# CLOSING LOOPS

**Optimizing unitized facades for Circularity by Design for Disassembly**

Master Thesis by:
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Title
"Closing loops - Optimizing unitized façade elements for disassembly"

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# FIRSTLY THANK YOU FOR SUPPORTING ME!

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# IN ABSTRACT TERMS

The overall aim of this research is to review existing facades produced by a leading façade manufacturer and develop new systems corresponding with the company's main product features and improved for Circular Economic performance by applying the principles of Design for Disassembly.
The study is based on a literature research about the Circular Economy, Design for Disassembly and relevant assessment systems for the two terms. Existing projects are reviewed and the findings translated into guidelines for future façade developments. With the guidelines in mind two new systems are developed and rated for their performance on Circularity and Disassembly.
The first part of the paper examines the current status of the existing facades for Circularity and Disassembly potential. The second part provides evidence that the adoption of the guidelines can lead to better performances, either incremental by applying limited changes as per produced guideline or more substantial by redesign.
For practitioners working on innovative façade systems in the realm of the circular economy this paper provides basic guidelines for designing and rating their concepts.
This paper reviews a specialist product on its potential for Circularity and Disassembly, aspects currently gaining in importance.

Keywords: Circular Economy; Design for Disassembly; Material Circularity Indicator; CO2 Footprint; Disassembly Potential; Unitized Facades

# CONTENT

# CONTENT

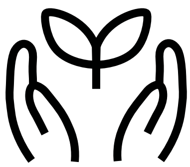
INTRODUCTION

# 1 | RESEARCH FRAMEWORK

## IN BRIEF

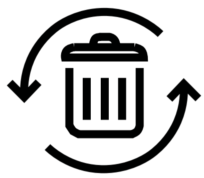
The first chapter outlines the context of the topic and describes the drive to undertake the investigation. The basic problem is analysed which leads to the formulation of one main and various subproblems. This in turn leads to the definition of corresponding objectives and subsequently a summary of research and design questions. Finally the methodology and approach to this research are explained in this chapter and its relevance clarified.

**SAVING RESOURCES**



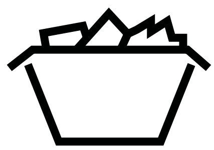
**Saving resources is one key to reduce the impact of climate change.**

**WASTE PREVENTION**



**Waste of materials and energy is to be prevented.**

**CONSTRUCTION WASTE**



**Construction accounts for approximately 30% of all waste generated in the EU.**

# 1. RESEARCH FRAMEWORK
## Introduction

## 1.1 Background

Context of the research project
Saving resources is one key to reduce the impact of climate change. Waste of materials and energy is to be prevented. Materials are to be saved to get a longer service life out of them. The use of energy is to be reduced to conserve energy resources. One concept which was developed to make an end to material and energy devastation is 'Cradle to Cradle'. The concept encourages 'designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (McDonough & Braungart, 2002).

In 2016, the total waste generated in the EU-28 by all economic activities and households amounted to 2 538 million tonnes (European Commission, 2020). Currently construction and demolition waste (CDW) is one of the heaviest and most voluminous waste streams generated in the EU (European Commission, 2016). It accounts for approximately 30% of all waste generated in the EU. Every single person in the EU accounts for approx. 160 t construction waste in his lifetime (European Commission, 2016).
One of the main components of a building is the façade. It is a highly technological component consisting of a multitude of materials (Knaak, Bilow, Klein, & Auer, 2007). After its service life the facade is removed and not re-used for various reasons. Firstly there is the change of ownership from the producer to the building owner which does reduce incentives for the producer to come up with long lasting, re-usable or recyclable facade designs. Secondly there is the uniqueness of design which is requested by architects and owners, which does hinder any later re-use of the façade. The third obstacle is the decreasing performance and value of the materials after demolition, making a full disassembly not very economical. And lastly it is the current way to assemble the unitized elements not enabling a quick and economical disassembly. This applies as well to the facades of Scheldebouw which is the partnering company on this thesis.
Basic problem analysis

The façades produced by Scheldebouw are not designed with disassembly in mind and hence their potential for material re-use is not fully exploited (Eichhorn, 2020).The various reasons for the low rate of re-use are mentioned previously. Some of the aspects can not be addressed by the company alone but require the combined effort of all stakeholders and amendment to the legislative environment. However others i.e. disassembly performance to enhance material or component re-use can be reviewed by Scheldebouw.
The vast majority of Scheldebouw's façade systems are based on unitized elements. After their service life the unitized facades are demolished and many of their materials are downcycled in the recycling procedure. One reason for the reduced re-cycling rate of the materials is the limited potential for disassembly of the units. The facades units are designed for quick assembly, performance, maintenance and even the occasional repair action but aspects enhancing the potential of later re-use or recycling are not taken into consideration at the design process (Eichhorn, 2020).
With ever increasing material consumption and the subsequent negative environmental consequences on our environment it is time to break the linear model of ''take-make-dispose' in favour of the circular model of 'take-make-reuse'. While some of the necessary steps require a different approach to ownership and hence ask for a new contractual or legislative approach (Ellen McArthur Foundation, 2013), other steps are of a more technical nature e.g. the optimization of the unitized façade elements for later disassembly and re-use or unmixed recycle of singular elements. This shall be the focus of the subsequent research.

## 1.2 Problem statement

**Main problem:**
The current unitized facades of Scheldebouw are not designed with the end of their service life in

mind. As a result at the end of their service life the facades are demolished and the materials involved elaborately downcycled, recycled or destined for landfill. Therefore great amounts of the material and energy involved to produce the facades in the first place are lost.

**Design problem:**

There is no existing design by Scheldebouw of a facede optimized for Disassembly and Circularity.

**Sub-problems:**

The term circularity is very vague and is unclear how it is applicable to the construction industry. Further there is uncertainty about the term Design for Disassembly and what it characterizes.

There exists no obvious and generally accepted rating scheme which allows a straightforward scan of the fitness of a façade regarding disassembly. Further, an assessment of a system on disassembly does not provide a full picture of the circularity of a façade since other factors e.g. material choice and emissions are not considered.

Multiple rating systems are used to express the Circularity and material usage of a product. It is not obvious which one is the most suitable for this research.

The company Scheldebouw and their design and production process is not known. Their knowledge and application of the principles of Circularity form another unknown variable. Further it is unexplained how they assemble their systems and what are the hurdles when disassembling an existing façade module which is based on current design and assembly praxis.

Scheldebouw produces a wide range of mostly tailor-made facade systems. In contrast to system suppliers e.g. Schüco, Reynaers or Wicona at Scheldebouw exists no standard systems. Their various solutions are based on a few returning principles instead. Hence a selection of typical average projects is to be selected for review regarding their circularity performance.

There is uncertainty about the current salvage procedure and the resulting material flow of demolished facades. There are no precise numbers regarding the re-use and recycling of façade material at the end of life.

In order to assess the circularity performance of façade systems manufactured currently by Scheldebouw they must be examined for their material types and quantities. Further the suppliers are to be located and the transport modes are to be ascertained.

The concept of Circular Construction is new to Scheldebouw. Their business model is based on a linear economy 'take-make-dispose' which is mirrored in their product design. There is a general ignorance in the company regarding Circular Economy and how their existing products can be improved for circularity.

## 1.3 Objectives

**Main objective:**

The main objective of the research is to determine how far the principle of Design for Disassembly can contribute to the optimization of a typical façade system from Scheldebouw to achieve an improved life cycle performance.

Design objective:

Optimize a façade as typical by Scheldebouw for Disassembly and Circularity.

**Subobjectives:**

In order to establish what the term Circularity means a general definition is to be found. Further clarification is required on how the aspects of Circularity affect construction. In this context surrounding principles should be reviewed to present a broader overview of the topic and highlight differences between relatively close definitions. Further the facets of Design for Disassembly are to be illustrated and their relevance shown.

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## Introduction

To calculate the Circularity of a system a suitable system needs to be established. From a range of systems the most applicable shall be picked for later operation. The same method is to be followed to find a fitting assessment for judging the degree of Design for Disassembly.

The company Scheldebouw B.V. is to be introduced and their design and production procedures are to be analysed. In this area falls as well the current practices applied to the manufacture of contemporary unitized façade systems. The reverse assembly of present facades shall be undertaken to gain deeper understanding of the hurdles which hinder dismantling.

A selection of suitable projects is to be checked for Circularity and Disassembly and the conclusions drawn from the exercise shall be applied to an amended design. To support the necessary input for the calculation the current salvage practice of (unitized) facades shall be researched helping to quantify the re-use and recycling returns at EOL state.

The current façade systems of Scheldebouw are to be reviewed for circularity and disassembly potential. Uncomplicated measures for improved circularity are to be tested on the systems and checked for their impact. By doing so a catalogue of initial measures is produced enabling the company to evaluate the effectiveness of the various amendments.
The gained knowledge of the existing projects is to be translated into a new improved design. The new design is to be designed and checked with the previously established rating systems towards their potential and if necessary changed in order to achieve a higher score.

**Final product:**
The research shall indicate a pathway to calculate the Circularity and Disassembly capacity of a unitized façade.
The further outcome of the research shall be a unitized façade system which is following the design principles of Scheldebouw while being optimized for disassembly and improved for its life cycle performance.
Hypotheses about the direction of solutions
When designing a building component with Circularity and Disassembly in mind various established design approaches are established already which can be followed.

As outlined by the Ellen McArthur Foundation in 2013, and summarized by Rizos et al. in 2017 there are three main circular economy processes that are to be applied. The first basic step is to limit usage of primary resources which can be achieved by a higher recycling efficiency, the efficient application of limited resources and employing renewable forms of energy only. The second measure consists of keeping materials and components at the peak of their worth or best quality. Products are to allow for repeated production, renewal and recurring application. The service life of the component is to be prolonged to achieve maximum return of the investment. The third action is to apply new forms of user arrangements. This can be in the form of rather than selling the product to lease the product in return for a guaranteed performance, divided ownership or a change in the behaviour of the end-user (Ellen McArthur Foundation, 2013) (Rizos, Tuokko, & Behrens, 2017).
With regards to Design for Disassembly Crowther provided a summary of recommendations that are beneficial for enabling a successful dismantling of a project. Among them are e.g. the application of recycled materials while on the other side avoiding toxic and hazardous materials. He further mentions the use of a minimum number of different types of connectors and the preference of mechanical connections over chemical ones. (Crowther, Closing the loop - Developing guidelines for designing for deconstruction , 2000) (Crowther, Design for buildability and the deconstruction consequences, 2002).
During the research, the facades should be evaluated for their assembly procedure and life cycle coordination of materials and its functions in the assembly. The role of the base-element is to be considered in the current constructions and if necessary to be freed from double or multiple functions (Durmisevic,

2010). Further to be analysed are the elemental and relational features of the used materials. Their quality and sustainable origin are to be considered as well as their utilization in either technical or biological cycle (Geldermans, 2016). Taken the findings of the research into account the new improved design should feature alternative connection details, amended material choices and overall design changes.

**Boundary conditions:**
The research is based on unitized façade systems from Scheldebouw. These projects are rather recent, feature the current praxis and technology used by Scheldebouw and hence render them as interesting samples for this research.

The project and data selection of the chosen projects is at the discretion of Scheldebouw. Care has been taken to select projects which resemble their standard approach and techniques.

The project selection is limited to three projects in order to limit time expenditure on data establishment and calculation running. A wider project selection might produce clearer results but might very likely go beyond the given time frame.

During the research, the three projects are rated with previous chosen rating methods with focus on recycling and reuse potential and the discoveries shall be applied for an optimized facade model.

The effects of a potential change of ownership i.e. lease model are not considered and offer an opportunity for students of other faculties.

## 1.4 Research questions

Considering the need to produce building components which are more environmental friendly the need for building components designed to comply with the principles of the Circular Economy the research tries to find answers to the following questions:

**Main research question**

***To what extent can Design for Disassembly contribute to optimize the facades of Scheldebouw for Circularity?***

**Design question**

***How does a standard façade of Scheldebouw look like when optimized for Disassembly and Circularity?***

In order to answer the main research  and design questions multiple sub-questions are to be answered first which will be subsequently be addressed in the coming chapters.

**Sub-question**

***What is does Circularity mean and how are its principles to be translated for construction?***
***What are the adjoining principles around Circularity?***
***What is Design for Disassembly and why is it significant?***

***Who are Scheldebouw B.V. and how do they handle the design and production of their products?***
***What is the current practice at Scheldebouw to manufacture their facades?***
***How can unitized façade elements be disassembled what can be learned from it?***
***What is the current salvage practice of Aluminium facades and to what extent do the materials return to the material stream?***
***How do the selected projects of Scheldebouw rate for Circularity and Disassembly Potential?***
***Which conclusions can be drawn from the results of the rating for a new design?***
***Which straightforward measures can be applied to the existing systems and how effective are they?***
***What are potential approaches for a new design of unitized systems?***
***How do the new designs rate regarding Circularity performance and Disassembly Potential?***

## 1.5 Approach and Methodology

The research shall follow the following approach:
Based on literature research the term Circularity shall be described at first and leading from there its adaption to the build environment shall be undertaken. The adjoining principles e.g. Blue Economy or Cradle to Cradle will be analysed in order to establish the distinctness of each theorem. Likewise the term Design for Disassembly is to be interpreted and its importance evaluated with the help of further literature research.
To find suitable rating methods for assessing Circularity and Disassembly several procedures are to be reviewed with the help of further literature research and the most suitable options are to be described in more detail.

For gaining understanding of the working practice of Scheldebouw interviews and meetings are conducted. In addition the current assembly process is documented by accompanying working personal in the plant and examining the steps undertaken in detail. In a separate investigation an existing unitized façade panel is dismantled. The required steps are documented and the findings are listed enabling conclusions for an improved facade design.

The current steps and state of façade recycling is established via a mix of literature research and expert interviews. The documents of material suppliers are explored for relevant data. The gained insights

# RESEARCH FRAMEWORK
## Introduction

are applied as input to the assessment systems. The projects provided by Scheldebouw for review are inspected for material types and distribution with the help of existing material charts and additional measurements done in CAD.
The data is computed with the rating procedures and the results are tabled, the facades are interpreted for their shortcomings and strengths. Finally the findings are translated into guidelines for improving the following design process.
A redesign is undertaken keeping the outcomes of the previous process in mind and eventually it undergoes the same rating procedure as the projects originally handed over by Scheldebouw. The outcome will be documented and compared with the previously received returns. The difference determines if Design for Disassembly can be beneficial to gain a higher level of Circularity and to what extent.

The research is divided into consecutive steps:
1. Definition of Circularity and its adaptation for the construction environment.
2. Showcasing adjoining principles and exploring Design for Disassembly (DfD).
3. Establishing a broad overview of existing rating systems for Circularity and DfD.
4. Selecting the most appropriate assessment systems and providing more insight.
5. Providing a profile of Scheldebouw and investigating their work methods.
6. Documenting facade assembly and disassembly steps and making conclusions.
7. Summarizing recycling flow and material info.
8. Describing the sample projects and rating them. Drawing conclusions.
9. Setting out objectives and generating new design approaches.
10. Rating the final designs for Circularity and Disassembly and evaluation.

Step-by-step approach or logical organisation scheme

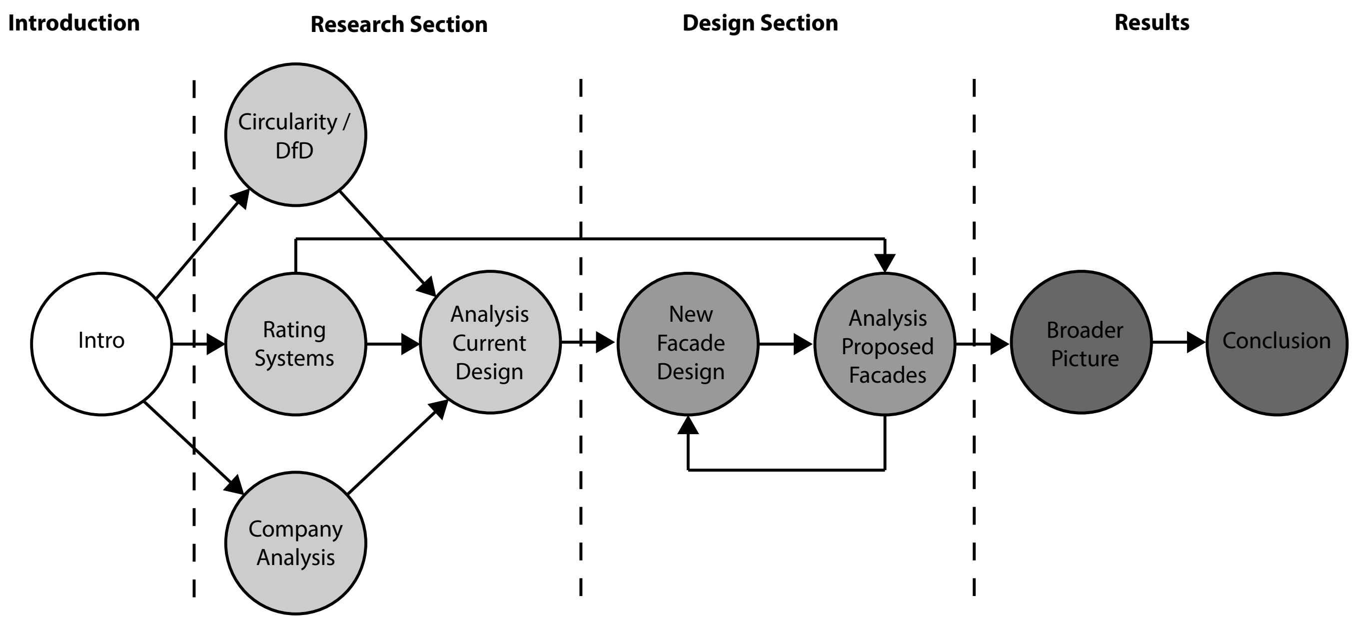



Fig. 1: Research methodology scheme (source: own image)

## 1.6 Relevance

Societal relevance

The dominance of the linear economic system based on the principles 'take, make and waste' leads to an immense loss of resources and cause severe environmental destruction. The Cradle to Cradle philosophy developed by McDonough and Braungart shows a way out of the problems mankind produced by its irresponsible squandering of resources. Design for Disassembly can contribute to reduce our energy and resource consumption. While other industries e.g. the car industry progressed in this field and benefitted from returning old products back into the circular lifecycle, the construction industry lags behind. This research aims to contribute to the ongoing discussion of transforming buildings to comply with a circular lifecycle approach. This happens with the intention to conserve the environment to the benefit of our society.

Scientific relevance: projected innovation

The focus of this research lies on improving the circularity of unitized façade systems. Currently façade systems are not designed with the intention of disassembly, with the resulting downcycling of material and energy loss. To the knowledge of the author not attempt was undertaken yet, to improve the tailor-made façade systems as Scheldebouw produces them for disassembly. In order to stop further resource depletion on account of unitized facades this exercise is undertaken which will hopefully show an alternative to the current design. With the support of Scheldebouw, an industry leading company, a partner is on board, which can transfer potential solutions into reality. The result will fortunately be helpful for the façade industry, contractors and architects.

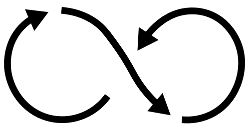
## RESEARCH SECTION

# 2 | CIRCULARITY AND DFD

## IN BRIEF

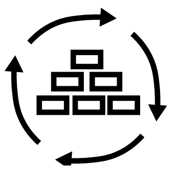
The second chapter introduces the concept of Circularity and shows what it means for the built environment. It entails a broader view on the framework that surrounds Circularity and focuses in detail on Design for Disassembly. The outcomes and definitions found in this chapter will help to understand the significance and nuances of the subject and contribute to a proper selection of rating systems.

**CIRCULAR ECONOMY**



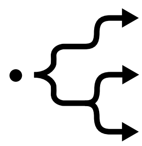
**The Circular Ecomy is considered the antidote to the dominant linear economiv model.**

**CIRCULAR CONSTRUCTION**



**Circular Construction is compliance with the principles of the Circular Economy regarding creation, planning, assembly etc.**

**DESIGN FOR DISASSEMBLY**



**DfD is considered as a coordinated action to divide a previously put together article.**

# 1. CIRCULARITY AND DESIGN FOR DISASSEMBLY
**Research Section**

## 2.1 Circular Economy

**Origin**

With the begin of the industrial revolution which was characterized by the change to new manufacturing processes in Europe and the United States between approximately 1760 to 1840 the adoption of the linear economic model took place. The linear economy stands for products which are mass manufactured from raw material, sold for a profit, enjoyed by the user for the time of their life span and then ditched as garbage. Considering the continuous rise of the world's population and with it the ever growing demand of successively shrinking resources it is obvious that the present economical model cannot be upheld indefinitely (Wautelet, 2018).

One of the first mentioning of the concept of Circular Economy goes back to Pearcer and Turner who compared the model with laws of thermodynamics. The laws are based on the principle that everything forms an input to everything else. When applying this thought onto the present linear economy they concluded that another economy is to be found which is based on circularity. They focused on the point of sustainable economic development and on a different regulative and analytical viewpoint. Their approach is featured by a connection between the economy and the ecosystem and thereby integrates three important economic functions of the environment together: resource provider, waste converter and begin of utilisation. Resources are the starting point pf production which creates a good. The good in turn leads to utility or benefit. At every step waste is generated consequently (Pearcer & Turner, 1989).

Previously Kenneth Boulding described two different types of economies: the 'cowboy' and the 'spaceman' economy. With the first type her refers to a mindset which considers the resources on earth as limitless. If at one place the resources are exhausted it is simply a matter of moving to another place with fresh resources. Consumption and production are seen as the measurements for success. This model represents the linear economy as it is dominant today. Boulding points out however that resources are in fact limited on Earth and mankind shall rather take cautious approach and limit production and consumption. Success in this model is based on the character and complexity of the total capital assets which incorporates the condition of peoples' body and mind. In short Boulding made a stand for the economy to adapt to the ecological system with its limited resources (Boulding, 1966).

In 1976 Walter Stahel and Genevieve Reday wrote a report to the European Commission about the potential of economic loops and their positive influence on employment, economical competing performance, reduction of resource depletion and their avoidance of further waste production. Later in 1981 Stahel determined that leasing products on a performance basis is a superior business model than selling goods since selling the right to use an article leads to continuous income flow on the letter's side while not outsourcing the costs of risks and waste on the leaser's side (Stahel & Reday-Mulvey, 1976) (Stahel W. R., 2020).

The idea of switching from the linear to a circular economic model was further developed by the Ellen McArthur Foundation in collaboration with the McKinsey Company highlighting the economic benefit of the model as a multibillion profit opportunity for a selection of European businesses alone (Ellen McArthur Foundation, 2013).

The understanding of the term changed over the recent decades by an increasing amount of research over the topic (Lieder & Amir, 2016). The idea of the Circular Economy was rephrased and amended to Industrial Ecology by Garner & Keoleian as 'a research discipline underpinned by a systems approach and involving a holistic perspective when dealing with human economic activity and sustainability' (Garner & Keoleian, 1995). The main idea of this discipline is the understanding of environment and industry working in the same way and featuring similar flows of material, power and data (Erkmann, 1997). Murray, Skene and Hayes conclude that 'the term 'Circular Economy' has therefore been linked with a range of meanings and by different authors, but what they generally have in common is the concept of cyclical closed loop system.' (Murray, Skene, & Haynes, 2017)

**Definition**

At present definitions of the Circular Economy read as follows:

*"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, systems and business models."* (Ellen MacArthur Foundation, 2014)

*"A circular economy preserves the value added to the products for as long as possible and virtually eliminates waste. The resources are retained within the economy when a products has reached the end of its life, so that they remain in productive use and create further value".* (European Commission, 2014)

*"The circular economy is a generic term for an industrial economy that, by design or intention, is restorative and eliminates waste. Material flows are of two types; biological nutrients, designed to re-enter the biosphere safely, and technical nutrients (nonbiological materials), which are designed to circulate at high quality, with their economic value preserved or enhanced".* (Wallace & Raingold, 2012)

*"The circular economy can be defined as an industrial economy with an resiliency as intention has and consumption where it is possible changes into usage. The circular economy is based on closing the loops and to (where possible infinite) extend a cycle. It invites therewith to more use of renewable energy, minimalize the pressure on the ecological system, eliminate the use of toxic substances, and assumes that waste is the start of the next phase of life and that reuse is included in the design phase".* (Schoolderman, et al., 2014)

When comparing those definitions the same aspects repeat and can be combined to form the following summary:

The Circular Economy is an industry based economy which is restorative to the environment by replacing the present end-of-life concept with a closed loop concept. By using renewable energy and eliminating waste production and toxic substances and considering waste the start of the next phase of life the Circular Economy keeps products and materials productive in order to preserve or enhance product and material value while simultaneously retaining resources.

