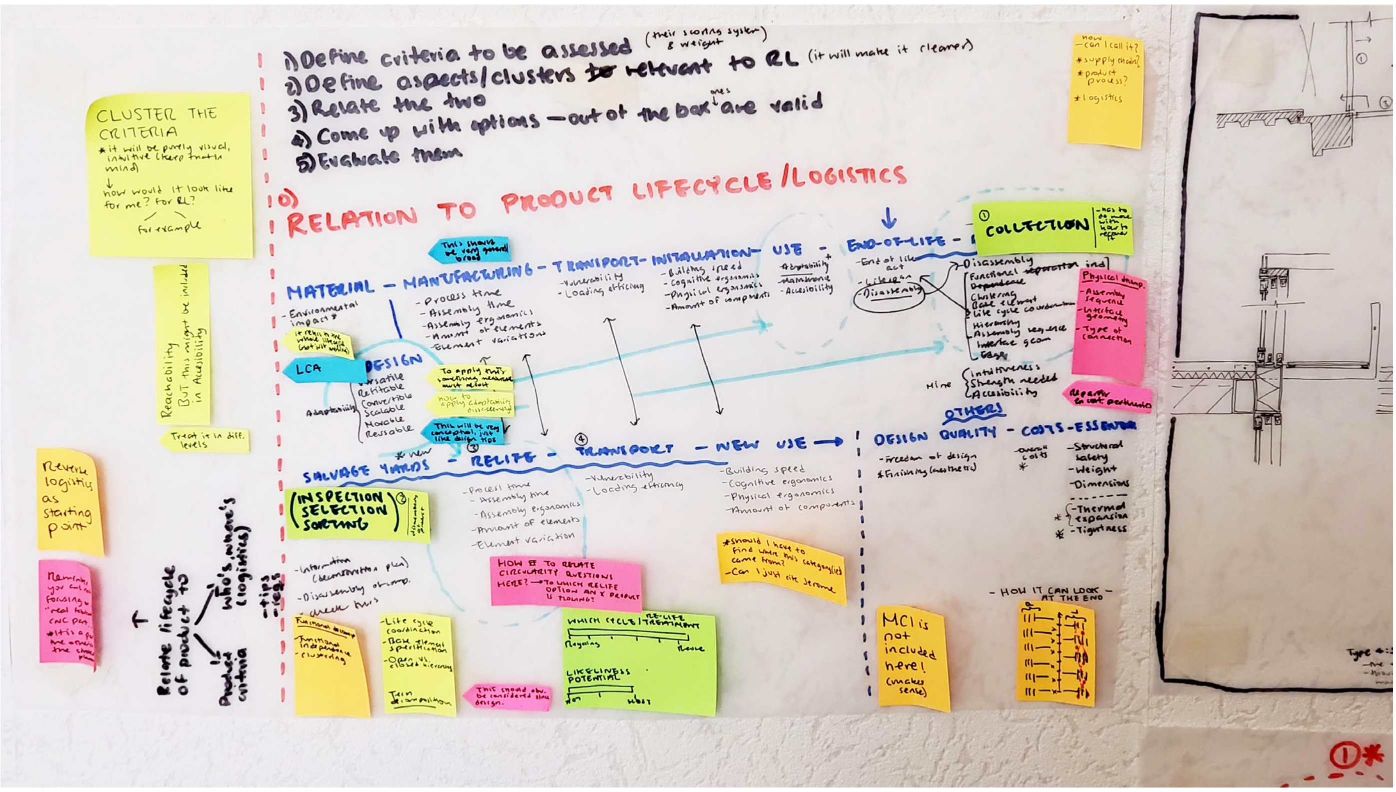
VI. FACADE FUNCTIONS



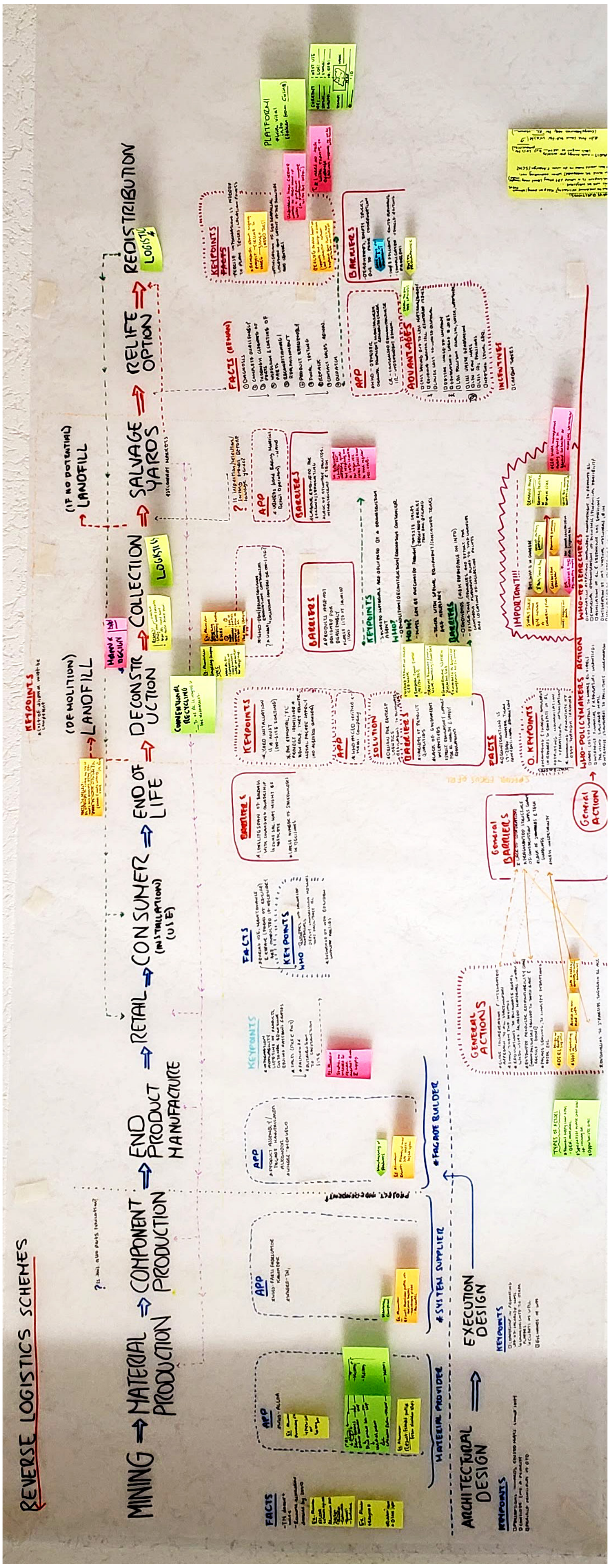
KNAACK, KLEIN ET AL. (2014)

