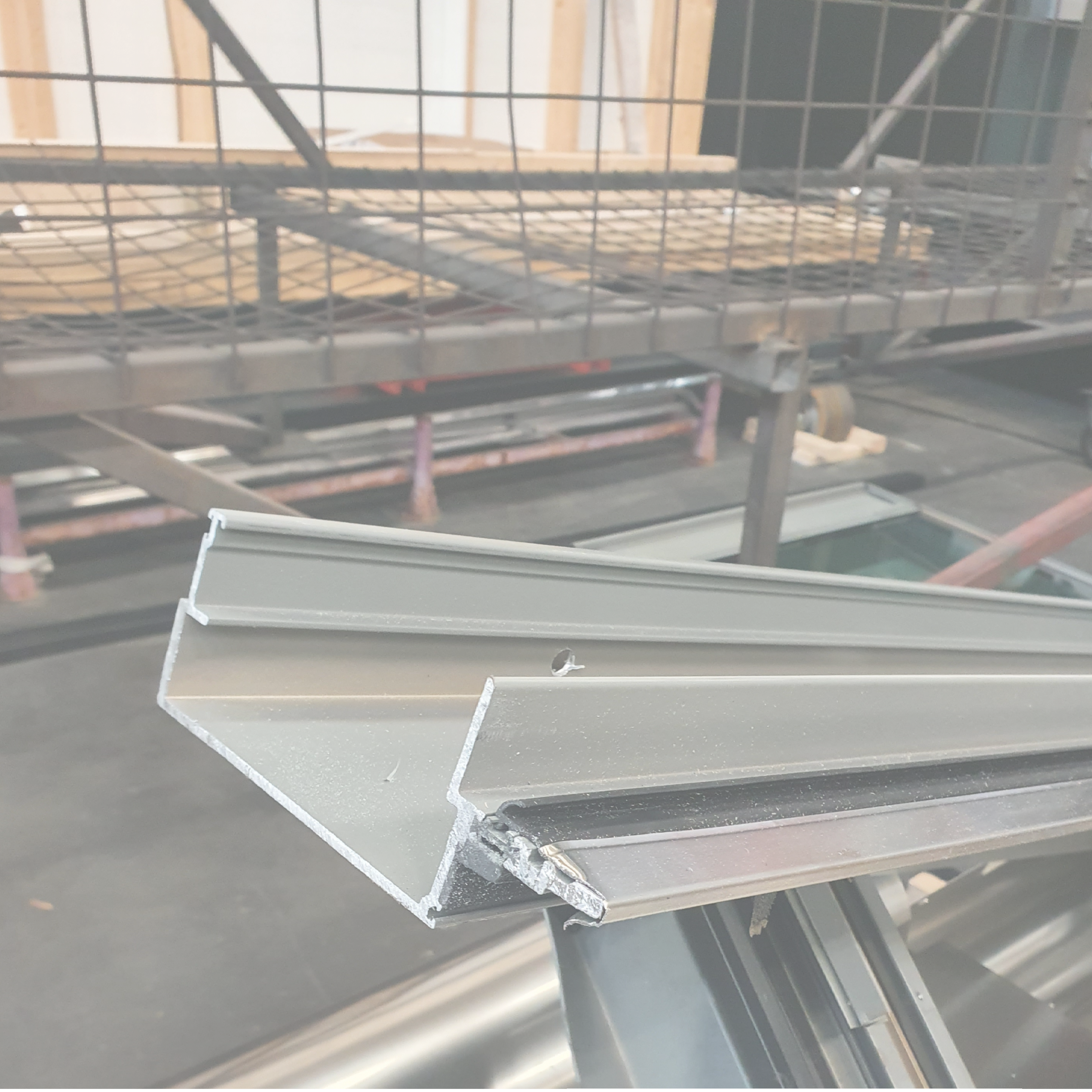

Circularity of existing aluminium unitised curtain wall facades

Unlocking Value from Waste

RJP
Teeuwen

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by

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Preface

This thesis concludes the Master of Civil Engineering at the Technical University of Delft. I was engaged in researching and writing the thesis *Circularity of existing aluminium unitised curtain wall facades*, over the course of December 2022 to September 2023. For now, I would like to thank everyone who contributed, directly or indirectly to this accomplishment.

First I would like to thank my graduation committee, Christian Louter, Roel Schipper Jagoda Cupać and Hans Jansen for their guidance over the course of this master's thesis. As this thesis was conducted at Scheldebouw, I would like to extend my special thanks to Hans, the Tender Leader at the company. I appreciate your guidance and for involving me in the actualities at Scheldebouw. Moreover, I would like to thank Janneke Verkerk, sustainability manager at Scheldebouw, for her interesting insights into sustainability and the current projects taking place both within and outside the company.

Secondly, I would like to thank Scheldebouw BV for the opportunity to execute my master's thesis at their production facility in Middelburg. Scheldebouw has given me the opportunity to work with their projects and specialities to gather information and knowledge about the topic of facades. In addition to that I would like to thank Scheldebouw BV for the opportunity to execute my master's thesis at their production facility in Middelburg. Giving me the chance to visit the dismantling of the Citibank facade, include me in a project at the Faculty of Architecture and take me on a site visit in London. This site visit showed me the relevance of the topic described in this thesis and gave me the enthusiasm to work on this project. Furthermore, the tender team in which I was welcomed gave me all the technical insights I needed and made me feel welcome in the office in Middelburg.

Last, I am grateful to my friends and family for their assistance and support during this process. Additionally, I want to thank U-BASE for allowing me to participate in several committees and work on my skill set. I want to specifically draw attention to the Concrete Canoe Event, organised during the writing of the thesis, in which Delft hosted 300 students from across Europe and the Netherlands to exhibit their creative concepts.

Rianne Teeuwen
Delft, October 2023

Abstract

The circular potential of existing aluminium curtain wall facades is investigated in this study. The focus is primarily on reuse, refurbishment and re-manufacturing, aiming to raise the value of materials that have not yet reached the end of their service life. The increasing concern about resource depletion, damage to the ecosphere and the need for sustainable development increases the demand for sustainable strategies in many industries. The building industry is one of the most polluting industries at current times and with governments incorporating laws regarding these topics, the need for methods to reduce the impact in this industry is needed. Facades have a great impact on the whole life carbon impact of a building and show potential for reuse. Scheldebouw, a facade producer in the Netherlands, connected to Permasteelisa, is looking for possible ways to make the construction industry more sustainable.

This study aims to reduce the take-make-dispose culture, by creating circular strategies for existing curtain wall facades. It was observed that those facades lose their function before their end-of-life stage is reached. The remaining value and potential that was wasted in this case could be avoided. The objective of this thesis is to develop strategies to reuse existing aluminium curtain wall facade elements, to diminish waste and reduce resource depletion. To quantify the impact of these strategies the life cycle analysis is used to calculate the amount of emitted carbon.

A mixed-method research was conducted, which involved integrating interviews with experts in the facade and material industry along with a review of literature, resulting in the development of a qualitative understanding. Integrating this with reference studies, the application of reuse was further examined. Lastly, strategies have been formed, which have been applied to a relevant case.

Facades do have the potential for reuse, as demonstrated in this study. Facades play a crucial role in enclosing indoor spaces, which leads to various specific characteristics that make both facade structures in themselves and in their reuse rather complex. Facade systems are often uniquely developed, making it difficult to locate a match for reuse. Eight general strategies have been defined to create incentives for reuse. A method for calculating the avoided carbon was created to quantify the potential of the strategies and provide an incentive for clients to include these circular strategies. Overall, the research outcomes offer a framework that has the potential to reduce resource depletion and increase value retention in the facade industry. Crucial elements were determined and components that show potential for reuse were defined. Risks and uncertainties have been identified, as well as the need for incentives for producers, clients, and policymakers. As mentioned above, finding a receiving project that matches the donor material and designing with these materials still appears to be difficult.

Regarding carbon emissions, beneficial strategies were defined. Refurbishment can achieve an 86% carbon reduction with 99% of the materials being reused. Re-manufacturing offers a 49% overall carbon reduction with a 59% material saving. Challenges lie in glazing reuse, particularly sealant and spacer components. Implementing re-manufacturing with glass replacement saves 27% embodied carbon and reduces waste by 21% at the donor building and 28% in the product and construction stages. Additionally, it was found that the refurbished and re-manufactured panels will outperform a traditional waste scenario when these results are balanced with operating emissions.

This research contributes to the incorporation of circular strategies in the design and construction of existing facade elements, creating a fitting extension to the existing frameworks: the 10R framework and the value hill. The case study, Citibank, is a typical project where, at the time of writing facade elements are becoming available. Strategies to reintegrate these panels into a new project are researched. The application of the circular strategies in an actual project illustrates the possibilities and benefits as well as the allocation of risks and challenges. Based on the study's findings, it is recommended to further experiment with these strategies, both on physical, financial and feasibility aspects.

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1
Introduction

Companies are placing more emphasis on circularity. The Netherlands wants to achieve complete circularity by 2050 (Ministerie van Infrastructuur en Waterstaat, 2022), which means that businesses are working to enhance their procedures towards becoming more circular. In addition, the problem of resource scarcity is getting worse every day while the demand for these resources is rising (Merrild, 2016)

Materials often do not reach their end-of-life stage within the building's functional life span, due to the demand in the building sector changing rapidly. Buildings lose their function or are torn down for various reasons, such as new developments or changes in function. One of these elements is the facade, apart from buildings losing their function, also, the facade might lose its function and be dismantled. This implies that used facade elements with remaining technical life are becoming available. To prevent these from becoming landfills this research is set in place.

In most businesses, linear material life, as presented in Figure 1.1, is still the main way of making use of materials. The general way of using materials is 'Take-make-dispose' (MacArthur, 2014). Materials are used inefficiently, where a lot of materials are wasted and disposed of after their first use. The construction industry accounts for 40 per cent of Europe's material and energy consumption (United Nations Environment Programme, 2021). To be able to make the transition to a circular economy there is a need to use materials to their full potential and implement circular strategies. The value of these materials can be increased and the negative impact on the environment reduced. This can be done by implementing the strategies of reuse, refurbishment, re-manufacture and recycling, which will be further discussed in this research.

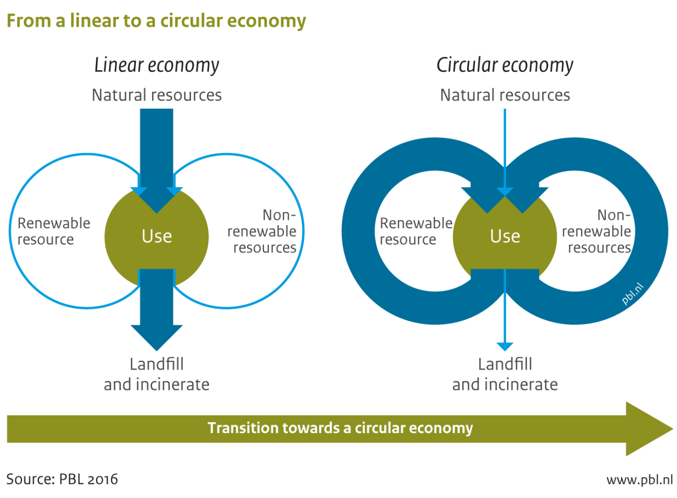


Figure 1.1: Transition towards a circular economy (PBL, 2017)

By recycling or reusing items, resources can be used more effectively and saved to accomplish the objectives set by the government and companies. Recovering the value of materials without requiring too many interventions is a smart approach to comply with the circular economy principles. This translates to re-purposing whole elements or disassembling them and reusing the components. In comparison, recycling materials requires more energy, when circular use of the materials is implemented, action can be reduced and components can be used to their full potential.

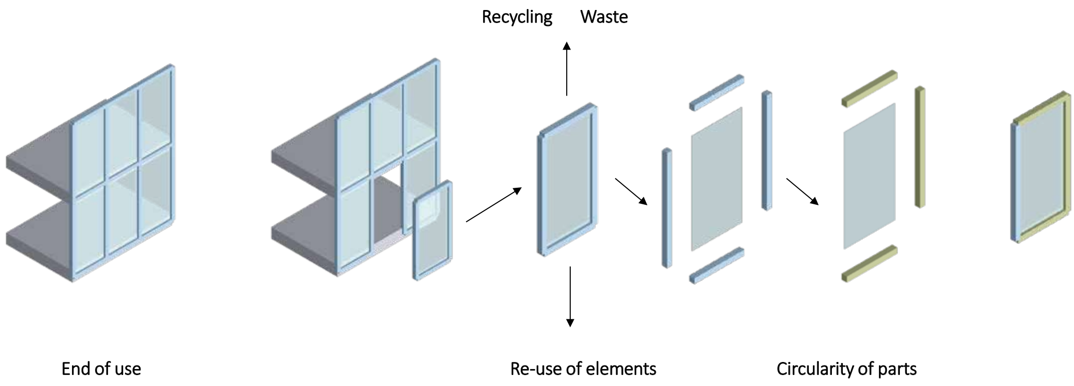
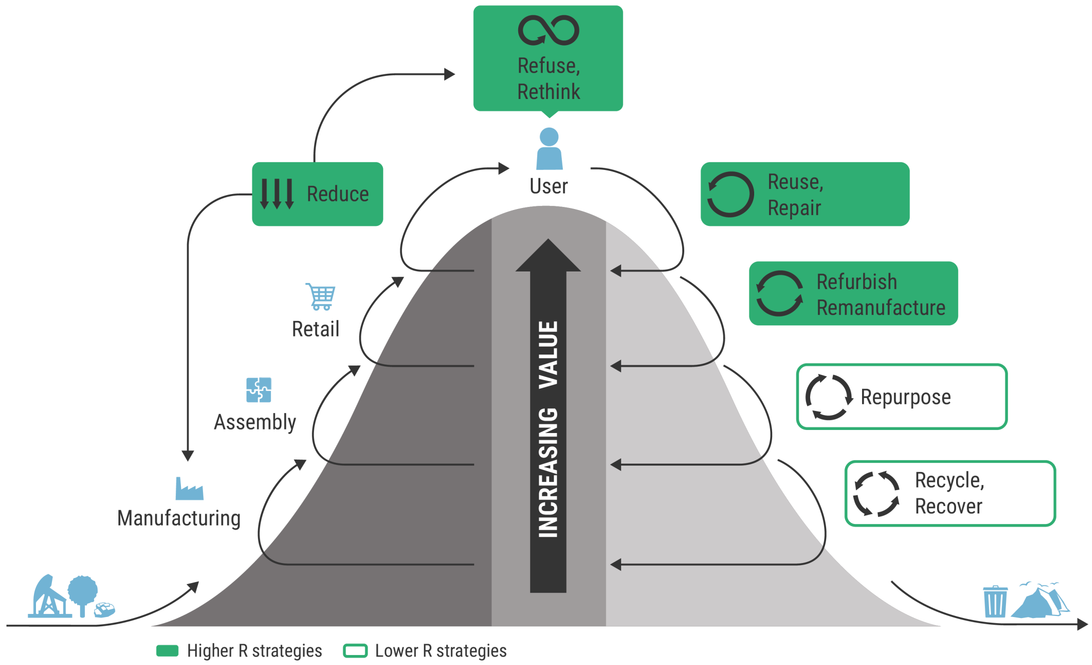


Figure 1.2: Overview of the research

One of these elements that are suitable for recycling and reusing are facade elements, and in specific aluminium curtain wall facades, which is the focus of this research (Figure 1.2). When looking at these facades, they are often replaced before the components reach their intended service life, and there is a vast opportunity to increase the value of these elements. Especially when looking at the different elements within these aluminium facade panels. Different materials within an aluminium curtain wall facade panel can be found which have varying life spans and potentials.

By showing the possibilities of implementing circular strategies, the way of thinking in the construction industry can shift to a more circular mindset. Savings regarding the environment can be made on different levels. The value of these materials can be recovered. In circular strategies, the value is retained within the material but the value is added to the component. According to Achterberg, 2016, there are 5 levels of this strategy, Repair/maintain, reuse/redistribute, refurbish, re-manufacture or recycle. The latter, recycling, still uses a lot of energy and these strategies are used more in the current age (Achterberg et al., 2016). It is more environmentally profitable to focus on the remaining strategies. Another frequently used framework is based on 10 common circular economy strategies: recover, recycle, re-purpose, re-manufacture, refurbish, repair, reuse, reduce, rethink and refuse. Metabolic has made a combination of the value hill of Achterberg and the 10R framework, this is pictured in Figure 1.3.



SMARTER PRODUCT USE AND MANUFACTURE

Refuse
Make product redundant by abandoning its function or by offering the same function with a radically different product.

Rethink
Make product use more intensive (e.g. by sharing product).

Reduce
Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.

EXTEND LIFESPAN OF PRODUCTS AND ITS PARTS

Reuse
Reuse by another consumer of discarded product which is still in good condition and fulfils its original function.

Repair
Repair and maintenance of defective product so it can be used with its original function.

Refurbish
Restore an old product and bring it up to date.

Remanufacture
Use parts of discarded product in a new product with the same function.

USEFUL APPLICATION OF MATERIALS

Repurpose
Use discarded product or its parts in a new product with a different function.

Recycle
Process materials to obtain the same (high grade) or lower (low grade) quality.

Recover
Incineration of material with energy recovery.

An adaptation of the Value Hill Model to include the 9R Framework. Buren, N., Demmers, M., Heijden, R., & Witlox, F. (2016). Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments. | Circle Economy, Het Groene Brein, Nuovalente, Sustainable Finance Lab, TU Delft (2016). Master Circular Business With The Value Hill. | Kirchherr, J., Reike, D. & Hekkert, M. (2017). Conceptualizing the Circular Economy: An Analysis of 114 Definitions. | Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring Innovation in the Product Chain.

METABOLIC

Figure 1.3: Adapted value hill model using the 10R framework (Metabolic et al., 2019)

1.1. Background and motivation

This thesis is done in collaboration with Scheldebouw, an aluminium curtain wall facade producer, looking to better understand the circular potential of their products. In addition, the regulations in both the Netherlands, but also Europe, in terms of sustainability started to become more strict.

1.1.1. Introduction to Scheldebouw

Scheldebouw was founded in 1933, during this time they manufactured aluminium parts and furniture for the shipping and aviation industry. In 1958 they started producing aluminium curtain walls. Over the years they grew to be a premium brand in facade construction in the Benelux, United Kingdom, Scandinavia and Central/East Europe. Scheldebouw creates a unique design for every project, it is tailored to fit the architect's view and meet the specific performance requirements. Their products are completely assembled in the production hall. Thus, limiting on-site work and reducing construction time as well as waste.

Scheldebouw is looking for a way to increase the circular mindset of the company. It happens more and more that facade elements are being brought back to the production hall before their end-of-life. Often these elements are discarded, however, Scheldebouw wants to improve its objective and start using the materials more circularly and, in this way, enhance sustainability within the company.

1.1.2. Dutch Government: Transition agenda

The Dutch government initiated a circular economy program in 2016. This was aimed at developing a fully circular economy in the Netherlands by 2050. For five sectors a transition agenda was published. One of these five is the construction industry. In this publication, a definition for a circular building was given:

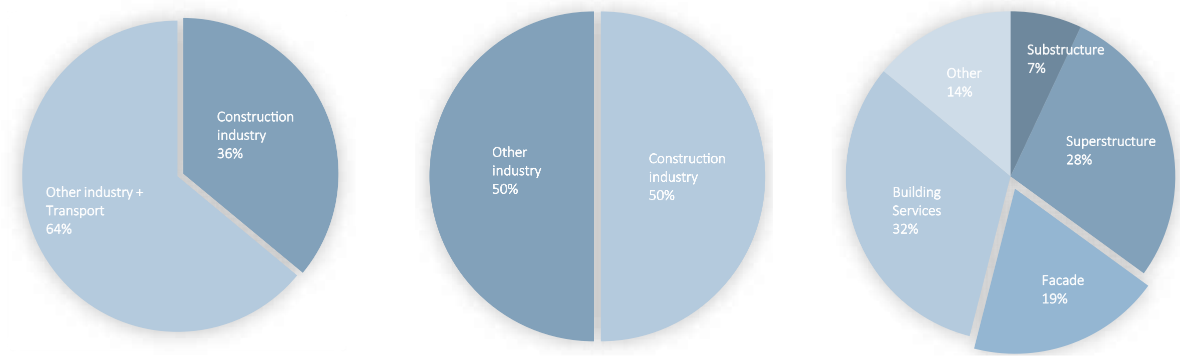
"The development, use and reuse of buildings, area and infrastructure, without avoidable depletion of natural resources, pollution of the environment or negatively impacting ecosystems. The construction which is economically responsible and contributes to the well-being of humans and animals, now and in the future" (Ministerie van Infrastructuur en Waterstaat, 2022, pp. 150–153).

In this document, the emphasis is on the necessity for the development of a uniform, accessible and reliable measuring instrument to assess circularity and how the added value of a circular building can be measured and communicated. The incorporation of circular strategies into the sector asks for a supply and demand for circular products and processes. But adding to this a market mechanism should be set into place to facilitate and encourage implementation processes and products. New policy regulations and laws relating to circularity have been developed, introduced and enforced from a national to a regional scale in the last couple of years.

1.2. Problem Statement

The built environment is thought of to be a linear industry (Merrild, 2016). Non-renewable resources are depleted and a lot of waste is produced. By depleting non-renewable resources and polluting the Eco-sphere a lot of damage is being done. The current mindset has a huge effect on global warming, resource scarcity, acidification of oceans, and disruption of ecosystems (Metabolic et al., 2019). These effects on the Eco-sphere are increasing and becoming more of an issue every day.

The building sector contributes significantly to these environmental issues. 40 per cent of the global energy demand and 30 per cent of the greenhouse gas emissions can be attributed to the building sector (Santiago Fink, 2011). A great level of potential is shown for the reduction of greenhouse gas emissions in this industry. The construction industry accounts for 50 per cent of the use of raw materials (Metabolic et al., 2019). Addressing these impacts through circular and climate-neutral development is thus crucial. These numbers can be seen in Figure 1.4.Facades account for between 10 per cent and 31 per cent of the embodied carbon of a building (WBCSD, 2020). After the main load-bearing structure and substructure, is the facade the highest contributor to the embodied carbon of a building.



(a) Share of global energy (United Nations Environment Programme, 2021)

(b) Raw material use (Metabolic et al., 2019)

(c) Distribution of CO_2e/m^2 overall life cycle stages (WBCSD, 2020)

Figure 1.4: Graphs that showcase the impact of reuse of facade materials

Within Scheldebouw it has been noticed that it is a reoccurring situation where facade elements are becoming available after a certain amount of use years. Opportunities for Scheldebouw arise for purchasing back these elements and finding a way to re-purpose these panels and thus improve the sustainability of the company. Nevertheless, at this moment there is limited knowledge about the opportunities and potential for these components. Their aim is to use the materials to their full potential and in this way reduce waste and recourse depletion. How much value can be recovered when taking apart these aluminium curtain wall facade elements and reusing parts of them? Can it be beneficial to use methods like re-manufacturing or refurbishment to improve the quality of parts and use them again? In this way, it saves a lot of materials from becoming waste and adds more value to these materials.

Problem statement: *Is it possible to re-purpose parts of aluminium curtain wall facade elements to cut down waste and add value to the materials in these elements?*

1.3. Research Objectives

The objectives of this research contribute to the macro-objective:

Making the built environment less damaging to the environment by implementing circular strategies.

This objective is large and cannot be solved by solely this research. in spite of that, it can contribute to it by manageable objectives. The objective of this research that will contribute to the larger objective is:

Diminishing waste in the construction industry by developing strategies to use existing aluminium curtain wall facade elements circularly.

Looking at the above-mentioned problem statement of this research and the macro objective, the facade industry could play a significant role in this. When a facade is taken off a building, in the linear economy, this element is discarded or pieces are remelted for recycling, though, this costs energy. When looking at reusing elements or components of a building by implementing circular strategies like re-manufacturing, reusing or refurbishing the materials that are in these elements, energy, and material can be saved, as well as waste, polluting the environment.

1.4. Research framework

In this section, the research framework will be discussed. The research will be subdivided into four main sections: Literature and interviews, reference study, Strategy development and application. These four sections will be used to show the research questions and methodology. The research methodology is visually represented in Figure 1.5.

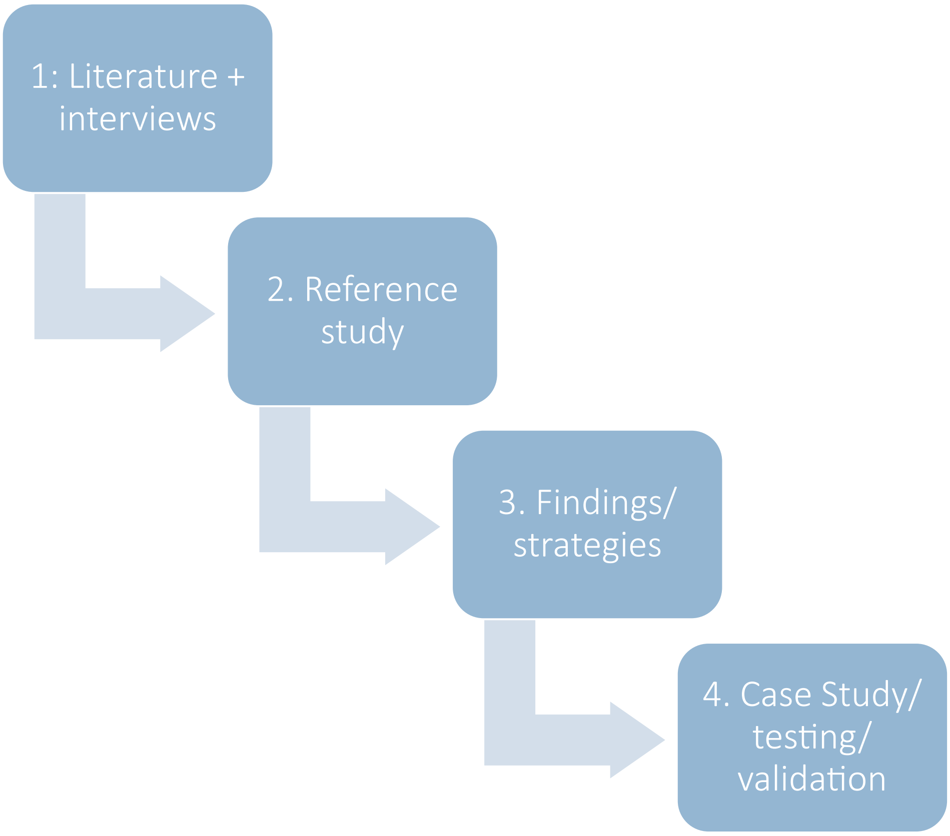


Figure 1.5: Visual representation of methodology

In regard to this research, a main question has been developed which will be answered with the sub-question developed in the paragraphs below. The questions have been grouped according to the corresponding section and method. The main research question:

What strategies can be developed to increase the circularity of unitised aluminium curtain wall facades?

Step 1: Literature and interviews

Scheldebouw has been making facades for over 60 years. Over the years, a great variety of projects have been realised. Learning from these projects and analysing their status gives more insight into these projects and their components. This is needed to obtain knowledge about the aluminium curtain wall facades that are used. Furthermore, professionals within Scheldebouw and outside, are consulted to further grasp the knowledge that is available by conducting interviews.

In addition, a literature review is done. The knowledge that is covered will be circular strategies that are known and which are applicable in this case. Furthermore, circularity within facades is further explored as to how this circularity can be accounted for.

Research questions

- Which strategies for circularity currently exist in the construction industry?
- How can circularity be accounted for in a life cycle analysis?
- What are the main characteristics of unitised aluminium curtain wall facades?
- What is the life span of the materials in an aluminium curtain wall facade?
- How are the materials in an aluminium curtain wall facade recycled?
- Why could unitised curtain walls lose their original function?

In this first part, mostly literature is used as well as interviews to obtain the knowledge of the professionals at Scheldebouw. The systems used within Scheldebouw are explored to get insight into the components and materials. These questions will be answered in Chapter 2 and Chapter 3.

Step 2: Reference Study

With the knowledge obtained a variety of reference studies are done to expand the knowledge of the facades. For these reference studies, a couple of projects are selected with a variety of characteristics and these are further explored. Interviews are conducted with professionals who are connected to these projects to further explore the opportunities and pitfalls of the circular use of facade components. The goal of this reference study is to gain knowledge about both sides of a reuse project, the donor side as well as the receiving side. By looking at projects where circularity principles have been applied, conclusions about these strategies can be made. The following projects are proposed to act as a reference study:

- *1 Triton Square - London*
- *Koningskade - The Hague / Floriade; The Natural Pavilion - Almere*
- *De Sateliet - Amsterdam*
- *Citibank - London*

Research questions

- What circular strategies have been applied in the reference studies?
- How were the environmental costs quantified in the reference studies?
- What have been the pitfalls in the reference studies?

The data needed for the reference study is provided by Scheldebouw, interviews and available information in the literature. It explores what strategies have been applied and what the benefits and shortcomings have been in these projects. Interviews with professionals who have been connected to these projects are executed. Adding to that the dismantling of a panel of Citibank gives insight into the method and options. These questions will be answered in Chapter 4.

Step 3: Findings/ Strategies
Next, the knowledge gathered in the previous steps and conclusions are combined and strategies are formed on the circular use of existing facade elements or components. Nevertheless, knowledge could be gained about circular design for new projects. This will not be a focal point of this study nevertheless it could improve the circularity of products that are created in the present day. Part of this stage is finding a way of categorising facades and strategies so that fitted strategies can be formed for different types of facades. Strategies for monetising these strategies are formed. This will be in the form of environmental impact expressed in kilograms of CO_2 that can be reduced.

Research questions

- What circular strategies can be formed from the information obtained in the previous steps?
- What data is needed to give a fitted monetisation of the circular strategies?
- What design improvements can be given to make current designs of aluminium curtain wall facades more circular?

Strategies for the circular use of existing elements are formed, however, shortcomings in the design might be found and improvements could be made to increase the circularity of the design of new projects. These strategies could differ based on various parameters that are compiled in the previous part of the research. These strategies are pictured in a flow chart with parameters of the characterisations that are found in the previous research steps. With these strategies, ideas of circular frameworks that can be applied to the unitised facade systems are formed. These topics will be regarded in Chapter 5.

Step 4: Application
Looking at the current projects of Scheldebouw, the strategies that were formed in the previous chapter can be applied. When applying these strategies and thus preventing waste generation and resource depletion, a reduction in the environmental impact is made. These values will be monetised and analysed. Insight can be given into the possibilities of the benefits that can be achieved using these strategies. The method and strategies developed in previous step are applied to a relevant case study.

- *Citibank - London*

Combining steps 3 and 4 a conclusion can be composed regarding the strategies. The risks and benefits are pictured as well as the impact of implementing these strategies.

Research questions

- What profits in environmental impacts can be achieved by implementing these strategies?
- How does the flowchart perform when applying it in the case study?

In the final part, the strategies that are found are further explored by looking at the results that could be achieved by implementing the strategies. By introducing the tool and this data about environmental impact, numbers can be added to this flowchart, so that the strategies made in the flowchart can be backed up by the benefits. The flowchart and the strategies in it will be tested against the case studies and example projects. An example can be seen in Figure 1.6. In this image, the material flow is pictured. This application is done in Chapter 6.

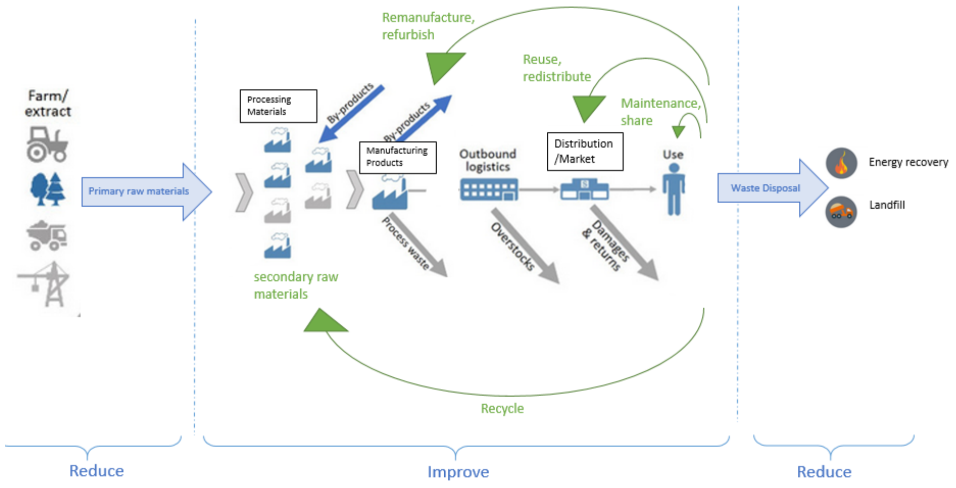


Figure 1.6: Example of a conceptual flowchart of a circular economy (Materialflows.net, 2021)

1.5. Report outline

A guide for the reader is shown in Figure 1.7. Chapter 1 consists of the introduction to the topic and the research framework and methodology. Chapters 2, 3 and 4 consist of the literature review of the topics involved as well as the knowledge obtained within the field research. In chapter 5 this information is gathered into the strategies which will be applied in chapter 6. Lastly, Conclusions and discussions are regarded in chapters 7 and 8.

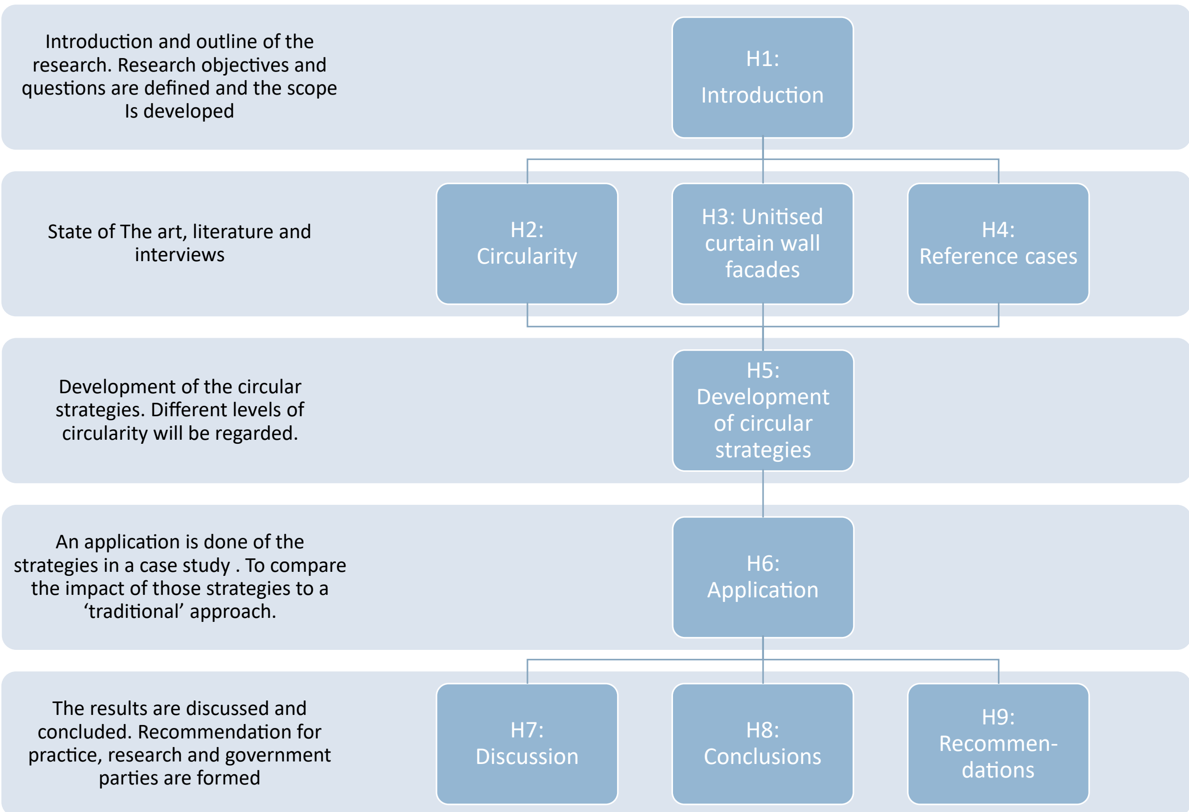


Figure 1.7: Report outline

2 Circularity

In this chapter, the concept of circularity is further explored and explained. Circularity is a broad concept and different strategies have been developed in different sectors over the years (Metabolic et al., 2019). This chapter starts by giving a general definition of circularity and will further specify itself into circularity for the construction and facade industry. Secondly, other industries are evaluated to gain insight into the developments. Next, a method for approaching the embodied carbon emission calculation within these circular strategies is made. The aim is to make a meaningful and fair comparison between cases and strategies.

A definition for a circular economy is given by MacArthur:

"A circular economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption" (MacArthur, 2014, p. 2).

MacArthur aimed in their research to redirect the current economy where materials are taken from the eco-sphere and after their useful service life (The Ellen MacArthur Foundation, n.d.), they are discarded. This can be described as a linear process or take-make-waste. By transforming this linear process into a circular process, waste is stopped from being produced in the first place, and material depletion is prevented. However, because numerous effect areas are covered and occasionally data is lacking or can be interpreted incorrectly, it is challenging and complex to create plans and evaluate consequences when taking into account all the processes involved.

In previous research done by the Institution of Metabolic (2019), seven general strategies that could be applied to all sectors have been defined, see the list given below.

- Prioritise regenerative resources
- Design for the future
- Preserve and extend what is already made
- Rethink the business model
- Incorporate digital technology
- Use waste as a resource
- Collaborate to create joint value

These seven general strategies give a first general outline of circular framework strategies that have been developed to make the current economy more circular (Metabolic et al., 2019). Within the built environment these general strategies are applicable as well.

2.1. Circularity in the construction industry

In previous research, it was tried to define a circular framework intended for the construction industry (Metabolic et al., 2019). A clear distinction between the strategies has been made. Firstly a definition defined by metabolic for a circular building is given:

"A building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demount-able and reusable, and biological elements can also be brought back into the biological cycle." (Metabolic et al., 2019, p. 11).

2.1.1. Value hill

As mentioned in the introduction, the Value Hill (Achterberg et al., 2016) serves as a framework to illustrate the circular utilization of materials, emphasizing their value preservation. The five levels presented—reuse, repair/maintain, refurbish, re-manufacture, and recycle—represent varying degrees of protecting the value of materials. By prolonging the lifespan of products through smarter usage, we can prevent unnecessary work and minimize waste. These strategies are categorized into pre-use, use, and post-use phases.

During the pre-use phase, value is added to materials through extraction, manufacturing, assembly, and sales, thereby increasing their worth. In the use phase, incorporating the "refuse" and "rethink" strategies allows us to maintain the value of materials. Finally, in the post-use phase, when materials are wasted, all remaining value is lost. Nevertheless, by employing the aforementioned strategies, we have the opportunity to restore or preserve the value of these materials.

2.1.2. Framework for circular design and construction

The circular strategies described before are further developed into four strategies for a circular building (Metabolic et al., 2019). In the next section, these four pillars are explained. These have been deducted from the seven general strategies mentioned before. These pillars form the base of the circular strategies in this research.

Reduce

When looking at reducing and mitigating impact the first thing that should be considered is avoiding producing products in the first place. By reducing the needed virgin materials in a project, the impact of mining the materials and manufacturing can be avoided. This pillar is mainly applicable to projects in which reused materials will be used. This first strategy is associated with the general strategies: *prioritise regenerative resources* and *'Design for the future'*.

Synergise

Synergise means that when two or more activities are combined or coordinated, the joint effect that is produced is greater than the sum of their separate effects. An example of this is using waste heat that is produced in a building. Single-solution choices are less preferred than multiple recourse demands. This strategy is associated with *'Preserve and extend what is already made'*, *'Use waste as a resource'*, *'Collaborate to create joint value'* and lastly *'Design for the future'*.

Supply

After applying the previous circular strategy frameworks, the next option would be to supply the remaining resource demands as clean, renewable, recycled or beneficial as possible. When looking at a building that is at the end of its service life a new supply can be generated from the materials that are within that project. The building can supply a new project. The strategies that are compliant with the donor building fall within this pillar. General strategies that are associated with supply are *'prioritise regenerative resources'*, *'Use waste as a resource'* and *'Design for the future'*.

Manage
The final method typically deals with how to manage circularity in the built environment. When circularity needs to be improved, data transparency and the creation of knowledge about when and how resources have been used are crucial. keeping track of input on the performance of systems while they are in operation and the sources that have been utilised. This can indicate a change in technology or behaviour. This final strategy could serve as a general approach for improving circularity in the built environment. With this last part the associated general strategies are, *'Rethink the business model'*, *'Design for the future'* and *'Incorporate digital technology'*.

The above-mentioned pillars form the input for the division of circular strategies in Chapter 4 and Chapter 5. The pillars *reduce, supply and manage* give a clear understanding of their part in the circular framework. *Synergise* does not fall inside the scope of this research, since there are no processes that generate energy. However, the use of donor materials and thus avoiding recourse depletion could be seen as a part of synergies. Synergise is chosen to leave out of this research. The division among the strategies is logical and clear when incorporating the aforementioned three pillars.

2.2. Circularity in the facade industry

A building consists of different layers with different characteristics and life spans: site, structure, skin, space plan, services and stuff (Brand, 1993)(Bergman, 2011). This is illustrated in Figure 2.1.

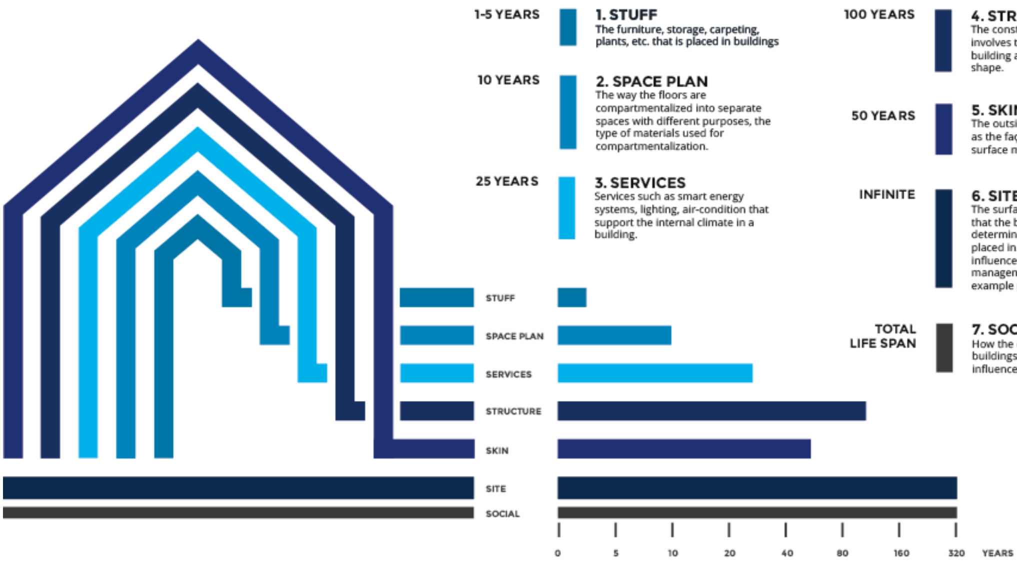


Figure 2.1: Layers of a building (WBCSD, 2018)

As described in Chapter 1, the facade does have an impact on the embodied carbon of a building. Despite it not having the biggest impact, it still is significant. As can be seen in Figure 2.1 the skin of a building is estimated to have a life span of 50 years. For aluminium curtain wall facades the life span of 60 years is mentioned (Contact nr. 2 and 8, 6-3-2023), (Hartwell & Overend, 2020), and the lifespan of the facade and its components are further researched in Chapter 3. Due to the multi-component nature of most facades, the service life is often determined by the service life of their nearest neighbour, so the lifespan of a component is greatly influenced by the part that is connected to it. This is illustrated in Figure 2.2. For example, the framing of a component might have a higher lifespan than gaskets or mechanical appliances. The life span and the potential of the components within a facade element are further elaborated in Chapter 3.

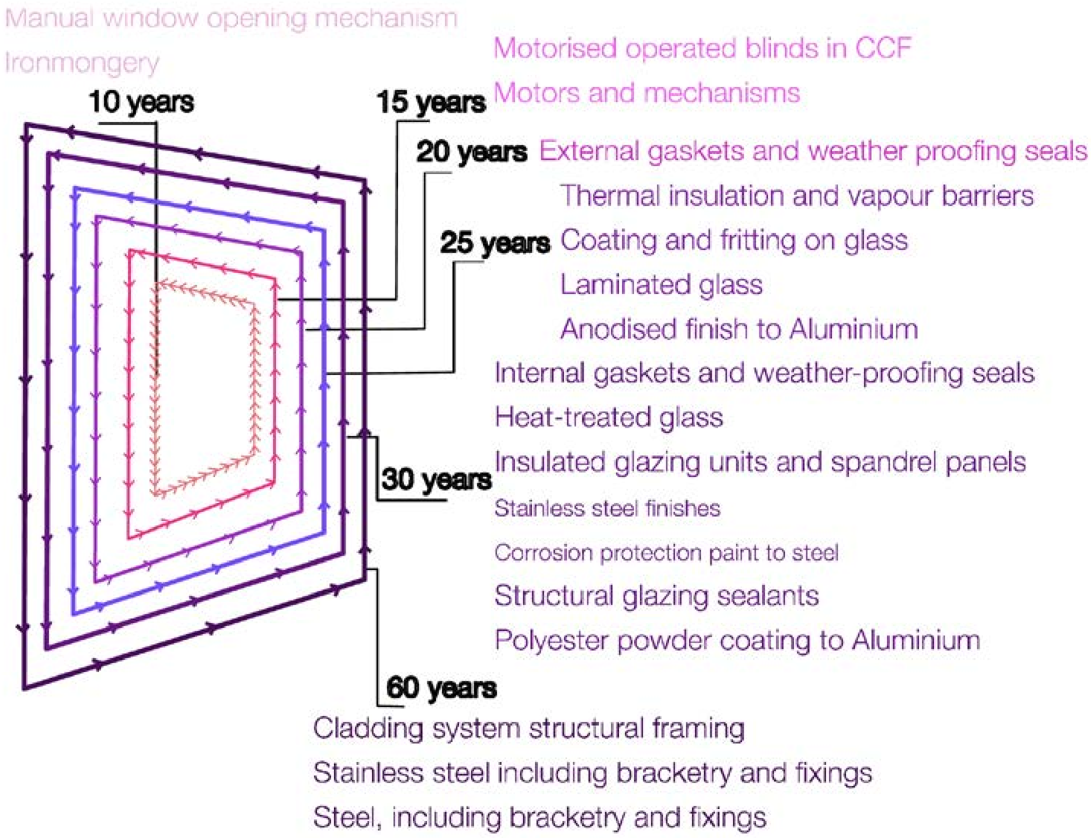


Figure 2.2: Layers of a facade (Hartwell & Overend, 2020) (Side note, laminated glazing can last up to 60 years (Contact nr 2, 2023)

When looking at boundaries within the facade industry to a circular use of facade components a couple of things could be noted. In the current economy, reuse is not stimulated by regulations, it is therefore often still more attractive to use raw materials (Contact nr. 5 and 6, 2-3-2023). Both the risks of re-using materials and the warranty that a client wants on its product obstruct circularity. However, when the legislation is put in place, and clients become more driven to make their buildings more circular a change may happen. Thereby, the willingness of the different parties involved shows that there is a positive attitude towards the use of circular materials (Hartwell, 2021).

2.3. Circularity in other industries

To gain knowledge on what can be accounted as a circular product or a circular process, other industries are also regarded. Inspiration can be achieved by looking at the approach and mindset of these industries. Some manufacturers have been evaluated and finally, a conclusion is made.

Re-manufacturing as a circular strategy in general has been in development for some years. A definition could be: "*To return a used product to at least its original performance with a warranty that is equivalent to that of the newly manufactured product. An added claimed benefit is that the costs of the products will be lower due to the saving of the materials*" (iCatching Design Ltd. Copyright 2018, n.d.). A number of industries have applied this strategy and have been successful. Examples of industries are the machinery and medical industry (The Ellen MacArthur Foundation, n.d.).

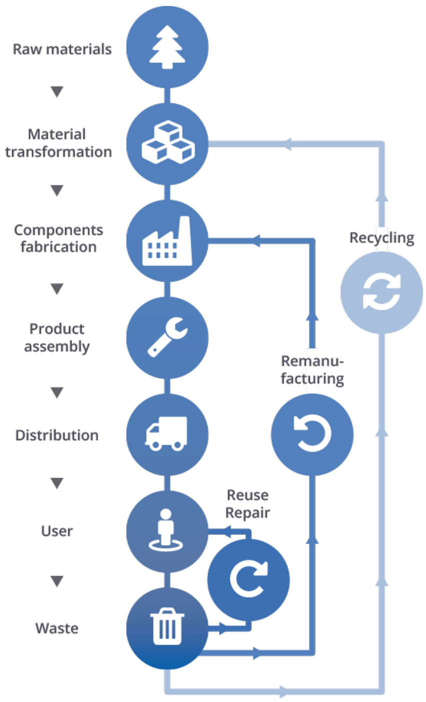


Figure 2.3: A representation of the product life cycle made by the ERN (iCatching Design Ltd. Copyright 2018, n.d.)

2.3.1. Caterpillar - manufacturer of heavy machinery

This heavy machinery manufacturer has developed a product that is intended for reuse several times. The business model has taken component recovery into account. The business is regarded as a pioneer in the creation of renewing technologies, that make it possible for more value to be recovered throughout the re-manufacturing process. It demonstrates the value of designing effectively rather than focusing only on efficiency. This is done by creating a product that is intended to be re-manufactured instead of using less product. According to Caterpillar, offering a machine at a lower price does not result in a lasting relationship with the customer. By reducing the owning and operating costs long-term benefits to the customer get more significant. They regularly maintain the products but are also beginning to embrace digital technology and add a product link, which is a digital diary, to their units as a way to keep track status of the components. The maker can thus keep an eye on a variety of status-related variables. When re-manufacturing components, they are rebuilt and tested to the same standards, as their new products. This also means they give out the same warranty as new material. According to Caterpillar, one of the main challenges facing the practice of re-manufacturing is the customer's comprehension and perception of the procedure. It is debated if re-manufacturing lowers quality and performance or even raises safety issues. Through its warranty program and strong brand recognition, Caterpillar aims to lessen this stigma (Ellen MacArthur Foundation and Caterpillar, n.d.).

2.3.2. Philips - Health technology company

The company Philips is a global health technology company that focuses on improving the health of people. The company has a leading position in the transition of the healthcare industry to become more circular. They are looking into products as a service, take-make schemes and refurbishment programs. These three options are developments of new business models. Medical equipment can be handed in by the users and refurbished by Philips. Philips states that the refurbished machines have an 'as new' quality with a performance guarantee. Rather than selling materials as a one-way transaction, a service contract is given on the equipment. Philips remains the owner and is thus responsible for the hardware. As a business, Philips improves their financial performance as well. An increased competitive advantage through long-term value creation (Ellen MacArthur Foundation and Royal Philips, n.d.).

In other industries, circular strategies have been applied already. By regarding their methods, the facade industry can be inspired. From these industries, general takeaways and attention points are gathered. What has been noticed in the construction industry, as well as other industries, is the stigma and misunderstanding of circular materials. Because of these well-known names and the thrust of the customers, this stigma has been decreasing. Additionally, it is proven by Caterpillar and Philips that a warranty and an 'as new' concept can be given to re-manufactured products. The products are subjected to testing, just as new products, and are monitored during their use, regular maintenance checks and innovative systems. Also offering products as service contracts offers an advantage to clients since the product and the maintenance stay on the side of the manufacturer. The companies regarded incorporate different fitting strategies to improve their impact. It shows that with the proper attention and methods, the doubts of customers can be worked around. In the fashion industry, a collaboration was made within the supply chain to develop a circular approach. All factors within the end-to-end process of a garment can add to the goal, which also makes these strategies more feasible. Ways are offered to consumers to deal with their clothing, and the company ensures it gets reused, donated or recycled. Also offering repair works to clients makes that customers get opportunities to make the most of their garments.

2.4. Calculating circularity

To be able to compare the impact of implementing circular strategies, a metric is connected to the strategies. Two of the mainly used metrics are calculating the embodied carbon or calculating the environmental costs (Platform CB'23, 2022). The latter is known in the Netherlands as *Milieu Kosten Indicatie*, or monetising method. In this method, different environmental indicators are calculated and monetised. However, when incorporating the end-of-life potential not a lot of data is available. More available data can be found on the embodied carbon of materials, in this research, the embodied carbon is used to evaluate the strategies found in Chapter 5. The carbon impact is one of the environmental indicators used in the monetising method. In NEN-EN 15643 (2021) a method is shown to calculate the impact, this is also used by CWCT (2022a) who further elaborated a framework to calculate facades. In this section, the general approach towards calculating the embodied carbon is described in Appendix B the formulas to be used are shown. Firstly the life cycle stages that are used in a life cycle analysis (LCA) are described. Next, a general attitude towards incorporating end-of-life benefits is described. This has been be applied to the case studies in Chapter 4 and explored when the strategies are applied in Chapter 6.

In Appendix B the equations needed to calculate the carbon of a project are shown. Adding to that data needed to create a complete calculation are mentioned as well.

2.4.1. Terminology

Before starting with the further development about the valuing of end-of-life components, some definitions from the NEN-EN-15643 and NEN-EN-15804 norms are given. (NEN, 2021, p. 10-27)(NEN, 2019, p. 8-13).

- *Waste:* Substance or object which the holder discards or intends or is required to discard.
- *reuse:* Operation by which products or components that are not waste are used again for the same purpose for which they have been conceived or used for other equivalent purposes without reprocessing, but including preparation for reuse.
- *Repair:* Actions outside planned maintenance to return components or assembled system to an acceptable condition through the renewal, replacement or mending of worn, damaged or degraded parts, but not changing its original parameters.
- *Refurbishment (deep renovation, deep retrofit)*: Planned large-scale (substantial) modification and improvements to existing construction works. Refurbishment can be undertaken to facilitate the continuation of the current function, including technical modernization and a change of space plan, or a change of function to new use.
- *Recycling:* Recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. Recycling does not include energy recovery and the reprocessing into materials that are to be used as fuels or for back-filling operations.
- *Disposal:* Waste treatment operation other than recovery even where the operation has a secondary consequence the reclamation of substances or energy.
- *Building component:* A prefabricated assembly of materials that form a product with a specific function.
- *Building element:* A major physical part of a building that fulfils a specific function, irrespective of its design, specification or construction.
- $kgCO_2e$: Carbon dioxide equivalent emissions, could also be referred to as 'carbon'.
- *Carbon factor:* The $kgCO_2e$ per unit of product, often this has the unit of $kgCO_2e/kg$ or $kgCO_2e/m^3$.
- *Embodied carbon[$kgCO_2e$]:* The total greenhouse gas emissions and removals associated with materials and construction processes throughout the whole life cycle of a component.
- *Carbon:* Carbon is used to refer to greenhouse gas (GHG) emissions, this is set out to be the Global warming potential.
- *Whole life carbon:* The sum of all greenhouse gas emissions and removals over the whole life cycle of a component.

2.4.2. Life cycle stages

When monetising the circularity of a component, the different life cycle stages that are defined form the basis of the calculations. Especially when looking at circularity the incorporation of all stages is required to get a complete and transparent outcome. In Figure 2.4 these life cycle stages are shown. In each stage, the component has an impact on the environment. The stages are further broken down into modules, which have their own meaning and boundary.

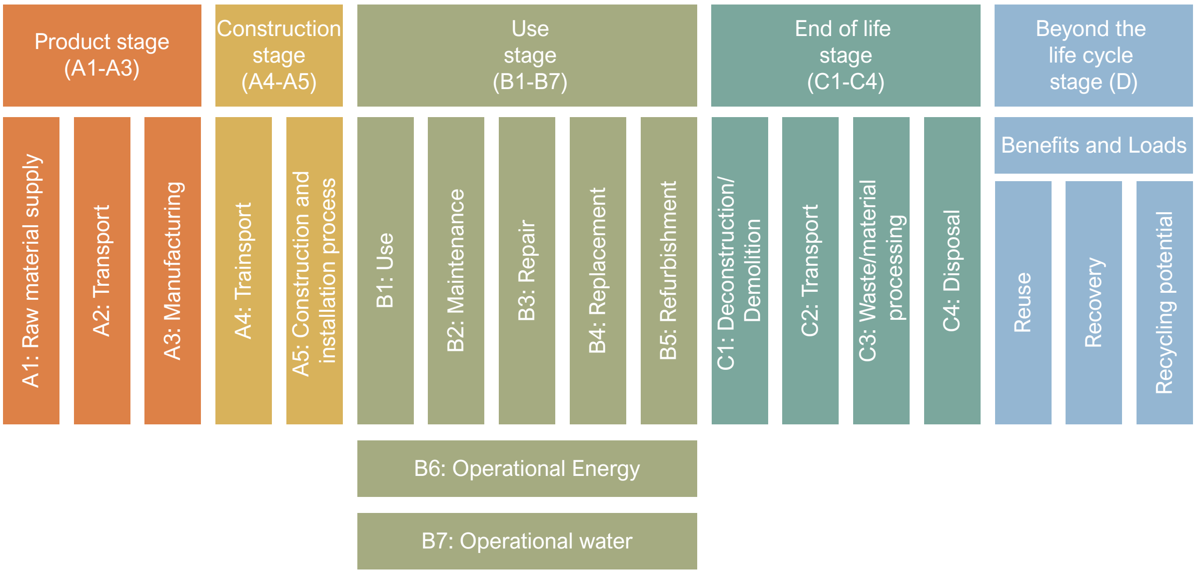


Figure 2.4: Life cycle stages of the LCA, defined by BS EN 15978:2011

Product stage (module A1-A3)

In this stage, firstly the emissions that can be accounted for material extraction, processing transportation and manufacturing are taken into account. These stages carry a large part of the impact. The product stage is further divided into three modules: *A1 raw material supply, A2 Transport and A3 Manufacturing*. Included in this module: are the extraction of the raw materials, transportation of the raw materials, processing of the raw materials into sub-components and the assembly of the sub-components into the end-product. Electricity used in the A3 stage is an average energy use calculated by the company per square meter facade. The A2 impact is the transport from the raw material to the production facility. A3 contains the impact, like electricity, needed to assemble and create the product in the production facility.

Construction stage (module A4-A5)

This stage contains the emissions that are caused when the product leaves the factory gate, including the transport of the product from the production plant to the construction site (A4), and secondly, the impact caused on the construction site. Including the waste produced during construction. The end-of-life impact of this waste is also included in the factors used for this stage. Also, the electricity used on site and the packaging that is used for the project is included. Because the company has records of their processes a yearly average of the different components can be developed. The construction stage is split into two modules: *A4 Transport and A5 construction and installation process*.

Use stage (module B1-B5)

Within this stage, the modules use, maintenance, replacement and refurbishment of the component are included. Most of these categories are often not taken into account when calculating the impact of a facade (CWCT, 2022a). Some of these stages are hard to predict and thus often neglected, this holds for B1, B2 and B3. However, when considering the life span of a facade and the lifespan of its components replacements need to be taken into account by multiplying the ratio of the years by the A-C impact and counting this towards B4: replacement. This however depends on the intention of the calculation and the referenced service life that is regarded. The use stage is split into the modules: *B1 Use, B2 Maintenance, B3 Repair, B4 replacement and B5 refurbishment*.

When considering refurbishment, so circular use of materials in the same building, B4 should be considered. Within this category, all impacts caused by the refurbishment should be accounted for. An example of this is 1 Triton Square which has been be used as a reference study in Chapter 4. All processes needed for a refurbishment should be taken into account then. This stage also consists of the A and C parts used in the LCA. When new materials are used the A1- A3 are used, en when elements are scrapped or dismantled the C stages come into play. A refurbishment means that the original project remains, so there is only an end-of-life stage for the products that are put to waste or recycled in this process will leave the original life span of the building. Because the original component does not leave its origin and does not change function this is not seen as an end-of-life scenario. However, still, the production of completely new elements has been saved and it can still be seen as a sustainable and circular strategy for a building. Materials that are still performing are not put to waste and materials that are not performing are replaced. This could be seen as an optimised use of available materials.

Operational carbon (module B6-B7)

The operational carbon is divided into *water (B6)* and *energy use (B7)*. When looking into the whole life carbon of a building this has to be taken into account. A facade does not use any energy and is often disregarded in operational carbon calculations (CWCT, 2022a). In spite of it not using energy, it does have a large influence on the energy demand. Especially when a facade panel ages and defects start to play a role. The energy losses through the building envelope do play a large role in the whole life of carbon. Various assumptions would need to be made when calculating the operational carbon, ventilation losses and internal heat gain of a room both have a large influence on the operational carbon but are not influenced by the facade. The formulas and calculation method are shown in Appendix B which are taken from the NTA-8800:2023. In order to assess the carbon associated with the facade, a sample room is created. In which parameters that are not influenced by the facade are assumed and kept constant. For this sample room, the operational carbon can be calculated and the difference in emissions can be assessed between options (Arup & Glass, n.d.).

Changing parts of a facade will influence the embodied carbon as well as the operational carbon. Balancing these effects in terms of carbon improves the decisions made in facades. The carbon payback period is calculated (CWCT, 2022b), this is a metric for assessing the relative carbon benefits of a design. The shorter the carbon payback period, the greater the benefits over time. Improvements made can then be compared to others.

End-of-life stage (module C1-C4)

The emissions related to the end-of-life scenarios of the component are included in this stage. Deconstruction and demolition, transportation, waste processing, and disposal are the different parts of this stage. Thus, this stage will be crucial when comparing circular strategies. First of all *C1 Deconstruction and demolition*. This stage includes all on-site activities that are required to dismantle, deconstruct and/or demolish the facade. Next *C2 Waste and Deconstruction transport*. Module C2 includes the emissions during the transportation of the component. It depends on the scenario chosen, the transportation according to the chosen scenario should be chosen. Different scenarios could be recycling, incineration or landfill. thirdly, *C3 Waste processing*. For this module, the processing of organic and inorganic waste materials and/or components. This contains processes that have to be done at the end of the life of a component. Processes that are meant in this process are the impact of recycling incineration or the actions that should be taken before the material can become a landfill. And lastly *C4 Disposal*. Here, the emissions related to material disposal are taken into account. This suggests waste management procedures. When materials are accounted for in the C4 there is no further use for them, and then the impact that is generated when putting products to landfill is accounted for.

Beyond the components life cycle (module D)

Module D is outside of the life cycle of the component. This stage consists of the benefits related to recycling, recovery or reuse of materials. Module D is not included in the embodied carbon and should be presented separately when calculated. The positive impact calculated is a guess at the time of making, it is thus a potential benefit. When a circular product is then used in a new project the actual amount of the circular product and the benefit can then be accounted in the new project. The net potential environmental impact occurs due to the circular use of materials and components beyond the boundary of the component's life cycle. Recycling, reuse and energy recovery fall into this category. It mitigates the demand for a new product or mitigates the depletion of raw materials. Also, the loads that are caused by the method that is applied should be accounted for. The value that is obtained in this stage is thus the potential benefit when the materials are used as estimation during the calculation.
In practice, this often leads to double counting of this benefit in both the receiving and donor building. In this research, a different approach is searched for in order to make a clear and fair comparison between strategies.

2.4.3. Functional Unit

The functional unit provides a functional basis to be able to compare different situations. This is required to draw the right conclusions and make a fair comparison.

For facades, it is recommended to use a 'bay'. This is a representative surface area of the facade system within a project (CWCT, 2022a). For unitised systems, this 'bay' is often defined as one element, since the elements are often repetitive. The total embodied carbon of a project can then be compiled by multiplying the result of a 'bay' by the total amount of panels applied within a project (CWCT, 2022a). When comparing different facades this could give some issues since panel sizes could differ. Then it could be brought back to the m^2 facade by dividing the outcome by the area of the panel. The formulas and calculation method are described in Appendix B.