A more comprehensive review of the term showed that a final definition of the term seems not possible as it receives much attention currently and is interpreted in various directions by many scholars. As a result the concept lines are blurred which leads to occasionally wrong usage too. (Kirchherr, Reike, & Hekkert, 2017)

**Principles of the Circular Economy**

Since the definition of the Circular Economy is hard to outline, the principles are reviewed to get a clearer understanding of the term. According to Ellen McArthur Foundation three main principles exist on which the system is based (Ellen McArthur Foundation, 2013).

1. The natural assets are to be preserved and increased by monitoring the material levels and

answering need by tapping sustainable resources.

2. The revenue of resources is to be improved by always making the best use of materials, components and products in terms of value and usage. Here it is important to differentiate between biological and technological materials. The effect of different loops of the systems are to be kept in mind:

- Power of the Inner Circle: The closer the loop is to the user or consumer the more value of the material or product is reserved.
- Power of Circling Longer: The more often the material is cycling and the longer the material keeps cycling the longer is the lifecycle of the material.
- Power of Cascades Reuse: applying to the biological circle only, extracting more value of the material by running it consecutively through functions of lesser category and therefore minimizing the need for virgin material inputs.
- Power of Pure Materials: the purer a raw material is the higher value is kept and therefore the higher quality is preserved the higher the efficiency of collection and recycling of the material, leading again to longer lifecycle and yield.

3. Monitoring system performance and preventing performance loss.

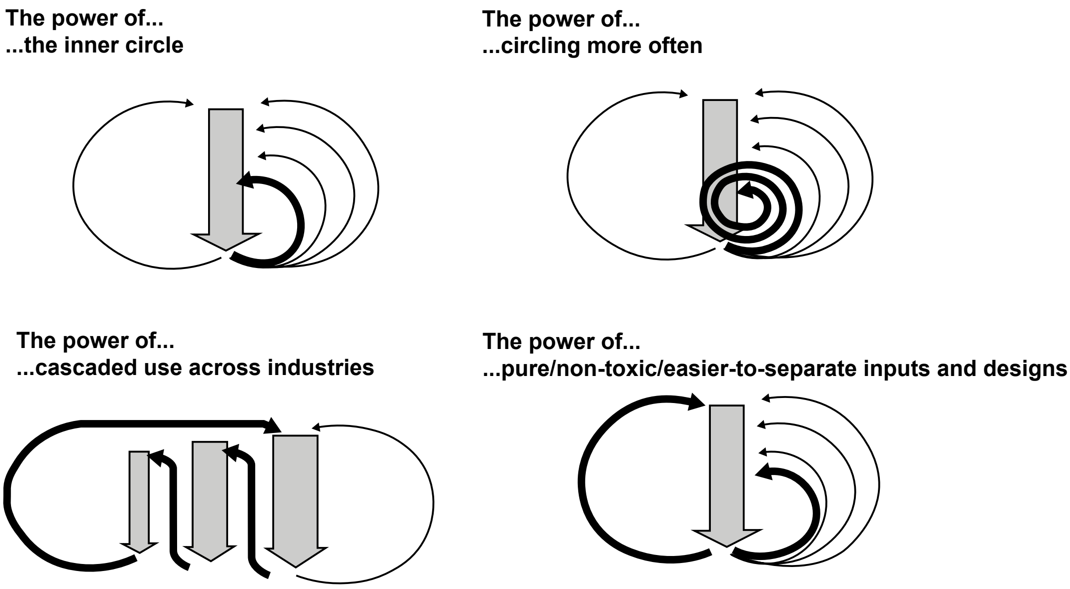



Fig. 2 - The power of circles (source: Ellen McArthur Foundation, 2013)

The Ellen MacArthur Foundation further distinguished the types of material in renewable and finite materials. The biological cycle features materials of biological nutrients which can be recovered. According to Ellen McArthur Foundation the following biological cycles exist (Ellen MacArthur Foundation, 2014):-

1. Cascading, closest loop to the consumer, reaping the stored energy of a material in an optimal way along various functions which ask for decreasing quality and thereby extracting maximum value.
2. Biochemical Extraction, converting biomass into electricity, heat fuels, power or chemical products.
3. Anaerobic Digestion, transforming biomass into biogas for energy and residual waste.
4. Composting, turning biological waste into compost with the help of microorganisms.

On the other hand materials the technical cycle shows limited materials which can be recovered and restored at the end of their service life. The cycles can be described as follows: (Durmisevic, 2010)

1. Design for Maintenance, closest loop to the user, supporting maintenance, allowing removal and replacement of components
2. Design for Reuse, extending lifetime by allowing reuse of components

3. Design for Remanufacture, remanufacturing components to achieve almost original condition, applying quality control
4. Design for Recycling, furthest loop from the user, up-cycling into new products or down-cycling into safe waste

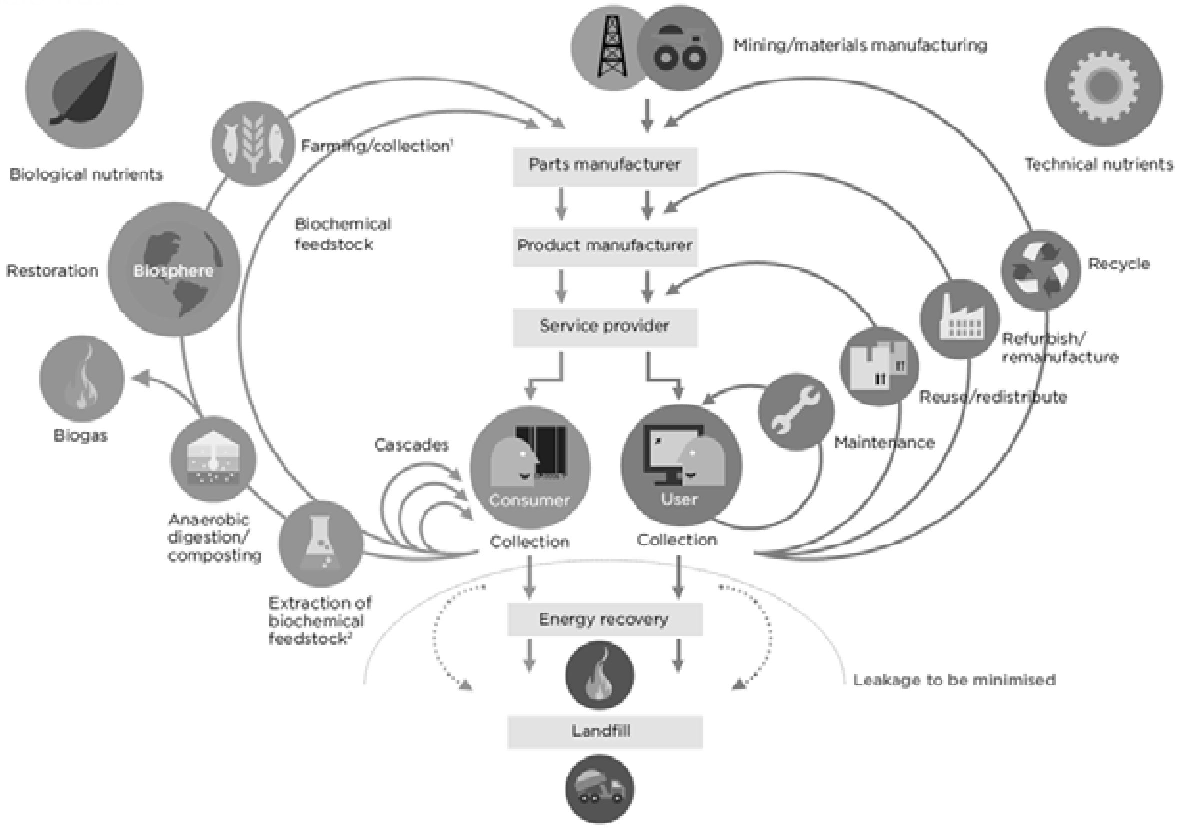



Fig. 3 - The Circular Economy (source: Ellen McArthur Foundation, 2013)

## 2.2 Framework Circular Construction

Several adjoining principles surround the Circular Economy have either direct or limited impact on its accomplishment. Some are rivalling concepts that work in a very close manner but aim for other goals. Knowing the framework and it nuances enables to understand the relations and dependencies of the Circular Economy better.

### Cradle to Cradle

The term Cradle-to-cradle describes a design approach for products and systems that imitates processes found in nature considering that waste does not exist but instead resemble nutrients for a new process or product. The authors start with illustrating the common thinking that industry and environment have opposed principles that can not be combined to be in harmony and support each other. The one can only thrive at the expense of the other. This view is not correct and authors go on to explain how:

The linear, one-way cradle to grave, model means that natural resources are collected, products made from them, the products are sold to customers and once the products are exhausted they end as landfill or get incinerated. The cradle to grave design is the dominant production method. Consuming less does not help either. To believe that being less bad is enough to find equilibrium with nature again is wrong. The problem is just delayed. The authors summarize that a new design and industry approach is requested in which e.g. buildings produce more energy than they consume, factories produce safe effluents and products become nutrients for other processes once they are broken.

The following prerequisites to allow for this approach are listed as follows:

- Waste equals food. In nature the concept of waste does not exist. Waste equals food as all waste enters the environment as nutrients again. As a result growth was good, resulting in more diverse environment and a stronger ecosystem. Industrial activity by humans resulted in materials which can not returned safely to the environment, they do not break down in nutrients. Since then two cycles exist, the biological and the technical. All waste is considered nutrient in Biosphere or Technosphere.

- Eco-effectiveness instead Eco-efficiency. While eco-efficiency might be better than standard practice it is still not right. Eco-effectiveness means doing the right thing. Nature does not follow the efficiency model of humans. Nature relishes in abundance and diversity. Growth is considered positive in nature, it is considered negative by environmentalists regarding industry. The industry sees no growth as threatening. The perception is that nature and industry can not be complimentary but that one must make sacrifices for the other. The main aspect is to make industries more efficient and having less impact but making them eco-effective.

- Embrace Diversity. The Earth is characterized by the diversity of nature. Even catastrophes do not hamper the spread of nature. Humans do not consider local settings, but rather apply everywhere the same principles, destroying natural habitats. Instead of evolution, humans create devolution all over the world. Distinctiveness contributes to enrich the environment and to find answers to our current problems.

- Leasing instead buying. The cycle of a consumer buying, using and discarding a product is to be broken. In place of buying a product comes buying a performance. The consumer rents the product for its performance only. When the product is broken or out of fashion, the producer brings a new model, takes the old one back, disassembles it and makes sure the parts are reused as new nutrients for a new product. The consumer gets the service he wishes for as long as he wants while the producer can develop and remains owning the precious components and materials. Precious technical nutrients are returned safely to the technical cycle. (McDonough & Braungart, 2002)

**Regenerative Design**

Based on the view that the ongoing trend of reducing fossil fuel consumption, emission output, waste production and water usage is heading in the right direction, but that it is not sufficient to halt ecological disaster in the long term, the built environment is to undergo changes to become a net contributor of positive effects on the environment. (Jenkin & Pedersen Zari, 2009)
It is understood that mankind and the built environment exist within one ecosystem.
Rather than eat up precious limited resources a building should produce a positive effect on its surrounding. The designer must completely comprehend the role of a project and nature to find the key to a regenerative design. A stepped process is to be applied in order to achieve a truly regenerative design. The three phases consist of:-

- A complete assessment of the place reviewing e.g. its culture, economy and climate. Further creating awareness of how humankind can help the place to prosper while being in coexistence of it.
- Converting the gained insights of phase one into a design which perfects the occupation of a place by man while creating a balance with it on a bigger scale.
- The third phase allows for combined transformation and growth of the system in the long run with the understanding that the design is never completed but an ongoing process. With the continued

change of the surrounding designers must provide ideas to the community for maintaining the bond with the place and at the same time highlighting upcoming chances regarding social, economic and ecological changes. (Mang & Reed, 2012)
Regenerative Design with its background in ecology, agriculture, urban planning and landscaping offers a broad view on the matter of circularity bearing in mind also ideas of culture and society.

**Blue Economy**

The term Blue Economy was coined by Gunter Pauli in 2010 with his book 'The blue economy: 10 years, 100 innovations, 100 million jobs'. He sets out to find a solution to change the current financial and communal deterioration based on today's economic system with all its shortcomings into a system which benefits society, builds up resistance to economical shocks, applies local resources, satisfies basic needs and builds a community spirit.
Gunter outlines an idea for a new industrial economy model aiming to change society from shortage to plenty while using local resources by tackling issues that cause environmental and related problems in innovative ways. The invention of new technology based on process and examples found in nature is a key element of the vision. Like the Cradle to Cradle principle the Blue Economy praises natural systems which circulate nutrients, matter and energy and in which the concept of waste is non-existent. (Pauli, 2010)
The Blue Economy has a strong focus on creating business opportunities applying modern technology based on processes which can be found in nature.

**Eco-efficiency**

The origin of the principle of Eco-efficiency can be traced back to a publication 'Changing Course' by the World Business Council for Sustainable Development (WBCSD) from 1992. The concept suggests to enforce complete change from an unsustainable growth to a sustainable growth. (Schmidheiny & Timberlake, 1992)

"In the analysis, ecological as well as economic aspects are considered from the customers' point of view. The product/process that provides the specific customer benefit of the lowest cost and lowest environmental burden is the most eco-efficient." The term is often connected with being a management principle that is adapted to achieve a higher level of sustainability with the means of bringing together ecology and efficiency in the most efficient manner. (Widheden & Ringström, 2007) Critique on the principle came from McDonough and Braungart who considered the change as insufficient as the present ways of industry and the consumptive behaviour with their negative results for the environment are not tackled enough. McDonough and Braungart laid out that minimizing people's impact on the environment is not the right way as a less destructive behaviour or production is still a destructive one. At best the principles achieves a neutral impact on nature while allowing for maximum efficiency (McDonough & Braungart, 2002).

**Restorative Design**

The emphasis of Restorative Design lies on restoring the ecosystems through development. It recognises that slowing degradation is not enough. Humans firstly must recognize the harm they cause to the environment and then take action to make good with new developments. For the process to succeed it is important that humans see themselves as part of a living system and amend their thinking and designing accordingly. Architecture and development play an important part in this system and benefit from the paradigm shift. (Couchman, 2007)

Restorative Design can be summarized as a process of humans managing and adapting the natural environment. Three main conditions for creating a regenerative framework must be fulfilled. The first is the realization of the main order of the location in question. The second condition is to derive a direction for the design and a concept from the local main order. The third aspect consists of continuously gaining knowledge and taking part by doing, communication and contemplation.
(Reed, 2007)

**Bio-inspired Design**

The term biomimicry dates to the 1960s and describes a design and production of materials, structures and systems reflecting biological entities and processes. It gained wider popularism after Benyus published her book Biomimicry - Innovation Inspired by Nature in 1997 (Pedersen Zari, 2008).

A Bio-inspired Design is featured by intimate knowledge about the relationship between biology/ecology and improvements in technology (biomimicry) or in psychological wellbeing (biophilia) (Pedersen Zari & Storey , 2007)
Its outcome can be regenerative, restorative, eco-efficient or conventional subject to the interpretation by the design team. It has the potential to contribute to regenerative design goals. (Benyus, 1997) (Pedersen Zari, Bioinspired architectural design to adapt to climate change, 2008) (Pedersen Zari & Storey , An ecosystem based biomimetic theory for a regenerative built, 2007)

Bio-inspired Design stands as opposite to the present way of construction being a main culprit of consumption and pollution. Knowledge of the location and surroundings are prerequisite but in addition deep knowledge of ecology. Biomimicry on the base of ecological systems represents the yardstick for judging if amendments to the built environment are suitable. It is an extremely powerful tool to create highly sustainable and lastly regenerative environments. (Pedersen Zari & Storey , 2007)

## 2.3 Circular Construction

Considering the gained knowledge about the CE the question arises how these qualities can be transferred in the construction world. Therefore the following section addresses the translation of the CE into the field of construction.

Pomponi and Moncaster criticized that the current research of the influence of CE lies too often on the macro level e.g. urban clusters or the micro level e.g. building components and too often neglects the meso level consisting of single buildings.

“A level of analysis which is currently lacking is the building as an entity per se. This is in stark contrast with the more standard practice of environmental impact assessment research, most often in terms of embodied energy and carbon footprint, for which buildings rather than cities or materials are the most common level of analysis in current literature.” (Pomponi & Moncaster, 2017)

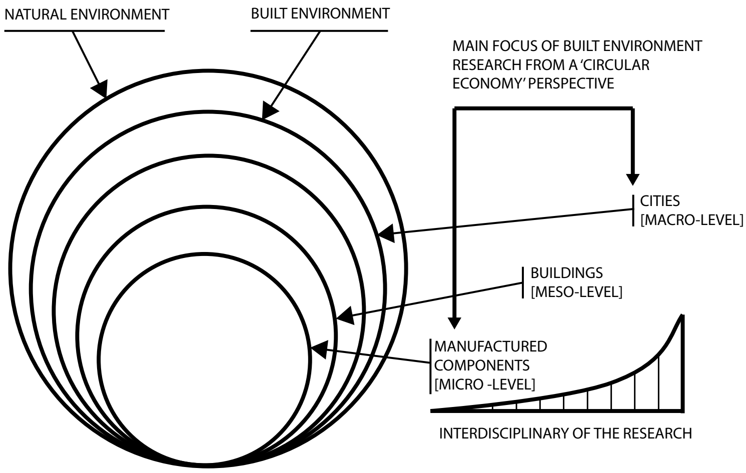



Fig. 4 – Framing of built environment research (source: Pomponi & Moncaster, 2017)

Therefore they commenced on finding the elemental definition of the CE and its core meaning for the built environment. After assessing the hurdles for the application of CE models in the built environment they reviewed the present status of CE research and found that six main directions are followed by researchers. By structuring the various approaches of other researchers they concluded that a building in order to follow the principles of CE has the be a construction created, planned, assembled, managed, upkept and dismantled in compliant ways to Circular Economy standards.

Further they state that:
'Every building can be considered as one-off project, tailor-made to a unique setting. This characteristic is further enhanced by a fundamental intricacy, with each material applied having a different life cycle and all material cooperating with each other. In addition buildings have to endure multiple changes over their long life span, with the little foresight what the next change might hold in store.' (Pomponi & Moncaster, 2017)

Considering the above Pomponi and Moncaster conclude that circular buildings are not created by limiting resource consumption, performance enhancement, bettered recycling rates and repeated usage but two additional conditions are to be taken into account:-
- Because of buildings lasting a long time, material with short life expectancy are no match for them. With buildings lasting that long future building stock will consist for the most part of present buildings. Solutions should be found for present building stock instead of looking into applications to new buildings.
- In order to construct a building many different material are assembled in exclusive way. Hence disassembly differs from one building to another. (Pomponi & Moncaster, 2017)

Another pair of researchers who examined the life cycle of building components were Frank Duffy and Stewart Brand. They described the shearing layers of change in buildings in relation to the hierarchy of components in the building. They reduced structures to six different layers: interior, space plan, services, structure, skin and site. Each layer is considered to have a different life cycle with the interior having the smallest and the site having the longest. This layer principle turns problematic in present day buildings which combine many layers in one. In this case layers of short time cycles mix with layers of long term cycles. As a result replacement of short time layers causes damage to long term layers. The researchers conclude that this leads to the building breaking itself apart. (Brand, 1995)

## 2.4 Design for Disassembly

The previous chapter reviewed the framework of the Circular Construction and highlighted similarities and differences of the surrounding concepts. The role of the Design for Disassembly and when its application is considered to be beneficial will be examined in this chapter.

First design principles for the various retention loops are described and then the key position of Design for Disassembly clarified.

**Design for Repair**

In reference to the power of circles as per Ellen MacArthur Foundation and mentioned before the Design for Repair forms the most inner circle. Since the loop is closest to the user or consumer the most value of the material or product is reserved.

The main characteristic of Design for Repair is its enabling the removal and substitution of parts or components which goes beyond ordinary maintenance in order to prolong the use phase of an component or a system. (Giudice et al., 2006)

Stahel sees this as the key feature for lifetime extension and to reach highest material efficiency yields. Furthermore the process of repairment creates manifold valuable opportunities for businesses in the private sector. Reuse, repair and remanufacture take place within the limited regional and therefore reduce the need for extensive wrapping and transport emissions. And if the product remains with the original owner no costs for changes of ownership occur. (Stahel, 2013).

The question of ownership was emphasized by another researcher. It is considered an important point that Design for Repair applies to the use□phase of the product meaning that a change of ownership does not necessarily take place as it is with other design approaches. (Tecchio, McAlister, & Ardente, 2017)

**Design for Remanufacturing**

Design for Remanufacturing appears on the list of the circles as per Ellen MacArthur and while it does not preserves the same product value as Design for Repair or Design for Reuse it supports the prolonged use of the product by making good through by a the product manufacturer which in turn benefits economically.

Remanufacturing is a process of bringing used products to a "like□new" functional state with warranty. It reduces landfill and the levels of virgin material, energy and specialised labour used in production. It is preferable to recycling because it adds value to waste products by returning them to working order. (Ijomah, McMahon, Geoff, Hammond, & Newman, 2007)

Mabee et al. point out that the advantages of remanufacturing can be plentiful, starting from a cost reduction for remanufactured goods between 30-60% over useful insights about failure reasons for the manufacturer which lead to a better product design, less product failures to a higher customer satisfaction. They describe in more detail that Remanufacturing may involve partial replacement, repainting, milling and other forms of alteration or update. Furthermore the following steps of disassembly, sorting, cleaning, refurbishing and reassembly are to be followed to achieve Remanufacturing. (Mabee, Bommer, & Keat, 1999)

**Design for Recycling**

Recycling represents the least effective step for restoration following the principles of Ellen MacArthur. If a material can not be recycled it has not other option but for incineration or landfill.

According the Henstock Design for Recycling involves the collection, separation, and processing of products and materials for recovery to use in the form of raw materials in the manufacture of new products. Further recycling of parts and materials reduces the need for virgin material, thus reducing extraction (Henstock, 1988). However it reduces the used product to its raw material value (Hundal, 2000).

Within the European Union it is stipulated that recycling is the reprocessing of waste materials into products, materials or substances for the original or alternative purposes. While this entails the reprocessing of biobased substances it excludes energy regain and transformation into materials for fuel or backfilling (European Union, 2008).

McDonough and Braungart emphasized that the outcome of most recycling processes is of inferior quality in comparison to the quality of the original material i.e. downcycling. Repeated recycling reduces the quality of materials. Recycling requires energy to transform a material into a another product differing from its original application and thereby delaying their disposal or incineration by one or two product life cycles. In addition recycling may lead to the addition of dangerous substances which the original material did not contain before (McDonough & Braungart, 2002).

**Design for Assembly**

This principle represents an approach in which products are planned with ease of assembly in mind with the aim to increase assembly speed and reducing assembly costs by reviewing number and shape of parts, connection methods. This can be achieved by providing a component with features which make it easier to grasp, move, orient and insert them.

Hitachi was the first company to introduce Design for Assembly as a method to ease production. Their approach consisted of allowing one motion for one part. Complicated motions are evaluated via a point counting process. The original intention for the method was the rating automatic assembly (Boothroyd & Alting., 1992).

Another method to measure a product for Design for Assembly is the Lucas DFA method which was introduced in the begin of the 1980s by the Lucas Corporation from United Kingdom. By following a point scale the effort required for assembly is measured. The core of the system is based on three separate and subsequent analyses, which are conducted with the help of flowcharts imitating the assembly sequence (Anil, Desai, Subramanian, & Mital, 2014).

Notably is a method to measure the performance of Design for Assembly which started development in 1977 by Boothroyd and Dewhurst and was first published in 1980. The method encourages designers to reduce the number of parts, to improve handling of parts, either manually or automatic and to reduce production time.
Following the method leads to cost savings and a reduction of product fails (Boothroyd & Alting., 1992).

The principle does not form part of the restorative circles outlined by Ellen MacArthur Foundation but can be considered as a preliminary stage for Design for Disassembly.

**Design for Adaptability**

Design for Adaptability is based on the hypothesis that in general a product's life ends because the product's inability to adapt to change. The design principle intends to change inflexible products to active, adaptive systems with the adaption being undertaken by the user or producer. The user is enabled to extend the service life of the product while the manufacturer can adapt the design.
The potential for adaptability must be incorporated already at the design stage. Products can be designed to enable adaption of certain design features or performances by enhancing width of use, upgrading, diversity, and tailor-made adjustment. If no definite direction for adaptability is specified the product is planned to allow for general adaptability (Hashemian, Gu, & Nee, 2005).