VII. FRAMEWORK DRAFTS

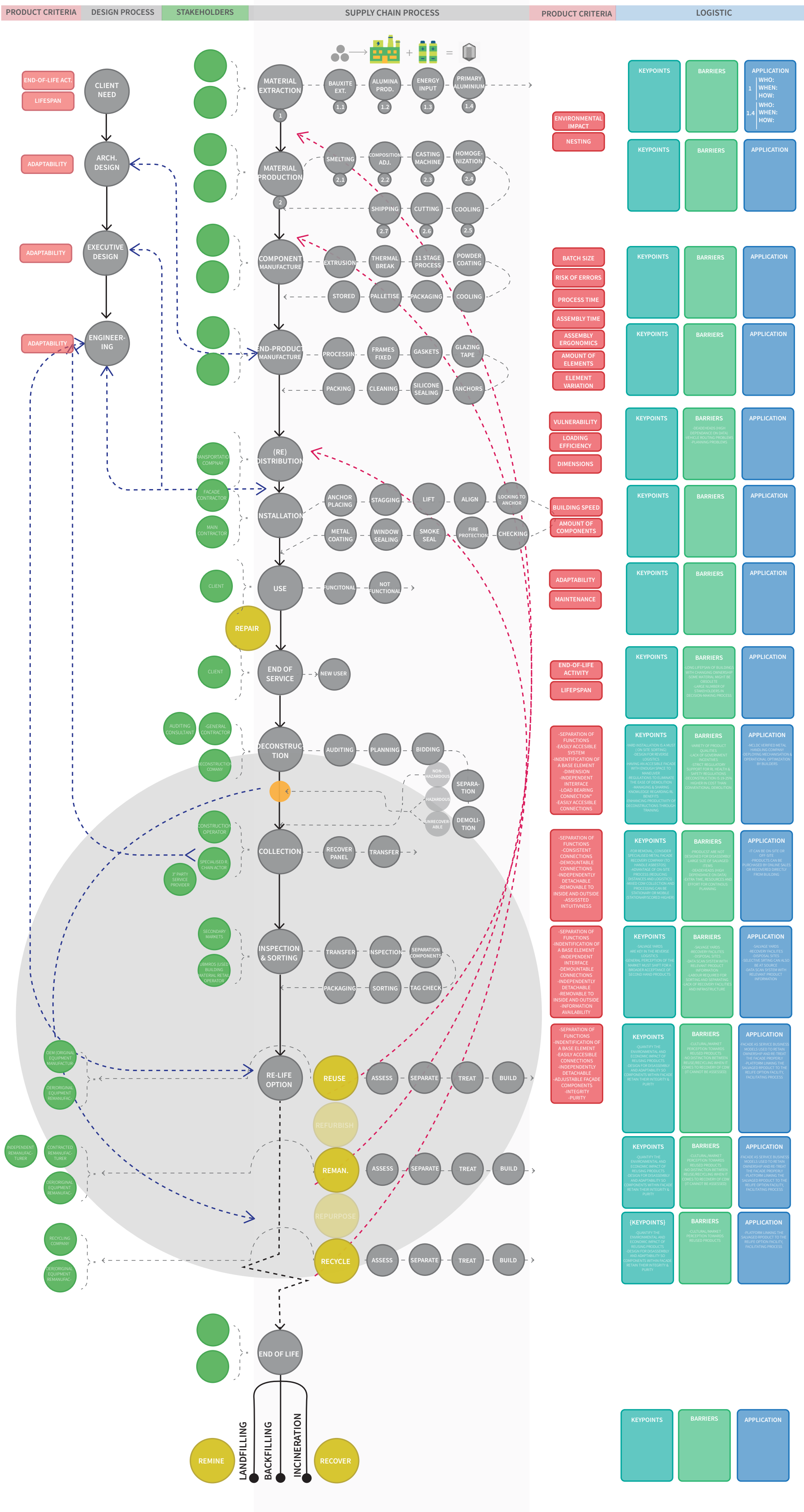




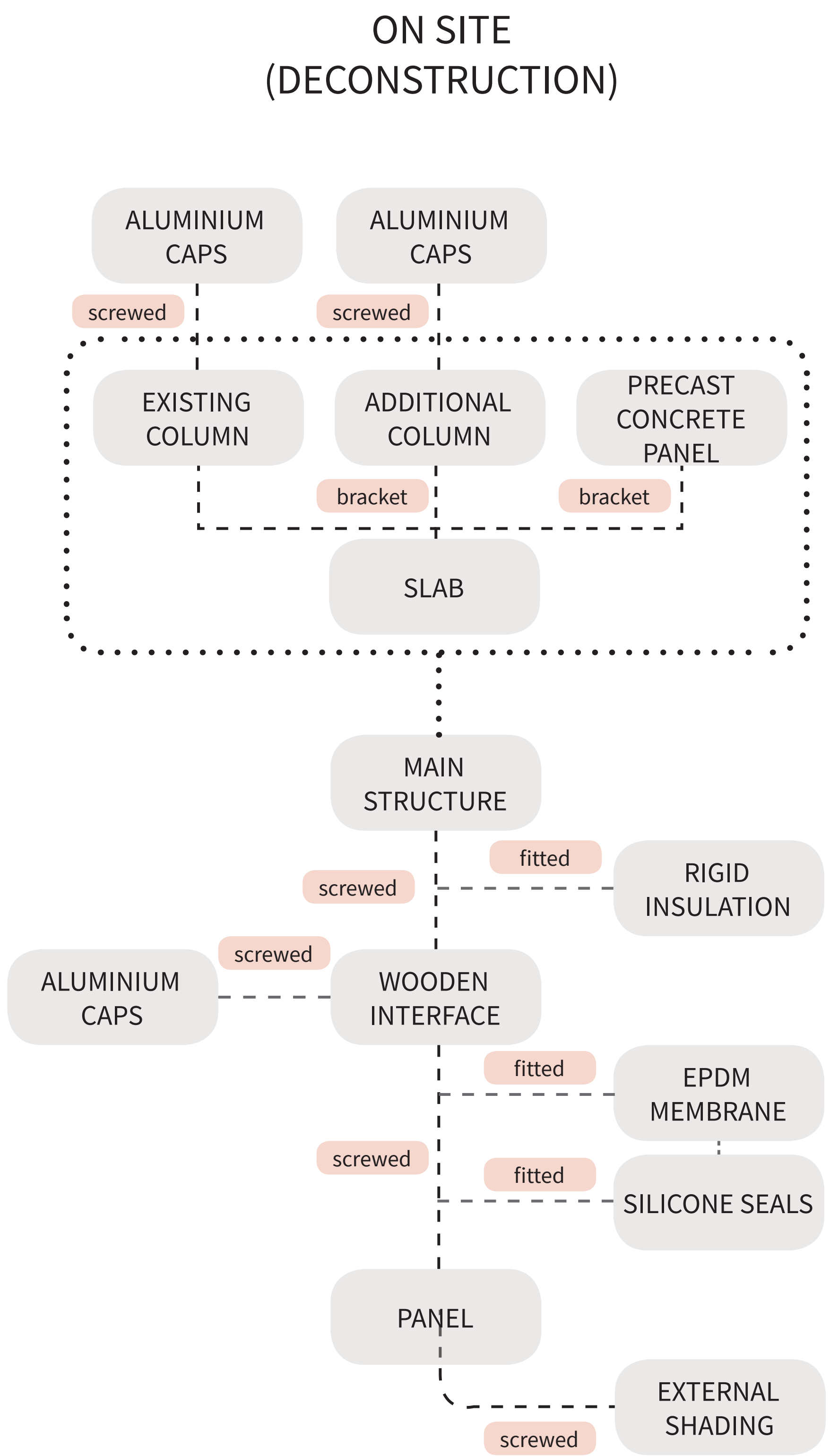
VII. FRAMEWORK DRAFTS



VII. FRAMEWORK DRAFTS

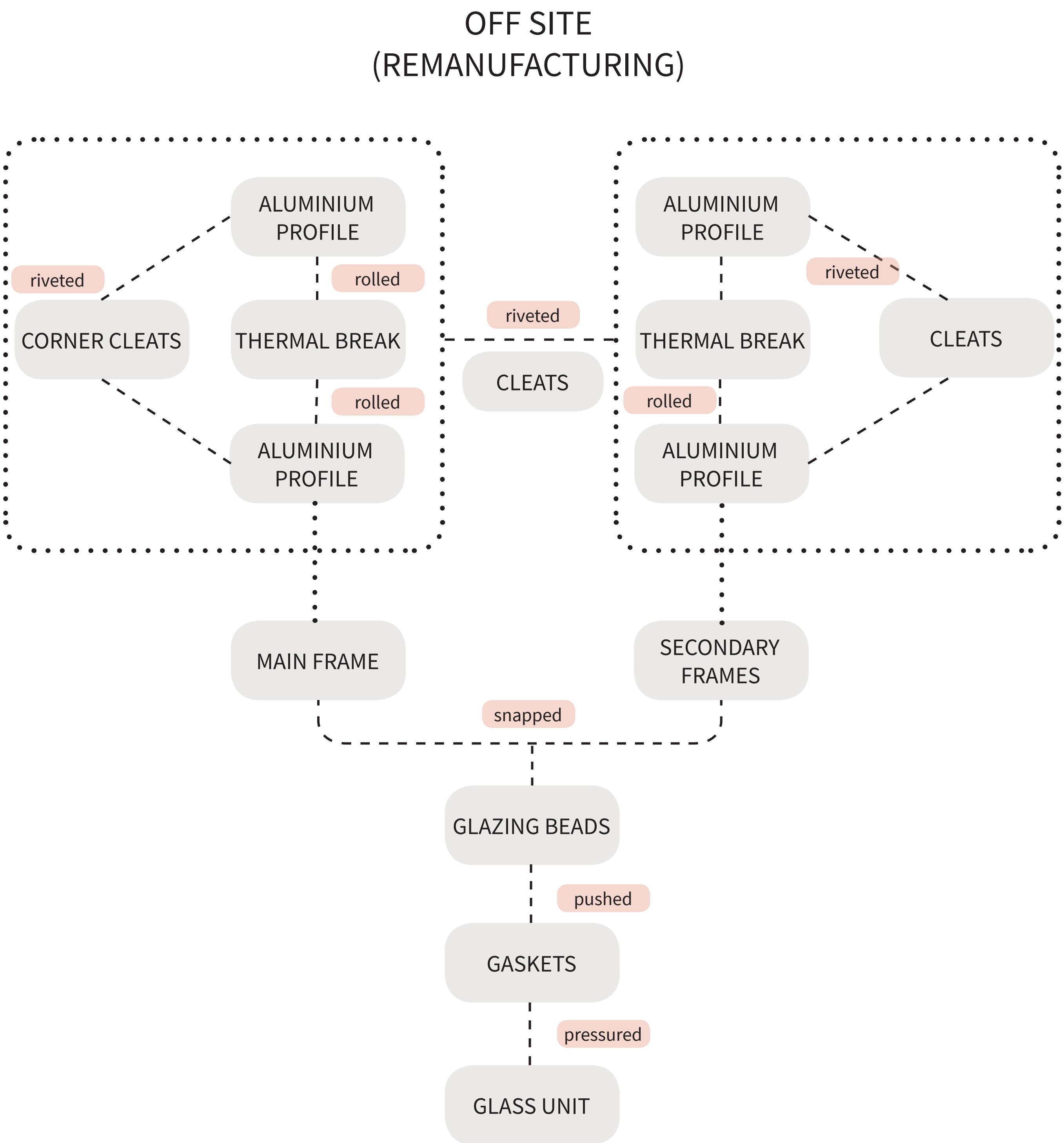


VIII. DECONSTRUCTION SEQUENCE



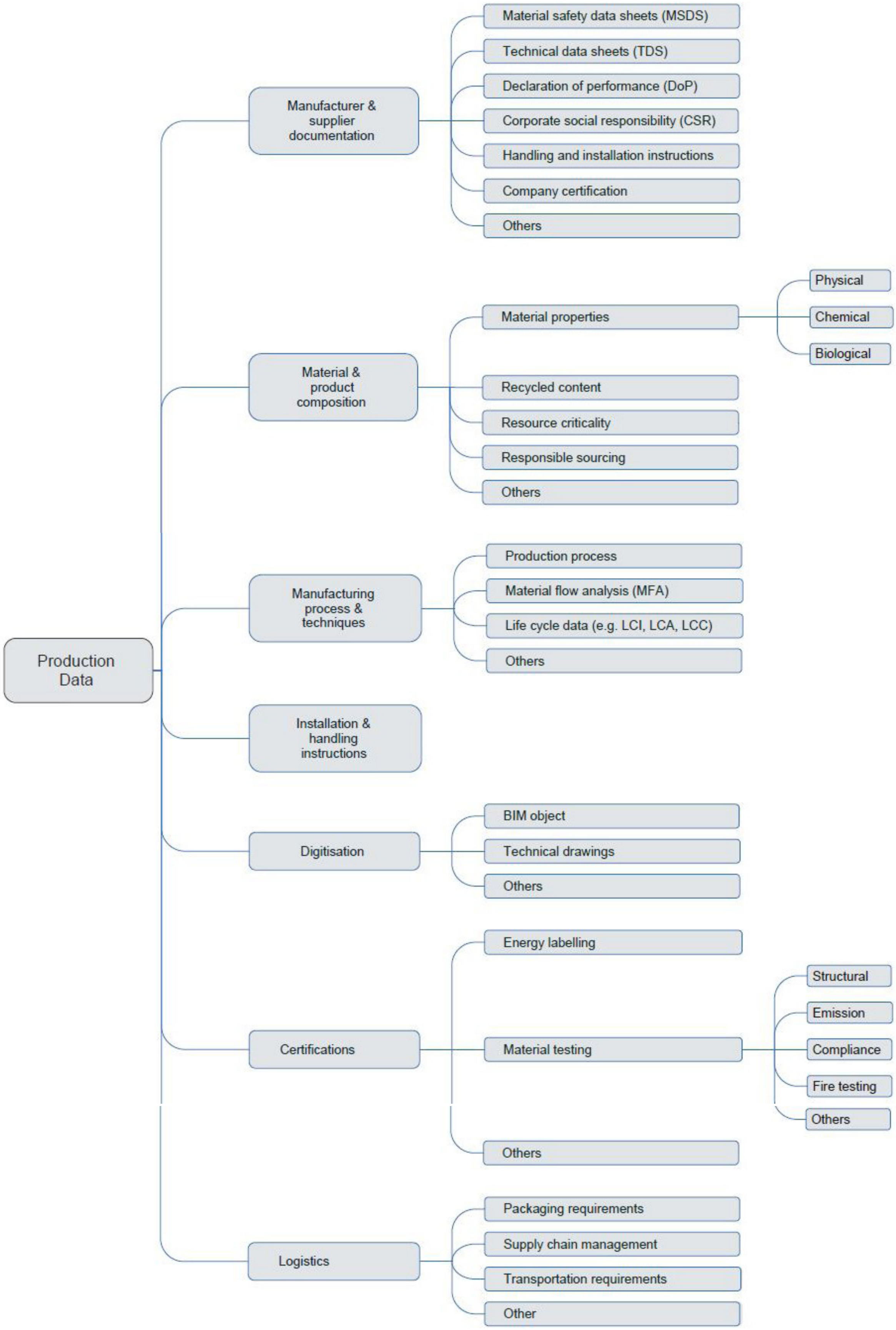
For simplification purposes, the diagram does not distinguish betwen system, sub-systems, components or elements. The intention is to show relations between elements.

IX. DISASSEMBLY SEQUENCE

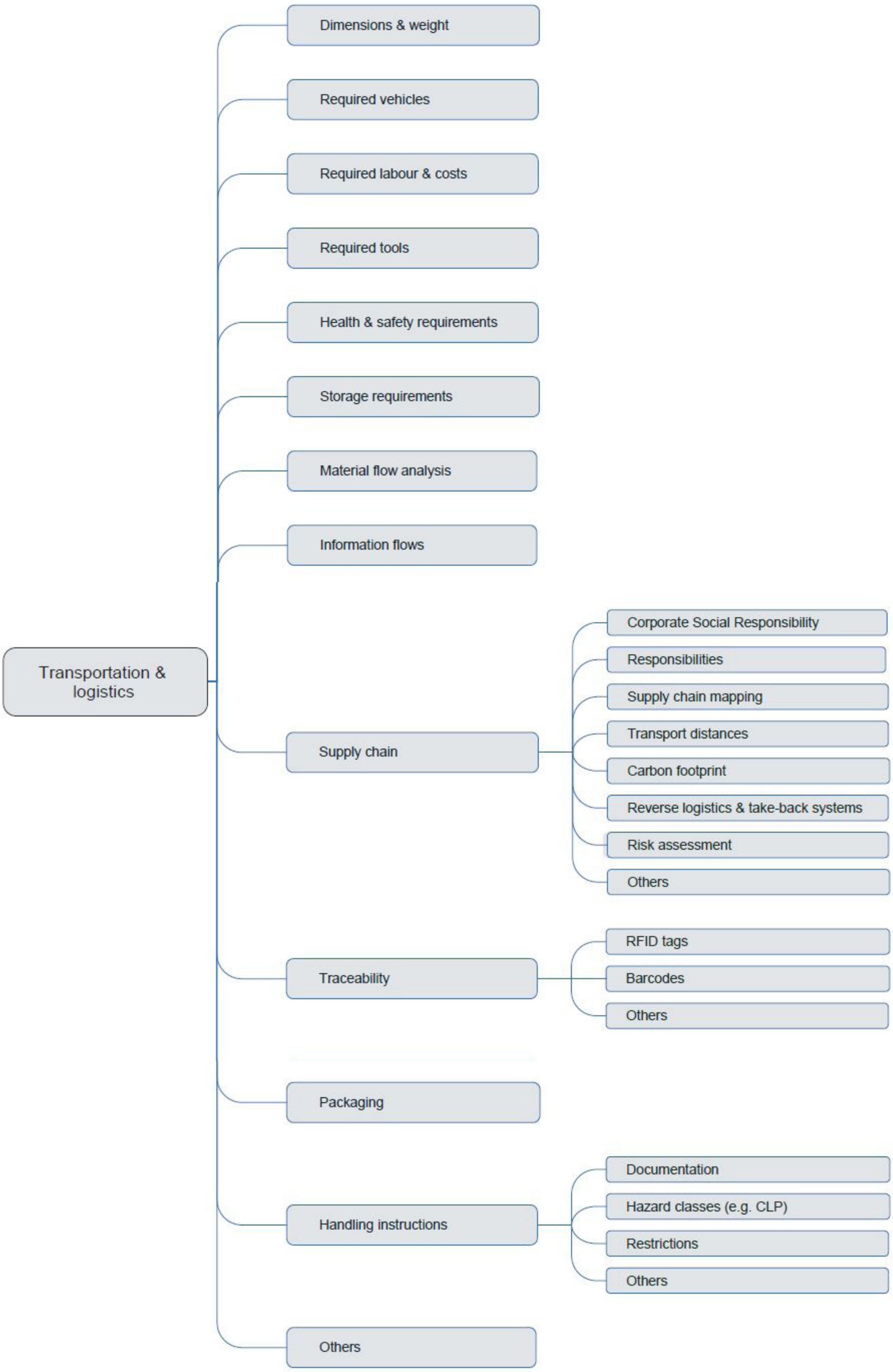


For simplification purposes, the diagram does not distinguish betwen system, sub-systems, components or elements. The intention is to show relations between elements.