For this research, the choice is made to calculate the bay as described above. To be able to get to a component of a facade, the rest of the attached components will influence the process as well. The facades regarded in this research are unitised panels and have thus been installed as panels on site. Therefore, a representative bay element including the connection to the backstructure has been taken to perform the calculations.

2.4.4. Inventory data

When performing a LCA, the required input data can be gathered from databases. Open-source network databases are available to download. For this research data is taken from Scheldebouw for the life cycle stages A1 to A5. Their data comes from suppliers and energy consumption measured over a year. It is thus assumed that for this life cycle stage, the data is of sufficient quality. Since the data for stages C and D are based on a national average, this data is taken from open-source databases as far as available, mainly the German database, Oekobaudat (Bbsr, n.d.) and the UK inventory (Department for Environment & (Defra), n.d.) are used. These databases are freely accessible and comply with ISO-14040.

2.5. Conclusion circularity

In conclusion, this chapter has explored the application of circularity in various sectors, using different applications and strategies. The definition of circular economy was described by MacArthur as a restorative and regenerative model that aims to keep products, components and materials at the highest utility and value. With as main aim to reduce the finite resource consumption encouraged by economic development. Furthermore, the value hill framework was described, which illustrates a circular use of material and emphasises the preservation of value through different levels of strategies. By emphasising the value created in the pre-use phase and therefore also the value discarded by throwing material away, the incentive to preserve value is created.

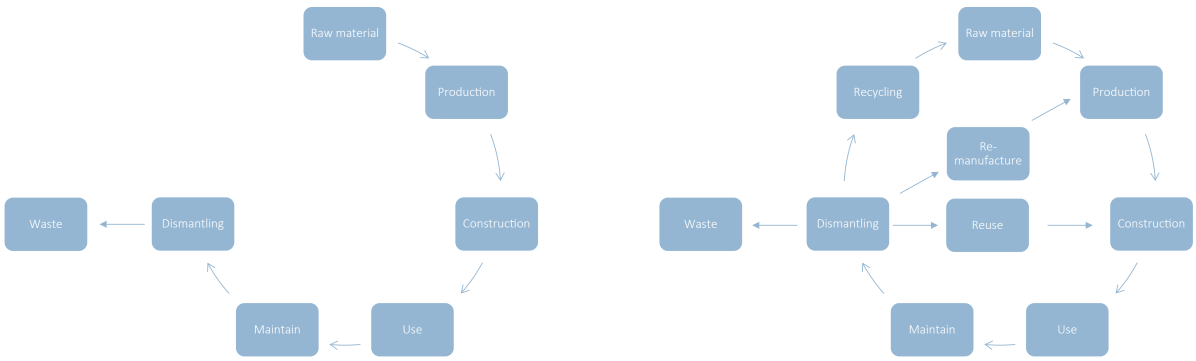


Figure 2.5: Closing of the loop

In the construction industry, four key pillars have been described: *Reduce, Supply, Synergise and Manage*. The four pillars have been formed to be the basis for developing circular building strategies that encourage a more sustainable built environment. In the industry currently, a linear way of thinking is known, as take-make-dispose. Strategies throughout the industry are developed to close this loop. This is schematically shown in Figure 2.5. Three pillars have been defined that will clarify the decision in the strategies *Reduce, Supply and Manage* while mentioning the limited applicability of Synergise in the scope of this research. These three pillars divide the process into three clear stages and ensure a clear way of distinguishing where the relevant areas lie within projects.

Moreover, it was explored that the impact of facades on the embodied carbon of a building does not have the largest overall carbon impact, but does play a crucial role in creating a more sustainable industry. When regarding the lifespan of both a building and a facade, the facade is identified as an important component in the whole life carbon impact of a building. In other industries, numerous examples of circular use of materials can be found. Looking at Catapillar and Philips, valuable insight and inspiration for the facade industry can be found. Stakeholders throughout a supply chain are included when developing a circular strategy

Last, in this chapter, carbon calculations have been described. By calculating the carbon impact of a facade the impact made on the environment can be expressed. The life cycle stages are expressed in modules: the product stage, construction stage, use stage, end-of-life stage and beyond the life cycle stage. In facade calculation, a 'bay' element is taken and is expressed into an impact per square metre. The Beyond the Life Cycle stage (Module D) is currently used to showcase the potential benefits when recycling or reusing materials. This, however, gives a distorted image in the current carbon calculations. A method for incorporating reuse is currently not generally used or known. In order to be able to compare the strategies created in this research a carbon calculation method has been developed.

To conclude, this chapter forms the basis for the circular strategies that have been developed in this research as well as a way to regard the aspects in a facade and reference studies done, emphasising the restoration of the value of materials, increasing the sustainability and recourse efficiency in the facade industry.

3 Aluminium curtain wall facades

Facades take up a great majority of the building costs within a project and are thus a great part of the construction of a building. For the users of a building, the facade has a great influence on the experience and comfort of the building. The facade should also fulfil a variety of characteristics:

- Architectural and aesthetics
- Tolerances and Movements
- Structural
- Building Physics
  - Thermal insulation
  - Moisture
  - Air-tightness
  - Acoustic
  - Solar gain
- Fire safety
- Assembly and disassembly
- Ease maintenance

The functions that a facade holds are vast, there for it is important that facades comply with the characteristics that are needed in each project. The quality and necessary performance standards must be met when using components from an existing facade.

3.1. Unitised curtain wall facades

The scope of this research is limited to unitised curtain wall systems. These are prefabricated enclosures that connect to a floor slab or a substructure. This creates a 'curtain'. This means that the facade carries the loads that act directly on the facade, and no loads from the supporting structure are transferred onto the curtain wall. The main structure of these curtain facades can consist of the following materials: aluminium, steel or wood. Further, depending on the architect's and client's wishes, other materials can be added. The structural material that this research is focused on is aluminium, which is the most commonly applied. In Appendix C facades have been analysed, and different architectural configurations and materials have been found, mainly glazing, aluminium and insulation.

The unitised aluminium curtain wall facade has some advantages over other systems. Mainly they are manufactured in a controlled environment and can achieve high quality. During construction, the panels are installed at a fast pace and the building can become wind and watertight with reduced action compared to more conventional systems (Watts, 2019). On the downside the curtain wall facade might be quite expensive, this also depends on the scale of the building since the more units that are created, the less expensive they become. This is why for unitised curtain wall facades it is preferred that large repetitive quantities are produced.

An aluminium curtain wall panel generally consists of four main part groups. Firstly, infills, which could be transparent or opaque. Opaque infills are often spandrel panels or shadow boxes, and transparent are generally insulated glazing units. Secondly, the framing carries the infills. Thirdly, the connection to the building, these materials makes sure the panel is connected safely to the building. Last the external elements like decorative elements or sun shading.

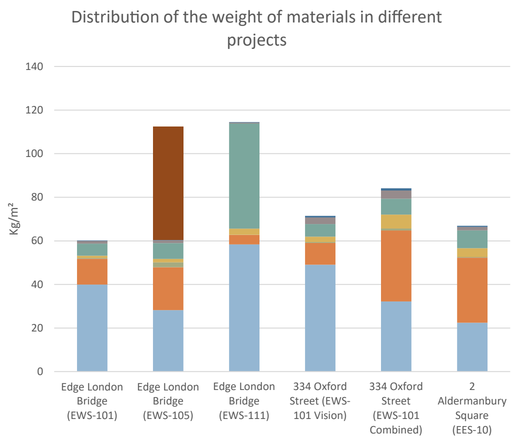
3.1.1. Materials within unitised curtain wall facades

In an analysis done in Appendix C, the main materials found in a unitised curtain wall facade have been found. Three facades have been analysed and a list of the main materials that are within a unitised curtain wall facade has been compiled. This list is presented in Table 3.1. The materials are subdivided into four categories, Infill, framing, External elements and the connection to the back structure.

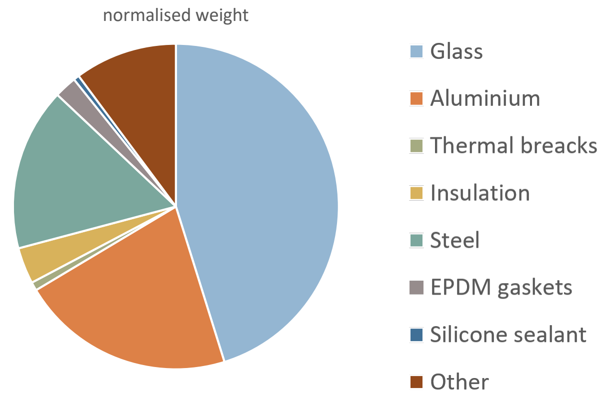
Table 3.1: List of materials

Infills		**Framing**	**Connection to back structure**	**External elements**
Opaque	*Transparent*			
Aluminium Sheet	Glazing	Aluminium extrusions	Steel	Aluminium
Steel Sheet	Sealant	EPDM gaskets	Insulation	Terracotta
Insulation	Spacer	Thermal breaks	Fire-stop	Steel
	Gas	Fasteners		Sun Shading
		Sealants		etc.

The materials presented in Table 3.1 have varying contributions to the environmental impact and share or weight of the facade. This impact for six projects has been analysed, resulting in a value assessment of these components. In Figure 3.1 the distribution of the normalised share in weight is shown of the analysed projects as well as a pie chart of the average impact. The values have been normalised by dividing the weight by an area to be able to compare the outcomes. When looking at the result of these calculations on average the glazing, aluminium and steel have the biggest share in weight. Within the aluminium fall both extrusions and sheet aluminium.



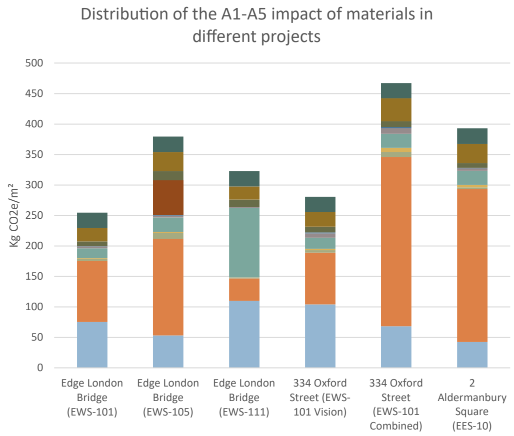
(a) Normalised distribution of the weight of the different materials found in a facade



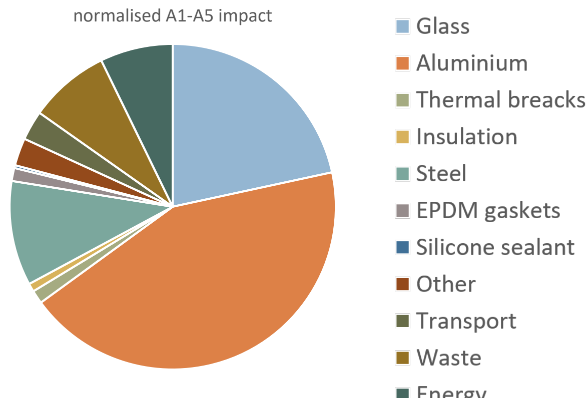
(b) Average Normalised distribution of the weight of the different materials found in a facade

Figure 3.1: Normalised weight

However, to complete this assumption the A1-A5 impact is regarded. The impact of certain materials can vary greatly. The impact has been normalised by dividing the impact per category by the total area of the unit. The outcomes are shown in Figure 3.2. Within the total impact energy, waste and transportation have been regarded, these are given their own category. From these graphs, the following conclusions can be made. The impact of aluminium is significant. 43 per cent of the total upfront carbon impact accounted towards the aluminium. Next the glazing with a share of 22 per cent. followed by steel with 11 per cent. The next biggest share is waste and energy. When looking at the most important materials in an average facade these could be said to be: Aluminium, glazing and steel.



(a) Normalised distribution of the A1-A5 impact of the different materials found in a facade



(b) Average Normalised distribution of the A1-A5 impact of the different materials found in a facade

Figure 3.2: Normalised A1-A5 impact

Since almost half of the upfront carbon impact comes from aluminium, this material is further subdivided into Extrusions, Sheets and Fixations. See Figure 3.3, 76 per cent of the aluminium carbon comes from aluminium extrusions, which is 33 per cent of the total average impact. 24 per cent can be accounted for the aluminium sheeting, which is 10 per cent of the total average impact.

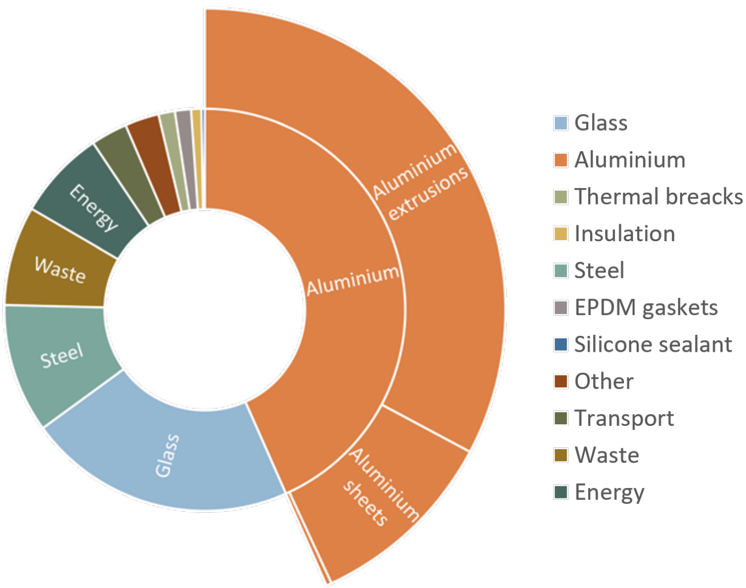


Figure 3.3: Normalised distribution of the A1-A5 impact of the different materials found in a facade, further specified by the aluminium

The circularity of the components and materials is regarded. What are the materials used for and what are the options for circular use? The choice of materials is based on the figures shown above. The materials that have been regarded are aluminium Extrusions, aluminium sheeting, glazing and steel since these materials are shown to have the biggest share of the impact within a facade.

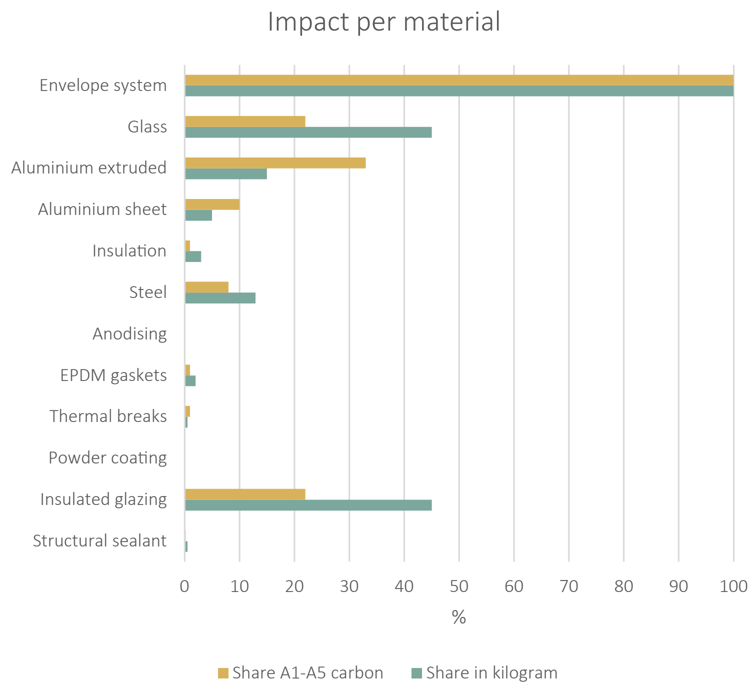


Figure 3.4: Kilogram and carbon impact distribution over the components

3.2. Life span of the components

Re-usability is influenced by the component's life span and the guaranteed lifespan. The life span of the different components found earlier is shown in Figure 3.5. The guaranteed life span is the life span that is promised by the manufacturer of the different elements. When a facade element has issues during this time frame the manufacturer is mandated to perform service and maintenance on that part. The estimated life span is the time the producer expects the part to perform sufficiently. There are no requirements connected to this, so no service and maintenance are mandated when a part is not performing up to the requirements. The parts with the lowest life span are the EPDM gaskets, sealant and insulated glazing. The total life span of the panel is 60 years, which means that in the lifetime of an element this component should at least be replaced once. The guarantee that is given on the elements is all 10 years. After this period, the performance of the facade is not guaranteed anymore.

The properties described in the previous section are theoretical lifespan expectancy, in practice, this could differ. In particular cases, the estimated lifespans could be exceeded (Contact nr. 5 and 6, 2-3-2023). When looking at reference projects some of the materials could outlive the lifespan given in Figure 3.5. Mainly steel and aluminium could outlive this number (Contact nr. 5 and 6, 2-3-2023). Concluded from the lifespan that in replacement situations often the materials replaced still have a life span left. Secondly, a replacement strategy should be in place for the components that reach their expected service life first. It was found that this was often not the case (Contact nr. 1, 2 and 6, 2023).

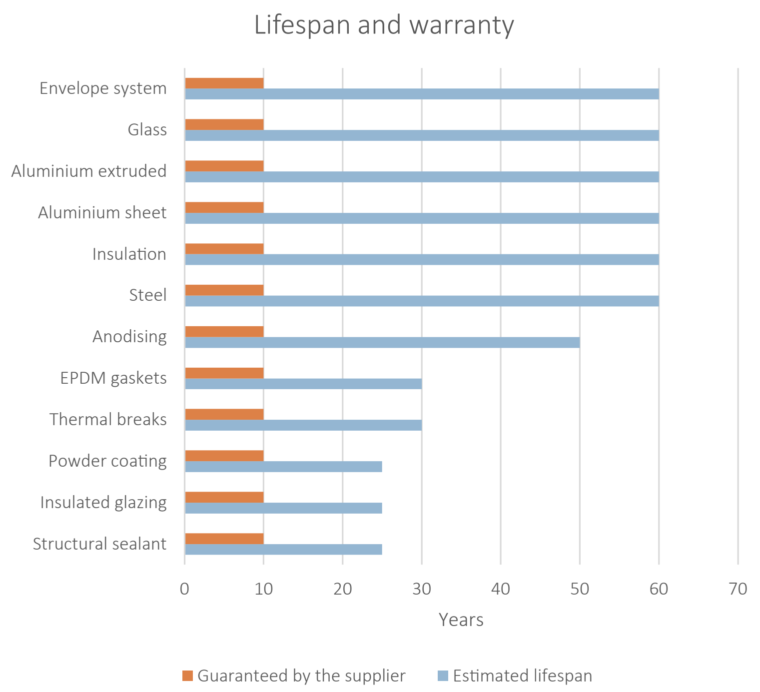


Figure 3.5: Guaranteed lifespan and estimated lifespan (Contact nr. 2, 8 and 12, 6-3-2023, 6-7-2023), (Hartwell & Overend, 2020)

3.3. Circularity of materials

In the next section of this chapter, the materials that are significant in an aluminium curtain wall facade are further researched. Examples from practice are shown and the nature of the material is explained. With the examples from practice, an overview has been given of the materials and the potential they carry.

3.3.1. Glass

Glazing makes up a great amount of surface area and weight within the facade. Over the years the use of insulated glazing units has increased, as well as the use of laminated glass. Other than glazing being a big part of a facade, it also has a great influence on the energy demand of a building. It connects the indoor spaces to the outside and lets in natural light. When designing an insulated glazing unit, different material selections come into play: the thickness of the glazing, the origin of the materials, heat treatments, the material and energy of lamination, the material and energy of the coating, and lastly, the material and energy that is associated with combining the units, such as spacers and sealants. Different typologies of glazing units are double-glazed units, triple-glazed units and double-skin facades. All consist of a configuration of sheets of float glass, which are toughened or annealed (Arup & Glass, n.d.). On the glazing a coating can be added which regulates the incoming solar radiation and U-value, also called the g-value. Laminated glazing has increased safety in case of failure, this is done by adding a PVB layer. Between the glazing often an air cavity is present which can be filled with gas such as argon. The air cavity has a certain width, which is set by a spacer and closed off with a sealant.

In the current industry, glass is mainly down-cycled (Rota et al., 2023). Glass is commonly deconstructed with a demolition excavator. The frames are removed, and the glass often breaks and falls to the ground, mixing with concrete rubble. This mixed glass waste is sold for landfill aggregate production. Despite the reuse and recyclable potential, glass is rarely recycled into new glass products (Hartwell & Overend, 2020). Saint-Gobain and AGC are looking into ways to recycle the cullet into new float glass (Saint-Gobain, 2023). The addition of coatings, interlayers and special adhesives, makes recycling often a challenge. These additives have to be separated from the glass to be able to recycle the glass into new float glass or The material is down-cycled into glass bottles.

The lifespan of insulated glazing units is about 25 to 30 years implying glass will have to be replaced during the life span of the facade. Breakage is another reason for replacement. These elements often span a large area of the facade, as seen in the reference projects, and carry a large amount of the wind load of the building. Glazing is also a vulnerable element due to its large size, brittle texture and small thickness. The strength of the glazing depends on the surface flaws. Over its life span, the glazing may accumulate these flaws (Sofokleous, 2022). When looking at an insulated glazing unit, the sealant and spacers will lose performance, which causes a drop in energy efficiency.

Refurbishment options

The re-usability of glazing as described above has great potential. The spacers and sealants however do need a replacement, currently varying tests on a small scale have been done (Groothoff, 2021). It is shown to be very labour-intensive and risky. The glass panes could be separated by removing the sealant and spacers by either removing the sealant or cutting the glazing to a smaller size (Rota et al., 2023). A small part of the glazing, sealant and spacers become waste. The panes could be used by itself or put in a new configuration. Gasses, foils or coatings can be added and even a third pane could be added to achieve the needed performance goal. This technique is in development at this time and has been applied on a small scale.

Cases

In the following section examples of cases are discussed where the glazing was replaced or technologies have been applied which could increase the potential of the facade.

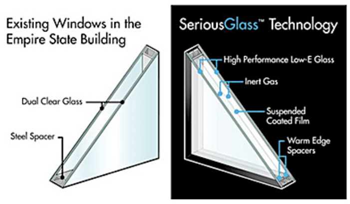
Lloyd's of London The first case is the case of Lloyd's of London. The building was originally constructed in 1987. At a certain time the glazing needed to be replaced. Because the glazing was bespoke, it could not be replicated again. The double and triple-glazed units have been removed and returned to the glass manufacturers. Here the units have been cut and cleaned and each panel was re-made in a new configuration (United Nations Environment Programme, 2021). The building remained operational during the refurbishment. The remaining panels have been stored for future replacement or used for furniture in the building (ISSUU, 2021).

Figure 3.6: The Lloyds Building in London (Contracts, n.d.)

Empire state building The second case is the Empire State Building. The Empire State Building is a building that was built in 1930. Around 2010, when the building was around 80 years old, the manufacturer Serious Materials decided to retrofit the windows of the building. 6514 windows have been refurbished and it was claimed that the energy efficiency became 4 times as good. When deciding on a strategy to refurbish the building, the building manufacturer did not want to discard over 26,000 panels of the existing glass so a way to insulate the double-hung windows was needed. This was done by removing the glass from the window frames, separating the glass, and cleaning it. Next, they installed new spacers between the planes and added a suspended coated film and a gas filling to the newly created combination. When this was done the new configuration using the old glass was reinstalled in the existing window frame. All of this was done on-site which further reduced the transportation costs. This is one of the largest-scale projects where the existing glass was refurbished. The work was finished in December 2010(Guevarra, 2010).

(a) Production line inside the Empire State Building (alpenHPP, 2018)

(b) Workers reinstalling the glazing at the Empire State Building (alpenHPP, 2018)



(c) Retrofit diagram of the Windows in the Empire State Building (Guevarra, 2010)

Figure 3.7: The Empire State Building in New York

Pre- and post-consumer glazing is currently still mainly put to recycling at the end of its life. Glass is often, due to coatings and interlayers, Down-cycled. However, there are some manufacturers who are looking into high-value recycling of glazing from the construction industry. That makes it possible to reuse the cullet coming from construction glazing in new glazing. Since recycling still costs energy, the direct reuse of glazing panels could increase the circularity of the glazing. Because of the sealant and spacers which are connected to the edge seams, this remains a challenge. Companies are still not able to work around that. Nevertheless, in the case of the Empire State Building, this has been done. A potential implementation lies in this strategy. The glazing has a long life span, but because of the needed attachments, it is still a bottleneck in most facades.

3.3.2. Aluminium

Within the facade elements, a lot of aluminium is present. Different kinds can be found. These have already been shown in the Figure 3.3. Aluminium sheeting and aluminium extrusions. Aluminium is used for the structural integrity of the panel, but also aluminium is used for decorations.

Aluminium wrought alloy extrusions

Aluminium extrusions are mainly used for the structural framing of the facade, the transoms and mullions. Fins and other exterior elements can also be made out of these alloy extrusions. The extrusions are made by forcing the aluminium alloy material through a cross-sectional profile. These cross-sections are often made specifically for a project for Scheldebouw. At other companies, more standard profiling is used. After the aluminium leaves the die, a mill finish is left on the object. The tooling marks, a dull appearance and oxidation can be present on the aluminium. To give the aluminium the appearance and the protection it needs, the aluminium is finished. This can be done in a variety of different colours and finishes, but the main types are anodising and powder coating. After the aluminium is finished, the extrusions are cut to size and holes are put into place where needed (Contact nr. 12 12 7-7-2023)(Contact nr. 13, 11-7-2023). Within the aluminium profiling ducts are present where two extrusions can be connected by bolts. The connections are at a 45-degree angle. Aluminium extrusions have a long life span, depending on damages and corrosion the aluminium could exceed 60 years (Contact nr. 12, 7-7-2023). PerpetUal, set up by the VMRG and working together with the complete supply chain, is working on a feasibility study on the circular use of aluminium extrusions (Contact nr 13, 11-7-2023). Initiatives are being set up throughout the whole supply chain.

Finishes Two main types of methods of finishing can be found for aluminium extrusions: anodising and powder coating(Contact nr.14, 2023). Both use a different chemical process which finishes and protects the aluminium.

Anodising Anodising aluminium is an organic process. The aluminium is used as an anode with an electrolyte bath. The oxygen reacts with the surface of the aluminium which creates an oxide layer in the surface of the aluminium. This layer can be dyed to achieve the desired colour and finish. Anodising ensures protection towards corrosion and wear resistance. The anodising is not influenced by UV lighting, only when colour is added it is influenced.

Powder coating When an element is powder-coated the aluminium goes through an electrostatic process, which is inorganic. The powder, which is negatively charged, is applied to the positively charged aluminium object. This ensures a temporary adhesion, after heating, the paint turns permanent. This process creates an extra layer on top of the aluminium. Powder coating can be done in a variety of colours. Vibrant colours and unique textures are possible. It is of a lower cost than Anodising, however, the powder coat is not resistant to UV lighting.

Other finishes that are not widely applied to the aluminium are also possible. Such as PVDF coating which is a resin-based coating that is embedded with colour pigment. This finish is corrosion-resistant and applies to exterior finishes. It doesn't need to go into the oven for curing. Another form is sublimation, where a wrap is put onto the aluminium surface. With this patterns can be created. Despite them not being applied that much in the current facade industry this could be a solution to revive the aluminium to be able to be refurbished.

Refurbishment options The aluminium framing offers great potential for reuse. It has a long life span and seems not to degrade over time. The initial environmental impact of this product is high which offers a great impact when opting for reuse. The profiling of the aluminium might offer challenges, the framing is often uniquely designed for each project to fit the design and performance requirements. This is thus a boundary condition. Lastly, when a sealant is used in the structurally glazed configurations sealant might be left on the framing which needs to be removed.

The aluminium can be cut to size and holes for connection points can be added. The remaining holes from the original configuration could be resealed if needed, to maintain the air tightness and hide the holes from the building users. The aluminium framing, as described in previous chapters, often exists out of an inner structural framing and an outer cap profile. The two are connected by a thermal break profile. These three components are permanently connected, and therefore not possible to take apart. The cover caps, which could be of any material, offer the opportunity to give a different look to the framing or add aesthetic elements. The same holds for adding additional framing to add openable windows or other features. Options for replacing the thermal break could increase the thermal properties of the framing and offer increased spacing for applying thicker insulated glazing units. Lastly, the finishing could be changed or upgraded. Which will change the appearance but might also increase the quality of the element and protect it again from weather influences.

De-anodising is possible, chemically or mechanically. The aluminium will lose a slight amount of thickness, but a new colour could be possible. The powder coat can also be taken off by sanding or chemically treating the aluminium. With sanding the aluminium should be checked for corrosion. when the chemical treatment is used the frame should be connected (Contact nr. 12, 7-7-2023). Another option that was found was wrapping, however, this is very time-consuming.

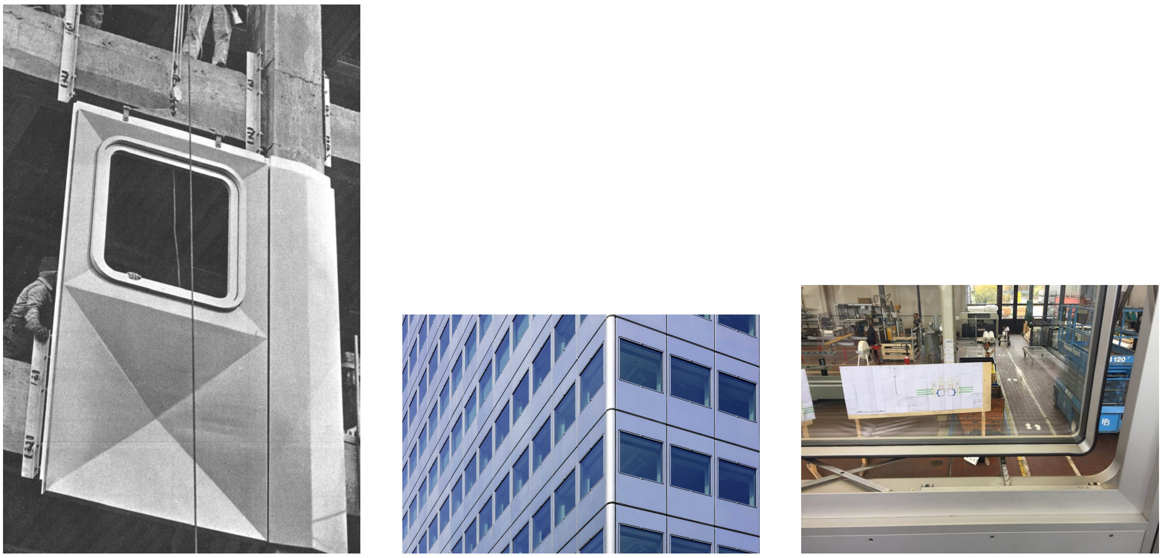
Sheet

Next to extruded aluminium, also aluminium sheeting is used. This is made by passing a strip of aluminium through high-pressure rollers. This sheeting is often used in spandrel panels as a finish or as extra elements in a facade. The Aluminium sheeting can have the same finishes as the extruded elements

Refurbishment options When reusing aluminium sheeting with refurbishment practices a variety of options is possible. Aluminium is a durable material and is thus reusable. The size constraints are still in place since the new user will also have to be exactly the same size or smaller. However, by cutting and/or bending it, the sheet can be formed into any shape needed. Also as for the extruded profiles, a new finishing can change the appearance but also protect it against indoor and outdoor conditions.

Commerzbank Tower

A project where aluminium was reused is the Commerzbank Tower in Düsseldorf. The building was originally built by Gartner. The facade of this building was disassembled and reassembled. The original anodised aluminium sandwich elements have been upgraded and reinstalled with an added layer of insulation. The original building was built in 1962 after a design by the architect Paul Schneider-Esieben. The facade elements are $1.72mx1.1m$ and consist of an inner and outer shell of $2mm$ thick aluminium sheets. In between the two sheets insulation was placed. The building was listed as a historical monument. And it was vacant for a couple of years, after an investor bought the building in 2015, intending to refurbish it as a hotel. Because of the low weight and the corrosion-resistant properties the aluminium sheeting was suited for reuse. After shipping the elements to the factory, the elements have been opened and checked for damage. The insulation was replaced by rock wool insulation. The aluminium was abrasively cleaned and then resealed. This resulted in some colour irregularities (Grom & Putz, 2022).



(a) Mounting the facade panels in 1953 (Schaal, 1961)

(b) The Commerzbank after the upgrade and conversion in 2021 (HPP, n.d.)

(c) The panels of the Commerzbank during the refurbishment (HPP, n.d.)

Figure 3.8: The Commerzbank high rise

3.3.3. Steel

Steel is the third material regarded in this research, which is mainly used for brackets and the back sheet of panels. The brackets that connects the aluminium framing to the main load-bearing structure are often made from steel and connected by anchors to the concrete. These brackets provide the possibility for movements and tolerances and offer the load path of the facade. These are made from often galvanised steel. Steel, just like aluminium, is a metal which has three times the weight of aluminium, but also has a significant impact on the carbon emissions of a facade. Same as aluminium, steel has a long life expectancy. Since brackets are used on the inside of the facade, they are not subjected to weather influences. Brackets are placed on top, below or in front of the floor. It could be the case these brackets are poured over by the top floor which makes them difficult to reach.

The most used function of steel sheeting is the backside of the spandrel panels. These spandrel panels are opaque infills in a panel, these are filled with a type of insulation material. A box is created by a steel back-plate, aluminium framing and finishing material. This spandrel panel can also be seen in Appendix C, as well as in the Citibank case. This steel is not subjected to weather influences. Lastly, the different parts within a facade are connected using a screwed connection. This is achieved by using fasteners, which often are made of chromium steel parts.

Refurbishment options

Brackets Before reusing these elements the structural capacity should be checked in order to be able to ensure the panels are safely connected to the building. Secondly, the dismantling of these brackets might cause challenges due to the way they are constructed. The brackets are connected to the floor by steel anchors that are poured into the concrete to the structural floor. However, when a top floor is used the brackets might have to be broken out of the concrete first. The refurbished reuse of these elements will have some of the same challenges. Still, the size constraints stay in place. Cleaning and a new coating are however still possible. small adjustments in the size however are possible but the challenge to fit it into a new building or new panel remains. Structural safety is important for this component.

Steel sheeting The reuse of steel sheeting offers great potential. Steel sheeting is often used in the back of spandrel panels. So the material is not subjected to outside conditions. The life span of steel is sufficient for reuse. When looking into refurbishment strategies for steel sheets, this offers great potential. The material can be cut to the needed size or bent into new shapes. There is a limit to the bending since the steel will fatigue in these areas.

3.4. Connection between components

In the next section, the connection between the components is further explored. The nature of the connection will have an influence on the method of disassembling. An example of this is given in Figure 3.9. This shows the way the different parts of a product are connected.

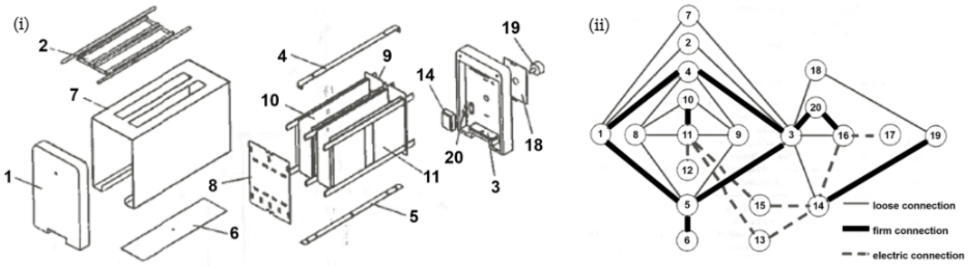
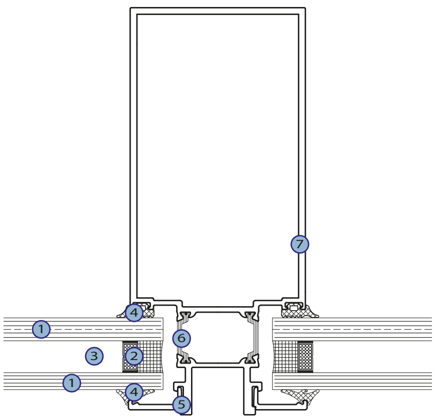
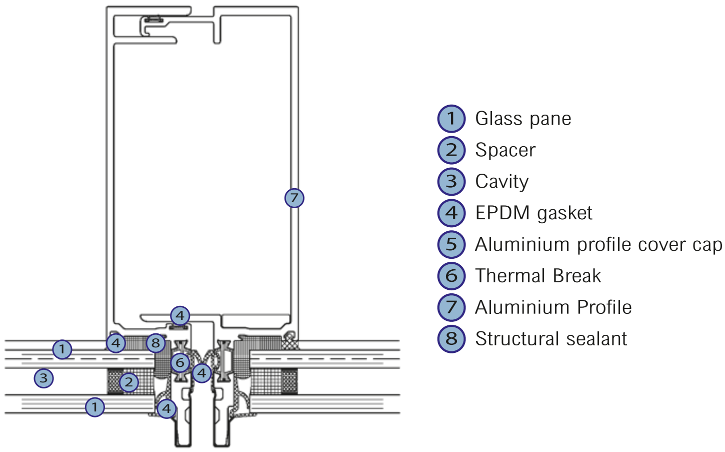


Figure 3.9: A connection diagram of a toaster (Lambert & Gupta, 2003)

As a start, all components in the facade are numbered and labelled. From the analysis done in Appendix C, the conclusion was made that there are two main types of ways to include the glazing in a frame. ”Structurally glazing” and ”dry glazing”. The components and their names are shown in Figure 3.10. As can be seen in the profiles in this image the inside part is similar to each other. The profiles are often thermally separated from the outside profiles by thermal breaks. The main difference between the two types is in the way the glazing is kept in place. In the first case, dry glazed, the glazing is kept in place by an external profile. Second, structurally glazed, the glazing is structurally bonded to the inside profile. A smooth outside finish can be achieved. There are some extra profiles and EPDM gaskets to keep out the water. But this is also based on the architectural look the facade needs to be achieved.



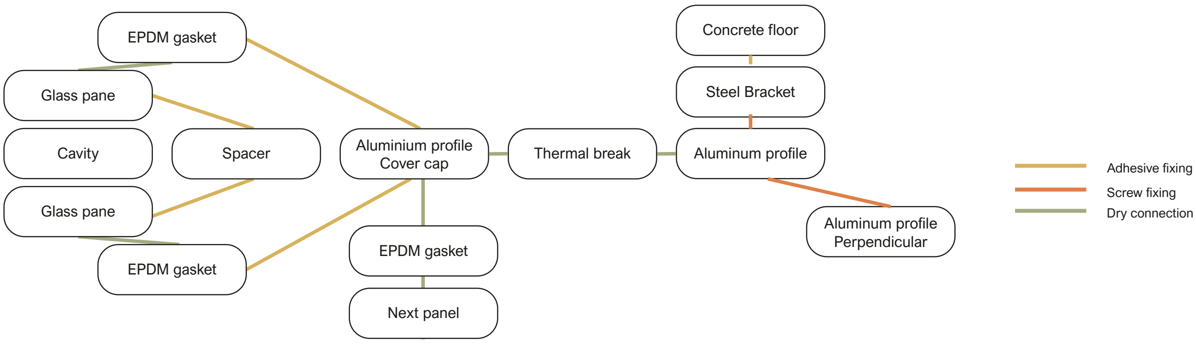
(a) Dry glazed element



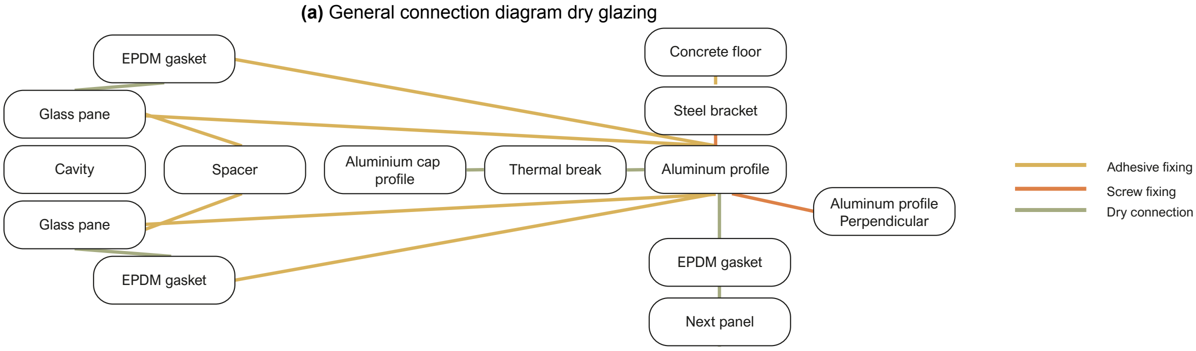
(b) structurally glazed element

Figure 3.10: Numbering of the components within the facade

In Figure 3.11 the diagrams of the connection between the components in a facade element are pictured. In the difference between the structurally glazed and the dry glazed it can be seen that a lot more adhesive fixings have been used. These adhesive fictions will increase the level of difficulty in order to take apart the elements. Especially the elements that have been found to have a shorter life span expectancy. Screw fixtures are manageable to unscrew, however, when rust or weather impacts impacted the screws this could increase the difficulty. In reports made by Scheldebouw, it was also found that often the profiles that are perpendicular to each other are screwed, also a sealant is used to ensure the water tightness of the facade (contact nr. 1, 2023). When looking at the critical elements in a facade, the aluminium and glazing, the glazing could cause an issue in replacing or dismantling. The sealant will have to be cut and this can leave damage to the glazing or framing, as well as the sealant that is left on the elements. This can also be seen in the dismantling done on the Citibank, see Appendix D.



(a) General connection diagram dry glazing



(b) General connection diagram Structural glazing

Figure 3.11: Connection diagram for dry and structural glazing

In the first instance, the sealant was not seen as a crucial part of a facade element, however, when incorporating the disassembly of the panels, this sealant becomes an important element. Both because it increases the difficulty of disassembly but also because of the life expectancy.

3.5. Demands for circular strategies

In recent times circularity and sustainability requirements have been included in the client's brief for new building projects. In a current project at Scheldebouw (Contact nr. 2, 3-4-2023):

- *"For each item in the table of service life described above, the contractor shall identify how materials can be removed and how they might dispose of them at the end of their service life."*
- *"Where practical, the components of the facade system shall be easy to dismantle and remove from the site, so they can be readily reused or recycled. Arrangements that require partial demolition of elements before removal from the site should be avoided where practical."*
- *"The contractor shall provide evidence that the materials and components have been designed, selected and procured so that they will be processed within a closed-loop, circular economy."*
- *"Where possible, materials shall be returnable to the supply chain, both for repair and replacement during the service life and for reuse or recycling at the end of the service life."*
- *"Where practicable, materials shall be procured from suppliers with a commitment to receive back the materials at the end of their service life and to process them for reuse or recycling. The contractor shall obtain an undertaking from the supplier, which shall be transferable to the client."*

3.5.1. Change of requirements

The requirements of facades have changed over the years. The Dutch Building Decree was first released in 1995. Back then the U-Value requirement in the Netherlands was $2.5W/m^2K$ (Ministerie van Volkshuisvesting, 1995). These values have decreased over the years. In the 2003 version this value was lowered to $0.4W/m^2K$ (Rijksoverheid, 2003). In 2012 this was lowered to $0.2W/m^2K$ (Rijksoverheid, 2012). Adding to these requirements new incentives have been created like BREEAM or Zero Energy buildings, where additional requirements can be set to the characteristics. Not only the thermal insulation requirements have increased over the years, same holds for fire safety, air tightness, ventilation and solar challenges. The increasing requirements over the years have been increasing challenges during the process of re-using. Characteristics might not match the needed requirements. Therefore upgrading certain elements is needed.

Not only for the Netherlands requirements have changed. In different countries, due to different climates, the characteristics are different, as can be seen at "Portal Platform CB'23" (n.d.).

3.6. Facade as a service

In Section 2.3 the product as a service was described. In research by J. Azcarate-Aguerre together with TU Delft, a facade leasing pilot was set up. A client does not buy a facade but leases it, it hires the energy performance and user comfort that are required in its building. Performance contracts could increase the feasibility of implementing circularity. Putting the responsibility of management and upgrading on the suppliers' side, the incentive is created to optimise their systems. The suppliers keep ownership over the facade and will gain profit when their product reaches its full-service life and thus achieves its maximum value (Azcarate-Aguerre et al., 2022). On a building of the TU Delft, a facade leasing project was set up to further develop the complex system of contracts, financing and services required (Azcarate Aguerre & Klein, n.d.)

3.7. Refurbishment or new

As mentioned before it is often a choice for a client or building owner to refurbish or choose a new building. In some cases, the choice is made to invest in a new facade. Why are these choices made? This could give more insight into how to make sure clients and building owners are able to make more sustainable and circular choices.

The modern curtain wall facade has been applied increasingly over the past 40 years, mainly in office facades. High-rise has become more popular and thus also this typical facade. However, as mentioned before, the life span of some elements has been estimated at around 25 to 30 years (Ebbert, 2010). A lot of these facades will need attention in the coming years. Adding to that is that a lot of companies, due to corona, and also due to digitising of services, are closing down offices. A lot of office space is becoming vacant (NU.nl, 2022). In order to improve this kind of facade to be able to meet the requirements of different functions, such as housing, changes need to be made. When looking at buildings built 30 years ago, use different specifications as required during recent times. Often the insulation capacity of the framing and the glazing does not meet the requirements anymore. This means in order to achieve an energy-efficient building often a new facade needs to be installed.

According to Hartwell (2021) the reasons for the end of service life can vary. The factor that has been found to have the largest influence is aesthetic-related reasons. a new appearance or character is desired by a building owner, which leads to a new envelope. Next to aesthetics also performance is an important factor, the degradation of components or the need to upgrade the performance may lead to the replacement of a facade. Reducing the energy demand of buildings is a reoccurring reason for replacements (contact nr. 2, 2023). As mentioned before performance is related due to degradation or to improving energy efficiency. Also to reduce maintenance costs during use. Sometimes, when a function change happens, it could be due to legislation and performance issues. Lastly, safety reasons are due to structural problems. All are relevant reasons for building owners to choose a new and upgraded facade. However, most of the time elements that are within a facade could still meet the requirements needed or could be used with a different function.

In a reference study done in the ISSUU (2021), a couple of cases have been evaluated where the choice was made between a refurbishment and a new facade. In the first building from 1980, de-lamination of the skin was found, and the fasteners that secured the skin have been failing which caused safety concerns. In the end, the choice for refurbishment was made because the performance of the facade was still satisfactory. The incoming daylight, the views to the exterior and the cooling capacity have been up to standards. A refurbishment was done and the service life of this facade was extended. In a second case from 1960, the skin was causing water infiltration (ISSUU, 2021). The clips that held together the facade have been failing which caused panel deformation. Some of the insulated glass units have been damaged. After an extensive cladding assessment based on the parameters: interior and exterior visual reviews, and infrared thermography frost point testing, the decision was made to re-clad. The conditions of this facade were not up to standards anymore and a refurbishment strategy would have caused a lot of issues. Lastly, another case from the 1960s where a cladding assessment was done on the following parameters: Composition, moisture management, thermal performance and functional defects. Also in this case a renewal of the facade was done. A conclusion made from this reference study published in the ISSUU is that whether or not a refurbishment is done will depend on a lot of parameters. The cladding assessments will take time, also the refurbishment will cause technical and logistical challenges. The financial impact could influence the eventual choice. And lastly, a change in ownership of the building can influence the choice.

For a refurbishment to be beneficial to a building, but also to the building owner, a lot comes into play. It should therefore be regarded for each case as whether it is worth it or not. Also when refurbishing existing elements to be used in a different project this should be kept in mind. As described before the facade has a vast variety of performance requirements and is therefore an important part of a building. However, when the right things are taken into consideration elements can achieve a lot more than they are used for now.

3.8. Conclusion Aluminium curtain wall facades

A facade has a variety of functions to fulfil, which makes it a complex component in a building. It encloses an indoor space from the outdoor environment and regulates different influences internal and external. The facade has a significant impact on the overall building costs, the users' experience and comfort. It thus needs to comply with a multitude of characteristics, ranging from architectural appearance to structural integrity, thermal insulation, moisture control, acoustic performance and more, all while considering safety during construction, fire and use. Unitised curtain wall facades commonly use aluminium framing elements. This type of facade ensures a fast installation and is efficient when used in large repetitive quantities.

A configuration of different materials exists within an aluminium unitised curtain wall facade. Aluminium framing, glazing, and steel components were shown to significantly contribute to the environmental impact and overall weight of a facade element. The circularity potential of these materials has been examined. Examples from practice show the potential to exceed their expected life span and reuse potential. In the industry, strategies are being developed to create opportunities for reuse of these individual components. An overview of potential and impact is shown in Table 3.2. These components are connected using different methods, which have an influence on the de-mountability of the panel. In reuse, connections found within a facade play a crucial role. From the varying analysis, it has been concluded that the framing and glazing components showcase the most potential for reuse.

The decision between refurbishing existing facades or choosing to construct a new one is influenced by various factors. Factors that have been found are aesthetics, performance, legislative changes and safety concerns. In each case, careful consideration has been made to determine the most optimal approach. Taking into account these reasons when looking at reuse gives an impression of the quality of the component which could lead to a successful reuse case.

Table 3.2: Summary of materials found in the facade, and their potential for reuse

Material	Estimated life span	warranty by supplier	Share in kilo's	Share in A1-A5 carbon	Potential
Envelope system	60	10	100	100	A complete element can be removed top-down
Glass	60	10	45	22	High potential, difficult to disassemble
Insulated glazing	25	10	45	22	High potential, connection is difficult
Aluminium Sheet	60	10	5	10	High potential, connection is manageable
Aluminium Extruded	60	10	15	33	High potential, connection is manageable
Anodising	50	10			High potential, connection is manageable
Steel	60	10	12.9	8	High potential, the connection is manageable if not poured into the top layer of the concrete
Thermal breaks	30	10	0.5	1	Low potential, permanently connected do framing
Insulation	60	10	3	1	Low potential, could be removed, performance is questionable
EPDM gaskets	30	10	2	1	Low potential
Structural sealant	25	10	0.5	0.2	Low potential

To conclude this chapter it was found that the aluminium curtain wall facade shows potential in reuse scenarios. Since every project is one of a kind, the type of components, materials and connections play a crucial role in deciding on circular strategies.

4

Reference studies

In this chapter, reference studies are done to explore the methods that have been applied in practice. What were their successes and what were their pitfalls? Within the reference study, the original building and the refurbishment are analysed. The methods used and the results obtained are regarded. Lastly, the pillars that were defined in Chapter 2 are applied to the reference studies. A LCA approach is developed to further explore the life cycle stages and how to view a circular project. Within this research, four cases are explored, of which the two first cases are already executed so a complete analysis can be conducted. The last two cases are projects where a circular approach is intended to be applied. Firstly 1 Triton Square in London. In this project, the exterior facade was refurbished and replaced in the same building. Secondly Koningskade in The Hague, the curtain wall was refurbished by replacing the glazing that was reused in a secondary project. Thirdly Citibank in London is currently in the last phases of engineering. Lastly, De Sateliet in Amsterdam has been completely dismantled and is currently stored.

4.1: 1 Triton Square - London
4.2: Koningskade - The Hague
4.3: The Citibank - London
4.4: De Sateliet - Amsterdam




4.1. 1 Triton Square - London

Architect:	*Arup*
Location:	*London, United Kingdom*
Originally built:	*1990*
Original facade contractor:	*Scheldebouw BV*
Original client:	*First National bank of Chicago*
Original contractor:	*British Land*
Function:	*Office*
Year of refurbishment:	*Start 2016*
Client:	*British Land*
Contractor:	*Lendlease*
Facade contractor:	*Gartner*
Facade consultant:	*Arup*

Figure 4.1: Properties of 1 Triton Square (Pooley, 2021)

4.1.1. Original building

The original building of 1 Triton Square was constructed in 1990 to be a trading building. This was built for the First National Bank of Chicago by the British Land.

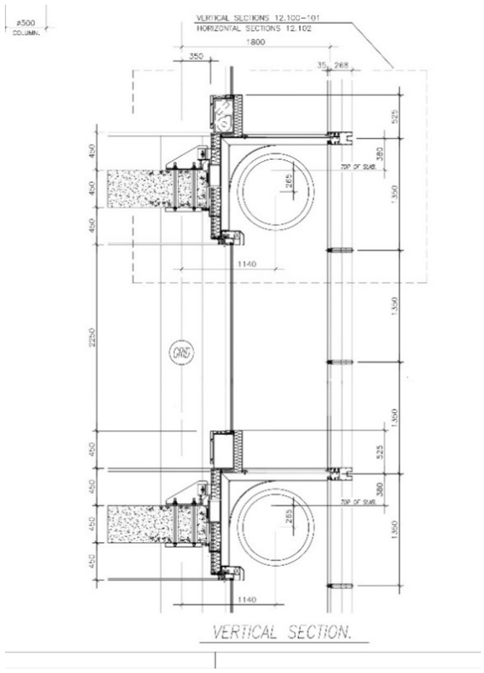
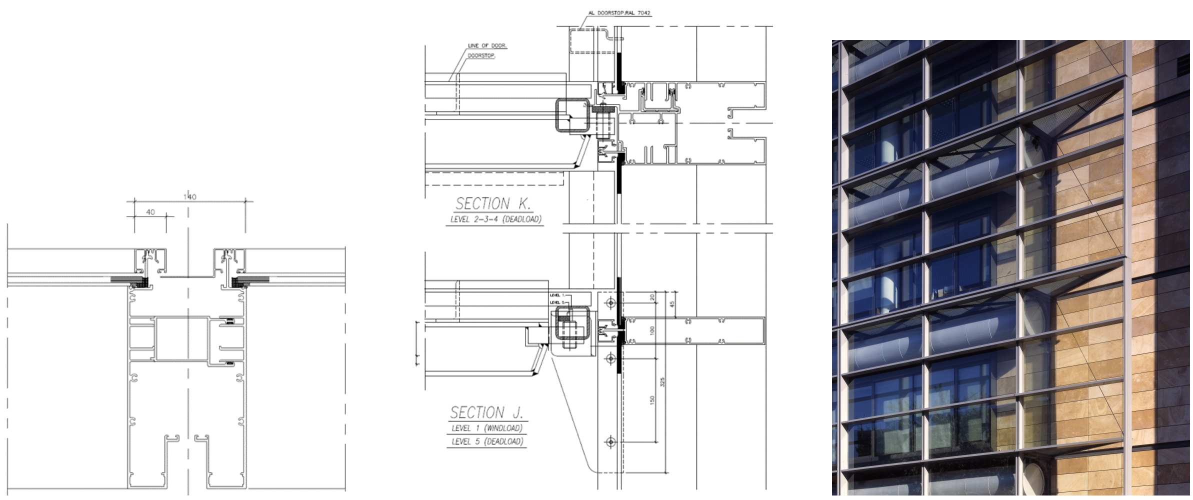


Figure 4.2: Original section by Scheldebouw (1997)

Original facade

The original facade was a 'pioneering' double-skinned construction. At that time it was one of the first times a double-skin facade was applied. The outer layer was made out of monolithic glazing and the inner layer of double-glazed ribbon facades (Pooley, 2021). The outer skin was made out of story-high panels that were three meters wide. The aluminium is powder-coated. They were hung from the top and restrained at the bottom to the steel brackets. The inner skin was double-glazed ribbon windows installed into a strong back system. They were a storefront facade and the panels were part of the thermal line and made sure the building was air and water-tight. The cavity between those two elements was one meter wide. On each floor, an open-able entrance was present in order for workers to enter the cavity and clean the inside of both planes. The glazing is structurally bonded to the aluminium profiling. As can be seen in image Figure 4.3b, the glazing is also mechanically supported by the framing. Galvanised steel grates were placed on top of gallow brackets to ensure a walkway between both elements. These brackets not only carried these walkways but also the outer skin. The gallow brackets are made of steel and powder-coated. The facade was a performance-led and integrated mechanical system(ISSUU, 2021). As can be seen in Figure 4.2 large ventilation tubes were present in the cavity of the facade. In Figure 4.3 the original detailing can be seen.



(a) Original horizontal section, showing vertical profiling

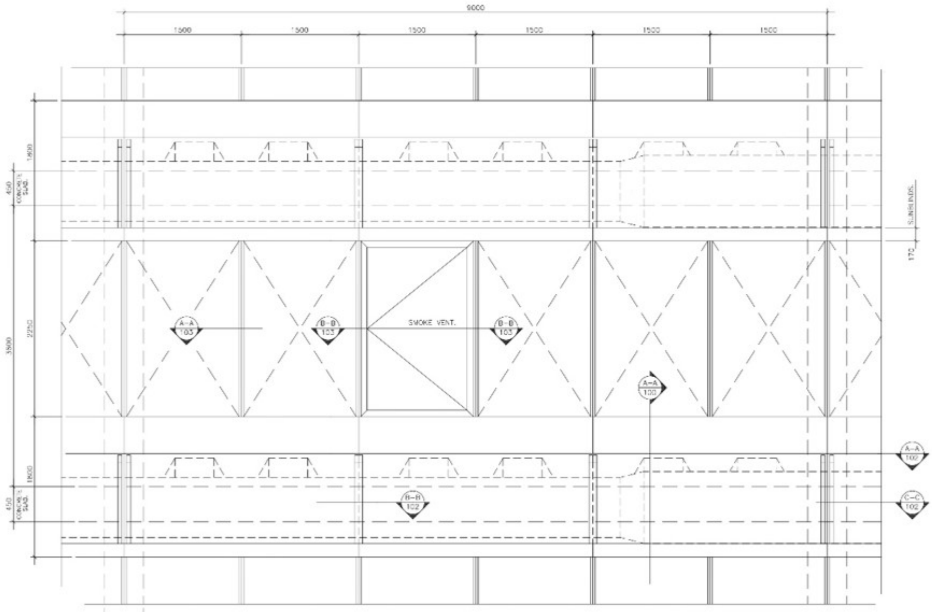
(b) Original vertical section, showing horizontal profiling

(c) Pictures of original the facade of 1 Triton Square, made by Scheldebouw

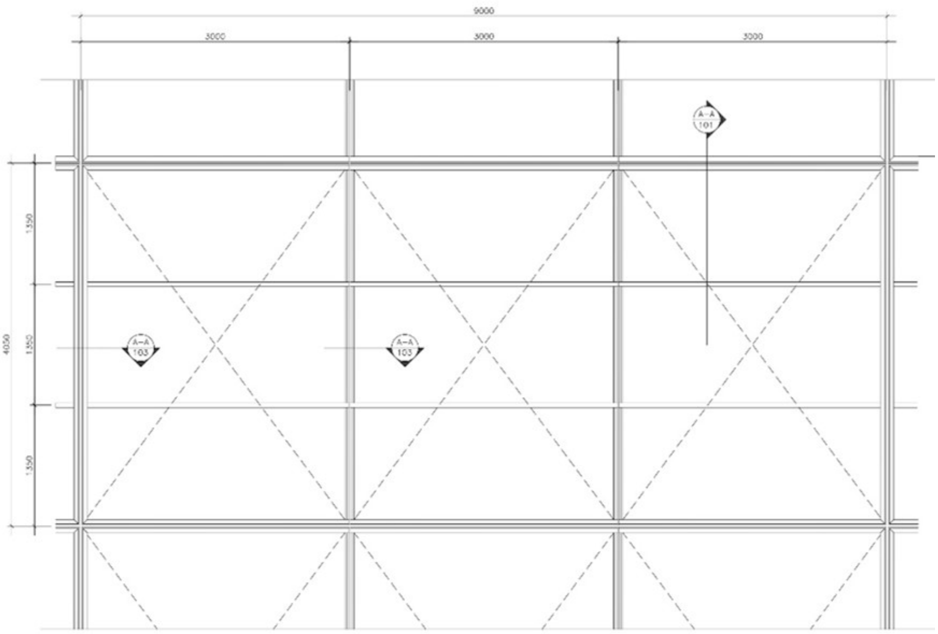
Figure 4.3: Original profiling, made by Scheldebouw (1997)

Because of the evolving needs of the users, British Land made the decision it was time to re-evaluate the building. Which led to the decision to transform the structure to comply with the current standards and today's work styles. the building had a well-performing load-bearing structure which was sufficiently over-dimensioned to increase the volume of the building. The client and contractor decided that the building was suitable for a circular approach as a starting point. Both shared a commitment to developing a sustainable building in design, construction and operation. A focus point was to retain as much value in the existing materials and reuse as many materials and components as possible. To be able to achieve this the original contractor was involved. Also, the original facade contractor and consultancy were gathered.

The original double facade was in a robust condition. This made it possible to dismantle and reuse the external skin. The glazed units were still performing great at 20 years old, in spite of that the future performance could not be guaranteed (Lomas, 2021). After visual inspections and re-evaluations, the decision was made that it would be possible to reuse this part of the building.



(a) Original elevation inner facade



(b) Original elevation outer facade

Figure 4.4: Original elevations, made by Scheldebouw (1997

4.1.2. Refurbishment

The building of 1 Triton Square was completely refurbished and expanded. The work started in April 2016. Time, money and carbon were saved by implementing refurbishment strategies for the total structure (Contact nr. 4, 15-2-2023). The philosophy of *"How much can we retain and reuse"* was taken on and kept in mind during the process. A marginal gains strategy was used, which meant by implementing a lot of small improvements great results could be obtained. (Arup & Glass, n.d.). A depiction of the general approach is given in Figure 4.5, showing the circular approach for the facade designed by Arup.

Figure 4.5: Sustainability diagram (Arup & Glass, n.d.)

In general, the new design consists of three extra floors which has increased the floor area by 70 per cent. The large Atrium in the middle of the building was decreased. $500m^2$ of green roofs were applied and five panoramic terraces were created. $3300m^2$ of limestone, $35000t$ of concrete and $1900t$ of steel were reused(Lomas, 2021). A diagram of the new design is shown in Figure 4.6. Next to the sustainable goal of the building also the goal of achieving a BREEAM outstanding certificate was present. Lastly, what this reference study will focus on, is that $3500m^2$ of the facade has been dismantled and refurbished.

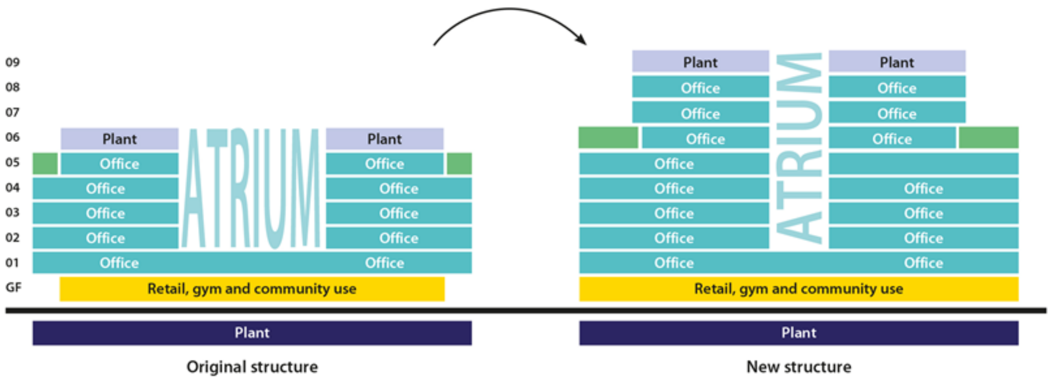


Figure 4.6: Diagram of the new design (Ferguson, 2021)

The facade consists of a couple of elements. An overview of this is given in Figure 4.7. The external glass screen was completely remounted, inspected, cleaned and reinstalled, after remounting, the panels were shipped to the pop-up factory. The steel grills in the cavity were inspected, cleaned on-site and directly reused. The galvanised gallow brackets, which carry the external glazing, were cleaned in the pop-up factory and repainted. The ventilation ducts were reused, and the external cladding and the internal insulation were inspected. The galvanised steel trusses that are in front of the floors are also cleaned repainted and reused. The work was done in the pop-up factory. The inner screen was replaced with mainly new elements. The existing facade frame, a strong back system, was reused. The internal and external shading were removed. New blinds were installed by the tenant. Solar gain is regulated by the coating on the new glazing. The Glass and aluminium carrier frame of the inner skin was replaced by a new laminated insulated glazing unit. This was done because the performance of the glazing did not meet the requirements in order to achieve the BREEAM outstanding. This new inner leaf was designed for disassembly.