**Design for Disassembly**

Due to concerns for the environment, people's health and resource scarcity in the industrialized countries the principle gained attention and was taken up first by the motor companies and then the computer industry in order to tackle the growing waste amounts. (Boothroyd & Alting., 1992)

The concept of Design for Disassembly is logical consequence of Design for Assembly. It aims to ease dismantling of products or structures by allowing to split products into its elemental components, sub parts, elements. By doing so it facilitates maintenance, repair, re-use, remanufacturing or recycling. (McDonough & Braungart, 2010)

Other researchers defined the principles as an coordinated action to divide a previously put together article. The reason for disassembly ranges from allowing upkeep, boost usefulness or to facilitate the various end of life options i.e. maintenance, repair, re- use, remanufacturing or recycling. The rising popularity of Design for Disassembly is owed to the increased realization of the environmental importance and that the principles enables various end of life options (Desai & Mital, 2003).

In the previous chapter the various value retention options of the technical cycle as set out by Ellen MacArthur Foundation were described; they include repair, reuse, remanufacture and recycle.

More recent studies show that the number or retention cycles can be increased from previously 3 or 4 to 10, from R0 being refusal by the product consumer until R9 which resembles re-mining of old land-fills. The following separation can be applied:-

1. Short Loops with highest value retention
RO = Refuse
R1 = Reduce
R2 = Resell
R3 = Repair

2. Medium loops with reduced value retention
R4 = Refurbish
R5 = Remanufacture
R6 = Repurpose

3. Long loops with least value retention
R7 = Recycle
R8 = Recover
R9 = Remine
(Reike, Vermeulena, & Witjes, 2018)

# CIRCULARITY AND DESIGN FOR DISASSEMBLY
## Research Section

By applying the aforementioned retention loops to a linear product life and adding first the retention loops and secondly the various design approaches the key role of Design for Disassembly can be graphically demonstrated.

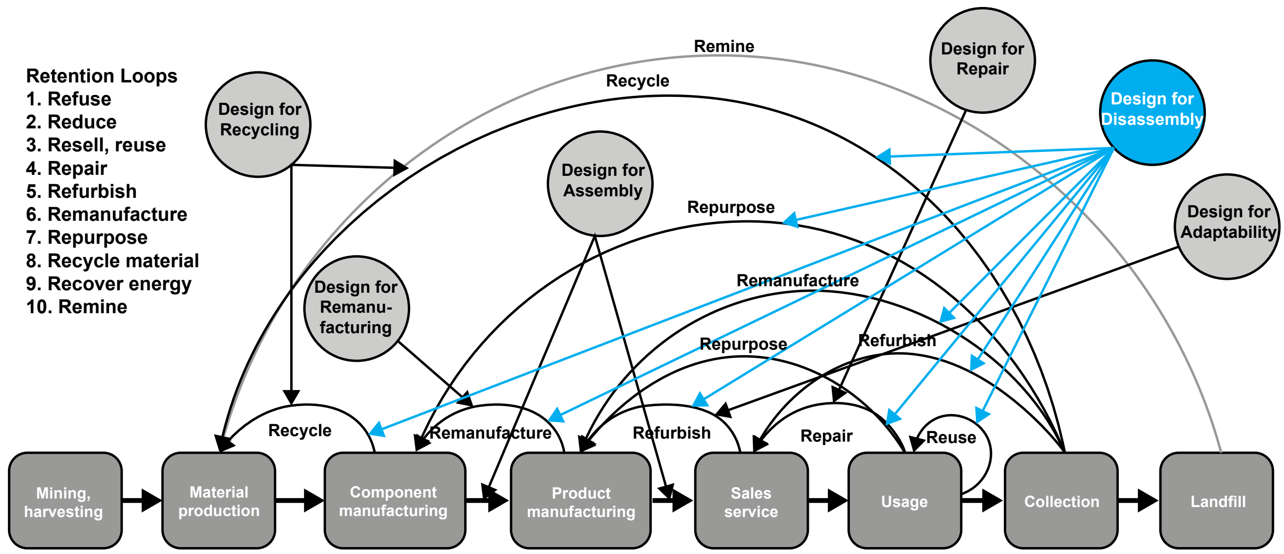



Fig. 5 – Retention loops and design approaches (source: own image)

Further confirmation for the key role of DfD can be found in the research done by Bocken et al. in 2016. Their work confirmed the importance of DfD for the Circular Construction.
'Finally, "Design for Disassembly" is a strategy, which is overlapping with, and contributing to Design for a Technological and Biological cycle. It is about ensuring that products and parts can be separated and reassembled easily. This strategy is also vital for separating materials that will enter different cycles (biological from technological).' (Bocken, de Pauw, Bakker, & van der Grinten, 2016)
Bocken et al. take over the system of slow and closed loops which they based on earlier research from Stahel and McDonough & Braungart. (Stahel W. , 1994) (McDonough & Braungart, 2002) The paper distinguishes between two different strategies regarding the cycling of resources:
1. Slow resource loop: By improving the durability of a product its service life is prolonged which result in a longer life span and the resource flow is lowered.
2. Closing resource loops: By returning the product after usage to recycling the materials are re-turned and made ready for production, creating a circular material flow.
Bocken et al. conclude that DfD is an applicable strategy for the creation of both loops, the slow and the closed type, making DfD the only strategy contributing in both cases.

| **Design Strategies to slow loops** | **Design strategies to close loops** |
|---|---|
| **Designing long-life products** | Design for a technological cycle |
| Design for attachment and trust | Design for a biological cycle |
| Design for reliability and durability | Design for dis- and reassembly |
| **Design for product-life extension** | |
| Design for ease of maintenance and repair | |
| Design for upgradability and adaptability | |
| Design for standardization and compability | |
| Design for dis- and reassembly | |

Fig. 6 – Design strategies for loop characters (source: Bocken et al., 2016)

The findings of this chapter shows the key role of the principle of DfD. It supports the circularity framework, is applicable to most retention loops and is the only principle contributing to either slow and closed cycling routes. Hence DfD is most beneficial in achieving the aims of the Circular Economy.

## 2.5 Principles of Design for Disassembly

As the role of DfD is ascertained the principles of the term are to be examined in more detail.
Brennan et al. defined disassembly as
"the process of systematic removal of desirable constituent parts from an assembly while ensuring that there is no impairment of the parts due to the process."
Reasons for disassembly are of economic and environmentally nature (Brennan, Gupta, & Taleb, 1994).
Boothroyd & Alting pointed out that DfD has tremendous consequences for the recyclability, reuse, remanufac-ture easily and economically. They emphasized that several life cycle stages are affected by a products poten-tial for disassembly. During the use phase disassembly enables for repair and service. After usage it encourages recycling, re-use or remanufacture either in parts or in total. DfD may come also into play when constructions are too big to transport and require on site assembly or the chosen transport mode limits size or dimensions of the product. Lastly DfD is often applied for consumer goods which are constructed by the consumer. (Booth-royd & Alting., 1992)

DfD practices can be divided in destructive and non-destructive approaches with the destructive method aiming to recover materials while the non-destructive advance promotes the recovery of parts (Jovane, et al., 1993).
On the other hand Beurskens et al. make a point that disassemble shall be of a non-destructive manner so that salvaged elements and parts can be used again without having lost any of their value e.g. embodied energy or labour in the process. By implementing DfD in the design process the product and its materials are opened for entering the various retention loops of the Circular Economy. DfD can be defined as "The concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guaranteeing the possibility, of all circular building product levels to undergo re-life options (service, reconfiguration, redistribution, remanufacture, recycling, cascaded use, and biosphere) in a hierarchical way, achieved by the implementation of disassembly determining factors in building design." (Beurskens, Bakx, Ritzen, Durmisevic, & Lichtenberg, 2016)

Bokken et al. explain that DfD coincides with and provides for designing technological and biological cycle. DfD allows for effortless separation and re-connection of goods or components of them. DfD is crucial for materials arriving in their destined cycle, the biological or the technological one (Bocken, de Pauw, Bakker, & van der Grinten, 2016).
Assembly and disassembly are contrary operations by definition and handle quality, quantity, and reliability of the involved parts in different ways. As a result DfD can be considered the main key for recovering and enabling repeated usage of parts and components of a product to the fullest extent (Tiwari, Sinha, Kumar, Rai, & Mukhopadhyay, 2002). A study by Crowther (1999) on successfully disassembled buildings shows following characteristics of the structures:

- Light materials
- Separation of structure and enclosure
- Minimum technology solutions
- Completeness of the building system
- Open rather than closed systems
- Standard module of construction
- Limited number of standard parts
- Use of industrialised mass production processes
- Sequencing of disassembly
- Disassembly at all levels, from part recycling to whole building reuse

Crowther summarized his and other researcher's results a more comprehensive list. See appendix.

Detailed recommendation for the material selection is provided by Geldermans. He reviews materials based on their elemental and relational properties. Material properties for circular construction shall be high quality, sustainable origin and non-toxic. The relational properties of materials for circular construction shall feature the potential for either the biological or the technical cycle, standardised dimension. Further physical connections, an open system and standardised dimension shall be features of the applied materials to enhance circular building practice. (Gelderman, 2016)

Aspects that are relevant for a design to be successfully disassembled later but often forgotten were considered by Guy & Ciarimboli. During the design materials and methods for deconstruction are to be documented for later usage. Mechanical, electrical and plumbing (MEP) systems are to be separated. At all stages during deconstruction the safety of the workers is to be kept in mind. (Guy & Ciarimboli, 2003)
An approach based less on experience but on a systematic level to describe the principles of DfD comes from Durmisevic. In her opinion the principle 'design for disassembly' concentrates on the dismantling of structures or products by provisioning them with an independent design from the start and making them thereby exchangeable. She proclaims a product or building design based on several disassembly determining factors. (Durmisevic, 2010)
She aims to improve the transformation capacity of a structure to enable amendment of the same and to increase the reuse potential of components and materials.

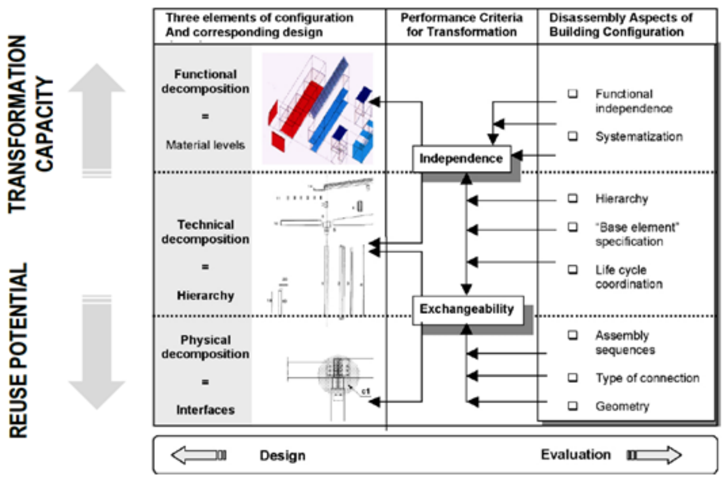



Fig. 7 – Reversible building design protocols (source: Durmisevic, 2010)

Durmisevic concentrates on three main areas to judge the transformation potential of a structure or the reuse options of components and materials. The three main criteria are described as Functional Decomposition, Technical Decomposition and Physical Decomposition. Each main criteria can be further divided into two or three sub-criteria which in turn determine the performance of the parent. The following main and sub-criteria as described as follows:-

1. Functional Decomposition
The Functional Decomposition represents the level of functions being included into a building component. This level is influenced by material selection and how the selected materials answer changing circumstances. Further materials differ in life span, durability and movement, making some material combinations unfavourable.

- Functional Independence. This sub-criteria describes the degree of split between functions within one composition and in how far the single components can function independently from each other. The separation of functions is considered helpful as it enables replacement of one component without compromising the performance of others.
-Systematization. The level of clusters to form a building component are determined with this sub-category. Clusters form sub-assemblies within a component and the higher the number of sub-assemblies within a component, the less requirements for physical connections. Further a high level of systematisation using sub-assemblies facilitates performance control during repair- or maintenance periods.

2. Technical decomposition
The aspect of Technical Decomposition examines in how far a component is built up on a clear hierarchy, allowing for a precise labelling of functions and elements. Further it is considered if the substitution of short lived elements is taken into account and if the design of the main structural element allows for hassle-free element exchange.
- Relational Pattern. This sub-category examines in how far the parts of a component are independent from each other and therefore allow for separate exchange. Separate exchange of component parts causes less destruction. Buildings with highly interwoven Relational Pattern on material level are considered static. Buildings with a systematically arranged Relational Pattern are flexible assemblies with open hierarchies.
- Base element specification. In buildings with open hierarchies parts are separated from each other and only connected to certain elements within the same assembly or component. These elements are vital to hold the component together and they are regarded therefore as base elements. The number of functions of a base element and its physical exchangeability determines the flexibility of the whole component.
- Life Cycle Coordination. The life span of materials influences the overall life span of components. Elements with a high level of reliance and therefore made of materials with long life cycles are to be installed first. On the other hand elements of lesser significance and lower life-cycles are to be assembled last. The disassembly procedure should mirror the assembly sequence.
Further the coordination of use and technical life cycle is to be considered to prevent on the one hand material failure during use life of the component and on the other hand overspecification by applying materials exceeding by far the use life cycle.

3. Physical decomposition
This main level reviews the forms and interfaces of components and in how far they help or hinder disassembly. Further the assembly sequence is examined to draw conclusions about the complication of the disassembly procedure.
- Geometry. The interface design of product edges has imminent effect on the effort to be spent for dismantling. The geometries enabling disassembly with the least effort are ‘open’ or ‘linear’ geometries with straight edges allowing for sliding out of assemblies. The worst scoring interface design is ‘closed’ or ‘integral on both sides’.
- Assembly sequence. The order of the assembly is influenced by the various factors material types, connection types, interface geometries and material life cycle. By assembling materials become interconnected and thereby depending on each other. The main character of flexible structures is the ability for dismantling with minimal effort and demolition. The assembly order creates an inverse blueprint for the disassembly procedure. Hence an assembly sequence where parts can be assembled simultaneously (in parallel) accelerates both assembly and disassembly. Similarly, a consecutive assembly order, in which one element is fixed to the one fixed previously, creates dependencies and slows down assembly and disassembly alike.
- Connections. The nature of the links between materials represent another factor to determine the effort required for dismantling a structure. Connections can be divided into three classes:-
Integral ‘direct’ connections are formed with the component edges, either overlapped or integrated. Accessory connections are produced with the deployment of an additional device e.g. a screw. Two

types of accessory connections are distinguished: internal and external. The internal accessory is inserted into the component and while this might contribute to the overall shape of the component, disassembly proves difficult as it creates a sequential assembly order.
The external accessory connection allows for easier disassembly as the connection is easier to access and does not promote sequential assembly.
Filled connections. The trademark of filled connections are that they are produced on site by applying a chemical binder between two components. Examples are concrete filling, gluing and welding. These connections are the hardest to loosen and allow in many cases for destruction only.

**Conclusion**

This chapter introduced the topic of the Circular Economy. The following sub-questions were answered:

***What is does Circularity mean and how are its principles to be translated for construction?***

The Circular Economy is an industry based economy which is restorative to the environment by replacing the present end-of-life concept with a closed loop concept. By using renewable energy and eliminating waste production and toxic substances and considering waste as the start of the next phase of life the Circular Economy keeps products and materials productive in order to preserve or enhance product and material value while simultaneously retaining resources.

A circular building was being found as construction created, planned, assembled, managed, upkept and dismantled in compliance with CE standards.
But limiting consumption, increasing performance, recycling and repeated usage are not enough to create a circular building. Disassembly procedures and material choices to match the long life of buildings are to two further main aspects to be considered for translating CE principles into construction.

***What are adjoining principles around Circularity?***

The chapter described related principles of the Circular Economy and provided insights in their features and origins. Cradle to Cradle, Regenerative Design, Blue Economy, Eco Efficiency, Restorative Design and Bio-inspired Design surround the CE and have either direct or limited impact on its accomplishment. Some are competing schools of thought that work in a very close manner but aim for other goals.

***What is Design for Disassembly and why is it significant?***

Design for Disassembly was as the process of systematic removal of desirable constituent parts from an assembly while ensuring that there is no impairment of the parts due to the process. Its significance lies in its support of enabling most of the return loops for products after their life-span has expired. Hence it is a crucial principle to meet the aims of the CE.

## RESEARCH SECTION

# 3 | RATING SYSTEMS

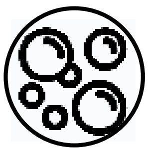
## IN BRIEF

The following chapter seeks to find answers for how to rate a structure regarding circularity and disassembly. To do so various rating systems will be reviewed and checked for their rightness. The most suitable systems will be chosen and explained in more detail.

### MATERIAL CIRCULARITY

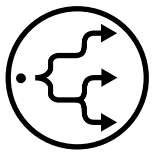
**The MCI aims to analyse the material flow during the usage of a device.**

### CO2 EMISSIONS



**The carbon footprint of a product indicates its emission level over its life span, from material production to End-of-Life Potential.**

### DISASSEMBLY POTENTIAL



**An assessment method for judging the capacity of a structure for dismantling.**

# 3. RATING SYSTEMS
## Research Section

### 3.1 Rating Systems Circularity

When looking for an appropriate way to measure the circularity of a product or construction one realizes that there no established and widely recognized method that can be applied without some level of doubt about its acceptance. Although much research has been undertaken in this field recently and the term circularity gained much attention, when it comes to rating the designer must make the decision for the rating method applied and can not revert to a common practice. Several systems compete for the designer's attention. To find a suitable system, criteria are to be found, which indicate the right choice.

The task of classifying environmental index-based methods and their capability of rating CE was undertaken by Elia, Gnoni and Tornese. They produced a systematic way to choose the most fitting method to assess CE. The crucial requirements for a rating method to measure are:

Reduction of input and use of natural resources
Reducing emission levels
Reducing material losses
Increasing share of renewable recyclable resources
Increasing the value durability of products.

(Elia, Gnoni, & Tornese, 2017)

These categories were deducted from an earlier research by Reichel et al. on behalf of the European Environmental Agency (Reichel, De Schoenmakere, Gillabel, Martin, & Hoogeveen, 2016). The criteria are being applied to review the fitness of several rating systems for judging their compliance with the principles of CE.

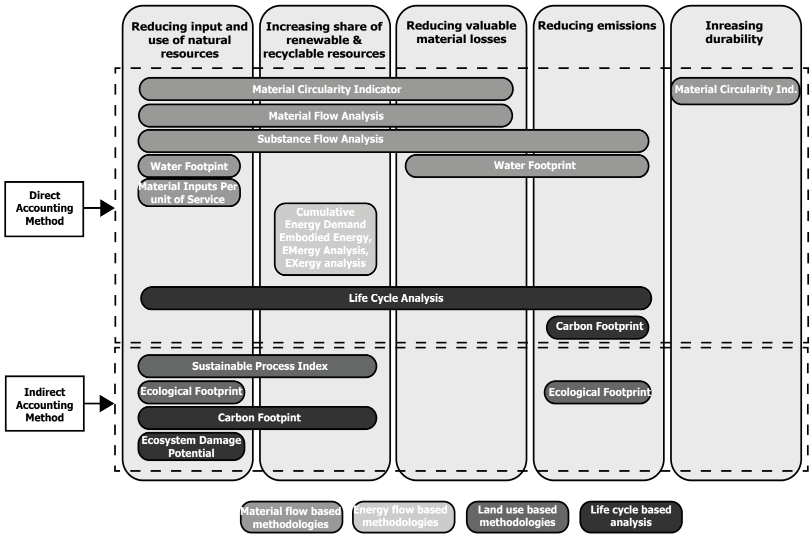



Fig 8 – Comparison of assessment methods for CE (Source: adapted from Elia Gnoni Tornese, 2016)

An illustration created by Elia, Gnoni and Tornese shows multiple rating systems and the crucial requirement they satisfy (Elia, Gnoni, & Tornese, 2017). A selection is reviewed to establish their fitness for subsequent rating process. Rating systems which cover les then three categories were neglected, the same applies to very specialised rating system i.e. Substance Flow Analysis, which concentrates on the flow of chemical substances. In comparison MFA includes a much wider scope with the term 'material' referring not only to substances but to elements like building material (Brunner & Rechberger, 2004).

**Life Cycle Assessment (LCA)**

Life cycle assessment is understood as a dependable and effective analysis method to rate environmental impacts, even complying with ISO 14040 standards. The method covers environmental impacts of a building component or system or the whole building, stretching from material extraction over construction phase to end-of-life. Researchers found that LCA has a proven track record to achieve environmental friendly answers to design questions. The all-encompassing approach of an LCA leads to an improved comprehension on the overall effect of the structure. (Kayacetin & Tanyer, 2018)

A lot of time and effort is needed to conduct the data intensive LCA studies. The quality of and access to relevant data are decisive factor for the success of a study. Information on e.g. environmental data, raw material flow, energy demands for production processes play important roles to establish the LCA. Comparing the results of LCA's produced by different researchers can cause difficulties since studies usually vary subject to the system boundaries set by the researchers. The result is that LCA studies which do not adhere to standards contain subjectivities and uncertainties (Kayacetin & Tanyer, 2018).

The framework as per BS EN 15978 shows the building assessment subdivision of a building's life cycle information in product stage, construction process, use stage, and of life stage.  (Jensen, 1998)

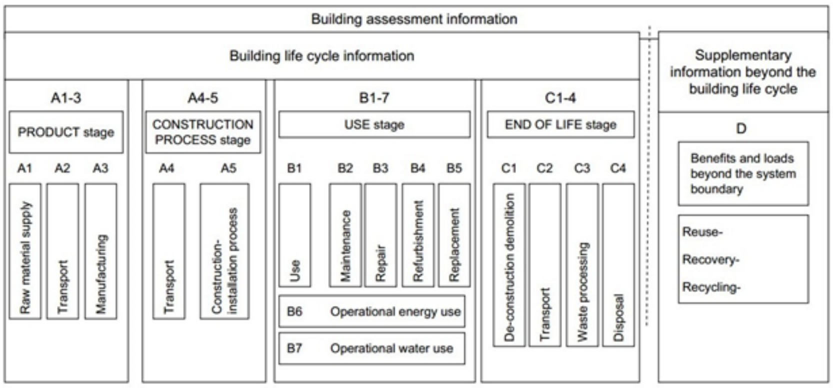



Fig. 9 - Building assessment information (Source: BS EN 15978:2011)

A close inspection of the diagram as per BS EN 15978 shows that a LCA considers most aspects outlined by Elia, Gnoni and Tornese for a complete measure of a products conformity with principles of CE. At the product stage a reduction of natural resources is reflected, emission levels are considered e.g. in Transport and Operational Energy Use. Potential material losses are covered at the end of life stage and an increased share of renewable recyclable resource are at production and end of life stage. In summary LCA provides data for four out of five classifications. The aspect missing is the durability of products.

**Material Flow Analysis (MFA)**

MFA is regarded a beneficial instrument for understanding inputs and outputs of regional processes and activities such as development of the built environment, transport, usage and rubbish disposal. MFA analyses and links in detail the type and amounts of material entering a defined system (e.g. a fabrication plant), the flows and stocks of material and energy within the process and the matters leaving the system. The results of the analysis can be applied to assess the relevance and priority of flows and stocks. Further the outcomes help to manage material flows and stocks to reach individual targets e.g. a fixed sustainability level. (Hendriks, et al., 2000)

According to Brunner and Rechberger a current MFA is conducted along the following steps:
1. Definition of a clear system boundary regarding space, time, process and flows. Clarification of matters to be analysed within the system. Every stock must be assigned to a process and every flow joins two processes. The start and end of flows can be outside boundary limits.
2. All system variables are to receive a specification and name, that includes all flows, processes, stocks. To avoid mistakes all variables must clearly show if they refer to a flow, process or stock and this is to be expressed in the selected naming and mathematical signs.
3. System variables are to be backed up by research data, experiment info or literature research results.
4. The sum of all inputs and outputs, the processes and stocks must tally up.
5. For easier understanding and checking creating a diagram as e.g. a box-and-arrow scheme or a Sankey diagrams is advisory.
6. The production of an all comprising report outlining the system boundary, the measured variables and the control of the mass balance. (Brunner & Rechberger, 2004)

When holding the findings about MFA against the crucial requirements for a rating system towards CE by Elia, Gnoni and Tornese the following conclusions can be reached: MFA is a useful to compute input of natural resources and material losses. However the system does not evaluate environmental burden or emission levels, instead paying attention material flows only (Elia, Gnoni, & Tornese, 2017). Further it does not allow for any calculation of product durability. In total MFA satisfies three of the five rating categories.