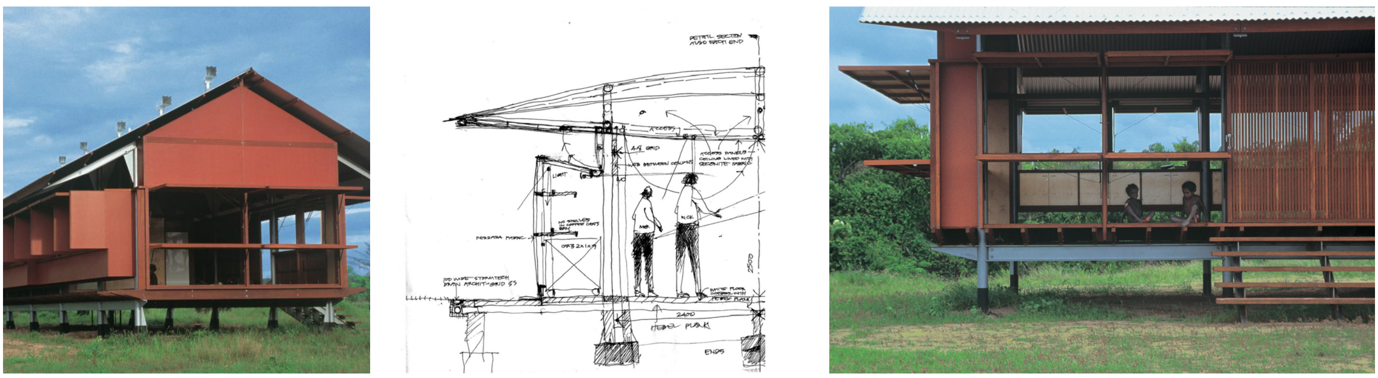
X. MATERIAL PASSPORT DATA



X. MATERIAL PASSPORT DATA

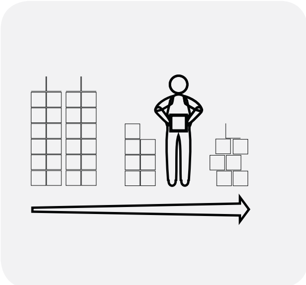


XI. AUXILIARY RESEARCH ON OFFICES: REFERENCES

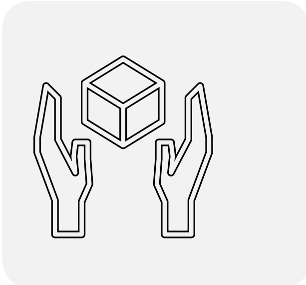


1| USM Haller system. Modular furniture design based on node-joining methods. Born from Fritz Haller's archietcture
2 | Murcutt's buildings do not represent anything. They seem constructed from standardized kits of parts. They are absurdly specific.
3 | Haller's Mini, Midi and Maxi buildings and steel construction systems. Building worker becomes a fitter (Detail, 2015)
4 | Various: Kullmann Steel modular system | Chamaleon House | Ecosteel system

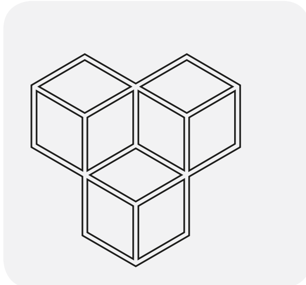
XI. AUXILIARY RESEARCH ON OFFICES: GUIDELINES



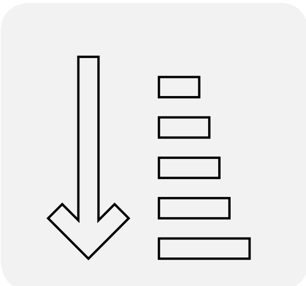
1 | Design for disassembly, easily separable elements.



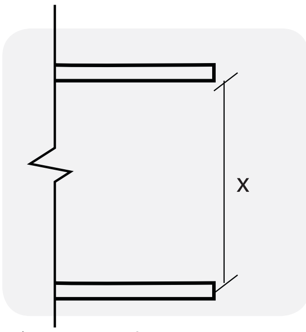
2 | Easily accesible elements & connections. *Provide means for handling.*



3 | Use modules. *Ideal architetcure module of office space is 1.20 or 1.50 m*

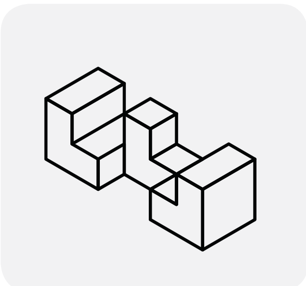


4 | Use no specific dimensions. *Always round up/down to next 10 cm.*

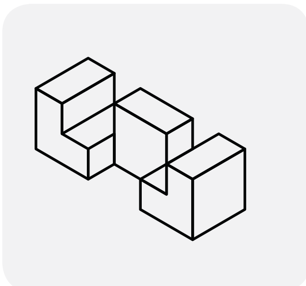


5 | Standard floor heights. *Common practice: 4.0-4.2 m. Use 1.2m module instead.*

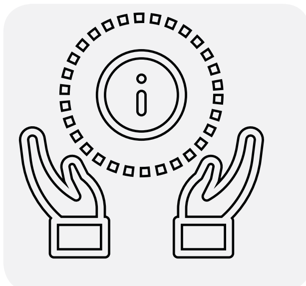
6 | Design with transportation in mind. *Products no bigger than 2x module.*



7 | Mechanical connections, dry, fewer connections.

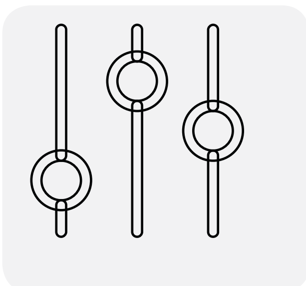


8 | Use intermediaries, not interlocking.

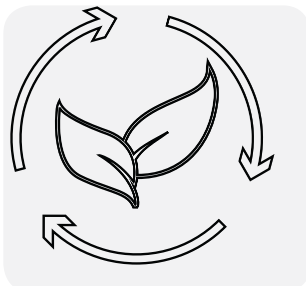


9 | Provide identification system of products.

10 | Permanently identify points of disassembly.



11/12 | Allow for flexibility and adjustability in configurations.



13* | Use sustainable materials sustainably. *(Recyled, recyclable at least, reusable at most, lighweigth)*

XI. AUXILIARY RESEARCH ON OFFICES: FACTS

PHYSICAL

Modular grids are based on actual location and dimension of building elements. They are used in panel and modular systems. In the US they are based on 2 ft increments. Most basic products are naufactured in 2 ft dimensions. (Smith, 2010)

Generally dimensional requirements for modular construction are determined by transportation restrictions. Width 13-16 ft; Length 52-60 ft; Height 12 ft (Smith, 2010)

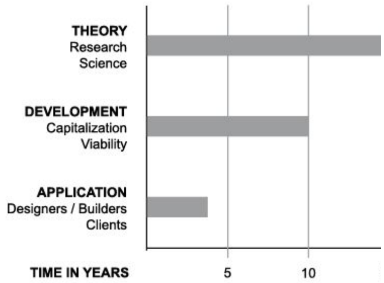
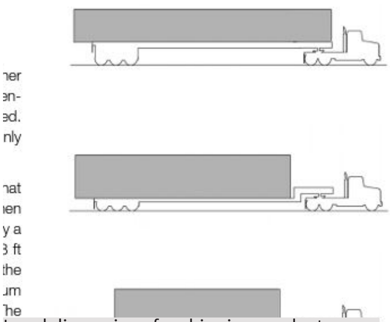


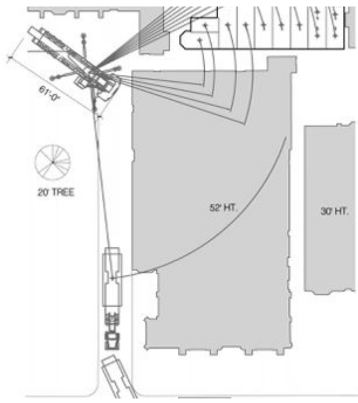
Figure 11.1 The three levels technological development are mapped against duration. ment includes the financing or capitalization of the idea to evaluate its viability; and app illustrates that whether a technology such as prefabrication takes hold is the responsibi and architects making decisions regarding prefabrication on a daily basis on building pr

PHYSICAL



Legal dimensions for shipping products:
Height 1 ft, width 8ft-6in
Length semitrailer 48 ft. (front to back)

Transportation presents a major consideration of the desing of elements and how they come together in the overall structure. Breaking down elements limits size and also final aesthetic. (Smith, 2010)



PSYCHOLOGICAL

"It was previously thought that full collaboration was best," he says. "But there are introverts and extroverts, and offices need to accommodate both." (Dawood 2019)

"There's an ongoing trend for industrial aesthetic," he says. "The scrappiness gives soul and allows users to feel like they can change the space. It doesn't feel polished and perfect, giving people autonomy to make a workspace theirs." (Dawood 2019)

"When I leave my office at night, there is nothing left of me in it" (Hall, 2016)

PSYCHOLOGICAL

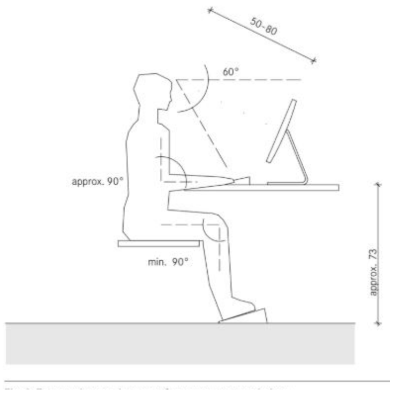
Boeing 137 can be built in 11 days. Zara delivers new clothing in six weeks. Constructions lacks innovation. (Smith, 2010)

The absence of color in the interiors of the building, particulary in the long corridors on each floor, was something that many people in our sample commented on. (Hall, 2016)

Design does not allow for personal touches. Managament wants to preserve purity and keep out "Micky Mouse" touches. (Hall, 2016)

XI. AUXILIARY RESEARCH ON OFFICES: FACTS

PHYSICAL



Standard floor-to ceiling height is 2.7 meters and 4.1 m of floor-to-floor. (Hall, 2016)

In the US and Asia, the floor-to-floor height of a typical high-rise office building is between 4.0 to 4.2 m. In Germany and France the typical dimension is 3.75 m. (Hall, 2016)

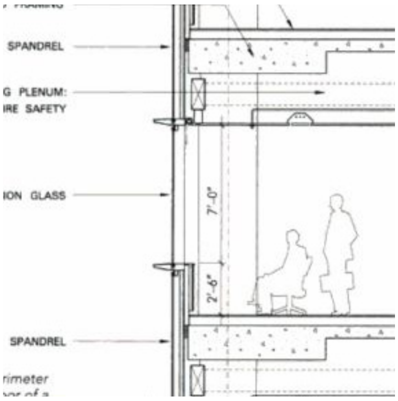
Tab. 10: Design data for c

Room type	Clear room height
Cellular office	≥ 2.50 m
Group office	≥ 2.50 m to ≥ 3.00 m
Small groups	≥ 2.50 m to ≥ 2.75 m
Large groups	≥ 2.75 m to ≥ 3.00 m
Combi-office (cellular anc	≥ 2.75 m to ≥ 3.00 m
Combi-office (combi-zone	
Open-plan office	≥ 3.00 m to ≥ 3.25 m

■ Tip: The volume *Basic*
Bielefeld and Sebastian

PHYSICAL

Floor to floor height is defined by the intended finished ceiling height, which is typically 2.6 or 2.75 m, although the trend in the 90's increased this height. (Hall, 2016)



Depth of raised floor is also a factor to determine height, 150 mm is the standard. (Hall, 2016)

PHYSICAL

The ideal architectural module of office space is 1.20 m, but could be between 1.20 and 1.40 metres (Comission 2011)

Doors should be 201. 5 cm in height.

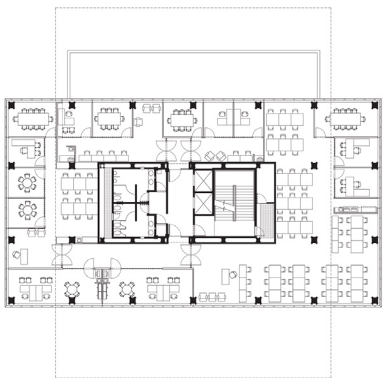
Windows must be across the full width of the booth. Height of the pane must be at least 1.20 m from the working surface upwards.