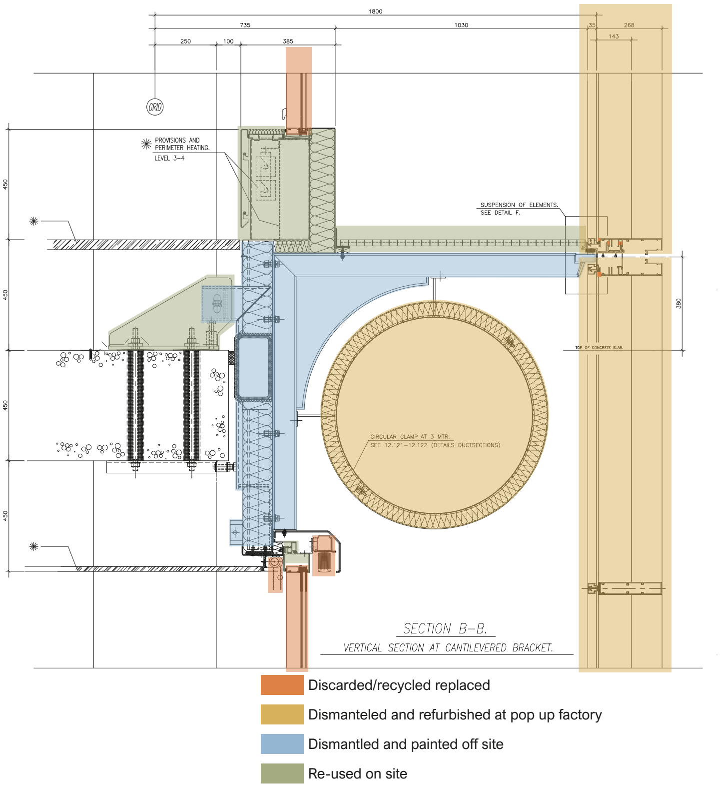


Figure 4.7: Overview of elements in the facade

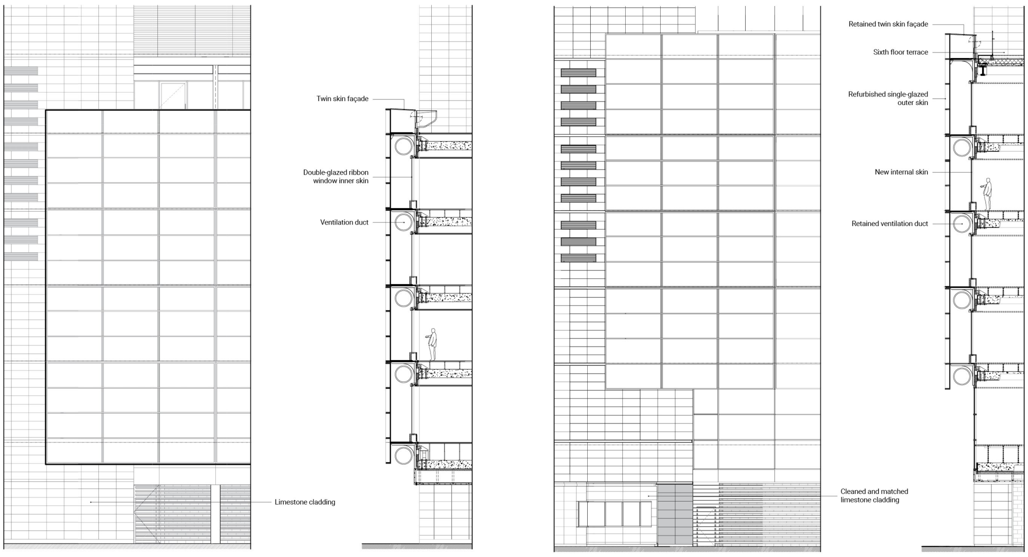
Dismantling

In order to dismantle the 3 metres wide panels the connection to the back brackets needed to be loosened. The panels were dry-fixed to the gallow brackets with bolts (CWCT, n.d.). Those gallow brackets were connected to the concrete flooring by steel connection plates. Both elements were disassembled by loosening the bolts. Because the original facade contractor was involved in the dismantling and started where the construction originally ended. The sequence of disassembly was important to keep track of so all the panels were carefully labelled. The last component that came off, would be the first element to be placed back. This also meant the refurbishment in the pop-up factory could only start after all elements were disassembled. The aluminium panels were shipped to the pop-up factory where further work took place. The gallow brackets were sent off to the pop-up factory (Figure 4.11b) and after cleaning they were painted at an external location. Next, the inner facade could be dismantled and new panels could be placed. This process is for this reference study out of the scope since this was a newly produced facade. Next, most of the insulation that was placed in front of the floors was kept. New fire breaks were installed in order to ensure the fire safety was still of sufficient level. The insulation was also kept in place and increased in some places. Lastly, the galvanised steel walkways that ensured workers cleaned the inside of the facade are directly reused. They were cleaned on-site and placed back when the panels were reinstalled.

Figure 4.8: Picture from the construction site (NSC, 2019)

The steps that were undertaken during disassembly were (Contact nr 3, 15-2-2023):

1. Finding out the sequence
2. Loosening bolts at the panel
3. Lifting off the panel and placing it on the carrier
4. Labeling panel
5. Loosening bolts at the floor
6. Taking of gallow bracket
7. Shipping the panels to the pop-up factory, Shipping gallow bracket to paint shop



(a) Section of Triton Square 1 in 1990

(b) Section of Triton Square 1 proposed

Figure 4.9: Sections of 1 Triton Square (Lomas, 2021)

Pop-up Factory

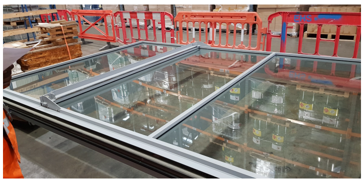
Figure 4.10: Picture from the construction site (Arup & Glass, n.d.)

When making the plan for refurbishment off-site, first it was planned to send back the panels to the production hall in Germany. Later the idea came to set up a pop-up factory nearby to avoid transportation miles, around 25000 transport miles were saved (Pooley, 2021). The factory was set up by the contractor. At this site, all the panels were stored, see Figure 4.11c. During the refurbishment, the panels were set up as a structure, this can be seen in Figure 4.10. The panels were deep cleaned and the sealant was checked. In the places where it was possible the EPDM gaskets were taken out and replaced, see Figure 4.12. Same as for the bracket it was a challenge to find EPDM gaskets that would fit into the framing because they were designed over twenty years ago. The EPDM gaskets were at the end of their life span, so they were scrapped in the process. In the previous section, it was described the sealant has a tested life span of 25 years, despite after inspection, it was decided that these elements did not have to be replaced. There was also no delamination found in the glazing. As described before the glazing is structurally bonded by the sealant but also mechanically supported. This led to the decision to place the panels back on the structure without replacing the sealant. During the process at the pop-up factory also one element broke. The broken element could be replaced.

The steps that were undertaken at the pop-up factory (contact nr. 3, 15-2-2023):

1. The elements arrive at the factory
2. Storing the panels
3. Lifting the panel, by a crane of the carrier and putting it on a glazing-carrier
4. Glazing and aluminium are cleaned
5. The panel is inspected
6. EPDM gaskets are replaced (as far as possible)
7. The panels are stored again
8. When assembly time has come, the panels were shipped back to the site

The refurbishment works were done in an empty warehouse in Essex. This provided jobs in the area. At this place, a crane was present to lift up the elements (Figure 4.11) and a forklift to move around the carriers with the panels on it. A total of eight construction workers worked in a sequence to carry out the work that was needed. The total refurbishment works at the factor took around three months.



(a) Facade panel lying in the pop-up factory, images made by site contractor (Contact nr. 3, 15-2-2023)(2018)

(b) The gallow brackets set up in the pop-up factory, pictures made by the site contractor (Contact nr. 3, 15-2-2023)(2019)

(c) Storage of the facade panels at the pop-up factory, pictures made by site manager (Contact nr. 3, 15-2-2023)(2019)

Figure 4.11: Pictures at the pop-up factory

(a) Detailed view of the condition of the framing

(b) Replaced EPDM gaskets

Figure 4.12: Condition of the elements in the pop-up factory, pictures made by site manager (Contact nr. 3, 15-2-2023)(2019)

Re-mantling

After the elements returned from the refurbishment, they were put back into their original place. Except for the panels from the first floor, they were moved up to the sixth floor. This can be seen in the section in Figure 4.9. The gallow brackets were also assembled back, except for the brackets on the first floor. A similar element was created to be connected to the sixth floor. Some of the end pieces of the brackets were damaged during construction. These were replaced. This was quite a challenge to find producers that produce identical elements as before (Contact nr. 3, 15-2-2023). During the assembly stage, one glass element broke, which they were able to replace. In total the facade refurbishment took over three years and the re-installing began in the summer of 2019. This includes the other works that had to be done to the building.

Warranty and liability

For this project, a new contract was proposed with the main contractor. In this contract, the warranty of the facade is evaluated. The facade contractor did not give a new warranty on the refurbished facade. The original warranty of the facade was 10 years and those years have passed. However, the service life was discussed before composing this contractor, in a talk with the director he mentioned that before the contract was made a joint inspection of the facade was done. The service life was revisited. Despite that, there was no new warranty given a new service life was proposed (contact nr. 2, 8, 6-3-2023). This is shown in Table 4.1, it can be noticed that the predicted service life of the refurbishment is the same as the difference between the original predicted life spans and age at that time, see Equation 4.1. This method is logical and is thus also presented in the sub-contract of this project.

Table 4.1: Referenced service life of the refurbished facade in 1 Triton Square

Item	Predicted service life original	Age during refurbishment	Predicted remaining service life
Cladding system	50	22	18
Structural steel elements	60	22	38
Aluminum framing	60	22	38
Glass units	25	22	3
Laminated glazing	25	22	3
anodising	50	22	28
Gaskets internal	30	22	8
Gaskets external	30	22	8
Structural sealant	25	22	3
Insulation	60	22	38
EPDM membranes	30	22	8

Another important part is the liability during construction since the building is the property of the owner and not of the construction consortia. It, therefore, was important to check who was liable for what. Before and during construction the facade stayed the property of the building owner. The responsibility of handling the elements was on the contractor's side. however, when after certain actions, it seemed that the panel's quality was off it was at the owner's liability. If for example during the lifting of the panels, the structure got damaged or the glazing broke it was of responsibility of the contractor. The intellectual property also stayed at the owner's side. This means that the architect who designed the element was not able to intervene.

$$PredictedRemainingServiceLife = PredictedServiceLife - CurrentAge \tag{4.1}$$

Findings

General successes and pitfalls were found during this analysis (Contact nr 3, 15-2-2023). A challenge, which was already described in the sections above, was finding elements that are similar to the elements originally used. The elements were designed over 20 years ago so finding ”like for like” is first important for the look of the building but also the connection, but secondly difficult to find. As mentioned by most of the sources one of the factors that made this project a success was an early engagement of the original parties that were involved in the original construction and design. The as-built drawings of all the elements were available, and the knowledge of the original parties involved helped ensure the refurbishment was possible. A remark that was made by the site contractors was to assemble an as-built digital model before construction, this could be done by making a point cloud or using scanning software. The facade consultant from ARUP also mentioned that because the refurbished facade was not part of the thermal line or the main line of defence, the refurbishment could be done. No further requirements were set for this outer facade, only the inner facade which was part of the thermal line. Because of the performance required to achieve BREEAM standards the inner facade was improved by replacing it with a new ribbon facade. No quality control was carried out during the construction works. Lastly, only two glazing panels broke, as mentioned before, on-site and one in the pop-up factory. When looking at the total project, this means that the panels were efficiently dismantled. The dismantling was possible and fairly simple by unscrewing the bolts.

Technically when looking at the success and pitfalls of this project. The powder-coated aluminium and the repainted steel brackets did not show any ageing effects. This shows great potential for the circular use of these metal elements. Also the glazing, despite some damages during construction, showed no de-lamination and had only minor defects that occurred during its life span. The weakest link in the facade are the spacers and gaskets, the gaskets were replaced in this project. Because the glazing in this refurbishment did not have spacers, this was not an issue in this case. The EPDM EPDM gaskets and the spacers have the lowest tested life span insurance. During the design of such a panel, these elements should be kept in mind.

A last challenge that was brought up by the facade consultant but also mentioned in the previous chapter is the reassurance and warranty of such a circular facade. Who bears the risk of this facade being safe? As described before, there was no new warranty given for the refurbishment. This is because the sub-contractor was not confident.

4.1.3. Circular strategies

The division of circular approaches applied are divided in the table below. A distinction is made between three pillars, this is described in Chapter 2. This division is shown in Table 4.2. A distinction between the two projects has been made however some clear overlaps happen between the both.

Table 4.2: Pillar distribution of 1 Triton Square

Reduce	**Supply**	**Manage**
The thermal line was improved, the energy efficiency of the building was improved	The panels could be demounted as a system	Original contractor and advisors were involved
Materials that were not put back were put into recycling	The panels were connected by a bolted connection	Original drawings were available
Brackets were reused in the same location	Panels were not part of the thermal line	No new warranty, also no requirements
Exterior panels were reused in the same location	Parts were cleaned	
Steel walkways were reused in the same location	EPDM gaskets were changed	
The refurbishment was done close to the construction site	Visual inspection	

Carbon analysis

To develop an understanding of an application of the circular approach of these projects, looking at the facade is given in illustration in Figure 4.13. In this image, it is shown that this project is a refurbishment. This is placed in B4. Within this stage, the dismantling of the inner skin and brackets, and transport back and forth between the construction site and the pop-up factory are counted. Next the works in the pop-up factory and the re-mantling. Also, the waste during this stage should be accounted for. Next, the old EPDM gaskets that were taken out are transported (C2) and put into a landfill (C4). Also, the old inner skin was dismantled and disassembled (C1) and transported to the waste processing (C2) And some parts were recycled (C3 and C4). Lastly, the new EPDM gaskets that were put into the refurbished facade and the new inner skin are again taken from the raw materials for the construction (A1-A5). The savings made by implementing this circular process can be found by seeing what the difference in impact would be between this and a 'traditional approach'. Which would be dismounted, wasted and a new facade.

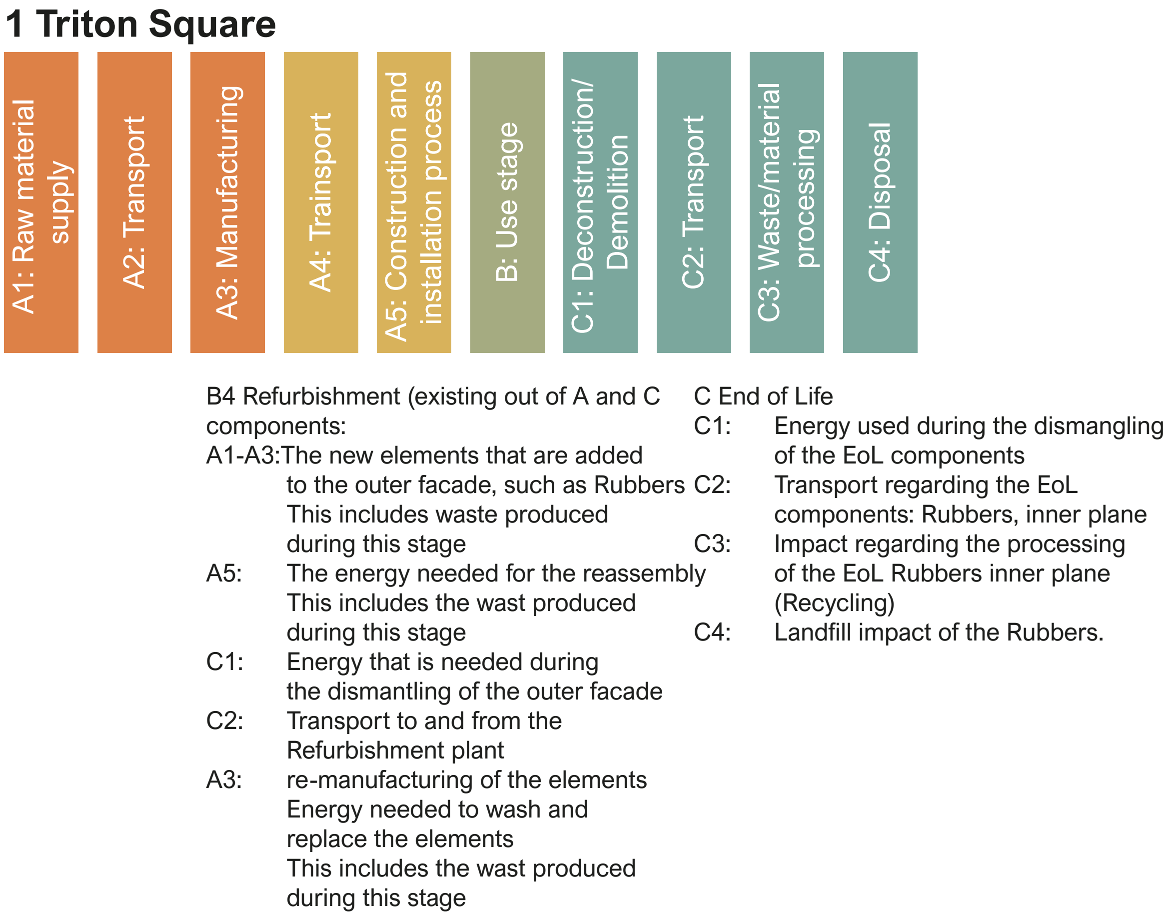


Figure 4.13: Sketch image of circularity at 1 Triton Square

4.2. Koningskade - The Hague

Architect:	*Rog Hootsmans*
Location:	*The Hague, The Netherlands*
Originally built:	*1969*
Original facade contractor:	*Scheldebouw*
Original client:	*Het Nederlands Instituut voor Toegepaste Geowetenschap pen, TNO*
Function:	*Office*
Year of refurbishment:	*2021*
Client:	*Rijksvastgoedbedrijf*
Contractor:	*Boele and van Eesteren, HBG Utiliteitsbouw en Hillen and Roosen*
Facade contractor:	*Scheldebouw BV*

Figure 4.14: Properties of Koningskade 4 (Hootsman, 2008)

4.2.1. Original building

The original building at the Koningskade 4 in The Hague, one of the first curtain wall facades in the Netherlands was introduced. This facade was a double-skin facade with an air cavity between. Hence this building has a monumental status (VMRG et al., 2022), the facade contains an aluminium framing with a large gasket and a sheet of float glass in it. This float glass had no coating or other additives on it. An impression of the original facade is given in Figure 4.15. In 2003 already a renovation was done. The double skin with air cavity was maintained and refurbished. The indoor climate could meet the current requirement.

(a) The original facade of the Koningskade

(b) The view of the EPDM gaskets and the status of the framing in the Koningskade

Figure 4.15: Conditions of the original facade, made by Scheldebouw (2020)

4.2.2. Refurbishment

In 2000 a refurbishment was planned. This office building, like most other office buildings, didn't comply with the regulations at that time. The building was vacant for seven years already, because of the 'sick building syndrome' (BAM, 2001). During the winter it got too cold inside the office rooms, and during summer the heat was not bearable. In 2003 the renovation was performed. A couple of years later, in 2021, the outer shell needed to be replaced. The main reason for the glass replacement was safety reasons. It should be replaced by laminated safety glass. To make the indoor climate more comfortable a new approach needed to be developed, without losing the characteristic aluminium facade. To achieve the requirements of that time the glass would need to be replaced. This was done by replacing the gasket and the glazing with a newly developed aluminium profile which fitted onto the original structure and glazing with the appropriate thickness which was compliant with the regulations at that time. Throughout the entire building, the glazing was replaced. The architectural value had to be retained because of its monumental status. This could be achieved by applying this new profiling (VMRG et al., 2022). During the refurbishment, a double skin was introduced (Biedboek, n.d.). A comparison between the new and old drawings is shown in Figure 4.17. In total 2215 units were replaced.

(a) The aluminium profile after the glazing was removed

(b) The aluminium profile after the glazing was removed, from the inside

Figure 4.16: Pictures during the refurbishment, made by Scheldebouw (2020)

A comparison between the new and old drawings is shown in Figure 4.17. From this figure clearly, the new framing in comparison to the old EPDM EPDM gaskets can be seen. Laminated glazing was installed to ensure fall-proofing. The difference in thickness between the two glazing types was not significant. This also ensured that the weight of the infill, the aluminium framing including the glazing, was comparable to the old infill. No extra structural measures needed to be taken.

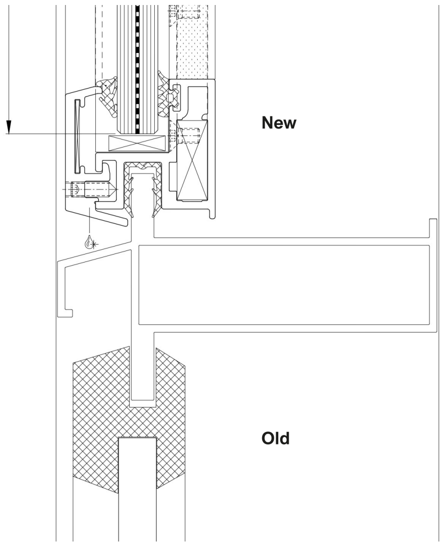


Figure 4.17: Comparison between the old and new connection of the koningskade facade, made by Scheldebouw (2020)

Construction site

On the construction site, a couple of facilities were present. Such as a 'hefsteiger' to reach the highest floors. This is pictured in Figure 4.18b. This structure was moved each time an elevation was finished. Scaffolding was used on the low-rise parts of the facade, this can be seen in Figure 4.18a.

(a) Refurbishment works **(b)** 'Hefsteiger' **(c)** Scaffolding

Figure 4.18: Pictures of the works on site, made by Scheldebouw (2022)

During construction the following steps were taken, This is also pictured in Figure 4.20 (Contact nr. 6, 2-3-2023):

- The original glazing is cut out of the EPDM gaskets
- The EPDM profiling is removed from the original profiling, and the remaining sealant is cut off
- Existing profiles and the space between the windows inside and the curtain walling are cleaned. See Figure 4.16a for an impression of the status of this area.
- The Aluminium profiles are delivered in parts on-site
- A new EPDM framing is applied to the remaining aluminium profiling.
- Vertical mullions are placed. After the corner piece is connected also the horizontal mullions can be placed. Both are mechanically connected
- EPDM frame is placed which is for the water tightness of the frame, and the supporting parts for the glazing are positioned
- The new laminated glazing is placed in the original framing
- The exterior framing is placed which is kept in place by EPDM gaskets and mechanically connected to the framing

In order to collect the float glass out of the original framing, the following method was used. The glass was not collected in a container, to avoid contamination, but it was placed on the frames the new glazing was brought to the site. The glass was transported to a storage room after that the glazing was placed in a large container and shipped to Saint Gobain France. In the construction reports provided by Scheldebouw, it was also mentioned that the new framing should be connected by using a sealant in between the gasket gaskets and the newly positioned framing. This is something to keep in mind for future refurbishments (Contact nr. 6, 2-3-2023).

(a) Scrapped EPDM gaskets of the koningskade, made by Scheldebouw (2020)

(b) Comparison of the refurbished and old facade, upper right is the old connection, upper left is the new connection. Made by Scheldebouw (2020)

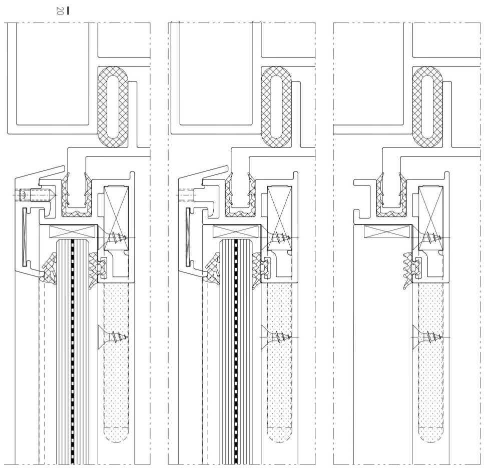


Figure 4.20: Drawings of the construction sequence, made by Scheldebouw (2020)

Testing

After the installation of the new framing and glazing, some tests were executed to assess the new performance of the facade. A site hose test was done, on the original and refurbished facade. Secondly, a sound test was done on the original and refurbished facade. Both indicate that the performance of the facade was improved after the works. An impression of the site hose test is shown in Figure 4.21. Both tests came back positive which indicates the refurbished facade performed better than the original. However, still, leakage issues were still found in the framing of the original facade.

(a) Site hose test

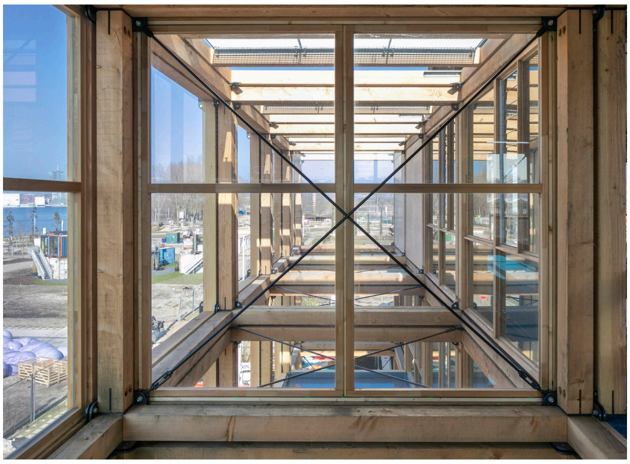
(b) Results of the site hose test

Figure 4.21: Testing of the water tightness, pictures by Scheldebouw (2020)

4.2.3. Repurposed

During the tender phase of this project, it was a priority that circularity would be Incorporated. They described the circularity on different levels: reuse of the products in a similar function, reuse in a different function, and reuse of the materials to make new products. The latter could imply recycling. An estimation of the total amount of glass that was in the project is around $170000kg$. $12500kg$ is being reused in another application, this is around 400 planes. In the end, no similar use was found for the glazing panels because of their thickness and size. The float glass that was not reused, was recycled. This glass was pure and used for high-value recycling which means that the glass was used for new float glass and thus not down-cycled. Saint Gobain claims that this float-glass is fully circular (VMRG et al., 2022).

Floriade: The Natural Pavilion



Architect:	*DP6 architectuurstudio*
Location:	*The Floriade in Almere*
Year of construction:	*2022*
Client:	*Flriade Expo*
Contractor:	*Post Bouw Urk, Lomans \ Totaalinstallateur*
Function:	*Office, meeting and congress location (Temporary)*

Figure 4.22: Properties of The Natural Pavilion (Scagliola & Brakkee, n.d.)

As mentioned a part of the glazing has been directly reused in a different project. The glazing is reused in the Natural Pavilion. The Natural Pavilion was part of the Floriade of 2022 and was aimed to be a bio-based and de-mountable building. The glazing from the Koningskade has been used in this project. The building was temporary and thus designed in a way that the separate elements within this building could be dismounted and reused again. When this building was designed the size of the materials influenced the design. The building material led the design. The framing for the window was designed around the glass plane, in standard design, this process is in reverse when comparing it to a standard process. This meant that the glazing mainly did not have to be cut to size. It is also claimed that the framing is made of 100 per cent bio-based and circular frames, the frames including the glazing are available for a second and third time. (Woningbouwatelier, 2022). The total project was a collaboration between a vast group of companies which made this project a success ("Nieuws and Video - The Natural Pavilion", 2023). Next to the glazing in the facade parts are reused in around 50 solar panels. The panels are reused from the glazing of the office building, the glass is cut to size and a solar film is applied. These are supplied to the energy network. The efficiency of these panels is not expected to be high, however, the energy that is generated is used for the installations, and the operation of the windows and lamellas (Woningbouwatelier, 2022).

Figure 4.23: The Floriade (Scagliola & Brakkee, n.d.)

The building of the Natural Pavilion is currently still in use. At first, it would be de-mounted after the Floriade ended. However, it is now still in use as an office, meeting and congress location. The aim is that after dismantling the parts or the whole building of the Natural Pavilion will get a new purpose in the same place or somewhere else.

4.2.4. Circular strategies

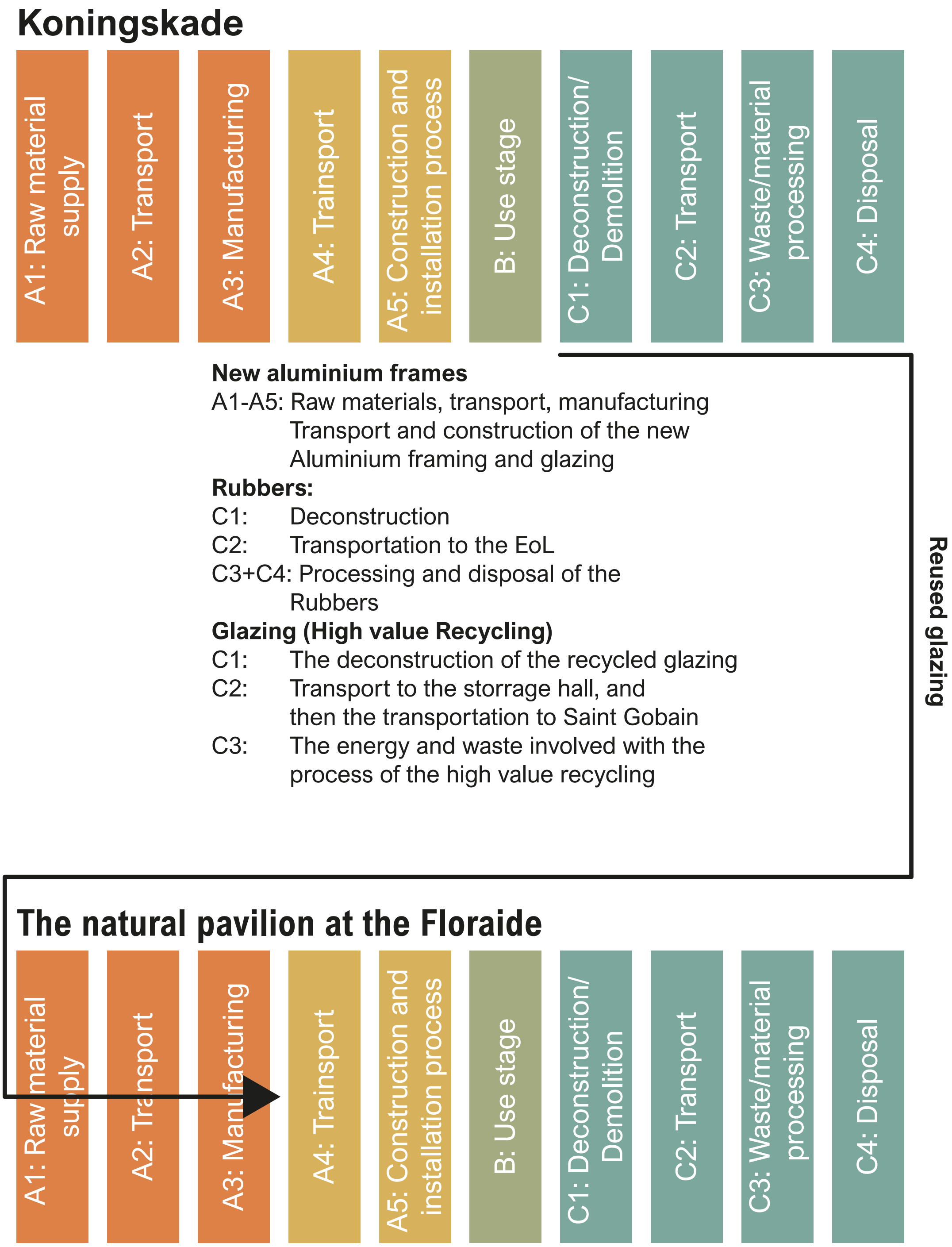
The division of circular approaches applied are divided in the table below. A distinction is made between three pillars, this is described in Chapter 2. This division is shown in Table 4.3. The strategies have been subdivided between the two projects, some clear overlaps happen between the both.

Table 4.3: Pilar distribution of KoningsKade/ Floriade

Reduce	**Supply**	**Manage**
Koningskade 4		
Original framing was kept in place	Original EPDM gaskets and sealant could be cut, to take out the glazing	A new destination for the old glazing was found
Energy losses are reduced by replacing the glass	New framing of the Koningskade replaces the EPDM gaskets	Testing was performed on the refurbished facade
Part of the old glazing is recycled as new float glass	Pure float glass was in the original situation of the office building	The status of the materials was known
A new use was found for part of the float glass	Glazing was carefully taken out and placed on the structure the new glazing was brought in on	
The Natural Pavilion at the Floriade		
The design of the new building was adjusted to the available materials	The old glass used in the Floriade	Design was adjusted to the available material
Part of the old glazing is directly reused as exterior glazing in the Floriade	De-mountable connections in the Floriade	Consortium of companies
	Framing is designed according to the available materials	Initial effort to reduce the impact

Carbon analysis

Secondly to develop an understanding of an application of a project the circular approach of these projects, looking at the facade is given in illustration in Figure 4.24. From here it can be found that in the project of the Koningskade in the B4 stage, a refurbishment took place. As described in the previous chapter the B phase exists out of another layer of the A and C stages. New material was brought in to supply the improved glazing, the new aluminium framing and new EPDM gaskets. The site activities and the waste that is caused by both mentioned processes. Next, the gaskets were discarded thus they get into their EoL stage and undertake transport and landfill/recycling, a picture of the scrapped gasket can be seen in Figure 4.19a. Next, the old glazing, part of it follows the same route as the gaskets since it is not used in this project anymore thus it undergoes transport and recycling. The glazing that is reused in the new Floriade, transfers over to this new project and skips the A1, A2 and A3 stages, A4 accounts for the transport that is needed between the projects. Stages C3 and C4 are skipped in the original project. The glazing is redirected in the A5 stage and constructed in its new framing on site. Lastly, the new 'bio-based' framing has been accounted for in the A1, A2, A3 and A4 stages. The new 'bio-based' framing is factored into stages A1, A2, A3, and A4. Savings in Floriade result from the avoided carbon in the product stage, while Koningskade savings derive from comparing the 'traditional' process with this scenario.



Reused glazing
A1: The deconstruction of the glazing that is reused in the Floriade (Mining)
A2: Transport from Koningskade, to the glazing manufacturer
A3: Cutting down the glazing to size
A4: Transport from the glazing manufacturer to the Floriade
A5: Installation of the glazing panels

Benefit: is the avoided mining and manufacturing that would have been done if new glazing wold be used, also the waste scenario is avoided

Figure 4.24: The interpretation of the LCA of Koningskade and Floriade

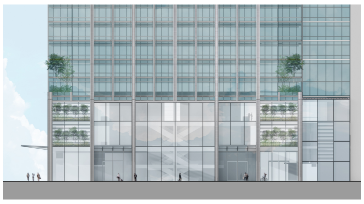
4.3. Citibank - London

Architect:	*César Pelli*
Location:	*London, United Kingdom*
Originally Built:	*1998-2001*
Original facade contractor:	*Scheldebouw BV*
Original Client:	*American Multinational investment bank*
Year of refurbishment:	*Start in 2023*
Function:	*Commercial*
Facade contractor:	*Scheldebouw BV*

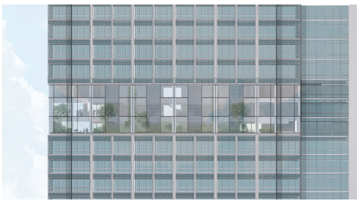
Figure 4.25: Properties of Dochlands Square 5 (Buck, 2019)

4.3.1. Original building

The Citibank building, also known as Dochlands Square 5 (DS5), is located in Canary Wharf, London. Originally constructed as an office building in 1998, it spans 45 floors and serves as the primary office for Citigroup Inc. After 25 years, the client decided to revamp their company's image and the building itself, redesigning their workspace to reflect their character. Out of the 45 floors, 10 are undergoing redesign: three on the ground floor (Citi Square connectivity), three in the middle (Citi High Street), and four on the top (Citi Beacon). Consequently, these ten floors will yield reusable facade panels, as the facade's lifespan is not yet exhausted. Scheldebouw and Citigroup are actively seeking new purposes for these panels, with plans to commence dismantling in the summer of 2023. This project has been a topic of research at the company. Various tests have been performed to safely dismantle the panel. Therefore this project has been an interesting reference study regarding the stages of donor building.



(a) Citi Square Connectivity impression



(b) Citi High Street Impression

(c) Citi Beacon impression

Figure 4.26: Renders of the redesigned parts of the Citibank, made by Buro Happold

Facade principle

The facade type in this project is an aluminium unitised panel system with horizontal male-female interlocking connections, resulting in distinct left and right transom framing. The aluminium framing is powder-coated. This can be seen in the detail shown of the as-built situation in Figure 4.27. The panels span one floor, which varies throughout the building. The width varies between $1.5m$ and $0.4m$. The facade pattern repeats every 9 meters and comprises two main panels: a stainless steel-finished spandrel panel and a transparent panel with a shadow box, including two transparent sections and horizontal stainless steel elements. (See Figure 4.28). The panel connection vertically between panels is done by a connection profile. The building is structurally glazed and has some stainless steel elements on the outside of the framing. Next to that, the glazing has a coating on the inside. At the location of the columns, a vertical spandrel panel is placed existing out of a layer of $75mm$ of hard insulation and a $1.5mm$ sheeting on both sides. As a cover, the stainless steel cover cap is placed with a linen finish. At the floor levels cover caps are placed as well as a shadow box. This consists of a $75mm$ thick insulation layer with an aluminium cover and a steel back-plate.

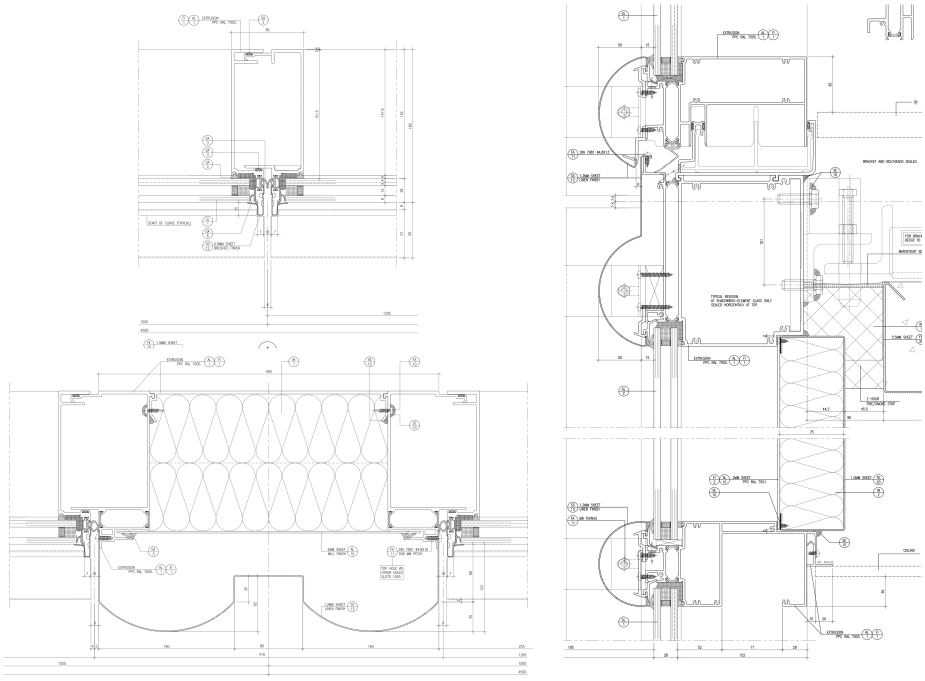


Figure 4.27: Horizontal and vertical framing detailing, made by Scheldebouw (2002)

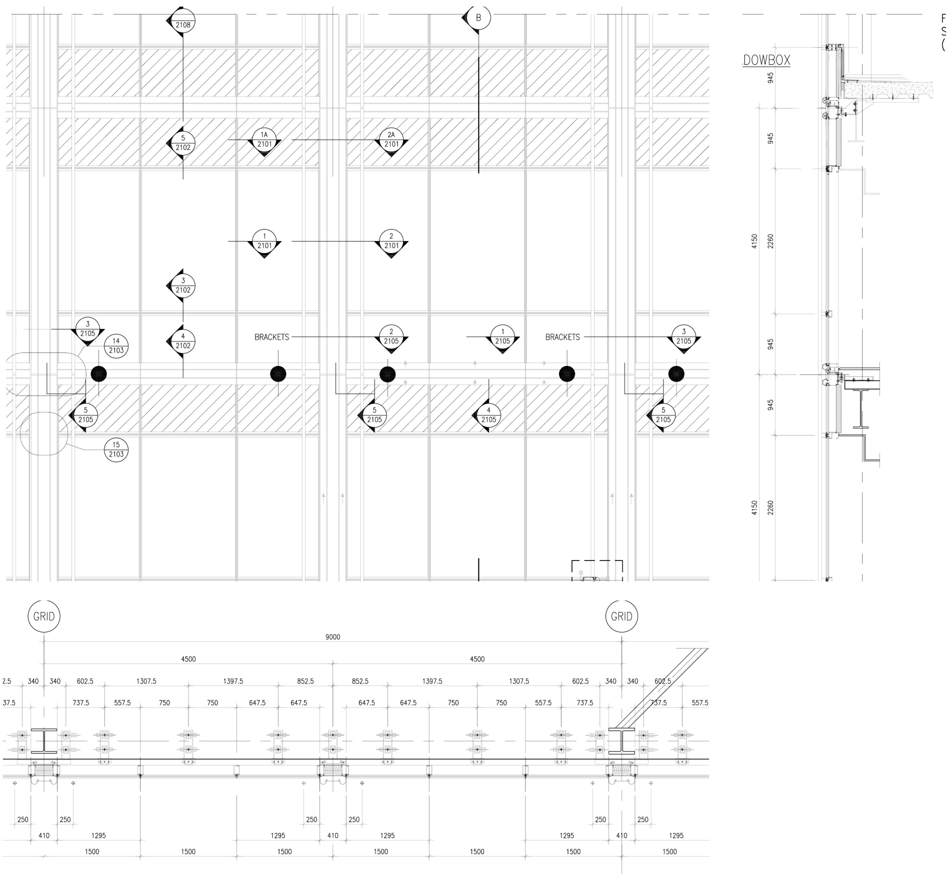


Figure 4.28: Horizontal and vertical section of the Citibank, and elevation, made by Scheldebouw (2002)

4.3.2. Dismantling

Information in this next section is gathered internally within the company Scheldebouw (contact nr. 1, 2, 2023). At the time of this writing, the dismantling has not started yet. The planning and engineering have been done for the most part. As described before the dismantling and the Citibank panels have been subject to extensive research. A mock-up dismantling has been done in the production hall in Middelburg as well as a dismantling of a whole panel. Next to that studies have been done on the potential options available for these panels. As described above three floors in the middle of the building will be removed. A dismantling plan is in place, as depicted in Figure 4.29, which outlines the panel removal sequence on-site. To ensure safety, a scaffold fan will be erected one floor below the dismantling area. This requires temporarily removing some small insulated glazing units, which will be reinstalled upon completion. Glass removal will be executed using glazing robots equipped with vacuum pads attached to the inner glass surface. The process involves removing the bull-nose, cutting silicone joints, and implementing additional safety measures. Once the glass is detached from the frame, it's moved back into the building and placed on a frame near the removal zone. Access to the outside of the facade will be facilitated using a birdcage. Dismantling will progress from the top down, starting by securing the units above the floors slated for removal to the slab. Subsequently, the bull-nose will be removed from the outside, and the small glass plane extracted, following the previously described method. Finally, the mullions and top transoms will be cut from the inside before removing both panel parts. Next, the mullions and top transoms are cut from the inside. After both panel parts are removed using the glazing robot. The panels below are removed as panels using a spider mini-crane.

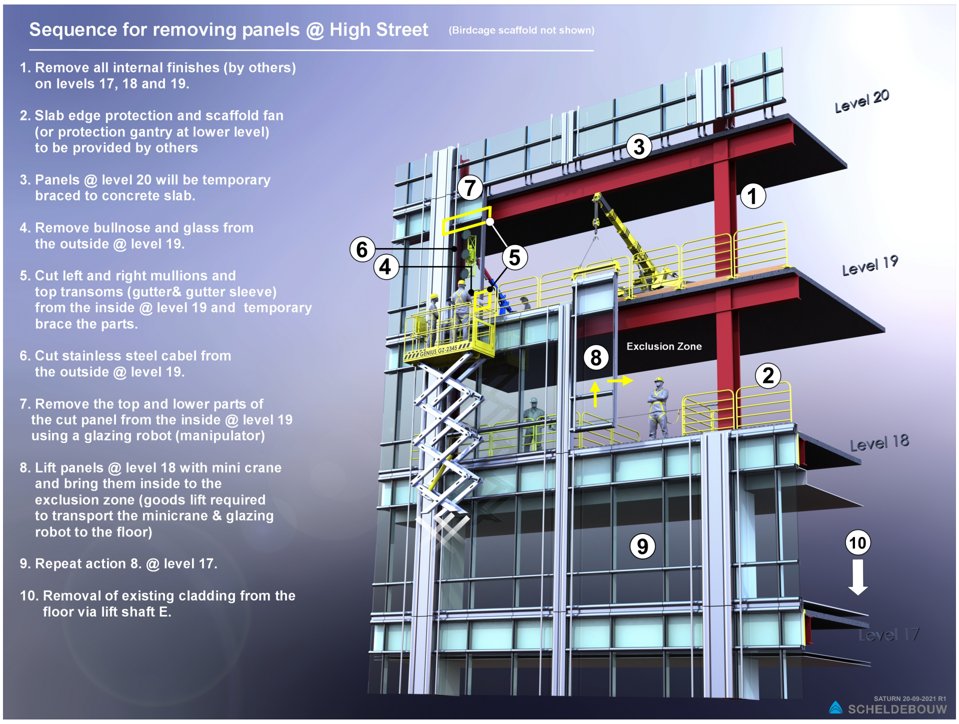


Figure 4.29: Sequence for removing panels, made by Scheldebouw (2023)

The actions that were evaluated during the dismantling in the production hall showed some additional actions. Which are later on in this section shown in the pictures. In Figure 4.29 it is also mentioned that after cutting the panels on one floor, the rest of the panels can come out completely. However, it was also mentioned by workers that connection profiles that are used to connect different panels are often connected by a lot of sealants. This might make dismantling the panels as a whole more difficult than is pictured. This is done on-site and is different from the as-built drawings.

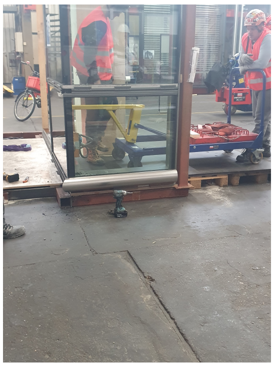
Dismantling construction mock-up

The complete analysis of the dismantling of the mock-up setup of the panels can be found in Appendix D. In the production hall in Middelburg, a test set-up with spare panels that were kept over the years was done. The goal was to try the dismantling of the panels by the construction workers in a safe environment. To see if it was convenient and possible to take out the panels. An added observation was done on the status of the materials that were left. In Figure 4.30 the sequence in the production hall is pictured. First, the stainless steel elements were taken off the outside framing and the gaskets on the outside of the framing were pulled out. To give the framing room to remove the glazing, the framing was sawed and the sealant holding in the glazing was cut, after which the glazing could be removed. This process is repeated for the other glazed units. After which the remaining framing can be removed

(a) Workers dismantling the outside element

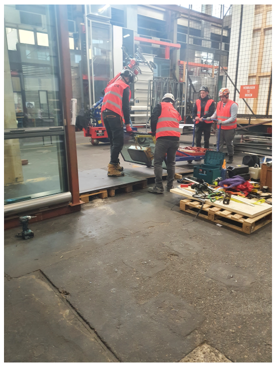
(b) Closer view of the holes drilled in the framing

(c) Cutting the sealant of the windows



(d) The machine connected to the glazing

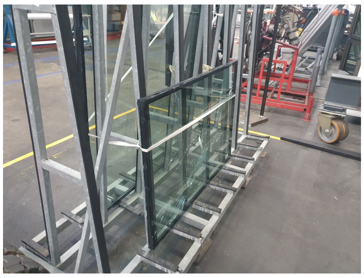
(e) Workers forcefully taking out the glazing



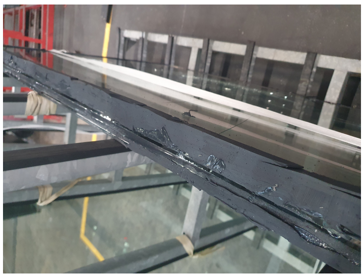
(f) The glazing taken out of the framing

Figure 4.30: The process of the dismantling (2022)

The remaining components of the dismantling are regarded. Of the six glazing elements, the three smaller elements got broken. The big glazing panels could be taken out without damage. The edges of the glazing still contained the structural sealant. The glazing was damaged at the edges from cutting the seal, this can be seen in Figure 4.31.



(a) The dismantled glazing, which in some instances was broken



(b) The leftover sealant on the slightly damaged glazing which was cut from the aluminium framing

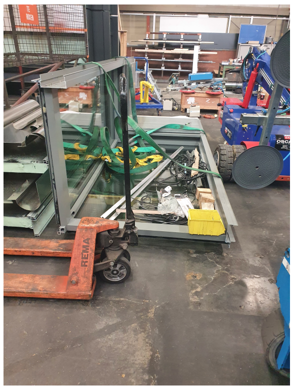
Figure 4.31: The glazing during the dismantling (2022)

The aluminium and stainless steel elements were left. As can be seen in Figure 4.32 most of the elements were cut or slightly damaged. The leftover sealant can still be found on the inside of the framing as well. However, in most cases, the gaskets are still in place and large parts of the aluminium and stainless steel are left. The holes that are needed to construct the framing can be seen in the images. When redesigning with these elements these things should be documented and kept in mind.

(a) Aluminium elements with insulation in them, were cut down for them to be removed.

(b) Aluminium profiles were cut for them to be removed. This element in particular was the top or bottom mullion where the elements were connected to each other.

(c) Some more leftover debris that was left over from the dismantling. The sealant that was cut off the windows is still visible and the aluminium elements that were cut up.



(d) The last piece of the test element, which was a corner element was taken out in one piece. Some damages can be found on the aluminium as well as some misshaping of the parts. The glazing was kept intact.

Figure 4.32: Scrapped materials (2022)

After the test, the remainder of the panels have been stored at the production hall. From the images in Figure 4.33 the remainder of the sealant and the cut aluminium profiles are clearly visible.

(a) The cut elements stored outside the production facility of Scheldebouw

(b) One of the vertical cut profiles, remaining of the sealant can be seen, as well as the mechanical strips that keep in the glazing.

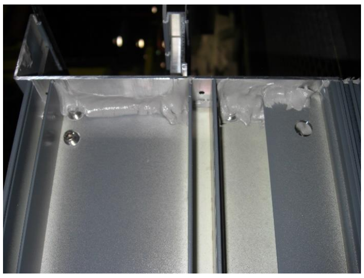
(c) The remaining cut profiles, Sealant is clearly visible

Figure 4.33: Stored panels (2023)

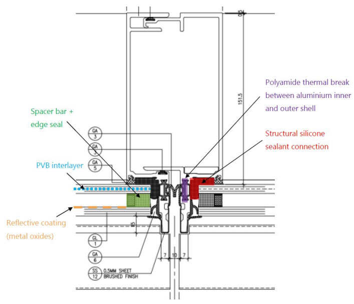
The status of the remaining elements is still of good quality, the panel has been in for the duration of the life of the building in the production hall. The panel has thus been in indoor condition however the conditions inside the production hall are comparable with conditions inside an office building (contact nr. 1 and 5, 2023). The quality of the materials is thus comparable to the materials of a facade that are not subjected to weather conditions. Sun, rain and wind impacts have a great impact on the conditions of the components.

Dismantling panel

In research performed by a colleague at Scheldebouw (contact nr. 1, 2023), a panel that was kept in the production hall was dismantled. First, a virtual disassembly was done, by taking the drawings and the expertise of a colleague who was connected to the assembly of the panels. An overview of the connections is given in Figure 4.34b.



(a) The connection between the mullion and transoms with sealant, made by Scheldebouw (Contact nr. 1)(2020)



(b) Horizontal framing detail of the Citibank tower, made by Scheldebouw (Contact nr. 1)(2020)

Two of the most challenging connections in the facade were found to be the structural sealant that keeps the glazing units in place and secondly, the screws that connect the mullions and transoms, which were covered by a sealant. This sealant was in place for the air and water tightness. An image of this connection is shown in Figure 4.34a. The panel was taken apart and timed using a Hotspot mapping approach (Flipsen et al., 2020). Flipsen has defined five indicators. These are Time, the difficulty of the activity, the priority of the part, environmental impact and economic value. From the dismantling done on the Citibank panel, three hotspots had been defined. Firstly the glazing units, score high on all indicators. Secondly, the aluminium frames score high on the environmental and economic aspects. Lastly, the screws are covered with sealing. Because of the high difficulty to remove them. Just as in the mock-up site disassembly the removal of the glazing takes time and damages the glazing and aluminium. To completely disassemble it took almost three hours. A total of 62 steps were taken and 30 tools were used. In this test, the complete panel was disassembled.

4.4. De satelliet - Amsterdam

Location: Amsterdam
Originally built: 1988
Original facade contractor: Geilinger
Function: Office building
Year of dismantling: 2021
Client: Re:Born
Contractor: New Horizon

Figure 4.35: Properties of De Satelliet (Bink, 2020)

4.4.1. Original building

The satelliet is the round building of the Nederlandse Bank Office, which was originally built in Amsterdam. It was decided that the building should be demolished. However New Horizon and Re:BORN took this opportunity to try and give the building a second life in a new location. The complete building, including Floors, columns staircases and the facade has been dismantled. Extensive research has been done towards this facade and the possibilities. Destructive dismantling has been done and the reuse and refurbishment options have been extensively researched. Technical analysis has been done on both building physics and material levels. Currently, the parts of this building are stored in a storage facility in Amsterdam-Noord.

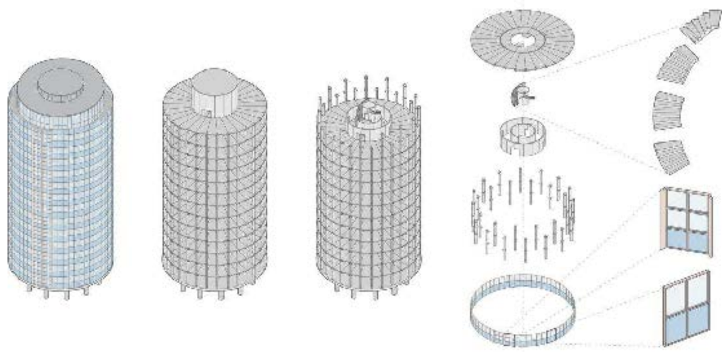


Figure 4.36: Representation of the dismantling of the satelliet, made by RE:BORN

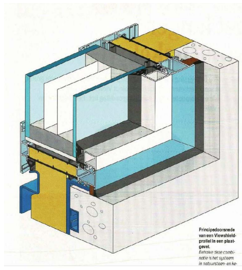
The building itself was initially designed informatively for its time. The building was built with a high amount of repetitive and prefab elements. This was because the original office building should remain in function during the construction of the building. The building should thus be constructed at a high speed. For the facade, this meant that these were connected with three anchors to the floor below. However, this meant that the elements should be dismounted from top to bottom (RenovatieTotaal, 2022).

Facade

The facade consists of panel-type configurations. These panels have a dimension of $3.75m$ high and $2.80m$ wide. With half of the infill an opaque spandrel panel, and half transparent. The transparent part is made out of double glazing with an air cavity. Float-toughened glass is used for the outer glazed planes. In the air cavity, two PET foils are tensioned, this is done by a frame in the edges which contains a system that holds the foils into place. On the edge of the glazing, a tin U profile is used which is glued. The glazing is a wide type it is around $90mm$ thick. It is a so-called HIT-Ganzmetaal from the producer Geilinger, the glazing type is pictured in Figure 4.37c. The opaque part consists also of a glass layer, a cavity filled with rock wool and a steel box. The framing is made out of an aluminium curtain wall profile which is thermally broken and filled with rock wool. The aluminium is anodised. The panels are connected, horizontally using a profile on the outside, and vertically by EPDM gaskets and a screwed connection. The profile used is a bronze profile. This is thus not a completely unitised system. Despite that, similar properties are found in this facade. The facade is connected to the floor by steel brackets (Havers, 2021).

(a) The facade (RenovatieTotaal, 2022)

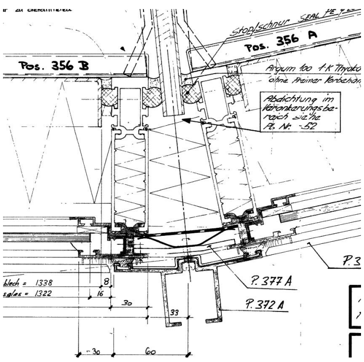
(b) Picture destructive testing, the aluminium framing, bronze cover profile and the glazing unit can be seen (Booosting, 2022)



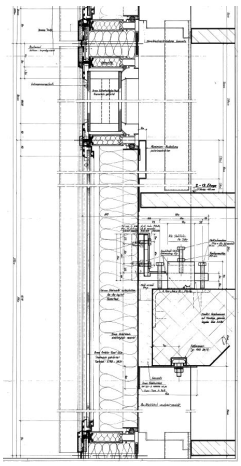
(c) glazing principle of the satelliet (Geilinger, n.d.)

Figure 4.37: Impression of the facade

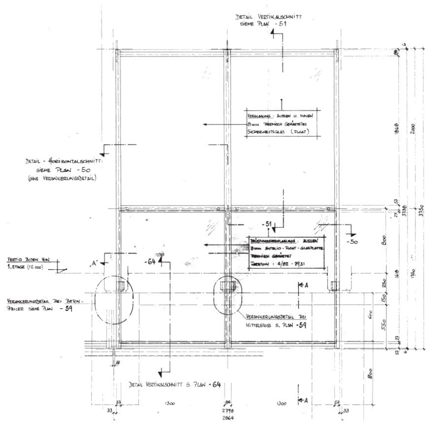
When looking at the detailing, shown in Figure 4.38, the principles described above can be noticed. The 'traditional' aluminium curtain wall facade principles can be found. An aluminium framing with a thermal break in between. The glazing is connected to the framing. A big difference however is the fact that the frames of the satelliet are not completely unitised. The bronze profile on the outside, which closes the gap because of the round floor plan, Is a loose element and not part of the framing.



(a) Horizontal detail of the spandrel panels



(b) Vertical detail



(c) Elevation

Figure 4.38: Detailing of the satellite (Geilinger, 1987)

4.4.2. Dismantling

In the process of dismantling the sequence of disassembly was adjusted to the mining partner. It was chosen to start in the middle of the building. one floor was cut in half. This made it possible to dismantle the lowest floor from top to bottom. Next, the top floors were dismantled. After that, the interior and the concrete structure were dismantled. Images during the dismantling show the sequence and the status of the elements, see Figure 4.39. The dismantling was done by New Horizon and they called this process 'Urban Mining'. Urban mining is a term used for the dismounting or disassembling of buildings. Materials are harvested for reuse. A better alternative to demolishing (Horizon, 2021).

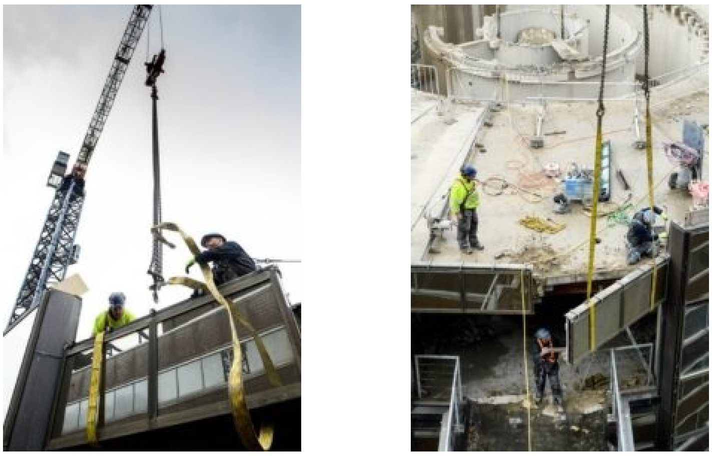


Figure 4.39: Pictures of site actions (RenovatieTotaal, 2022)

The building has a high amount of repetition. During the dismantling, some disruptive testing was done to find out what the most favourable disassembly sequence could be. It was then found that the elements could be dismantled as elements. A picture during this process can be seen in Figure 4.40.

Figure 4.40: Picture during the disruptive testing on the construction site (RE:BORN, 2020)

After the facade was dismantled and the brackets were removed. The concrete skeleton was left. These elements were disconnected and also removed from top to bottom. Images of this stage are shown in Figure 4.41b.

(a) During construction

(b) The concrete casco

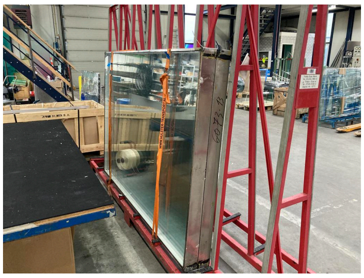
Figure 4.41: Pictures during construction (RE:BORN, 2020)

Status

To test the status of the elements and their connection, multiple disruptive tests have been done. As described before on the construction site a sample element was dismantled. But other than that, a couple of elements have been dismantled by specialists. Building physics analyses have been done, disruptive testing was done, and lastly, the glazing was dismantled and tested. This was all done off the site at the production hall of specialists.

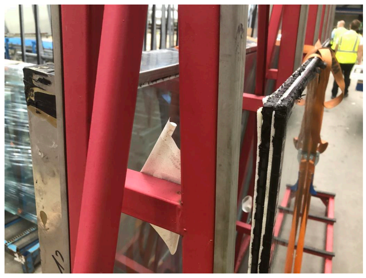
Alkondor has been looking at possibilities of refurbishment and reuse of the elements. In a report by Alkonder assumptions have been made about the elements. One of the methods they explored is using a special method to clean and restore the bronze elements so they become as good as new. As far as the elements Alkondor claims that the elements are very well reusable. They were over-dimensioned for that time. Especially due to the thick glazing package and the robust thermal breakage. The wide glazing type could be replaced, with new EPDM gaskets and new glazing beads. They are planning on reusing the framing and the thermal breaking. Structural testing has been done on the framing to see what the strength is after 30 years. The spandrel panels could also be remounted, the glazing could be removed and the steel back plate as well, this is connected by a sealant, but this has to be cut first. The quality of the elements differs from element to element (Havers, 2021).

In research done by BW-Bouwadvies and Si-X, the condition of the glazing was regarded. The tension system of the foils within the air chamber of the glazing is in great condition. The sealant in the edge profiles of the glazing is still flexible. Due to weather influences, the glazing is not clear anymore. Surface flaws have developed which decrease the strength. It was shown that this could be solved by using a polishing technique, however, no strength tests were done. In the lower profiling of the glazing, leakage has been found due to water infiltration. This was found by looking at watermarks, the EPDM gaskets in the bottom framing caused this water infiltration. It was assumed in this research that the glazing units are generally not leaking, despite this, in other documents, it can be found that the units were leaking. Three approaches were suggested, one-to-one reuse of the existing glazing, reuse of the glazing while adjusting the shortcomings and lastly, disassembling the glass construction and reusing the float glass. However, it was advised that the water barriers in the facade should be checked by replacing the EPDM gaskets on the outside. The tin U-profiling should be checked for leakage, especially at the edges. The facade itself has leakage problems, however, it is possible to solve these. Images of the results and the process of this research are shown in Figure 4.42.