**Material Circularity Indicator (MCI)**

The Ellen MacArthur Foundation in collaboration with Granta Design produced the MCI as part of their 'Circular Indicators Project' project. The calculation enables companies to quantify the circular performance when designing new product and compare different material choices regarding their circularity. It enables companies to set certain threshold of circularity that their products must achieve. Stakeholders from outside the company can examine the circularity of products and companies if they are provided with the info.
The MCI is applicable to materials from the technical cycle from limited resources, however there are ways to include some standard materials from the biological cycle e.g. timber which are often found included in product design of technical origin.
The scope of the analytical tool is reduced in comparison to the circular economy which comprises complete system evaluations, the mixture of design and business models and the performance of material flows and material returns.
Hence the MCI concentrates on the restoration of material flows at various levels and foots on the following aspects:-

application of input from reused or recycled material
repeated use of elements or materials after disposal of a product
extension of the usage of products e.g. by reuse or reallocation
enhancing the usage of products by comparison of efficiency or service time

In comparison with a LCA the MCI shows some similarities and differences.
The aspect the systems have in common that much data required for computing an LCA can be applied to calculate the MCI as well. The system differ regarding their focus. While the LCA aims to calculate the effects on the environment of a product's life cycle by simulating various settings, the MCI aims to analyse the material flow during the usage of a device (Ellen MacArthur Foundation, 2015).

It can be concluded that the MCI answers four out of the five categories to measure the CE performance as set out by Elia, Gnoni and Tornese. It values the application of natural resources and computes increased proportion of renewable and recyclable resources. Further it contributes to reduce material losses and considers the durability of products. The only aspect missing is the emission reduction.

## 3.2 Rating Systems Disassembly

Similarly to the options for rating CE exist various assessment methods to compute the performance of a system regarding its ability to be dismantled. Most methods refer to products of micro level e.g. domestic devices or personal computers. Following is a brief overview:

With the beginning of the 20th century estimation methods were created which assume that the time difference it takes for dismantling tasks by trained labourers are tiny (Kroll & Hanft, 1998).

**Method Time Measurement (MTM)**

Created in 1948 the MTM represents the first accessible rating system measuring the
time needed to make specific moves for disassembly. Its precision and results gained wider recognition. Since the method presupposes a detailed examination of the motions and elements moved, time and work has to be spend upfront prior the utilization of the method. Often the expenditure needed to start the method are scrutinized as too high and improbable. (Kroll & Hanft, 1998)

**Maynard Operation Sequence Technique (MOST)**

Wider acceptance among engineers and professional of multiple industries for calculating operation time found MOST which depicts the efficiency of a normally skilled worker at normal working speed and in standard work circumstances.

MOST is built upon on basic tasks called standard sequences which consist of a series of movements. The method divides between three movements: General Move, Controlled Move and Tool Use. A series includes several movements and actions as depicted below.

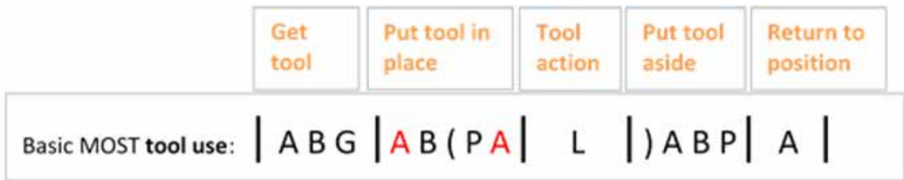



Fig. 10 – MOST sequence for tool use (source: Kroll & Carver, 1999)

Regular work sequences can consist of the following movements:
A stands for a horizontal movement over a distance,
B refers to a vertical movement,
G defines the action of control equipment e.g. a hand tool,
P to the action of placement,
L describes the process of loosening.
Each operation is referenced back a defined data collection with detailed levels of complexity and the relevant time frame to fulfil the task at hand. By calculating the movements, the tool operations and relating the complexity of the actions to the relevant indexes of the data base a general statement can be made about the time needed for the operation (Kroll & Carver, 1999).

In addition to the aforementioned basic movements are three different ways to include new actions:-
-by comparison with existing motions and choosing a matching index value.
-by splitting the action required into basic motions and finding a comparable mix of general and con-

trolled movements in the reference value set.
-by analysing the new task in detail, creating a detailed time and movement plan and applying the found results as input. (Zandin, 2002)

Other systems are designed to calculate the disassembly time based on actual observation of disassembly performances. The average times of disassembly procedures form the basis for these assessment systems. Among others the following systems are considered the most popular:
1. Philips ECC method
2. Desai & Mital method
3. Kroll method

**Philips ECC method (ECC)**

Created by Philips to compute the costs of End of Life expenses it calculates the time needed for disassembly by applying a database of dismantling durations of loosening actions for standard connections, special operations, tool exchange and handling.

Research of actual work situations came to comparable results for unfastening connections of the same type and similar dismantling tasks of domestic appliances. Hence the originators of the assessment method concluded that the won data can be transferred to other calculate other disassembly tasks. (Boks, Kroll, Brouwers, & Stevels, 1996)
After entering the dismantling order and the type of joints, the method computes the actions, mechanisms and dismantling time for each step by referencing them to the previously found data. The sum of all actions determines the total disassembly time as per table below shows in parts.

| Connector | Time (s) |
|---|---|
| Screw | 6.5 |
| Screw hard | 10.5 |
| Click | 3.5 |
| Click hard | 7.5 |
| Wire connections | 2.0 |
| Change screwdriver | 4.0 |
| Nuts / bolts | 11.5 |

Fig. 11 - Disassembly times in accordance to Philips ECC database (source: Stevels, 2015)

The method is relying on a database about the dismantling of specific types of domestic appliances. Its accuracy will be questionable when used to other types of machinery or appliances (Boks, Kroll, Brouwers, & Stevels, 1996).

**Desai & Mital Method (DMM)**

The method presented by Desai & Mital relies on calculating the disassembly time by considering five aspects: strength, material handling, tool employment, access to components and fixings, and tool positioning. The assessment is in fact a further development of the MTM method discussed previously however it includes punishment aspects if certain circumstances appear. The researchers set a standard action of a competent labourer as benchmark. The disassembly time for standard procedures are listed as per meticulous research results. (Desai & Mital, 2003)

This approach has been criticized for not including any preparation operations e.g. selecting the tool, lifting it in position and returning it. The overall time of the operation is not considered, just a fraction of it (Justel Lozano, 2009).

**Kroll Method (KM)**

The emphasis of the Kroll Method lies on including more recycling into product design. Its assessment is based depends on results from timing dismantling exercises of computer hardware. (Kroll & Carver, 1999) (Kroll & Hanft, 1998)
KM provide the designer with an instrument to indicate options for increasing the speed of dismantling. (Boks, Kroll, Brouwers, & Stevels, 1996)
The authors specified the following dismantling actions:
1. Loosen 2. Spin 3. Wedge/Pry 4. Cut 5. Take out 6. Flip 7. Deform 8. Push/Pull 9. Hold /Grip 10. Saw 11. Drill 12. Hammer 13. Peel 14. Cleanse 15. Grind 16. Examine
(Justel Lozano, 2009) (Kroll & Hanft, 1998)
To a set standard duration for the 16 actions another 4 indexes of complications are added for more precision:-
1. accessibility to the connection
2. positioning of the device
3. force required for the operation
4. 'special' for unforeseen circumstances
This way of computing base time and extra duration for complication is like the MOST method (Kroll, Application of Work-Measurement Analysis to Product Disassembly for Recycling, 1996)

Further the four complications receive a scale of 1 to 10 each, with each figure standing approximately for the additional seconds it takes the device to dismantle.
This step might be criticized as adding uncertainty since these figures are subject to the device in question for disassembly and need to be adjusted for each type of device. The KM has been successfully applied to calculate the disassembly time of various electronic devices (Kroll & Hanft, 1998)

In summary it can be said that the above mentioned assessment systems can be successfully applied to lower the difficulty level of disassembly actions in quantitative way. Besides, it allows the designer to check if ongoing designs can be taken apart easily later, and with the time estimated a cost calculation can be produced.

**Disassembly Potential (DP)**

Unlike the previously explained ratings Elma Durmisevic offers an approach with a clear focus on disassembly of building components. She scrutinizes that the building industry of today is not aware how to create buildings in an efficient manner since they consider structures as permanent while in reality they are often adapted to user needs. The result of static structure which cannot be adapted is demolition and with that huge amounts of waste.

Structures are unification of spatial, technical and material systems. Most buildings are interwoven structures of materials, components, systems and space.

Three fields are crucial for creating adaptable, decomposable structures:-
1. Spatial transformation, permitting continuous usage of a structure by adaption of space to needs.
2. Structural transformation, supporting uninterrupted application of the structure and its parts by allowing exchange, repeated use, retrieve.
3. Element and material transformation, prolonging the employment of materials by recycling.

Structural transformation in combination with disassembly are the main driver for the proposed three-dimensional transformation capacity. Disassembly enables spaces to adapt and breaks the linear life cycle model leaving no option but demolition and waste.

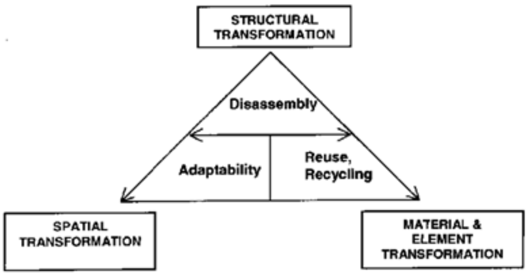



Figure 12: disassembly - the key for building transformation (source: Durmisevic, 2010)

Durmisevic argues that disassembly is a key requirement for buildings to comply with the principles of CE. Buildings designed with reference to DfD allow for easier adaption and reuse of material, thus either prolonging the life-span of the structure or the reuse and recycle of its materials. The proposed system to assess the performance of a building to enable dismantling she calls Disassembly Potential. The higher the DP of a structure the more it allows for reconfiguration, reuse and recycle. (Durmisevic, 2010).

DP stipulates several rating aspects to assess a buildings DP performance. For example one aspect refers to the life span of materials and their position in the assembly process. As Brand stated “because of the different rates of change of its components, a building is always tearing itself apart.” (Brand, 1995) Brand referred to the different life-spans of building layers but in the same way a the life-span of the materials within a building component can be reviewed so that their durability is coordinated with each other.

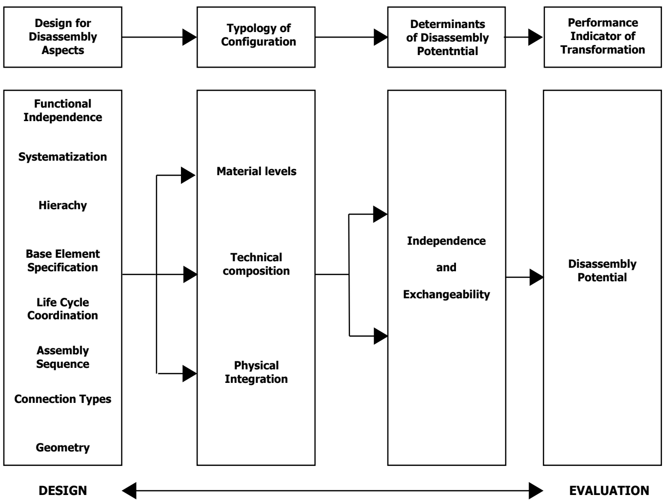



Figure 13: Conceptual Model of Design for Disassembly and its evaluation (adapted, source: Durmisevic, 2010)

The model can be summarized as a four step procedure. In the first step several disassembly aspects are evaluated which resemble the input of the second step, the Typology of Configuration which is set together of various aspects of Material Levels, Technical Composition and Physical Integration. Once the aspects of the Typology of Configuration are established, the Disassembly Potential can be determined, which states the Independence and Exchangeability of a structure. Last, with this data concluded a Performance Indicator Transformation can be finalised which tallies the overall Disassembly Potential (Durmisevic, 2010).

A low score at DP indicates a static structure, a medium score expresses a partly-open structure and a high value of DP characterises a 'dynamic' structure. Static buildings cannot be adapted to user changes and do not provide for material reclaim. The end of their life cycle is demolition and waste. Structures of a partly-open level allow for a partially adaption to changes of usage and a slight amount of material recycling or reuse after dismantling. Dynamic structures provide for the highest level of amendment and in addition enable reuse or recycling of its materials.

As conclusion can be stated that the DP examines relations and connections within components and structures. The study of multiple sub-levels allows for making a precise statement on how easy it is to take a structure apart. It does not measure how circular the materials chosen are. Hence a sole rating system it is not enough to state how circular a structure is.

## 3.3 Selection Rating Systems

This chapter summarizes the findings of the previous chapter and explains which rating system is chosen to rate the accordance of structure with the principles of circularity and disassembly.

**Assessment Method for Circularity**

As per the study undertaken by Elia Gnoni Tornese no available rating systems cover all five assessment criteria they consider crucial for rating a systems compliance with the principles of the CE. The system with the highest cover of the principles are Material Circularity Indicator (4/5), Material Flow Analysis (3/5) and Life Cycle Analysis (4/5), which each review 4 out of 5 aspects.

The LCA is considered a very exact tool to assess the performance of a product or structure regarding its conformity with the principles of CE taking all stages of a structure into account, from production, construction process, usage and including the end of life. (Jensen, 1998)
It covers 4 out of 5 aspects, does however not consider any emissions caused in the process and therefore leaves this aspect blank. Furthermore, LCA is an assessment tool which requires a high data input or otherwise is scrutinized to fall short of its aim (Kayacetin & Tanyer, 2018). Given the time frame of the study it seems unrealistic to create a convincing calculation with the use of LCA.

The MFA covers three out of the five aspect required to state CE performance. Although the method checks for natural resource input, amount of renewable or recyclable resources and material losses it does not give any answers on emission levels caused and durability produced. The MFA is considered a very useful tool to compute material flows (Brunner & Rechberger, 2004) it shows various shortcomings for the task at hand.

The MCI allows for drawing conclusions on four of the five principles required to state compliance with CE. It measures natural resources, renewable and recyclable resources, material losses and durability of products. Only the emissions levels are missing. It shares certain input data with the LCA albeit to a lesser amount which should be beneficial for receiving results in time.

In accordance with a previous study by Quirine Henry it is concluded that the MCI is the most suitable assessment method for reviewing in how far a product or structure complies with the principles of CE. To provide the missing information about the emission levels another method shall be chosen.

**Assessment method emissions**

In general emissions are described as an amount of gas that harms the environment and that is sent out into the air (Cambridge University Press, 20202). One of the most harming gas emitted and contributing to climate change is $CO_2$ (Houghton, Jenkins, & Ephraums, 1991).

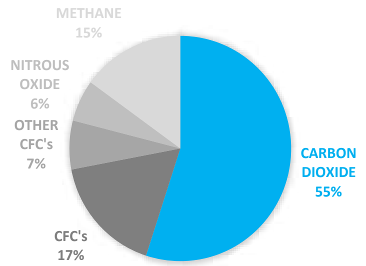



Fig. 14 – distribution of human-made greenhouse gases (source: Houghton, Jenkins, & Ephraums, 1991)

Since multiple data input is required to calculate emissions at the various levels they occur e.g. production, transport, use, EoL (Charles, Rolls, & Tennant, 2000) and keeping the time frame of the study in mind the decision was made to apply an available software instead.

GRANTA EduPack is a collection of material training tools helping materials selection in engineering, design, science and sustainable improvement. The software comprises of material databases and process information, tools to compare material choices, and further supporting mechanisms. The collection of materials data and the method to display material features was developed by Professor Mike Ashby.

There are three levels for students to chose a subject for their direction and depth of research. The data base or material universe contains 3,500 records providing various information e.g. physical, cost, mechanical, thermal, electrical, optical, durability, environmental data etc. In addition the data base lists comprehensive data on 240 fabrication processes.

The software contains an eco-tool which provides the user a quick evaluation of the impact of their design on the environment. It shows ways how to decrease the ecological consequences by showcasing energy consumption and $CO_2$ footprint and listing them according to their life phases production, manufacture and transport and End of Life (Granta Design, 2020).

**Assessment method for disassembly**

In the previous chapter several rating systems for disassembly procedures were discussed. When compared the following results can be found:-

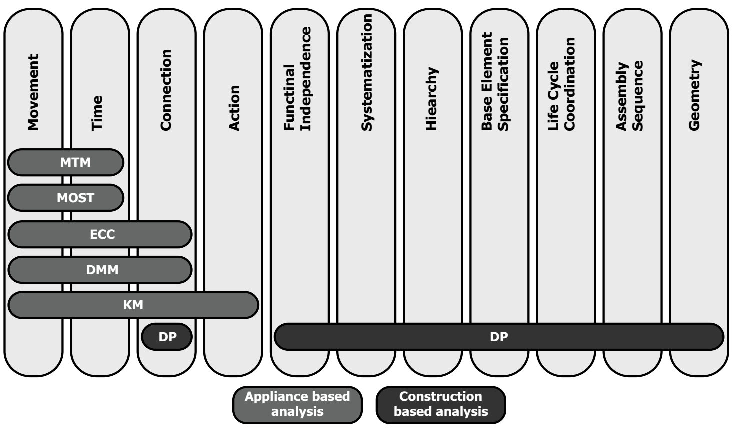



Fig. 15 – Comparison of assessment methods for disassembly (source: own image)

The appliance base rating methods have a clear focus to ascertain movements and time required to dismantle the appliance. The more advanced systems i.e. ECC, DMM and KM distinguish between the type of connections to be loosened and the necessary manual operations to do so. With the time frame clarified for the disassembly per unit conclusions can be drawn for the costs and potential returns of the undertaking.
The DP on the other hand concentrates on assembly sequences, systematization, life-cycle coordination and others aspects to produce an assertion of how fit a structure is for dismantling. It takes eight rating aspects into consideration and therefore much more than the other rating systems. It shares only the investigation of the connection types with the other rating systems.

In conclusion it can be said that the Disassembly Potential is the most suitable rating method for disassembly. It takes many more aspects up than the other rating systems and considers construction specific issues. The appliance based rating system are very limited in the number of reviewed aspects and have many shortcomings. The comparison shows however that DP does not allow for any statements about duration of the process and hence no financial calculation can therefore be based on it.

## 3.4 Details Rating Systems

As the rating systems are chosen an inspection of them in more detail follows. The following systems will be examined for their operation: Material Circularity Indicator, Granta EduPack and Disassembly Potential.
Material Circularity Indicator (MCI)
The MCI was chosen for determining the circularity compliance of the facades of Scheldebouw, with supporting info from the emission calculation. The outcome of the calculation will be a value between ‘0’ and ‘1’, with zero standing for a completely linear product of which all materials are of virgin origin and no recycling or reuse takes place after disposal. On the other hand ‘1’ is received for a completely circular product which is entirely made out of recycled or reused materials and which is completely recycled or reused without material losses at the end of its life-span.
Each façade will be analysed separately, starting with computing the material weights per m2 façade based on material take-off calculations provided by Scheldebouw as Excel sheets and extended with materials not previously covered. Further input for the calculations are percentages of recycled and reused material and the recycling efficiencies of each recycling step. The calculation can be viewed as the translation of a diagram into a calculation.

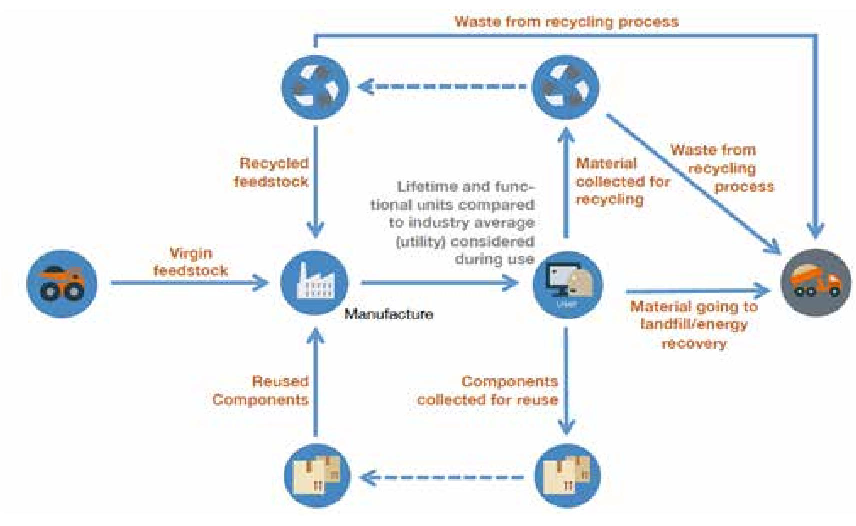



Fig 16 – Diagrammatic representation of material flows (source: (Ellen MacArthur Foundation, 2015)

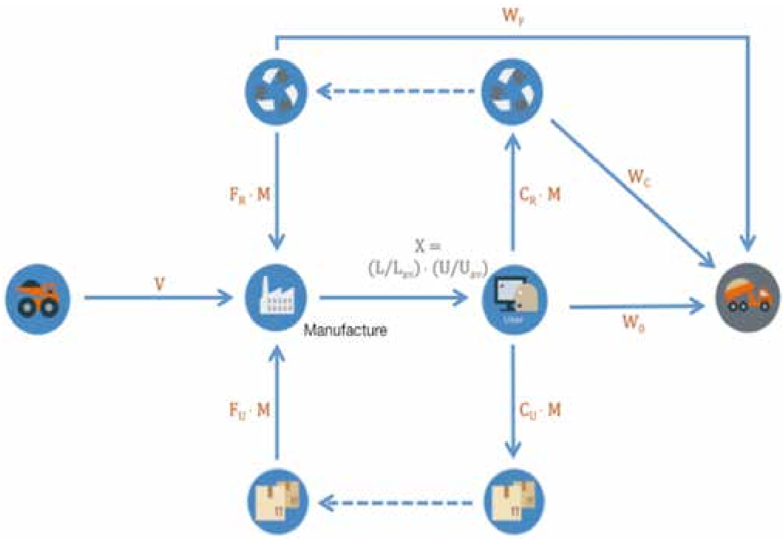



Fig 17 – Diagrammatic representation of material flows (source: (Ellen MacArthur Foundation, 2015)

All input data shall be product specific, in the case of specific data not being accessible generic data shall be used. The recycled content applied in the calculation shall be based on actual recycling rates, alternatively global or local average values. Recycled feedstock for a new product can come from the very same cycle the product is a part of or can come from another product cycle, a total different source. The recycling collection rates shall be product specific or alternatively based on sector specific data. The recycling efficiencies shall be material and process specific. It has to be noted that fluctuation of recycling efficiencies are likely to appear as they are subject to recycling technology and demand. The computed MCI will provide info about the circularity of each material only. To make a statement about the overall performance of a façade the percentage of its usage per m2 façade is considered. The calculation steps are summarized as following (based on a comprehensive approach for a product consisting of numerous parts, sub-assemblies and materials):

**Step 1: Calculation Virgin Feedstock**

$$V_{(\chi)} = M_{(\chi)}\left(1 - F_{R(\chi)} - F_{U(\chi)}\right)$$

| Symbol | Definition |
|---|---|
| $V_{(\chi)}$ | Virgin feedstock per subassembly/material |
| $M_{(\chi)}$ | Mass of product (kg) |
| $F_{R(\chi)}$ | Fraction of mass of product’s feedstock from recycled sources |
| $F_{U(\chi)}$ | Fraction of mass of product’s feedstock from reused sources |

$$V = \sum_{\chi} V_{(x)}$$

| Symbol | Definition |
|---|---|
| $V$ | Total amount of virgin feedstock |
| $V_{(x)}$ | Virgin feedstock per subassembly/material |

**Step 2: Calculation Unrecoverable Waste**

$$W_{0(\chi)} = M_{(\chi)}(1 - C_{R(\chi)} - C_{U(\chi)})$$

| Symbol | Definition |
|---|---|
| $W_{0(\chi)}$ | Mass of unrecoverable waste of a product's subassembly/material ending as landfill, incinerated for energy recovery or rendered in any other way unrecoverable |
| $M_{(\chi)}$ | Mass of product's subassembly/material |
| $C_{R(\chi)}$ | Fraction of mass of a product's subassembly/material being collected for recycling at the end of the use phase |
| $C_{U(\chi)}$ | Fraction of mass of a product's subassembly/material being collected for reuse at the end of the use phase |

$$W_{C(\chi)} = M_{(\chi)}(1 - E_{C(\chi)})C_{R(\chi)}$$

| Symbol | Definition |
|---|---|
| $W_{C(\chi)}$ | Mass of unrecoverable waste of a product's subassembly/material caused during recycling parts of a product |
| $M_{(\chi)}$ | Mass of a product's subassembly/material |
| $E_{C(\chi)}$ | Efficiency of the recycling process used for the portion of a product collected for recycling |
| $C_{R(\chi)}$ | Fraction of mass of a product's subassembly/material being collected for recycling at the end of the use phase |

$$W_{F(\chi)} = M_{(\chi)} \frac{\left(1 - E_{F(\chi)}\right) * F_{R(\chi)}}{E_{F(\chi)}}$$

| Symbol | Definition |
|---|---|
| $W_{F(\chi)}$ | Mass of unrecoverable waste of a product's subassembly/material caused during producing recycled feedstock of a product |
| $M_{(\chi)}$ | Mass of a product's subassembly/material |
| $E_{F(\chi)}$ | Efficiency of the recycling process of a product's subassembly/material used to produce recycled feedstock for a product |
| $F_{R(\chi)}$ | Fraction of mass of a product's feedstock from recycled origin |

$$W = \sum_{\chi} (W_{0(\chi)} + \frac{W_{F(\chi)} + W_{C(\chi)}}{2})$$

| Symbol | Definition |
|---|---|
| $W$ | Total mass of unrecoverable waste related to a product |

**Step 3: Calculation of Linear Flow Index (LFI)**

$$LFI = \frac{V + W}{2M + \sum_{\chi} \frac{W_{F(\chi)} - W_{C(\chi)}}{2}}$$

| Symbol | Definition |
|---|---|
| $LFI$ | Linear Flow Index |
| $V$ | Total amount of virgin feedstock |
| $W$ | Total mass of unrecoverable waste related to a product |
| $M$ | Mass of product (kg) |
| $W_{F(\chi)}$ | Mass of unrecoverable waste of a product's subassembly/material caused during producing recycled feedstock of a product |
| $W_{C(\chi)}$ | Mass of unrecoverable waste of a product's subassembly/material caused during recycling parts of a product |

**Step 4: Calculate Utility Factor (X)**

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right)$$

| Symbol | Definition |
|---|---|
| $X$ | Utility Factor |
| $L$ | Actual average lifetime of a product |
| $L_{av}$ | Actual average lifetime of an industry-average product of the same type |
| $U$ | Actual average functional units achieved during the use phase of the product |
| $U_{av}$ | Actual average functional units achieved during the use phase of an industry-average product of the same type |

$$F_{(\chi)} = \frac{0.9}{X}$$

| Symbol | Definition |
|---|---|
| $F_{(\chi)}$ | Utility factor built as a function of the utility X of a product |

**Step 5: Calculation Material Circularity Indicator (MCI)**

$$MCI_P^* = 1 - LFI \cdot F_{(\chi)}$$

| Symbol | Definition |
|---|---|
| $MCI_P^*$ | Calculation Material Circularity Indicator |
| $LFI$ | Linear Flow Index |
| $F_{(\chi)}$ | Utility factor built as a function of the utility X of a product |

**Data sources**

As the facades are manufactured in the Netherlands, the data input for the calculation is based on Dutch NBA Database (Haas & van Beijnum, 2013). The authors estimated the average technical lifetimes of building components and construction products by consulting professional of their fields. They are emphatically practical values of generic values construction products. Further information regarding the life span of materials was taken from SBR publication 'Levensduur van bouwproducten - Methode voor referentiewaarden' (Straub, van Nunen, Janssen, & Liebregts, 2011). Based on practical values for 500 construction products, this catalogue provides current service life according to ISO standard 15686. The mass of the products has been established by consulting manufacturers' data (see appendix) sheets and online data bases i.e. The Engineering Toolbox (The Engineering Toolbox, 2020). The end of life scenarios has been researched by specialist interviews.