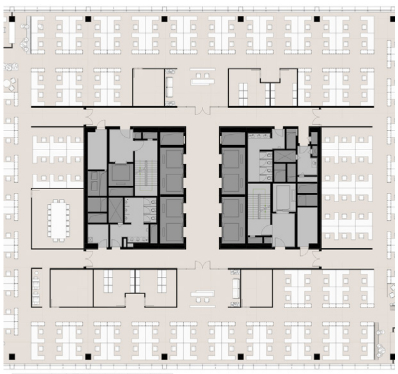
(Comission 2011)

Typical planning modules:
-US 1.5 m
-Japan 1.6 and 1.8 m
-Europe and Asia 1.2 m and 1.5 m (Hall, 2016)

PSYCHOLOGICAL

A few people mentioned to us that they found the building tiring. (Hall, 2016





XII. LOCATION DEFINITION FOR GEOGRAPHICAL ASSESSMENT

RECYCLE		
1	~~MATERIAL EXTRACTION~~	
	Where:	Various locations
		Lundevågen, 4550 Farsund, Noruega
		Alcoa Fjarðaál, Islandia
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
		Massena, NY 13662, Estados Unidos
	Who:	Alcoa
	How much:	-
2	~~MATERIAL PRODUCTION~~	
	Where:	Lundevågen, 4550 Farsund, Noruega
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
	Who:	Alcoa
	How much:	-
3	SYSTEM MANUFACTURE	
	Where:	33609 Bielefeld, Alemania
	Who:	Schuco
	How much:	988
4	PRODUCT MANUFACTURE	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	156
5	INSTALLATION	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	194
6	USE	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	-
7	MAINTENANCE	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	194
8	DECONSTRUCTION/COLLECTION	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	Deconstruction company (HKS)
	How much:	-
9	INSPECTION & SORTING	
	Where:	Wolframkade 2, 3812 RC Amersfoort
		*Havenweg 1, 3295 XZ 's-Gravendeel
	Who:	Recycling Company (HKS)
	How much:	45
10	RE-LIFE (RECYCLE)	
	Where:	Minervastraat 1, 6468 ET Kerkrade
	Who:	Melting company (E-Max Aluminium Remelt)
	How much:	210
11	MATERIAL MANUFACTURE...	
	Where:	Oosterhorn 20-22, 9936 HD Farmsum
	Who:	Extruder of alumnium (DAMCO Aluminium Delfzijl)
	How much:	374
	To system f	252
	To new dest	11
	TOTAL	
		1048

*The analysis only focuses on Aluminium and is highly hypothetical (it doesn't show the actual flow, but what the flow could look like given the circumstances).
**For the total distance travelled, the distance from the extraction points and material manufacturing to the system manufacturing are not taken into account, as the sourcing points are several and not possible to track.
***The strikethrough titles refer to the steps of the process being skipped due to the choosen re-life option/ strategy.
****The cell in orange refer to the reprise of the process after the last step in the corresponding list.

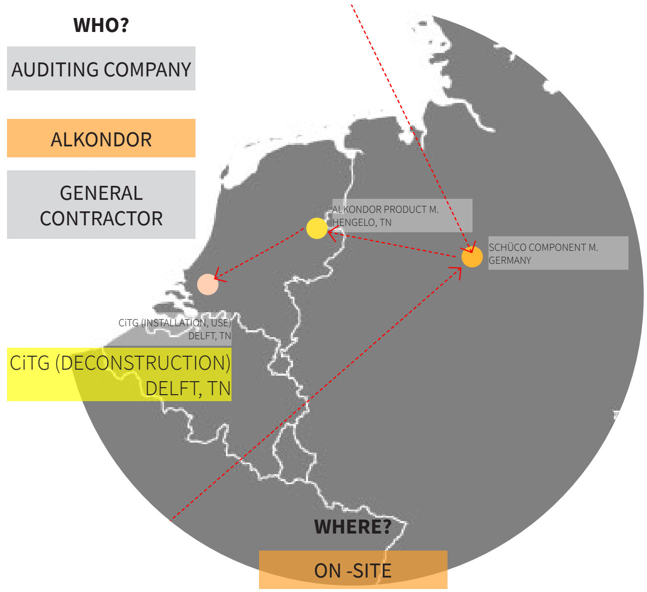
REMANUFACTURE		
1	~~MATERIAL EXTRACTION~~	
	Where:	Various locations
		Lundevågen, 4550 Farsund, Noruega
		Alcoa Fjarðaál, Islandia
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
		Massena, NY 13662, Estados Unidos
	Who:	Alcoa
	How much:	-
2	~~MATERIAL PRODUCTION~~	
	Where:	Lundevågen, 4550 Farsund, Noruega
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
	Who:	Alcoa
	How much:	-
3	~~SYSTEM MANUFACTURE~~	
	Where:	33609 Bielefeld, Alemania
	Who:	Schuco
	How much:	988
4	~~PRODUCT MANUFACTURE~~	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	156
5	~~INSTALLATION~~	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	194
6	USE	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	-
7	MAINTENANCE	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	194
8	DECONSTRUCTION/COLLECTION	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	Deconstruction company (HKS)
	How much:	-
9	INSPECTION & SORTING	
	Where:	RDM-kade 59, 3089 JR Rotterdam
	Who:	Inspection Contractor (New actor in RDM Campus)
	How much:	24
10	RE-LIFE (REMANUFACTURE)	
	Where:	WCP7+J8 Róterdam
	Who:	Remanufacturer (Aldowa)
	How much:	17
	NEW INSTALLATION	
	Where:	De Veldmaat 8, 7522 NM Enschede (a "compatible" renovation project)
	Who:	Remanufacturer (Aldowa)
	How much:	199
	TOTAL	
		240

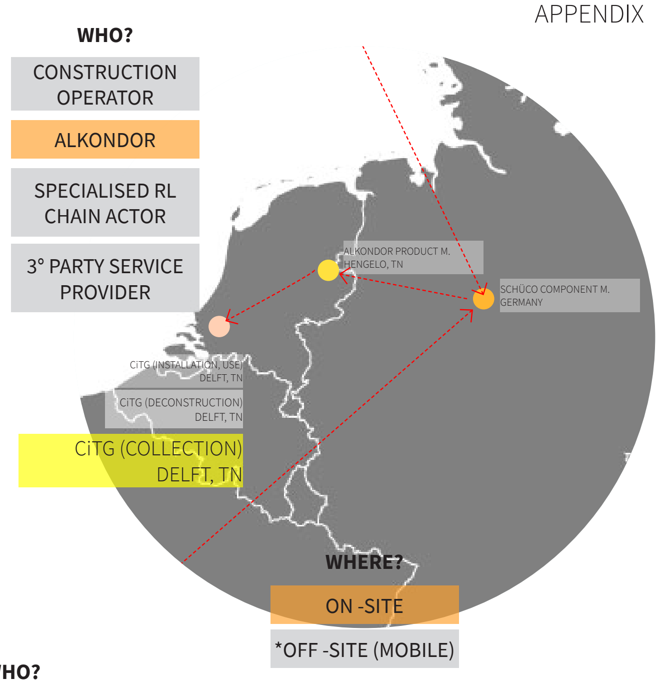
*The analysis only focuses on Aluminium and is highly hypothetical (it doesn't show the actual flow, but what the flow could look like given the circumstances).
**For the total distance travelled, the distance from the extraction points and material manufacturing to the system manufacturing are not taken into account, as the sourcing points are several and not possible to track.
***The strikethrough titles refer to the steps of the process being skipped due to the choosen re-life option/ strategy.
****The cell in orange refer to the reprise of the process after the last step in the corresponding list.

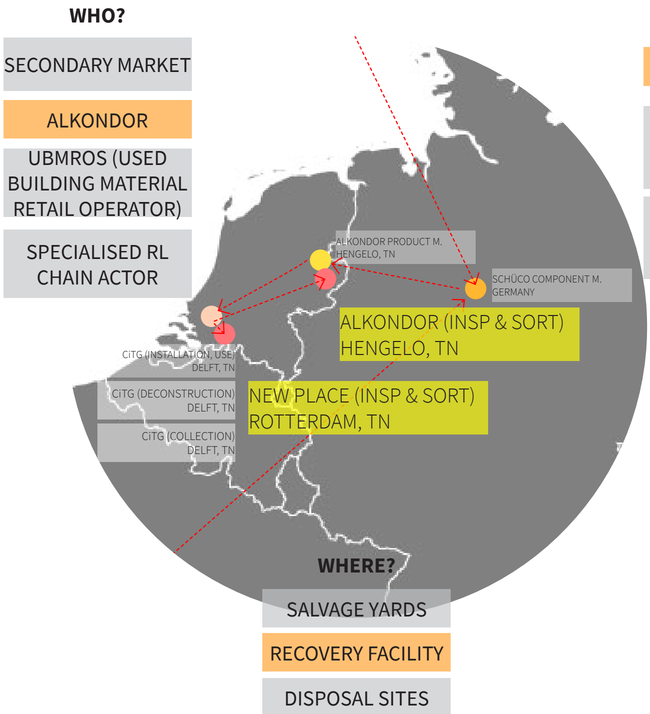
NEW VISION		
1	~~MATERIAL EXTRACTION~~	
	Where:	Various locations
		Lundevågen, 4550 Farsund, Noruega
		Alcoa Fjarðaál, Islandia
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
		Massena, NY 13662, Estados Unidos
	Who:	Alcoa
	How much:	-
2	~~MATERIAL PRODUCTION~~	
	Where:	Lundevågen, 4550 Farsund, Noruega
		1 Boulevard des Sources, Deschambault, QC G0A 1S0, Canadá
	Who:	Alcoa
	How much:	-
3	~~SYSTEM MANUFACTURE~~	
	Where:	33609 Bielefeld, Alemania
	Who:	Schuco
	How much:	988
4	~~PRODUCT MANUFACTURE~~	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	156
5	~~INSTALLATION~~	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	194
6	USE	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	TU Delft
	How much:	-
7	MAINTENANCE	
	Where:	Wegtersweg 7-19, 7556 BP Hengelo
	Who:	Alkondor Hengelo
	How much:	194
8	DECONSTRUCTION/COLLECTION	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	Specialised RL actor (New actor)
	How much:	-
9	~~INSPECTION & SORTING~~	
	Where:	Stevinweg 1, 2628 CN Delft
	Who:	Specialised RL actor (New actor)
	How much:	-
10	~~RE-LIFE (REMANUFACTURE)~~	
	Where:	Schieweg 9, 2627 AN Delft (Industrial area)
	Who:	Remanufacturer (Aldowa)
	How much:	2
	NEW INSTALLATION	
	Where:	De Veldmaat 8, 7522 NM Enschede (a "compatible" renovation project)
	Who:	Specialised RL actor (New actor)
	How much:	205
	TOTAL	
		207

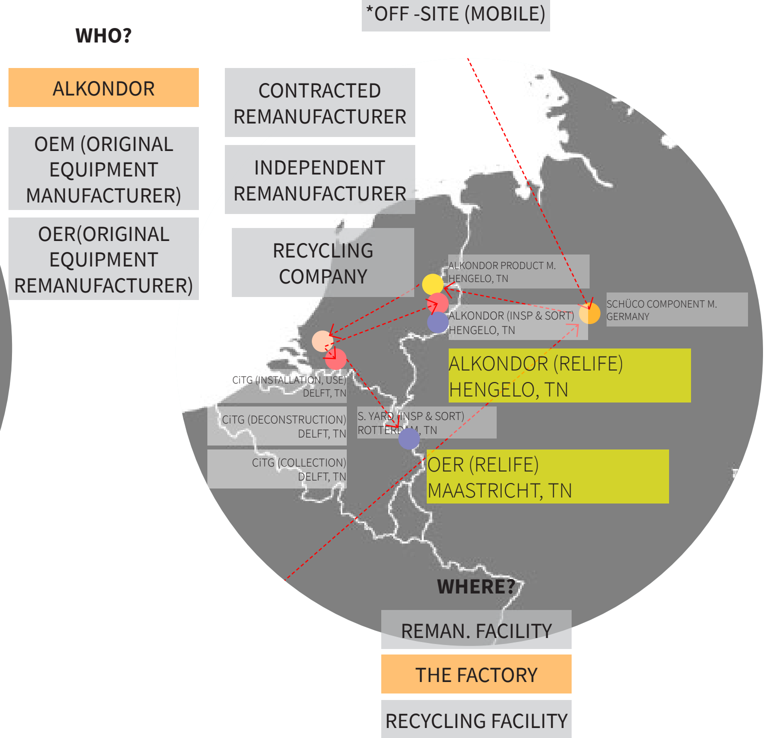
*The analysis only focuses on Aluminium and is highly hypothetical (it doesn't show the actual flow, but what the flow could look like given the circumstances).
**For the total distance travelled, the distance from the extraction points and material manufacturing to the system manufacturing are not taken into account, as the sourcing points are several and not possible to track.
***The strikethrough titles refer to the steps of the process being skipped due to the choosen re-life option/ strategy.
****The cell in orange refer to the reprise of the process after the last step in the corresponding list.