(a) Glazed panels

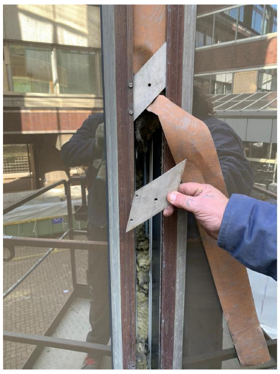
(b) Glazing in its framing



(c) Float glass taken out of the glazing construction, The edge seal is visible

Figure 4.42: Disruptive testing done on the glazing by BW-Bouwadvies and Si-X (2021)

Also, disruptive testing was done on-site by Kruiswijk. A couple of images are shown in Figure 4.43. What can be noticed is that most of the elements are still in good condition. The outside of the elements, which have been subjected to the weather, like sun rain and wind, do show some corrosion or discolouration (Havers, 2021). For example, the bronze profiles have turned green. A method was proposed to clean these profiles for them to be reused.



(a) The edge of the elements

(b) The edge of the elements and the insulation inside the spandrel panel

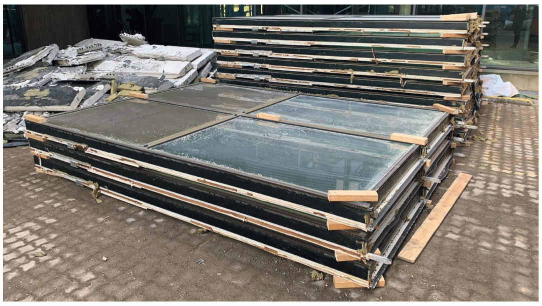
(c) Picture profiling during the disruptive testing (RenovatieTotaal, 2022)

(d) The inside of the panel

Figure 4.43: Images that show the status of the elements at the site and at the disruptive testing facility made by Kruiswijk (2021)

Storage

The elements that were suitable for reuse, the facade, floors, intermediate walls and staircases, were shipped to a storage location in Zaandam and Amsterdam-Noord. This was done by electric transportation over the water. This as well had a positive influence on the emissions (RenovatieTotaal, 2022). Currently, the elements are still stored at this facility, there has not yet been found a suitable location and purpose for the elements. After some small-scale tests in the production location in Hengelo on three elements, the plan is to set up a refurbishment production line at the storage facility in Zaandam to make sure the elements or components are ready for their next use.



(a) Picture stored elements

(b) Transportation by boat (RenovatieTotaal, 2022)

Figure 4.44: Pictures of the dismantling of the Sateliet, published by Re:BORN

4.4.3. New purpose

As described before the elements have not found their definitive purpose yet. In current times a lot of testing is still done on the status of the elements. In different manners, the possibilities design-wise have been explored. Due to regulation changes over the past 30 years, it was decided that rebuilding it as a high-rise is not possible. It is planned to split the building into three low-rise parts. A project has been found in which it might be possible to reuse the different parts. It is claimed that the elements will be used in the construction of a care home (nieuws, 2021). It is still being researched how to build with these existing elements. It is in addition still the question if it will be possible to reuse complete elements or parts of the element.

4.5. Conclusion reference study

From this chapter practical knowledge about the case studies was obtained. Methods that were used have been researched and the quality of components have been analysed. In addition, decisions made in the early stages and challenges during the process have been observed. In the next subsections, a conclusion has been made about the individual projects. Lastly, a general conclusion has been made regarding the reference studies.

4.5.1. 1 Triton Square - London

In the project of 1 Triton Square the reuse of the outer facade was possible because the requirements for these components were low. The contrary was true for the inner facade, which is part of the thermal line, so it was replaced. The things the project team did to successfully reuse the elements were involving the original construction team and obtaining the original drawings. What was advised for a similar project is to make a digital point cloud model of the existing situation. Some challenges during the construction were finding similar products as those used 25 years ago to replace broken or end-of-life products. As far as the warranty, there was no new warranty given on the refurbished facade. When looking at the materials that were in the facade, the aluminium and glazing were cleaned. The steel galvanised brackets, after cleaning and repainting were in great condition. A finding that gives potential is the structural sealant, this was still intact and functional despite the glazing being mechanically supported.

4.5.2. Koningskade - The Hague

In the Koningskade project, the original facade has been upgraded to improve the performance requirements. Instead of the original EPDM gaskets a new aluminium framing was developed which fits into the original framing. The different parts were mantled on site, so size deviations could be fixed in place. For the EPDM gaskets and the glazing, the end-of-life scenarios have been regarded. The EPDM gaskets were at the end of their life and thus discarded. The float glazing which was not glued offered an opportunity for circular use. The float glass was used for a test run by Saint Gobain to recycle it into new float glazing. Next to that, the glazing component was directly reused in the Natural Pavilion at the Floriade. The design was adjusted to the available sizes of the glazing in such a way that cutting losses were minimal. Within the design of the Natural Pavilion, a consortium of companies was involved. Which worked together to achieve a common goal.

4.5.3. Citibank - London

In the building of Citibank, in the near future, a significant amount of panels will lose their original function. The facade panels represent a vast majority of the facades made at Scheldebouw (contact nr. 1 and 2, 2023). Especially the structurally sealed glazing, which gives challenges in the reuse of the components. A dismantling plan has been made and tested in the production facility in Middelburg, in which the conclusion was made that dismantling a panel is time-consuming. It does show that it is possible and the glazing can be dismantled from the framing despite it being structurally sealed. At this moment a new purpose for the components or elements is being searched for.

Since the purpose of this project has not yet been determined. This project has been used as a case study in Chapter 6. Here the strategies formed in Chapter 5 have been applied and tested against the carbon impact of these scenarios.

4.5.4. De Satelliet - Amsterdam

In the case of De Satelliet, the complete building originally built in 1988 was completely dismantled, including floors and the load-bearing structure. The building was successfully dismantled and is currently stored in a storage location in Amsterdam. Various destructive tests were done on the panels on and off site, to test the dismantling process as well as the remaining quality. The design possibilities and characteristics of the aged panels were assessed. The vast testing has made it possible to assess the risks and possibilities that are involved with reusing the components. It was decided that the elements with some interventions still can be reused.

4.5.5. General

The reference cases regarded in this chapter showcase that strategies are being applied and possibilities are being explored. Especially the potential of the various materials after their expected life span show potential, especially the glazing and aluminium. Additionally, methods used in managing circular projects are seen. The first is involving stakeholders from the original project or forming a consortium between involved parties. Secondly is keeping track of all elements, to be able to know where each element is from and where it has to go as well as keeping track of the quality of elements or components. Lastly, various testing on the original facade on and off-site as well as on the finished facade. To show the performance and the quality of the elements that have been used or have been produced. What can be noted is that each project is one of a kind, and will come with its specific challenges. Weather influences and degradation can vary from location to location. Connections and performance requirements have a great influence on the potential and the intended use of a component.

5

Development of circular strategies

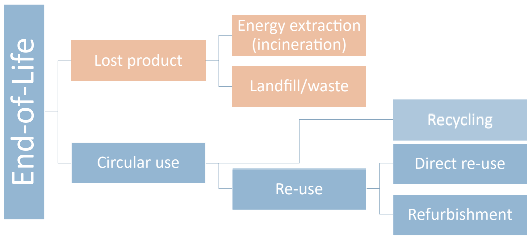
In this chapter, eight strategies for the circular use of unitised curtain wall facades are presented. The strategies apply to the situation where a facade is at the end of its service life, but the components are not at the end of their life. The strategies have a theoretical foundation, however, practically the options should be explored. The framework has been developed with the knowledge from the chapters above. First, an explanation has been given of how the strategies have been set up, what the different phases are, and the constraints regarding requirements and characteristics. Next, the challenges found when applying circular strategies are mentioned, these have been found in the literature and reference cases (Chapter 4). After this, the main outline and background are described and the eight strategies are explained. The eight strategies are subdivided into four main categories: refuse, panel-based, component-based and end-of-life. After the strategies are explained, the avoided carbon method is elaborated. This method is then applied to a general case using the strategies defined before. Last a method of application is created, where the steps to incorporate these strategies are described. Using this systematic approach the incorporation of circular strategies is generalised.

5.1. Phases and choices in circular reuse strategies

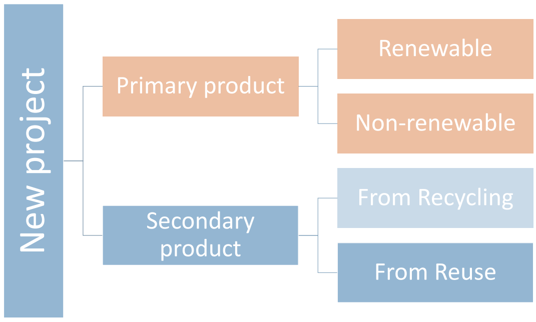
In a strategy for the circular reuse of facade panels, four basic elements are included. In all strategies, a form of transport occurs. Elements and components are moved back and forth between the donor and receiving building, refurbishment sites, end-of-life destinations and other necessary locations. Following that, the required actions take place, including dismantling, refurbishment, assembly and waste treatments. In some cases, new materials are added to replace or upgrade components. For these raw materials, processing and transport are happening. Lastly, in each strategy, waste is produced. This could be because of damages during the works, but also consequences due to size differences and discarding of end-of-life components.

5.1.1. Decision points in managing end-of-life scenarios

When elements in a project reach the end of their service life, decisions should be made regarding the handling of the remaining materials. The same holds for when elements are needed in a project different choices about the whereabouts of these materials can be made. A basic outline of the options in this decision moment is shown in Figure 5.1. With the strategies developed in this research, the choice for reuse and secondary product are encouraged, by supplying methods of reuse and showing the benefits achievable when incorporating these strategies. In an ideal situation, the timing of both decisive moments would line up.



(a) Choice distribution of an end-of-life scenario



(b) Choice distribution when considering a new project

Figure 5.1: Choice distribution

5.1.2. Phases in circular use

The phases through which a project or component could undergo can be simplified. From the reference studies (Chapter 4), three main phases were determined. Firstly the donor building, of which the materials are harvested and the dismantling needs to be done. Then in the next stage, the refurbishment actions take place. This could be in a different location; for instance, in the reference studies made regarding Triton Square, this was the pop-up factory or at the construction site. In an ideal situation, the refurbishment actions could take place either on-site or not at all. This is assuming that no or little refurbishment work needs to be done and transportation to and from the production hall can be avoided or reduced. Lastly, the destination of the panels or components. When the panels are used in a similar function, the receiving project will be a building. This receiving building could be the original building, although this is not the prime focus of this research it still can be seen as a circular strategy since it saves the material from becoming waste and losing its value. As a last option, it could be reused in a different function and even in another industry, as shown by examples that are explored in the following paragraph. A schematic representation of the phases is given in Figure 5.2.

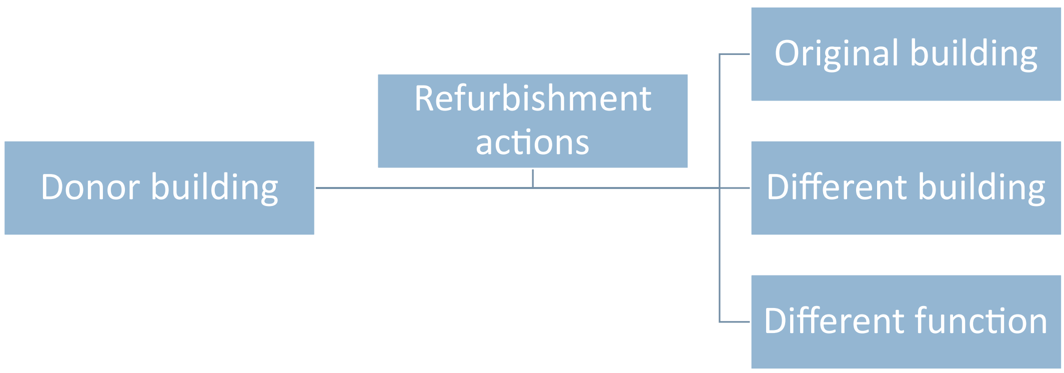


Figure 5.2: Scheme of phases that are within a strategy

5.1.3. reuse in a different function

When considering the circular use of facade panels, the function of the elements might change. The panels might not be used as a facade again but could find their purpose in another industry or function. The value of the material is preserved, it will lose its function, but in spite of that the materials do not end up in a landfill or recycling and get a new purpose.

A new function could be found within the construction industry or even outside. There are existing situations where old glazing has been used in interior elements like partition walls or furniture. Industries outside of the building sector might benefit from it. The festival, fashion, and retail industry, where stages or display settings are made for single use. Building furniture, like tables, chairs or separation structures. Art sculptures can be made from scrapped materials. Another option is greenhouses or other shelter functions. When existing elements could be used in those industries both can benefit from it.

5.1.4. Reason for replacement

The reason for the replacement or dismantling of a facade can give a general idea of the status of the facade (Section 3.7). When the reason is performance-related, upgrades might be needed. The reason could also be aesthetically related or a change of function of the building, while the facade in itself could still be well performing in this case.

5.1.5. Requirement match

When searching for components to use or looking for a project for the components to get a new purpose, an important aspect (Chapter 3) are the characteristics of the donor component and the characteristics needed for the new building. The needed lifespan is important as well as the thermal, acoustic, safety and structural characteristics. When a match can not be made the components could be upgraded or new material added to achieve the desired characteristics. This is schematically shown in Figure 5.3.

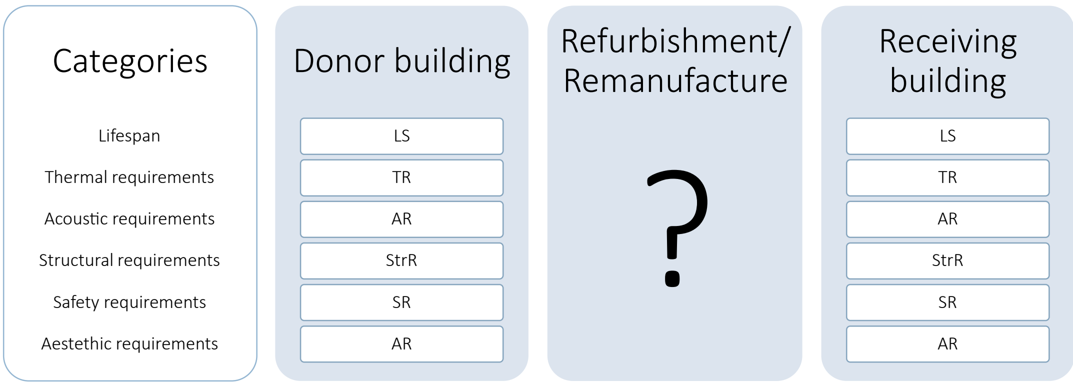


Figure 5.3: Sketch of requirements matching between both situations

5.2. Challenges regarding reuse

This section will be used to describe the challenges that are being faced when incorporating circular strategies. The challenges are subdivided into six main categories.

5.2.1. Warranty

One of the main challenges in a systematic reuse strategy is the warranty of the facade elements after and during construction. As seen in the reference study 1 Triton Square a new warranty could not be given. The risks in handling and storing the elements are higher than new elements. The panels have proven to be functioning over the period of their original life. This is due to factors such as maintenance and the remaining quality which is often difficult to predict. It has been proven in other industries to be possible to offer a new warranty on a refurbished product. By implementing and performing regular tests on existing components but also on refurbished components an estimation and a new standard for the reused materials could be made by the industry. Similar tests and certifications can be applied to the facade industry. This serves a dual purpose: initially assessing its performance and demonstrating to future clients that the associated risks are manageable. Next to that, sufficient maintenance during the lifespan of elements will extend the lifespan in itself but also protect the quality of the materials. It has been mentioned that the risks are too high for now to start implementing these strategies (Contact nr. 8, 6-3-2023). With new testing methods and certifications, these risks can be lowered.

5.2.2. Business case

In spite of it not being the focus point of this research, it should still be mentioned that the business case surrounding reuse is still difficult. The perception of second-hand products being less valuable continues to exist within the construction industry. Next to that, the change of ownership will oppose challenges. The facade is sold by the owner to the facade manufacturer or to the new owner directly or even to a new third party. In all cases the owner of the facade changes, risks of damages or not finding a new destination are present. The timing between the decision of dismantling, dismantling and the receiving project will have a big influence on costs and risks. The need for storage and transport will increase the costs, and it is not known who will pay these costs. When there is no receiver yet at the time of 'buying' the old facade, the risk of it not being sold is still present (Contact nr. 14). When regarding circularity a new business case has to be developed in order to make it profitable and the risks bearable.

5.2.3. Design

When applying existing elements in a new project the design options are limited to the available properties of the donor panels. A certain level of compliance is needed from the architect and clients to work with these elements. When a larger reuse network is developed the choice becomes greater and more options may be possible. With certain additions, however, a new look can be achieved. Adding a new coating or finishing, cutting to size, adding external features or replacing elements can bring a great variety of design options.

5.2.4. Logistics

The logistics of a circular strategy will need an adjusted approach. When dismantling a facade with the intent of reuse will ask for different handling processes than when a component is intended for waste or recycling. Extra safety measures are needed to reduce damages during dismantling, transport and handling. Next, constructing with existing elements will ask for more attention, it is more prone to size differences and damage. Lastly, when working with reused elements it may be needed that a large amount of materials need to be stored during refurbishment works or even when looking or waiting for a receiving project.

5.2.5. Connections

Since an existing structure is used, The connections within this structure are important. Firstly, the connection to the original structure. As described in Chapter 3, a curtain wall facade is generally connected to the main load-bearing structure using steel brackets and bolts. However, when a top floor is poured over these bolts it may cause difficulties in reaching these bolts. Secondly, the connections of the intermediate components. Especially adhesives and sealants oppose risks and challenges. Since these sealants, most of the time have a lesser life span than the other components it is not of great importance to keep them intact. Replacing them will eventually be needed. Sealants are difficult to disconnect from their components and are seen to be cut out most often. The screwed connection may break after unscrewing or dismantling parts. Lastly the differences between as-built drawings and reality. It has been noticed that in the manufacturing hall and on-site extra interventions are added to either increase the strength or air tightness, differences between as-built drawings and actualities might occur (contact nr. 5, 2023). Such as sealants at the corners of the aluminium and sealants between two panels.

When using existing panels and dismantling them opposes an opportunity to improve the connections of the refurbished panel. Interventions can be added to increase the disassembly in the future or to make maintenance or further reuse more convenient. The connection that increases the workload and creates the most risks is the use of structural sealants and adhesives.

5.2.6. Quality and condition

As mentioned in Chapter 3 each facade project has its one unique qualities. To assess the quality and conditions of a panel and estimate its potential different options are available. First, sufficient maintenance during its life span can maintain the quality of the components over the years. Things like age, detailing and materials that are available can already be assessed before executing tests. Visual inspections and different types of testing are available to assess the remaining quality. One panel can be used for destructive testing to assess the connections and quality of the remaining conditions of the materials. Damages that are present due to weather influences or impact would be documented in a material passport. These tests can be used to estimate the risks of the refurbishment and the life span or maintenance needs for the refurbished elements.

5.3. Strategy possibilities

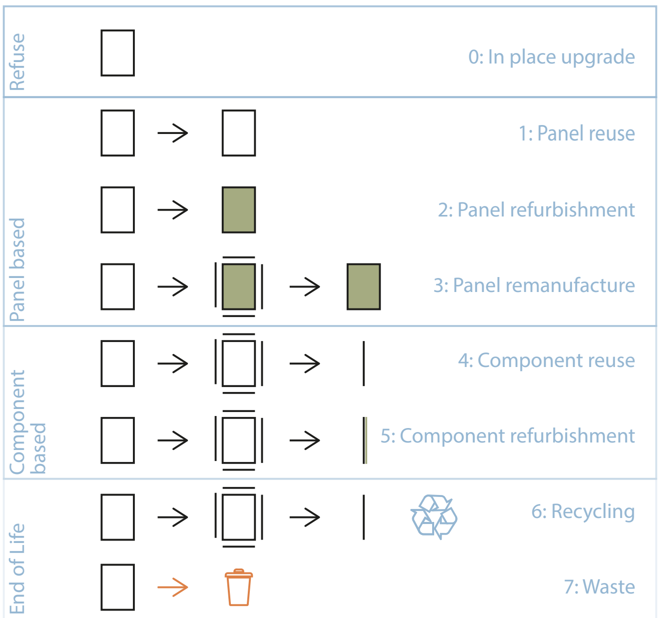


Figure 5.4: Scheme of the strategies designed

In this section, the strategies for the circular use of unitised facades are developed to reduce the waste of materials and avoid recourse depletion. A subdivision is made on four different levels. Refuse, Panel-based, component-based and end-of-life. Within each level, different strategies fall. It has been chosen to incorporate a refuse level, where the choice for in-place upgrade is encouraged. The decision for replacement could be prevented since the facade panels have the best fit in their original location. The key element of each strategy is represented by an icon, which is displayed in the Figure 5.4. Strategy 0: in-place upgrade, which is part of the refuse level. In the panel-based level, three different strategies are found, strategy 1: panel reuse, strategy 2: Panel refurbishment and strategy 3: panel re-manufacturing. Next the Component-based strategies, strategy 4: Component reuse and strategy 5: component refurbishment. Last the end-of-life strategies, strategy 6: recycling and strategy 7: waste. The strategies have been described in further detail in the following sections. Basic steps are shown together with an imaginative LCA analysis.

The strategies are inspired by practice both in the facade industry and other industries (Table 5.1). The two strategies that do not have a receiving building are not included in this table, since no clear strategies have been defined or used yet. From this table, it can be seen from which strategy was inspired by what project.

Table 5.1: Circular Facade Strategies applied on the reference study projects

Strategy	1 Triton Square	Koningskade	Floriade	Caterpillar	Philips
Strategy 0: In-place upgrade					
Strategy 1: Panel reuse					
Strategy 2: Panel refurbishment	X				X
Strategy 3: Panel re-manufacturing				X	X
Strategy 4: Component reuse		X		X	X
Strategy 5: Component refurbishment	X		X	X	X
Strategy 6: Recycling		X			
Strategy 7: Waste					

5.3.1. Refuse based

Strategy 0: In place upgrade

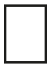
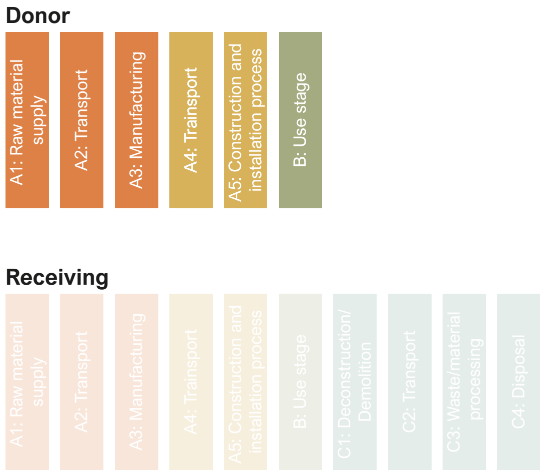


Figure 5.5: Scheme of Strategy 0

Within this strategy, the choice is made to not remove the current facade and leave it in place. This can be accounted for as a refuse strategy, which is often included in circular frameworks like the 10R framework. No waste and limited new material is needed. To implement this strategy successfully, the current facade must meet safety standards and maintain a comfortable indoor climate with minimal interventions. Operational carbon considerations will also be a crucial factor. Minor replacements or adjustments could be executed which would then fall into the B module of the life cycle of the building. In this situation it cannot be said that there is a donor or receiving building, it therefore falls outside of the scope of strategies that have been described above. Nevertheless, it is still included as a level zero strategy to propose the option of keeping a well-performing facade in its place. This is where the panels fit best in terms of size.

- The panels stay in place
  - Minimal reduction in operational carbon
  - Extension of life span
  - Minor adjustments or replacements could be done
- There is no receiving building



(a) Life cycle stage interpretation of Strategy 0

Figure 5.6: Life cycle estimation of Strategy 0

5.3.2. Panel based

+ Complete elements
+ Fewer interventions
+ higher amount of material used
- Size constraints
- Performance constraints
- End-of-life-components are harder to replace
- Appearance constraints

Strategy 1: Panel reuse

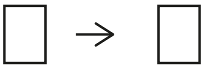
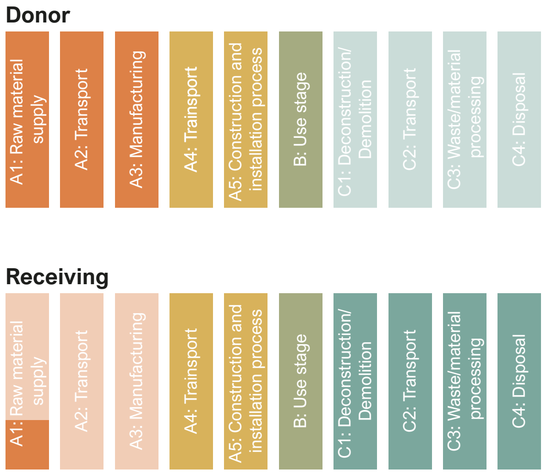


Figure 5.7: Scheme of Strategy 1

This strategy holds the facade panels that are reused without any interventions. This is highly unlikely since there will always be some end-of-life components or damage. In spite of its unlikeliness, it could happen and will be the most convenient strategy in terms of carbon emissions in reuse. The direct reuse of complete panels could happen in buildings where the performance requirements of the element are less than the current performance.

- Dismantling of the donor panels
- Transport to the receiving building
- Construction of the reused panels on the receiving building



(a) Life cycle stage interpretation of Strategy 1

Figure 5.8: Life cycle estimation of Strategy 1

Strategy 2: Panel refurbishment

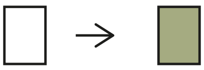
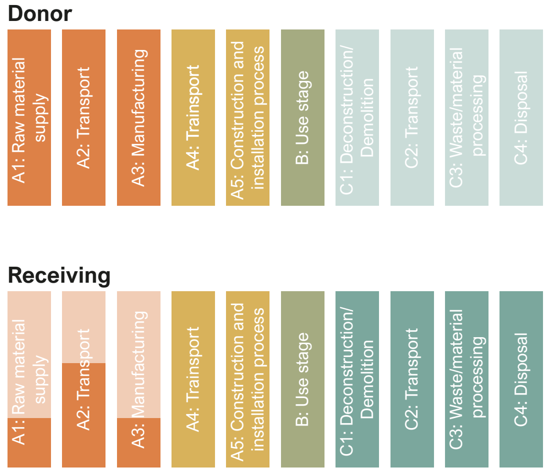


Figure 5.9: Scheme of Strategy 2

This strategy holds the facade panels that will be reused with refurbishment. The refurbishment works will be performed without taking the panel apart. The interventions that can be applied will be limited due to this. Small replacements of end-of-life components are possible. If the works can be done on site or near site transportation kilometres can be reduced. The appearance of the original panel will not change vastly.

- Dismantling of the donor materials
- Transportation to the production facility
- Refurbishing
- Transportation to the receiving building
- Construction of the reused panels on the receiving building
- *Input of new materials and waste in the different stages are not taken into account*



(a) Life cycle stage interpretation of Strategy 2

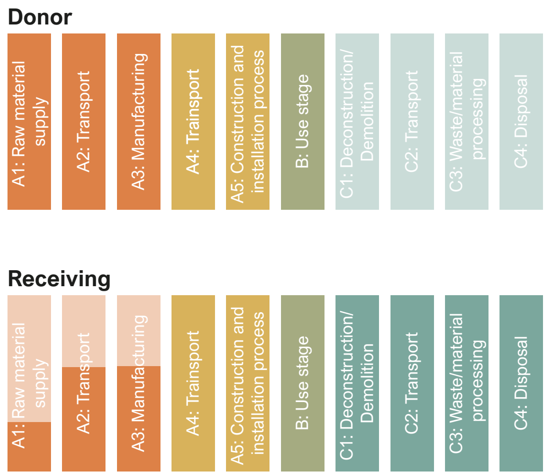
Figure 5.10: Life cycle estimation of Strategy 2

Strategy 3: panel re-manufacturing

Figure 5.11: Scheme of Strategy 3

Within this strategy the panel is dismantled into components, refurbishment works are executed on these components, and the panel is assembled in the original configuration. Dismantling is when one or more of the larger components, like glazing or framing, are taken apart. Larger elements can be replaced and the elements separately can be upgraded. A greater variety of interventions are possible and thus performance upgrades are an option.

- Dismantling of the donor materials
- Transportation to the production facility
- Dismantling of the element into components
- Component refurbishment
- Assembling of the panel
- Transportation to the receiving building
- Construction of the reused panels on the receiving building
- *Input of new materials and waste in the different stages are not taken into account*



(a) Life cycle stage interpretation of Strategy 3

Figure 5.12: Life cycle estimation of Strategy 3

5.3.3. Component-based

+ more possibilities
+ Performance upgrades are possible
+ Aesthetic upgrades are possible
+ Large replacements are possible
+ Size adjustments are manageable
- Will need more actions in the production hall
- More new materials needed
- More waste
- More prone to breakage

For both strategies 4 and 5, the panels are completely or partly dismantled. Dismantling is seen when one or more of the larger components, like glazing or framing, are taken out. The materials within the panel are split up so components can be used in a suited way. Components can be used separately from their original situation, which opts for a larger variety of options for reuse. This makes it better applicable when needing to adjust to new characteristics. It has been found that the dismantling of the panel might be tedious and difficult, due to the time and costs. Some connections have been found to be difficult to dismantle. When these component-based strategies become more common, the work becomes more standard and easier. Dismantling techniques will be developed and the costs and time will decrease.

Strategy 4: Component reuse

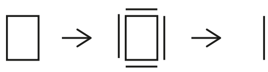
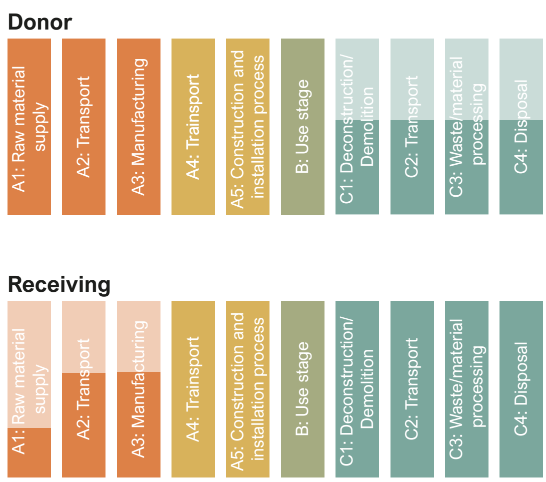


Figure 5.13: Scheme of Strategy 4

In strategy 4, as described before, the panel is dismantled into components. The components are then used in a different panel or function. Contrary to strategy 3, the components might be used in different configurations. For this strategy, no refurbishment works are performed. This strategy could be combined with former strategies, when for example a large component is dismantled and replaced in strategy 3, this component could still be used in a different configuration.

For this calculation it is assumed that half of the materials are reused. So half of the materials are put to waste, and half is new material.

- Dismantling of the donor materials
- Transportation to the production facility
- Dismantling of the element into components
- Mounting component into a new configuration
- Transportation to the receiving building
- Construction of the reused panels on the receiving building
- *Input of new materials and waste in the different stages are not taken into account*



(a) Life cycle stage interpretation of Strategy 4

Figure 5.14: Life cycle estimation of Strategy 4

Strategy 5: Component refurbishment

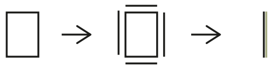
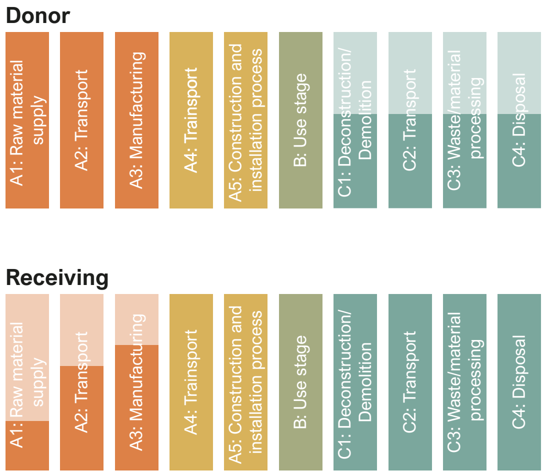


Figure 5.15: Scheme of Strategy 5

In strategy 5, just as in strategy 4, the panels are dismantled into components. Refurbishment works are performed on these components. performance and visual improvements are better implementable. Also, size constraints are better adjustable. The components are used in a different configuration than their original situation. Components harvested from a panel that needed replacement could be used in this strategy. A combination of strategies could happen.

For this calculation it is assumed that half of the materials are reused. So half of the materials are put to waste, and half is new material.

- Dismantling of the donor materials
- Transportation to the production facility
- Dismantling of the element into components
- Component refurbishment
- Mounting component into a new configuration
- Transportation to the receiving building
- Construction of the reused panels on the receiving building
- *Input of new materials and waste in the different stages are not taken into account*



(a) Life cycle stage interpretation of Strategy 5

Figure 5.16: Life cycle estimation of Strategy 5

5.3.4. End-of-life

+ New performance requirements can be achieved
+ Achievable
- Lost of the value of the materials
- Waste
- Raw material extraction

For these last two strategies, it is assumed that the panel or components are not reused as the material that it has been intended for. Through recycling, the material is entirely disintegrated and then transformed into new materials using various methods, either being of lower quality or the same. This still demands a lot of energy. The last strategy accounts for the waste scenario, which is the strategy that should be avoided.

Strategy 6: Recycling

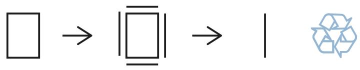


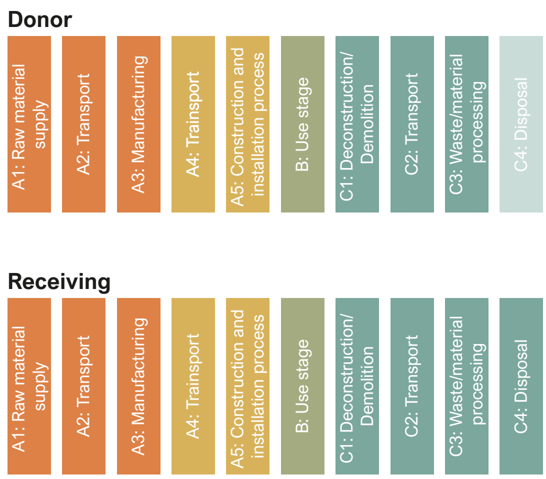
Figure 5.17: Scheme of Strategy 6

When products cannot be reused anymore or are not needed in a project, recycling strategies can be used. Different methods for different materials are in place. The main methods will be regarded here, however, recycling is not the focal point of this research so no in-depth research has been done towards these methods.

High value recycling High-value recycling is the recycling of materials into new materials of the same quality. When these methods are applied the old scrap material is able to be used in the same manner as before. High-value recycling is possible for float glazing and cullet with no impurities, which is often not the case in construction waste. Aluminium can be recycled into new aluminium, the same holds for steel. Lastly, some insulation materials are available for recycling. Natural fibres, mineral wool and fibreglass can be recycled into new materials.

Down cycling For some materials it is, at this time, not possible to recycle them into the same quality materials as it has been before. Glazing which is impure will be down-cycled into bottles or fibreglass insulation. Coatings and construction rubles will make the glazing impure. Rubbers are still down-cycled into artificial grass components or other granulate applications.

- Dismantling of the donor materials
- Transportation to the recycling facility
- Recycling (Down/high value)



(a) Life cycle stage interpretation of Strategy 6

Figure 5.18: Life cycle estimation of Strategy 6

Strategy 7: Waste

Figure 5.19: Scheme of Strategy 7

This last strategy is not circular and can be avoided by implementing the strategies mentioned before. It is taken into account in the strategies to be able to see what impact can be avoided. Materials that are put into landfill will potentially damage the environment as well and the materials will also lose their value. Especially when the material would still be able to be reused in the building industry or other industries.

- Dismantling of the donor materials
- Transportation to the waste plant
- Landfill

(a) Life cycle stage interpretation of Strategy 7

Figure 5.20: Life cycle estimation of Strategy 7

5.3.5. Refurbishment and re-manufacturing options

Within the strategies, refurbishment and re-manufacturing have been given as options. In this next section, a variety of options will be given. These will be subdivided into the main materials found in Chapter 3 and into a general category.

In general cleaning of the components or panels can be done to remove dirt. As well as replacing end-of-life components, which are generally the EPDM gaskets. When the gaskets have not been designed specifically for a project this is quite a low-impact measure. Replacement of the sealant will offer more difficulties since this needs to be cut out or removed from the components it is attached to. Replacing external elements can change the appearance of the panel. Changing transparent elements into opaque parts, a spandrel or shadow box, can reduce the internal solar gains and also change the appearance. The addition of parts is an option, like openable parts, architectural elements or framing can be thought of. Recoating the aluminium, which is labour-intensive, is possible. Lastly, resizing the components can be done to fit the new design, however, it is more manageable when a design is adjusted to the available materials. The panel or components could be placed in a new framing, which solves size differences or constraints and could also improve the inter-panel connection. The panel could also be rotated on its side which could increase the possibilities of reuse.

Glazing

As mentioned in previous chapters the IGU itself can be upgraded, be replacing the sealant and spacers, which are the components that reach their end of life first. Adding a gas filling or adding an extra pane could increase the insulative properties of the IGU. Lastly, adding a coating can increase the properties of the glazing. It should be kept in mind that the thickness of the glazing is limited to the capacity of the aluminium framing.

By cleaning and polishing the glazing the appearance can be restored, which can have a negative impact on glass strength. Checking for surface damages or using testing, the structural capacity can be checked.

Aluminium framing

The aluminium framing has great potential for reuse. Changing the finish of the aluminium can change the appearance of the framing, this is a demanding task and might influence the thickness and strength of the aluminium. Resizing the aluminium increases the application. Adding insulation inside the framing increases the thermal properties. Holes within the framing could be filled up with an aluminium paste. The screw ducts within the framing might be damaged when completely dismantling a panel.

Sheeting

Aluminium or steel sheeting can be cleaned and recoated in some cases. The sheets however do have a specific size or shape. When placed back into a similar configuration the sheets can be reused, and slight size changes that are smaller than the original can be made. Bending will be difficult due to the fatigue of the material.

5.4. Accounting for embodied carbon savings

The method that has been developed for this research does not use the earlier described module D in Section 2.4. It rather uses the avoided carbon emissions by not putting products in waste or not having to extract raw material. This is because including the D module is a prediction of the use of materials and as described in Chapter 2 it can give a distorted image since the inclusion of a positive carbon impact. The avoided carbon method creates a clear distinctive manner to include reuse in a fair manner. This method is developed by looking at existing reuse projects and the route of the materials that are used in reuse cases. As well as regarding the original methods in the LCA and finding their shortcomings.

The avoided carbon method creates a comparative method where the avoided use of raw materials or waste is compared to a more traditional method. A circular strategy results in the involvement of two projects, meaning it involves two life cycles: the donor and the receiving project. At a certain point in the life span of the donor building a decision has to be made about components which are assumed to be at their end of service life. From this decision moment, the avoided carbon method begins. This is after the Use module (Module B) in a standard LCA. Module C then holds the end-of-life impact at the side of the donor building. Materials go from the donor building to a receiving project which then starts over with module A. The avoided carbon method stops when the materials are in use again before module B of the receiving project. This is figuratively shown in Figure 5.21.

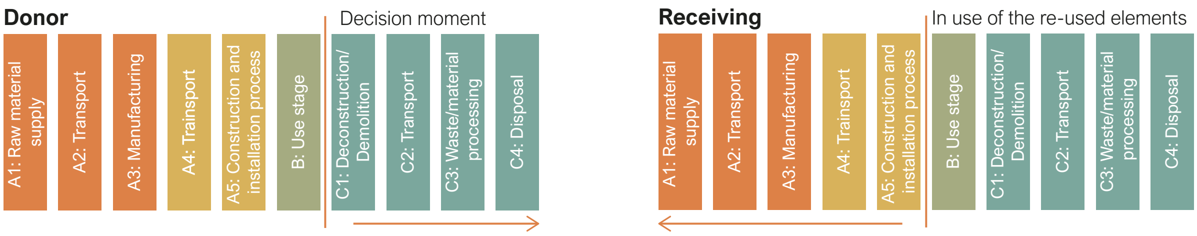


Figure 5.21: Scheme of the approach of the Carbon estimation

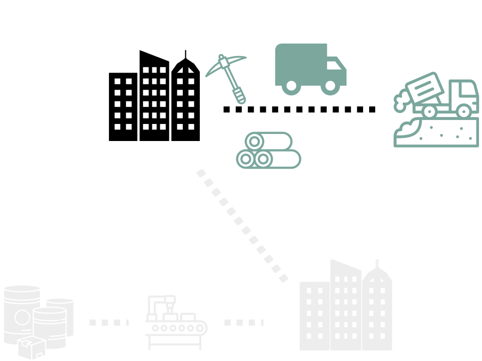
In an ideal reuse scenario where components are directly reused from the donor project to the receiving project (strategy 1) stages C1, C2, C3 and C4 can be avoided in the donor project and stages A2 and A3 can be put to zero in the receiving building. The 'mining' of the materials is put into A1, as a dismantling impact. In the A4 stage, transportation of the reused materials to the new site is accounted and the construction of the materials in the A5 stage. The benefits achieved are thus avoiding the A1 to A3 impact in the receiving project and avoiding waste in the donor building. This ideal situation is pictured in Figure 5.22 and Figure 5.23. The black line in Figure 5.23 figuratively shows the material that goes from one project to the other. By using this avoided carbon method a comparison between strategies can be done in a clear manner. In the other strategies, waste is generated which is then accounted for in the C module of the donor building. As well as raw material extraction and production which is subsequently accounted for in the A module of the receiving building. A summation of the distribution of the impact throughout the modules is given in the list below:

Donor building

- C1: Dismantling impact needed for the components that are at the end of their life
- C2: Transportation of the end-of-life components to the end-of-life location
- C3: Impact generated by end-of-life treatments like recycling
- C4: Impact generated when elements are put into landfill

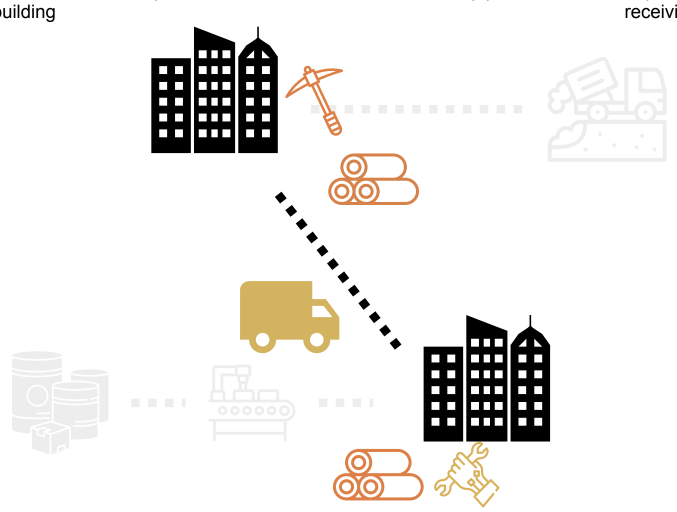
Receiving project:

- A1: The impact that is associated with the raw materials extraction that is needed in the receiving project
- A1: "Mining impact" of the reused materials, the dismantling impact
- A2: Transport of the new materials to the production facility as well as the transportation of the reused materials from the donor building to the production facility
- A3: Impact generated associated with the refurbishment and re-manufacturing of the components
- A4: Transport of the components to the receiving building
- A5: Energy associated with the assembly of the components to the receiving building



(a) Schematised complete waste scenario, the impact for the donor building

(b) Schematised complete new scenario, impact for the receiving building



(c) Schematised complete reused scenario, avoided impact

Figure 5.22: Schematised scenarios, showing in which life cycle stage carbon impact falls

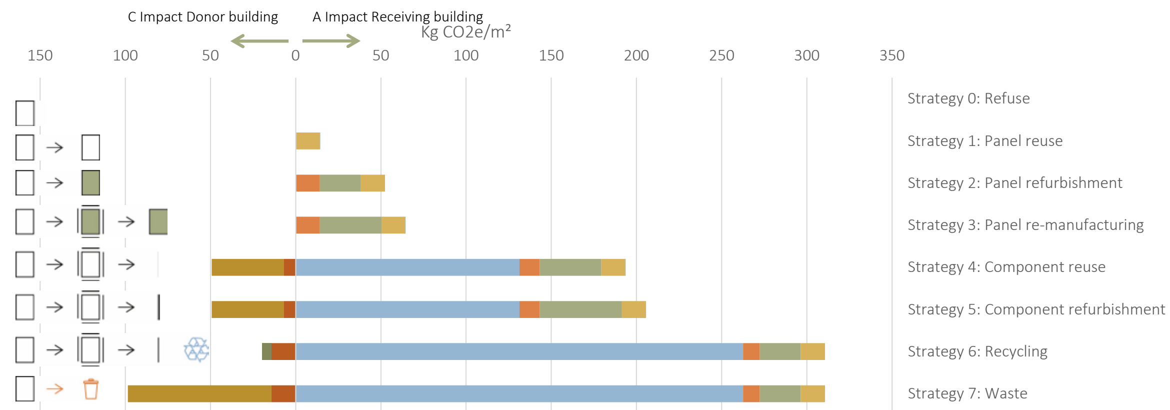
Figure 5.23: Picture of the ideal case of reuse of a component

5.4.1. Carbon estimation of the strategies

To obtain a general idea about the impact of the strategies developed in this section, an estimation of the carbon impact is done. In Appendix B the equations and general assumptions have been presented, and in Section E.2 the in and output of these calculations have been shown. The estimative calculations are based on an existing project for which a carbon calculation has already been done. It has been determined what would happen to the materials and where the carbon impact would be for each option using the method described above. For each strategy, the specific assumptions have been described in Section E.2. The general assumption of these estimative calculations is that when the material is put to waste or recycled, the same material needs to be newly resourced. For strategies 0 to 5 in Figure 5.4, it is assumed that materials that are not used, are put to waste. Lastly, all raw materials are assumed to be made as new, and no secondary content is used. For the component-based strategies, 4 and 5, it has been assumed that half of the materials are reused, so half of the materials is newly resourced and half is wasted. The outcome of this calculation is compared in an overall graph. These calculations are based on the NOVA N2 project (Contact nr. 1, 7-3-2023), which is a project of Scheldebouw where a LCA calculation was made. A detailed outcome of each strategy can be found in Section E.2

5.4.2. Comparing carbon estimations of the strategies

Comparing the outcomes of this carbon estimation (Figure 5.24) it can be noted that carbon can be saved when applying circular strategies. As already found the most significant carbon can be saved within the A1 phases by avoiding the use of raw materials. Strategies 1, 2 and 3 make the most significant impact by completely avoiding the waste but also avoiding the production of raw materials. Strategies 4 and 5 lie relatively close to each other, when incorporating actual project parameters and materials this difference will become more significant. In Chapter 6 this has been done for a case study. Noted should be strategy 0, whereby maintaining and upgrading the original components in place a lot of carbon can be saved at that point. The panels will have the best fit in their original location. Since there is no receiving project this strategy is difficult to compare to the others, also the impact of upgrading is not incorporated since this would fall in module B. The end-of-life strategies show the carbon impact when the current strategies are applied. Recycling, and therefore avoiding waste already a reduction of 20 per cent over the total can be achieved. When also using recycled materials instead of raw materials, like Hydro Circal (Hydro, n.d.), further reductions in the A1 module can be made.



	Strategy 7: Waste	Strategy 6: Recycling	Strategy 5: Component refurbishment	Strategy 4: Component reuse	Strategy 3: Panel re-manufacturing	Strategy 2: Panel refurbishment	Strategy 1: Panel reuse	Strategy 0: Refuse
A1	262,52	262,52	131,36	131,36	0,20	0,20	0,20	0,00
A2	9,77	9,77	11,87	11,87	13,96	13,96	0,00	0,00
A3	24,12	24,12	48,25	36,18	36,18	24,12	0,00	0,00
A4	13,96	13,96	13,96	13,96	13,96	13,96	13,96	0,00
A5	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,00
C1	-0,20	-0,20	-0,10	-0,10	0,00	0,00	0,00	0,00
C2	-13,96	-13,96	-6,98	-6,98	0,00	0,00	0,00	0,00
C3	0,00	-5,60	0,00	0,00	0,00	0,00	0,00	0,00
C4	-84,33	0,00	-42,16	-42,16	0,00	0,00	0,00	0,00

Figure 5.24: Overview of the estimated carbon emissions of the strategies

5.5. Method of application

In order to apply the strategies, a flowchart containing a general outline is created and shown in Figure 5.25. In a reuse situation, two projects are present which set the scope of this situation. First, the donor building should be analysed based on various aspects to estimate risks and uncertainties. Similarly, an analysis is conducted for the receiving building or project. A minimal match based on both sets of characteristics should be established. After the analysis of both projects, the strategies are matched and can be implemented either directly, through upgrades or by considering individual components. Risks and uncertainties are then analysed, and a decision is made on whether to accept or mitigate them. If not, further testing or additional research may be necessary to find a suitable match with acceptable risks and uncertainties. If no match can be found or risks and unknowns can not be solved, a new choice of applicable strategy should be made. If no match can be made at all, a suitable end-of-life strategy should be considered, which avoids damaging the environment as much as possible.

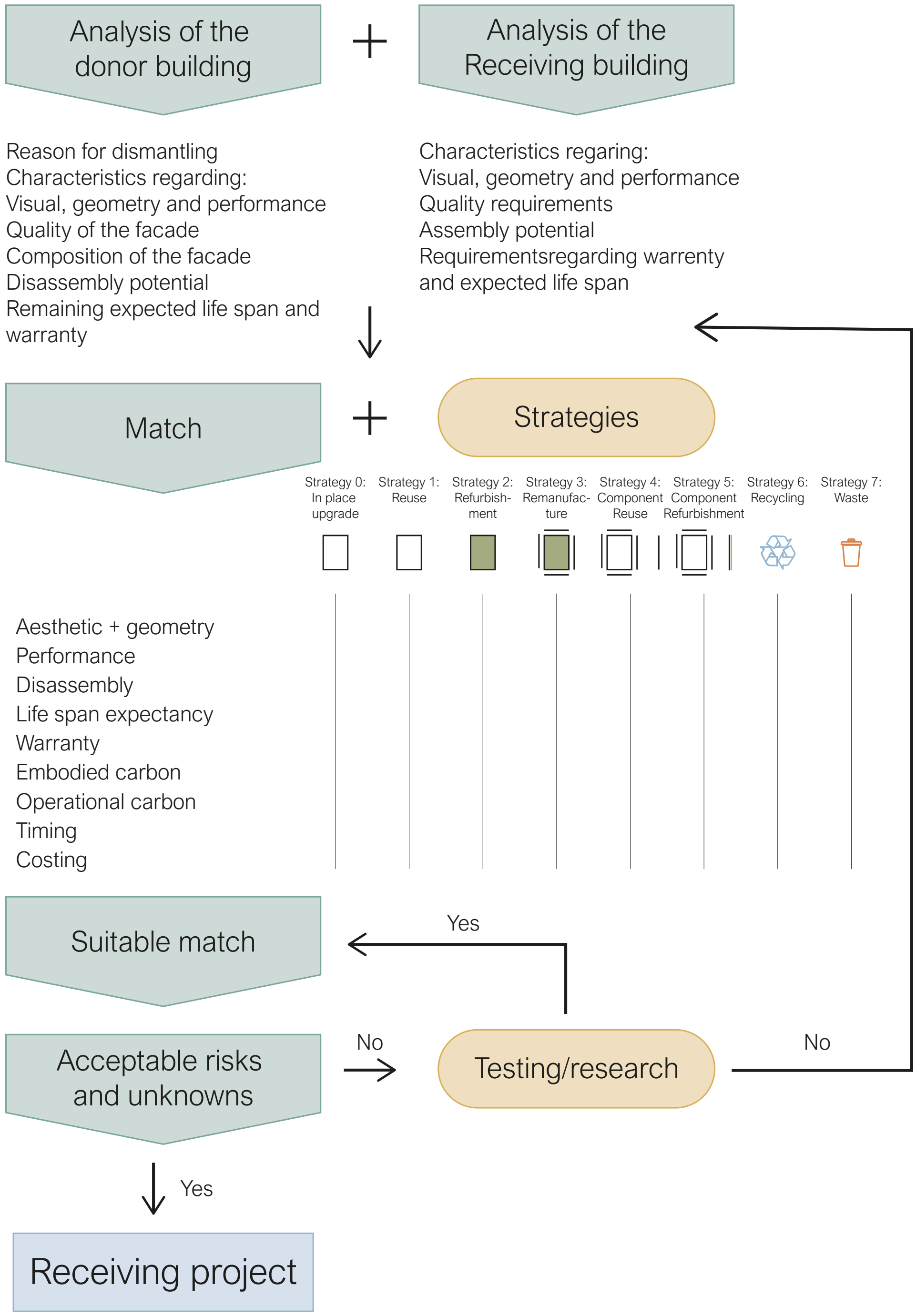


Figure 5.25: Flow chart of applying circular strategies

5.6. Conclusion Strategies

The strategies developed in this chapter show a variety of opportunities for closing the material loop for the unitised curtain wall facade (Figure 5.27). Challenges and risks still should be kept in mind. An overview of the strategies is given in Figure 5.26.

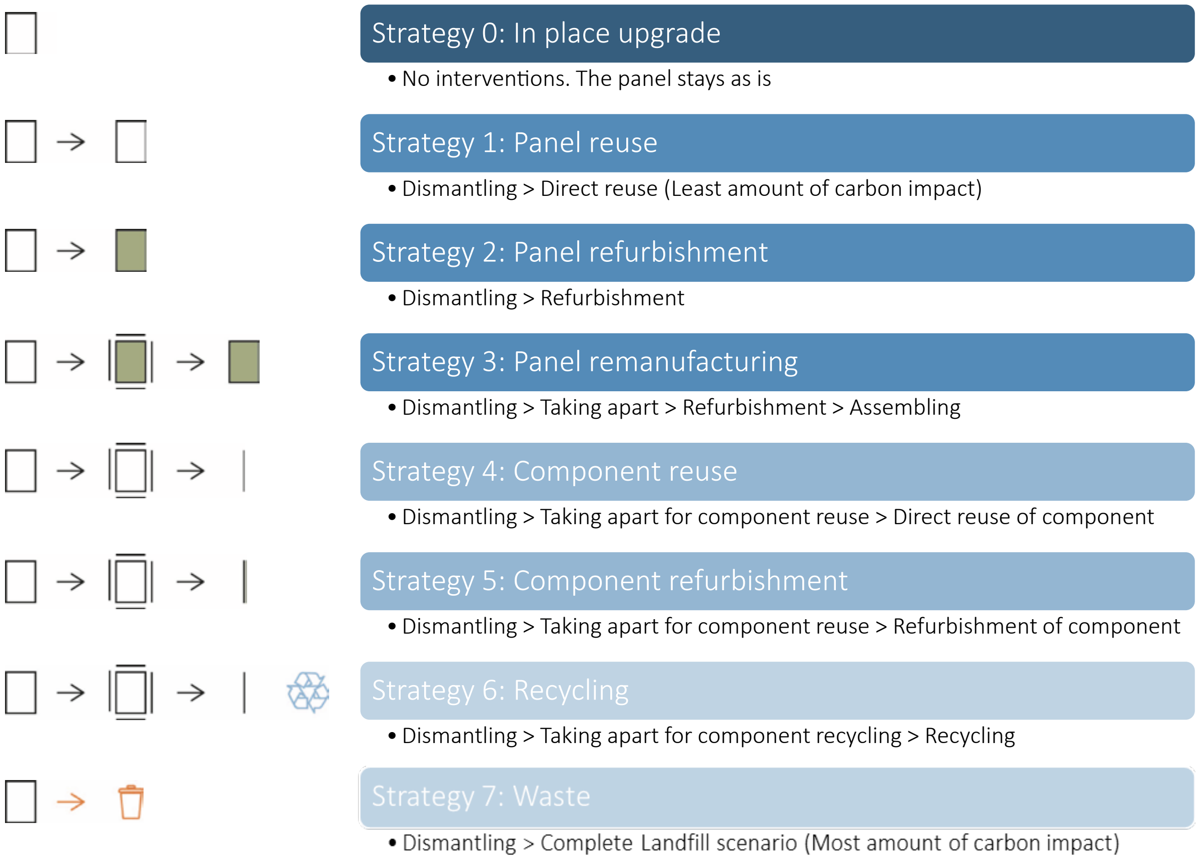


Figure 5.26: Overview and summary of the strategies developed in the research

The strategies offer guidance when a facade enters its end-of-service life but not yet has reached its end-of-life. The decision made at that point, whether it be recycling, waste or reuse, has an impact on the environment but also on needed work. For both the donor building and receiving building or project, a different set of actions is required in comparison to a linear way of designing. Characteristics of the donor elements or components should match the characteristics of the receiving. This can be achieved by either a direct match or an upgrade.

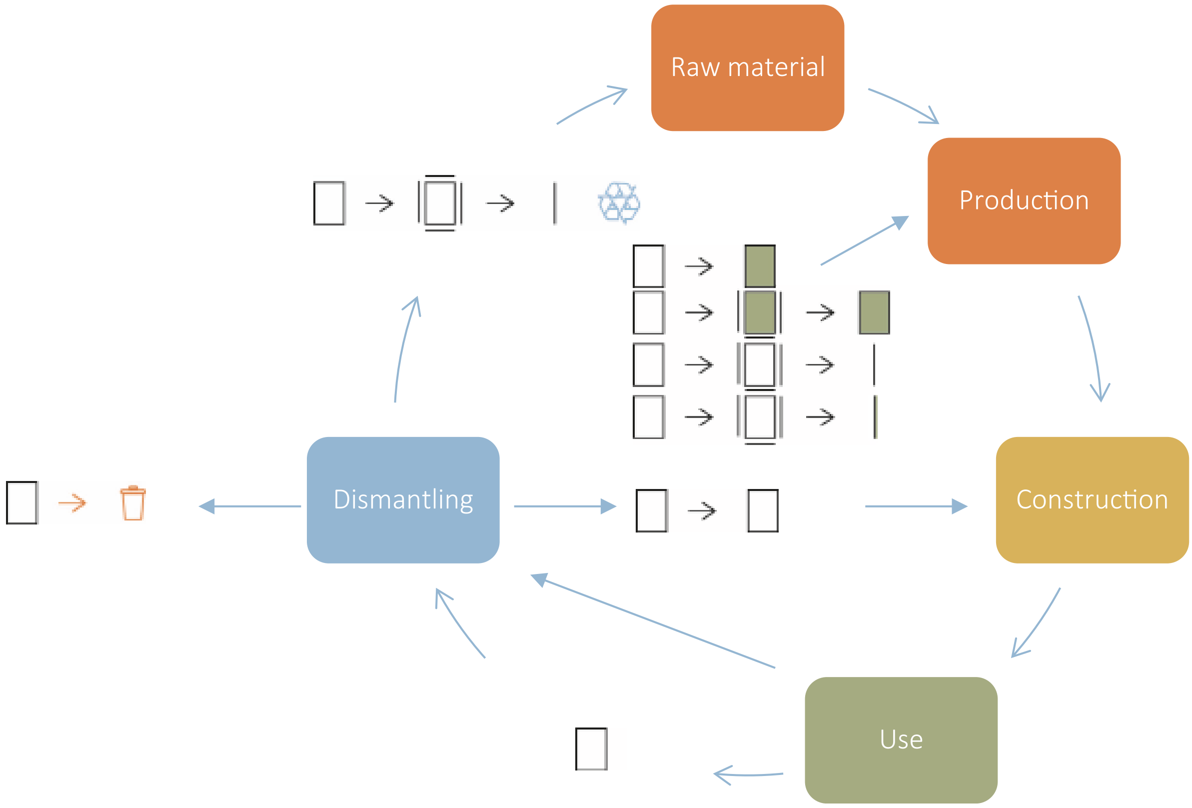


Figure 5.27: Placement of the circular strategies in Figure 2.5: Closing of the loop

The implementation of circular strategies also comes with its challenges. The warranty of the panels and the liability of the company or owner are different than of a traditional project. Ownership of the panels changes during this process. Not only a characteristics match is needed but also a timing match. Logistics like transport and storage become a larger issue when the timing doesn't match, when a project is dismantled and stored before a receiving project is known, the risk of not finding such a project is big. The status and conditions of the components have of big impact on the reuse. Warranty can be based on these conditions, as well as estimating the risk. The difference in connections in the facade as to the as-built drawings imposes a risk. Beforehand it is difficult to predict how the components and materials are coming off. These risks can be accepted by examining the practice and performing in situ or disruptive tests.

Table 5.2: Circular Facade Strategies performance on the properties

Strategy	Upgrade possibility	Circular	Reduce	Supply	Manage
Strategy 0: In-place upgrade	- -	++	++	- -	+/-
Strategy 1: Panel reuse	- -	++	++	-	-
Strategy 2: Panel refurbishment	- -	+	++	+-	-
Strategy 3: Panel re-manufacturing	+	+	++	+	+/-
Strategy 4: Component reuse	+/-	+	+	+	- -
Strategy 5: Component refurbishment	++	+	+	+	-
Strategy 6: Recycling	-	-	-	-	++
Strategy 7: Waste	-	- -	- -	- -	- -

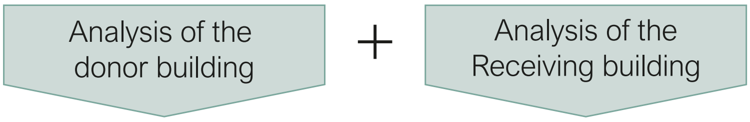
The strategies developed are designed with existing frameworks in mind. To give a summary of the impact and characteristics an overview is shown in Table 5.2, a judgement has been made in terms of upgrade possibility and circularity, including the three pillars designed in Chapter 2. Starting with the refuse strategy, where the choice for in-place upgrading is made, the life span is extended. The panels have the best fit in their original location and therefore sizing issues can be avoided. However, the reason for replacement has a big impact on choosing this strategy. This strategy does not involve a receiving project and thus is different to the rest of the strategies. Moreover the panel-based strategies. Where a panel could be directly reused when a direct requirement match can be made (Strategy 1), or refurbishment actions on the panel keeping it together (Strategy 2). Lastly, an upgrade by dismantling the original panel and replacing or adding features to match the requirements in its original composition (Strategy 3). Then the component-based strategies, where first the panel is dismantled into components, next the refurbishment (Strategy 5) or direct reuse (Strategy 4). These strategies offer the option of using fitting elements in a new configuration or panel parts. Last the end-of-life strategies, which in this research are desired to be avoided, recycling and waste. The eight strategies are inspired by examples in practice and other industries. An estimated embodied carbon calculation has been made to show the possible avoided carbon impact and to further show the relevance of the strategies. By avoiding waste (C4) and raw material extraction (A1) a large impact can be made in terms of carbon impact for both the receiving and donor building. These calculations are based on basic assumptions, when applying the strategies to a case study more specific calculations can be made. An overview of the impact of the strategies based on the circular pillars and the upgrade possibility has been given in Table 5.2.

6
Case study

In this chapter, the panels of Citibank are used as a case study for the method created in Chapter 5. This application shows the context-specific assessment of the strategies. The exploration of the scenario and options provides insight into the avoidance of carbon emission in different options, balancing between operational and embodied carbon. First, the context of this application is analysed. The project in itself, the layers of the facade, lifespan and characteristics are researched. Then the strategies are analysed based on the characteristics of the building and the scenario designed for this chapter. Combined with the general impact and effort needed the most applicable strategies are selected. The most effective strategies are then further developed by designing five options. After considering these options from a variety of aspects, a carbon analysis is done. From the various characteristics of the options and the carbon analysis, general conclusions are made about the applicability of options and aspects that could influence the optimal choice in different situations.