The information about the recycled feedstock FR has been received from the material suppliers, the amount of material going to landfill after usage W0 was provided by the dismantling company and the efficiencies of the recycling processes EC and EF were found by consulting recycling machine manufacturers and by literature research. The efficiency of reuse is estimated with 100%.
The average life time of a façade has been set to 25 years according to Dutch NBA Database (Haas & van Beijnum, 2013) as an industry average, and the life span of the facades made by Scheldebouw has been set at 30 years as per interview with Scheldebouw (Eichhorn, 2020). These two durations produce the Utility Factor X since the facades cannot be measured in functional units.

**GRANTA EduPack**

The Granta EduPack features a menu called 'Eco Audit Tool' which allows the designer to grade the environmental impact of a product, and to make suggestions on how to reduce it. The focus lies on the environmental stressors energy usage and CO2 footprint, and finding at which main life phases (material, manufacture, transport, use, and end-of-life) they create the most environmental burden.
This info forms the foundation for ecological aware product design. After the phase producing the most emission level or energy consumption is found, the design can be amended to reduce the environmental footprint. The conclusions of the eco audit set the directions for a new product design. The objective is subject to prevalent phase and product use.

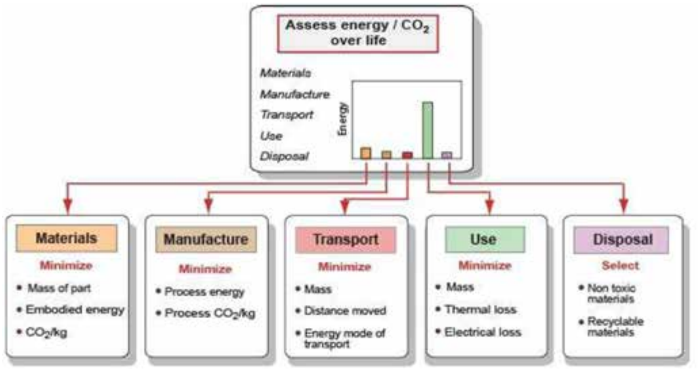



Fig. 18 - Strategies for reducing environmental impact, source: (Granta Design, 2020)

The data input required consists of material, transport and use.

1. Material, manufacture, and end of life
This section asks for the definition in order to establish a bill of materials. The quantity and component names are to be added. Then the materials can be selected from the material data base. The system automatically checks for available choices for primary process and end of life.

For further information on the use, source, and precision of environmental data in the eco audit tool see: data usage, data sources, and data precision. Further the options available for recycled or reused content are computed and a choice entered accordingly. The student version features a limited list of options and does not allow precise input of recycled input but offers 'virgin' (= 0% recycled content), typical (varies from material to material, from database) and reused. Typical recycled content is available for materials where end of life recycling has become integrated into the supply chain.

The material mass (kg) is entered and multiplied by the quantity field value to calculate the total mass of these components in the component. A selection of primary process are offered for choice, adjusted to the type of material chosen. A secondary process  and a specification of waste of the processing are not available in the student version.

Another menu allows to choose from various End of Life options. Subject to material type the following are available: landfill, combustion, recycle, downcycle, re-manufacture, reuse, and none. 'Landfill' is the default option. A precise specification of material amount to be recovered is not available in the student version. The recovery rates in the software are based on industry standards and depend among others on availability of recovery infrastructure, disassembly potential of product and demand. Recovery rates for materials as steel and glass which have been collected for a long time are higher than for materials as plastics which possess hardly any recovery support.

2. Transport
In this section the necessary transport distances and transport modes can be entered. The distance is defined as from the material manufacturer to the customer. The transport mode can be chosen via ship, train, road and air with various sublevels available. The energy consumption and emission levels are based on industry average and multiplied by the distance and the product mass.

3. Use
This input phase determines the use phase of the product. The following input is requested: product life, country electricity mix and mode of use (mobile or static).
The product life indicates how long the product lasts in years, starting with 1 year as a standard. In the

following menu the designer can select the mix of fossil and non-fossil fuel of the country of the product use. Three options are available: global regions, individual countries, and fossil fuel percentage. The standard selection is 'World'. The environmental effect of electricity generated from fossil fuels is bigger than the one of electricity produced with renewable sources. Further two mode uses are available: static and mobile operation. 'Static' are products which are stationary and need energy to work. 'Mobile' use occurs in machines for transportation.

Report
After computing all info the software produces a report consisting of a summary page, a detailed energy consumption and a detailed $CO_2$ footprint. Each life phase of the product is checked for energy and emission levels and the indication of the dominant phase can be used for improving the design (Granta Design, 2020).

Input
The input data has been established as follows: the material selection is subject to the materials used by Scheldebouw. The quantities was calculated via the material take-off lists provided and added by a few missing items. A quantity for a façade of 10.000m2 was simulated. The info of the recycling amount in the materials was collected from the manufacturers. Primary processes were chosen in accordance with manufacturer's practice and recovery rates were selected as per findings from the MCI calculation. The transport modes were entered according to info from Scheldebouw and the distances to the manufacturers were calculated using Google Maps. The life phase of the facades were set at 30 years and The Netherlands entered as country of use to determine the energy mix. Since the facades do not need energy neither static nor mobile were chosen as mode use.

**Disassembly Potential (DP)**

The assessment method for judging the capacity of a structure for dismantling is the Disassembly Potential as created by Durmisevic in 2010. She developed eight assessment criteria which combined lead to an overall indicator expressing how much a structure is applicable to transformability. For each of the eight assessment criteria a certain amount of points can be gained, ranging from 1 as the lowest score to 10 as the highest score. The more points, the higher the DP. The first two criteria, Functional Decomposition and Systematisation, determine the Material Level of the structure. The following three criteria - Relational Pattern, Base Element Specification and Life Cycle Coordination – dictate the rate of Technical Decomposition. Finally, Assembly Sequence, Connections and Geometry, evaluate the Physical Decomposition (Durmisevic, 2010). In detail the eight criteria are built up as follows:-

1. Functional Decomposition
One of the first questions designers encounter at designing flexible structures is the level of decomposition and how many functions they pack into one building element. This determines how far a structure can change later and falls under the specification of material level. Allocation of different functions to individual elements supports to increase a higher level of autonomy and therefore increase functional decomposition.
Buildings are separated into different components with different purposes. Each component fulfills a certain task. As functions have different life-cycles, a transformation might be compromised if more than one function is packed into one component. Durmisevic defines four levels of functional incorporation affecting the functional independence:-

Total or unplanned integration
Planned interpenetration
Unplanned interpenetration
Total separation/autonomy

The effect of total integration can be observed when new facades are installed and the adjacent walls and structures need to be demolished to allow for implementation of a new façade.

2. Systematisation
The organisation of single elements into groups characterizes this criteria. Once single elements form a sub-assembly they function as a unit during the production, service and end of life phase. More integration results in less physical connections and less site work and a more efficient material usage. Also sub-assemblies lead to more structures organization supporting repair or maintenance. Bundling of elements can be divided into four levels:-

Grouping on system level
Grouping on component stage
Grouping on system, element or material level
No grouping

Forming elements into separate groups in accordance to their function helps coordinating of tasks and life cycle. It benefits planning of assembly and disassembly.

3. Relational Patterns
Technical decomposition starts with the examination of the orders within an assembly. One main aspect is the hierarchy or relational pattern between the multiple sub-assemblies and how open or unhindered they are arranged. One can easily differentiate between structures not featuring any evident arrangement and those which present an orderly and unobstructed order with fabrication hierarchy and a coordinated exchange plan of elements highly subjective to change.
The structure of traditional buildings show complicated relational patterns. Replacement of one element within this entangled hierarchy has severe effects on adjacent parts. The amount of relations has therefore strong influence on how flexible a structure is to change.

The relations between subassemblies determine how flexible a structure is. Arrangements which show a strong vertical orientation of its subassemblies are considered dynamic and facilitating transformation and reuse while arrangements with a horizontal orientation are described static and hinder change or salvage. Relational pattern are therefore categorized as follows:-

Vertical throughout the schema
Horizontal in lower zones
Horizontal between upper and lower zone in the diagram
Horizontal in upper zone

Preferably direct connections between groups of different functions should be avoided. Only horizontal connections between base elements of a subassembly and base elements of the super structure as the latter ones will be disassembled last.

4. Base Element Specification
As every building contains assemblies and sub-assemblies with each subassembly being a group of parts which perform a certain function. To achieve autonomy of parts within one group from another, each group should have a designed shell or frame, a base element which contains all parts within that group. These base elements perform as carrier of parts within itself and as intermediary to other groups. A base element can be defined as follows:-

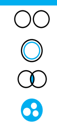
Base element with intermediary between two clusters
Base element on two levels
Element with two functions (base element and one building function)
No base element

The base element which performs only a load bearing function and has an intermediary is considered the optimum as it allows installation and exchange of assemblies without affecting another.

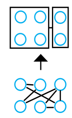
# RATING SYSTEMS

## Research Section

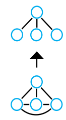
| 1. Functional Decomposition | Points |
|---|---|
| Total separation/autonomy of functions | 10 |
| Planned integration of functions | 8 |
| Unplanned integration of functions | 2 |
| Total integration of functions | 1 |



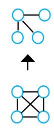
| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



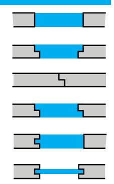
| 3. Relational Pattern | Points |
|---|---|
| Vertical throughout the scheme | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone of the diagram | 4 |
| Horizontal in upper zone | 1 |



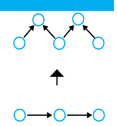
| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions (BE and one building function) | 4 |
| No base element | 1 |



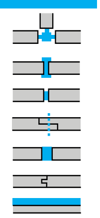
| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |



| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |



| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |



| 8. Cife Cycle Coordination | Points |
|---|---|
| Use life cycle and technical life cycle coordination | 10 |
| Use life cycle without technical life cycle coordination | 6 |
| Technical life cycle, no use life cycle coordination | 4 |
| No technical life cycle, no use life cycle coordination | 1 |

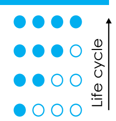



Fig. 19 – Score system of DP (source: Durmisevic, 2010, adapted)

5. Geometry
The design of connections play a vital part when assessing dismantling or changing a structure. The geometry of the interfaces can be assessed according to how strong it is linked with its adjoining parts. The following rating order can be formed:-
- Open/linear geometry
- Symmetrical overlapping
- Overlapping on one side
- Unsymmetrical overlapping
- Insert on one side
- Insert on two sides

Elements with open interfaces are easy to disassemble opposed to elements with interpenetrating or closed edge geometry on two or more sides which are hardest to dismantle.

6. Assembly Sequence
The order in which systems are assembled mirror the order of dismantling. When connecting building elements, dependencies are the consequence. An assembly order illustrates the fitting process step by step. The assembly sequence can be divided in two types: parallel and sequential order. The parallel assembly order enables fast construction. The sequential assembly order leads to interconnections between the installed parts and handicaps replacement. The assembly direction is divided in:-

Parallel/open assembly
Stuck assembly
Base element in stuck assembly
Sequential base element

One more type of sequence is created when one element is the base element for all other elements. This type relies heavily on the type of connections between the elements.

7. Connections
The geometry defined the interfaces allowing elements to slide in and out of assemblies. Connections make sure the elements stay in place. Before any disassembly can take place, connections must be loosened. Three classes of connections exist: direct (integral), indirect (accessory) and filled.
When the form of a component forms an entire connection an integral connection is created. These can be further divided into overlapped and interlocked joints. Overlapped connection can be seen in façade panels. Disassembly of them can depend on many factors e.g. material, assembly order and hierarchy. Interlocked connections are e.g. tongue and grove joints meaning they are hidden and a result of corresponding interface shapes.
Additional parts are used to produce accessory connections. Again, two types exist: the internal and the external joints. An internal connection is imbed in the materials and hard to loosen. External connections are easier to spot, to access and as a result to unfast.
Filled connections are created by applying chemical binders between two materials. Disassembly is often not possible and demolition is the result.
In general to develop systems which support disassembly the following guidelines should be followed:-

Materials and elements should be kept apart, interlocking is to be avoided.
Chemical connection should be prevented and dry connection preferred.

8. Life Cycle Coordination
Building materials have different life spans and that can lead to reduced life spans of the building components if no consideration was given to this aspect at the assembly stage. Materials with long life spans should be assembled first and short-lived materials assembled last so that less disassembly dependency is produced and materials with short-life spans can be easily replaced.
When comparing assembly and disassembly diagrams with each other, they show parallels if the correct assembly order was adhered to, meaning that long life materials are assembled first and short lived

materials last. In case of disassembly the short lived materials can be dismantled first, long-life elements can remain untouched. If the assembly order was not coordinated with the life-span of the materials, the disassembly order is confused and as result the assembly and disassembly sequences will show some degree of symmetry.

Not only the different life cycles of materials are to be coordinated in an assembly, the functions of materials have different life cycles too and must be coordinated with each other. A material must fulfil the functional life cycle as well, otherwise the structure might fail before the anticipated end of the use life cycle (Durmisevic, 2010).

**Conclusion**

In this chapter various rating system were reviewed for ascertaining the compliance of structures with the principles of CE and DfD. The chapter concludes two subquestions:

***Which is a suitable system to calculate the Circularity of a building component?***

On the basis of a list of principles created by Elia, Gnoni and Tornese several rating systems were reviewed for their suitability to assess circularity of structures. MCI was chosen for the checking circularity. Since emission levels are not reflected in the MCI, the software Granta Design is applied in addition to calculate CO emissions.

***What is an appropriate assessment method to judge Design for Disassembly of a building component?***

Several rating systems were reviewed for their process to rate the fitness of a structure for disassembly. Based on the number of aspects they consider DP was selected to rate the ability of a structure for dismantling.

In the next chapter the company Scheldebouw is reviewed to get a better understanding of their product and working practice.

RESEARCH SECTION

# 4 | SCHELDEBOUW

## IN BRIEF

The following chapter provides an overview of the company Scheldebouw and examines their design and production procedures. The current assembly practice is documented and a disassembly exercise undertaken to gain first-hand experience and insight into the hurdles of dismantling a façade system.

**COMPANY OVERVIEW**

**Scheldebouw focuses on developing and manufacturing sophisticated building envelopes.**

**DESIGN & PRODUCTION**

**Design and production of the facades follow rigid process patterns with the involvement of many departments.**

**ASSEMBLY & DISASSEMBLY**

**The documentation of the assembly process and the disassembly of an existing facade unit deliver useful insights.**

# 4. SCHELDEBOUW
## Research Section

### 4.1 Company Introduction

Scheldebouw focuses on developing and manufacturing sophisticated and monumental building envelopes and answering design proposals with the best suitable solution. They strive to combine the best of architectures and technology while considering budget and time frame.

The company started trading in 1933, first as a producer of Aluminium and furniture parts for the marine and airplane industry. By 1958 the company grew to include curtain walls for which they quickly became a main player for the European market with standard and bespoke solutions. In 1995 Scheldebouw became part of the Permasteelisa group, a global manufacturer of high-end building envelope systems. At present the company employs 500 people at their offices in the Netherlands. Scheldebouw remains true to the origin with the development of furniture in collaboration with a branch of its Italian mother company. In their 61 years of existence the company completed more than 250 projects successfully and covered some 154.000m2 with their façade solutions.

The production facility covers 27.500m2 and is located at their headquarter in Middelburg. The facility is divided into five independent assembly lines, supported by a CNC machine division of the highest standards and a visual mock-up department. The assembly lines consist of automatic and manual labour stations and operate subject to project needs. Production on one of the lines can be undertaken under 'clean-room' conditions since it offers extraordinary glass washers and inspection equipment. Further features of the production facility include a fully certified testing facility so that inhouse testing can be guaranteed to be independent (Scheldebouw B.V., 2020).

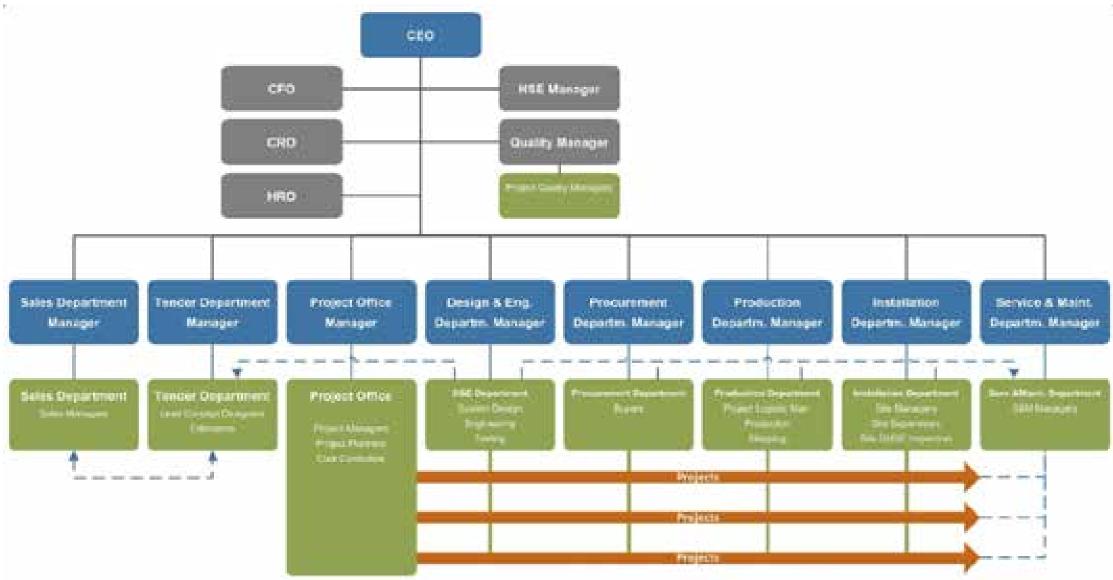



Fig. 20 – Organigram Scheldebouw (source: Scheldebouw)

The organigram of Scheldebouw reflects the stepped approach of the design, production and installation process.

**Business Model**

An integrated approach is the main characteristic of Scheldebouw's business model. The company offers architectural support, design and engineering, project management, testing, quality checks, manufacture and procurement, installation and after-sales service as a complete package or in parts to their clients.

The company offers their expertise of façade systems to architects at the outset of the design phase and help designers to find practical and cost effective solutions from initial sketch to implementation.

Experienced project managers continuously oversee the project progress from design to engineering and act as intermediators between the clients and the company's other departments.

Meticulous checking protocols has been developed to ensure and maintain highest quality standards so that customers can be certain to receive the best value for their budget and a smooth trouble-free process is achieved.

Installation of innovative systems bring often challenges with them and ask for new ways of fitting on site. Scheldebouw plan installation sequences very precisely in order to reduce time and cost expense without neglecting quality issues and health and safety aspects. Innovative façade systems are fitted by likewise ingeniously installation methods. Material transports are prudently planned ahead and executed to enable in time installation.

Advanced computational techniques and models are used to transfer architectural concepts from sketch design to reality. 2D drawings, 3D simulations and BIM in combination with structural calculations and physical mock-ups are applied to realize complicated projects. Inhouse expertise of practical and theoretical aspects allow development of new systems and original designs.

Custom-made systems require testing prior installation to check if they are fit for purpose. Visual mock-ups are produced to ascertain aesthetical aspects and performance tests are either carried out in the inhouse test facility or in external test centers complying with the customer's stipulations. The Innovations and Solution department develops and tests regularly new materials and systems.

For testing new designs and technical solutions prototyping is required so that the ideas can be evaluated for aesthetics and performance. Clients and architects can inspect designs at actual scale and determine material choices before production starts. Advanced machining and assembling technologies are used in the company's own production facilities to build and ascertain prototypes and first models.

An active attitude towards post-sales assistance secures a positive and long lasting client relationship and provides client's support throughout the life cycle of the products (Scheldebouw B.V., 2020)

## 4.2 Design and Production

**Design Phase**

Scheldebouw proceeds the design of a new project in four steps. Since many of their projects are in the United Kingdom they apply procedures corresponding to project phases as outlined by the Royal Institute of British Architects (RIBA).

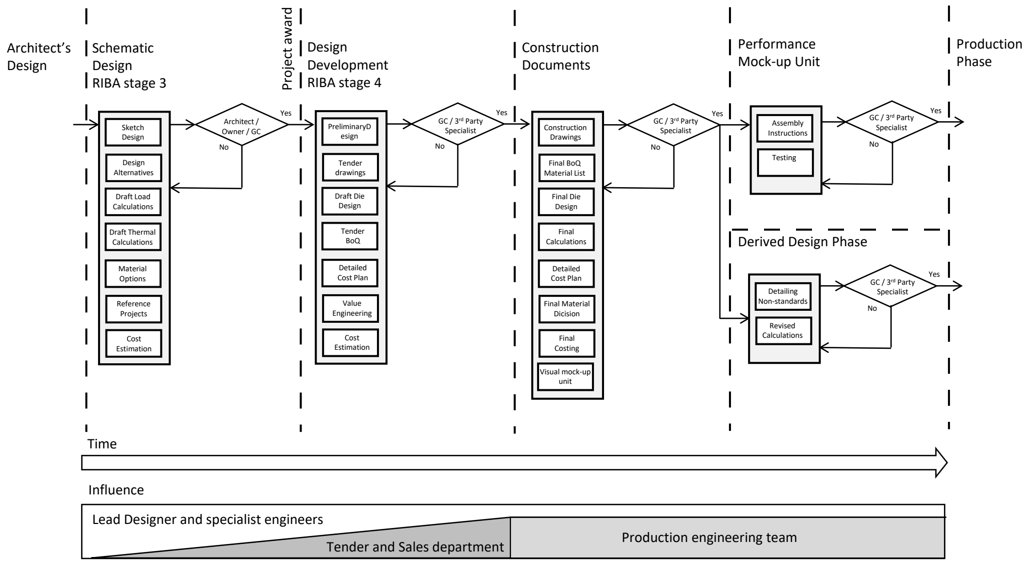



Fig. 21 – Design Phase diagram (source: own diagram)

Schematic stage: After receiving the initial design from the architect the Lead Designer starts to develop sketch design ideas and a few alternatives as an early basis for discussion. Draft structural and physical calculations are produced, reference projects are discussed and an early cost estimation presented. Over the process the tender and sales department gets more involved. If the owner, architect and general contractor agree to the proposal the next phase begins.