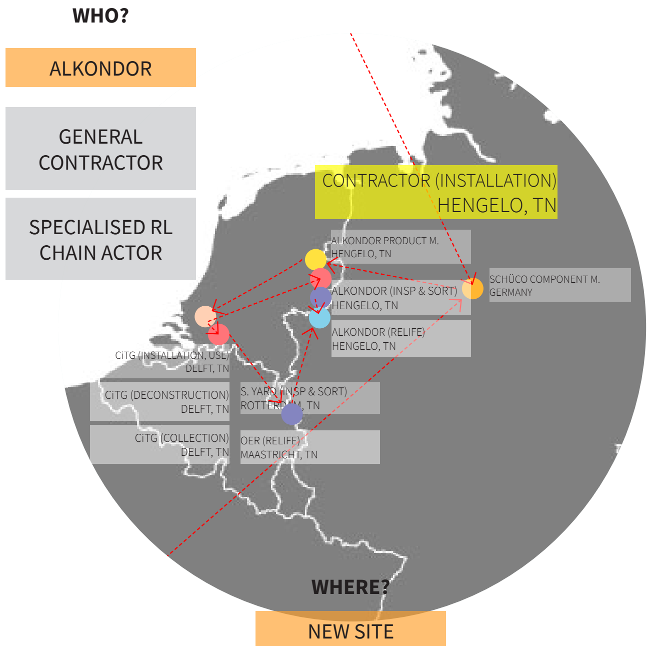
New most “compatible” use

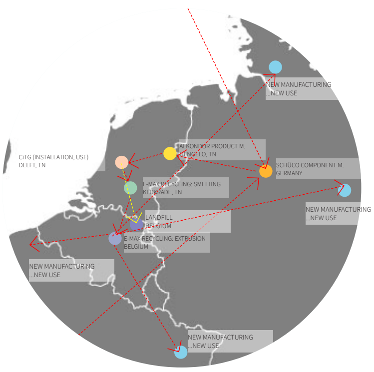




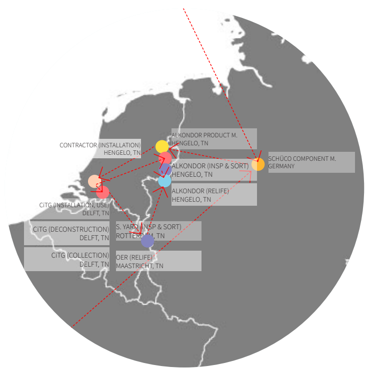








CONVENTIONAL PROCESS



APPLYING RL PROCESS

XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

MCI: Recycling Scenario

PRODUCT THAT IS RECYCLED

Mass	Volume (m3)	Density (kg/m3)	M (kg)
Aluminium frame	0.01	2710	27.1
Thermal break	0.0085	1150	9.775
Glazing bead	0.002	2710	5.42
Gaskets	0.004	1522	6.088
Glass	0.07512	2500	187.8
Infill panel- Alu	0.0045	2710	12.195
Infill panel- Insulation	0.028	30	0.84
Insulation	0.0092	30	0.276
EPDM*	0.008	115	0.92
Wooden interface	0.06	700	42
Steel column	0.004	8050	32.2
		TOTAL	**324.614**

Fraction from recycled	Fr	Fraction from reused	Fu	Fraction for recycling	Cr	Fraction for reusing	Cu
Aluminium frame	0.47	Aluminium frame	0	Aluminium frame	0.9	Aluminium frame	0
Thermal break	0.001	Thermal break	0	Thermal break	0.9	Thermal break	0
Glazing bead	0.47	Glazing bead	0	Glazing bead	0.9	Glazing bead	0
Gaskets	0.001	Gaskets	0	Gaskets	0.05	Gaskets	0
Glass	0.25	Glass	0	Glass	0.7	Glass	0
Infill panel- Alu	0.47	Infill panel- Alu	0	Infill panel- Alu	0.9	Infill panel- Alu	0
Infill panel- Insulation	0.001	Infill panel- Insulation	0	Infill panel- Insulation	0.3	Infill panel- Insulation	0
Insulation	0.001	Insulation	0	Insulation	0.3	Insulation	0
EPDM*	0.001	EPDM*	0	EPDM*	0.05	EPDM*	0
Wooden interface	0.001	Wooden interface	0	Wooden interface	0	Wooden interface	0
Steel column	0.4	Steel column	0	Steel column	0.9	Steel column	0

Efficiency of proces for recycling	Ec	Efficiency of process from re Ef	
Aluminium frame	0.2	Aluminium frame	0.7
Thermal break	0.001	Thermal break	0.001
Glazing bead	0.2	Glazing bead	0.7
Gaskets	0.001	Gaskets	0.001
Glass	0.2	Glass	0.8
Infill panel- Alu	0.2	Infill panel- Alu	0.7
Infill panel- Insulation	0.5	Infill panel- Insulation	0.5
Insulation	0.5	Insulation	0.5
EPDM*	0.2	EPDM*	0.2
Wooden interface	0.001	Wooden interface	0.001
Steel column	1	Steel column	1

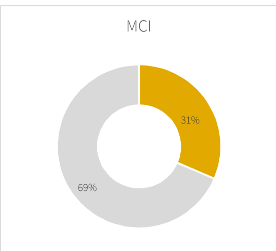
Results

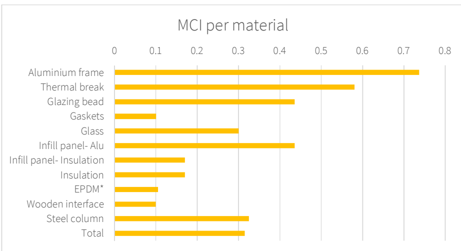
Virgin Feedstock	V	Unrecoverable waste	Wo	Waste from recycling	Wc	Waste for recycling	Wf	Total amount of unrec	W
Aluminium frame	14.363	Aluminium frame	2.71	Aluminium frame	19.512	Aluminium frame	5.4587143	Aluminium frame	15.19536
Thermal break	9.765225	Thermal break	0.9775	Thermal break	8.788703	Thermal break	9.765225	Thermal break	10.25446
Glazing bead	2.8726	Glazing bead	0.542	Glazing bead	3.9024	Glazing bead	1.0917429	Glazing bead	3.039071
Gaskets	6.081912	Gaskets	5.7836	Gaskets	0.304096	Gaskets	6.081912	Gaskets	8.976604
Glass	140.85	Glass	56.34	Glass	105.168	Glass	11.7375	Glass	114.7928
Infill panel- Alu	6.46335	Infill panel- Alu	1.2195	Infill panel- Alu	8.7804	Infill panel- Alu	2.4564214	Infill panel- Alu	6.837911
Infill panel- Insulation	0.83916	Infill panel- Insulation	0.588	Infill panel- Insulation	0.126	Infill panel- Insulation	0.00084	Infill panel- Insulation	0.65142
Insulation	0.275724	Insulation	0.1932	Insulation	0.0414	Insulation	0.000276	Insulation	0.214038
EPDM*	0.91908	EPDM*	0.874	EPDM*	0.0368	EPDM*	0.00368	EPDM*	0.89424
Wooden interface	41.958	Wooden interface	42	Wooden interface	0	Wooden interface	41.958	Wooden interface	62.979
Steel column	19.32	Steel column	3.22	Steel column	0	Steel column	0	Steel column	3.22
Total	**243.7081**	**Total**	**114.4478**	**Total**	**146.6598**	**Total**	**78.55431**	**Total**	**227.0549**

Linear flow index	(V+W) / (2M + (V	(V+W) / (2M)
Aluminium frame	0.62659007	0.545357143
Thermal break	0.999073148	1.024025
Glazing bead	0.62659007	0.545357143
Gaskets	0.999575676	1.2367375
Glass	0.777301927	0.680625
Infill panel- Alu	0.62659007	0.545357143
Infill panel- Insulation	0.921578811	0.88725
Insulation	0.921578811	0.88725
EPDM*	0.99445005	0.9855
Wooden interface	0.99959992	1.24925
Steel column	0.35	0.35
Total	**0.803902596**	**0.812428084**
Total	**0.79675711**	**0.780672704**

Utility factor	L	Lav	X	F(X)
Aluminium frame	75	35	2.142857143	0.42
Thermal break	75	35	2.142857143	0.42
Glazing bead	35	35	1	0.9
Gaskets	15	15	1	0.9
Glass	15	15	1	0.9
Infill panel- Alu	35	35	1	0.9
Infill panel- Insulation	15	15	1	0.9
Insulation	15	15	1	0.9
EPDM*	30	30	1	0.9
Wooden interface	15	15	1	0.9
Steel column	35	75	0.466666667	1.928571

Materials	MCI	1-LFI*F(X)
Aluminium frame	0.7368322	
Thermal break	0.5803893	
Glazing bead	0.4360689	
Gaskets	0.1003819	
Glass	0.3004283	
Infill panel- Alu	0.4360689	
Infill panel- Insulation	0.1705791	
Insulation	0.1705791	
EPDM*	0.104995	
Wooden interface	0.1003601	
Steel column	0.325	
Total	**0.314698**	
	0.6853016	
	0.394393	
	0.6056073	





*As a conclusion, I could say the MCI is not se useful as it does not take into account the subtleties of the process (like, if it being reused, it doesn't take into account the energy/resources that went into it to make it a reusable product again... it doesn't even consider the efficency factor it has for the recycling scenario), let alone other relife options like remanufacturing or repurposing.

XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

MCI: Reman. Scenario

PRODUCT THAT IS REUSED (ONLY MINOR THINGS ARE REPLACED)

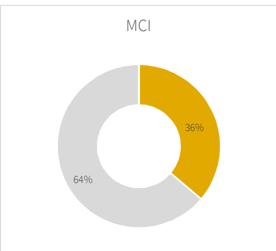
Mass	Volume (m3)	Density (kg/m3)	M (kg)	Fraction from recycled	Fr	Fraction from reused	Fu	Fraction for recycling	Cr	Fraction for reusing	Cu
Aluminium frame	0.01	2710	27.1	Aluminium frame	0.47	Aluminium frame	0	Aluminium frame	0	Aluminium frame	0.9
Thermal break	0.0085	1150	9.775	Thermal break	0.001	Thermal break	0	Thermal break	0	Thermal break	0.9
Glazing bead	0.002	2710	5.42	Glazing bead	0.47	Glazing bead	0	Glazing bead	0.9	Glazing bead	0
Gaskets	0.004	1522	6.088	Gaskets	0.001	Gaskets	0	Gaskets	0.05	Gaskets	0
Glass	0.07512	2500	187.8	Glass	0.25	Glass	0	Glass	0.7	Glass	0
Infill panel- Alu	0.0045	2710	12.195	Infill panel- Alu	0.47	Infill panel- Alu	0	Infill panel- Alu	0	Infill panel- Alu	0.9
Infill panel- Insulation	0.028	30	0.84	Infill panel- Insulation	0.001	Infill panel- Insulation	0	Infill panel- Insulation	0.3	Infill panel- Insulation	0
Insulation	0.0092	30	0.276	Insulation	0.001	Insulation	0	Insulation	0.3	Insulation	0
EPDM*	0.008	115	0.92	EPDM*	0.001	EPDM*	0	EPDM*	0.05	EPDM*	0
Wooden interface	0.06	700	42	Wooden interface	0.001	Wooden interface	0	Wooden interface	0	Wooden interface	0
Steel column	0.004	8050	32.2	Steel column	0.4	Steel column	0	Steel column	0.9	Steel column	0
		TOTAL	**324.614**								

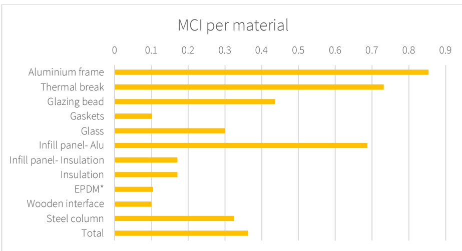
Efficiency of proces for recycling	Ec	Efficiency of process from re Ef	
Aluminium frame	0.2	Aluminium frame	0.7
Thermal break	0.001	Thermal break	0.001
Glazing bead	0.2	Glazing bead	0.7
Gaskets	0.001	Gaskets	0.001
Glass	0.2	Glass	0.8
Infill panel- Alu	0.2	Infill panel- Alu	0.7
Infill panel- Insulation	0.5	Infill panel- Insulation	0.5
Insulation	0.5	Insulation	0.5
EPDM*	0.2	EPDM*	0.2
Wooden interface	0.001	Wooden interface	0.001
Steel column	1	Steel column	1

Results

Virgin Feedstock	V	Unrecoverable waste	Wo	Waste from recycling	Wc	Waste for recycling	Wf	Total amount of unrec	W
Aluminium frame	14.363	Aluminium frame	2.71	Aluminium frame	0	Aluminium frame	5.4587143	Aluminium frame	5.439357
Thermal break	9.765225	Thermal break	0.9775	Thermal break	0	Thermal break	9.765225	Thermal break	5.860113
Glazing bead	2.8726	Glazing bead	0.542	Glazing bead	3.9024	Glazing bead	1.0917429	Glazing bead	3.039071
Gaskets	6.081912	Gaskets	5.7836	Gaskets	0.304096	Gaskets	6.081912	Gaskets	8.976604
Glass	140.85	Glass	56.34	Glass	105.168	Glass	11.7375	Glass	114.7928
Infill panel- Alu	6.46335	Infill panel- Alu	1.2195	Infill panel- Alu	0	Infill panel- Alu	2.4564214	Infill panel- Alu	2.447711
Infill panel- Insulation	0.83916	Infill panel- Insulation	0.588	Infill panel- Insulation	0.126	Infill panel- Insulation	0.00084	Infill panel- Insulation	0.65142
Insulation	0.275724	Insulation	0.1932	Insulation	0.0414	Insulation	0.000276	Insulation	0.214038
EPDM*	0.91908	EPDM*	0.874	EPDM*	0.0368	EPDM*	0.00368	EPDM*	0.89424
Wooden interface	41.958	Wooden interface	42	Wooden interface	0	Wooden interface	41.958	Wooden interface	62.979
Steel column	19.32	Steel column	3.22	Steel column	0	Steel column	0	Steel column	3.22
Total	**243.7081**	**Total**	**114.4478**	**Total**	**109.5787**	**Total**	**78.55431**	**Total**	**208.5143**