Figure 6.1: Picture of the Citibank facade, made by Scheldebouw

6.1. The scope



6.1.1. Donor building: The Citibank - London

The project of Citibank in London has been discussed in Section 4.3, here the dismantling process was described. A test dismantling was done in the production facility in Middelburg (Appendix D). A new purpose for the panels has yet to be found.

The main reason for the redesign of the building is the desire to change the appearance and upgrade the character of the building. Three areas in the building will be upgraded: the ground floor up to level 4, Between levels 16 and 20 and the levels above floor 40. So the facade of a total of nine floors will be removed. The new plan for the building is pictured in Figure 6.2. In orange the floors can be seen that will be replaced and of which the original panels will be removed. For now, the actual plan for construction has been made for dismantling and waste. Next, a completely new look and function is given to the facade, since the elements are still relatively young compared to the intended service life of the panel, a lot of potential is wasted by discarding these elements. A big opportunity lies in the circular use of these panels. In this chapter scenarios and options for reuse are examined.

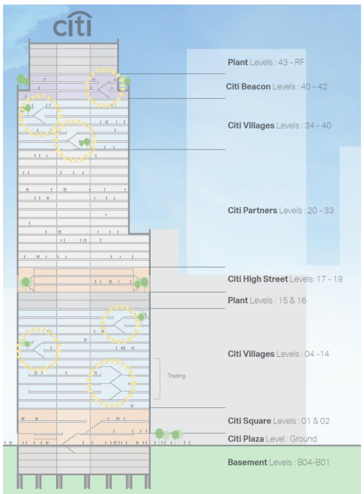
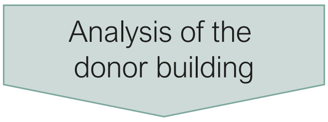


Figure 6.2: Section overview of the new design of the Citibank, made by Buro Happold

6.1.2. Receiving building: imaginative scenario

The receiving project should be understood in order to use the strategies in a useful manner. A specific analysis can be carried out in this way. The receiving project will be a building with relatively normal performance requirements. Buildings in a different country with changed requirements or a function that requires a performance that could be reached using the Citibank panels. An overall upgrade of the panel is desired in this scenario, where the thermal requirements are sufficient. An upgraded lifespan expectancy is desired and the client would want to know what sort of design upgrades are possible (Contact nr. 1, 2 and 14, 2023).

6.2. Analysis of the donor building



The Citibank's facade features a recurring pattern consisting of a 9-meter grid. The spandrel panels with a stainless steel cover, can be seen twice in one grid. A total of 5 different panels have been found within the grid of which 2 closed spandrel panels ($800mm$ and $400mm$ wide) and six transparent panels with a shadow box at the top, a large window in the middle and a smaller window panel at the bottom, the width of these panels vary throughout the grid. Of these six transparent panels two have the same width, $1500mm$. This makes for a total number of eight panels per grid, which is pictured in Figure 6.3. The height of the panels varies as well throughout the building, a standard size of $4100mm$ is assumed for this research. In a rough estimation, this means a total of 1584 panels will be dismantled. As described in Section 4.3 and Appendix D because of the location of the to-be-replaced section, one floor is cut in half in order to be able to take out the rest as a whole. For this application panel, a typical panel is regarded, which is a transparent panel of $1500mm$ wide. This panel represents the aluminium curtain wall facade in this research.

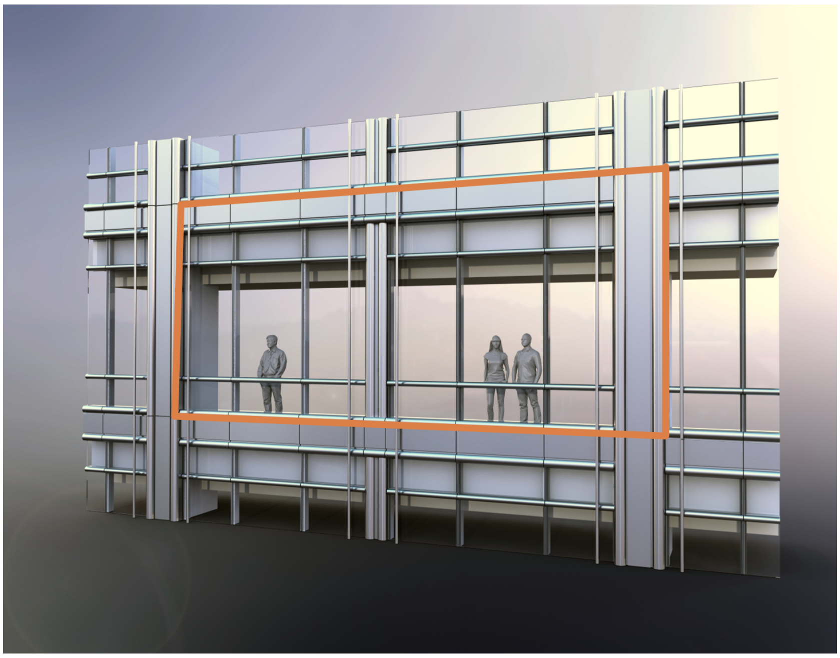


Figure 6.3: Typical facade elevation, made by Scheldebouw

6.2.1. Layers in the facade

In this next section, the layers of the facade panels are further analysed. The components, materials connection and the status of the components are regarded. This analysis will be used to estimate challenges and opportunities when applying circular strategies.

Components

The panels could be fragmented into infills, framing, connection to back structure and external elements. These categories are explained in Subsection 3.1.1. The materials of Citibank are shown in Table 6.1 where the materials are categorised into the four catogories.

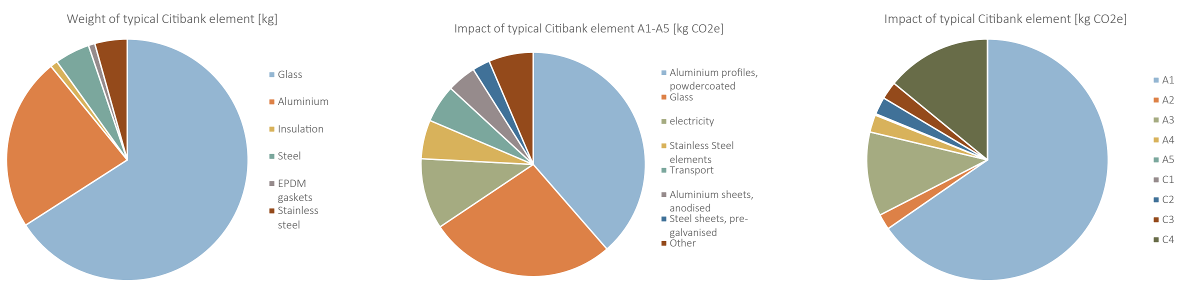
Table 6.1: List of materials, Citibank

Infills			**Framing**	**Connection to back structure**	**External elements**
Shadow box	*Spandrel panel*	*Transparent*			
Insulation	Spandrel glazing	Laminated glazing	Aluminium extrusions (Powder coated)	Steel brackets	Stainless steel sheets $1.2mm$
Steel sheet	Steel sheet	Sealant	EPDM gaskets	Insulation	Stainless steel piano strings
Coated glazing	Insulation	Spacer	Thermal breaks	Fire-stop	
	Stainless steel sheeting		Fasteners		
			Sealants		

Materials

The main materials within the Citibank facade are glazing and aluminium, this is shown in Figure 6.4a, where the material distribution of a standard facade panel is shown. A similar result was observed in Chapter 3. Additionally, the carbon emissions for the A1 to A5 modules have been assessed for the standard panel, as illustrated in Figure 6.4b. Again the most amount of impact can be found in the aluminium, the glazing and the energy that is needed to produce and install the components. Then thirdly when looking over the whole life cycle of the carbon impact, shown in Figure 6.4c, the most amount of impact can be counted for the A1 stage and the C4 stage, these results were also found in Chapter 3.

Some materials worth mentioning are the insulation materials and the stainless steel elements. In some of the panels fire hazardous materials have been used, mainly PIR insulation. Fire regulation would prohibit the use of this material. The stainless steel elements have a notable presence in the facade.



(a) Kg distribution of typical panel **(b)** CO_2 impact of typical panel **(c)** CO_2 impact of typical panel

Figure 6.4: Distribution of kg and $kgCO_2e$ for the Citibank typical panel

Connections

The panel largely consists of double glazing, which is structurally bonded to the aluminium framing. The glazing is capped using stainless steel elements. The connections have been described in Section 3.4 and shown in Figure 3.11b. As described before the replacement of the glazing was not taken into account in the original design. In order to take out the facade panels some glazing will have to be taken out to place the scaffolds. It was also tested in the production hall during the mock-up dismantling (Appendix D). Pictures of this are shown in Figure 4.29 It is therefore assumed to be possible to dismantle the glazing from the framing, the same holds for the cover caps. In Section 4.3 prior research was described about a test dismantling of the components within the panel. It was shown that it is possible to dismantle structurally glazed components, but it is quite labour-intensive. Details of the Citibank facade can be seen in Figure 4.27.

Status of the components

The fact is that the majority of the panels, which are similar to the ones that will be taken off, will keep their function. It can be assumed that the quality and the characteristics are still achieved by the original facade. In Figure 4.30, it is seen that visibly no defects or ageing of the components can be observed, after having been stored in the production hall over the same time span as the building. One aspect that should be noted is that the one-floor level of each section described above will have to be cut in half in order for the remaining panels to be dismantled as a whole, the scraps during the mock-up dismantling can be seen in Figure 4.32. This implies that one-third of the panels will not be intact and cannot be reused as a complete panel. It was found that the glazing has been cut out, which was described to be difficult due to the structurally bonded glazing, but still manageable. If the glazing stays intact during this process, this could still be used as a component, the remains of this are shown in Figure 4.31. The vertical framing elements have been cut, however, most of the horizontal framing was kept intact and could be taken out. This framing could be reused as a component as well, the cuttings do offer an added constraint to the sizes. The stainless steel elements have been taken off quite easily. Last, the spandrel panels have been cut in some places as well. With the right new function, these elements are all still usable.

By external parties, the facade has been inspected in situ. The typical failures have been described. Damages to the stainless steel features have been mentioned, like loose, damaged or missing elements. Condensation inside the IGU has been found, which could imply that the sealant is not intact anymore. Next to that the gaskets were not intact in several places. Internal fractures in the glass units have been found. In spite of the breakage, no glass replacements took place until this time. Lastly, it has been noted that there was no strategy in place for replacements of the infills in the facade.

6.2.2. Lifespan analysis

The facade of Citibank is currently 22 years old. In Section 3.2 the life span and warranty of the components within a facade have been analysed. By using the equation for the remaining service life Equation 4.1, it becomes possible to approximate the lifespan of the components. On this facade, a warranty of 10 years was given and this period has expired. In Figure 6.5 the service life and the components are portrayed as an application of Figure 3.5.

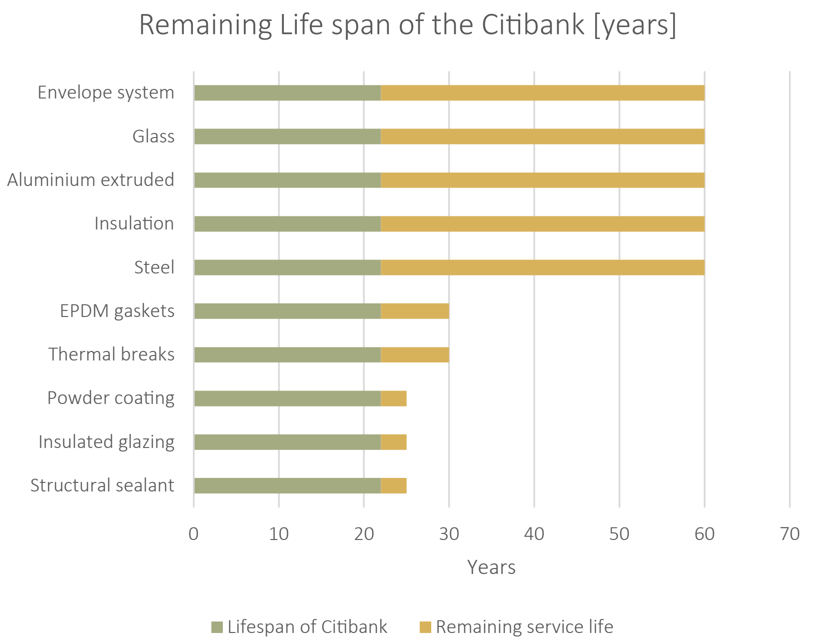


Figure 6.5: Lifespan analysis components in the Citibank facade

Most of the components still have a relatively high life span expectancy. However, the gaskets, Thermal breaks and sealants are almost at the end of their estimated lifespan. As found before these elements do have the potential to exceed these lifespans.

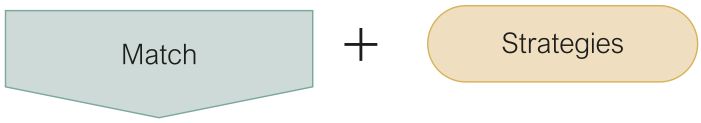
6.2.3. Characteristics

To be able to implement the correct circular facade strategy the performance of the current facade should be known. A match has to be made between the existing properties and the desired properties in the receiving project. Or a refurbishment is applied to achieve these properties. This is described in Subsection 5.1.5. The main characteristics, being the most impactful, that will be regarded in the application are the thermal, aesthetic and lifespan properties. Next to that safety requirements are still kept in mind.

Most of the characteristics of this facade have been mentioned in Section 4.3. The U-value of the shadow boxes was designed to be $0.34W/m^2K$, the spandrel panels have a U-value of $0.2W/m^2K$ and the double glazing has a U-value of $1.33W/m^2K$ and a G-value of 0.34. Which gives an overall U-value of $2.05W/m^2K$. The typical panel has a window-to-wall ratio of 74%.

Aesthetically the facade has a repetitive pattern and high transparency. The Stainless steel elements and the spandrel glazing are the most noticeable elements in the pattern of the facade. (Figure 6.1).

6.3. Strategy evaluation and selection



In the scenario designed for this case study, the lifespan has a decisive impact. The end-of-life components will need replacements in order to upgrade the facade panel or component sufficiently. For some components it has been found that they have the potential to exceed their expected life span, by doing visual inspections, tests or additional research, these components might not need replacement. The framing, including its coating and thermal break, and the glazing are assumed to be able to exceed their expected life span when proper maintenance is done.

Because a circular scenario is desired within this application, and it is already known that these panels will be replaced, strategy 0 and strategy 7 are not used. Same for strategy 6, the aim is for the materials to be reused in the scenario described. Due to the age of the panels and the components that are reaching their expected end of life, replacements need to be made to create a panel that could live another 30 years, as described in the scenario. This implies that strategy 1: Panel reuse is not possible. Depending on the magnitude of the refurbishment and the amount of dismantling strategies 2 and 3 are applicable to this scenario. Strategies 4 and 5 are also applicable, new configurations can be made using the fitting components within the facades. Size deviations and more aesthetic changes are possible with these strategies. The scenario defined does not include size constraints.

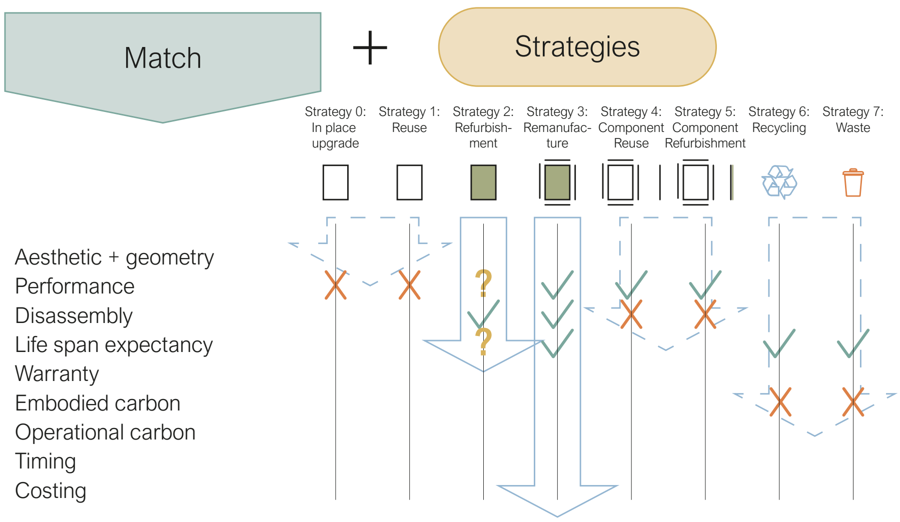


Figure 6.6: Matching of the strategies for this case study

In the impact effort diagram in Figure 6.7 the strategies are graded on their estimated impact with respect to their effort. Strategies 6: recycling and 7: waste are in the lower-left quadrant, reflecting their limited sustainable impact given the current take-make-dispose strategy. Recycling takes more effort since the materials need to be separated. The strategies in the outer right quadrant are estimated to need the most effort, strategy 2: panel refurbishment and 3: panel re-manufacturing are able to achieve a high impact saving but still need effort. The same holds for strategies 4: component reuse and 5: component refurbishment, however because of the work and the waste that is generated due to sizing, the impact is less. Strategies 1: panel reuse and 0: in-place upgrade are found to have the most impact reduction and the least amount of effort (Contact nr. 14, 12-7-2023). From the impact/effort analysis, it is concluded that strategies 0 to 3 show potential in current reuse projects. For the option development that has been done in the next section strategies 2 and 3 are used. In addition, the end-of-life strategies are used to show the difference in regard to carbon impact.

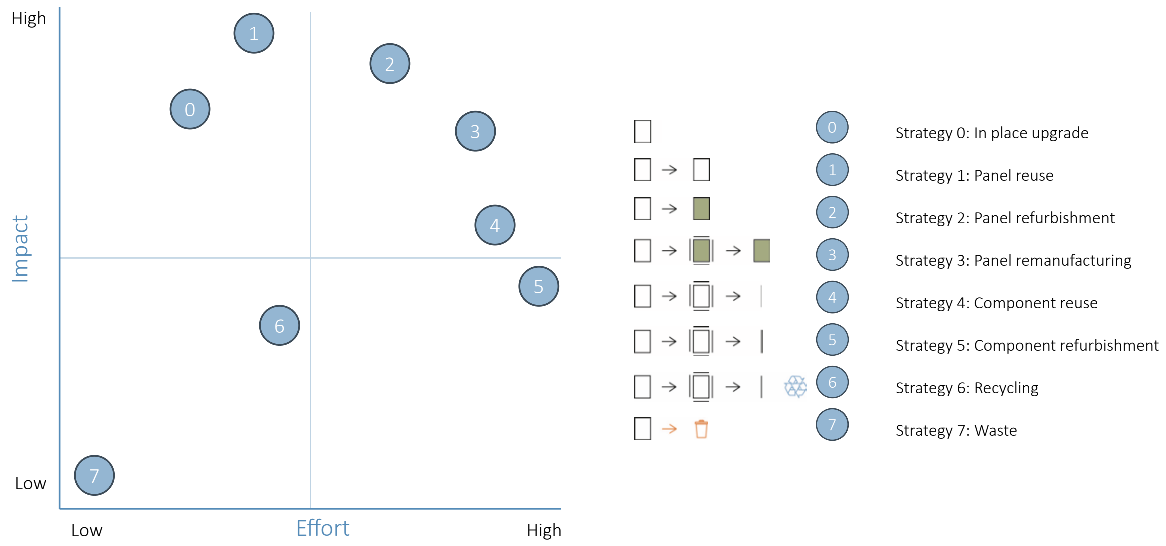


Figure 6.7: Impact effort diagram Strategies

6.4. Evaluation of upgrade options of the circular strategies

In the previous section, the strategies designed in Chapter 5 were filtered and it was found that strategies 2: panel refurbishments and 3: panel re-manufacturing have the most potential in this scenario. The assumption is made that for these the size of the original panels is sufficient. Upgrading the panel in such a way that the desired thermal and life span requirements are achieved. Refurbishment options are developed and evaluated to see the impact in terms of CO_2.

Five options have been developed for this case study. The options vary in level of intervention and level of upgrade of the requirements. For all options, the replacement of the gaskets is assumed. The first option is to replace all of the glazing. This is to deal with the sealant and is intended to increase the U-value of the glazing. Secondly, the option to replace one of the transparent parts and place a spandrel zone as well as replace the shadow box with a spandrel zone. This is to decrease the incoming solar radiation and upgrade the insulating properties of the glazing. For this option, it has been assumed that an upgrade of the IGU is not needed. In the third option the same work is done as option two, however for this option also the glass is completely replaced. Last, in option four the same application was done as in option two, but also the external stainless steel elements were replaced by aluminium and an additional glazing bar was placed to help improve the insulating properties of the panel. Option 0 will be taken as a base-level option, to be able to compare the interventions and upgrades to the original facade. A visual representation of the upgrade is shown in Figure 6.8 where the replacement of the shadow box and the added spandrel are shown compared to the original elevation.

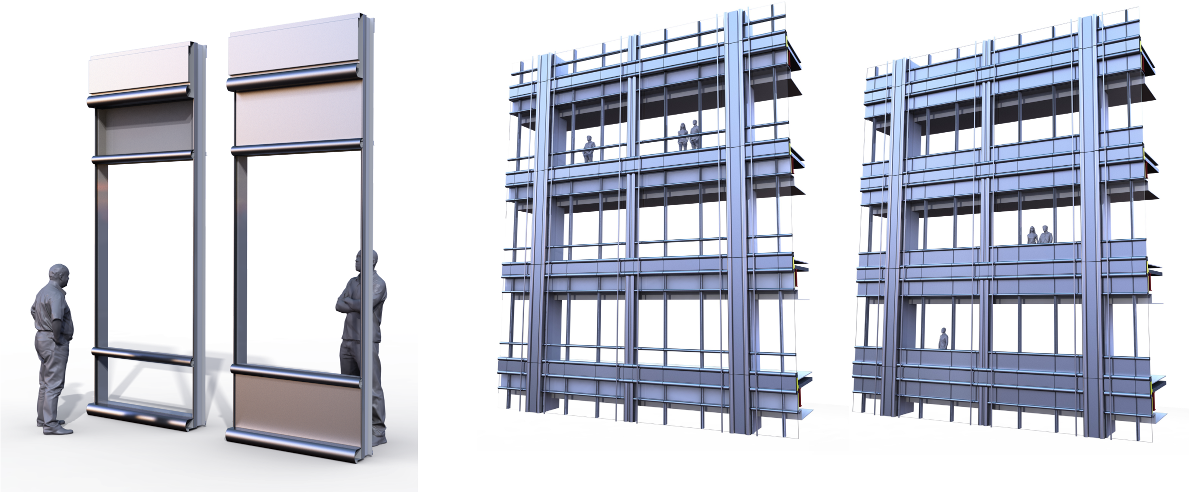


Figure 6.8: Renders of the refurbished Citibank panels made by Scheldebouw (Appendix F)

Actions that are similar for all options are the dismantling of the panels on the construction site. For now, it is assumed that the panels will be dismantled as a whole. After which the panels are transported to the production facility in Middelburg. The option for a refurbishment location close to the site is disregarded since the transportation does not have a significant share in the overall carbon impact. In the production hall first, the coupling gutter needs to be cut, this is connected by a sealant. Then secondly the replacement of the gaskets and cleaning of the elements are reoccurring. After the refurbishment, it might be needed for the panels be stored at a storage facility. This is necessary when timelines between the dismantling and the receiving project do not match up. Then last the transportation and installation of the components on the receiving building.

6.4.1. Assumptions and parameters in the carbon calculations

The embodied and operational carbon calculations are made based on several assumptions. The first assumption is that when the material or component is not reused, it is put to waste. However, recycling is still an option, which will further increase the savings. The donor and receiving locations both are assumed to be in London. The impact in the production facility (A3) is assumed to be equal to that of a new panel. This includes primer, cleaner, wooden packaging, plastic packaging, electricity and gas. Additionally, it is assumed that the energy required for the dismantling of the panel from the donor building is equal to the construction of a new panel. No clear data is available currently to confirm this assumption. Last, in the end-of-life strategies it is assumed the same panel has to be made using raw materials.

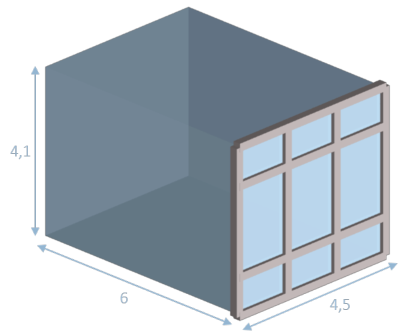


Figure 6.9: Sample room used in the operational carbon calculations

In terms of operational carbon, parameters have been assumed, the temperature inside has been assumed to be $21°C$ degrees, and the temperature outside $10.8°C$. Which are average temperatures in the United Kingdom (Climate-Data.org, n.d.). Ventilation transmissions have been estimated according to the data of Arup (Arup & Glass, n.d.). Average solar radiation is assumed to be $239W/m^2$ according to the KNMI. A sample room of HXBXD:$4.1m \times 4.5m \times 6m$ is taken shown in Figure 6.9. The internal heat is set to $1359W$ which is a result of the sum of the internal heat of three people, appliances and lights. The results are thus representative of the inputs mentioned above, it can not be used for a generalised output for other facades.

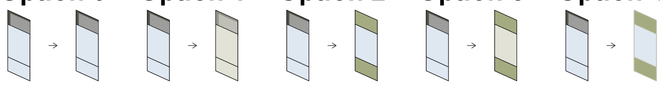
The in and output of the calculations presented in this section can be found in Section E.3. As well as the report made in collaboration with Scheldebouw regarding this topic in Appendix F.

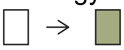
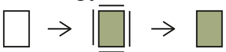
6.4.2. Refurbishment options based on the strategies

The options are developed based on the refurbishment actions found in previous research and interviews done within Scheldebouw (Contact nr. 14, 24-7-2023). They have been developed based on the demands described in the scenario for this case study and components that would need upgrading. A variety of interventions was examined to see the impact on both the operational carbon as well as embodied carbon. U-values have been calculated by colleagues at Scheldebouw. As mentioned previously, the refurbishment options are based on the application of two strategies, strategy 2: panel refurbishment and strategy 3: panel re-manufacturing. For each option, it is figured out what strategies fit the option (Table 6.2).

- 6.4.2.1 Option 0: Base option
- 6.4.2.2 Option 1: Replacement of the glazing
- 6.4.2.3 Option 2: Insulated spandrel zones
- 6.4.2.4 Option 3: Insulated spandrel zones with glass replacements
- 6.4.2.5 Option 4: Insulated spandrel zones with upgraded framing

Table 6.2: Overview of the options



Strategy	**Option 0**	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Strategy 2: Panel refurbishment 	X				
Strategy 3: Panel re-manufacturing 		X	X	X	X

Option 0: Base level

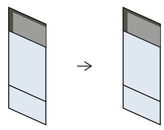


Figure 6.10: Scheme of Option 0

For the base option, the assumption that the panel is still of enough quality is made. The only component that is replaced is the gaskets. This base option shows the potential of the element when no major elements are replaced. This option is using strategy 2. At the production hall, the gaskets will be dismantled, this is relatively easy. Then new gaskets are placed and the panel is cleaned.

The properties of the panel will be that of the original. The U-value of $2.05W/m^2K$, a window-to-wall ratio of 74% and a g-value of 0.34.

Life span When regarding the lifespan it can be seen that the main bottleneck in the lifespan analysis is replaced (Figure 6.11). The powder coating, when maintained properly, could exceed its life span (Contact nr. 12, 2023). The same holds for insulated glazing as seen in reference projects and projects at Scheldebouw. Structural sealant has been seen to exceed its life span, however, it should be inspected for safety reasons.

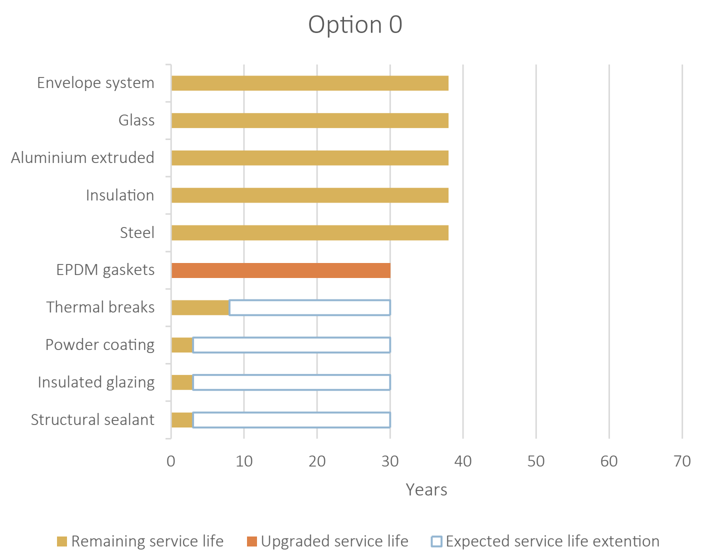
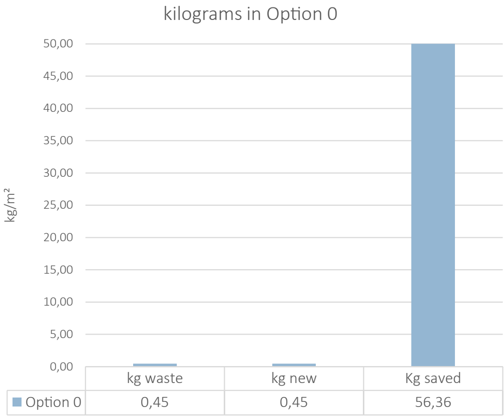
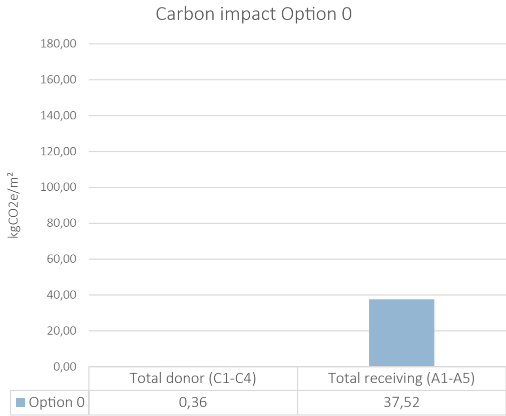


Figure 6.11: Lifespan analysis of the components in the Citibank facade, after applying option 0

impact In this option, a large amount of the materials are saved (Figure 6.12a). With minor actions, a vast amount of kilogram material can be saved with a relatively low impact (Figure 6.12b). In this basic option, the U-value is not upgraded. This option emitted 14 per cent of the carbon compared to the total impact of a complete waste strategy. For the receiving building, this means a saving of 83 per cent. In terms of operational carbon (Figure 6.25), it does not perform well. This is due to the high transparency, so a high solar load, as well as a non-optimal U-value.



(a) Overview of kilograms materials of option 0



(b) Carbon impact option 0

Figure 6.12: Carbon and kilogram analysis of option 0

Option 1: Replacement of the glazing

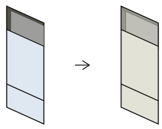


Figure 6.13: Scheme of Option 1

In option 1 the replacement of all glazing is applied. The glazing in all three compartments in the framing is replaced with higher-performing glazing. Due to the size constraints in the framing, the glazing options are limited due to the thickness. It was found that an increase in thickness in the glazing causes issues in the framing. Since one of the biggest components in the facade is dismantled this option falls into strategy 3: panel re-manufacturing. The glazing component that is taken out could be reused in a different setting, this would then fall into strategy 4 or 5: component reuse or refurbishment.

The new properties for the panel will be a U-value of $1.97W/m^2K$. This is not as significant as expected because of the restricted space in the framing, limited glazing possibilities were found. The window-to-wall ratio is 74% and the g-value of the glazing is 0.34.

Actions that need to be taken at the production facility are dismantling the horizontal stainless steel elements, and cutting the sealant of the glazing in the three compartments. Cleaning the sealant off the framing. When that is done the original glazing can be replaced with the new glazing. New sealant is placed together with the gaskets. Lastly, the original horizontal stainless steel features are placed back.

Life span Compared to the basic option most of the critical elements in the life span analysis are replaced and the lifespan of the overall component is increased (Figure 6.14). The powder coating will remain a risk, as described in Chapter 3 it is possible to replace the coating, but this will be more labour-intensive and increase the costs.

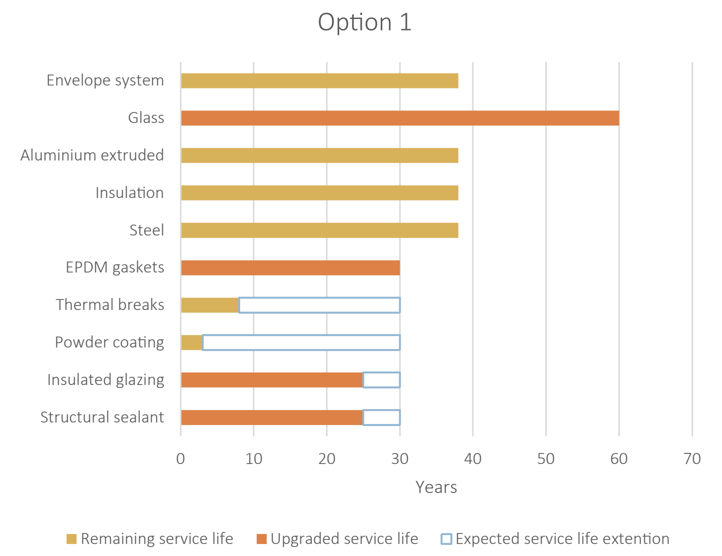
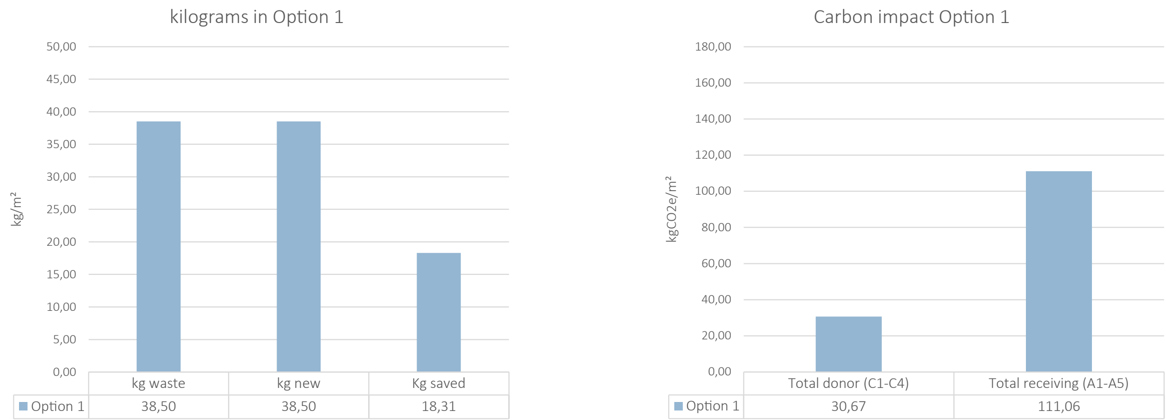


Figure 6.14: Lifespan analysis of the components in the Citibank facade, after applying option 1

impact By implementing this scenario 48 per cent of embodied carbon impact can be saved compared to a strategy (strategy 7). In the A1-A5 modules of the receiving building 51 per cent can be saved in carbon impact. In terms of operational carbon (Figure 6.25), it is not improved. The slight decrease in transmission losses is counteracted by the high solar loads due to the high level of transparency in the facade. In terms of operational carbon, it performs worse than the base option.



(a) Overview of kilograms materials of option 1

(b) Carbon impact option 1

Figure 6.15: Carbon and kilogram analysis of option 1

Option 2: Insulated spandrel zones

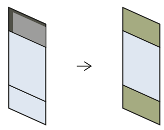


Figure 6.16: Scheme of Option 2

In this option, the overall transparency is reduced by replacing one part of the glazed elements with a spandrel. To upgrade the panel also the shadow box is replaced by a similar element. The spandrels consist of a steel backplate, insulation material and finishing. This finishing is in this option assumed to be a stainless steel plate, to match the horizontal external elements. The larger components like the glazing and aluminium framing are reused in this option. This option falls within strategy 2: panel refurbishment.

The new properties for the panel will be a U-value of $1.97W/m^2K$. The window-to-wall ratio is 54% and the g-value remains 0.34.

Actions that need to be taken at the production facility are dismantling the horizontal stainless steel elements, and cutting the structural sealant of two smaller compartments, well as the shadow box. Next, the remaining sealant needs to be removed from the aluminium framing. The two smaller glazing elements are replaced with spandrel panels and then sealed again. Next, the gaskets are placed and the horizontal stainless steel features are placed back.

Life span Same as the previous options the most critical element, the gaskets, are replaced. Based on references and future tests, this could be validated. In Figure 6.17 the new life span of the components is shown.

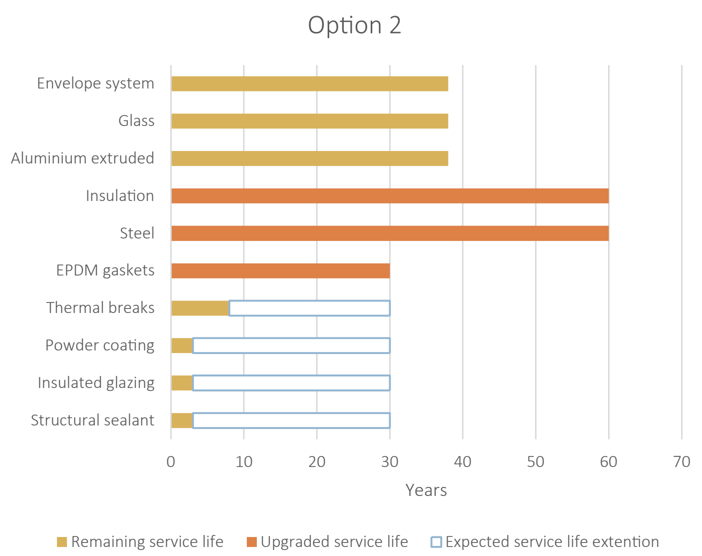
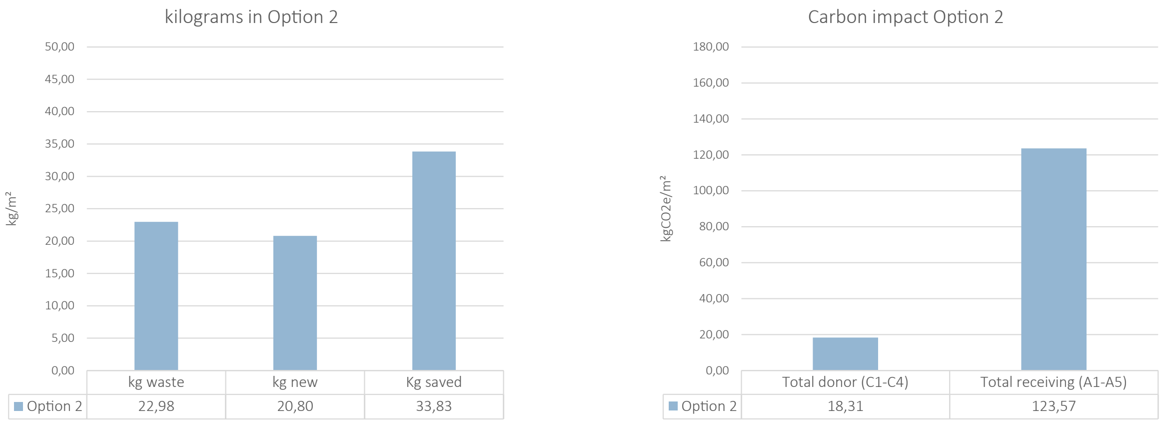


Figure 6.17: Lifespan analysis of the components in the Citibank facade, after applying option 2

impact By using this option a total of 18 per cent of carbon can be saved compared to a standard strategy. In the A1-A5 module of the receiving building up to 46 per cent can be saved. In terms of operational carbon (Figure 6.25), it performs well. The improvement is the highest compared to the other options. As well as the embodied carbon can be observed as low. By replacing the shadow box and reducing the incoming solar radiation benefits can be achieved.



(a) Overview of kilograms materials of option 2

(b) Carbon impact option 2

Figure 6.18: Carbon and kilogram analysis of option 2

Option 3: Insulated spandrel zones with glass replacements

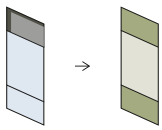


Figure 6.19: Scheme of Option 3

Option 3 is similar to option 2, however, also a glass replacement is done. So all glazing in the current panel will be taken out. The smaller sections will be filled with a spandrel panel with a stainless steel finish, insulation and a steel backplate. In this option, the aluminium framing is reused with a new infill. This option falls into strategy 3: panel refurbishment. Discussed could be whether this could fall into strategies 4 and 5: component reuse or refurbishment. Since the framing components are reused, the rest are replaced.

The new properties for the panel will be a U-value of $1.73W/m^2K$. The window-to-wall ratio is 54% and the g-value of the new glazing is assumed to be still 0.34.

Actions that need to be taken at the production facility are dismantling the horizontal stainless steel elements, and cutting the structural sealant of the three compartments, as well as the shadow box. Next, the remaining sealant needs to be removed from the aluminium framing. The two smaller glazing elements are replaced with spandrel panels and then sealed again. The glazing in the middle compartment is also replaced. Next, the gaskets are placed and the horizontal Stainless steel features are placed back.

Life span Shown in Figure 6.20, most of the components have been replaced. Only the aluminium framing is kept, together with the thermal breaks, which has some risks includes. These have been described in the previous options.

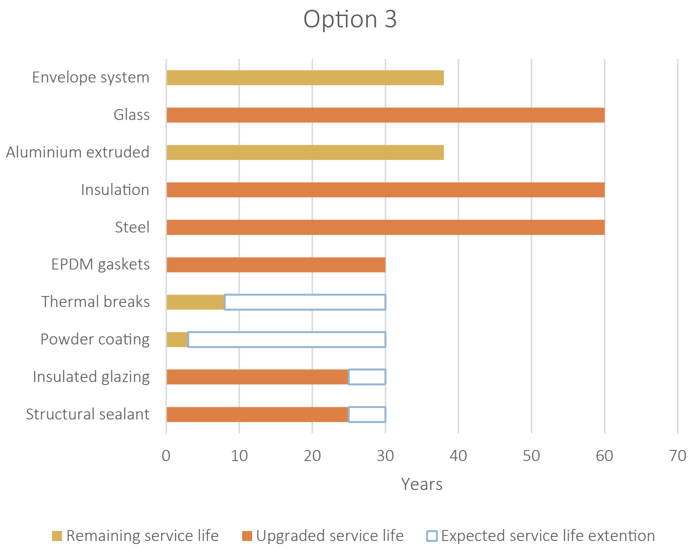
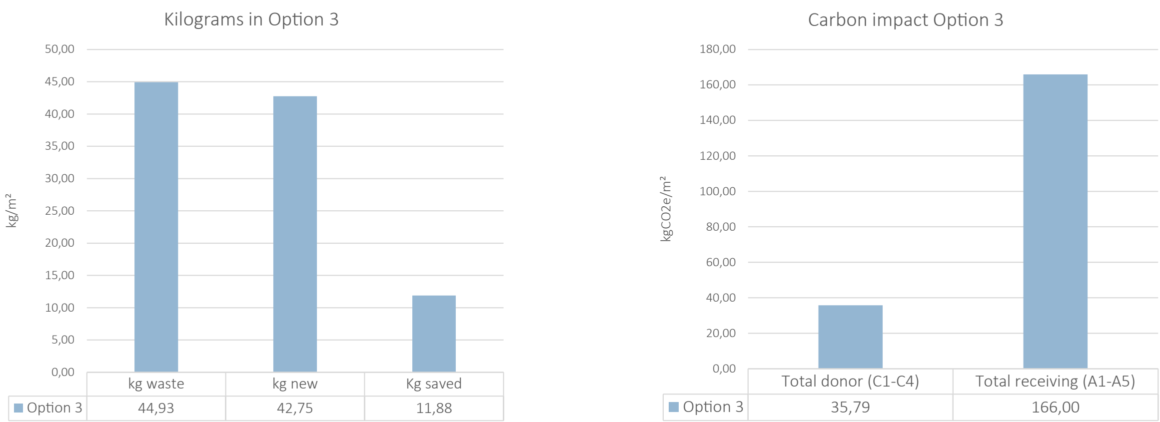


Figure 6.20: Lifespan analysis of the components in the Citibank facade, after applying option 3

impact In this option, a total of 27 per cent of embodied carbon can be saved compared to a complete waste strategy (Strategy 7). 28 per cent in upfront embodied carbon is saved for the receiving building. In terms of operational carbon, this strategy does perform well. In spite of the embodied carbon being high, the operational carbon is reduced.



(a) Overview of kilograms materials of option 3

(b) Carbon impact option 3

Figure 6.21: Carbon and kilogram analysis of option 3

Option 4: Insulated spandrel zones with upgraded framing

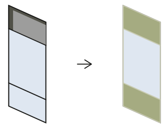


Figure 6.22: Scheme of Option 4

In option 4 the same upgrades are applied as in option 2. The glazing is reused in the biggest opening and insulated spandrels are placed in the smaller openings. In addition to option two also the horizontal stainless steel parts are replaced with newly designed aluminium cover caps as well as the addition of vertical glazing bars. The spandrels are finished with an aluminium plate to tie into the new aesthetic of the panel.

The new properties for the panel will be a U-value of $1.75W/m^2K$. The window-to-wall ratio is 54% and the g-value of the new glazing is assumed to be still 0.34.

Actions that need to be taken at the production facility are dismantling the horizontal stainless steel elements, and cutting the structural sealant of the glazing in the two smaller compartments, well as the shadow box. Next, the remaining sealant needs to be removed from the aluminium framing. The panel is then cleaned. The two smaller glazing elements are replaced with spandrel panels and then sealed again. These infills could vary, for this case, an aluminium finish is chosen. the new gaskets are placed. New aluminium glazing bars and horizontal external elements are designed and engineered to fit the panel. These are connected to the original framing.

Life span In terms of life span the most impactful upgrade is made with the replacement of the EPDM gaskets. Nevertheless, the same as in the other options still a risk is with the coating of the framing and the sealants.

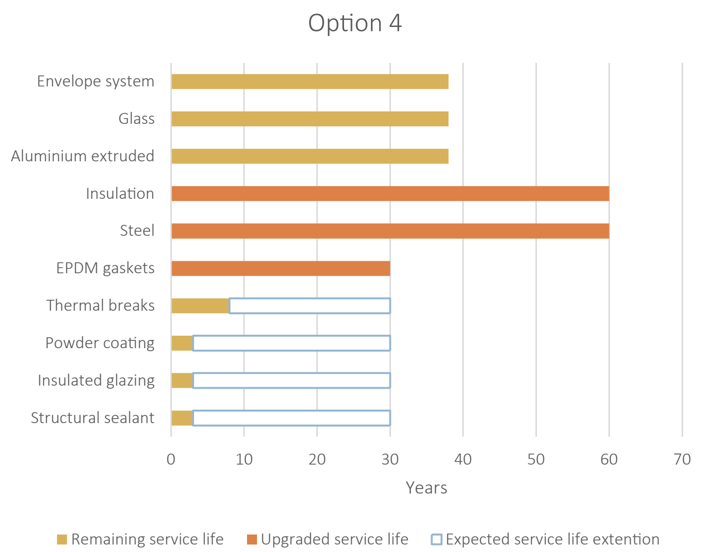
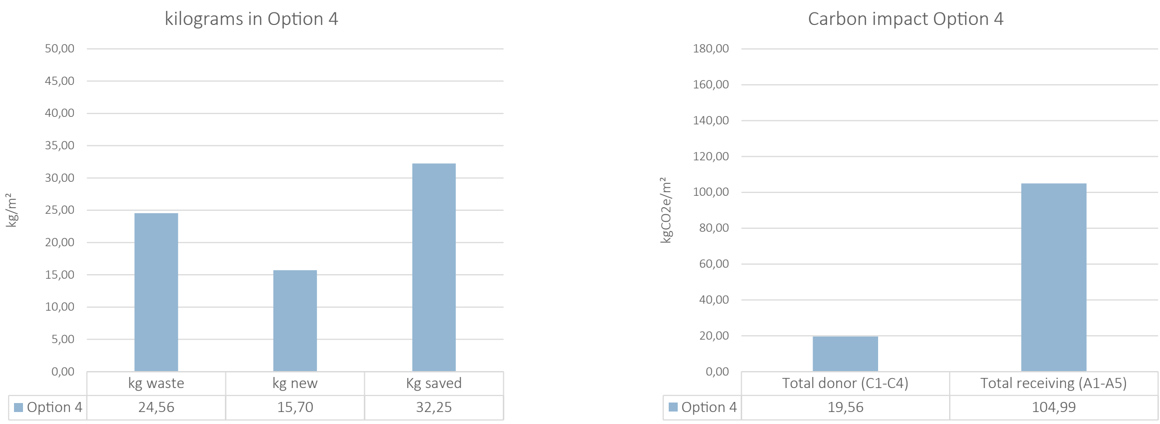


Figure 6.23: Lifespan analysis of the components in the Citibank facade, after applying option 4

impact In this option, the external element and infills can give an architect or client some design freedom. The overall look can be adjusted to the desire of the client. The total carbon that is saved compared to strategy 7: waste is 61 per cent. The upfront carbon can be reduced by 62 per cent. In terms of embodied carbon, this option performs relatively well compared to the other options. It has the second lowest embodied carbon impact, mainly because not replacing the glazing has a high impact.



(a) Overview of kilograms materials of option 4

(b) Carbon impact option 4

Figure 6.24: Carbon and kilogram analysis of option 4

6.4.3. Operational carbon

An overview of the operational carbon impact of the options is presented in Figure 6.25. Analysing the embodied carbon in relation to operational carbon provides valuable insights into the feasibility of upgrade options in terms of carbon impact can be made. Option 1 fails to enhance operational carbon compared to the base option and leads to a higher carbon footprint. On the other hand, both Options 2 and 4 achieve improvements in operational carbon compared to the base option, along with reduced embodied carbon during production. Additionally, Option 3 does achieve a reduced operational carbon impact; however, the embodied carbon impact comes close to end-of-life strategies 6 and 7. When assessing the embodied and operational carbon against a hypothetical new panel with improved properties to the original, it is evident that the embodied carbon impact will be the highest among the options that score better than the basic option and the hypothetical new panel. This is due to the reduction in the window-to-wall ratio, which also leads to decreased operational carbon emissions.

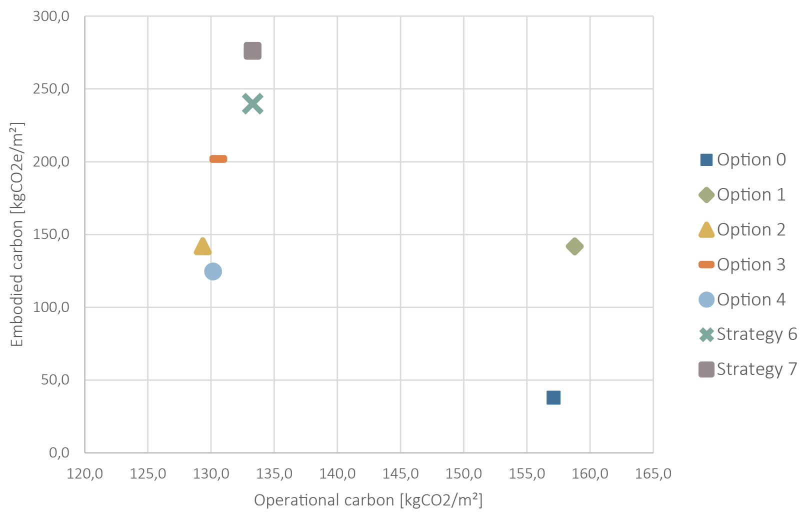


Figure 6.25: Overview of embodied vs operational carbon of the options

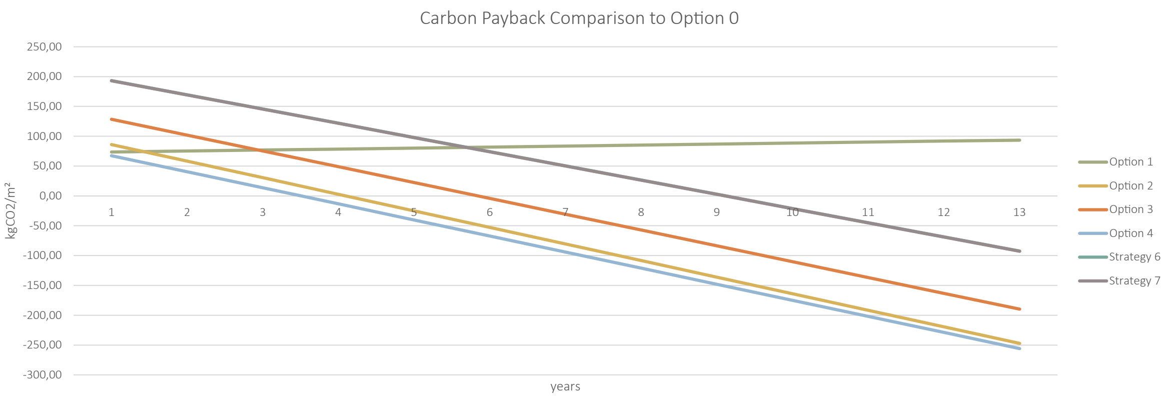


Figure 6.26: The carbon payback shown over the years

Carbon payback period To put these two concepts into perspective, the carbon payback period is calculated for the options. The payback period is calculated compared to the base option: Option 0. The results are presented in Figure 6.27. When choosing the waste strategy, where all materials are wasted and new material has to be generated, compared to option 0 it takes 10 years to earn back the generated carbon. The carbon payback period is graphically presented in Figure 6.26, where the line of an option crosses the x-axis when an equal carbon output is achieved. Option 1 has a negative carbon payback period, so it will never regenerate its impact over the years compared to option 0. This option would not be beneficial when comparing it to the base option in terms of the balance between operational and embodied.

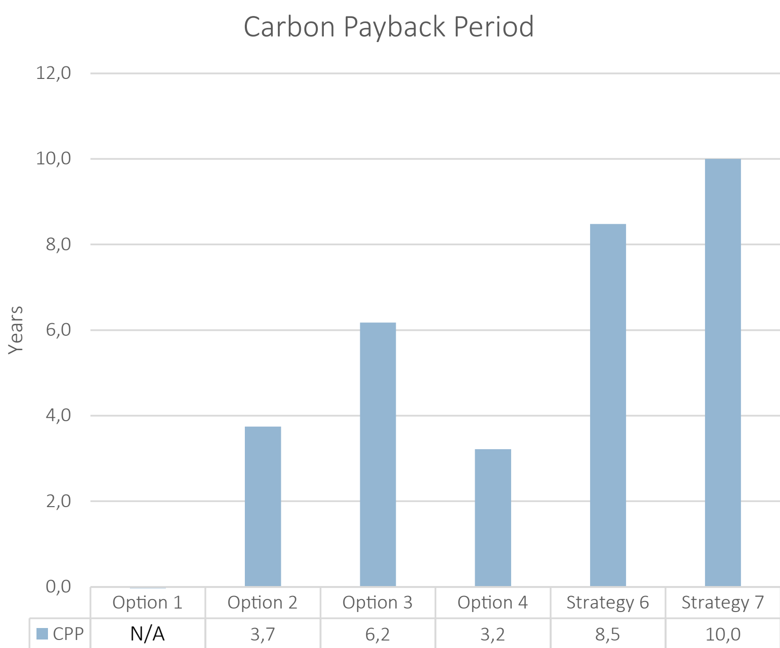
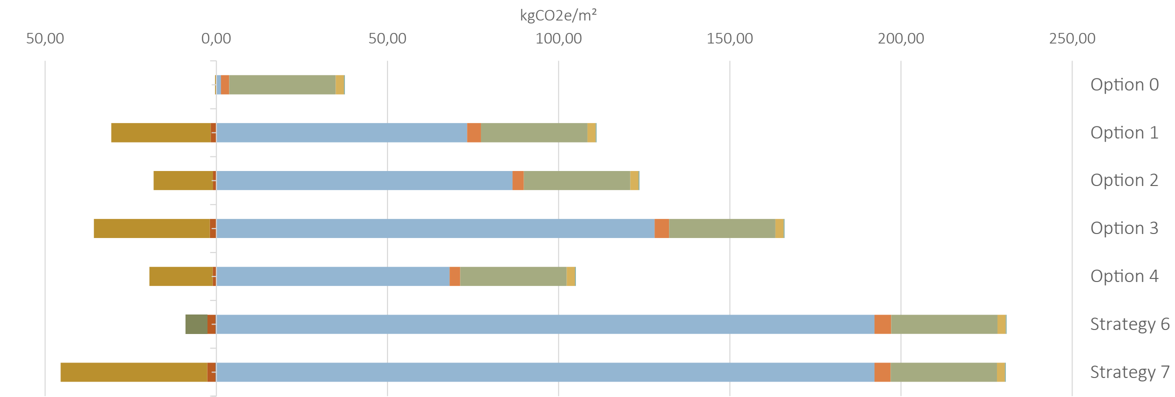


Figure 6.27: The Carbon Payback Period compared to base option 0

6.4.4. Comparisons

Upon examining the carbon results of the options alongside the two end-of-life strategies, a noticeable reduction in impact becomes evident. As depicted in Figure 6.28, the impact shows variations across both the donor building and the receiving building. However, the most significant impact can be achieved by minimising the demand for raw materials in the receiving building. In option 0, 94 per cent of the total embodied impact can be saved compared to the waste scenario. For option 4, 54 per cent of the embodied carbon can be saved compared to the waste scenario. For option 2, 60 per cent of the end-of-life impact at the donor building can be avoided.



	Strategy 7	Strategy 6	Option 4	Option 3	Option 2	Option 1	Option 0
A1	192,26	192,26	68,15	128,00	86,52	73,25	1,33
A2	4,71	4,85	3,09	4,25	3,31	4,07	2,44
A3	31,08	31,08	31,08	31,08	31,08	31,08	31,08
A4	2,29	2,42	2,42	2,42	2,42	2,42	2,42
A5	0,24	0,24	0,24	0,24	0,24	0,24	0,24
C1	-0,24	-0,24	0,00	0,00	0,00	0,00	0,00
C2	-2,42	-2,42	-1,05	-1,92	-0,98	-1,64	-0,02
C3	0,00	-6,34	0,00	0,00	0,00	0,00	0,00
C4	-42,83	0,00	-18,51	-33,87	-17,32	-29,03	-0,34

Figure 6.28: Overview of the estimated carbon emissions of the options

An additional approach to further mitigate the waste impact involves incorporating strategy 6: recycling into the options. This measure, coupled with the utilisation of secondary content materials instead of raw materials, can contribute significantly to reducing the overall carbon footprint. By reusing components, not only can the carbon impact be reduced, but also the value of the materials is retained. Looking at the kilograms that are saved, wasted or newly produced (Figure 6.29), a reduction can be found compared to a strategy 6 or 7. Option 4 is especially noted where a large part of the materials is saved, In addition, less new material is needed for the new product in terms of kilograms. The panel observed that originally weighted $350kg$, when applying option 2, $208kg$ is saved and reused, which in comparison to the other options saves the most amount of kilograms, excluding the base option.

As described in the options and in the analysis of the donor building, assumptions were made about the remaining service life and remaining potential of the components. It has been expressed that these assumptions impose risks, these risks are shown in Table 6.3, in addition to the risks a mitigation strategy was proposed.

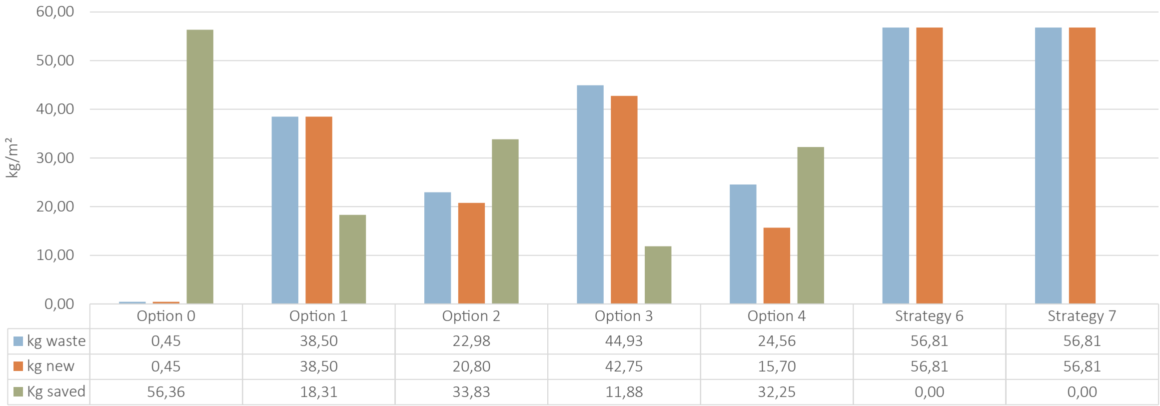


Figure 6.29: Overview of kilograms wasted, new and saved of the options

Table 6.3: Risks of the components in the Citibank facade

	Probability	**Impact**	**Risk**	**Mitigation**
Gaskets not usable anymore (UV or age)	Medium	Low	Low	Upfront measurements, Gasket types
Powder coating quality insufficient	Medium	High	Medium	Upfront visual inspection
Glass breakage	High	High	high	Replace glazing, Careful handling
Corrosion in aluminium	Low	High	Medium	Upfront visual inspection
Damage during dismantling	High	High	High	Careful handling, Replacement strategy of components
Damage during transportation	Medium	High	Medium	Careful handling, Replacement strategy of components
Damage during refurbishment	Medium	High	Medium	Careful handling, Replacement strategy of components
Structural bonding on existing sealant	High	Unknown	Unknown	Testing of bonding properties after resealing
Age of glazing when not replacing, to old	Medium	Medium	Medium	Replacement strategy, Testing and references

Choice of options

When deciding what option and strategy suits the best for this case study different factors play a role. In practice, decisions are not always based solely on CO2 impact. In this next section, a decision is made on the varying characteristics of the receiving building and the wishes of the client. When only regarding the embodied carbon impact option 0 would become the best option. Despite a carbon saving of 97 per cent, it is not possible to achieve the desired life span of 30 years without the risk of the expiring expected life span of the sealant in the glazing. in Table 6.4 an overview of the various aspects that are involved in a reuse case are shown, and the options are analysed and graded on those aspects. Depending on the focus point of a client or building owner, different options might become more convenient. When solely looking at the embodied carbon at the receiving building options 0 and options 4 would be the most beneficial. However, when incorporating the wish of a client to reduce risks, the glazing would have to be replaced because of the life span of the sealant and spacers. Then options 1 and 4 where would fit better, while still reducing the embodied carbon of the receiving project. The wish for an overall well-performing facade on both operational and embodied carbon would lead to the choice of option 2 or option 4. When incorporating the wish or reduced effort due to time or availability in the production facility. Options 0 or 2 might be more fitting. Depending on the focus of each project different options become more optimal, even producing a new facade could have more benefits in certain aspects compared to reuse.