Design Development: The approved schematic design is further developed to a more detailed Preliminary Design. This includes the creation of tender drawings, draft die drawings, a Bill Of Quantities and a detailed cost plan. At this stage the Tender and Sales department is heavily involved too. At this stage usually a change of party in charge takes place. From this stage onwards a General Contractor company will be the main decision making party since it is appointed to undertake the construction on behalf of the owner. A 3rd party specialist i.e. a façade consultant can participate in the decision process too.

Construction Documents: once approval of the Design Development has been received, the drawings of Preliminary Design are elaborated to Drawings for Construction which carry a much higher level of detailing. This entails finalizing the design of the new dies, the structural calculations, the material choices, the costs and building a visual mock-up. At this stage the Tender and Sales department handed the responsibility over the Production Engineering team. The participation of the Lead Designer and other specialist engineers is reduced. In some case the client and the architect reserve the right to small design amendments after inspecting the visual mock-up.

Performance Mock-up Unit:  Subject to the confirmation of the General Contractor the model for the performance test is built. Prior testing the necessary assembly drawings and instructions are created. Depending on the result of the test and with confirmation of the General Contractor the project goes into Production Phase.

Derived Design Phase: In tandem with the Performance Mock-up Unit detailing of non-standard units takes place in the Derived Design Phase. This stage comprises as well any redoing of calculations and general amendments to the design.

### Production Phase

Similar to the Design Phase the Production Phase undergoes a fixed schema which can be subdivided into precise steps.

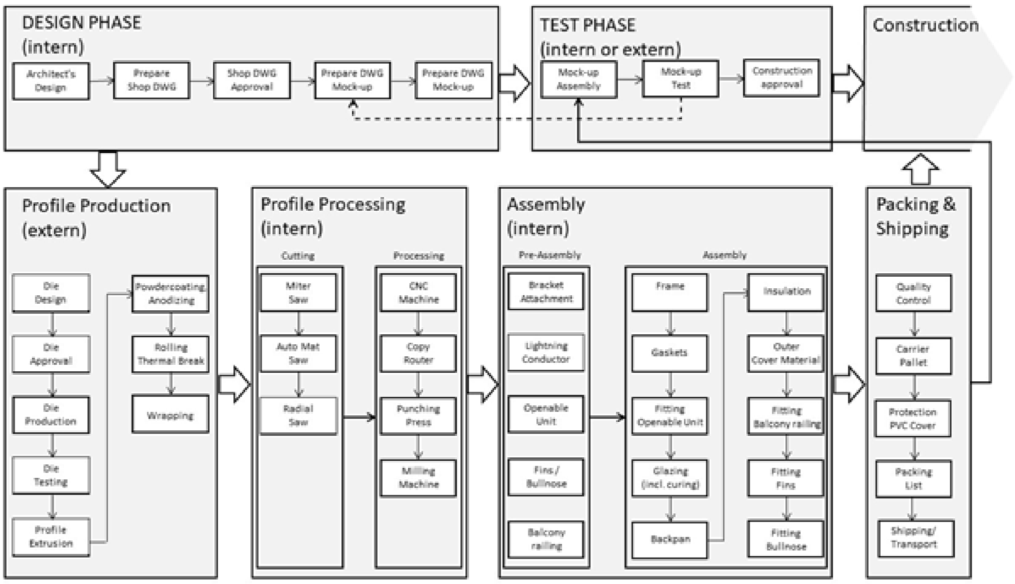



Fig. 22 – Production Phase diagram (source: own diagram)

Profile Production: With the conclusion of the Design Phase the final die design is finalized and approved for production. After manufacture and testing of the dies profile production can start at the extruding company. After the profiles are extruded, finished e.g. powdercoated and wrapped they are transported to Scheldebouw where the manufacture can start.

Profile Processing: After the profiles' arrival they are cut to size with the help of a miter saw, an automat saw and a radial saw. The cut profiles are further processed using first a CNC machine using first a CNC machine and optionally a copy router, a punching press and a milling machine. After this process the profiles are ready for assembly.

Pre- assembly: At first the profiles are fitted with all parts that are necessary or easier to fix before the frame is formed. This includes the corner cleats, which are inserted into the ends, the brackets and hooks for receiving later fins, railings or bullnoses. Also at this stage any counter plates or pieces of foam can be slid into the frames. Gaskets are already rolled into the groves and left standing over for later cutting. Further at this pre-assembly stage components are assembled for later incorporation into the frame. This can be opening units like openable windows, balcony railings or sunshades.

Assembly: The frame is assembled first in this step as it receives all following components and elements. Further gaskets are slid into to the groves followed by any opening frames for windows or doors. Then the glazing unit is introduced into the frame and depending if it is bonded via silicone to the frame curing time has to be accounted for. The steel backpan is fitted and the insulation pins glued onto it. Then mineral wool is fitted tightly onto the backpan and the protruding tops of the insulation pins receive a cop to hold the mineral wool in place. The spandrel panel is subsequently closed with an Aluminium sheet. Any remaining gaskets are fitted now into the receiving groves and all gaskets are now cut to their final length. As the last step of the assembly sequence all outer element like fins, railings, sunshades or bullnoses are fitted.

The assembly order is subject to the design of the unit and assembly steps might be exchanged to allow an uncomplicated manufacturing order.

Packing & Shipping: After a quality control via a checklist the finished units are placed on a carrier pallet and wrapped in PVC cover to protect them for the journey to site.

Test Phase: The first units will be needed for building a mock-up for testing. In case where the test results in amendments being required the profile processing and the assembly will be changed accordingly. If the test is approved, the production for construction can begin.

## 4.3 SWOT Analysis

In order to get a better understanding of the company's character a SWOT analysis is undertaken. A SWOT analysis is a useful way to gain insight into the strengths, weaknesses, possibilities and threats of companies. SWOT stands for: S = Strengths, W = Weaknesses, O = Opportunities, T = Threats.

A SWOT analysis reviews strength and weakness within a company and the opportunities and threats coming from the surrounding of the company.
The internal analysis is applied to recognize assets, abilities, main expertise, and any competitive superiority of the company within its market.
By undertaking the external analysis the chances in the market and dangers through competition, the industry circumstances, and the general business climate are established.
SWOT aims to help a company forming its business strategy by applying the knowledge a company has about its internal and external environment. (Sammut-Bonnici & Galea, 2014)

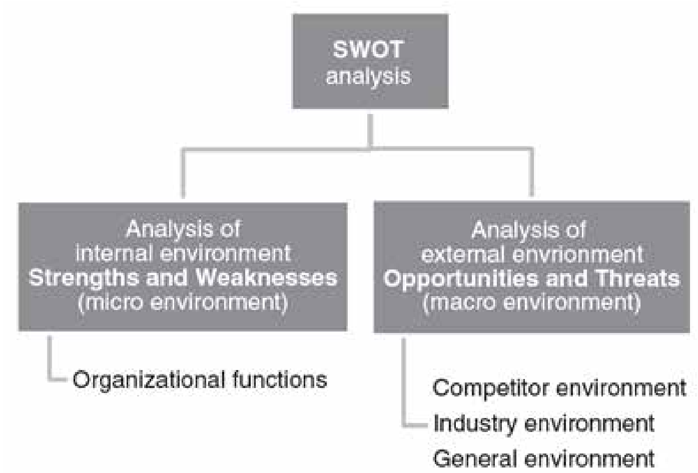



Fig. 23 - SWOT analysis main components (source: Sammut-Bonnici & Galea, 2014)

When looking at the internal side of the company the following strengths and weaknesses can be obtained:
The company represents one of the few market leaders. Very few companies operate on the same technological level, especially in Europe.
Innovative products are created within the company's own research department and actively proposed to the market.
With the tailor-made solution the company distinguishes itself from other companies which cater for the mass market.
The quality of their products set high standards and is regularly monitored.

Referring potential clients to the company's exceptional references projects is a convincing marketing tool. Being part of the Permasteelisa Group the company possesses a worldwide network which is useful no a technical and a business level. Scheldebouw offers a complete support package which covers all project phases and encourages a client to chose for them.

On the downside the product of Scheldebouw is very costly when compared to solutions from the competition. The company might not offer the same service and quality but aim at winning project at lower costs. Scheldebouw offers individual façade solutions. Their welfare is strongly connected with the economic stand of the building industry and real estate sector. The market spectrum Scheldebouw concentrates on is limited, tall or big buildings with sufficient budget for an individual and impressive façade are not a mass market. Hence the company is dependant on winning the projects that fall into their market spectrum. The product, unitized facades, have high upfront costs. Unlike stick curtain wall façades which can be bought and installed in relative small quantities, unitized facades require a bulk of material to be bought upfront by Scheldebouw to produce a substantial amount of unitized elements. The lead time for production in the factory results in later installation on site which in turn delays payment by the main contractor. The engineering and the manufacturing of tailor-made facades is a labour intensive process. The customization requires a lot of effort.


Fig. 24 – SWOT diagram (source: own diagram)

Looking at the external environment of Scheldebouw shows the following opportunities and threats:
The continuous urban growth should be beneficial to the company as it means that inner city locations become more expensive, resulting in higher and bigger projects.
Stricter environmental means that the facades have to fulfil higher performances which will result in more complex structures, a core competence of Scheldebouw, pacing them well in the market.
With architects creating more complex building geometries thanks to CAD, the number of competitive companies is reduced and the chances for Scheldebouw for winning are rising.
Threats comes from cheaper competition which offers similar products at a reduced quality but at a lower price. This applies for example to smaller fabricators which team up with system suppliers.
Scheldebouw realized many of its projects in the United Kingdom. With Brexit this market might soon no longer available to them or only with difficulty.
The material and labour costs are constantly rising. This might result in competition which offers facades produced with less material and higher automation being able to undercut projects from Scheldebouw.

The result of the SWOT analysis shows typical characteristics of a high-quality manufacturer in a com-

petitive market. While on the one side the expertise, complete service and product quality are the strengths of the company, the weak spots are high financial burdens for material and labour, a narrow bandwidth of products and a strong dependency on a restricted market.
The opportunities for Scheldebouw lie especially in the ongoing urbanization, especially the growth of mega-cities and the more complex designs. Political uncertainty of one of their main markets and high labour costs are the main threats to Scheldebouw.

## 4.4 Assembly process

To gain more insight in the production process the assembly process of a unit for a project in London is documented. The unit consists of an Aluminium frame, a fixed and openable glazing insert, a glazed balustrade with Terracotta fins and an Aluminium bullnose. The production adheres to traditional assembly line procedures with each operator being in charge of certain manufacturing steps. The full description of the process can be found in the appendix.

Date: 22.01.2020
Time: 12.00h – 16.00h
Location: Scheldebouw, Middelburg
Project sample: One Crown Place, London UK
System: female-female unitized system
Dimensions: 3.21 x 1.80m

Fig. 25 – Installation of glazing and closure of backpan (source: own image)

**Summary**

Several items reach the assembly line in a pre-assembled state already.
The assembly takes place in a traditional assembly line work, where every employee fulfills a limited number of working steps.
Three types of adhesives are used in the assembly and applied generously.
The number of various screw types is high, the number of screw head types is limited to two.
The assembly sequence is clearly defined and can not be freely modified.
The waste production during assembly is limited.
The quality of the units are high, there are few units with quality defects.
Heavy items i.e.. the glazing units are lifted in via crane.

## 4.5 Disassembly exercise

For better understanding of the hurdles for disassembly a façade unit was dismantled in Scheldebouw's production plant. The element in question was a test sample of the project Lillie Square in London, UK. It had been exposed to the elements for some time so that its insulation was thoroughly wet and moss had started to grow on it. It had been stored horizontally so that no moisture could flow out. Not all cover elements were still in place but there were sufficient elements still in place to simulate all steps required for a disassembly. The full description of the process can be found in the appendix.

Date: 22.01.2020
Time: 10.00h – 16.00h
Location: Scheldebouw, Heerlen
Project sample: Lillie Square, London UK
System: female-female
Dimensions: 4,72 x 2.99m

Fig. 26 – Element prior disassembly (source: own image)

**Summary**

The disassembly procedure took approximately six hours. In the opinion of the craftsmen the disassembly took longer than the assembly. The application of hand tools and power equipment was manageable. The main challenges that prevented fast progress were glued connections. Their strength was surprisingly high. The riveted connections and the sheer number of them were exhausting. The backpans were fixed with several hundreds of them to the frame. Since the reverse logistic was unknown, the correct sequence of disassembly steps needed to be discussed first before applying. The weight of the GRC elements and of the glazing unit asked for careful handling which slowed down the disassembly process. The overall size of the element resulted in much time spend on walking around the sample. Several foam pieces came to the light after removing sealants. When pulling them, they broke very easily and it took a good amount of time to remove them. The fact that most of the insulation was very wet was very detrimental to the removal process. All screwed connection on the other hand were very simple and quick to be loosened. Gaskets which were not glued in could be removed effortlessly. The lightweight materials as Aluminium, Rockwool, Rubber and Plastics were handy to remove. Any usage of the lifter crane slowed down the logistics immensely.

## 4.6 Conclusions

The chapter provided a detailed description of the business model and design and production process of Scheldebouw. The SWOT analysis delivered more insight about the assets and hindrances of the company and the external opportunities and threats of their trade. The comprehensive research on assembly and disassembly procedures contributed to further comprehension of the challenges for dismantling future unitized systems.

As a result of this review three sub-questions can be answered as following:

Who are Scheldebouw B.V. and how do they handle the design and production of their products?
Scheldebouw is a leading building envelope manufacturer concentrating on producing bespoke façade systems for exceptional and big buildings. Their in-house expertise allows them to produce innovative designs and tailor-made solutions, the finely tuned design and production process follows a stepped method ensuring a successful project completion. They operate in a relative small niche market which makes them vulnerable to economic changes.

***What is the current practice at Scheldebouw to manufacture their facades?***
A traditional assembly line production is used to manufacture the unitzed elements at Scheldebouw. The employees operate a limited amount tasks each on the several assembly stations. No consideration is paid for a potential disassembly after the service life of the façade. The building components feature complex interfaces and a generous application of sealants. The assembly line is especially tuned to output performance and quality.

***How can unitized façade elements be disassembled what can be learned from it?***
The disassembly exercise showed how much influence the choice of connections has on the disassembly speed. It matched as well findings by Durmisevic e.g. clustering being beneficial. Further it highlighted factors not mentioned in the Disassembly Potential which are the weight of the elements and the overall condition of the sample. The outdoor storage had a very negative effect on the sample leading to a substantial increase in time spent on dismantling.

RESEARCH SECTION

# 5 | EXISTING SYSTEMS

## IN BRIEF

This chapter describes three projects of Scheldebouw and examines how they rate for circularity and disassembly potential. Since the recycling ratio of materials is important for the calculation of the MCI, one part of this chapter investigates the current recycling practice. The chapter closes with a conclusion on the findings, enabling to draw conclusions for the design of an improved system.

### PROJECTS INFORMATION

**Scheldebouw provided info on three realized projects for the research, featuring their common design approach.**

### RECYCLING PRACTICE

**The current recycling practice for facade systems is researched to provide a base for the subsequent rating.**

### RATING RESULTS

**With the info about the material deployment of the projects and the recycling practice the rating can take place.**

# 5. ANALYSIS EXISTING SYSTEMS
**Research Section**

## 5.1 Introduction sample projects

The three projects for review are Lime Street, 8 Bishopsgate and One Crown Place, all located in London. The choice was based on the façade being a unitized system, the façade being completed or under construction and following standard design characteristics. The projects are described as follows:

**52 Lime Street**

The project at Lime Street is an office tower in the City of London and the headquarter of global insurance business W. R. Berkley Corporation. The architects KPF designed the tower to be approximately 190m tall over 35 floors above ground and mezzanine levels.
The total floor are comprises 59,400 m2 for office usage The façade of the simple geometric form consists of partially reflective glass and bright metallic fold lines. (Kohn Pedersen Fox, 2020). The project is completed.

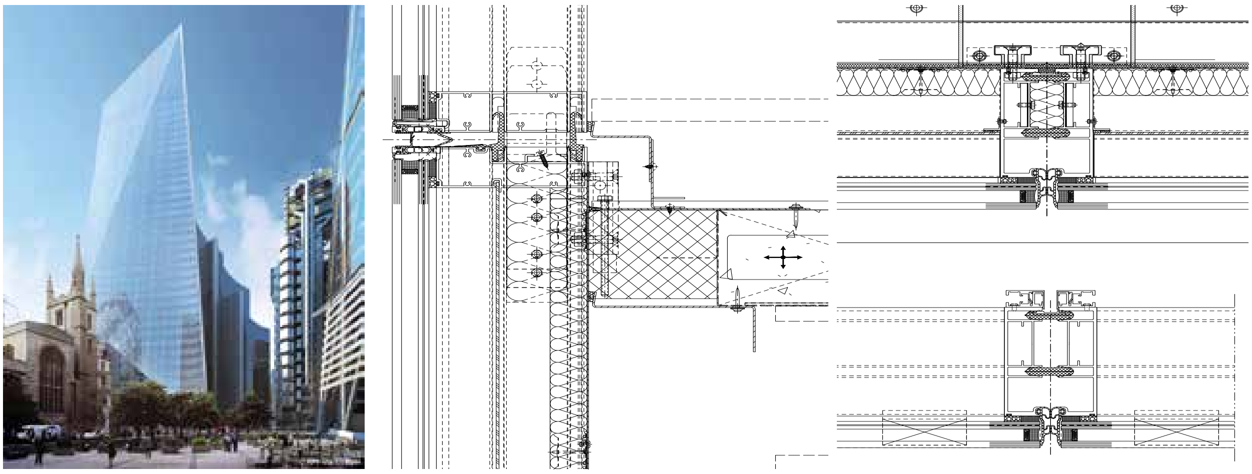


Fig. 27 – 52 Lime Street, London, source: (Kohn Pedersen Fox, 2020)

**8 Bishopsgate**

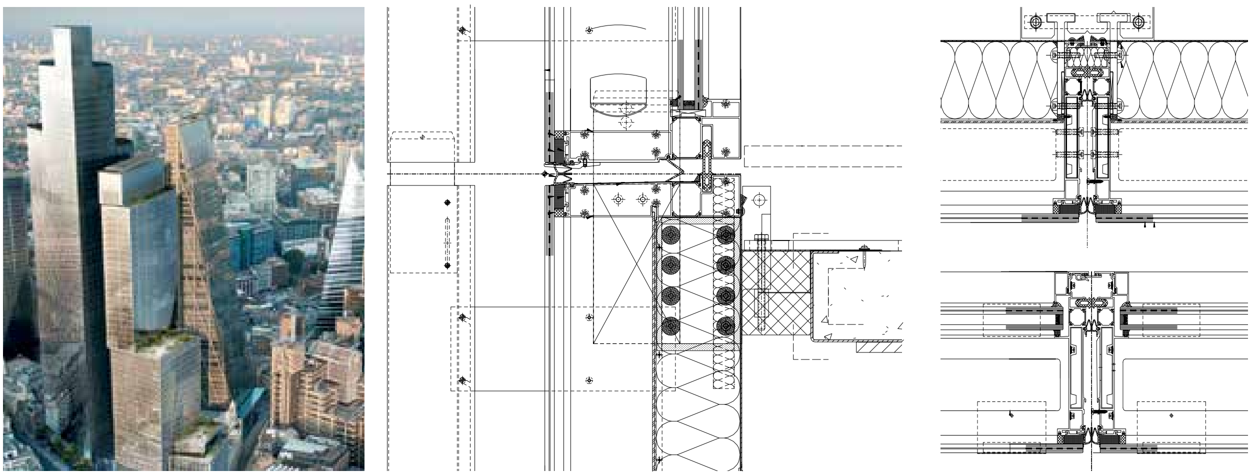


Fig. 28 – 8 Bishopsgate, London, source: (WilkinsonEyre, 2020)

On a key site in London the architects Wilkinson Eyre designed the new business tower to be approximately 202m high over 51 storeys in total. The tower offers space for offices and mixed use on its 71.500m2 floor area. The client, Mitsubishi Estate London, asked for a sustainable design solution, which was achieved with a BREEAM "Excellent" rating (WilkinsonEyre, 2020). The project is under construction.

**One Crown Place**
Being a regeneration project in the London Borough of Hackney, One Crown Place has been designed by KPF to blend with the city surroundings. The two new residential towers accommodate 246 apartments over in combination with 10.650m2 newly created retail and office space at ground and mezzanine level. Further a boutique hotel and members' club occupy a row of existing Georgian terraces on the same plot. The scheme offer in total 56.000m2 floor area. The external perimeter facades have glazed terracotta elements. Screen printed façade panels are installed on the interior facades as a contrast (Kohn Pedersen Fox, 2020). The project is under construction.

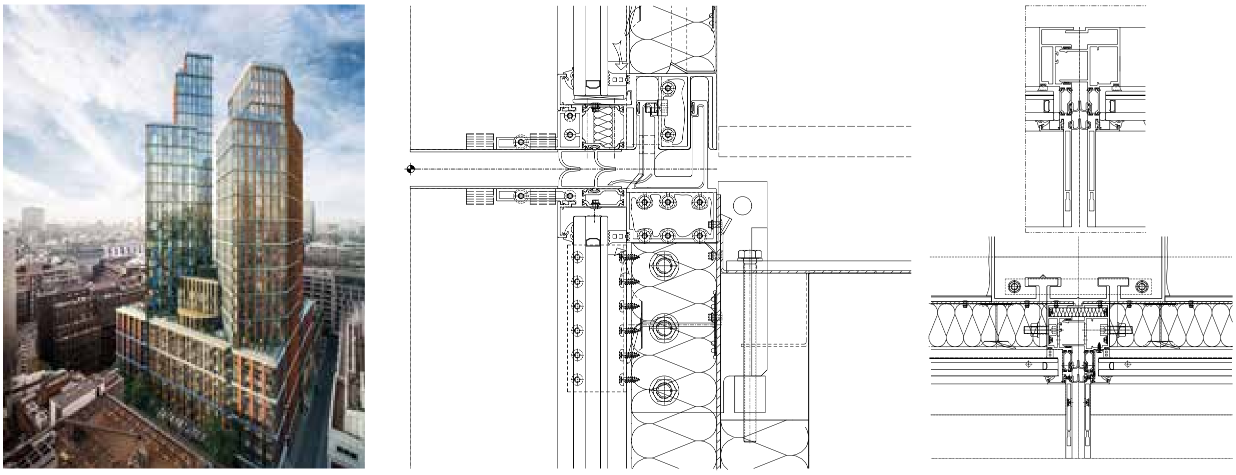


Fig. 29 – 52 One Crown Place, London, source: (Kohn Pedersen Fox, 2020)

## 5.2 Current recycling practice

The rating of the MCI presupposes detailed knowledge of the recycling processes. Since this data is not readily available in literature, research with the involved companies was undertaken.

**Dismantling**

A general overview about the life cycle for Aluminium frames can be obtained from research undertaken by Carlisle, Friedlander and Faircloth (Carlisle, Friedlander, & Faircloth, 2015). They outlined the life cycle stages for Aluminium window frames but did not add any recycling rates to it. For better understanding of the recycling rates it is helpful to follow the material flow after the dismantling of the façade.

After the use life the facades are dismantled by a specialist contractor e.g. Beelen or A. van Liempd from Rotterdam. As per interview with Beelen B.V., see appendix, the facades are removed and the profiles are sawn into smaller pieces so they fit into a shredder at the first recycling station. According to Beelen 100% of the façade materials are removed from site, with only the mineral wool being sorted out since there is no recycling circle for them. The glazing is separated to be collected by Vlakglas Recycling Nederland. The remaining materials are sold as scrap metal to a scrap metal recycling company e.g. HKS Dordrecht B.V. (Hendriks, 2020).