Linear flow index	(V+W) / (2M + (V	(V+W) / (2M)	Utility factor	L	Lav	X	F(X)	Materials	MCI	1-LFI*F(X)
Aluminium frame	0.34784087	0.365357143	Aluminium frame	75	35	2.142857143	0.42	Aluminium frame	0.8539068	
Thermal break	0.639527906	0.79925	Thermal break	75	35	2.142857143	0.42	Thermal break	0.7313983	
Glazing bead	0.62659007	0.545357143	Glazing bead	35	35	1	0.9	Glazing bead	0.4360689	
Gaskets	0.999575676	1.2367375	Gaskets	15	15	1	0.9	Gaskets	0.1003819	
Glass	0.777301927	0.680625	Glass	15	15	1	0.9	Glass	0.3004283	
Infill panel- Alu	0.34784087	0.365357143	Infill panel- Alu	35	35	1	0.9	Infill panel- Alu	0.6869432	
Infill panel- Insulation	0.921578811	0.88725	Infill panel- Insulation	15	15	1	0.9	Infill panel- Insulation	0.1705791	
Insulation	0.921578811	0.88725	Insulation	15	15	1	0.9	Insulation	0.1705791	
EPDM*	0.99445005	0.9855	EPDM*	30	30	1	0.9	EPDM*	0.104995	
Wooden interface	0.99959992	1.24925	Wooden interface	15	15	1	0.9	Wooden interface	0.1003601	
Steel column	0.35	0.35	Steel column	35	75	0.466666667	1.928571	Steel column	0.325	
Total	**0.720534992**	**0.759266721**						**Total**	**0.361876**	
									0.6381236	
Total	**0.665750876**	**0.697133418**							**0.468529**	
									0.5314705	





*As a conclusion, I could say the MCI is not se useful as it does not take into account the subtleties of the process (like, if it being reused, it doesn't take into account the energy/resources that went into it to make it a reusable product again... it doesn't even consider the efficency factor it has for the recycling scenario), let alone other relife options like remanufacturing or repurposing.

XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

MCI: Reuse Scenario

PRODUCT THAT IS REUSED (AND SOURCES ARE ALSO FROM REUSED PRODUCTS)

Mass	Volume (m3)	Density (kg/m3)	M (kg)
Aluminium frame	0.01	2710	27.1
Thermal break	0.0085	1150	9.775
Glazing bead	0.002	2710	5.42
Gaskets	0.004	1522	6.088
Glass	0.07512	2500	187.8
Infill panel- Alu	0.0045	2710	12.195
Infill panel- Insulation	0.028	30	0.84
Insulation	0.0092	30	0.276
EPDM*	0.008	115	0.92
Wooden interface	0.06	700	42
Steel column	0.004	8050	32.2
		TOTAL	324.614

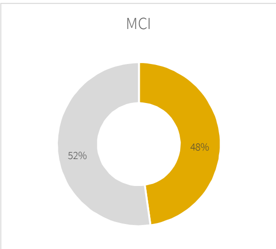
Fraction from recycled	Fr	Fraction from reused	Fu	Fraction for recycling	Cr	Fraction for reusing	Cu
Aluminium frame	0.2	Aluminium frame	0.8	Aluminium frame	0	Aluminium frame	0.9
Thermal break	0.001	Thermal break	0.8	Thermal break	0	Thermal break	0.9
Glazing bead	0.47	Glazing bead	0	Glazing bead	0.9	Glazing bead	0
Gaskets	0.001	Gaskets	0	Gaskets	0.05	Gaskets	0
Glass	0.25	Glass	0	Glass	0.7	Glass	0
Infill panel- Alu	0.2	Infill panel- Alu	0.8	Infill panel- Alu	0	Infill panel- Alu	0.9
Infill panel- Insulation	0.001	Infill panel- Insulation	0	Infill panel- Insulation	0.3	Infill panel- Insulation	0
Insulation	0.001	Insulation	0	Insulation	0.3	Insulation	0
EPDM*	0.001	EPDM*	0	EPDM*	0.05	EPDM*	0
Wooden interface	0.001	Wooden interface	0	Wooden interface	0	Wooden interface	0
Steel column	0.4	Steel column	0.8	Steel column	0.9	Steel column	0

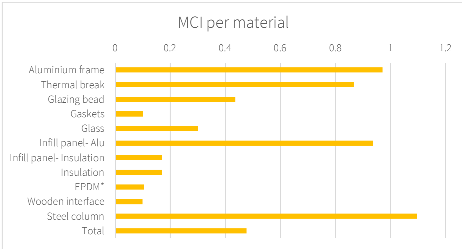
Efficiency of proces for recycling	Ec	Efficiency of process from re	Ef
Aluminium frame	0.2	Aluminium frame	0.7
Thermal break	0.001	Thermal break	0.001
Glazing bead	0.2	Glazing bead	0.7
Gaskets	0.001	Gaskets	0.001
Glass	0.2	Glass	0.8
Infill panel- Alu	0.2	Infill panel- Alu	0.7
Infill panel- Insulation	0.5	Infill panel- Insulation	0.5
Insulation	0.5	Insulation	0.5
EPDM*	0.2	EPDM*	0.2
Wooden interface	0.001	Wooden interface	0.001
Steel column	1	Steel column	1

Results

Virgin Feedstock	V	Unrecoverable waste	Wo	Waste from recycling	Wc	Waste for recycling	Wf	Total amount of unrec	W
Aluminium frame	0	Aluminium frame	2.71	Aluminium frame	0	Aluminium frame	2.3228571	Aluminium frame	3.871429
Thermal break	1.945225	Thermal break	0.9775	Thermal break	0	Thermal break	9.765225	Thermal break	5.860113
Glazing bead	2.8726	Glazing bead	0.542	Glazing bead	3.9024	Glazing bead	1.0917429	Glazing bead	3.039071
Gaskets	6.081912	Gaskets	5.7836	Gaskets	0.304096	Gaskets	6.081912	Gaskets	8.976604
Glass	140.85	Glass	56.34	Glass	105.168	Glass	11.7375	Glass	114.7928
Infill panel- Alu	0	Infill panel- Alu	1.2195	Infill panel- Alu	0	Infill panel- Alu	1.0452857	Infill panel- Alu	1.742143
Infill panel- Insulation	0.83916	Infill panel- Insulation	0.588	Infill panel- Insulation	0.126	Infill panel- Insulation	0.00084	Infill panel- Insulation	0.65142
Insulation	0.275724	Insulation	0.1932	Insulation	0.0414	Insulation	0.000276	Insulation	0.214038
EPDM*	0.91908	EPDM*	0.874	EPDM*	0.0368	EPDM*	0.00368	EPDM*	0.89424
Wooden interface	41.958	Wooden interface	42	Wooden interface	0	Wooden interface	41.958	Wooden interface	62.979
Steel column	-6.44	Steel column	3.22	Steel column	0	Steel column	0	Steel column	3.22
Total	**189.3017**	**Total**	**114.4478**	**Total**	**109.5787**	**Total**	**74.00732**	**Total**	**206.2408**

Linear flow index	(V+W) / (2M + (V	(V+W) / (2M)	Utility factor	L	Lav	X	F(X)	Materials	MCI	1-LFI*F(X)
Aluminium frame	0.06993007	0.071428571	Aluminium frame	75	35	2.142857143	0.42	Aluminium frame	0.9706294	
Thermal break	0.319463893	0.39925	Thermal break	75	35	2.142857143	0.42	Thermal break	0.8658252	
Glazing bead	0.62659007	0.545357143	Glazing bead	35	35	1	0.9	Glazing bead	0.4360689	
Gaskets	0.999575676	1.2367375	Gaskets	15	15	1	0.9	Gaskets	0.1003819	
Glass	0.777301927	0.680625	Glass	15	15	1	0.9	Glass	0.3004283	
Infill panel- Alu	0.06993007	0.071428571	Infill panel- Alu	35	35	1	0.9	Infill panel- Alu	0.9370629	
Infill panel- Insulation	0.921578811	0.88725	Infill panel- Insulation	15	15	1	0.9	Infill panel- Insulation	0.1705791	
Insulation	0.921578811	0.88725	Insulation	15	15	1	0.9	Insulation	0.1705791	
EPDM*	0.99445005	0.9855	EPDM*	30	30	1	0.9	EPDM*	0.104995	
Wooden interface	0.99959992	1.24925	Wooden interface	15	15	1	0.9	Wooden interface	0.1003601	
Steel column	-0.05	-0.05	Steel column	35	75	0.466666667	1.928571	Steel column	1.0964286	
Total	**0.604545391**	**0.63309789**						**Total**	**0.477576**	
									0.5224238	
Total	**0.540624359**	**0.556010969**							**0.540139**	
									0.4598606	





*As a conclusion, I could say the MCI is not se useful as it does not take into account the subtleties of the process (like, if it being reused, it doesn't take into account the energy/resources that went into it to make it a reusable product again... it doesn't even consider the efficency factor it has for the recycling scenario), let alone other relife options like remanufacturing or repurposing.

XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Frame | Recycling Scenario

Aluminium frame with polyamide thermal break

RECYCLE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.771E+009	33.3	422.878	31.7
Manufacture	7.126E+008	3.5	56.704	4.2
Transport	5.843E+007	0.3	4.207	0.3
Use	1.274E+010	62.7	849.438	63.6
Disposal	2.597E+007	0.1	1.818	0.1
End of life potential	-5.378E+009	-26.5	-326.436	-24.5
Total (for first life)	**2.031E+010**	**100**	**1335.045**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	1.354E+009		8.900E+001	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminum frame	Aluminum, 6060, T4	0.5%	27.1	1.0	27.1
Thermal break	PA69 (unfilled)	Virgin (0%)	10.0	1.0	10.0
Total				2.0	37.1

Cont.

Energy (J)	%	CO2 footprint (kg)	%
5.378E+009	79%	351.8	83%
1.393E+009	21%	71.1	17%
6.771E+009	100	422.9	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Metal powder forming	27.1	6.510E+008	91.3	52.1	91.8
Thermal break	Polymer extrusion	10.0	6.166E+007	8.7	4.6	8.2
Total			7.126E+008	100	56.7	100

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	1.050E+006	5.843E+007	100.0	4.2	100.0
Total		1.050E+006	5.843E+007	100	4.2	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	27.1	4.268E+007	73.0	3.1	73.0
Thermal break	10.0	1.575E+007	27.0	1.1	27.0
Total	37.1	5.843E+007	100	4.2	100.0

USE

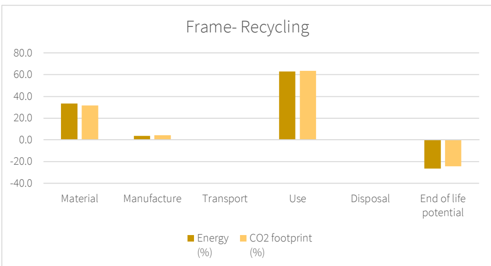
Energy input and output type	Electric to mechanical (electric motors)
Country of use	Netherlands
Power rating (kW)	0.1
Usage (hours per day)	10.0
Usage (days per year)	200.0
Product life (years)	15.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Recycle	1.897E+007	73.0	1.1	73.0
Thermal break	Recycle	7.000E+006	27.0	0.5	27.0
Total		2.597E+007	100	1.6	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Recycle	-4.458E+009	82.9	-279.5	85.6
Thermal break	Recycle	-9.206E+008	17.1	-46.9	14.4
Total		-5.378E+009	100	-326.4	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Frame | Reman. Scenario

REMANUFACTURE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	6.771E+009	33.4	422.878	31.8
Manufacture	7.126E+008	3.5	56.704	4.3
Transport	1.113E+007	0.1	0.801	0.1
Use	1.274E+010	62.9	849.438	63.9
Disposal	7.420E+006	0.0	0.519	0.0
End of life potential	-6.660E+009	-32.9	-415.087	-31.2
Total (for first life)	**2.024E+010**	**100**	**1330.339**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	1.350E+009		88.7	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminum frame	Aluminum, 6060, T4	0.5%	27.1	1.0	27.1
Thermal break	PA69 (unfilled)	Virgin (0%)	10.0	1.0	10.0
Total				2.0	37.1

Cont.