Table 6.4: Choices based on different characteristics

Aspect	**Option 0**	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Recycling**	**Waste**
Aesthetic and geometry changes	0	0	+	+	+	+ +	+ +
Performance: U-Value	- -	-	0	+	0	+ +	+ +
Disassembly effort	+	-	+	- -	-	-	+ +
Life span expectancy: 30 years	- -	+	-	+	-	+ +	+ +
Embodied carbon: *Total*	+ +	0	0	0	+	-	- -
Donor building (C1-C4)	+ +	0	0	-	0	+	- -
Receiving building (A1-A5)	+ +	0	0	0	+	- -	- -
Operational carbon	-	- -	+ +	0	+	0	0
Balance between operational and embodied	0	0	+	0	+ +	-	- -

Change in scenario

When looking at other applications of these strategies to the case study of the panels of Citibank London, it is figured that the two other scenarios could be differentiated. First, a scenario where the performance requirements are relatively high, which could be an office function. This would require extensive upgrading of the current panel configuration to reach these high-performance requirements. With the panel-based strategies, it is not possible to obtain such upgrades as seen in the options. With an application of strategy 3: panel re-manufacturing it would be possible to come close to the performance requirements. For this scenario strategies 4 and 5 would be more applicable. The use of components which are sufficient and add new materials to increase the performance. A second scenario could be one where the performance requirements are lower than the existing performance properties. In a greenhouse or a second skin configuration like 1 Triton Square, the panels could be fitted without upgrades. Strategies 1 and 2 would fit this scenario. The requirements of this scenario do not require extensive upgrade work. A last option that should be mentioned is leaving the original panels in their original location, which would imply strategy 0. For the Citibank case, the decision for dismantling and replacement has already been made, so currently this strategy is not possible anymore. However, as mentioned before the panels in the remaining floors of the building remain functioning. With limited intervention, this facade could perform sufficiently in its original location.

6.5. Conclusion Application

In this chapter, the strategies and methods developed prior were applied. The Citibank building, a high-rise building in London, was investigated through an imaginative scenario.

Through analysing the strategies and the scope of the donor building it was found that the direct reuse, refurbishment or re-manufacturing (Strategies 1, 2 and 3) of the panel offers promising benefits in applying these strategies. Regarding the scope of the donor building, the Citibank and the receiving building, five options were developed with varying interventions and refurbishment measures. Carbon calculations were done, which shows the potential to reduce both operational and embodied carbon impacts. Options 2 and 4 stood out due to their significant embodied carbon savings and performance. In option 2, the smaller compartments were replaced with new spandrel panels and in option 4 the spandrel zones were applied combined with an upgraded framing. almost 60 per cent of the material can be saved which results in a total embodied carbon saving of 45 per cent. Due to the refurbishment actions the U-value can be upgraded from $2.05W/m^2K$ to $1.8W/m^2K$ combining this with reducing the window-to-wall ratio, led to a reduction of operational carbon emissions, it has been found beneficial in balancing the two as well compared to a new facade. In option 4 not only the embodied carbon was reduced compared to the waste strategy (Strategy 7) as well but an aesthetic upgrade was also achieved. It was found that in option 4 55 per cent of the materials were saved and an overall reduction of 55 per cent in embodied carbon impact. In addition, similar to option 2 a reduction of the operational carbon was achieved due to a combination of reduced transparency and upgraded thermal performance. The balance between the operational and embodied carbon impact gives an impression of the potential of the options. In option 1, replacement of the glazing component, the embodied carbon was reduced by almost 50 per cent, however, due to limited replacement options of the glazing, following the available space in the framing, no improvement in the thermal performance was made. When balancing operational en embodied carbon it was found that no improvements were made. The carbon payback period, calculated for all the options compared to the base option, and the improvements based on carbon were found. This finding shows the significance of the application of circular strategies and the variety of options, where a recycling and waste strategy have a carbon payback period of 8.5 and 10 years and strategy 3 can obtain a carbon period between 3.2 and 3.7 years. The choice of the best option for a specific situation is highly dependent on decisions and wishes made by the client. When the estimated extension of the life expectancy of the glazing is not accepted, the glazing will need replacement and options 2 and 4 will not suffice. Lastly, the nature of the receiving project influences the strategy selection greatly. Boundaries are set by the donor building in possibilities, but the destination of the panel will further limit the options and possibilities.

7 Discussion

In the following chapter, the results of the research will be discussed. The main objective and research questions will be evaluated. Implications and limitations of the results will be regarded. The chapter is subdivided into the main research steps described in Section 1.4.

In this research 14 research questions have been developed with their main objective to aim at: *Diminishing waste in the construction industry by developing strategies to use aluminium facade elements circularly.* This objective has been reached by researching the current status in the industry combined with literature. Diminishing waste is achieved by using circular strategies for existing aluminium curtain wall facades.

7.1. Answering of the research questions

The research questions that were developed in this research have been answered in this section of the research. Starting with the main research question, followed by the sub-questions. These sub-questions have been divided into the steps described in Section 1.4

Main research question

What strategies can be developed to increase the circularity of unitised aluminium curtain wall facades? The study demonstrates through literature and interviews that various strategies can be found to enhance the circularity of unitised aluminium curtain wall facades, aiming to improve their sustainability, reusability and overall environmental impact. Existing circular frameworks have been used combining the characteristics of these facades to create a fitting framework for the panels. In addition, it was examined how circularity can be accounted for in a life cycle analysis. In an application the performance of these strategies has been assessed, considering both embodied and operation carbon. Eight potential strategies were developed and categorised into four main categories: refuse, panel-based strategies, component-based strategies and end-of-life strategies.

Literature and interviews

Which strategies for circularity currently exist in the construction industry? Two main frameworks have been found in the construction industry. The first is the value hill, where the process of manufacturing, assembly and retail in the pre-use phase is seen as adding value to the product or material, where the circular strategy reduce can be found. Next, is the use phase, during which the product or component reaches its maximum value. Lastly, the post-use is where the value of a product could be wasted by putting materials in the garbage. On this side of the hill, the value could be maintained with the strategies: Repair, refurbish re-manufactured and recycle. The concept of looking at the value of components and their value being wasted increases the incentive of circularity. A second framework was found, that describes a framework for circular design and construction by using four principles reduce, supply, synergies, and manage. Three of those pillars are decided to be used throughout the research while mentioning the limited applicability of synergies in the scope of this research. With reduce: prioritise regenerative resources and design for the future. Supply: Prioritise regenerative resources, use waste as a resource and design for the future. And lastly manage: rethink business model, design for the future and incorporate digital technology. Inspiration can be found in other industries than the built environment. In the machinery industry and the health technology industry, circular strategies have been successfully introduced.

How can circularity be accounted for in a life cycle analysis? To express the impact of building components a Life Cycle Analysis is applied. In this, the carbon impact is calculated throughout the life stages of a product, component or building. The stages are the product stage (A1-A3), construction stage (A4-A5), use stage (B1-B7), end-of-life stage (C1-C4) and beyond-the-life cycle stage (D). The last is an expectation of the benefits that could be achieved when the product is at the end of its life. A positive impact can be achieved by assuming the products go into recycling or are reused. This will always be an expectation. In the current calculation methods, this D stage can be subtracted from the carbon impact which does not give a transparent impact and can seem counter-intuitive. Therefore, a different method developed in this research was used. By not using the 'positive' impact method, but a avoided carbon method, a fair comparison can be made between strategies. Calculating the avoided carbon by not wasting products or not having to produce materials, gives a more fair and comparable result. Benefits are allocated to the projects involved. These two projects are defined as the donor project and the receiving project In the traditional calculation method, the benefits that can be achieved in the receiving project are often also accounted for in the donor project. This leads to accounting benefits twice or it not being feasible to use circular materials in a donor project. This method separates the benefits achieved by the two projects. The benefit of avoiding waste is accounted to the donor project, and the benefit of avoiding newly produced materials is accounted to the receiving project. This leads to a fair distribution of the benefits, an incentive for a receiving project to use secondary products and a clear comparison between strategies.

What are the main characteristics of unitised aluminium curtain wall facades? Similar to a building, a facade consists of layers; infills, framing, external elements and the connection to the back structures. These layers can be made up of different materials. For the unitised aluminium curtain wall facade the framing is made of aluminium. As an infill, it could be transparent, so a glazing type is placed inside the framing. or an opaque infill, which consists of a steel back plate, insulation and finishing. The connection to the back structure is made of a steel bracket which connects the panel to the main load-bearing structure. Next to that insulating materials with different properties can be found. External elements are extra elements added to create an appearance to the facade or provide shading. These components are connected in different ways. Mainly mechanically, by using bolts or clamping fixtures, glued, using sealants, or dry fixtures, often including gaskets. When looking at the weight and embodied carbon impact of these components, it was found that the aluminium extrusions, the glazing and the steel have the highest share. Including the connections, the aluminium extrusions, glazing, sealants and gaskets are the most impactfull components in a facade. Since the facade is the component that separates indoor spaces from outdoor elements, it needs to fulfil a variety of requirements, including structural, thermal, acoustic, safety, and aesthetic considerations, as well as ensuring the longevity of its components.

What is the life span of the materials in an aluminium curtain wall facade? According to the life span analysis, a curtain wall facade has a theoretical lifespan of 60 years. The life span of the different components is shown in Figure 7.1, where it can be noticed that the sealants, the finishing of the aluminium and the gaskets have the lowest expected life span. The life span of an insulated glazing panel is highly influenced by this sealant since the glazing in itself can exceed this. This sealant is therefore a bottleneck in the life span of a facade panel. In maintenance strategies, the replacement of the glazing is included, nevertheless, a large part of the value of the component is influenced by the sealant. Strategies are being developed in practice to upgrade the sealant in place or in a production facility. In the reference studies and examples from practice, it was concluded that some components can outlive this expected lifespan. Especially the coatings, when maintained properly and the sealant has been seen to outlive this expected life span. Despite the fact that the sealant and finishing are not major components, safety concerns may arise when they are not performing.

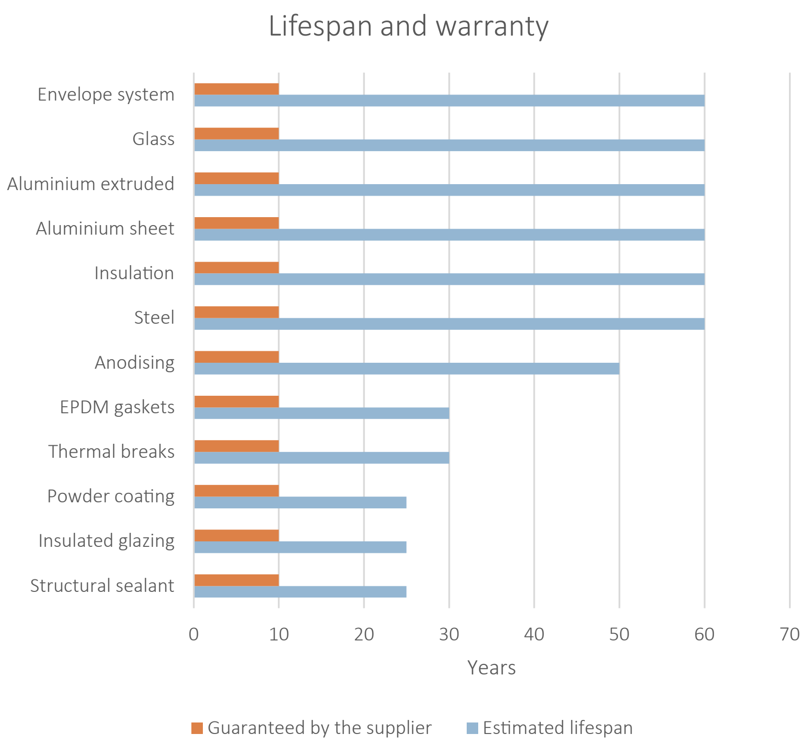


Figure 7.1: Guaranteed life span and estimated lifespan

How are the materials in an aluminium curtain wall facade recycled? In current practice, the take-make-waste strategy is often applied. Despite of that recycling strategies are being used increasingly. Aluminium extrusions and sheets are recycled into new elements of the same quality, the same holds for steel. For glass, this is still a challenge, because of coatings, sealants and impurities. Clear float glass has been recycled into new float glass, nevertheless, it is often not possible to obtain clear float glass from a construction site. The industry is evolving fast, and technologies are being developed to ensure high-value recycling of glazing. As for now, glass is still down-cycled into glass bottles and fibreglass insulation, the EPDM gaskets are also down-cycled. The demand for products with secondary content is increasing, in despite that the supply still cannot reach the demand. A decreased end-of-life impact can be obtained when recycling, as well as a decreased A1, raw material impact is included. Benefits can be achieved by ensuring materials get recycled and recycled materials are used.

Why could unitised curtain walls lose their original function? The reason for a facade to be replaced or dismantled has a direct consequence on the reuse potential. This gives an insight into the critical parameters of the characteristics of a facade. Factors that have been found are aesthetics, performance, legislative changes and safety concerns as reasons for facade replacement. Especially performance factors will play an increasing role, the heating and cooling demand of a building has a large influence on the operational costs and carbon of a building. Lastly, the cost aspect could have a decisive impact in a situation where a decision is to be made, When the costs of refurbishing or using reused elements exceed the costs of a new facade clients are still more likely to choose a new facade.

Reference Study

What circular strategies have been applied in the reference studies? In this research, four reference studies have been considered. Two of these are completed and two are still in the dismantling phase or looking for a donor building. Strategies that have been applied in the reference studies have been subdivided into the three pillars mentioned before. First, in the *reduce* pillar, the following main strategies have been found. Improving energy efficiency by strategically improving components, high-value recycling, reuse of products in the same location, reducing transportation movements by creating pop-up factories, component reuse in a different project, and design based on the parameters of an existing component. Next, the *supply* pillar, demountable connections have been used, performance requirements of the reused elements have been reduced, critical elements are replaced, visual inspection prior to dismantling, on and off-site testing and reuse of components. Then, at last, the *manage* pillar, the original specialist and drawings were involved, a reduced or no warranty was given, the design of the receiving project was adjusted to the parameters of the available materials, testing on the refurbished facade, status of the materials was documented and a consortium of stakeholders have been included.

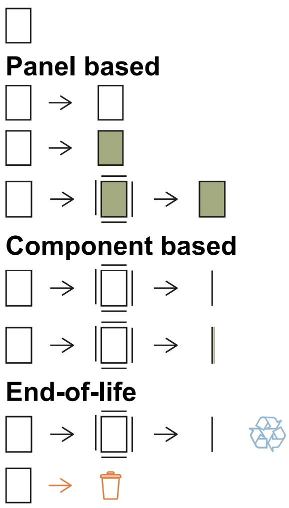
How were the environmental costs quantified in the reference studies? In most case studies, no carbon impact calculations have been executed. In the reference study of Koningskade and the Floriade, the savings have been expressed in kilograms saved and recycled material. For the case study 1 Triton Square, the carbon savings have been expressed by calculating the difference between constructing a completely new building and the carbon needed for the refurbishment. Nevertheless, no clear calculations have been found or given, thus the parameters for a new building are unknown. This method does show potential by expressing the carbon impact that was avoided by not having to construct a new construction.

What have been the pitfalls in the reference studies? Pitfalls have been identified in the two reference studies where no receiving building had been defined. The challenge lies in locating a client interested in incorporating these materials into their designs. This entails the requirement for a project that aligns with the characteristics of the donor materials, ensuring their quality remains suitable for use in a new project. Storage of donor materials can become a burden in the absence of a receiving project. Furthermore, even though the panels have been connected using bolted joints, the practical dismantling process has proven to be more intricate. Not only is the connection to the back structure complicated but the intermediate framing connection is as well. A key consideration involves the assessment of the residual value of reusable components. Due to time and external influences, the components can degrade in performance. This introduces uncertainties when estimating the enduring quality of these materials. Another crucial factor pertains to the associated costs of the reuse process. It raises the question of whether clients are willing to cover expenses linked to material reuse, storage, and transportation. Such costs have the potential to escalate, especially when the timing between the dismantling at the donor project does not align with the construction of the receiving project or even the design of a receiving project.

Findings/Strategy

What circular strategies can be formed from the information obtained in the previous steps? The knowledge from literature, interviews and observing reference studies, eight strategies have been defined. The strategies apply to the situation where a building owner makes the decision that their facade needs replacement, upgrading or removing. This project is now called the donor project which is at the supply pillar. Before components can go from the donor project to the receiving project, actions are undertaken, where the strategies come into play. Actions include transport, storage, waste and refurbishment or re-manufacturing works. "Secondly, the receiving project, which could be the same project, a new project where it will have the same function or a project where it will acquire a new function, whether in the built environment or elsewhere. Before a strategy can be chosen the original panel is analysed, and it is figured if a requirement match can be made. The list of strategies is given in Table 7.1.

Table 7.1: Strategies



Refuse	
	Strategy 0: In-place upgrade
Panel based	
	Strategy 1: Panel reuse
	Strategy 2: Panel refurbishment
	Strategy 3: Panel re-manufacturing
Component based	
	Strategy 4: Component reuse
	Strategy 5: Component refurbishment
End-of-life	
	Strategy 6: Recycling
	Strategy 7: Waste

What data is needed to give a fitted monetisation of the circular strategies? When monetising circular strategies in this research, the carbon emissions are calculated. Environmental impact data from the materials that are within a facade component are summed. This data is subdivided into modules. In a circular situation, this calculation has to be performed over two projects, the receiving project and the donor project. The general data that is needed is the amount of materials that are, wasted, recycled, reused and newly produced. Next, the carbon factor of the materials in different modules is multiplied by the amounts. Then the transportation emission factor is multiplied by the transportation kilometres travelled in the different phases. The impact associated with each module is shown in the lists below:

- Donor building:
  - C1: Dismantling impact needed for the components that are at the end of their life.
  - C2: Transportation of the end-of-life components to the end-of-life location.
  - C3: Impact generated by end-of-life treatments like recycling.
  - C4: Impact generated when elements are put into landfill.
- Receiving building:
  - A1: Impact related to the raw material extraction of the new materials needed.
  - A1: "Mining impact" of the reused materials. The dismantling impact.
  - A2: Transporting new materials to the production facility and the reused materials from the donor building to the production facility.
  - A3: Impact associated with the works done on the components and panel.
  - A4: Transport of the components to the receiving building.
  - A5: Energy associated with the assembly of the components to the receiving building.

Furthermore, certain assumptions should be taken into account. The energy required during production within the manufacturing facility lacks current data. Similarly, the emission of carbon during panel dismantling at the donor building is assumed to be equivalent to the carbon emitted during construction at the receiving building. Lastly, when integrating operational carbon into the calculations, assumptions related to this aspect would also be necessary.

What design improvements can be given to make current designs of aluminium curtain wall facades more circular? The general aim of this research is the circularity of existing aluminium curtain wall facades. By investigating both the research itself and the currently existing elements, potential bottlenecks in the current facade's reusability are identified. The first is the connection within a panel and the connection to the main load-bearing structure. Different adhesive fixtures are used for component connection, in particular structurally bonded elements. These sealants often play a critical role, yet their expected lifespan is shorter than that of the components they connect. These adhesive connections not only present challenges when it comes to interchanging components but also highlight the fact that, despite this being a known issue, replacement strategies are often not well thought out. When replacement strategies for these particular components are in place, the dismantling in a reuse situation becomes more convenient. A second connection that opposes challenges is the connection to the main load-bearing structure. Typically, facade panels are fixed using steel brackets and bolts to the top of the floor, often followed by the pouring of a top floor. When wanting to dismantle, it becomes difficult to reach the bolts beneath the concrete top floor. A different connection that poses difficulties is the inter-panel screw connections within the aluminium profiles. These screw ducts are expected to not withstand the dismantling process. Improving this connection could facilitate more refurbishment and re-manufacturing options.

Additionally, the unique designs made by Scheldebouw should be acknowledged. Introducing a degree of standardisation in the connections or profiles could enhance the reusability or upgrade possibilities of the components. Lastly, the skill of designing using existing materials could improve the practicality of using reused components or materials.

Application

How do the strategies perform when applying them in a case study? The application of the strategies has been done to the project Citibank and an imaginative receiving scenario. First, possible scenarios have been explored to grasp the application levels of each of the strategies. In an impact effort diagram, it was found that circular strategies 1 to 3 offer potential for reuse in Citibank. These strategies have been further explored in the scenario where the panel needs minor improvements in characteristics, design-wise it would suffice. Five design options have been made, including a basic level option where the bare minimum was improved. These options have been compared to end-of-life strategies 6 and 7.

What profits in environmental impacts can be achieved by implementing these strategies? By applying the strategies described earlier, carbon can be avoided. After the carbon estimation of the strategies and an analysis of the scenarios, an impact effort diagram was made. Including the boundary condition of the case study, it resulted in the conclusion that strategies 2: panel refurbishment and 3: panel re-manufacturing show the most potential in this analysis. In panel refurbishment (strategy 2) it was found that 83 per cent of upfront carbon and 99 per cent of waste can be avoided compared to the waste scenario (strategy 7). Although meeting the required performance standards is challenging, these carbon reductions could provide an additional incentive for the implementation of strategy 2. In strategy 3: panel re-manufacturing a variation op options have been designed. Between 28 and 62 per cent of upfront carbon was avoided and 60 to 21 per cent of waste could be avoided, compared to the waste scenario (strategy 7). When balancing these results with the operation carbon output, which takes into account the performance upgrades, options appear to be better performing than others. Replacing the IGUs was found to be not feasible in terms of carbon. Due to limitations in the framing system, not enough improvements have been made to make this option worthwhile. In spite of these carbon results, when the expected life span of the sealant in the glazing is not accepted, the glazing replacement is required. Compared to option 0, the carbon payback period was calculated, which shows the balanced impact of the strategies. A carbon payback period between 10 and 2.5 years was found, varying between the options.

7.2. Strategy discussion

According to the application and carbon estimates, the eight created strategies will be discussed in this section. The strategies were developed based on references in and outside of the facade industry. A general framework was made as well and technical possibilities and refurbishment options for the materials were created. Options are endless, and a selection was used in this research. Starting with strategy 0: In-place upgrade, in spite of this strategy not involving a donor building, it could reduce emissions by not replacing a well-performing facade. A different set of options could be possible to upgrade the panels in its place to upgrade the performance or life span. Next the component-based strategies. These are quite similar to each other and a grey area is present. Strategy 1: Panel reuse, is a strategy that is quite unlikely to happen when the function remains a facade. Glued and screwed connections are difficult to reuse without refurbishment. Strategy 2: Panel refurbishment has the most potential of the strategies. Minor replacements and upgrades can revive a used panel. Strategy 3, panel re-manufacturing, also holds significant potential. Compared to Strategy 2, it allows for more extensive upgrades and replacements. A classification was defined to make the distinction between strategies 2 and 3 clear. It was described that the distinction was made at the large components found. When one of those is dismantled it is classified as strategy 3. This classification does influence the subdivision of strategies. When components are dismantled in strategy 3, this component could be reused as well, this would imply two strategies can be combined. The component reuse strategies were found to be unsure in the application. In theory, this reuse could be promising, however, the risks and unknowns are significant. Strategy 4: Component reuse and strategy 5: Component refurbishment is similar despite the refurbishment actions in strategy 5. Refurbishment is most likely to be needed in a component reuse situation, strategies 4 and 5 could be combined. Strategy 6: Recycling was included in the strategies as an end-of-life strategy, however still seen as circular. In spite of recycling not being a focal point in this research, it was noticed that improvements in the recycling strategies can be made. Several initiatives are being made to increase the recycled content and high-value recycling. Recycling had a greater impact on the donor building than avoiding waste. The last strategy that was incorporated was strategy 7: Waste. This is not a circular or sustainable strategy, it was used to show the impact of such a strategy. The incorporation of the end-of-life strategies could be discussed, same as for strategy 0, there is no receiving building. For strategies 6 and 7 the life of the components ends. The strategies give general subdivision in strategies, for each individual project and situation a fitting strategy should be formed through careful research. Concluding, the strategies that show the most potential in reuse scenarios are strategies 0 2, and 3. Strategies 4 and 5 could become more interesting when industries and branches become more experienced in the reuse of components.

7.3. Implications

The strategies contribute to a broader field of sustainable construction and design, offering guidance for architects, engineers, policymakers, and facade producers looking to improve the environmental performance of facades. The new strategies are a development of the Value Hill and the 10R strategies, preserving material value and promoting circularity. It fills the gap of knowledge in existing circular frameworks. Giving a guideline for designing with existing components and elements. This research shows the development and application of circular strategies for existing unitised facades. It emphasises the benefits achieved in terms of carbon emissions which further proves the relevance of applying circular strategies.

7.4. Limitations

It is important to acknowledge the limitations of this research, because, in assumptions made towards the carbon calculations limitations were created towards the results. However, due to these assumptions, a conclusion could be made about the impact of these strategies. These assumptions influence the outcomes of these calculations and could change the conclusions made. These generalisations were made based on literature and knowledge from Scheldebouw, which are presented in the list below.

Assumptions regarding embodied carbon

- Data from Scheldebouw was obtained regarding electricity and gas use. This is actual data gained from the production facility and construction site. This data is limited to Scheldebouw.
- Construction impact is the same as the dismantling impact (A1=A5).
- Components that are not reused are put to waste, while recycling is an option as well
- No secondary content was accounted for when new materials were required. By using secondary content in new materials carbon can be further reduced.
- When new components or complete panels were needed, it was assumed that this would be the same as the original panel. When in reality components are discarded and new designs are made, different choices can lead to different impacts a materials. Which also influences the operational energy used in a building.

Assumptions regarding operational carbon

- Properties of the new facade in strategies 6 and 7 were assumed to be similar to the original facade. When designing a new facade, the properties that influence operational carbon will influence the outcome.
- The dimensions of the room were assumed to be three standard panels wide and 6 metres in depth. Changes in these parameters do influence the operational carbon outcome.
- In and outdoor temperatures were set at 10.8 and 21 degrees Celsius, which are average temperatures, these influence the transmission and ventilation losses which also influence the operational carbon.
- The number of persons in the room was estimated to be three persons. Changing the amount of persons changes the internal heat gain and the ventilation demand which consequently also changes the operational carbon.
- *Assumptions about the control room do not have an influence on the carbon payback period, since changes are the same for all options. This was found through iterations of the calculations of the carbon payback period.*

next are the technical limitations, dismantling, transporting and handling of vulnerable components. It is still uncertain whether a component can be dismantled as conveniently as found in theory. Limitations toward dismantling and handling are expected to be found when practically applying the strategies. The last limitation has been the decision towards the scenario in the Citibank case study. It was concluded that the receiving project has a significant impact on the choice of strategies, but in the absence of a receiving project, choosing strategies becomes more challenging. In the case study, a figurative scenario was designed to test the application of the strategies. It was found that finding this receiving project poses great risks and challenges for the application. However, showcasing options and possibilities helps with presenting possibilities and might inspire future clients.

8

Conclusion

This research provided valuable insight into improving the circularity of the facade industry, particularly the circularity of existing unitised aluminium curtain wall facades. This is to reduce landfill and recourse depletion while also retaining the value of the components as much as possible. Strategies have been developed that provide a framework for achieving a more sustainable and environmentally aware building and facade sector. Which were proven to be more beneficial in terms of carbon than traditional waste scenarios.

From circular frameworks currently existing in the construction industry and in other industries, the following insights can be taken. The value of materials and value retention is a driving force in the reuse of components. By implementing the three key pillars of reuse in the construction industry a basis for developing circular strategies has been made: reduce, supply and manage. To develop measurements that demonstrate circularity, a method of monetising circularity is required in addition to the framework. The life cycle assessment method does currently not give fair incorporation of carbon emissions in circular use.

Facades are a valuable component in a building, they protect the user from influences from the outside and play a significant role in safety strategies regarding fire. The facade has a large share in the overall building costs and influences the appearance of the building. The diverse range of properties that facades are required to satisfy introduces considerable risks and uncertainties in a reuse scenario. The facades produced by Scheldebouw are all one of a kind and are uniquely tailored to the wishes of the client and designers. Which makes creating strategies increasingly difficult and dependent on each project involved. Additionally, the unique framing types, connections and components increase the difficulty of reuse and replacement of components. By standardising components or connections, this could be increased. When a component is glued or connected to a part with a less life span, this directly influences the life span of the component. The theoretical life span of a component was found to differ from the practical life span, which increases the potential of these components. Additionally, possibilities for component refurbishing are expanding quickly, although for now, these are still expensive and risky. The costs and risks are likely to become less in the future after more research and a wider application.

In varying projects, circular strategies have been applied, from which the following lessons can be obtained. Four reference studies have given insight into strategies already applied. The requirements of the receiving project influence the decisions made in a reuse situation greatly. Projects without a known receiving project are left with endless possibilities, and finding a fitting donor building was found to be challenging. These projects have applied on and off-site testing, including destructive testing to estimate the remaining value and potential of the components. The predicted remaining service life of components was found to be less than the practical service life.

The strategies developed through this study address the challenges of the reuse of facade elements. By examining existing circular frameworks, analysing reference studies and considering the environmental impact, a wide set of strategies has been developed. Varying from refuse, panel, component and end-of-life based strategies. For the two projects involved, the donor and receiving project, challenges and risks are present. The main challenge is finding a suitable receiving project, with a client who is willing to accept a reduced warranty and reduced life span of the components. The challenge of measuring circularity has been partly solved by developing the avoided carbon method. The impact generated and avoided during reuse has been fairly distributed between the two involved projects. The use of the avoided carbon method, within the life cycle analysis, enhances transparency and offers a way to compare strategies.

Practical application of the developed framework and method within the context of Citibank has shown that the characteristics of the donor building are crucial in determining reuse boundaries. Specifically for Citibank, it was discovered that the panels still hold significant value, since the facade is only partly dismantled. Throughout various analyses, five options were created using the refurbishment and re-manufacture strategies. The choice of strategies and refurbishment interventions is greatly influenced by the requirements of the receiving building, and the estimated lifespan of the components impacts the extent of reuse. Additionally, various challenges including risks, related to storage, transport, costs and design, must be considered. By applying the strategies and creating multiple options, it was found that the overall carbon impact can be reduced in both the donor and the receiving building. This reduction was calculated using the avoided carbon method, which was developed as part of this research. This reduction was primarily achieved by decreasing the demand for raw materials, minimising waste, and in some options reducing operational losses. The options show an improvement in carbon impact compared to a traditional waste strategy. When using the refurbishment strategy, an overall carbon savings of 86 % can be achieved, with 99 % of the materials repurposed. In terms of performance, the facade performs 20 % worse than a new alternative. When opting for a re-manufacturing strategy, an overall saving of 49 % can be achieved, along with an overall material saving of 59 %. In this case, operational emissions have improved slightly compared to a new facade, mainly due to a reduction in transparency in the facade. However, bottlenecks have been identified in the reuse of glazing and its expected lifespan, particularly regarding the sealant and spacer components. When implementing a re-manufacturing strategy that includes glass replacement, 27 % of the total embodied carbon can still be saved, reducing waste impact at the receiving building by 21 % in the product and construction stage. This ensures a reduction in the risks associated with glazing while also allowing for the reuse of other components. Operational emissions are relatively similar to those of a new facade, primarily due to the limited upgrade possibilities due to the available space in the framing.

Considering incentives for the producers, despite the Dutch government's transformation agenda, the client is frequently the driver of the circularity incentive. Using carbon emissions as a driver for reuse strategies could supply this incentive. The strategies encourage a broader outlook on circular design and construction, offering a practical approach that could be adopted in the industry. The moment of decision influences the achievability and level of risks of the strategies. In conclusion, reusability is technically feasible and minimises waste and resource depletion in the construction industry. It has been proven to be more environmentally beneficial in terms of carbon emissions compared to traditional approaches, despite the risks and challenges in the sector.

9

Recommendations

The research has discovered recommendations for the future that could further improve circularity in both the facade and construction industries. This chapter is divided into two main topics. The first recommendation is to focus on improving the Life Cycle Assessment (LCA) method currently used. This will create a fair and accurate way to monetise the circular strategies and further indicate their relevancy. Secondly is the recommendation that involves the testing of existing facade elements and components. These tests would be able to estimate unknowns related to the remaining quality of components and the potential value of materials. Furthermore, testing helps in assessing the risks associated with circular strategies. Creating standardised testing protocols can enhance the reliability and feasibility of reuse in the facade industry.

9.1. Recommendations regarding monetising circularity

As found in this research, no clear and formally approved calculation method or code for fairly monetising circular strategies exists for now. The LCA method inadequately encompasses and rewards the benefits of reuse. The positive impact created in the D module of the LCA allows for misinterpretation and unfair distribution of benefits. Therefore, it's recommended to develop an approach that is an extension of the existing LCA method, with a monetising method that incorporates circular strategies to more accurately distribute the loads and the benefits of reuse over the two projects involved. In this research, a method was developed for comparing strategies, and further research into creating an approved calculation method or code is recommended. A new monetising method will lead to the ability to fairly compare circular strategies and create more incentive to incorporate these strategies for the parties involved. In addition, this helps policymakers to establish a code-based legal framework regarding the environmental impact of buildings and components. Comparable to the planned transition agenda is expected to stimulate companies to explore circular strategies, including a fair method of monetising, which gives an added method for stakeholders to demonstrate their impact.

9.2. Recommendations regarding the Citibank project

In the Citibank project, if dismantling goes according to plan, four panels will be shipped to the production facility of Scheldebouw in Middelburg to perform various testing on. Regarding those panels, a strategy has been described in Table 9.1. Evaluation of the possibilities and unknowns in the reuse and refurbishment of existing panels is aided by the chance to conduct experiments and put refurbishment plans into practice. For all the proposed actions the goal is to see the technical bottlenecks and possibilities in replacing various replacement strategies. In addition, it showcases the various possibilities with the panels to future clients.

Table 9.1: Recommended tests or actions with the Citibank facades

Goal	Method
Dismantling from the building (All panels)	
Examining the feasibility of disassembling entire panels from the original building is crucial. It's essential to evaluate potential damage and determine the feasibility of repair. In cases of extensive damage, consideration must be given to replacing components. What is the remaining quality of the panel and components after dismantling and transportation from the donor building to the production facility?	
1: Dismantling of the panel (Panel 1)	
Find out how far the element can be dismantled and establish the quality and usability of the remaining components. What are the possibilities with these components, until what level are the components still usable?	Using a method like the Hotspot method, bottlenecks in the dismantling for this panel specifically can be found. Adding to that the level of dismantling that is feasible for the connections in the panel can be found.
2: Base option (Option 0)	
Testing the properties of the panel after implementing minimal upgrade methods. Is it possible to create a panel which is wind and watertight?	Testing the panel for wind and water tightness can assess the functionality and level of upgrade of the original materials while replacing the EPDM gaskets
3: Glass replacement (Option 1)	
Replacement of the glazing, which was the design proposition in this option was found to not be beneficial in the upgrading of the performance of the panel. In other situations, this would be needed due to warranty or lifespan reasons. Next to that, the glazing component can be used for tests regarding the remaining life span of the glass and sealants.	Replacing the glazing would mean cutting out the existing structural bonding and rebonding the new glazing to the old framing. Tests should be performed on the new bearing capacity of the bonding. Also, the wind and water tightness can be tested to check the quality of the new sealant and glazing in combination with the old framing.
4: Spandrel application (Option 2)	
In this option, the two smaller compartments are replaced with a spandrel panel. Varying infills could be used to get a different look in the panel.	Same as for the previous testing situation, the wind and water tightness after the replacement of the compartments should be checked. By executing this option the visual upgrade can be shown.

9.3. Recommendations regarding testing and quality of components

In the field of facade production and construction, uncertainties and risks continue to play a significant role. The aluminium industry (PerpetuAl) and the glass industry (Saint-Gobain, AGC) are already testing and developing methods for the circular use of these materials and components. Additionally, other industries, including steel and concrete, are making substantial progress in practical reuse. To address the technical uncertainties and risks involved in reuse, conducting tests on materials and configurations is strongly recommended. Recommendations regarding these tests are shown in Table 9.2 and in Table 9.1. The goal of these tests is to estimate and reduce the risks, indicate unknowns, and research the potential found in reference projects regarding the estimated life span. In addition, an updated warranty could be more feasible when the remaining potential and quality of the components involved are known. In Table 9.2 the unknowns and risks regarding the components within a facade panel are shown, the involvement of the life span and connections described, and a proposition is made for a testing strategy.

Next, to test the quality of the components, a recommendation towards the current design of aluminium curtain wall facades can be made. Performing design iterations and testing towards configurations within the panels and components can improve their reusability of them. Upgrading this would make refurbishment in the future easier. In the application towards Citibank, it was found that the space available for IGUs is limiting in terms of upgraded performance. Designing the framing with this in mind can create the opportunity to increase the performance of the glazing. Another option is looking into other types of glazing, like vacuum glazing, which requires less space than double or triple-glazed units. Within these glazed units another bottleneck lies, the spacers and sealants. Developing an IGU design which uses different sealants which have a longer life span, or are more convenient to replace increased refurbishment options in the future. Sealants in general are a large bottleneck inside the facade design. They have a relatively low share in weight, nevertheless, they have a crucial function within a facade. Reducing the use of sealants in facade design reduces the risk of condensation within the panels and eliminates a component which is difficult to replace. Especially in structurally glazed components, this becomes an issue. It is therefore recommended to reduce the use of sealants or create methods for replacing and upgrading which could mean creating a debonding strategy. Mechanical connections are more favourable for future reuse and refurbishment.

Table 9.2: Recommended tests and research for the components involved

Risk	**Lifespan**	**Connection**	**Method**
Thermal break			
Due to the connection type and the ageing, when assuming the lowest life span, this component is a bottleneck in the expected life span of the component.	The expected life span of this component is 30 years, compared to an expected life span of 60 years for the framing	The thermal break is permanently connected between the two parts of the framing.	Further research in the expected lifespan of the thermal break. Can this component become replaceable? Gives an added opportunity to increase space in the framing for upgraded glazing.
Powder coating			
The visual appearance might deteriorate as well as the protection of the aluminium, which can cause corrosion of the aluminium. Recoating is possible, however, it increases effort.	The expected life span of the powder coating is 25 years compared to the expected life span of the framing of 60 years	The coating is attached to the surface of the aluminium, which is difficult to remove	Various tests can be done to test the feasibility of decoating and recoating of changing the coating. Last, anodising does have a better impact regarding the expected life span. Is anodising a more sustainable option? The actual life span of the powder coating was seen to exceed its expected lifespan, further research can be done towards this.
Insulated glazing			
Reduced performance of the glazing due to leakage of the gas or condensation inside the cavity. Additionally, glazing is prone to breakage and delamination	The glazing panes have an expected life of 60 years, in spite of that have the sealant, and spacers a life span of 25 years. The potential of the glazing is significantly reduced, which has a large share in the overall weight and impact of a panel.	The glazing panes are connected around the edge by sealant and kept apart by spacers, containing desiccant and sealants. A cavity between the panes can be filled with gas, and coatings or foils can be applied to the glazing. The sealant acts as a moisture barrier and contains the gas.	Tests with upgraded glazing have already been done by various companies. Large-scale applications could be tested. Testing spacers can indicate how much potential is present for extending their expected remaining life span
Structural sealant			
This sealant keeps, in a structurally glazed element, the glazing in place. This sealant thus has a crucial function. In replacing this sealant the risk of the bonding on the structural sealant arises.	The expected life span of the structural sealant in a glazed component has an expected life span of 25 years, compared to the envelope system and the framing of 60 years	This sealant structurally bonds the glazing to the aluminium framing. It is possible to detach the components when structurally bonded, however, this is labour and time-intensive.	Testing the bonding of structural sealant on prior removed sealant. Previous tests have been done already in dismantling when this connection is used. From references, it was also found that this component can exceed its expected lifespan. Testing of the aged bonding. Last the application of a structural sealant is a bottleneck in reuse
EPDM gaskets			
Gaskets are crucial in the wind and water tightness in the panel and between panels	Gaskets have a reduced expected life span compared to the total expected life span of the envelope system	It was found that these gaskets are relatively easy to replace	A test regarding the wind and water tightness can assess the performance of these gaskets in age and after replacement.

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A

Contacts

Table A.1: List of Contacts

Contact nr.	Role of contact	Type of correspondence
1	Sustainability manager Scheldebouw	Online conversation, conversation face-to-face
2	Tender leader Scheldebouw	Online conversation, face-to-face conversation
3	Construction manager Permasteelisa (UK), Installation Manager Permasteelisa (UK), Senior Installation Manager Permasteelisa (UK)	Face-to-Face interview E-mail conversation
4	Senior Engineer Arup UK	Face-to-Face interview
5	Installation, service and maintenance manager Scheldebouw	Face-to-Face interview
6	Design and Engineering Scheldebouw	Face-to-Face interview
7	Post Doctoral Researcher, TU Delft	Face-to-Face conversation
8	Key Account Director, Permasteelisa UK	Online conversation
9	Manager educations VMRG	Online conversation
10	Technical Advisory service manager, AGC Glass Europe	e-mail interview
11	Head of Major Projects, Saint Gobain	e-mail interview
12	Technical advisor ION	Online conversation
13	PerpetuAL VMRG	Closing meeting
14	Tender team Scheldebouw, BLDG.SYSTEMS	Circularity sprint workshop

B

LCA method

In order to put a value to the impact of a strategy and to be able to make a comparison. A life cycle impact analysis can be made. In this appendix, the calculation method will be evaluated and defined. Also, some generic data sets will be given. Before starting with the calculations, a general description of the product should be given. So the name of the project, where it is located, and what is included like fixings or fire stops. And the size and total weight. A general description of the materials within the facade. And a short description of the assumed processes involved in the component and assumptions about the component. In this appendix, a standard calculation method for a component is given. Specifications on the approach when circular strategies come into play will be described in Chapter 2

At the company, the calculations regarding embodied carbon are done using the program Rethink. However, mainly the impacts of life cycle stage A are used in communications with clients. In this research, a combination of Rethink and Excel calculations is used. Because the End of life scenario's are hard to program in Rethink

B.1. Method

When calculating the impact of the scenarios a step-by-step method will be used. The method used has been a combined effort of different research done by Hartwell and Overend, 2020, CWCT, 2022a and The Institution of Structural Engineers, 2023. These three research both describe a similar way of calculating the impact. Hartwell had developed a structured manner in order to take into account End of Life scenarios which is of relevance to this research.

To start with calculating the carbon impact the weight of all the materials that were used should be calculated. This can be done by getting the surface area from various drawing software and multiplying this with the length that was used, which frequently is the size of the panel. This gives the volume of the elements that are used. in Equation B.1 the calculation of the kilograms can be seen. ρ is the density of the material and V is the volume of the element.

$$Q = V \times \rho \tag{B.1}$$

B.1.1. Initial impact (Module A)

In order to compare the results even further the initial impact of the facade can be calculated by executing the calculations needed for the first life cycle stage. Which is A1 to A5. In this section, the equations needed for this will be given.

A1: Raw materials supply

As mentioned before the amounts of the different materials have been given in kilograms. In order to find the impact of the raw materials the kilograms of each material are multiplied by the impact factor of the material. This is shown in Equation B.2.

$$EC_{A1} = Q \times ECF_{A1} \tag{B.2}$$

A2: Transport to manufacture

In this stage, the transport impact from the supplier to the production facility of the manufacturer is calculated. This thus depends on the location of the supplier, the mode of transport and the amount of material. For Scheldebouw the average for every material has been developed. This has been done by looking at the most used suppliers over the years. For some materials, this will be shown in Table B.1. The calculation for a material is shown in Equation B.3.

$$EC_{A2} = Q \times ECF_{A2} \tag{B.3}$$

$$ECF_{A2} = \sum_{mode} TD_{mode} \times TEF_{mode} \tag{B.4}$$

Table B.1: Average transport distance, data from Scheldebouw

Supplier (typical)	Transport Conveyance 1	Distance 1 [km]
Plastic Packaging	Lorry (Truck), unspecified (default) | market group for (GLO)	0.75
Wood packaging	Lorry (Truck), unspecified (default) | market group for (GLO)	7.4
Glazing	Lorry (Truck), unspecified (default) | market group for (GLO)	1000
Aluminium profiles	Lorry (Truck), unspecified (default) | market group for (GLO)	877
Aluminium profiles	Lorry (Truck), unspecified (default) | market group for (GLO)	877
Aluminium profiles	Lorry (Truck), unspecified (default) | market group for (GLO)	877
Aluminium sheets	Lorry (Truck), unspecified (default) | market group for (GLO)	372
Rockwool	Lorry (Truck), unspecified (default) | market group for (GLO)	199
Steel sheets	Lorry (Truck), unspecified (default) | market group for (GLO)	161
Steel bracket	Lorry (Truck), unspecified (default) | market group for (GLO)	206
EPDM gaskets	Lorry (Truck), unspecified (default) | market group for (GLO)	390
Fasteners	Lorry (Truck), unspecified (default) | market group for (GLO)	156
Sealant	Lorry (Truck), unspecified (default) | market group for (GLO)	104

A3: Production Process

At this stage, the energy consumption during the process is accounted for. For this also an average of energy use per m^2 has been calculated over the years. In Table B.2 the average values are shown.

Table B.2: Average energy consumption, data from Scheldebouw

Description	Environmental profile	Amount per m^2 facade
Electricity	Electricity (NL) - low voltage	33.65 kWh
Fossil fuel gas	Gas, natural gas	1.347 m^3

Also in this stage is the production waste. The production waste is based on wastage percentages, also generated by averages calculated over the years:

- Materials without machining at Scheldebouw: 3 per cent
- Gaskets, aluminium profiles and thermal breaks: 15 per cent
- Sealant: 50 per cent

The waste that is caused by the production process and the end-of-life stage is also concluded in this stage.

Next to the waste and electricity also packaging materials and cleaning is within this stage. Just as the other elements mentioned before also an average has been calculated. The data is shown in Table B.3

Table B.3: Average manufacturing amounts, data from Scheldebouw

Description	Environmental profile	Amount per m^2 facade
Plastic packaging	Polyethylene, low-density (LDPE), packaging film / foil | production (EU)	0.690 kg
Wooden packaging	EUR-flat pallet | production (EU) per kg	2.052 kg
Primer	Isopropanol {RER}| production | Cut-off, U	0.069 kg
Cleaner	Non-ionic surfactant, fatty acid derivate | production (GLO)	0.015 kg

A4: Transport
Most of the time phases A1 to A3 are the most convenient to calculate and also contain the biggest impact of all the stages. In the next stage, the transport distance of the component from the manufacturer to the construction site is accounted for. The calculation of this stage is similar to the calculation of A2. The calculation is shown in Equation B.5

$$EC_{A4} = Q \times ECF_{A4} \tag{B.5}$$

$$ECF_{A4} = \sum_{mode} TD_{mode} \times TEF_{mode} \tag{B.6}$$

A5: Construction
During construction, energy is used to lift and construct the elements. For the goal of this research an estimation over the year is taken, the values are shown in Table B.4.

Table B.4: Average construction energy, data from Scheldebouw

Description	Environmental profile	Amount per m^2 facade
Site equipment	Electricity (GB) - low voltage (max 1kV)	0.37 kWh

The waste that is generated during this stage will be also accounted for in this stage. B Scheldebouw an assumption of 3 per cent is made. Also, the needed new materials and end-of-life scenarios for this waste are accounted for in this stage. Also, the packaging material will be put to waste in this stage. The end-of-life impact will also be included in this stage.

B.1.2. Use stage (Module B)

B4: Replacement
When the referenced service life of the separate components is less than the service life of the complete component. In its lifetime replacement should be accounted for. The number of repair cycles is calculated by dividing the Referenced service life of the complete component by the Referenced service life of the part. This will then be again multiplied by the A1to A5 impact and the C impact. To account for the new product, manufacturing, site works, and end-of-life scenarios.

B5: Refurbishment
Refurbishment is seen as a circular strategy and the approach will thus be covered in Chapter 2.

B.1.3. Operational carbon

The operational carbon that can be accounted for in the facade has to do with energy losses and gains of a room. The energy demand of a room can be calculated by taking into account various parameters in a room. Parameters not influenced by the facade are assumed for this research. The energy demand for space heating and cooling is calculated by four main energy transfer processes: *Transmission, Ventilation and Infiltration, solar gains and Internal heat gains*. An energy balance is made by summing the four energy transfer processes, then the heating or cooling demand can be obtained (NTA-8800:2023-nl, 2020).

$$Q_{tr} = U \times A \times (T_o - T_i) \tag{B.7}$$

$$Q_{vent+inf} = ((1-\eta)m_v - m_i) \times C_p(T_o - T_i) \tag{B.8}$$
$$m_v = \rho \times V = (V_p \times N_{people}\rho_{air})/3600 \tag{B.9}$$
$$m_i = (ACH \times V_{room})/3600 \tag{B.10}$$

$$Q_{sol} = f \times g_{shade} \times g_{glass} \times A_{window} \times P_sol \tag{B.11}$$

$$Q_{int} = N_{people} \times q_{people} + q_{lighting} \times A_{floor} + q_{appliances} \times A_{floor} \tag{B.12}$$

By calculating the sum of the transfer processes the heating or cooling demand over an hour can be calculated. This is shown in Equation B.13, where the sum of equations B.7, B.8, B.11 and B.12 is taken. When summing this for all 8766 hours in a day the energy demand can be calculated. By multiplying this by the carbon intensity factor for electricity $0.233kgCO_2e/kWh$ the carbon impact of the facade can be estimated. In the calculation of the embodied carbon of a building also the electricity demand and hot tap water demand is taken into account. This however is not influenced by the facade in itself. Last, to generalize this outcome it is divided by the area of the facade and floor area of the room.

$$Q_{year} = (Q_{tr} + Q_{vent+inf} + Q_{sol} + Q_{int})/1000 \tag{B.13}$$

Carbon payback period
To give a comparison between scenarios the carbon payback period can be calculated to incorporate the balance between embodied and operational carbon.

$$\delta_{EC} = EC_B - EC_A \tag{B.14}$$

$$\delta_{OC} = OC_B - OC_b \tag{B.15}$$
$$CPP = \delta_{EC}/\delta_{OC} \tag{B.16}$$

B.1.4. End-of-Life

C1 Demolition and deconstruction (Module C)
In Equation B.17, Equation B.18 and Equation B.21 the energy that is needed for the processes that are involved in demolition and disassembling. Where Q is the weight of the material and RC is the recycling coefficient, DiC is the Disassembly coefficient and DeC is the Demolition coefficient. The value of the demolition and disassembly coefficient will be the same as the coefficients used in the A5 stage

$$EC_{Demolition} = Q_{Demolition} \times DeC \tag{B.17}$$

$$EC_{Disassembly} = Q_{Dissassembly} \times DiC \tag{B.18}$$

The total impact of the end-of-life stage processes is the sum of the equations above for all the materials. The total gives the energy and/or carbon that is needed to perform the different end-of-life scenarios.

C2 Transportation
With Equation B.19 the environmental impact made by transportation can be calculated. This is for both materials, components and systems. The calculation method is the same as A2 and A4 In this equation Q is the weight, TD is the transportation distance, and TEF is the Transportation emission factor.

$$EC_{Transport} = Q_{EoL} \times TD \times TEF \tag{B.19}$$

The total impact of the transportation made at the End-Of-Life scenario is calculated by summing up all the modes of transport. T

C3 and C4 Waste and disposal

With Equation B.20 the impact that is caused by disposing of and landfilling the environment with a specific material. Q is the weight of the element and WC is the waste coefficient. RC is the impact connected to the recycling of the material.

$$EC_{Waste} = Q_{Waste} \times WC \tag{B.20}$$

$$EC_{Recycle} = Q_{Recycle} \times RC \tag{B.21}$$

The waste coefficient or waste processing and disposal factor could be estimated to be around 0.013 $kgCO_2e/kg$ waste. This will only be used whenever there is no information available about the C3 and C4 life cycle stages. The total impact is then calculated by Equation B.22.

$$EC_{Waste-total} = \sum_{i=1}^{n} EC_{waste,i} + \sum_{i=1}^{n} EC_{Recycle,i} \tag{B.22}$$

Where n is the total amount of components or materials in the Unit. [$i = 1, 2, 3$]

B.1.5. Beyond the life span (Module D)

As described in Chapter 2 stage D is an estimation of the scenarios that could happen with the products when not put to waste. However, this can not be accounted for the total embodied impact of the project. The calculation done in this stage is split up into three main parts. reuse, Re-cycle and Incineration. First the reuse scenario. The savings that can be achieved are the impact of a similar new product. The calculation is shown in Equation B.23. Next the re-cycle scenario, For this the savings are the extraction of raw materials and the energy needed to recycle. This is combined with an embodied carbon factor for recycling. The calculation in is shown in Equation B.24

D reuse/Recycle

$$EC_{reuse} = Q_{reuse} \times ECF_{A1-A3} \tag{B.23}$$

$$EC_{Recycle} = Q_{Recycle} \times ECF_{recycling} \tag{B.24}$$

With Equation B.25 the process of heat recovery, which can be converted into usable energy, heat or combined heat and power can be calculated. The calculated amount is the energy that is saved by executing this strategy. In this formula, Q is the weight gain and IC is the Incineration coefficient. Incineration is a waste treatment where combustion is used.

$$EC_{Incineration} = Q_{Incineration} \times ECF_{Incineration} \tag{B.25}$$

Nomenclature

η	Efficiency of heat recovery	-
ACH	Air change per hour	-
A	Surface area of the facade	m^2
A_{floor}	Surface area of the room	m^2
A_{window}	Surface of the window	m^2
CPP	Carbon Payback Period	-
C_p	Specific heat of air	1000J/kgK
DeC	Demolition Coefficient	-
DiC	Disassembly Coefficient	-
ECF	Embodied carbon factor	-
EC	Embodied carbon	$kgCO_2e$
EDC	Energy Density coefficient	-
GIA	Gross internal area	m^2
IC	Incineration coefficient	-
N_{people}	Number of people in the room	-
OC	Operational carbon	$kgCO_2$
P_{sol}	Global solar radiation on window	W/m^2
Q	Quantity of a material	kg
Q_{int}	Internal heat gains due to people, appliances and lighting	W
Q_{sol}	Solar heat gain	W
Q_{tr}	Heat transmission through the facade	W
$Q_{vent+inf}$	Ventilation and infiltration heat transfer	W
Q_{year}	Heating or cooling demand for an hour	kW
RC	Recycling coefficient	-
TD	Transportation distance	km
TEF	Transportation emission factor	-
T_i	Inside temperature	K
T_o	Outside temperature	K
U	Heat transfer coefficient	W/m^2K
V	Volume	m^3
V_p	Flow rate per person	36m^3/h
WC	Waste Coefficient	-
ρ	Density	kg/m^3
ρ_{air}	Density of air	1.2kg/m^3
f	Reduction factor for heavy buildings	-

g_{glas}	Solar factor of the glazing	-
g_{shade}	Solar factor of the solar blinds	-
m_i	Mass flow rate of infiltration, air	kg/s
m_v	Mass flow rate of ventilation	kg/s
$q_{appliances}$	Appliances power	8W/m^2
$q_{lighting}$	Light power	25W/m^2
q_{people}	Heat gain per person	117W/m^2

C
Facades analyse

To get a general knowledge about the principles of this facade are analysed based on their characteristics. Firstly a general analysis of the principle of the facade. Next, the materials that are within the facade are distinguished. In addition, exploratory LCA calculations will be executed for the facades mainly for life cycle stages A1-A3 to gain knowledge about the distribution of materials and their impact on the facades. Lastly, documentation is searched about the current state of the facade and whether maintenance has been carried out during recent years.

Figure C.1: Legend analyses

C.1. Ichtus Rotterdam

Figure C.2: Image of Ichtus Rotterdam

Table C.1: Properties of Ichtus Rotterdam

Architect	EEA (Erick van Egeraat)
Location	Rotterdam
Project Realisation	1999-2000
Project Design	
Address	Posthumalaan 90, Rotterdam
Facade type	Climate facade, unitised facade
Building type	Educational building

Facade principle

The Ichtus building from Rotterdam is an educational building. This building as can be seen in Figure C.2 exists of an almost complete transparent facade with horizontal fins attached to the building. From the drawings, it was found that three different types of facade principles were applied. All three exist out of floor-spanning panels made of aluminium framing with glazed panels. The first type is a unitised curtain wall system, the second is a double-skin facade using a curtain wall system on the outside which is placed in front of the floors, and the second skin is placed in between the floors. Lastly a rain-screen facade, this facade does provide a wind and water protection layer, however, the facade does not provide a thermal separation.

When looking at the detailing of the framing 4 different connections can be found. This can be seen in Figure C.3. Number one is the structural sealant. This sealant has been tested for 25 years So this sealant should be either replaced or inspected and tested. For the second seal, the same holds as for the first. Thirdly a weather seal is placed, this is used when no outer framing is visible. This sealant should be inspected as well and replaced when the performance is not sufficient anymore. Lastly, number four is butyl with a desiccant (droogmiddel), Both of these are also tested to perform for 25 years. In some places it was found that this seal was not applied well, this caused the inside of the glazing to form condensation and moisture to act up inside the cavity.

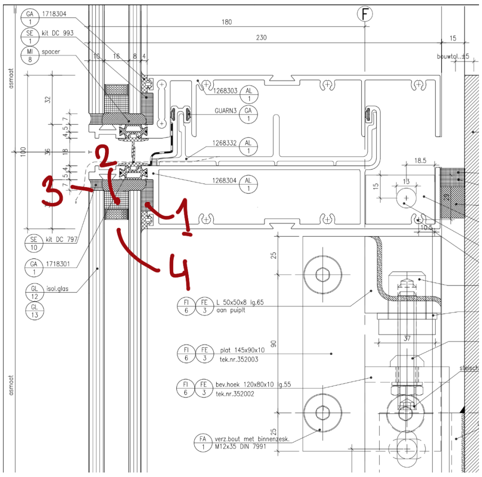
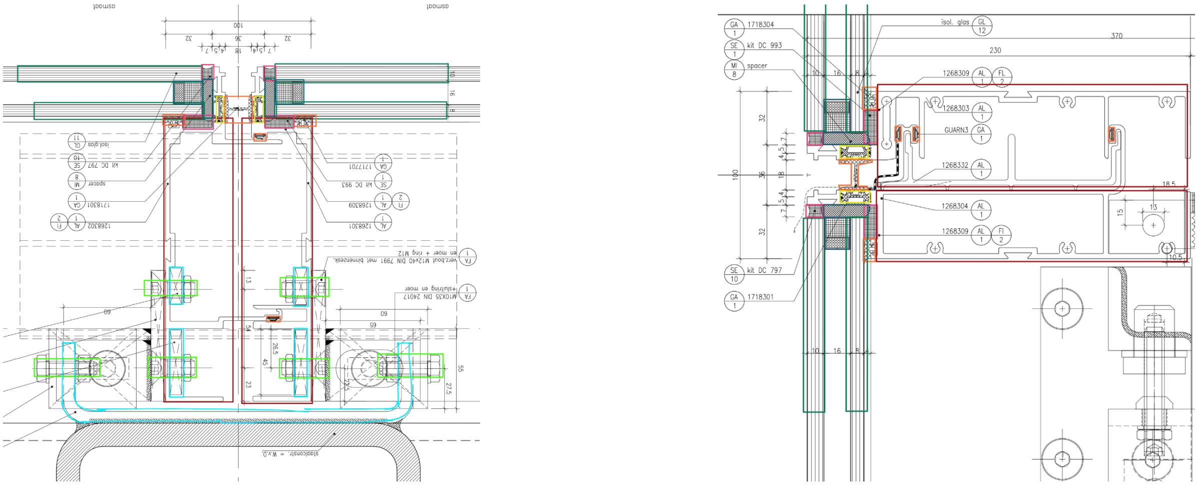


Figure C.3: The different sealants in the detail

Materials

In Figure C.4 The different materials in the unitised system are again highlighted. A split between the framing can be seen which indicates this system is a unitised system. No outside framing is used to get a more transparent look. Other steel plates in connection to the main load-bearing structures are used together with nuts and bolts. The climate facade uses generally the same framing.



(a) Horizontal detail

(b) Vertical detail

Figure C.4: Analysis of materials of Ichtus

However, a second leaf of glazing is connected to the load-bearing structure on the inside of the facade. Also, sun shading is placed within this cavity. This is shown in Figure C.5. In this image also the horizontal fins that were used can be seen in this detail.

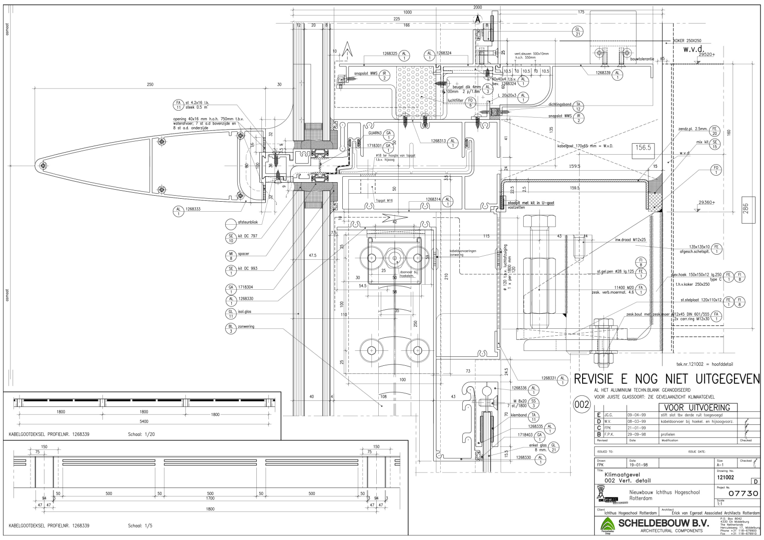


Figure C.5: Detail of the double skin facade of Ichtus

Current state

The building is currently over 20 years old. Over its lifetime research has been done on the quality and performance of the facade. Also, renovation actions are planned upon happening. It is stated that there have been maintenance actions in the past couple of years. The first research was done in 2016 the relevant information will be summarized. Problems were found with the glazing, the facade elements, silicone, gaskets, fins, glass clamps and insulation. Most of the damages or shortcomings are due to the design and construction, others due to wear and tear or influences from nature, so it is difficult to conclude which findings are due to the age and which are due to actions that were made in the design and construction stage. The repair actions that were found then are the Replacement of the glazing, renewing sealants, replacing the gaskets, renewing the fins and improving their connectors, adding glass clamps and fastening, filling the insulation seams and cleaning the panels.

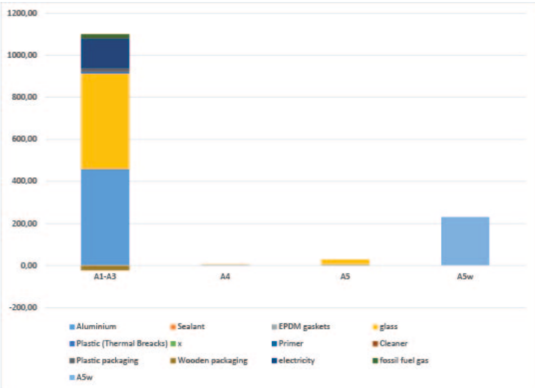
In 2022 new scenarios were made for the facade of the Ichtus building. First a summary of the current problem statementsthat could be caused due to the age of the building. Dome other defects were found, but they are due to some design issues, they will not be mentioned here.

- Fins; not constructed for thermal expansion, outdated/weathered and partly incomplete

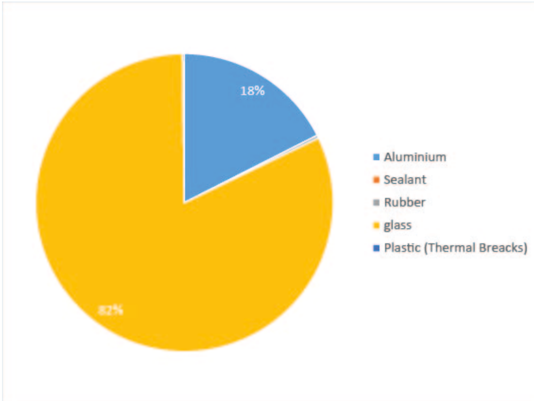
- U-value of the insulated glazing units; due to delamination of the insulation value has decreased significantly.
- Cracks and damages to the insulated glazing units, leaking glazing

LCA calculation

Prelimary LCA calculations have been made for this project. The calculations are shown in a couple of figures. In Figure C.6a the distribution of the impact in life cycle stage A is shown. As can be concluded s that the raw material extraction of the glazing and the aluminium have the biggest share. Also when looking at Figure C.6b, the distribution of the weight of the materials is shown. The glazing contributes over 80 percent of the total weight. Comparing this with the impact the conclusion can be made that aluminium has the biggest impact on the embodied carbon of Ichtus. The glazing influences the embodied carbon hugely as well.