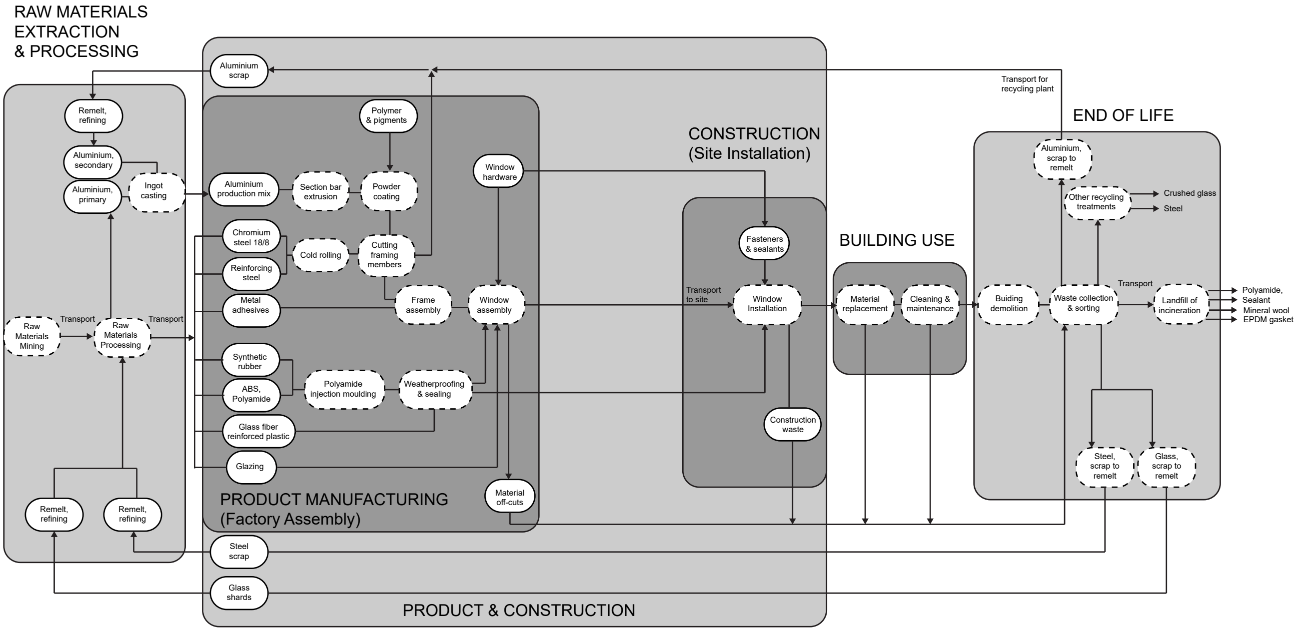



Fig. 30 – Life Cycle stages Aluminium window frame, source: (Carlisle, Friedlander, & Faircloth, 2015), adapted

### Glazing

Vlakglas Recycling Nederland B.V. does collect the material but does not further process it (Vlakglas Recycling Nederland, 2020). They merely collect the sorted out glazing elements and sell them to dedicated recycling companies e.g. Maltha Glasrecycling. In an expert interview with the Technical Manager of Maltha the recycling procedures and efficiency rates were discussed, see appendix. The Technical Manager stated that they generally achieve a recycling rate of 90% for the incoming float glass since it is contaminated with many other materials (Modesti, 2020). This value will be applied for the first recycling station as per MCI.
As the recycled material consists of ground glass fragments and is no new float glass yet further processing is necessary. On the basis of Conradt (Conradt, 2010) Hubert stated in 2014 that the efficiency of the float glass production lies at approx. 83% since the material undergoes various chemical processes e.g. evaporation (Hubert, 2020). This number shall be applied for the efficiency of the second recycling step of glazing.

### Metals

The other materials except glazing and mineral wool are transported to a scrap metal recycler. Since the scrap metal recycler HKS Metal did not reply to enquiries, companies producing the sorting machines were contacted for efficiency details. In expert interviews the process steps and relevant efficiency performances were discussed.

Redwave, a manufacturer of recycling machines from Austria informed about the procedures. In the first step an air classifier filters out 95% of all Silicon, EPDM gaskets and Polyamides, which end up at incineration or landfill. In the second step 93% of all ferromagnetic metals as Iron and Steels are sorted out via a overband magnet. At a third step 93% of all non-iron metals i.e. Aluminium are sorted out. All remaining materials, fragments of Silicon, rubber, plastics and iron are brought to landfill or incinerated.

Further sorting of the non-iron metals into pure metals or single classes of Aluminium alloy is possible but not common yet (Diesenreiter, 2020).

Another expert interview delivered a similar result. Goudsmit, a manufacturer of magnetic separators, provided recycling efficiencies of their machines and stated that 85% of Aluminium is recycled, up to 95% of the iron and steel are sorted out and that 100% of sealants, rubbers and plastics are incinerated or landfilled (van den Braak, 2020). For interviews see appendix.

Similar to the glazing, remelting metals comes with further material loss, in the case of metal as slag. Boin and Bertram calculated that the efficiency of Aluminium remelting lies at 98%, the rest ends as slag (Boin & Bertram, 2005).
As for steel the remelting procedure is characterized by an efficiency of 92% as Bowyer et al., the rest of the material is slag as well (Bowyer, et al., 2015) These two number will be used for the efficiency of the second recycling procedure.

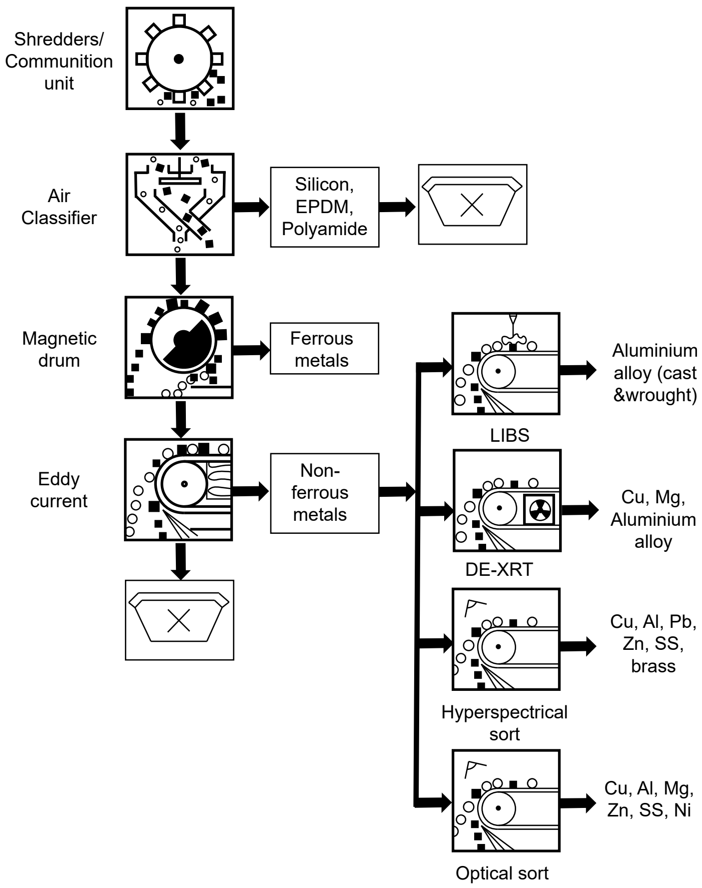



Fig. 31 – Recycling procedure, source: (Gundupalli, Hait, & Thakur, 2017), adapted

According to Diesenreiter the recycling procedure starts with the material being shredded into small pieces of approx. 10cm length (Diesenreiter, 2020). There are various forms of reducing bulk waste material into smaller particles of uniform size by applying forces produced by pressure, impact, cutting or abrasion during comminution, for convenient handling and to remove contaminants. The most often manners for comminution are swing hammer shredders, rotating drums, alligator shears, hammer mills, ring mills, shear shredders, and impact crusher (Gundupalli, Hait, & Thakur, 2017).

**Air Classifier**
The following procedure is to remove the lighter materials as silicon, EPDM and Polyamide from the metal via an air classifier. An air classifier consists of an empty cylindrical casing with an up-side down hopper at the bottom of the casing. An outlet for the lighter commodity is located at the inner of the upper wall of the casing. Two ducts lead at opposite spots into the air classifier: the first of duct lets in material by air-support and the other duct is for air inlet. Above the top of the casing a motor drives a vertical shaft through the top cover. The shaft turns a disc on the inside of the air classifier which separates the lighter material to the lower end of the rotary shaft at a boundary between the outer hull and hopper. Guide vanes in the casing walls produce the mix of air and material flow and lead the lighter material into the casing body (U.S.A. Patent No. 4,296,864, 1981).

**Magnetic Overhead Belt**
In the next step an magnetic overhead belt segregates ferrous waste fractions from the mixed waste stream. The magnetic overhead belt produces a magnetic field acting normal to the direction of mixed waste flow. Therefore metal fragments are lifted up and removed from the mixed waste stream. The rotating belt transports the metal parts towards a collection skip and releases it there (Gundupalli, Hait, & Thakur, 2017).

**Eddy Current**
Non-ferrous metals are sorted out in the next step via eddy current: a rotating drum carries out the separation with Neodymium magnets which feature alternating North and South poles. A conveyor belt transports a thin layer of non-ferrous metal and non-metallic fractions to the rotary drum. The alteration of external magnetic field rejects all non-magnetic electrically conductive metal parts and therefore separates the non-ferrous metal fractions from the remaining waste. The advantages of this separation method lies in low running costs and a high level of purity of the retrieved metal. The only disadvantage is that some metal can turn hot in the eddy current and harm the magnets (Gundupalli, Hait, & Thakur, 2017).

The non-ferrous metals can be further divided by several other methods.
**Laser Induced Breakdown Spectroscopy (LIBS)**
LIBS uses a high power laser pulse which produces a high dimensional spectrometric information allowing analysis of metal alloys, plastics and treated wood waste.
A LIBS system consists of a solid state Neodymium-doped yttrium aluminium garnet laser, a CCD spectral range spectrometer and a computing module for fast data analysis. In the inspection area the bulk waste is hit by the laser pulses induce plasma at waste pieces on the conveyor belt. Plasma radiation is detected in backward direction using fibre optics and grating spectrometer with a CCD detector and fast read-out electronics.
An optical spectroscopy analyses and categorizes the typical atomic emission lines and allows a quick analysis of the bulk waste and subsequently the discovery of the materials types. After that a mechanical system i.e. an air jet divides the detected constituent materials into allocated bins.
LIBS allows fast separation of plentiful waste in comparison to the eddy current method but the waste has to be free from lubricants, paints, or oxide layers which might not be possible (Gundupalli, Hait, & Thakur, 2017).

**X-ray based sorting (XRT)**
XRT is considered an indirect sorting method. It functions by taking X-ray images in fractions of a second. Concentrates X-ray beams are produced by am image module and sent out to penetrate the waste material. The X-rays pierce the waste particles and some of the energy is being absorbed by the material, the rest of the energy reaches a detector at the bottom of the conveyor belt. The energy received by the detector allows to conclude the density of the scanned particle and therefore its material type. Two types of X-ray sorting exist:
Dual Energy X-ray Transmission (DE-XRT) and X-ray Fluorescence (XRF) (Gundupalli, Hait, & Thakur, 2017).

**Spectral imaging based sorting**
Spectral imaging is a combination of spectral reflectance measurement and image processing technologies. To the spectral imaging based techniques count NIR, VIS (visual image spectroscopy) and HSI (hyperspectral imaging).
A hyperspectral imager produces images over a continuous range of spectral bands and assists the progress of the spectroscopic data analysis. The conveyor belt moves the waste below the scanning station, and the spectral CCD camera collecting data continuously with regular frequency. The waste is classified after initial data processing via calculation of the spectral data and the application of an algorithm to enable the material separation. At the end of the conveyor belt a line of nozzles bursts out compressed air subject to the material type detected and therefore transports the different materials to their allocated skips.
A special algorithm was computed to separate non-ferrous materials like Aluminium, white copper, stainless steel, brass, copper, and lead at a categorization rate of 98%. Only stainless steel can not be separated from the waste stream since it carries the same spectral information as other non-ferrous metals (Gundupalli, Hait, & Thakur, 2017).

**Optical based sorting**
Camera based sensors are the foundation for the recognition of waste types in optical sorting. For the identification of different metals. A combined system of colour vision and an inductive sensor array allows the recognition of copper, brass, zinc, aluminium, and stainless steel.

The material is identified on the basis of colour and electrical conductance. When the waste is scanned regions of different colours appear. Areas with a larger red component in an image stand for copper and brass, and areas of blue signify stainless steel and Aluminium. The electrical properties of the waste particles are determined by a battery of induction sensors. Surface contamination which represent a limitation to non-hybrid techniques do not affect the performance of the hybrid technique.
Optical sorting relies on complex examination using a combination of shape detection via cameras and weight scales built in the conveyor belt.

Non-ferrous metals as magnesium and aluminium can be recovered at 85% with this method while paint, grease, dust and even the shape do not influence its efficiency.
The advantages of the Optical based sorting are lower installation and running costs in comparison to XRT or LIBS. By fine-tuning the multiple data a higher efficiency can be achieved. Another improvement can be achieved by combining 3D colour area scan camera with a laser beam, called triangulation scanning. The efficiency of this method is considered of 98% for non-ferrous metals and 99% for plastic fractions (Gundupalli, Hait, & Thakur, 2017).

LIBS, XRT, Spectral imaging- and Optical based sorting are not widely common in the recycling industry according to the specialist interviews, see appendix A.

## 5.3 Rating Circularity

To calculate the MCI the recycled and reused material content of the materials is to be determined. The three façade systems consist by large of the same material selection:
1. Aluminium 6060 T4 for the mullions and transoms,
2. Galvanized steel for the brackets and the inner cover of the spandrel panel,
3. Float glass for the vision panel and the outer finish of the spandrel panel,
4. EPDM rubber for the gaskets,
5. Polyamide T6 for the insulating webs,
6. Silicone sealants for general damp and water proofing,
7. Mineral wool for the insulation of the spandrel panel.

Only the materials are considered of which quantities were given in the take-off list or could be measured from the provided drawings.

According to Scheldebouw no reused materials were used (Eichhorn, 2020). The recycled content in the applied materials were determined by contacting the supplier directly.

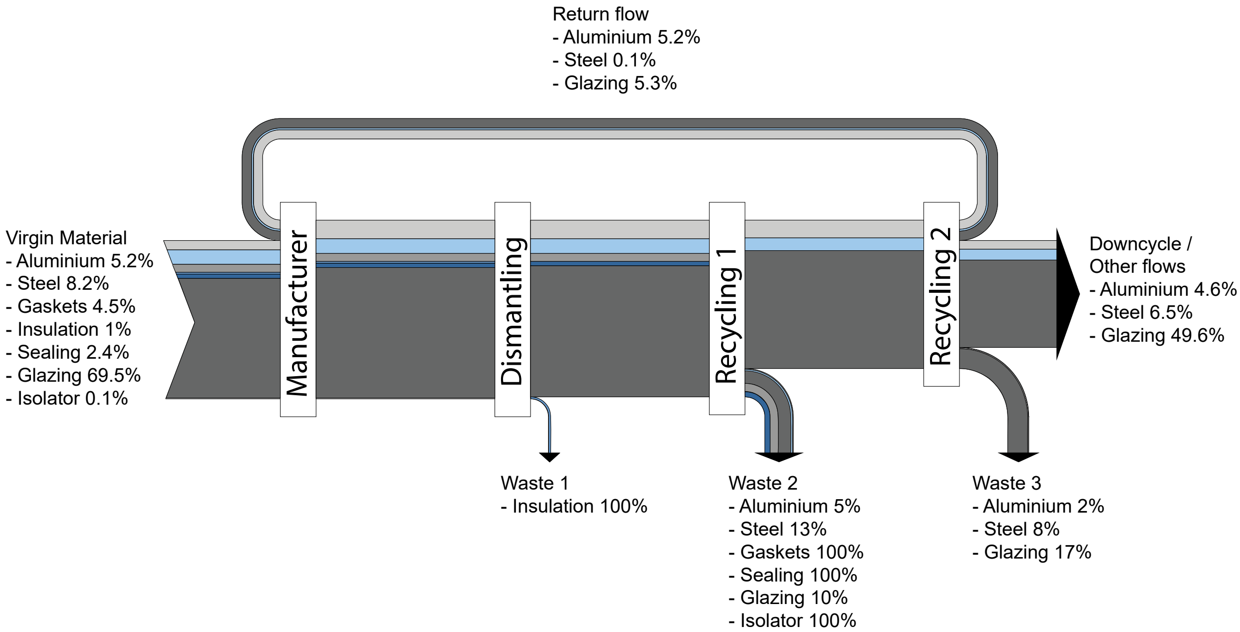



Fig. 32 – Material flow according to expert interviews, source: own diagram

The recycled content of the feedstock are according the exports as follows:
1. Aluminium 6060 T4 – Hydro, recycled content 50% (Kamphuis, 2020)
2. Galvanized steel - ArcelorMittal Europe, recycled content 0.8% (Meert, 2020)
3. Float glass – AGC Glass Europe, recycled content 5.3% (Kurian, 2020)
4. EPDM rubber – TTP, 0% (Brokking, 2020)
5. Polyamide – Technoform, 0% (Ott, 2020)
6. Silicone sealants – Sika, 0% (Woldorf, 2020)
7. Mineral wool – Rockwool, recycled content 2% (Spronken, 2020)

For interview scripts, see appendix.

The calculation of the MCI value is four stepped as previously explained. After the weight per material is calculated it is divided by the area of the façade unit to allow comparison between the three systems independent from the panel size.

As second step the virgin feedstock is calculated by determining recycled and reused feedstock. Here the number provided by the manufacturers apply.

At the third step the unrecoverable waste is computed with the data collected from the expert interviews. Two recycling stations are to be considered with each material having a different efficiently rates at each station.

Finally, at the last step the Linear Flow Index is calculated from the ratio of mass, virgin material and total unrecoverable waste. The LFI allows together with the Utility Factor to the MCI value.

Following the calculation method rigorously concludes for

**Lime Street**

| **Step 1: Calculation of material masses** | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.015 | 2700 | 40.500 | 5.89 | 6.876 | 10.4% |
| Steel | 0.004 | 8000 | 32.000 | 5.89 | 5.433 | 8.2% |
| Gaskets | 0.011 | 1600 | 17.600 | 5.89 | 2.988 | 4.5% |
| Insulation | 0.056 | 70 | 3.920 | 5.89 | 0.666 | 1.0% |
| Sealing | 0.007 | 1370 | 9.316 | 5.89 | 1.582 | 2.4% |
| Glazing | 0.114 | 2500 | 285.775 | 5.89 | 48.519 | 73.4% |
| Isolator | 0.000 | 1300 | 0.094 | 5.89 | 0.016 | 0.0% |
| | | | **389.205** | | **66.079** | |

| **Step 2: Calculation of Virgin Feedstock** | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0 | 3.438 |
| Steel | Technical | 0.008 | 0 | 5.389 |
| Gaskets | Technical | 0 | 0 | 2.988 |
| Insulation | Technical | 0.02 | 0 | 0.652 |
| Sealing | Technical | 0 | 0 | 1.582 |
| Glazing | Technical | 0.053 | 0 | 45.947 |
| Isolator | Technical | 0 | 0 | 0.016 |
| | | | | **60.013** |

| **Step 3.4: Calculation of overall amount of unrecoverable waste W** | | | | |
|---|---|---|---|---|
| | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Total unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 0.756 | 0.070 | 0.413 |
| Steel | 0.000 | 0.380 | 0.024 | 0.202 |
| Gaskets | 0.000 | 0.149 | 0.000 | 0.075 |
| Insulation | 0.666 | 0.000 | 0.000 | 0.666 |
| Sealing | 0.000 | 0.079 | 0.000 | 0.040 |
| Glazing | 0.000 | 4.852 | 0.527 | 2.689 |
| Isolator | 0.000 | 0.001 | 0.000 | 0.000 |
| | | | | **4.085** |

| **Step 4: Calculation of MCI-value** | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | **0.78** |
| Steel | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Gaskets | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | **0.26** |
| Sealing | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | **0.62** |
| Isolator | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| | | | | **Total MCI** | **0.63** |

**0 = complete linear product**
**1 = complete circular product**

Fig. 33 – MCI Lime Street - Original calculation (source: own diagram)

By following the calculation method as set out by Ellen McArthur Foundation the following issues are noticed. Firstly, when entering the Efficiency of recycling process EF as ‘0’ for some materials, the calculation stalls as it can not divide through ‘0’ as per original formula design. Secondly, when circumnavigating the issue by manually setting ‘0’ as the result of Unrecoverable Waste Wf for Landfill or Incineration, the calculation runs and MCI’s are obtained but they seem not realistic since materials with no recycled or reused content and no recycling or reuse after their life span receive a relative high MCI-value of 0.61 – 0.62. Compared with another material which has a tiny fraction of recycled content i.e. Insulation and achieves an MCI of 0.26 the results of Gaskets, Sealing and Isolator seem questionable. At the same time Steel, which is recycled to great extent, does achieve an MCI of 0.61 too.

The reason for this is the calculation method of the MCI which is designed to prevent double counting some or all of the waste generated during the two recycling processes. When however as in our case the second recycling process does not apply, a flaw seems to appear.

To bypass the issue the waste flow is amended slightly. Since the expert interview revealed that Gaskets, Sealants and Isolators are completely landfilled or incinerated, their full quantity is considered as waste going to landfill or incineration (Wo) at the outset of the calculation sequence. By doing so the full amount of their weight is considered as unrecoverable waste. Running the amended calculation delivers a more reasonable return.

**Lime Street**

| **Step 4: Calculation of MCI-value** | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | **Total MCI** | **0.60** |

Fig. 34 – MCI Lime Street – Amended waste flow (source: own diagram)

Now the individual results of the material are more in tune with expectations. Linear materials (with no recycled or reused content and not being recycled or reused) score a low MCI of 0.25. The full calculations can be found in the appendix. Applying the same method delivers for the other two projects the following:

### One Crown Place

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | Total MCI | 0.64 |

Fig. 35 – MCI One Crown Place – Amended waste flow (source: own diagram)

### Bishopsgate

| Step 4: Calculation of MCI-value | | | | | | |
|---|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value | |
| Aluminium | 0.29 | 50 | 2.00 | 0.45 | 0.87 | |
| Steel | 0.52 | 50 | 2.00 | 0.45 | 0.76 | |
| Gaskets | 1.00 | 25 | 1.00 | 0.90 | 0.10 | replacement after 25 years |
| Insulation | 0.99 | 50 | 2.00 | 0.45 | 0.55 | |
| Sealing | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| Glazing | 0.51 | 50 | 2.00 | 0.45 | 0.77 | |
| Isolator | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| | | | | Total MCI | 0.76 | |

Fig. 36 – MCI Bishopsgate – Amended waste flow (source: own diagram)

The results for the MCI per project can be summarized as follows:

Lime Street = 0.60 [ ]
One Crown Place = 0.64 [ ]
Bishopsgate = 0.76 [ ]

When calculating the masses, it was noticed that the amount of glass at all three systems is strikingly high. The glazing amount ranges from 47.4 to 73.4% making it the most substantial material in all assemblies.

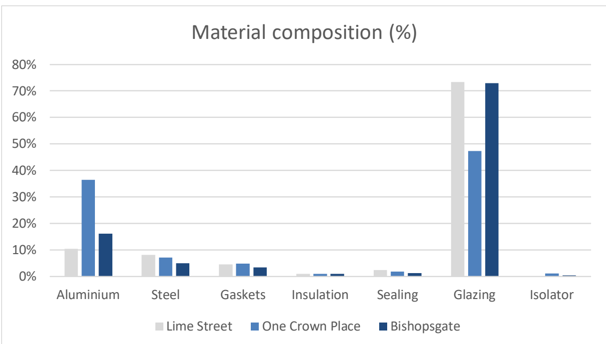



Fig. 37 – Material composition (source: own diagram)

Due to its low recycling content in the feedstock, glass accounts as well for the highest amount of virgin material due to its low recycled content of just 5.3%. Glazing accounts for 56.7% to 78.4% of all virgin material required for the three systems.

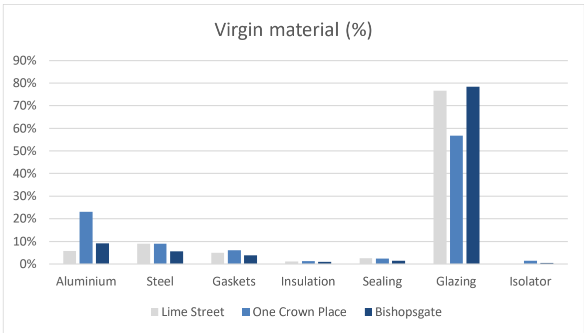
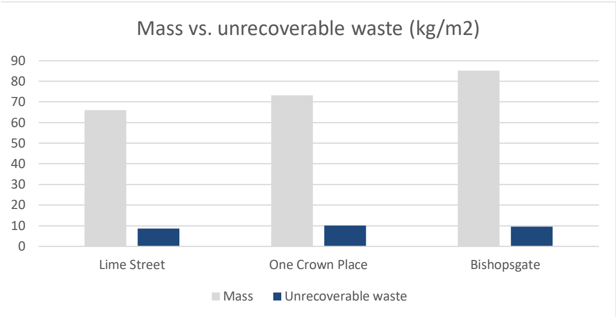



Fig. 38 – Virgin material (source: own diagram)

When reviewing the unrecoverable waste it is noticed that all three project show a similar ratio between mass and unrecoverable waste. The unrecoverable waste ranges from 12.9 to 13.9%.




| | Lime Street | One Crown Place | Bishopsgate |
|---|---|---|---|
| Mass | 66.079 | 73.102 | 85.194 |
| Unrecoverable was | 8.556 | 10.197 | 9.560 |
| Percentage | 12.9% | 13.9% | 11.2% |

Fig. 39 – Mass vs. unrecoverable waste (source: own diagram)
Fig. 40 – Mass vs. unrecoverable waste (source: own diagram)

The main contributors to the unrecoverable can be retrieved from the table below. It shows similar trends for all three projects. The main parts of unrecoverable waste stem from gaskets and glazing.