Energy (J)	%	CO2 footprint (kg)	%
5.378E+009	79%	351.8	83%
1.393E+009	21%	71.1	17%
6.771E+009	100	422.9	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Metal powder forming	27.1	6.510E+008	91.3	52.1	91.8
Thermal break	Polymer extrusion	10.0	6.166E+007	8.7	4.6	8.2
Total			7.126E+008	100	56.7	100

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	1.113E+007	100.0	0.8	100.0
Total		2.000E+005	1.113E+007	100	0.8	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	27.1	8.130E+006	73.0	0.6	73.0
Thermal break	10.0	3.000E+006	27.0	0.2	27.0
Total	37.1	1.113E+007	100	0.8	100.0

USE

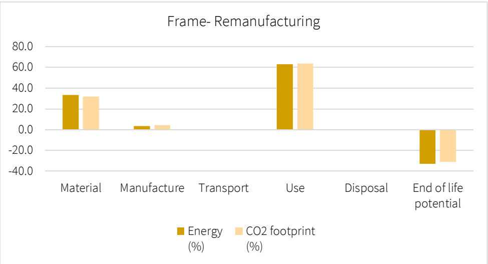
Energy input and output type	Electric to mechanical (electric motors)
Country of use	Netherlands
Power rating (kW)	0.1
Usage (hours per day)	10.0
Usage (days per year)	200.0
Product life (years)	15.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Re-manufacture	5.420E+006	73.0	0.4	73.0
Thermal break	Re-manufacture	2.000E+006	27.0	0.1	27.0
Total		7.420E+006	100	0.5	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Re-manufacture	-5.297E+009	79.5	-346.1	83.4
Thermal break	Re-manufacture	-1.363E+009	20.5	-69.0	16.6
Total		-6.660E+009	100.0	-415.1	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Frame | Reuse Scenario

REUSE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	0.000E+000	0.0	0.000	31.8
Manufacture	0.000E+000	0.0	0.000	4.3
Transport	1.113E+007	0.1	0.801	0.1
Use	1.274E+010	99.9	849.438	99.8
Disposal	7.420E+006	0.1	0.519	0.1
End of life potential	-6.660E+009	-52.2	-415.087	-48.8
Total (for first life)	**1.276E+010**	**100**	**850.758**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	8.507E+008		56.7	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminum frame	Aluminum, 6060, T4	Reused part	27.1	1.0	27.1
Thermal break	PA69 (unfilled)	Reused part	10.0	1.0	10.0
Total				2.0	37.1

Cont.

Energy (J)	%	CO2 footprint (kg)	%
0.000E+000		0.0	
0.000E+000		0.0	
0.000E+000	100.0	0.0	100.0

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame						
Thermal break						
Total				100.0		100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	1.113E+007	100.0	0.8	100.0
Total		2.000E+005	1.113E+007	100	0.8	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	27.1	8.130E+006	73.0	0.6	73.0
Thermal break	10.0	3.000E+006	27.0	0.2	27.0
Total	37.1	1.113E+007	100	0.8	100.0

USE

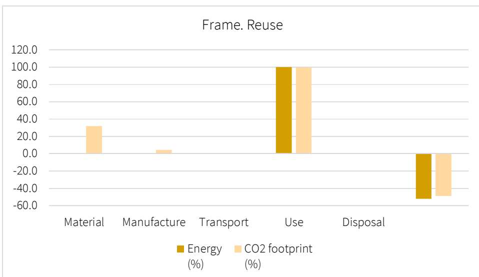
Energy input and output type	Electric to mechanical (electric motors)
Country of use	Netherlands
Power rating (kW)	0.1
Usage (hours per day)	10.0
Usage (days per year)	200.0
Product life (years)	15.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Reuse	5.420E+006	73.0	0.4	73.0
Thermal break	Reuse	2.000E+006	27.0	0.1	27.0
Total		7.420E+006	100	0.5	100.0

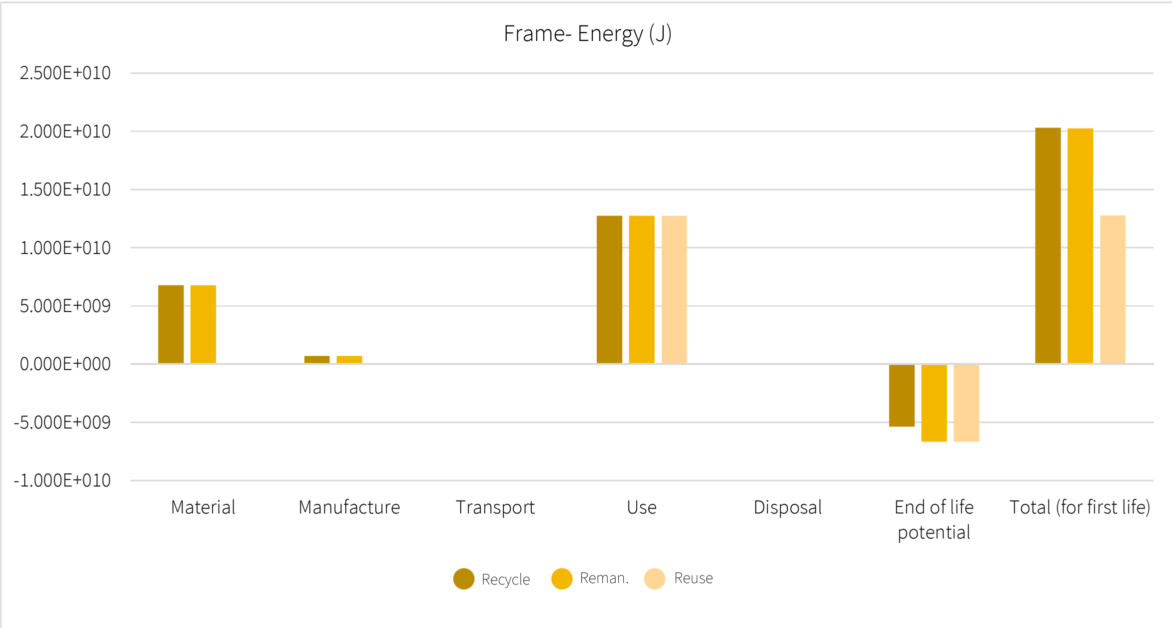
EOL POTENTIAL

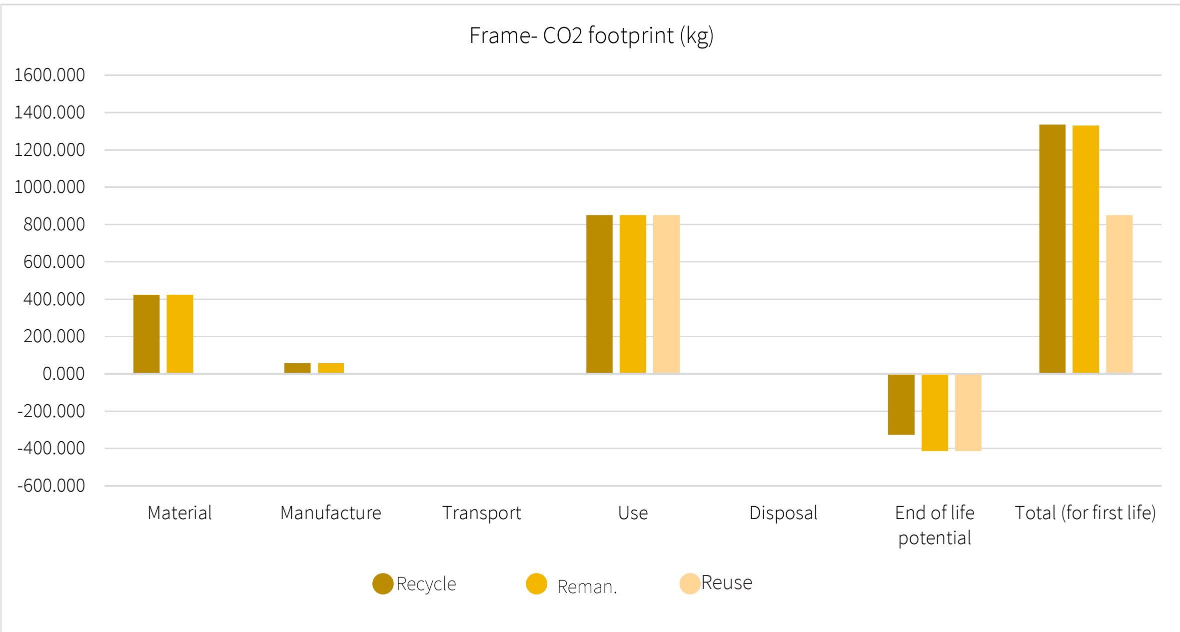
Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminum frame	Reuse	0.000E+000	0.0	0.0	0.0
Thermal break	Reuse	0.000E+000	0.0	0.0	0.0
Total		0.000E+000	0.0	0.0	0.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Frame | Comparison





XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Infill | Recycle Scenario

RECYCLE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1.645E+009	93.9	108.285	93.1
Manufacture	7.801E+007	4.5	5.95	5.1
Transport	2.079E+007	1.2	1.497	1.3
Use	0.000E+000	0.0	0.000	0.0
Disposal	8.740E+006	0.5	0.612	0.5
End of life potential	-1.159E+009	-66.1	-72.663	-62.5
Total (for first life)	**1.753E+009**	**100**	**116.344**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	1.155E+008		7.650E+000	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminium cover	Aluminum, 6060, T4	Typical %	12.2	1.0	12.2
Insulation	PVC foam (semi-rigid, closed cell, 0.500)	Virgin (0%)	1.0	1.0	1.0
Total				2.0	13.2

Cont.

Energy (J)	%	CO2 footprint (kg)	%
1.573E+009	96%	105.2	97%
7.202E+007	4%	3.1	3%
1.645E+009	100	108.3	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Extrusion, foil rolling	12.2	5.805E+007	74.4	4.35	73.2
Insulation	Polymer molding	1.0	1.997E+007	25.6	1.60	26.8
Total			7.801E+007	100	5.95	100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	1.050E+006	2.079E+007	100.0	1.5	100.0
Total		1.050E+006	2.079E+007	100	1.5	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	12.2	1.922E+007	92.4	1.4	92.4
Insulation	1.0	1.575E+006	7.6	0.1	7.6
Total	13.2	2.079E+007	100	1.5	100.0

USE

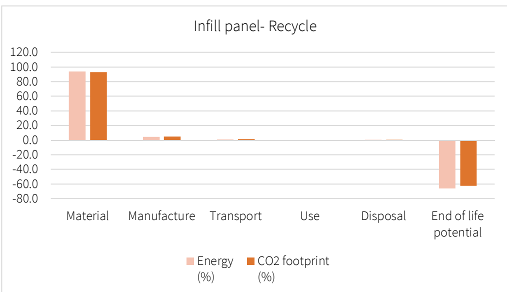
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Recycle	8.540E+006	97.7	0.6	97.7
Insulation	Landfill	2.000E+005	2.3	0.0	2.3
Total		8.740E+006	100	0.6	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Recycle	-1.159E+009	100.0	-72.7	100.0
Insulation	Landfill	0.000E+000	0.0	0.0	0.0
Total		-1.159E+009	100	-72.7	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Infill | Reman. Scenario

REMANUFACTURE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	1.645E+009	95.1	108.285	94.4
Manufacture	7.801E+007	4.5	5.951	5.2
Transport	3.960E+006	0.2	0.285	0.2
Use	0.000E+000	0.0	0.000	0.0
Disposal	2.640E+006	0.2	0.185	0.2
End of life potential	-1.605E+009	-92.8	-105.513	-92.0
Total (for first life)	**1.730E+009**	**100**	**114.706**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	1.153E+008		7.647E+000	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminium cover	Aluminum, 6060, T4	Typical %	12.2	1.0	12.2
Insulation	PVC foam (semi-rigid, closed cell, 0.500)	Virgin (0%)	1.0	1.0	1.0
Total				2.0	13.2

Cont.

Energy (J)	%	CO2 footprint (kg)	%
1.573E+009	96%	105.2	97%
7.202E+007	4%	3.1	3%
1.645E+009	100	108.3	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Extrusion, foil rolling	12.2	5.805E+007	74.4	4.35	73.2
Insulation	Polymer molding	1.0	1.997E+007	25.6	1.60	26.8
Total			7.801E+007	100	5.95	100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	3.960E+006	100.0	0.3	100.0
Total		2.000E+005	3.960E+006	100	0.3	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	12.2	3.660E+006	92.4	0.3	92.4
Insulation	1.0	3.000E+005	7.6	0.0	7.6
Total	13.2	3.960E+006	100	0.3	100.0

USE

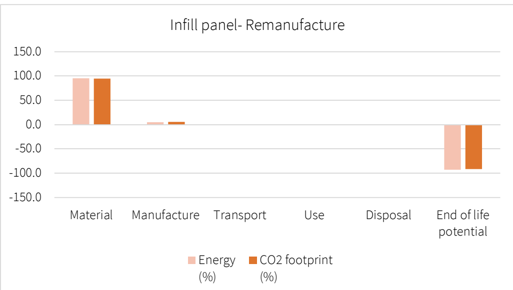
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Re-manufacture	2.440E+006	92.4	0.17	92.4
Insulation	Re-manufacture	2.000E+005	7.6	0.01	7.6
Total		2.640E+006	100	0.2	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Re-manufacture	-1.536E+009	95.7	-102.6	97.3
Insulation	Re-manufacture	-6.902E+007	4.3	-2.9	2.7
Total		-1.605E+009	100	-105.5	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Infill | Reuse Scenario

REUSE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	7.202E+007	73.1	3.086	59.9
Manufacture	1.997E+007	20.3	1.600	31.0
Transport	3.960E+006	4.0	0.285	5.5
Use	0.000E+000	0.0	0.000	0.0
Disposal	2.640E+006	2.7	0.185	3.6
End of life potential	-7.202E+007	-73.1	-3.086	-59.9
Total (for first life)	**9.858E+007**	**100**	**5.16**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	5.241E+006		2.371E-001	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Aluminium cover	Aluminum, 6060, T4	Reused part	12.2	1.0	12.2
Insulation	PVC foam (semi-rigid, closed cell, 0.500)	Virgin (0%)	1.0	1.0	1.0
Total				2.0	13.2

Cont.