(a) Distribution of Carbon emissions of life cycle stage A (Of Ichthus - Rotterdam eventually should become an average of analyzed projects



(b) Distribution of the weight of the elements in the Ichtus facade panel

Figure C.6: Analysis of materials of Ichtus

C.2. Amsterdam Passenger Terminal

Figure C.7: Image of APT

Table C.2: Properties of APT

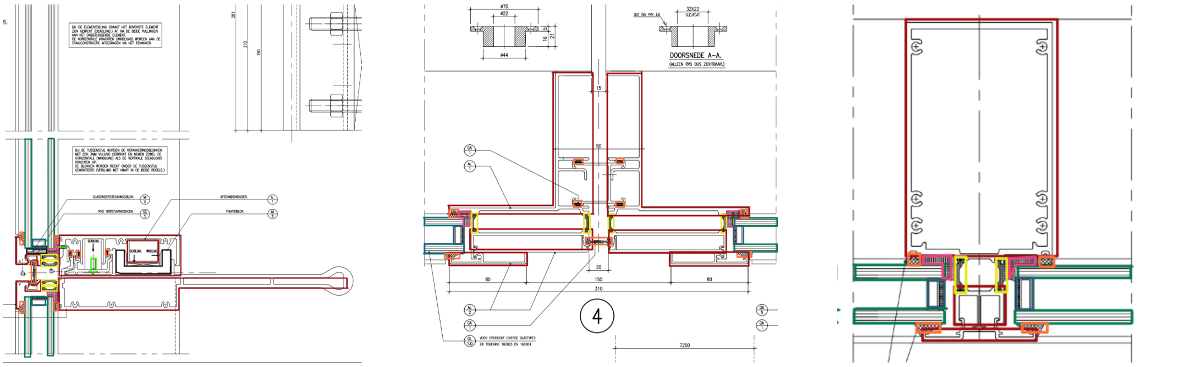
Architect	HOK, Londen
Location	Amsterdam
Project Realisation	2000
Project Design	1996
Address	Piet Heinkade 27, Amsterdam, The Netherlands
Facade type	unitised facade system
Building type	Cruise terminal/ event location

Facade principle

The facade of the Amsterdam Passenger Terminal exists out of fully transparent unitised panels. The front and back facades are straight facades however the roof and side facades are curved. These facades are left out of this analysing. The dimensions of the elements are 7.2m in width and 3.0m in height. This means these facades have a big dimension. The facade is mainly supported by a steel structure on the back side of the facade. As seen in the detail in Figure C.8a the framing has some reinforcement on the back to increase the moment of inertia and so the frames are able to carry over the wind load and won't deform too much. In some locations, these supports are also the connection to the main structure.

Materials

The materials in this facade are similar to the previous facades. The facade mainly consists of double glazing which is held in place by aluminium frames. In order to make the facade wind and watertight, gaskets and insulators are used.



(a) Vertical detail **(b)** Horizontal detail at panel intersection **(c)** Horizontal detail at mullion

Figure C.8: Analysis of materials Hoftoren

C.3. Hoftoren The Hague

Figure C.9: Image of The Hoftoren

Table C.3: Properties of Hoftoren

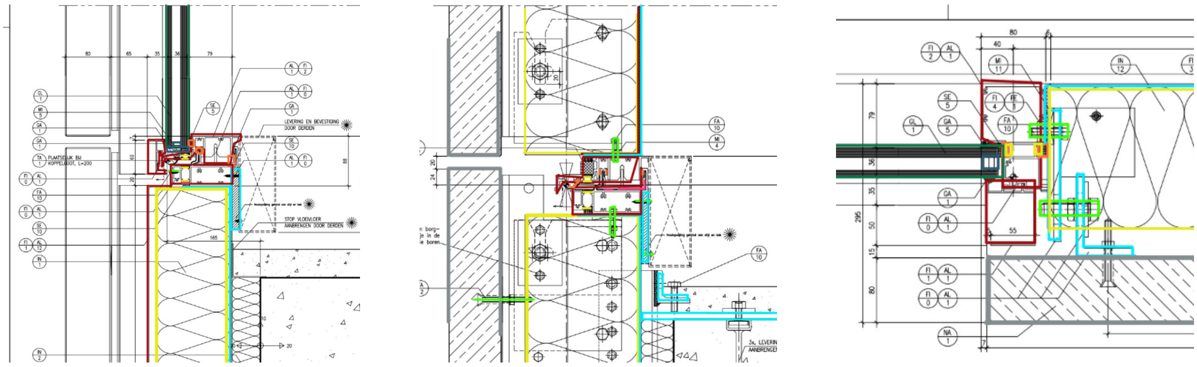
Architect	Kohn Pedersen Fox
Location	The Hague
Project Realisation	2003
Project Design	1997
Address	Rijnstraat 50, The Hague, The Netherlands
Facade type	unitised panels with a concrete finishing
Building type	Office, government building

Facade principle

The facade of the Hoftoren exists out of various panels. These panels consist of a configuration of transparent and opaque parts. The opaque parts are insulated with concrete finishing connected with bolts. The back plate is made out of steel sheets. This can be seen in the details in Figure C.8. The elements have a width of 1.8m and a height of 3.4m. In the details, it can be clearly seen that these panels are connected to the top of the floor with steel connection angles.

Materials

Due to the design also some concrete elements are included in the design. Same as more steel sheeting for the insulation. Still a split in the aluminium framing can be seen in order to connect the different panels. Less glazing is used in this case.



(a) Vertical detail with glazing **(b)** Vertical detail, opaque **(c)** Horizontal detail

Figure C.10: Analysis of materials Hoftoren

C.4. Concluding

The unitised system is always framed with mullions and transoms. Two systems were found, in a ”Female-male” system where both vertical profiles are different and slide into each other. The second framing type is where the framing on the panel interface is the same. The connection between the panels is made with insulators and gaskets. The joints allow for differential movements due to dead loads of the system itself or movements from the structure. Also, thermal expansion due to temperature differences can be taken up by the framing. gaskets are used for this, these ensure the air and water tightness of the facade. The gaskets and sealant are also used to hold in place the glazing units. The glazing makes up a large part of all of the facades. The insulated glazing units are kept in place in two main manners: Structurally glazed or dry glazed. Structurally glazed can be seen in the project of Ichtus. The glazing is structurally bonded with a sealant to the aluminium framing. In some cases, the glazing is next to the sealant mechanically supported by extra elements added to the framing. Dry glazed means that the glazing is put in from the outside and kept in place by an aluminium profile on the outside. This element is kept in place by strips of EPDM gaskets. The gaskets on the inside of the glazing ensure water tightness. The aluminium profiles are connected by insulators which keep the thermal line intact. A third special case was mentioned by a worker, which is glazing from the inside. However, this is not applied that often. Lastly, additional material is added for aesthetic purposes. Like concrete or Sheet aluminium.// A concluding list of the materials that are present in the facade system will be given below.

- Aluminium (Extruded/Sheet)
- Steel
- Thermal breaks
- Insulation
- EPDM gaskets
- Glazing
- Sealant
- etc.

When looking at the status of the projects analysed in this section and the information obtained from workers within Scheldebouw. The conclusion can be made that aluminium will not wear over the years. And remains performing. The glazing units are fragile within the component. They are prone to breakage and the sealant is shown to cause delamination which reduces the insulation capacity of the element. Both of these cause also leakages in the building. Also, it was found through interviews with maintenance experts that the replacement of the glazing can be quite difficult. The glazing needs to be removed from the exterior of the building. When the glazing is structurally bonded to the framing first the sealant has to be cut. This is also needed for the panels of Citibank. Replacement of EPDM gaskets and sealant is ought to be manageable and comparable easy.

regarding the carbon impact of a typical panel, the glazing and aluminium turn out to have the biggest impact. They also have the biggest share in weight. materials like EPDM gaskets and thermal breaks seem insignificant compared to the glazing.

D

Dismantling of facade panel of the DS5 7-12-2022

In the fabrication hall in Middelburg on the 7th of December, a facade panel of the Citibank centre in London was dismantled. The goal was to find out together with the construction workers from London how to dismantle the panel safely. This is to try the dismantling process before dismantling the panels at 70 metres height. An added observation was done for this research to check what obstacles could be found during the dismantling and whether or not the materials that were left could be used circularly.

In the new design, a couple of floors are redesigned and redeveloped. The first three floors, three floors in the middle of the building and three floors at the top of the building. The project is at this time approximately 20 years old. So 20-year-old panels will become available due to this development. To be able to take out panels in the middle of the building, one floor of storey-height panels need to be cut to take out the other panels. The dismantling done in Middelburg was to represent these panels that needed to be cut in half. So in this process in particular the framing will get damaged to properly take out these elements.

As can be seen in the images of the six glazing panels, three were broken. Which were the small windows. This glass could still be downcycled since there was a coating on the glazing. However, the glass units that were kept intact could however be further reused with perhaps some interventions. This will be further explored in this research.

The dismantling sequence of the panels on the construction site is illustrated in Figure D.1. To be able to carry out the work in a safe manner, it is planned to place a scaffold fan one floor below the dismantling. For this, it is mandatory to take out a couple of the small insulated glazing units which should be placed back after the work is finished. The glass will be taken out by using glazing robots. These use a vacuum pad which is attached to the inner surface of the glass, next the bull-nose is removed. Next, the silicone joints are cut, and a second safety device is secured. When the glazing is loosened from the frame it is manoeuvred back into the building and the glass is placed on a frame close to the removal area. Also, a so-called birdcage is used to have access to the outside of the facade. The removal will take place from the top down. Firstly the units above the floors that will be removed are braced to the slab. Next, the bull-nose is removed from the outside and the small glass plane is taken out, the same way as described above. Next, the mullions and top transoms are cut from the inside. After both panel parts are removed using the glazing robot. The panels below are removed as panels using a spider mini-crane.

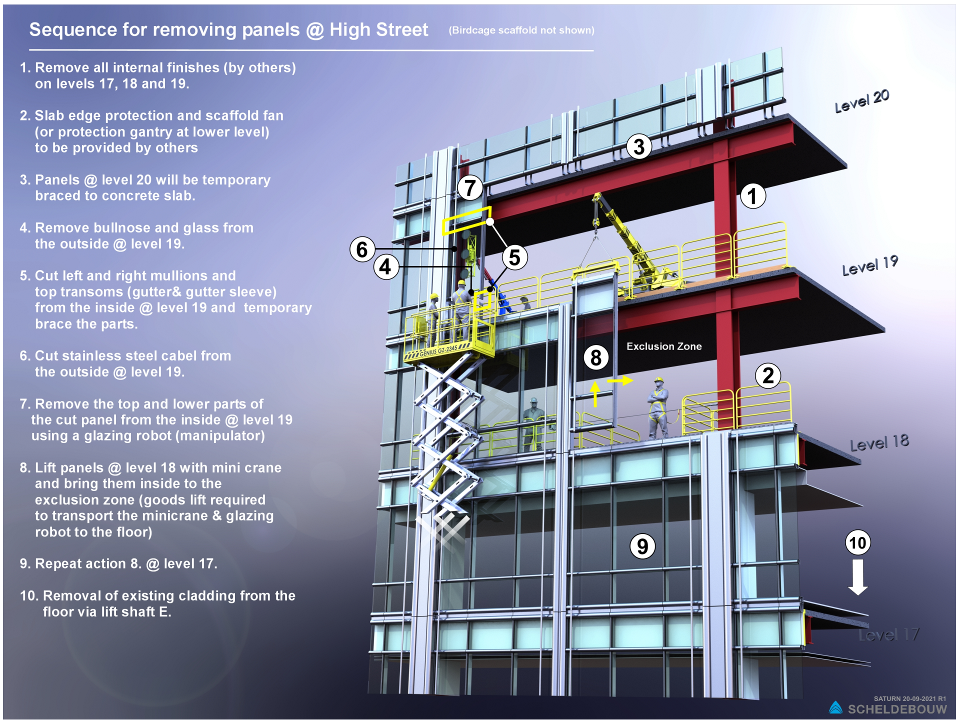


Figure D.1: Sequence for removing panels (Scheldebouw, 2023)

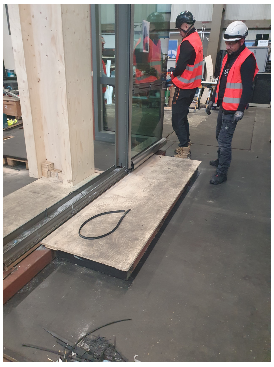
The actions that were evaluated during the dismantling in the production hall showed some additional actions. Which are later on in this section shown in the pictures. In Figure D.1 it is also mentioned that after cutting the panels on one floor, the rest of the panels can come out completely. However, it was also mentioned by workers that connection profiles that are used to connect different panels are often connected by a lot of sealants. This might make dismantling the panels as a whole more difficult than is pictured. This is done on-site and is different from the as-built drawings.
An important note to make with this dismantling is that this facade panel has been stored in the production hall in Middelburg since the construction of the project which was finished in 2001. So, the panel has not been experiencing all the wear and tear associated with weather conditions outside and/or conditions inside the building. This panel has been kept in indoor conditions and will thus still be in great condition. In despite of this fact it was also mentioned to workers that the indoor conditions of the production hall are comparable to a real situation, and the panels have not been maintained or cleaned over the years. So to a certain level, the wear of the indoor side of these panels is comparable.

D.1. Images

In this section pictures that were made during the dismantling of the facade panel are showcased. This section is split up into three subsections: Pictures of the materials that came out of this process, pictures of the glazing units and lastly pictures of the process during the dismantling.

D.1.1. Process

(a) Workers dismantling the outside element



(b) Drilling holes in the framing on the outside

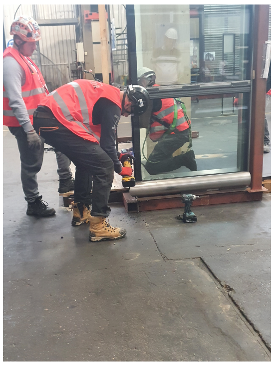
(c) Drilling holes in the framing on the inside

(d) View of the set up from the inside

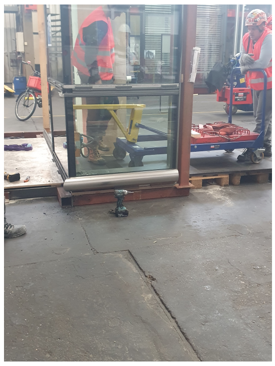
(e) Closer view of the holes drilled in the framing

(f) Cutting the sealant of the windows

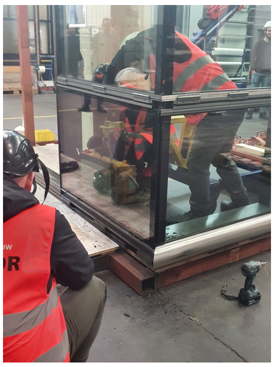
(g) The machine that will take out the window



(h) Dismantling of the windows

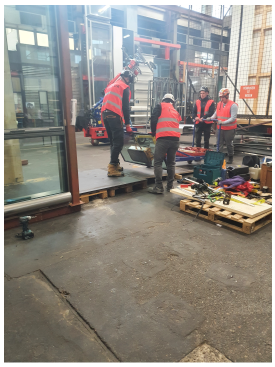


(i) The machine connected to the glazing



(j) The machine connected to the glazing, Cracks are forming

(k) Workers trying to take out the glazing, which took some force



(l) The glazing taken out of the framing

Figure D.2: Images of the process of the dismantling

D.1.2. Scrap pictures

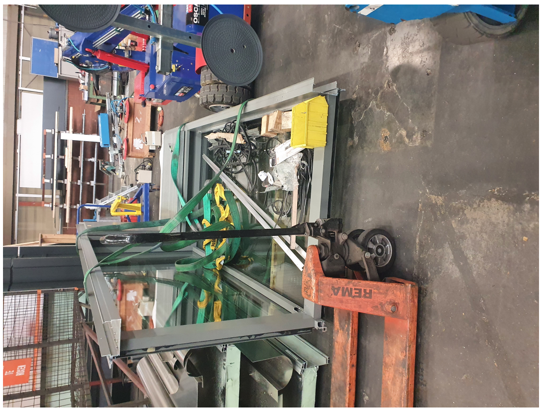
(a) Aluminium elements with insulation in them, were cut down in order for them to be removed.

(b) Rubbers that were in between the glazing and the aluminium were pulled out. Further debris from sawing the materials was left.

(c) Aluminium profiles were cut for them to be removed. This element in particular was the top or bottom mullion where the elements were connected to each other.

(d) The leftover sealant from the glazing can be seen in the groove.

(e) Some more leftover debris that was left over from the dismantling. The sealant that was cut off the windows is still visible and the aluminium elements that were cut up.



(f) The last piece of the test element, which was a corner element was taken out in one piece. Some damages can be found on the aluminium as well as some misshaping of the parts. The glazing was kept intact.

Figure D.3: Images of the scrapped materials

D.1.3. Glazing

(a) Picture of the glazing that was taken out. From this image, it can be seen that the glazing was broken in the process of taking it out of the elements.

(b) In this image the leftover sealant on the glazing can be seen. It was cut from the aluminium element in order to take out the glazing from the element. The glass was slightly damaged in this process.

Figure D.4: Images of the glazing during the dismantling

D.1.4. Storage

(a) The cut elements stored at Scheldebouw

(b) One of the vertical cut profiles, remaining of the sealant can be seen, also the mechanical strips that keep in the glazing.

(c) The remaining cut profiles, Sealant is clearly visible

Figure D.5: Images of the stored panels

D.2. Concluding

The dismantling test done in the production hall in Middelburg was meant for the construction site workers to see what steps have to be made to take out the panels safely. To be able to take out the panels in the middle of the building one floor of panels will need to be cut. As can be seen in this chapter the workers were successful in dismantling the panel. The vertical mullions were cut in half. The sealant in the glazing was cut, which left damage to the glazing, also some of the insulated glazing panels broke. However, when looking at the reuse potential of this project, the parts that came out could still be recycled when damaged. The other parts just like the glazing and some of the aluminium mullions and steel sheets from the shadow boxes should still be able to be reused when the proper project can be found. On the other floors that are dismantled in this project, the panels should be kept intact. The materials in these panels should be less damaged and thus be more useful for reuse. However, a side note should be made that this dismantling was done in a controlled environment, the same as the panels that were used. They were kept in a controlled space. Also as was mentioned by workers, the panel connection is often reinforced by using a structural sealant on site, which is not shown on the drawings. This could lead to the panels still having to be cut in practice.

E

Carbon calculations

In this appendix, the assumptions regarding the LCA calculations and the complete outcomes will be given.

E.1. Chapter 3: Unitised curtain wall facades

E.1.1. 3.3.1 Materials within unitised curtain wall facades

Table E.1: Input data for Figure 3.1 [kg/m^2]

	Edge London Bridge (EWS-101)	Edge London Bridge (EWS-105)	Edge London Bridge (EWS-111)	334 Oxford Street (EWS-101 Vision)	334 Oxford Street (EWS-101 Combined)	2 Aldermanbury Square (EES-10)	Average
Glass	39.93	28.25	58.38	49.06	32.17	22.42	38.37
Aluminium extrusions	10.73	13.60	4.31	9.53	18.86	23.75	13.46
Thermal breaks	0.37	0.53	0.07	0.43	0.93	0.24	0.43
Insulation	0.71	1.27	0.00	0.00	6.14	3.82	1.99
Aluminium fixations	0.00	1.27	0.00	0.45	0.00	0.00	0.29
Aluminium sheets	1.11	4.74	0.00	0.00	13.71	6.14	4.28
Terracotta	0.00	50.14	0.00	0.00	0.00	0.00	8.36
Steel brackets	2.10	1.27	5.56	0.70	0.92	1.11	1.94
EPDM gaskets	1.21	1.27	0.48	2.99	3.75	1.61	1.88
Silicone sealant	0.20	0.25	0.18	0.75	0.98	0.53	0.48
Fastners	0.73	1.43	0.71	0.51	0.67	0.53	0.76
Fire prevention	0.32	0.32	2.87	2.44	0.22	0.24	1.07
Steel sheets	2.75	4.58	41.93	4.63	5.76	6.53	11.03
HDPE	0.00	1.71	0.00	0.00	0.00	0.00	0.29
Total	60.16	108.91	114.49	71.48	84.11	66.94	84.35

Table E.2: Input data for Figure 3.2 [CO_2/m^2]

	Edge London Bridge (EWS-101)	Edge London Bridge (EWS-105)	Edge London Bridge (EWS-111)	334 Oxford Street (EWS-101 Vision)	334 Oxford Street (EWS-101 Combined)	2 Aldermanbury Square (EES-10)	Average
Facade area	5.61	5.61	5.61	8	12.2	5.66	
Glass	75.31	53.29	110.12	104.09	68.25	42.30	75.56
Aluminium extrusions	91.30	115.71	36.70	81.29	161.25	202.05	114.72
Thermal breacks	3.30	4.71	0.62	3.74	8.16	2.34	3.81
Insulation	0.77	1.35	0.00	0.00	6.57	4.09	2.13
Aluminium fixations	0.00	2.30	0.00	3.84	0.00	0.00	1.02
Aluminium sheets	8.89	40.42	0.00	0.00	116.72	49.40	35.91
Terracotta	0.00	52.49	0.00	0.00	0.00	0.00	8.75
Steel brackets	4.56	2.74	12.05	1.51	1.99	2.32	4.20
EPDM gaskets	2.91	3.04	1.16	7.18	8.99	3.86	4.52
Silicone sealant	0.39	0.50	0.36	1.51	1.99	1.07	0.97
Fastners	4.35	8.48	4.24	3.05	4.00	3.16	4.55
Fire prevention	0.34	0.34	0.73	2.60	0.24	0.25	0.75
Steel sheets	7.36	12.30	98.24	13.45	16.96	17.52	27.64
HDPE	0.00	5.02	0.00	0.00	0.00	0.00	0.84
Transport	8.09	15.08	11.85	9.49	9.44	7.73	10.28
Waste	21.87	31.37	21.55	23.76	37.59	31.61	27.96
Energy	25.26	25.26	25.26	25.25	25.25	25.10	25.23
Total	254.71	374.43	322.89	280.75	467.40	392.80	348.83

E.2. Chapter 5: Strategy development

In Chapter 5: strategy development carbon estimations for each of the strategies were made. The assumptions and outcomes will be given in this section.

E.2.1. Input

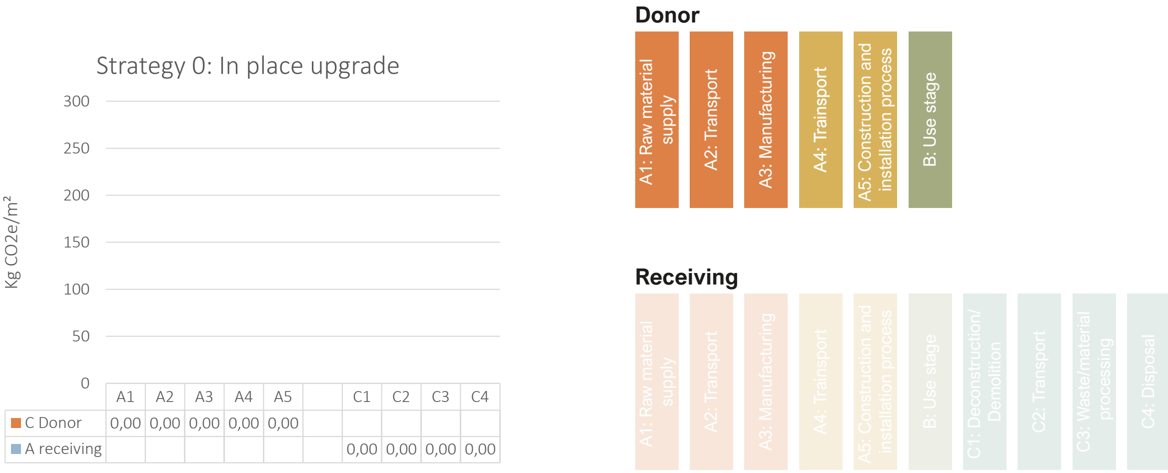
Table E.3: Material amount inputs for calculations Figure 5.24

Detailed material breakdown	Amount [kg]
Vision glass	328.00
Aluminium profiles. powder-coated	24.20
Thermal breaks	0.5
Steel sheets. pre-galvanised	36.20
Steel brackets. galvanised	222.16
EPDM gaskets	2.70
Silicone sealant	1.00
Fasteners (stainless steel)	4.00
Lamatherm firestop	1.00
Steel sheets. pre-galvanised	8.00
primer	0.39
cleaner	0.08
Plastic packaging	3.87
Wooden packaging	11.51
electricity	188.78
gas	7.56

Table E.4: Carbon input date for the calculation of Figure 5.24

Detailed material breakdown	**A1**	**A2**	**A3**	**A4**	**A5**	**C1**	**C2**	**C3**	**C4**	**Total**
Vision glass	618.70							0.42	247.18	866.30
Aluminium profiles powder-coated	205.89							6.76	18.24	230.89
Thermal breaks	4.40							1.06	0.38	5.84
Steel sheets pre-galvanised	107.50							10.11	27.28	144.89
Steel brackets. galvanised	481.42							0.00	167.42	648.84
EPDM gaskets	6.48							7.29	2.03	15.81
Silicone sealant	2.02							2.39	0.75	5.17
Fasteners (stainless steel)	23.80							1.12	3.01	27.93
Lamatherm firestop	1.07							0.00	0.75	1.82
Steel sheets. pre-galvanised	21.48							2.23	6.03	29.74
										0.00
primer			1.73							1.73
cleaner			0.42							0.42
Plastic packaging			11.55							11.55
Wooden packaging			-19.22							-19.22
electricity			124.00		1.14	1.14				126.29
gas			16.85							16.85
Transport		54.83		78.34			78.34			211.51
	A1	**A2**	**A3**	**A4**	**A5**	**C1**	**C2**	**C3**	**C4**	**Total**
	262.52	9.77	24.12	13.96	0.20	0.20	13.96	5.60	84.33	414.68

E.2.2. Strategy 0



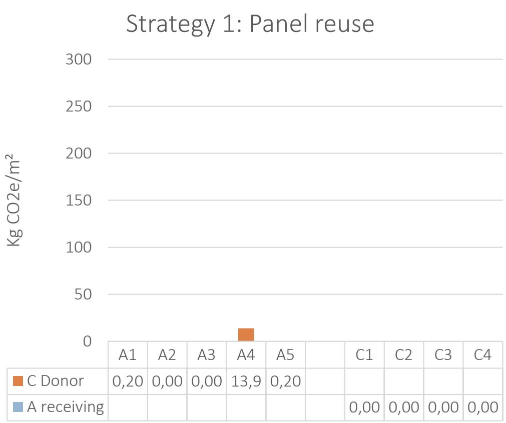
(a) Scheme of Strategy 0 **(b)** Life cycle stage interpretation of Strategy 0

Figure E.1: Life cycle estimation of Strategy 0

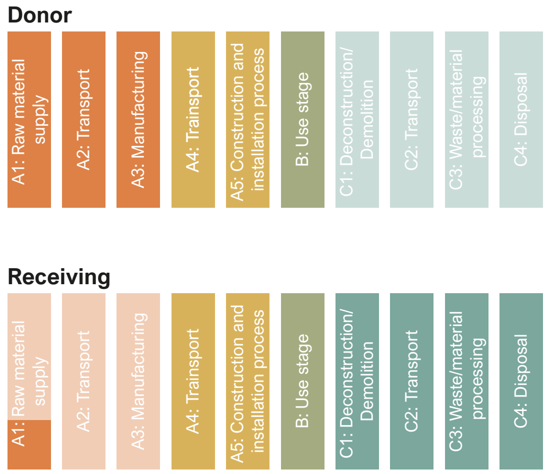
LCA assumptions

- Donor building
  - C phase remains 0 for now
- Receiving building
  - No receiving building

E.2.3. Strategy 1



(a) Carbon calculation estimation of Strategy 1



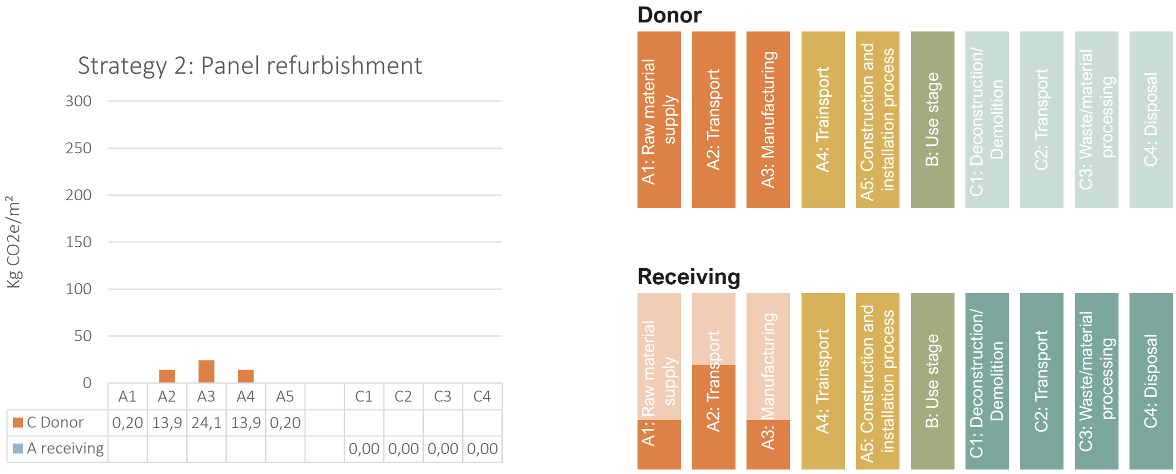
(b) Life cycle stage interpretation of Strategy 1

Figure E.2: Life cycle estimation of Strategy 1

LCA assumptions

- Donor building
  - C phase is 0
- Receiving building
  - A1 = C1 Donor
    - ‘Mining’ of the materials
    - The dismantling of the panels of the building
  - A2 = 0
  - A3 = 0
  - A4 = A4 donor
    - Transport donor-receiving
  - A5 = A5 donor
    - Mounting of the panels

E.2.4. Strategy 2



(a) Carbon calculation estimation of Strategy 2

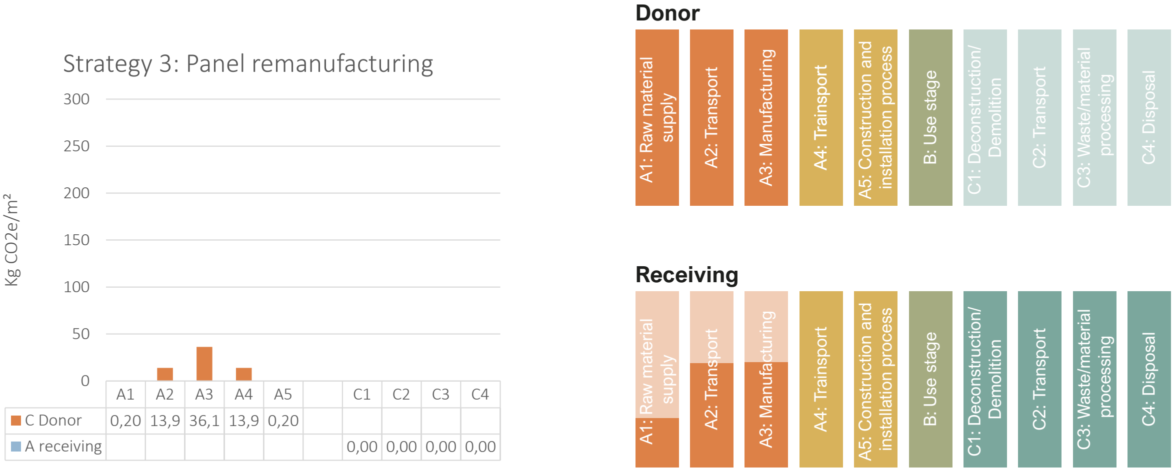
(b) Life cycle stage interpretation of Strategy 2

Figure E.3: Life cycle estimation of Strategy 2

LCA assumptions

- Donor building
  - C phase is 0
- Receiving building
  - A1 = C1 Donor
    - ‘mining’ of the materials
    - The dismantling of the panels of the building
  - A2 = A4 donor
    - Transport donor-production facility
  - A3 <= A3 donor
    - Panel refurbishments
  - A4 = A4 donor
    - Transport Production facility-receiving
  - A5 = A5 donor
    - Mounting of the panels

E.2.5. Strategy 3



(a) Carbon calculation estimation of Strategy 3

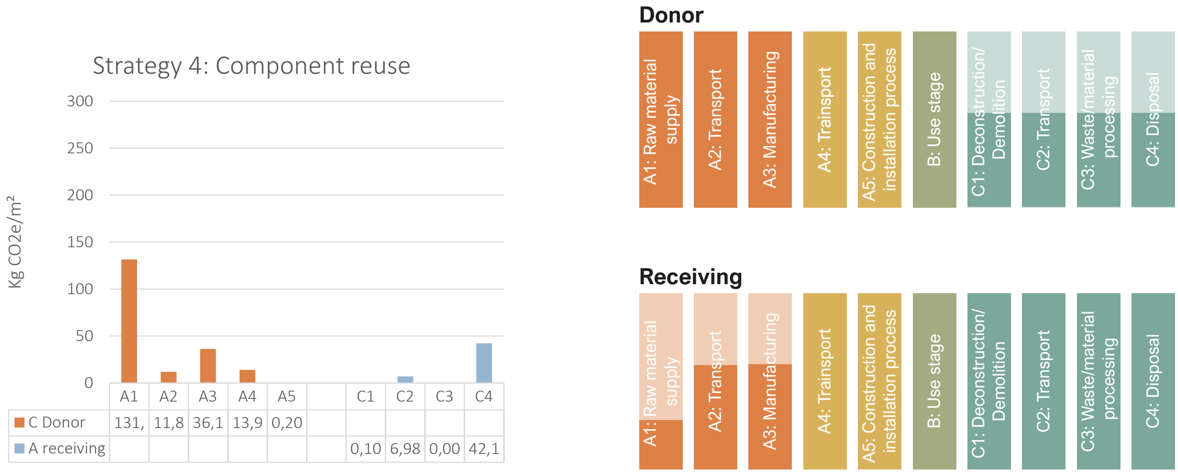
(b) Life cycle stage interpretation of Strategy 3

Figure E.4: Life cycle estimation of Strategy 3

LCA assumptions

- Donor building
  - C phase is 0
- Receiving building
  - A1 = C1 Donor
    - ‘mining’ of the materials
    - The dismantling of the panels of the building
  - A2 = A4 donor
    - Transport donor-production facility
  - A3 = 1.5*A3 donor
    - Dismantling the panel, refurbishments, mounting the panel
  - A4 = A4 donor
    - Transport Production facility-receiving
  - A5 = A5 donor
    - Mounting of the panels

E.2.6. Strategy 4



(a) Carbon calculation estimation of Strategy 4

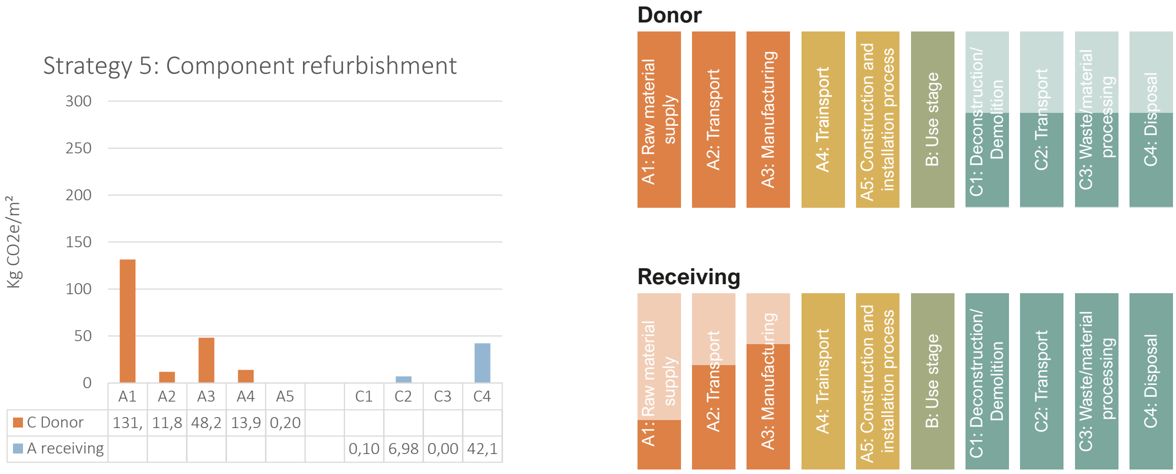
(b) Life cycle stage interpretation of Strategy 4

Figure E.5: Life cycle estimation of Strategy 4

LCA assumptions

- Donor building
  - C phase is half
- Receiving building
  - A1 = 0.5*C1 Donor + 0.5*A1
    - 'Mining' half of donor material
    - Half of the materials are new raw materials
  - A2 = 0.5*A2 Donor + 0.5*A4
    - Transportation donor – production facility of the donor materials
    - Transportation raw materials – production facility of the new materials
  - A3 = 1.5*A3 donor
    - Dismantling the panel, mounting the components into a new configuration
  - A4 = A4 donor
    - Transport Production facility-receiving
  - A5 = A5 donor
    - Mounting of the panels

E.2.7. Strategy 5



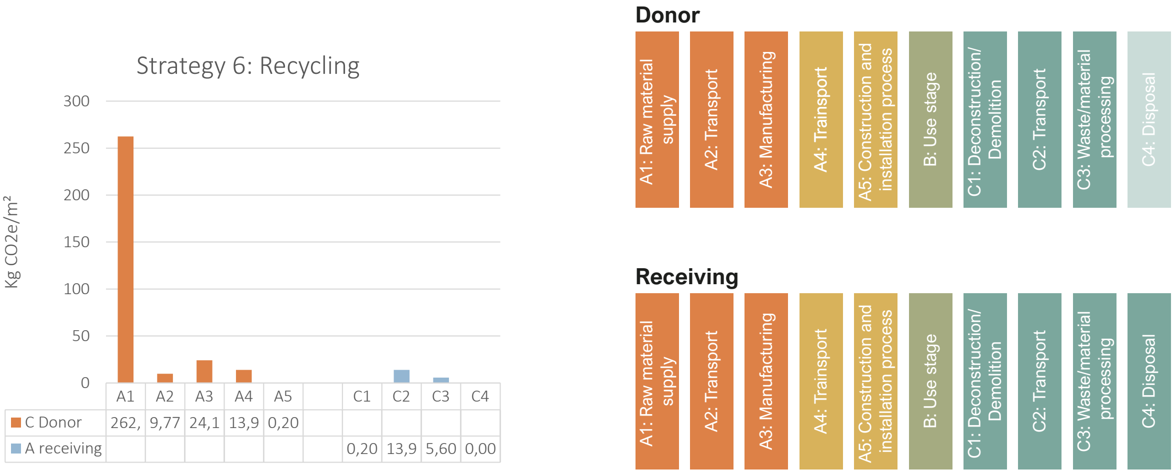
(a) Carbon calculation estimation of Strategy 5 **(b)** Life cycle stage interpretation of Strategy 5

Figure E.6: Life cycle estimation of Strategy 5

LCA assumptions

- Donor building
  - C phase is half
- Receiving building
  - A1 = 0.5*C1 Donor + 0.5*A1
    - 'Mining' half of the donor material
    - Half of the materials are new raw materials
  - A2 = 0.5*A2 Donor + 0.5*A4
    - Transportation donor – production facility of the donor materials
    - Transportation raw materials – production facility of the new materials
  - A3 = 2*A3 donor
    - Dismantling, refurbishing components, placing components in a new configuration
  - A4 = A4 donor
    - Transport Production facility-receiving
  - A5 = A5 donor
    - Mounting of the panels

E.2.8. Strategy 6



(a) Carbon calculation estimation of Strategy 6

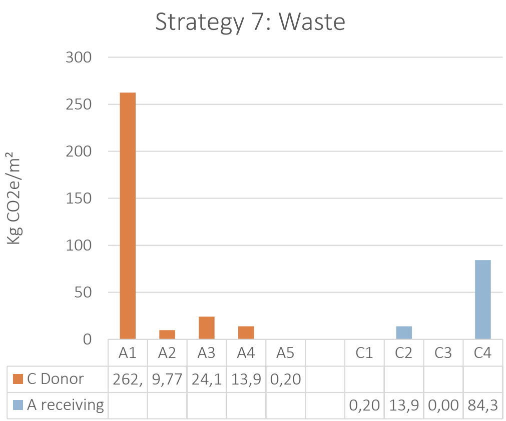
(b) Life cycle stage interpretation of Strategy 6

Figure E.7: Life cycle estimation of Strategy 6

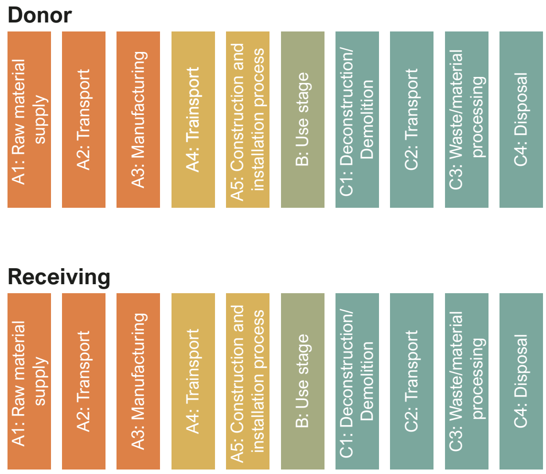
LCA assumptions

- Donor building
  - C1 = A5 Donor
    - Dismantling f the panels
  - C2 = A2
    - Transportation donor - recycling plant
  - C3 = Recycling impact
  - C4 = 0
- Receiving building
  - For the receiving building all new materials have to be sourced

E.2.9. Strategy 7



(a) Carbon calculation estimation of Strategy 7



(b) Life cycle stage interpretation of Strategy 7

Figure E.8: Life cycle estimation of Strategy 7

LCA assumptions

- Donor building
  - C1 = A5 Donor
    - Dismantling of the panels
  - C2 = A2
    - Transportation donor - waste plant
  - C3 = 0
  - C4 = Waste Impact
- Receiving building
  - For the receiving building all new materials have to be sourced

E.2.10. Output

Table E.5: Output data of Figure 5.24 [$kgCO_2e/m^2$]

	A1	A2	A3	A4	A5	C1	C2	C3	C4
Strategy 0: Refuse	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Strategy 1: Panel reuse	0.20	0.00	0.00	13.96	0.20	0.00	0.00	0.00	0.00
Strategy 2: Panel refurbishment	0.20	13.96	24.12	13.96	0.20	0.00	0.00	0.00	0.00
Strategy 3: Panel re-manufacturing	0.20	13.96	36.18	13.96	0.20	0.00	0.00	0.00	0.00
Strategy 4: Component reuse	131.36	11.87	36.18	13.96	0.20	0.10	6.98	0.00	42.16
Strategy 5: Component refurbishment	131.36	11.87	48.25	13.96	0.20	0.10	6.98	0.00	42.16
Strategy 6: Recycling	262.52	9.77	24.12	13.96	0.20	0.20	13.96	5.60	0.00
Strategy 7: Waste	262.52	9.77	24.12	13.96	0.20	0.20	13.96	0.00	84.33

Table E.6: Output data of Figure 5.24 [$kgCO_2e/m^2$]

	Total	Total A	Total C	Savings A	Savings C	Savings total	Savings A	Savings C	Savings total
				Previous			Compared to STR7		
Strategy 0: Refuse	0.0		0.0	100%	0%	100%	100%	100%	100%
Strategy 1: Panel reuse	14.4	14.4	0.0	73%	0%	73%	95%	100%	96%
Strategy 2: Panel refurbishment	52.5	52.5	0.0	19%	0%	19%	83%	100%	87%
Strategy 3: Panel re-manufacturing	64.5	64.5	0.0	67%	100%	73%	79%	100%	84%
Strategy 4: Component reuse	242.8	193.6	49.2	6%	0%	5%	38%	50%	41%
Strategy 5: Component refurbishment	254.9	205.6	49.2	34%	-149%	23%	34%	50%	38%
Strategy 6: Recycling	330.4	310.6	19.8	0%	80%	19%	0%	80%	19%
Strategy 7: Waste	409.1	310.6	98.5	NVT	NVT	NVT	NVT	NVT	NVT

E.3. Chapter 6: Application

E.3.1. Amount panels

Table E.7: Calculation of the number of panels coming off in the Citibank project

typical nr	**width of panel**		**east**			**west**			**north**			**south**			**Nr of panels**	**Area [m²]**
			top	mid	gf	top	mid	gf	top	mid	gf	top	mid	gf		
			6	7	7	6	7	7	5	6	7	5	6	7		
			3	3	4	3	3	4	3	3	4	3	3	4		
			18	21	22	18	3	2	15	18	20	15	18	28		
				61			23			53			61			
1	800	800	61			23			53			61			198	649.4
2	1100	2200	122			46			106			122			396	1786.0
2	1500	3000	122			46			106			122			396	2435.4
2	1300	2600	122			46			106			122			396	2110.7
1	400	400	61			23			53			61			198	324.7
total panels		9000	488			184			424			488			1584	7306.2

E.3.2. Option calculation

Option 0

Table E.8: Option 0: Waste amounts

Description	Material	kg	C3	C4
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10

Waste

Table E.9: Option 0: Amount of new materials

Description	Material	kg	A1
EPDM gaskets	EPDM gaskets	2.79	6.70

New

Table E.10: Option 0: Transportation impact

		Amount	TEF	TD	Impact
Transport	to waste	2.79	0.00010719	398	0.12
Transport	New product	2.79	0.00010719	398	0.12
Transport (complete panel)	To production	349.39	0.00010719	398	14.91
Transport (complete panel)	To site	349.39	0.00010719	398	14.91

Transport

Option 1

Table E.11: Option 1: Waste amounts

Description	Material	kg	C3	C4
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 2 (or. Glass)	Glass	135.00	0.17	101.78
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Sealant	Sealant	0.01	0.02	0.01

Waste

Table E.12: Option 1: Amount of new materials

Description	Material	kg	A1
EPDM gaskets	EPDM gaskets	2.79	6.70
Glass 1 (or. Glass)	Glass	48.00	90.72
Glass 2 (or. Glass)	Glass	135.00	255.15
Glass 3 (or. Shadow)	Glass	51.00	96.39
Sealant	Sealant	0.01	0.02

New

Table E.13: Option 1: Transportation impact

		Amount	TEF	TD	Impact
Transport	to waste	236.80	0.00010719	398.00	10.10
Transport	New product	236.80	0.00010719	398.00	10.10
Transport (complete panel)	To production	349.39	0.00010719	398.00	14.91
Transport (complete panel)	To site	349.39	0.00010719	398.00	14.91

Transport

Option 2

Table E.14: Option 2: Waste amounts

Description	Material	kg	C3	C4
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Insulation 3 (Rockwool 75mm)	Insulation	1.03	0.00	0.78
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	8.38	22.62
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	2.37	6.41
Sealant	Sealant	0.01	0.02	0.01

Waste

Table E.15: Option 2: Amount of new materials

Description	Material	kg	A1
EPDM gaskets	EPDM gaskets	2.79	6.70
Insulation 1 (New 180 mm?)	Insulation	2.55	2.73
Insulation 3 (New 180 mm?)	Insulation	2.55	2.73
SS sheet spandrel 3 (new)	Stainless steel	30.00	178.50
SS sheet spandrel 1 (new)	Stainless steel	30.00	178.50
Steel sheet 3 galvanized (new)	Steel sheets pre-galvanised	30.00	80.70
Steel sheet 1 powder-coated (new)	Steel sheets pre-galvanised	30.00	80.70
Sealant	Sealant	0.01	0.02

New

Table E.16: Option 2: Transportation impact

		Amount	TEF	TD	Impact
Transport	to waste	141.33	0.00010719	398.00	6.03
Transport	New product	127.90	0.00010719	398.00	5.46
Transport (complete panel)	To production	349.39	0.00010719	398.00	14.91
Transport (complete panel)	To site	349.39	0.00010719	398.00	14.91

Transport

Option 3

Table E.17: Option 3: Waste amounts

Description	Material	kg	C3	C4
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Insulation 3 (Rockwool 75mm)	Insulation	1.03	0.00	0.78
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	8.38	22.62
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	2.37	6.41
Glass 2 (or. Glass)	Glass	135.00	0.17	101.78
Sealant	Sealant	0.01	0.02	0.01

Waste

Table E.18: Option 3: Amount of new materials

Description	Material	kg	A1
EPDM gaskets	EPDM gaskets	2.79	6.70
Insulation 1 (New 180 mm?)	Insulation	2.55	2.73
Insulation 3 (New 180 mm?)	Insulation	2.55	2.73
SS sheet spandrel 3 (new)	Stainless steel	30.00	178.50
SS sheet spandrel 1 (new)	Stainless steel	30.00	178.50
Steel sheet 3 galvanized (new)	Steel sheets pre-galvanised	30.00	80.70
Steel sheet 1 powder-coated (new)	Steel sheets pre-galvanised	30.00	80.70
Glass 2 (or. Glass)	Glass	135.00	255.15
Sealant	Sealant	0.01	0.02

New

Table E.19: Option 3: Transportation impact

		Amount	TEF	TD	Impact
Transport	to waste	276.33	0.00010719	398.00	11.79
Transport	New product	262.90	0.00010719	398.00	11.22
Transport (complete panel)	To production	349.39	0.00010719	398.00	14.91
Transport (complete panel)	To site	349.39	0.00010719	398.00	14.91

Transport

Option 4

Table E.20: Option 4: Waste amounts

Description	Material	kg	C3	C4
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Insulation 3 (Rockwool 75mm)	Insulation	1.03	0.00	0.78
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	8.38	22.62
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	2.37	6.41
Sealant	Sealant	0.01	0.02	0.01
Stainless steel caps	Stainless steel	9.70	2.71	7.31

Waste

Table E.21: Option 4: Amount of new materials

Description	Material	kg	A1
EPDM gaskets	EPDM gaskets	2.79	6.70
Insulation 1 (New 180 mm?)	Insulation	2.55	2.73
Insulation 3 (New 180 mm?)	Insulation	2.55	2.73
Aluminium sheet 1 (new)	Aluminium sheets anodised	8.50	72.42
Aluminium sheet 3 (new)	Aluminium sheets anodised	8.50	72.42
Steel sheet 3 galvanized (new)	Steel sheets pre-galvanised	30.00	80.70
Steel sheet 1 powder-coated (new)	Steel sheets pre-galvanised	30.00	80.70
Sealant	Sealant	0.01	0.02
Glazing bars (new)	Aluminium	4.21	35.83
aluminium cover caps (new)	Aluminium	3.24	27.57
Glazing bars (new)	Aluminium	4.21	35.83

New

Table E.22: Option 4: Transportation impact

		Amount	TEF	TD	Impact
Transport	to waste	151.03	0.00010719	398.00	6.44
Transport	New product	96.56	0.00010719	398.00	4.12
Transport (complete panel)	To production	349.39	0.00010719	398.00	14.91
Transport (complete panel)	To site	349.39	0.00010719	398.00	14.91

Transport

Strategy 6

Table E.23: Strategy 6: Waste amounts

Description	Material	kg	C3	C4
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 2 (or. Glass)	Glass	135.00	0.17	101.78
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Mullion left (frame)	Aluminium profiles powder-coated	13.12	3.66	9.89
Mullion right (frame)	Aluminium profiles powder-coated	11.30	3.16	8.52
Transom top (frame)	Aluminium profiles powder-coated	11.90	3.32	8.97
900T (frame)	Aluminium profiles powder-coated	4.00	1.12	3.02
Intermediate transom (frame)	Aluminium profiles powder-coated	7.75	2.16	5.84
Intermediate transom small (frame)	Aluminium profiles powder-coated	4.70	1.31	3.54
Transom bottom(frame)	Aluminium profiles powder-coated	7.55	2.11	5.69
Thermal breaks	Thermal breaks	3.04	0.85	2.29
Insulation 3 (Rockwool 75mm)	Insulation	1.03	0.00	0.78
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	2.37	6.41
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	8.38	22.62
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Sealant	Sealant	0.01	0.02	0.01
Stainless steel caps	Stainless steel	9.70	2.71	7.31

Waste

Table E.24: Strategy 6: Amount of new materials

Description	Material	kg	A1
Glass 1 (or. Glass)	Glass	48.00	90.72
Glass 2 (or. Glass)	Glass	135.00	255.15
Glass 3 (or. Shadow)	Glass	51.00	96.39
Mullion left (frame)	Aluminium profiles powder-coated	13.12	111.65
Mullion right (frame)	Aluminium profiles powder-coated	11.30	96.16
Transom top (frame)	Aluminium profiles powder-coated	11.90	101.27
900T (frame)	Aluminium profiles powder-coated	4.00	34.04
Intermediate transom (frame)	Aluminium profiles powder-coated	7.75	65.95
Intermediate transom small (frame)	Aluminium profiles powder-coated	4.70	40.00
Transom bottom(frame)	Aluminium profiles powder-coated	7.55	64.25
Thermal breaks	Thermal breaks	3.04	8.18
Insulation 3 (Rockwool 75mm)	Insulation	1.03	1.10
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	72.42
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	80.70
EPDM gaskets	EPDM gaskets	2.79	6.70
Sealant	Sealant	0.01	0.02
Stainless steel caps	Stainless steel	9.70	57.69

New

Strategy 7

Table E.25: Strategy 7: Amount of wasted materials

Description	Material	kg	A1
Glass 1 (or. Glass)	Glass	48.00	90.72
Glass 2 (or. Glass)	Glass	135.00	255.15
Glass 3 (or. Shadow)	Glass	51.00	96.39
Mullion left (frame)	Aluminium profiles powder-coated	13.12	111.65
Mullion right (frame)	Aluminium profiles powder-coated	11.30	96.16
Transom top (frame)	Aluminium profiles powder-coated	11.90	101.27
900T (frame)	Aluminium profiles powder-coated	4.00	34.04
Intermediate transom (frame)	Aluminium profiles powder-coated	7.75	65.95
Intermediate transom small (frame)	Aluminium profiles powder-coated	4.70	40.00
Transom bottom(frame)	Aluminium profiles powder-coated	7.55	64.25
Thermal breaks	Thermal breaks	3.04	8.18
Insulation 3 (Rockwool 75mm)	Insulation	1.03	1.10
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	72.42
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	80.70
EPDM gaskets	EPDM gaskets	2.79	6.70
Sealant	Sealant	0.01	0.02
Stainless steel caps	Stainless steel	9.70	57.69

New

Table E.26: Strategy 7: Waste amounts

Description	Material	kg	C3	C4
Glass 1 (or. Glass)	Glass	48.00	0.06	36.19
Glass 2 (or. Glass)	Glass	135.00	0.17	101.78
Glass 3 (or. Shadow)	Glass	51.00	0.07	38.45
Mullion left (frame)	Aluminium profiles powder-coated	13.12	3.66	9.89
Mullion right (frame)	Aluminium profiles powder-coated	11.30	3.16	8.52
Transom top (frame)	Aluminium profiles powder-coated	11.90	3.32	8.97
900T (frame)	Aluminium profiles powder-coated	4.00	1.12	3.02
Intermediate transom (frame)	Aluminium profiles powder-coated	7.75	2.16	5.84
Intermediate transom small (frame)	Aluminium profiles powder-coated	4.70	1.31	3.54
Transom bottom(frame)	Aluminium profiles powder-coated	7.55	2.11	5.69
Thermal breaks	Thermal breaks	3.04	0.85	2.29
Insulation 3 (Rockwool 75mm)	Insulation	1.03	0.00	0.78
Aluminium sheet 3 (shadowbox)	Aluminium sheets anodised	8.50	2.37	6.41
Steel sheet 3 (shadowbox)	Steel sheets pre-galvanised	30.00	8.38	22.62
EPDM gaskets	EPDM gaskets	2.79	7.54	2.10
Sealant	Sealant	0.01	0.02	0.01
Stainless steel caps	Stainless steel	9.70	2.71	7.31

Waste

E.3.3. Output

Embodied carbon

Table E.27: Output of the carbon calculations in Chapter 6 in carbon

	A1	A2	A3	A4	A5	C1	C2	C3	C4
Option 0	1.36	2.44	31.08	2.42	0.24	0.00	0.02	0.00	0.34
Option 1	73.27	4.07	31.08	2.42	0.24	0.00	1.64	0.00	29.03
Option 2	86.54	3.31	31.08	2.42	0.24	0.00	0.98	0.00	17.32
Option 3	128.03	4.25	31.08	2.42	0.24	0.00	1.92	0.00	33.87
Option 4	68.18	3.09	31.08	2.42	0.24	0.00	1.05	0.00	18.51
Strategy 6	192.26	4.85	31.08	2.42	0.24	0.24	2.42	6.34	0.00
Strategy 7	192.26	4.71	31.08	2.29	0.24	0.24	2.42	0.00	42.83

Table E.28: Output of the calculations in Chapter 6 in kilogram

	kg waste	kg new	Kg saved
Option 0	0.45	0.45	56.36
Option 1	38.50	38.50	18.31
Option 2	22.98	20.80	33.83
Option 3	44.93	42.75	11.88
Option 4	24.56	15.70	32.25
Strategy 6	56.81	56.81	0.00
Strategy 7	56.81	56.81	0.00

Operational Carbon

Table E.29: Input of the calculations in Chapter 6 of the operational carbon part 1

	U_facade	A_facade	WWR	T0	Ti	Qtr	mv	mi	n	Qvent
Option 0	2.1	18.5	74	10.8	21.0	-385.8	0.03	0.05	0.85	-559.1
Option 1	2	18.5	74	10.8	21.0	-370.7	0.03	0.05	0.85	-559.1
Option 2	1.8	18.5	54	10.8	21.0	-336.9	0.03	0.05	0.85	-559.1
Option 3	1.7	18.5	54	10.8	21.0	-325.6	0.03	0.05	0.85	-559.1
Option 4	1.8	18.5	54	10.8	21.0	-329.3	0.03	0.05	0.85	-559.1
Strategy 6	1.6	18.5	54	10.8	21.0	-301.1	0.03	0.05	0.85	-559.1
Strategy 7	1.6	18.5	54	10.8	21.0	-301.1	0.03	0.05	0.85	-559.1

Table E.30: Input of the calculations in Chapter 6 of the operational carbon part 1

	f	gshade	gglas	Awindow	Psol	Qsol	ARoom	Nr of people	Qint
Option 0	1.0	1.0	0.34	13.7	239	1109.4	27.0	4.0	1359.0
Option 1	1.0	1.0	0.34	13.7	239	1109.4	27.0	4.0	1359.0
Option 2	1.0	1.0	0.34	10.0	239	809.6	27.0	4.0	1359.0
Option 3	1.0	1.0	0.34	10.0	239	809.6	27.0	4.0	1359.0
Option 4	1.0	1.0	0.34	10.0	239	809.6	27.0	4.0	1359.0
Strategy 6	1.0	1.0	0.34	10.0	239	809.6	27.0	4.0	1359.0
Strategy 7	1.0	1.0	0.34	10.0	239	809.6	27.0	4.0	1359.0

Table E.31: Input of the calculations in Chapter 6 of the operational carbon part 2

	Q [hour]	Q [year]	Q/m²	Carbon intensity factor for electricity	Operational carbon emissions
Option 0	1.5	13355.4	723.9	0.233	168.7
Option 1	1.5	13487.3	731.0	0.233	170.3
Option 2	1.3	11155.8	604.6	0.233	140.9
Option 3	1.3	11254.8	610.0	0.233	142.1
Option 4	1.3	11221.8	608.2	0.233	141.7
Strategy 6	1.3	11469.2	621.6	0.233	144.8
Strategy 7	1.3	11469.2	621.6	0.233	144.8

Table E.32: Output of the calculations in Chapter 6 of the operational carbon and the carbon payback period

	Difference operational carbon	Difference embodied carbon	Carbon Payback period
Option 0			
Option 1	-1.7	103.8	-62.3
Option 2	27.8	104.0	3.7
Option 3	26.5	163.9	6.2
Option 4	26.9	86.7	3.2
Strategy 6	23.8	202.0	8.5
Strategy 7	23.8	238.2	10.00

F
Options report of the Citibank

At the company Scheldebouw, in collaboration with the writer, options were developed. Calculations were executed by colleagues regarding costs and thermal performances. This data is used in the research. The same holds for visual renders, made as well by Scheldebouw. Environmental data, risk analysis, carbon calculations, actions and report processing have been done by the writer. in Table F.1 the names of the options used in this research and the names used in the report are shown. In this research options that did not have relevancy or had to match similarities were not used.

Table F.1: Name comparison of the options used in the Scheldebouw report and this research

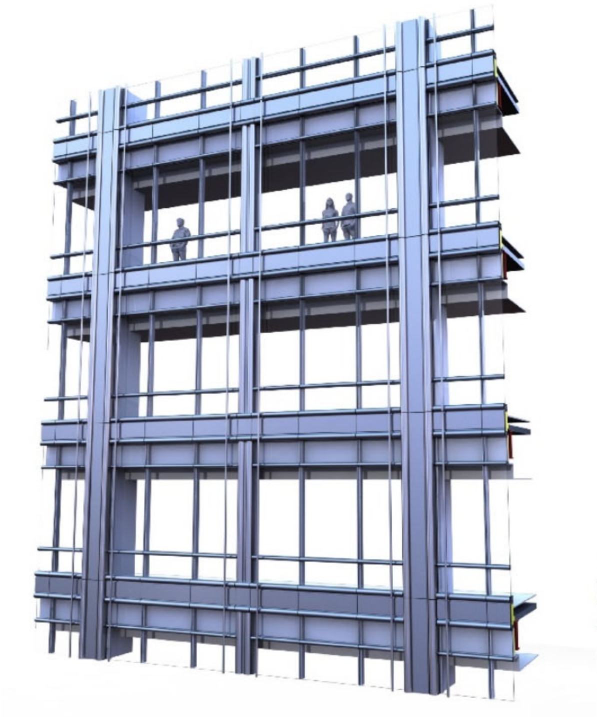
Scheldebouw report	This research
Option 0	Option 0
Option 0A	
Option 0B	Option 1
Option 1	Option 2
Option 1A	Option 3
Option 2	
Option 3	Option 4 + Bamboo
Option recycling	Strategy 6
Option recycling A1-aluminium	
Option waste	Strategy 7
Option 3 + aluminium infill	Option 4

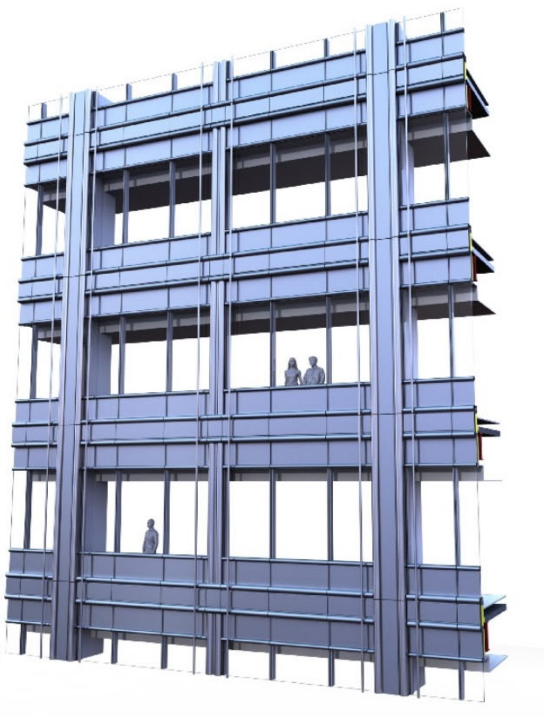
REFURBISHMENT ANALYSIS OF TYPICAL CITIBANK PANEL

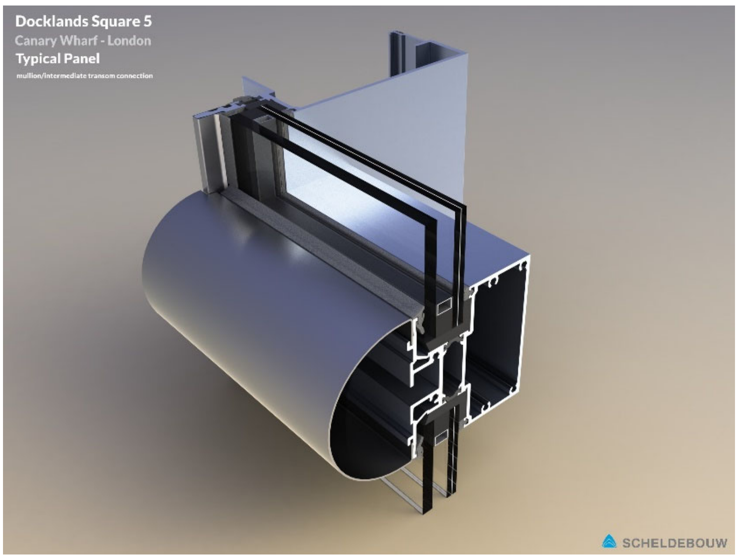
Contents

Citibank typical panel

The Citibank (Saturn or DS5) is an office project in London. At the time of this writing in three parts of the building façade elements of 22-year-old will be dismantled. Three main types of panels can be seen. Spandrel panels of 0.4 or 0.8 metres wide with a stainless-steel finishing. Transparent panels with varying widths. For this report the transparent panels are explored for re-use and refurbish options.