Energy (J)	%	CO2 footprint (kg)	%
0.000E+000	0%	0.0	0%
7.202E+007	100%	3.1	100%
7.202E+007	100	3.1	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Insulation	Polymer molding	1.0	1.997E+007	100.0	1.60	100.0
Total			1.997E+007	100	1.60	100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	3.960E+006	100.0	0.3	100.0
Total		2.000E+005	3.960E+006	100	0.3	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	12.2	3.660E+006	92.4	0.3	92.4
Insulation	1.0	3.000E+005	7.6	0.02	7.6
Total	13.2	3.960E+006	100	0.3	100.0

USE

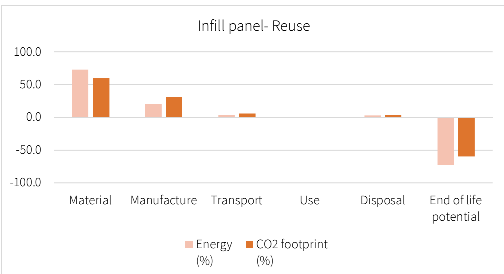
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Reuse	2.440E+006	92.4	0.2	92.4
Insulation	Reuse	2.000E+005	7.6	0.01	7.6
Total		2.640E+006	100	0.18	100.0

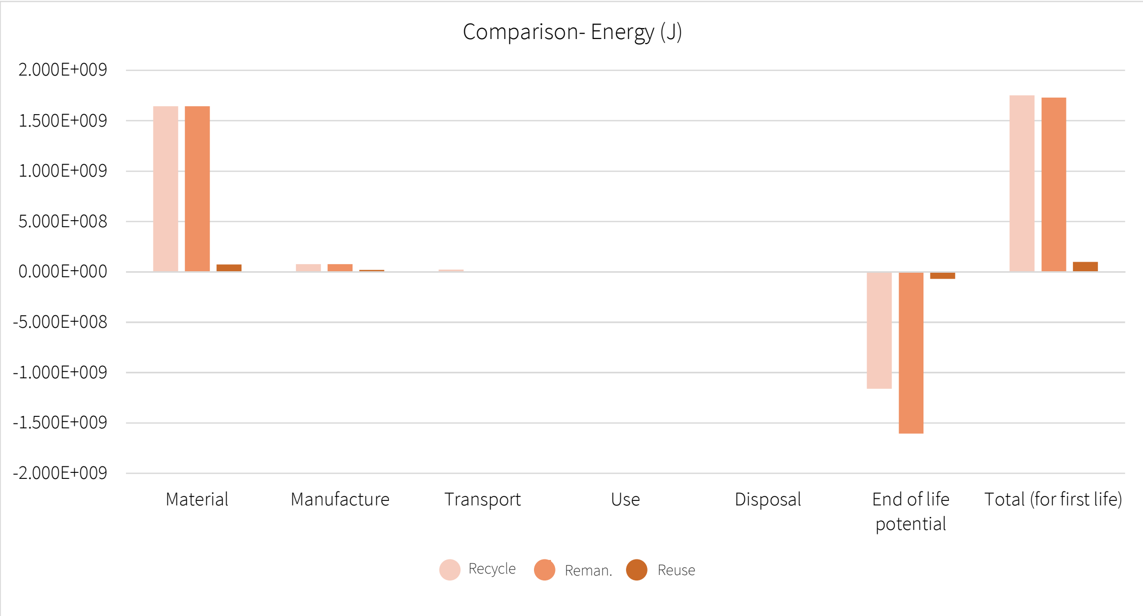
EOL POTENTIAL

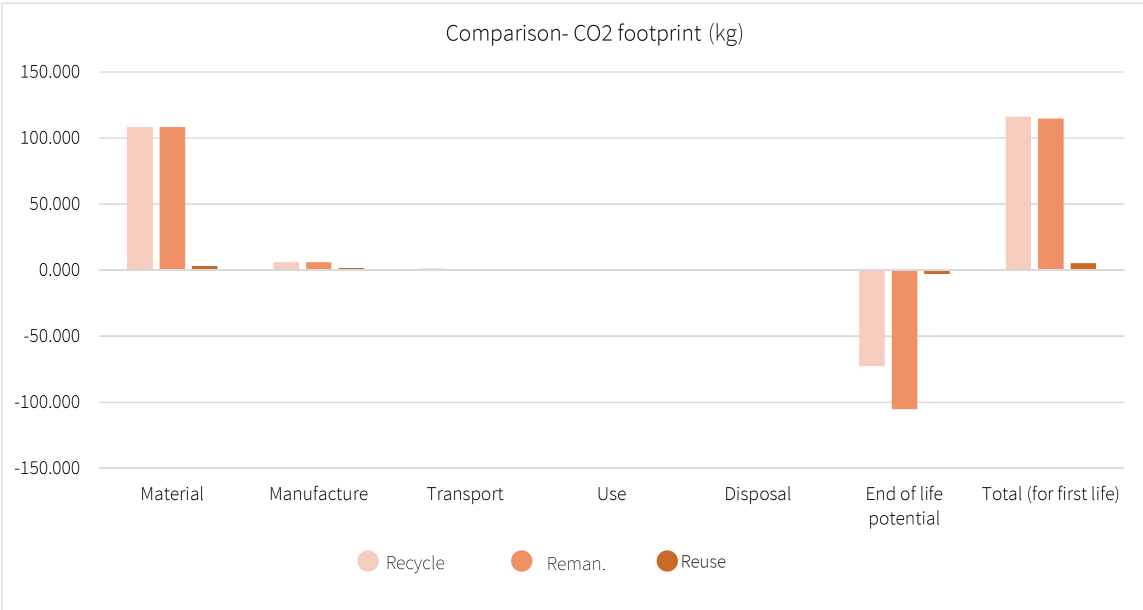
Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Aluminium cover	Reuse	0.000E+000	0.0	0.0	0.0
Insulation	Reuse	-7.202E+007	100.0	-3.1	100.0
Total		-7.202E+007	100	-3.1	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Infill | Comparison





XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Column | Recycle Scenario

RECYCLE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	5.848E+008	69.2	43.748	69.4
Manufacture	1.877E+008	22.2	14.08	22.3
Transport	5.040E+007	6.0	3.629	5.8
Use	0.000E+000	0.0	0.000	0.0
Disposal	2.240E+007	2.6	1.568	2.5
End of life potential	-3.122E+008	-36.9	-22.351	-35.5
Total (for first life)	**8.453E+008**	**100**	**63.024**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	5.635E+007		4.20	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Steel column	Carbon steel, AISI 1020, as	59.0%	32.0	1.0	32.0
Total				1.0	32.0

Cont.

Energy (J)	%	CO2 footprint (kg)	%
5.848E+008	100%	43.8	100%
5.848E+008	100	43.8	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Extrusion, foil rolling	32.0	1.877E+008	100.0	14.08	100.0
Total			1.877E+008	100	14.08	100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	1.050E+006	5.040E+007	100.0	3.6	100.0
Total		1.050E+006	5.040E+007	100	3.6	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Steel column	32.0	5.040E+007	100.0	3.6	100.0
Total	32.0	5.040E+007	100	3.6	100.0

USE

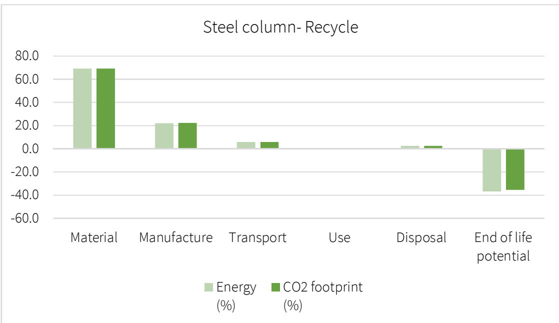
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Recycle	2.240E+007	100.0	1.6	100.0
Total		2.240E+007	100	1.6	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Recycle	-3.122E+008	100.0	-22.4	100.0
Total		-3.122E+008	100	-22.4	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Column | Reman. Scenario

REMANUFACTURE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	5.848E+008	74.2	43.748	74.2
Manufacture	1.877E+008	23.8	14.08	23.9
Transport	9.600E+006	1.2	0.691	1.2
Use	0.000E+000	0.0	0.000	0.0
Disposal	6.400E+006	0.8	0.448	0.8
End of life potential	-4.888E+008	-62.0	-37.028	-62.8
Total (for first life)	**7.885E+008**	**100**	**58.966**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	5.257E+007		3.93	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Steel column	Carbon steel, AISI 1020, as	59.0%	32.0	1.0	32.0
Total				1.0	32.0

Cont.	Energy (J)	%	CO2 footprint (kg)	%
	5.848E+008	100%	43.8	100%
	5.848E+008	100	43.8	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Extrusion, foil rolling	32.0	1.877E+008	100.0	14.08	100.0
Total			1.877E+008	100	14.08	100.0

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	9.600E+006	100.0	0.7	100.0
Total		2.000E+005	9.600E+006	100	0.7	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Steel column	32.0	9.600E+006	100.0	0.7	100.0
Total	32.0	9.600E+006	100	0.7	100.0

USE

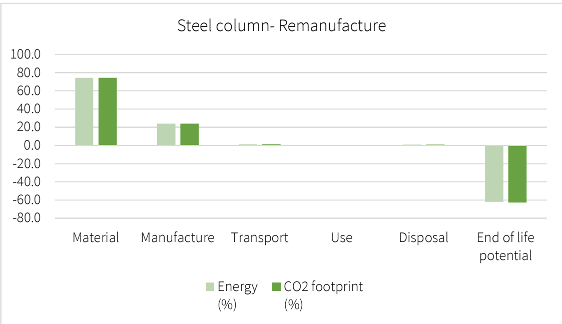
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Remanufacture	6.400E+006	100.0	0.5	100.0
Total		6.400E+006	100	0.5	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Remanufacture	-4.888E+008	100.0	-37.0	100.0
Total		-4.888E+008	100	-37.0	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Column | Reuse Scenario

REUSE

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	0.000E+000	0.0	0.000	0.0
Manufacture	0.000E+000	0.0	0.000	0.0
Transport	9.600E+006	60.0	0.691	60.7
Use	0.000E+000	0.0	0.000	0.0
Disposal	6.400E+006	40.0	0.448	39.3
End of life potential	0.000E+000	0.0	0.000	0.0
Total (for first life)	**1.600E+007**	**100**	**1.14**	**100**

	Energy (J/year)		CO2 (kg/year)	
Equivalent annual environmental burden (averaged over 15 year product life):	1.067E+006		0.076	

BREAKDOWN

MATERIAL

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)
Steel column	Carbon steel, AISI 1020, as	Reused part	32.0	1.0	32.0
Total				1.0	32.0

Cont.

Energy (J)	%	CO2 footprint (kg)	%
0.000E+000	100%	0.0	100%
0.000E+000	100	0.0	100

MANUFACTURE

Component	Process	Amount processed (kg)	Energy (J)	%	CO2 footprint (kg)	%
Total						

TRANSPORT

Stage name	Transport type	Distance (m)	Energy (J)	%	CO2 footprint (kg)	%
From CITG to U-park	14 tonne (2 axle) truck	2.000E+005	9.600E+006	100.0	0.7	100.0
Total		2.000E+005	9.600E+006	100	0.7	100.0

Component	Mass (kg)	Energy (J)	%	CO2 footprint (kg)	%
Steel column	32.0	9.600E+006	100.0	0.7	100.0
Total	32.0	9.600E+006	100	0.7	100.0

USE

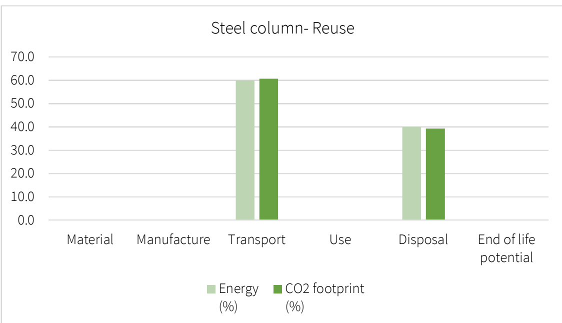
Mode	%
Static	0.0
Mobile	0.0
Total	0.0

DISPOSAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Reuse	6.400E+006	100.0	0.5	100.0
Total		6.400E+006	100	0.5	100.0

EOL POTENTIAL

Component	End of life option	Energy (J)	%	CO2 footprint (kg)	%
Steel column	Reuse	0.000E+000	100.0	0.0	100.0
Total		0.000E+000	100	0.0	100.0



XIII. QUANTITATIVE ASSESSMENT BREAKDOWN

Energy & CO_2: Column | Comparison