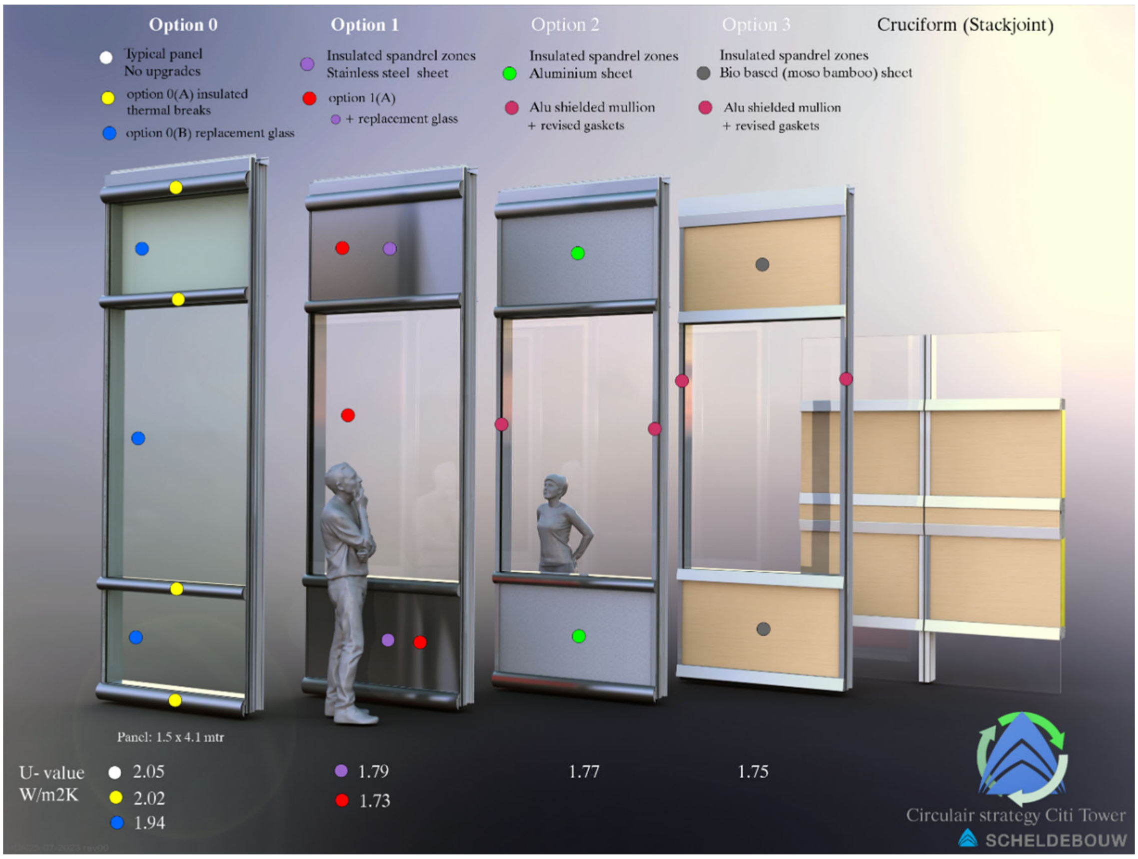


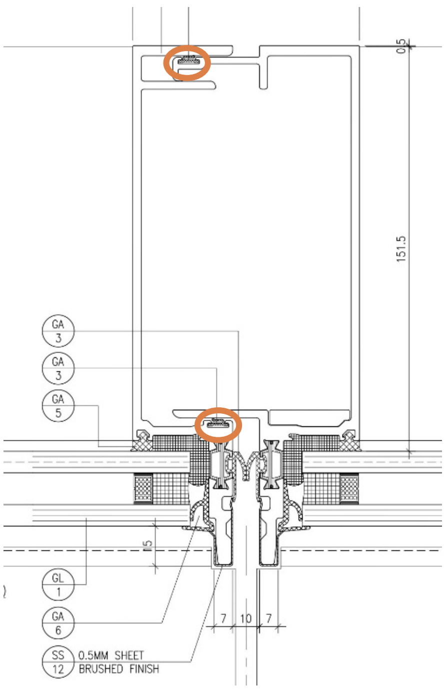


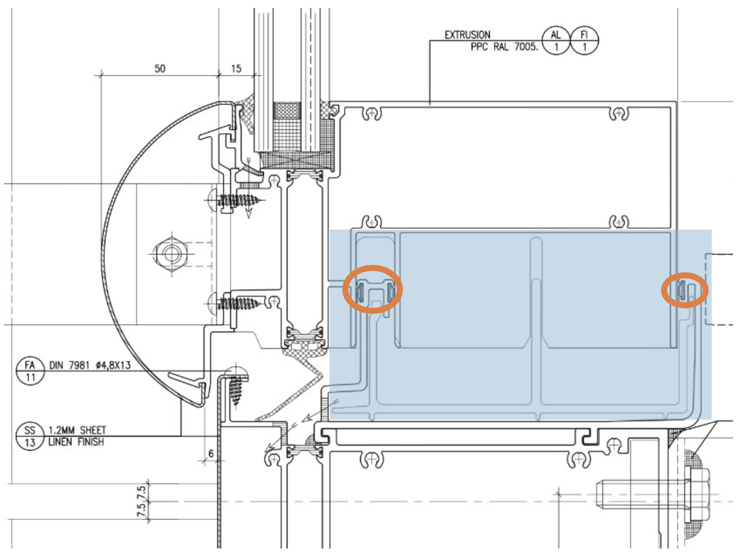


Refurbishment options

As part of a research strategies for re-use of existing aluminium facades have been explored. Within the research the strategy panel refurbishment and panel dismantling have been found to be fitting in this case. Below an overview of the options is shown. In terms of technical, environmental, and physics characteristics the panels have been explored and de option evaluated.







Carbon calculations:

The embodied and operational carbon calculations are made based on a couple of assumptions. The first assumption is that when material is not used in the new panel, it is put to waste. Recycling is however an option still. The new and old location both are assumed to be London. The impact in the production facility (A3) are assumed to be equal to that of a new panel. This includes primer, cleaner, wooden packaging, plastic packaging, electricity and gas. Also assumed the energy needed to construct the panel, is equal to the energy to dismantle. No clear data is known for this.

	typical nr	width of panel		east			west			north			south			Nr of pane	Size
				top	mid	gf	top	mid	gf	top	mid	gf	top	mid	gf		
				6	7	7	6	7	7	5	6	7	5	6	7		
				3	3	4	3	3	4	3	3	4	3	3	4		
				18	21	22	18	3	2	15	18	20	15	18	28		
					61			23			53			61			
	1	800	800	61			23			53			61			198	649440000
	2	1100	2200	122			46			106			122			396	1785960000
	2	1500	3000	122			46			106			122			396	2435400000
	2	1300	2600	122			46			106			122			396	2110680000
	1	400	400	61			23			53			61			198	324720000
total panels			9000	488			184			424			488			1584	7306200000

Risks

	Probability	Impact	Risk	mitigation
Gaskets not usable anymore (UV or age)	Medium	Low	Low	Up front measurements Gasket types
Powder coating quality insufficient	Medium	High	Medium	Up front visual inspection
Glass breakage	High	High	high	Replace glazing Careful handling
Corrosion in aluminium	Low	High	Medium	Up front visual inspection
Damage during dismantling	High	High	High	Careful handling, Replacement strategy of components
Damage during transportation	Medium	High	Medium	Careful handling, Replacement strategy of components
Damage during refurbishment	Medium	High	Medium	Careful handling, Replacement strategy of components
Structural bonding on existing sealant	High	Unknown	Unknown	Testing of bonding properties after resealing
Age of glazing when not replacing, to old	Medium	Medium	Medium	Replacement strategy, Testing and references

Option 0: Original element: Basic

U-value	2.05	W/m²K
WWR	74	%
g-value-glazing	0.34	-
g-value total	0.25	-

New material

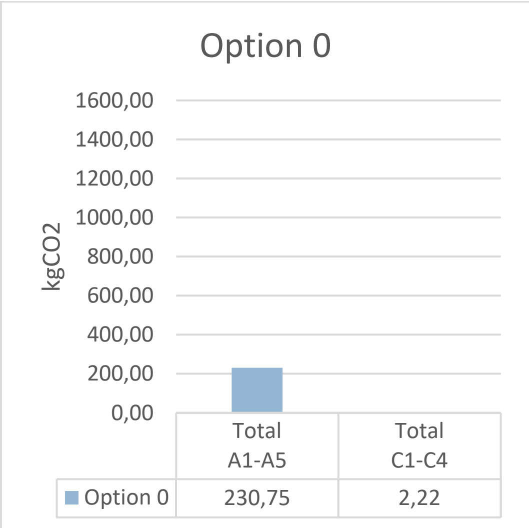
Gaskets (panel separation)	3 x 11.2	m
Koppelgoot	250	mm

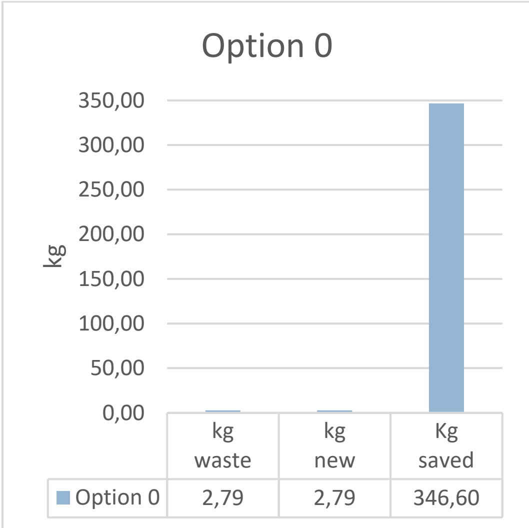
Actions

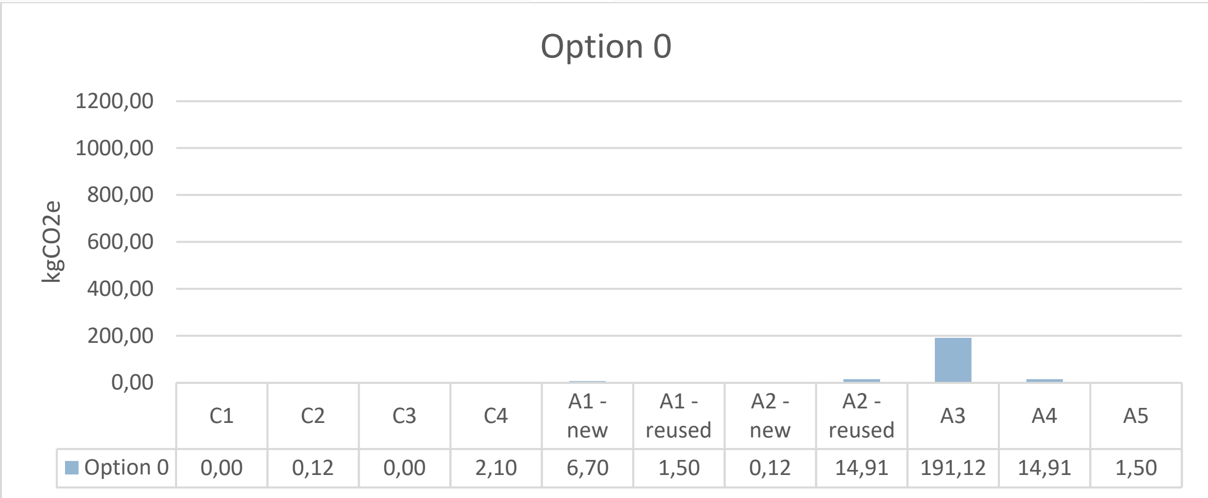
- Dismantling construction site
- Transportation to production facility
- Dismantling of “Koppelgoot”
- Dismantling gaskets (Panel separation)
- Cleaning
- Placing of gaskets

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	14%
A1-A5 carbon of waste scenario (Receiving)	17%
C1-C4 carbon of waste scenario (donor)	1%

Option 0A: Insulated horizontal thermal breaks

U-value	2.02	W/m²K
WWR	74	%
g-value-glazing	0.34	-
g-value total	0.25	-

New material

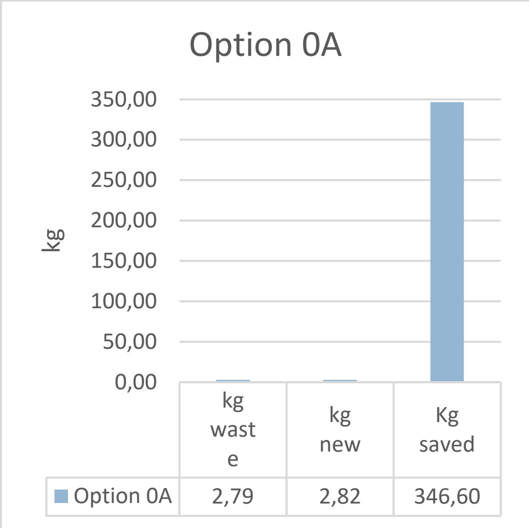
Gaskets (panel separation)	3 x 11.2	m
Koppelgoot	250	mm
Insulation (korrels)	0.03	kg

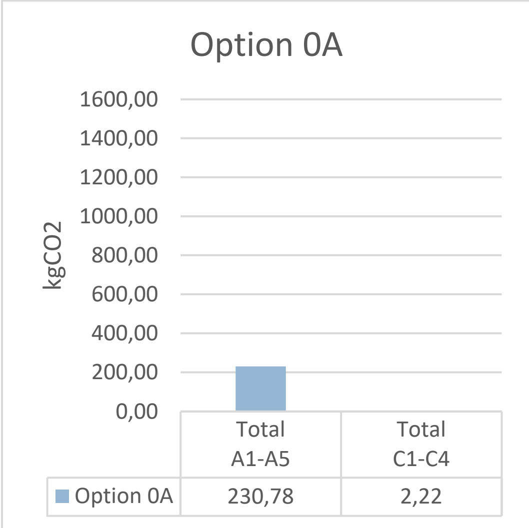
Actions

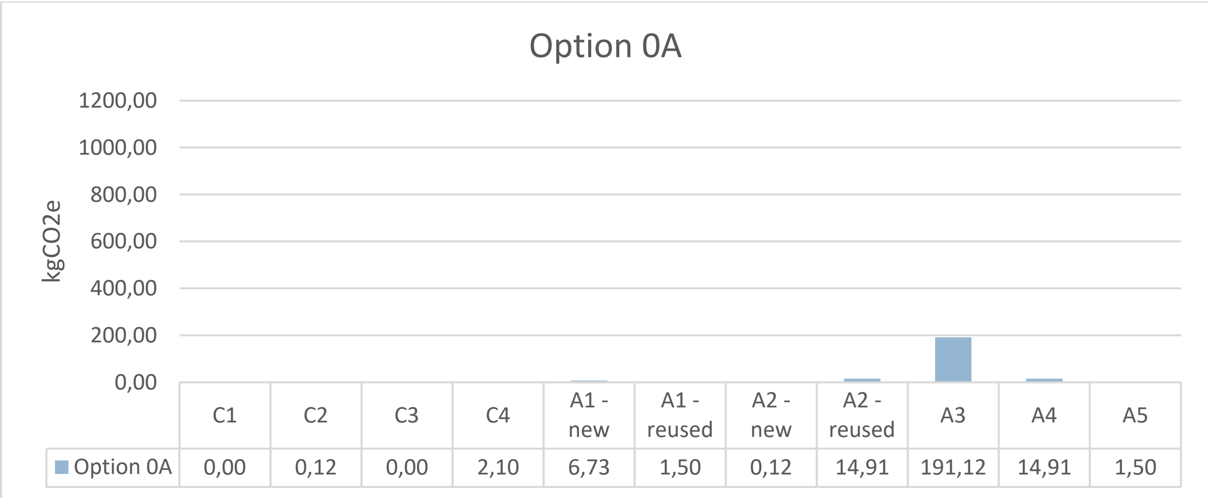
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Dismantling horizontal SS features
- Drilling holes in the framing
- Placing insulation in between spacers in horizontal framing
- Filling holes
- Mounting horizontal SS features
- Cleaning
- Placing of gaskets

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	14%
A1-A5 carbon of waste scenario (Receiving)	17%
C1-C4 carbon of waste scenario (donor)	1%

Option 0B: Replacement of glazing

U-value	1.97	W/m²K
WWR	74	%
g-value-glazing	0.34	-
g-value total	0.25	-

New material

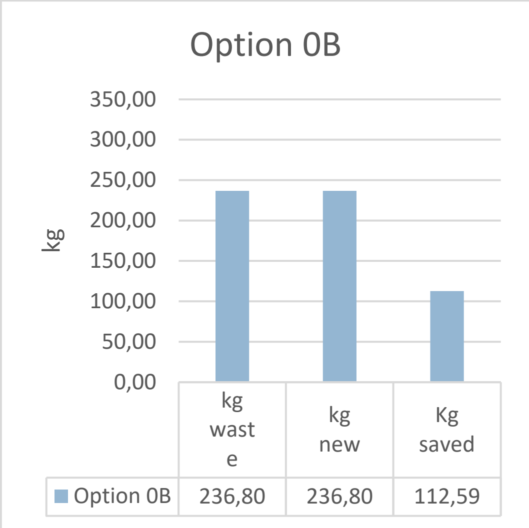
Gaskets (panel separation)	11.2	m	3
Koppelgoot	250	mm	
Gaskets (glazing)	7.4	mm	2
Glazing: 8-12-4-4-2 + HP coating	1.5 x 0.8	m²	2
Glazing: 8-12-4-4-2 + HP coating	1.5 x 2.15	m²	
Sealant	-		

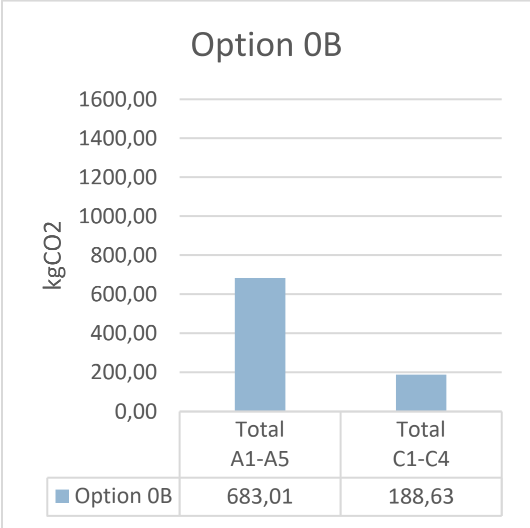
Actions

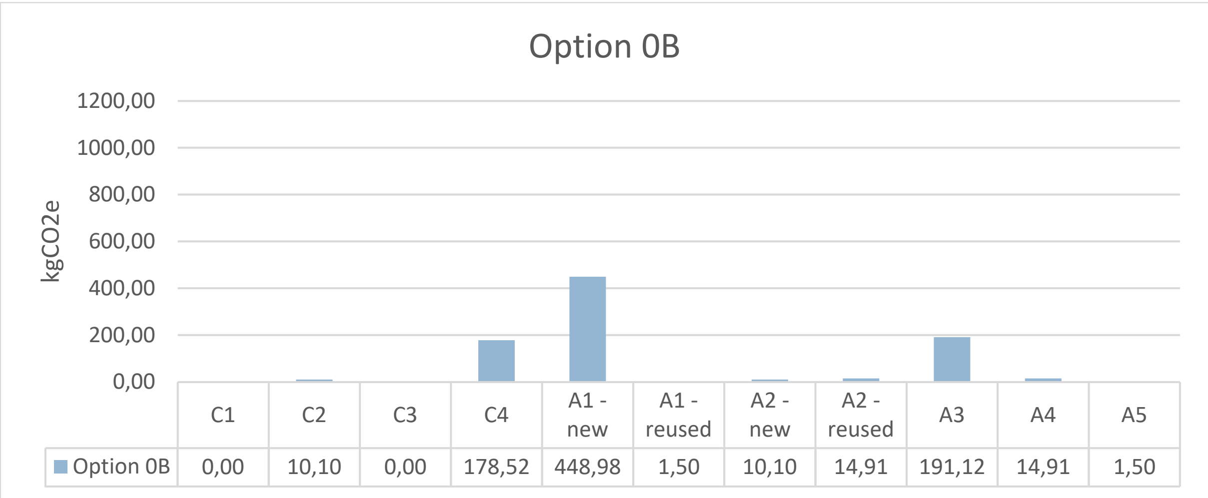
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Dismantling horizontal SS features
- Cutting structural sealant
- Cutting shadow box glazing
- Removing remaining sealant
- Dismantling original glazing
- Placing of new glazing
- Sealing new glazing
- Placing gaskets
- Mounting horizontal SS features
- Cleaning
- Placing of gaskets

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	52%
A1-A5 carbon of waste scenario (Receiving)	49%
C1-C4 carbon of waste scenario (donor)	67%

Option 1: Upgrade shadow box, adding of additional spandrel with a stainless-steel finishing

U-value	1.97	W/m²K
WWR	54	%
g-value-glazing	0.34	-
g-value total	0.18	-

New material

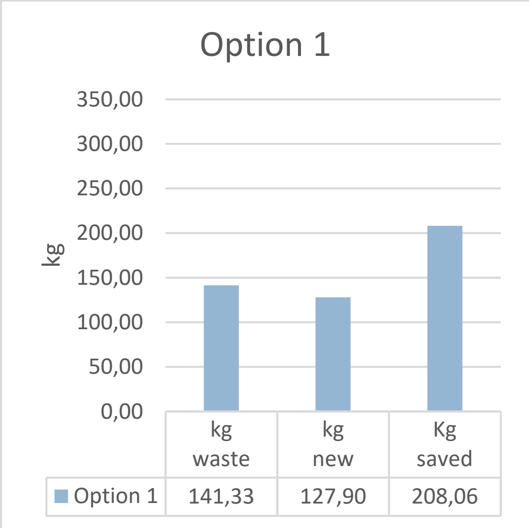
Gaskets (panel separation)	11.2	m	3
Koppelgoot	250	mm	
Insulation material 180mm	1.5 x 0.8	m²	2
Stainless steel sheet (spandrel) 1.5mm	1.5 x 0.8	m²	2
Steel sheet galvanized 1.5mm	1.5 x 0.8	m²	
Steel sheet powder coating 1.5mm	1.5 x 0.8	m²	
Sealant	-		

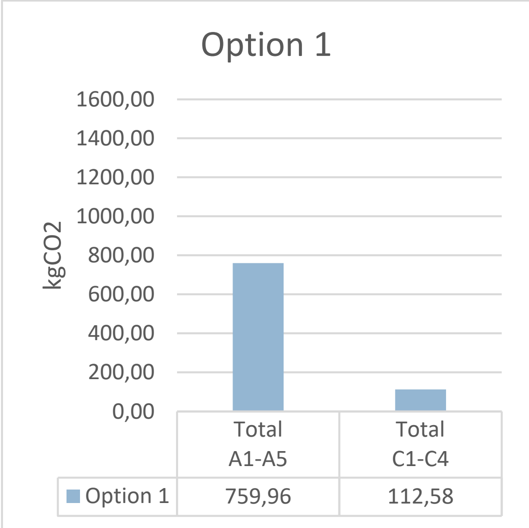
Actions

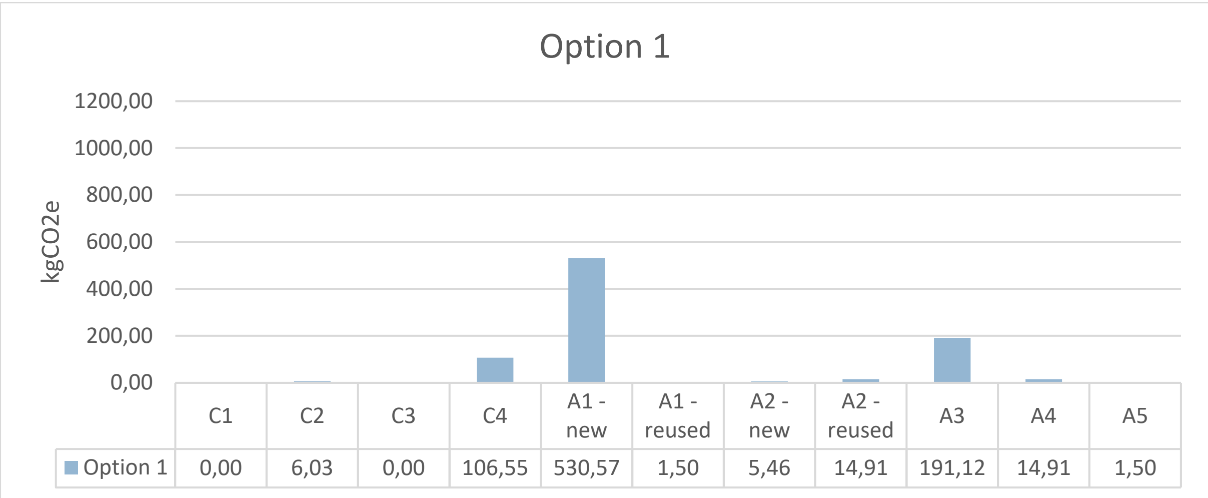
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Dismantling horizontal SS features
- Dismantling gaskets
- Cutting shadow box and glazing
- Cleaning of remaining sealant
- Placing of spandrel panels
- Placing of gaskets
- cleaning
- Mounting horizontal SS features

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	82%
A1-A5 carbon of waste scenario (Receiving)	54%
C1-C4 carbon of waste scenario (donor)	40%

Option 1A: Option 1 + replacing of glazing

U-value	1.73	W/m²K
WWR	54	%
g-value-glazing	0.34	-
g-value total	0.18	-

New material

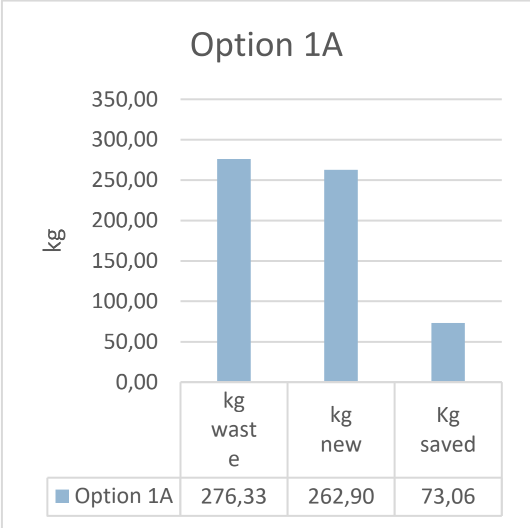
Gaskets (panel separation)	11.2	m	3
Gaskets (glazing)	7.4	m	2
Koppelgoot	250	mm	
Insulation material 180mm	1.5 x 0.8	m²	2
Stainless steel sheet (spandrel) 1.5mm	1.5 x 0.8	m²	2
Steel sheet galvanized 1.5mm	1.5 x 0.8	m²	
Steel sheet powder coated 1.5mm	1.5 x 0.8	m²	
Glass 8-12-4-4-2 + HP coating	1.5 x 2.15	m²	
Sealant	-		

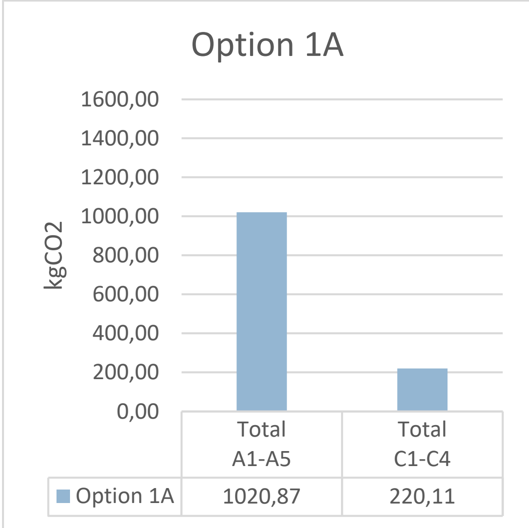
Actions

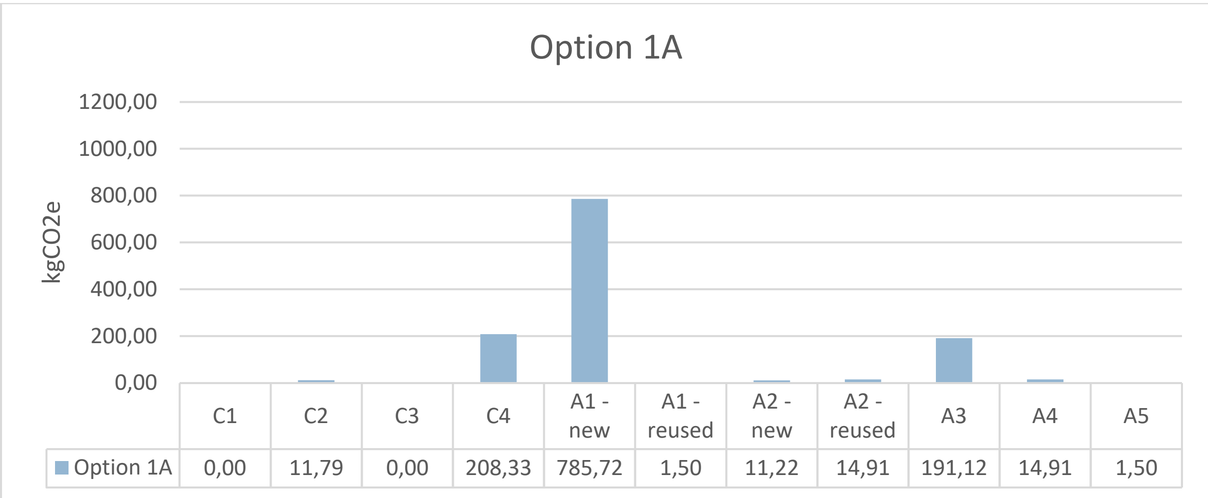
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Dismantling horizontal SS features
- Dismantling gaskets
- Cutting shadow box
- Cutting of original glazing
- Cleaning
- Placing of spandrel panels
- Placing and sealing of the new glazing
- Placing of gaskets
- Mounting horizontal SS features

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	73%
A1-A5 carbon of waste scenario (Receiving)	72%
C1-C4 carbon of waste scenario (donor)	79%

Option 2: Upgrade shadow box, additional spandrel, aluminium finishing with glazing bars

U-value	1.77	W/m²K
WWR	54	%
g-value-glazing	0.34	-
g-value total	0.18	-

New material

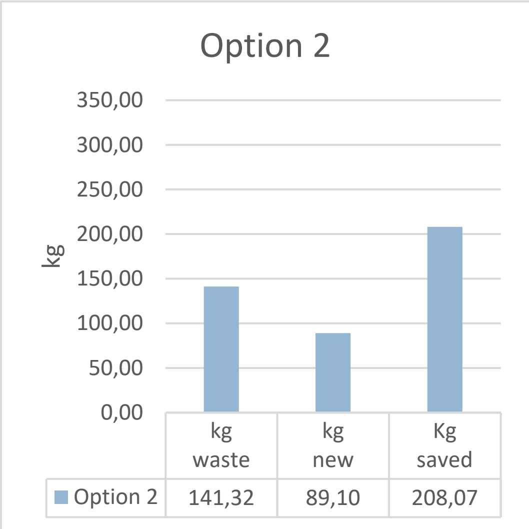
Gaskets (panel separation)	11.2	m	3
Koppelgoot	250	mm	
Insulation material 180mm	1.5 x 0.8	m²	2
Aluminium sheet (spandrel) 3mm	1.5 x 0.8	m²	2
Steel sheet galvanized 1.5mm	1.5 x 0.8	m²	
Steel sheet powder coating 1.5mm	1.5 x 0.8	m²	
Aluminium extrusion (new)	2 x 4.1	m	
Sealant	-		

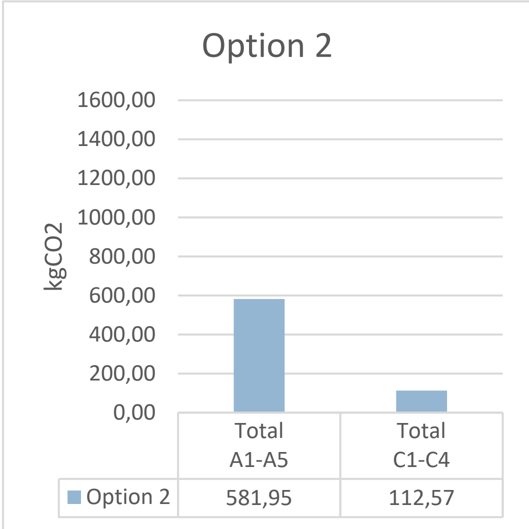
Actions

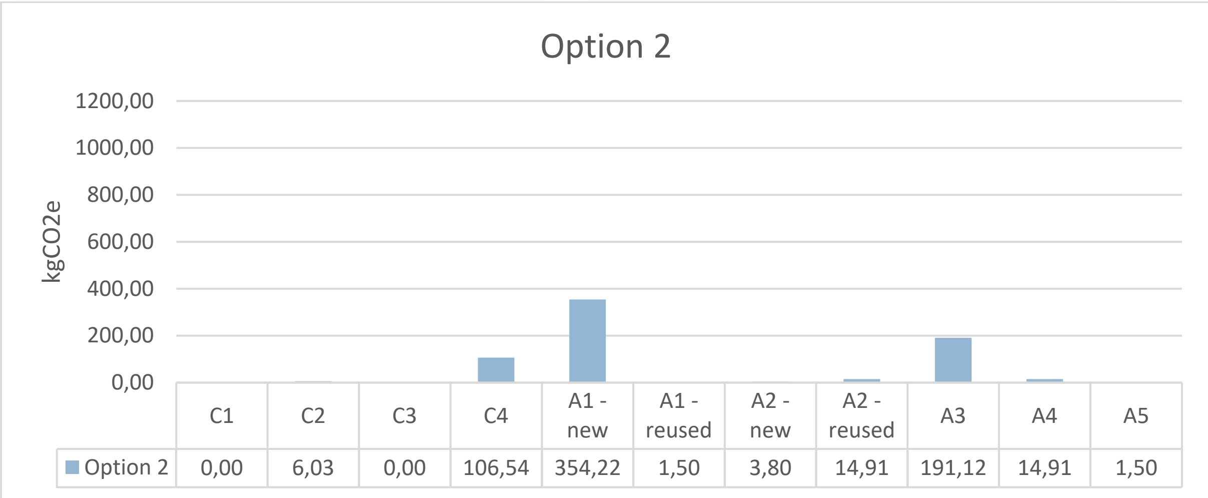
- Design and engineering glazing bars
- Extruding glazing bars
-
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Dismantling horizontal SS features
- Dismantling gaskets
- Cutting shadow box and glazing
- Cleaning of remaining sealant
- Placing of spandrel panels
- Placing of gaskets
- cleaning
- Mounting horizontal SS features
- Mounting glazing bars

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon estimation







Savings

Percentage carbon impact compared to the waste scenario.

Total carbon of waste scenario	41%
A1-A5 carbon of waste scenario (Receiving)	42%
C1-C4 carbon of waste scenario (donor)	40%

Option 3: Upgrade shadow box, additional spandrel, Aluminium finishing with new cover caps and additional glazing bars

U-value	1.75	W/m²K
WWR	54	%
g-value-glazing	0.34	-
g-value total	0.18	-

New material

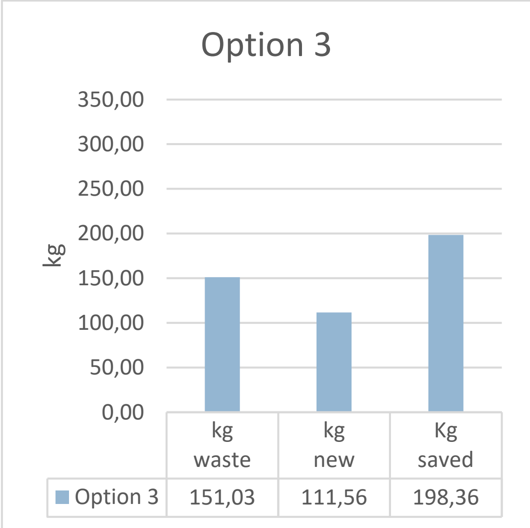
Gaskets (panel separation)	11.2	m	3
Koppelgoot	250	mm	
Insulation material 180mm	1.5 x 0.8	m²	2
Biobased moso bamboo sheet (spandrel infill)	1.5 x 0.8	m²	2
Steel sheet galvanized 1.5mm	1.5 x 0.8	m²	
Steel sheet powder coating 1.5mm	1.5 x 0.8	m²	
Aluminium extrusion (new) glazing bar	4.1	m	2
Aluminium extrusion	1.5	m	4
Sealant	-		

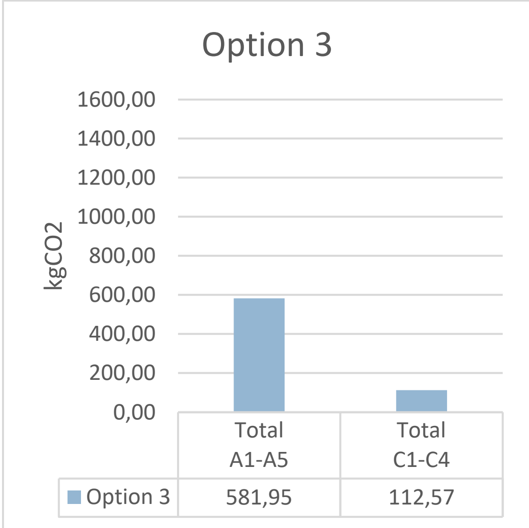
Actions

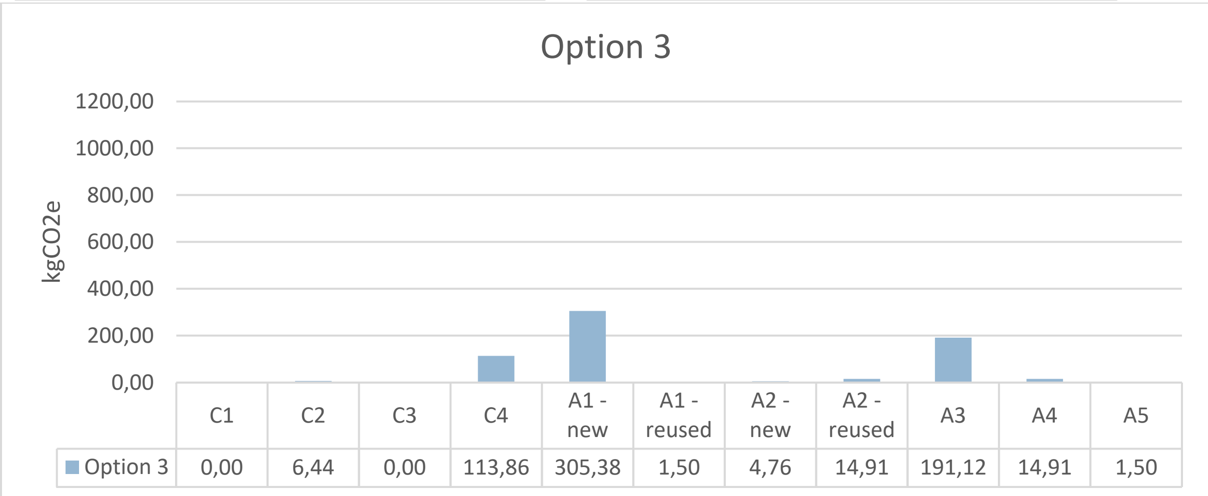
- Design and engineering new aluminium horizontal features and vertical glazing bars
- Extruding of aluminium features
-
- Dismantling construction site
- Transportation to production facility
- Dismantling of "Koppelgoot"
- Dismantling gaskets (Panel separation)
- Design/engineering of new extrusions
- Dismantling horizontal SS features
- Cleaning
- New extrusions + cutting + coating
- Dismantling gaskets
- Cutting shadow box
- Placing of spandrel panels
- Placing of gaskets
- Placing of new aluminium horizontal features and vertical glazing bar

- Packing
- Storage (depending on programme)
- Transport
- installation

Carbon calculation







Savings

Percentage carbon impact compared to the waste scenario.

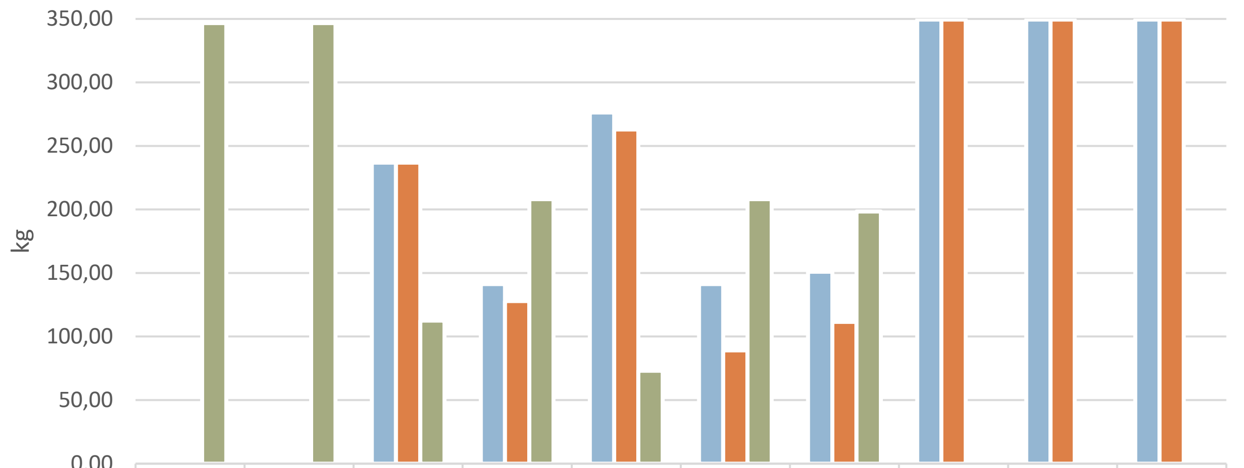
Total carbon of waste scenario	39%
A1-A5 carbon of waste scenario (Receiving)	38%
C1-C4 carbon of waste scenario (donor)	43%

Carbon overview

Explanation:

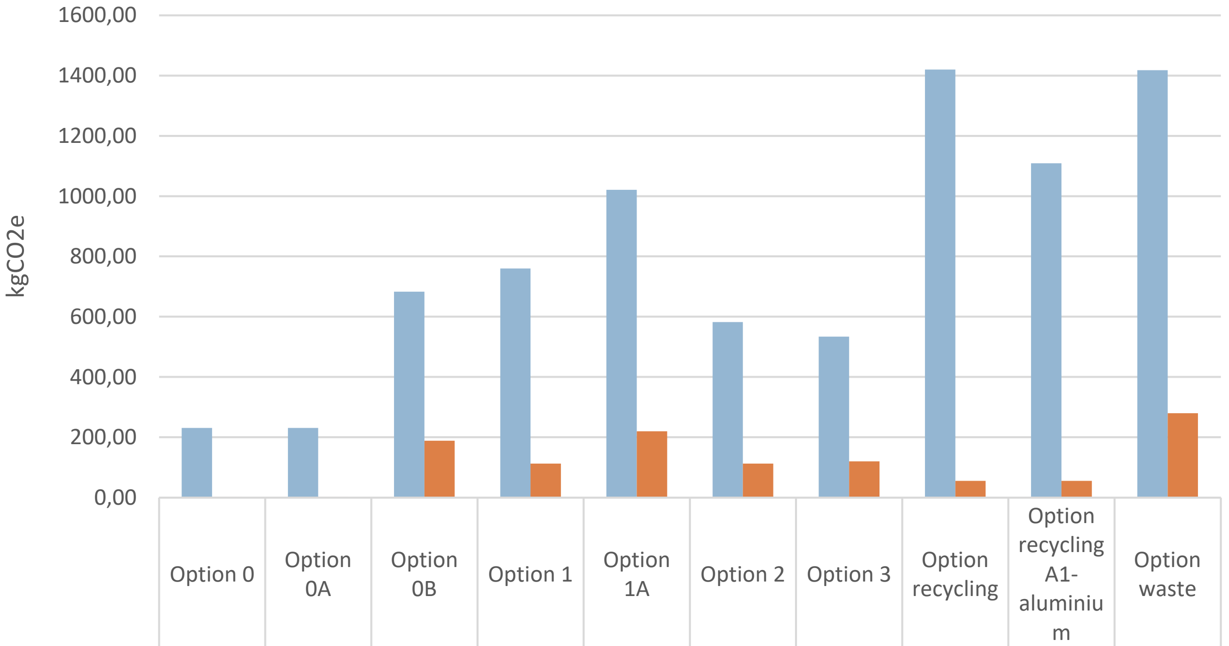
C1	Dismantling for waste
C2	transport to End of life location (Waste/Recycling)
C3	Impact for elements that are put into recycling
C4	Impact for elements that are put into waste
A1 - new	The impact of the raw materials needed
A1 - reused	"mining" of the reused materials. Dismantling impact
A2 - new	Transport of new materials to production facility
A2 - reused	Transport of reused materials to Production facility
A3	Re-manufacturing energy
A4	Transport of refurbished elements to receiving building
A5	Energy needed for mounting elements to receiving building

Kilograms analysis



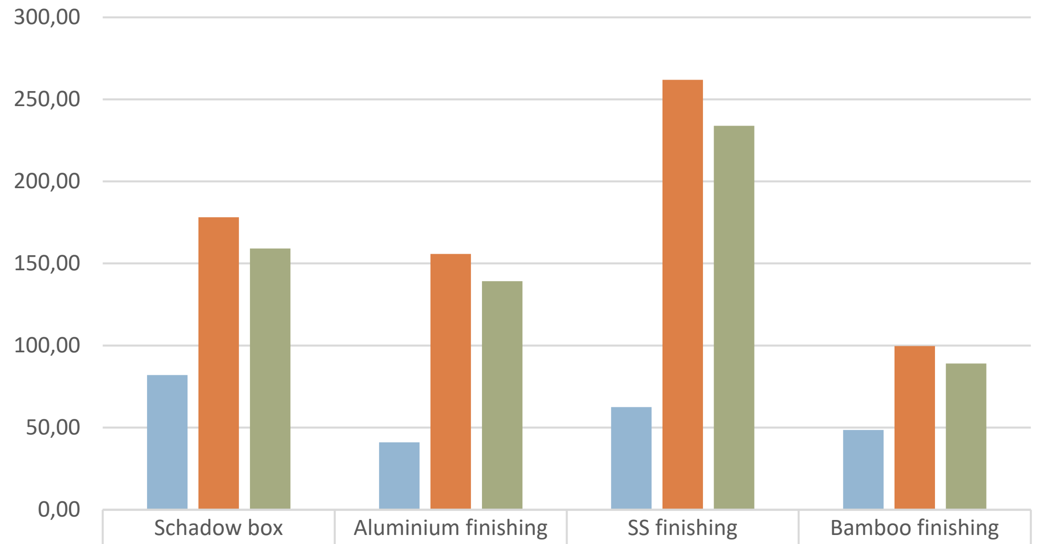
	Option 0	Option 0A	Option 0B	Option 1	Option 1A	Option 2	Option 3	Option recycling	Option recycling A1-aluminium	Option waste
kg waste	2,79	2,79	236,80	141,33	276,33	141,32	151,03	349,39	349,39	349,39
kg new	2,79	2,82	236,80	127,90	262,90	89,10	111,56	349,39	349,39	349,39
Kg saved	346,60	346,60	112,59	208,06	73,06	208,07	198,36	0,00	0,00	0,00

Carbon impact option



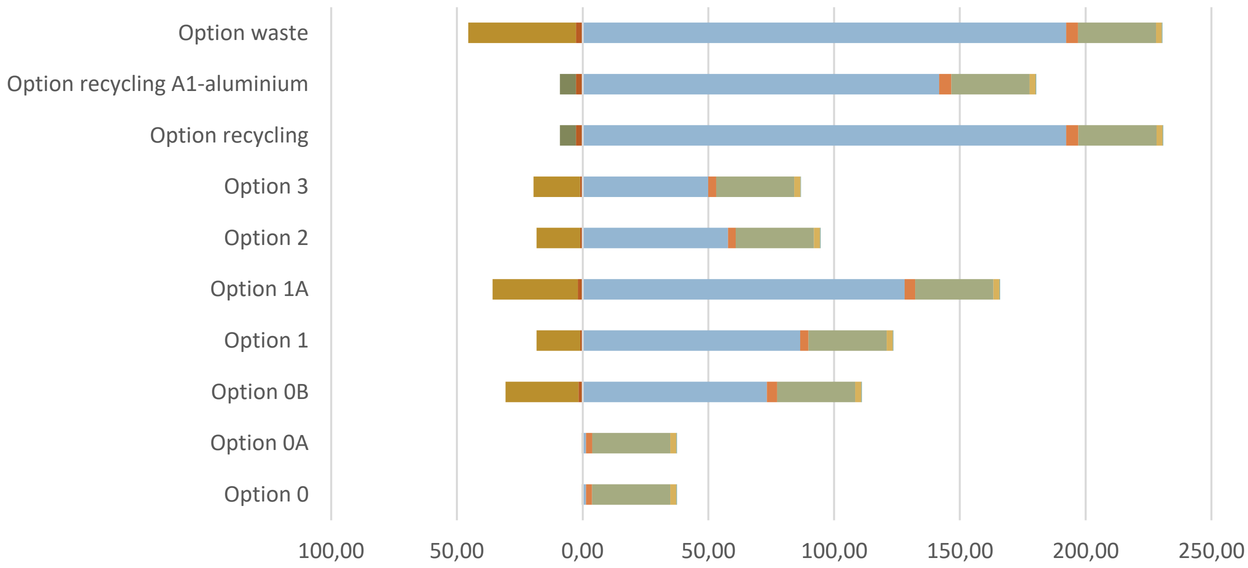
	Option 0	Option 0A	Option 0B	Option 1	Option 1A	Option 2	Option 3	Option recycling	Option recycling A1-aluminium	Option waste
Total A1-A5	230,75	230,78	683,01	759,96	1020,87	581,95	534,07	1419,72	1109,26	1418,07
Total C1-C4	2,22	2,22	188,63	112,58	220,11	112,57	120,30	55,43	55,43	279,81

Comparrisson of spandrel infills



	Schadow box	Aluminium finishing	SS finishing	Bamboo finishing
kg	82,03	41,05	62,55	48,55
A1 impact [CO2e]	178,19	155,85	261,93	99,72
Impact per m² [CO2e/m²]	159,14	139,18	233,92	89,05

Carbon impact per m² facade assuming materials go to waste

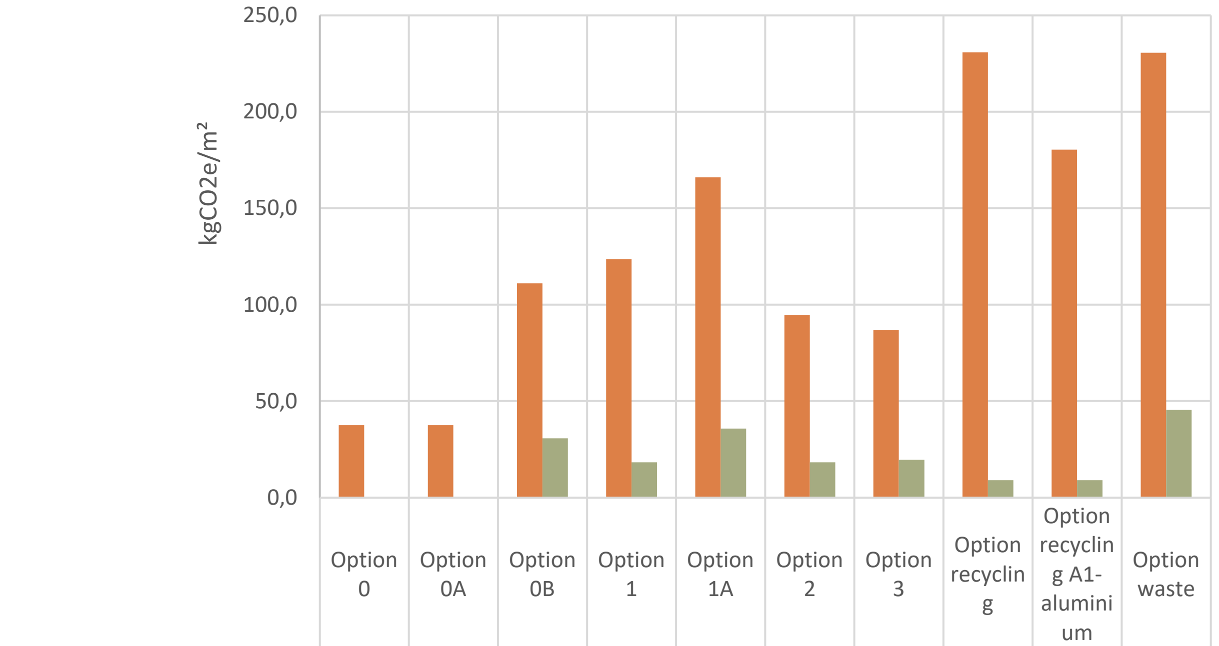


	Option 0	Option 0A	Option 0B	Option 1	Option 1A	Option 2	Option 3	Option recycling	Option recycling A1-aluminium	Option waste
A1	1,33	1,34	73,25	86,52	128,00	57,84	49,90	192,26	141,78	192,26
A2	2,44	2,44	4,07	3,31	4,25	3,04	3,20	4,85	4,85	4,71
A3	31,08	31,08	31,08	31,08	31,08	31,08	31,08	31,08	31,08	31,08
A4	2,42	2,42	2,42	2,42	2,42	2,42	2,42	2,42	2,42	2,29
A5	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24
C1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,24	-0,24	-0,24
C2	-0,02	-0,02	-1,64	-0,98	-1,92	-0,98	-1,05	-2,42	-2,42	-2,42
C3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-6,34	-6,34	0,00
C4	-0,34	-0,34	-29,03	-17,32	-33,87	-17,32	-18,51	0,00	0,00	-42,83

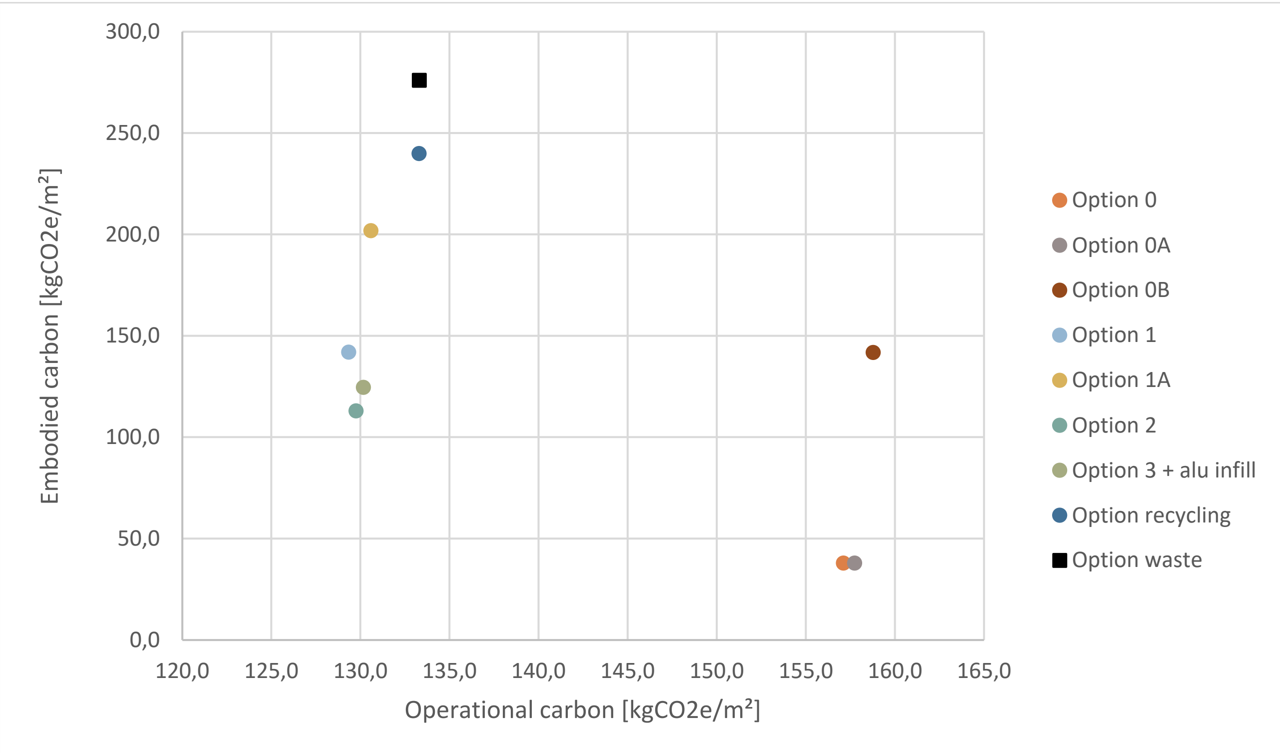
kgCO2e/m²

A1 A2 A3 A4 A5 C1 C2 C3 C4

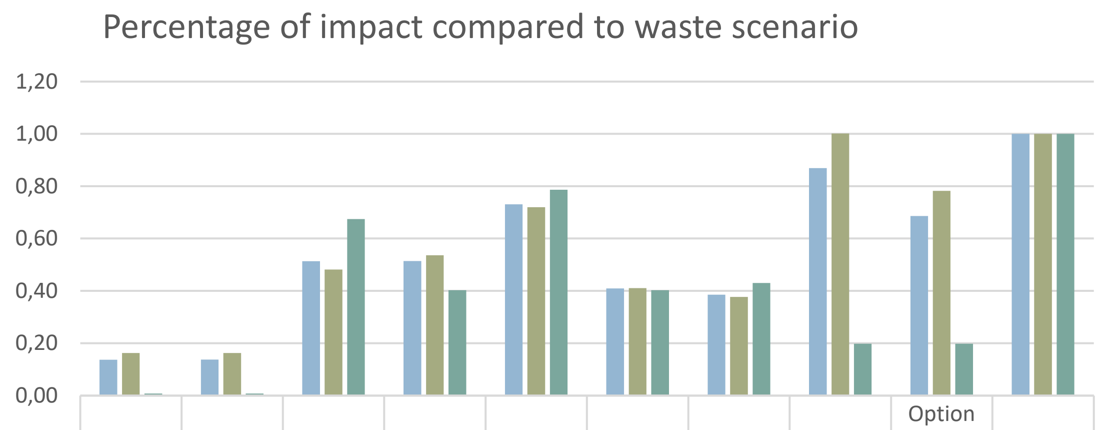
Embodied carbon comparison



	Option 0	Option 0A	Option 0B	Option 1	Option 1A	Option 2	Option 3	Option recycling	Option recycling A1-aluminium	Option waste
Embodied carbon (Receiving)	37,5	37,5	111,1	123,6	166,0	94,6	86,8	230,8	180,4	230,6
Embodied carbon (Donor)	0,4	0,4	30,7	18,3	35,8	18,3	19,6	9,0	9,0	45,5



Savings



	Option 0	Option 0A	Option 0B	Option 1	Option 1A	Option 2	Option 3	Option recycling	Option recycling A1-aluminium	Option waste
Savings of total	0,14	0,14	0,51	0,51	0,73	0,41	0,39	0,87	0,69	1,00
Savings of A1-A5	0,16	0,16	0,48	0,54	0,72	0,41	0,38	1,00	0,78	1,00
Savings of C1-C4	0,01	0,01	0,67	0,40	0,79	0,40	0,43	0,20	0,20	1,00

Savings of total   Savings of A1-A5   Savings of C1-C4

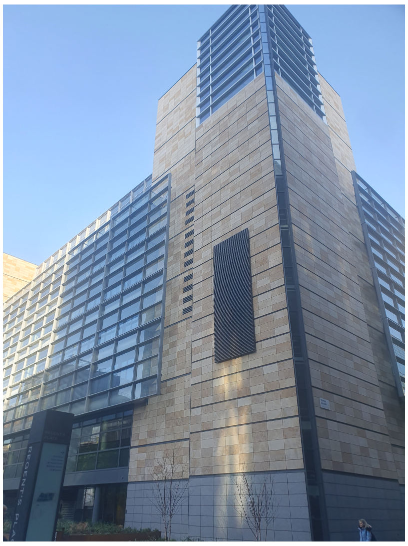
G

Visit Londen 15-12-2023

On the 15th of February, a couple of reference study projects in Londen were visited. During the visit, the building of 1 Triton Square was seen as the building of Citibank. During the stay there, interviews were conducted with three of the site managers involved with dismantling and refurbishing the facade panels. Next to that, the lead facade engineer who was involved in the majority of the project from the advisor site was interviewed in the Arup office. An outline of the questions that were asked will be given below:

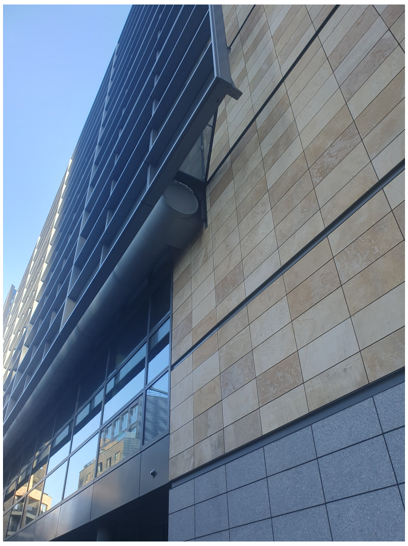
- Cold you give a general description of the project?
- What was the main reason the refurbishment was chosen instead of new a new facade?
- What variants were considered?
- Why was the current variant chosen?
- Would you consider implementing similar methods in other projects?
- What other approaches would you consider in refurbishment?
- What considerations made the refurbishment a success?
- What considerations caused issues during the refurbishment?
- What is the performance of the refurbished facade?
- What methods were used in the carbon analysis?
- What materials within a facade show potential for reuse
- What materials within a facade are not worth considering for circular strategies
- What actions were taken in refurbishing the facade panels of 1 Triton Square?
  - On the construction site (dismantling)
  - In the temporary factory
  - On the construction site (assemble)
- Were there damages during this process
- where were the panels stored
- What were the performance requirements for the refurbished panels

G.1. Images from the site visit



(a) Picture from the corner of 1 Triton Square

(b) Picture of the refurbished facade of 1 Triton Square



(c) Picture of the corner of the refurbished facade of 1 Triton Square

(d) Picture of Gallow brackets, walkways and tubing in the cavity of the refurbished facade of 1 Triton Square

(e) Picture of the elevation of the refurbished facade of 1 Triton Square

(f) Picture of the Citibank from street-level

Figure G.1: Pictures made during the site visit in London