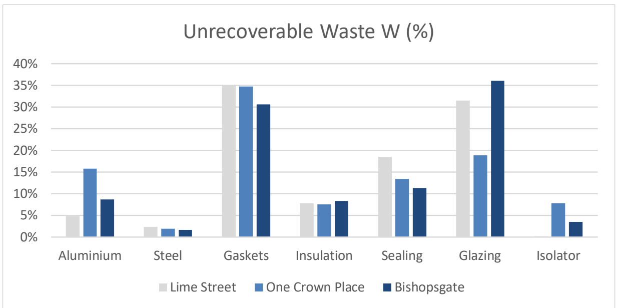



Fig. 41 – Unrecoverable waste W (source: own diagram)

| Material | Lime Street | One Crown Place | Bishopsgate |
|---|---|---|---|
| Aluminium | 4.8% | 15.7% | 8.6% |
| Steel | 2.4% | 1.9% | 1.6% |
| Gaskets | 34.9% | 34.7% | 30.6% |
| Insulation | 7.8% | 7.5% | 8.3% |
| Sealing | 18.5% | 13.4% | 11.3% |
| Glazing | 31.4% | 18.8% | 36.0% |
| Isolator | 0.2% | 7.8% | 3.5% |

Fig. 42 – Unrecoverable waste W (source: own diagram)

The results of the MCI calculations show that the projects' scores differ widely. While the scores of Lime Street and One Crown Place are close with 0.60 and 0.64, Bishopsgate stands out with 0.76 achieving a higher circular level. This is mainly due to the higher lifespan of 50 years, even when considering a change of sealants after 25 years doubling the usage of gaskets. The other projects have an expected life span of 30 years. Therefore increasing the life span of a system has a big effect on the MCI.

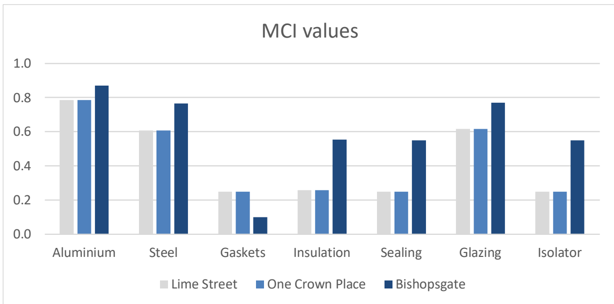



Fig. 43 – MCI values (source: own diagram)

With its high amount of recycled content and good recycling infrastructure Aluminium achieves the best MCI value of the materials, followed by steel and glass which have a recycling rate but also a small recycled fraction in its feedstock for various reasons i.e. in the case of steel an old furnace and in the case of glazing limits to contamination. The design for longevity at Bishopsgate has a positive influence on the MCI values of the single materials but gaskets which are planned for exchange after 25 years.

## 5.4 Rating Emission

The matching materials were selected from the software's database and the recycled content chosen as close as possible to match the suppliers information. In detail were chosen: Aluminium 6060 T4, Soda lime glazing – 0080, Coated galvanized steel, Ethylene propylene (diene) (EPDM/EPM, unreinforced) gasket, Silicone, phenyl-type (PVMQ, heat cured,10-30% fumed silica) sealant, T-glass insulation, PA6 (25% glass fiber) isolator. Aluminium, glazing and steel were computed with typical recycling content and the remaining components, the gaskets, sealant, mineral wool and isolator were computed with virgin material content only, since there was no other option for these materials in the database.

The part mass of the materials per m2 were entered as previously calculated for the MCI and multiplied with a factor of 10.000 to receive a reasonable material amount for a façade of 10,000m2. The amount of gaskets were doubled for Bishopsgate since a replacement of the same is considered after 25 years.

For the manufacturing the primary forming process could be entered. This was for the different materials as follows:
Aluminium: Extrusion, foil rolling.
Glazing: Glass molding
Steel: Forging
Gaskets: Polymer molding
Sealing: Polymer molding
Isolator: Polymer extrusion
The software does not show any primary process for the insulation of T-glass which produces an uncertainty about the emission of the material.

For the transport stage the transport mode and distances were entered. In agreement with a representative from Scheldebouw a 26 tonne 3axle truck was chosen for all materials. The distance between the material suppliers and Scheldebouw were computed with the help of Google Maps:

Aluminium: Hydro to Scheldebouw Middelburg: 130km
Glazing: AGC Glass Europe, Ottignies to Scheldebouw, Middelburg: 140km
Steel: ArcorMittal Dabrowa to Scheldebouw Middelburg: 1020km
Gaskets: TPP Vaassen to Scheldebouw Middelburg: 250km
Sealing: Sika Troisdorf to Scheldebouw Middelburg: 300km
Mineral Wool: Rockwool Roermond to Scheldebouw Middelburg: 210km
Isolator: Technoform Kassel to Scheldebouw Middelburg: 470km

Since the facades are not using any energy, neither static nor transport mode was chosen. The life span was considered 30 years for Lime Street and One Crown Place, 50 years for Bishopsgate.

The disposal methods were selecting according to the results of the research undertaken for the MCI and to the best suitable options available. Aluminium, glazing and steel were selected for recycling. Gaskets, sealants and isolators were selected for incineration and mineral wool for landfill. The end-of-life potential automatically copies the disposal selection.

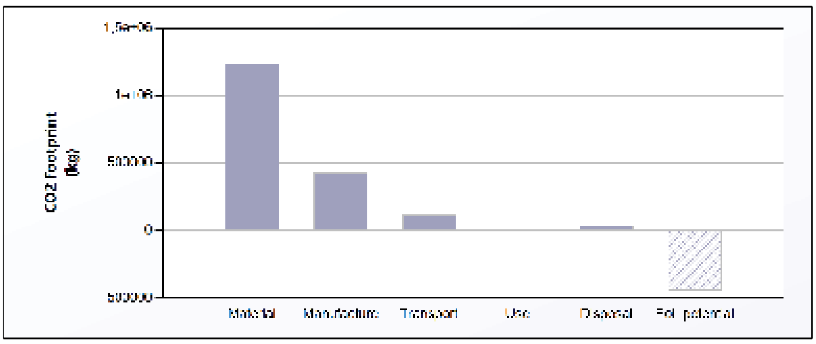
**Results calculation emissions**

With the data entered as above the computation was run. The following overall results were achieved:

| | | |
|---|---|---|
| Lime Street: | 60.442 | $CO_2$ kg/year (for 30 years) |
| One Crown Place: | 116.412 | $CO_2$ kg/year (for 30 years) |
| Bishopsgate: | 55.653 | $CO_2$ kg/year (for 50 years) |

The individual ratings for the projects and per phase as per tables below. The software does not take the End-of-Life potential into consideration for the equivalent environmental burden over the lifetime of the systems.

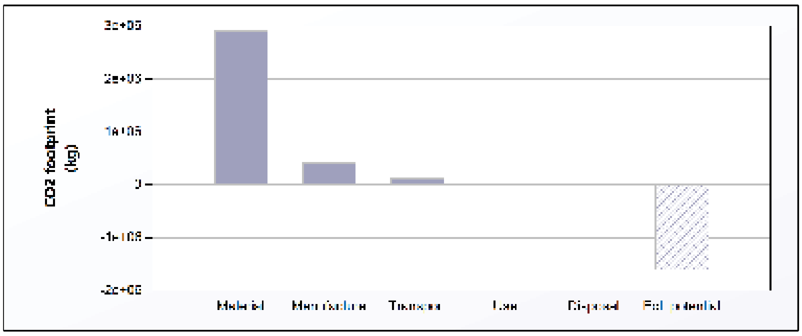
Lime Street




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 30 year product life): | 6,04e+04 |

Fig. 44 – Lime Street Overall $CO_2$ emission (source: own image)

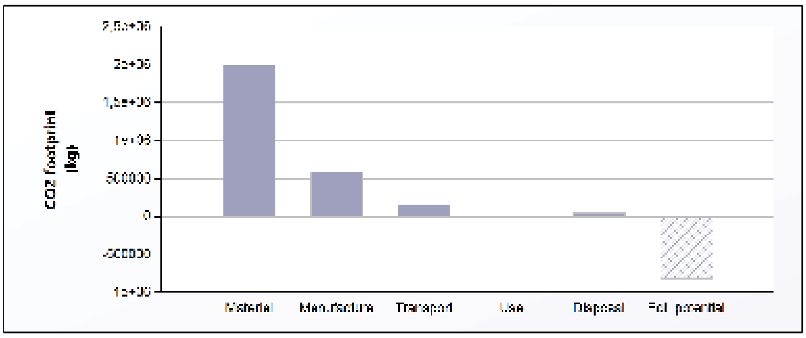
One Crown Place




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 30 year product life): | 1,16e+05 |

Fig. 45 – One Oak Place Overall $CO_2$ emission (source: own image)

Bishopsgate




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 50 year product life): | 5,57e+04 |

Fig. 46 – Bishopsgate Overall $CO_2$ emission (source: own image)

The results show that One Crown Place has the highest emissions over its life-span. The results of Lime Street and Bishopsgate are closer together. The considerable dominance of the material production is inherent in every project to be witnessed. Followed with a distance by the emissions of manufacture and to an even lesser degree transport emissions. The emissions during the use phase are nil as the facades do not actively consume energy. The dispose phase shows hardly any emissions. One Crown Place shows the highest End-of-Life potential.

Looking closer at the material phase it becomes obvious that Aluminium is the main driver of the emissions at this stage in all three projects. Although glazing has a much higher amount in the facades, it accounts only for 8.4 to 27.6% of the emissions at this stage. All other materials produce very little emissions, thanks to their limit use.

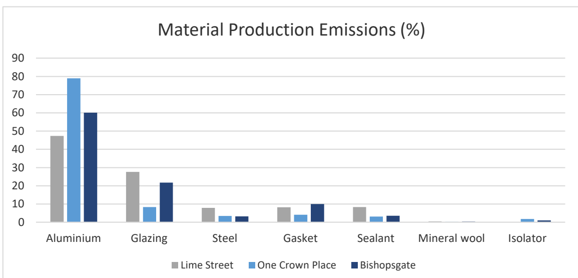



Fig. 47 – Material Production Emissions (%) (source: own image)

Examining the manufacturing phase the situation changes, with the glazing being the main culprit for emissions. It far exceeds all other materials, ranging between 57.8% and 78.1%. Notable is the manufacture of gaskets causing in two cases more emissions than the manufacture of Aluminium, although the amount of Aluminium is considerably higher.

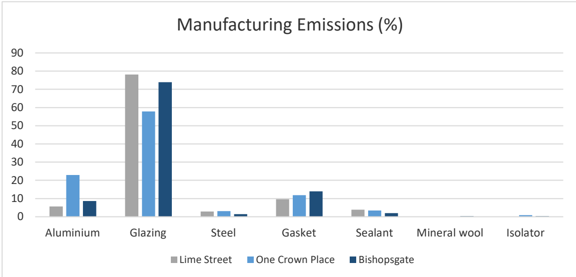



Fig. 48 – Manufacturing Emissions (%) (source: own image)

Reviewing the transport emissions the same picture appears as at the manufacturing stage. The material with the biggest weight share leads to the highest pollution for transport. The transport pollutions basically mirror distance and percentage of weight.

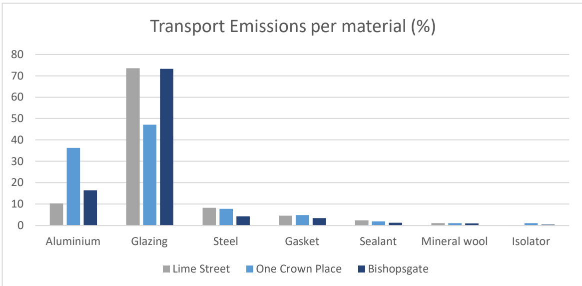



Fig. 49 – Transport emissions per material (%) (source: own image)

Looking at the emissions occurring at each phase, the dominance of the production phase becomes obvious. This phase is causing 83% to 68% of all emissions. With Aluminium as the main cause for emissions as established above. Gaskets, sealing, mineral wool have little overall impact on the $CO_2$ footprint.

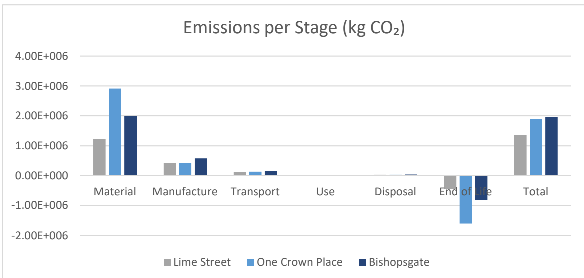



Fig. 50 – Emissions per stage (kg $CO_2$) (source: own image)

The emissions caused at the material level are approx. 3 to 7 times higher than the emissions of the manufacture level. They are even bigger in comparison with the transport emissions, which they exceed approx. 10 to 22 times.
The façade of Lime Street, which is the lightest of three features a relative good $CO_2$ emission level, however the impact of the longevity principle applied at the façade of Bishopsgate results in this façade having the least emissions per year during its lifetime. The façade of One Crown Place scores badly since it has a high amount of Aluminium per m2 (35%) compared with the others.

The production of the Aluminium is in all three facades the main factor for increased $CO_2$ emissions. Glazing comes second, despite its high weight ratio in the facades. The remaining material have little influence. To reduce Aluminium or glass will have a big impact on the system.

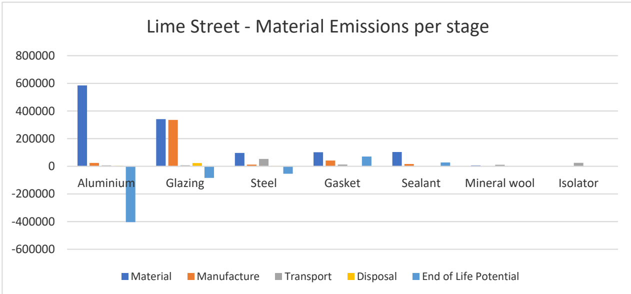



Fig. 51 – Lime Street – Emissions per material per stage (kg $CO_2$) (source: own image)

End-of-life Potential can redeem emissions produced at production stage however the software does not take it into account. Aluminium has the biggest End-of-Life potential of 65% and can therefore can redeem the majority of its emissions.
The emissions of steel, sealant, mineral wool and polyamide isolator are not significant in the small amounts that they occur in the designs. All results are considered with care as the software does not allow precise adjustment. Recycling rates, end-of-life options, material choices all have limitations in the student software. It is therefore to be considered as a guidance only.
The comparison of the recycle fraction in current supply as per software database and as per research findings indicate the level of ambiguity the software delivers.

| Material | Recycle fraction in current supply as per software (%) | Recycle fraction in current supply as per research (%) | Difference results from software and reseach |
|---|---|---|---|
| Aluminium, 6060, T4 | 40.5 - 44.7 | 50 | 9.5 - 5.3 |
| Soda Lime - 0080 | 22.7 - 25.1 | 5.3 | 17.4 - 19.8 |
| Coated steel, galvanized | 52.3 - 57.8 | 0.8 | 51.5 - 57.0 |
| Ethylene propylene (EPDM/EPM, unreinforced) | 0.1 | 0 | 0.1 |
| Silicone, phenyl-type (PVMQ heat cured, 10-30% funed silicone) | 0.1 | 0 | 0.1 |
| T-glass insulation | 23.8 - 26.3 | 2 | 21.8 - 24.3 |
| PA6 (25% glass fiber) | 0.1 | 0 | 0.1 |

Fig. 52 – Recycle fraction comparison CES database and research findings (source: own image)

The reason for the difference in the recycled content might be that the software's database assumes the percentage of recycled and downcycled material in total worldwide supply of the material whereas the research findings are detailed towards certain products in one or two European countries

## 5.5 Rating Disassembly

To establish the disassembly potential the eight rating aspects are reviewed for the three projects. Since the results are fairly close to each other, thanks to a similar constructive approach, the rating aspects are reviewed as follows and individual deviations of a system are mentioned separately.

1. Functional Decomposition (FD)
This aspect refers to the level of separation of different functions inside the same component. The more functions are separated, the more independence of the individual components is achieved. On the other side a total integration of functions leads to a high interdependence. The main elements of the unitized facades were reviewed in horizontal and vertical section. All three systems show a planned integration of functions as some elements show a combination of functions e.g. the glazed element insulate and separate inside and outside at the same time. Or the backpanel defines an enclosure and fixes the mineral wool as well. The multifunctionality of the elements is considered as being planned.

# ANALYSIS EXISTING SYSTEMS
## Research Section

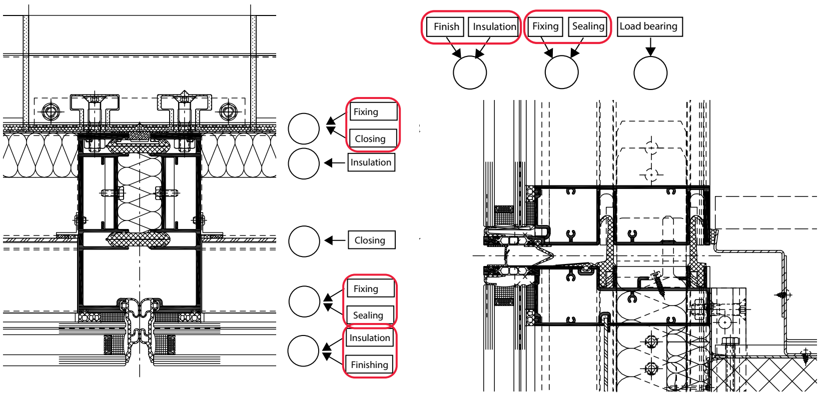



Fig. 53 – Functional Decomposition, Lime Street (source: Scheldebouw, adapted)

2. Systematization

By bundling individual elements into subassemblies more flexibility for assembly and disassembly is gained. Further the number of physical connections is reduced, making a system more suitable for disassembly and thereby preventing demolition. The three projects show different degrees of complexity since some projects include extra features e.g. a bullnose. In terms of this rating aspect they all show the same level of systematization though and receive the same grading.

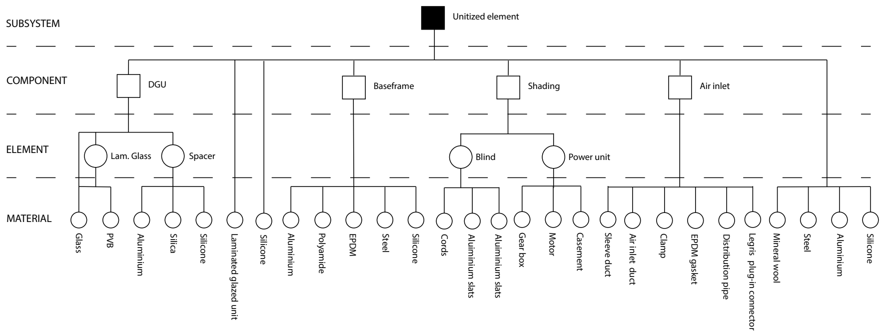



Fig. 54 – Systematization, Bishopsgate (source: own image)

3. Relational Pattern / Hierarchy

The relationships between building elements indicate the level of integration between them. Elements can be spilt into strings which represent functions and order of assembly. Vertical strings represent relations in the same function group, horizontal strings indicate links between groups of different functions. Horizontal strings are to be avoided as they stand for relations between different functional groups, enabling exchange and repairability. Bishopsgate and One Crown Place show horizontal connections in upper and lower zones, caused by their complexity. The Lime Street project shows only horizontal connections at the higher level and therefore scores slightly better in this field.

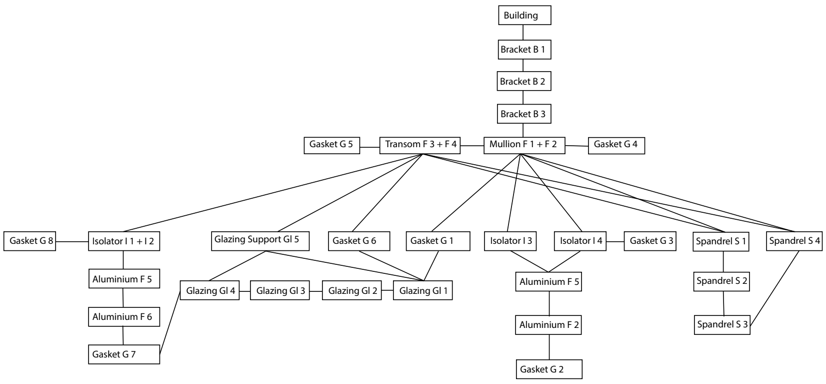



Fig. 55 – Relational pattern, One Crown Plaza (source: Scheldebouw, adapted)

4. Base Element Specification

The design of the base element or frame of a component has significant influence on the exchangeability of the component. In the cases of Bishopsgate and One Crown Plaza the base elements are thermally broken to prevent a cold bridge. The Aluminium frames support the façade units and in addition function as a thermal barrier. Hence their base element specification is of a lower level. The frame of Lime Street is not thermally broken and therefore scores better. Its frame is only supporting the façade assembly and therefore scores slightly better.

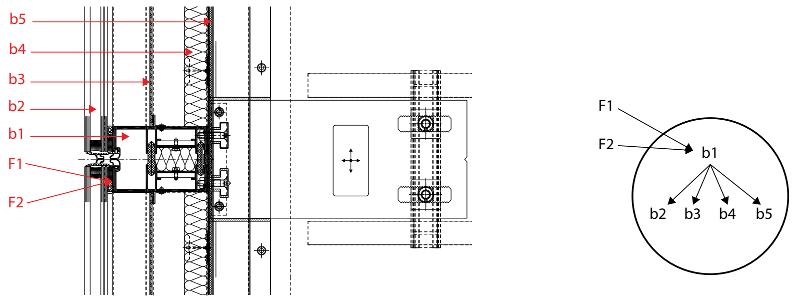



Fig. 56 – Base Element specification, Lime Street (source: Scheldebouw, adapted)

5. Geometry

The form of component edges can be divided into open and interpenetrating geometries. The open interface form allows easy dismantling while the interpenetrating form leads often to demolition. By identifying the interface forms and adding the relevant scores as per previously established score system, an average is for each system is found.
The three projects score almost the same with Lime Street and Bishopsgate scoring slightly better due to more open, linear geometries.

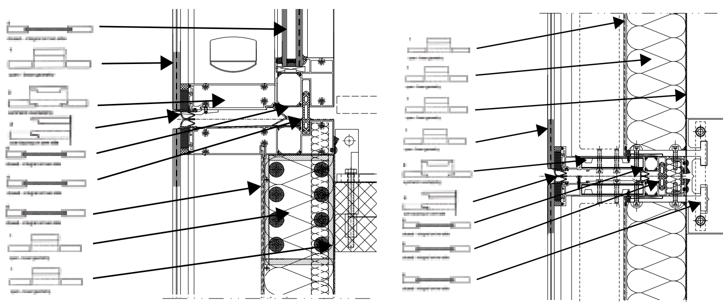


Fig. 57 – Geometry, Bishopsgate (source: Scheldebouw, adapted)

6. Assembly Sequence

Assembly orders lead to dependencies between individual elements since they are joined together. The sequence in which building elements are manufactured affects the disassemble order. Parallel and consecutive assembly order are to be distinguished. The first increase speed of assembly, the latter result in dependencies.

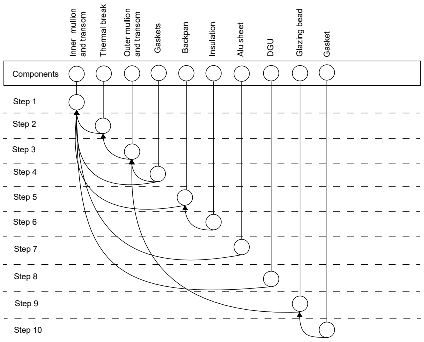



Fig. 58 – Assembly order, One Crown Place (source: Scheldebouw, adapted)

The three projects show all the same assembly sequence leading to the base element being stuck in the assembly caused by various elements assembled to the base element and connected with each other.

7. Connections

Similar to geometries the type of connections has a direct influence on the potential for disassembly. By reviewing the connections between the main elements and applying the score system as mentioned earlier, an average score was calculated for the projects.

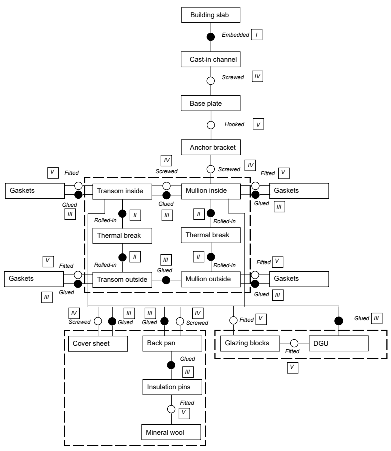


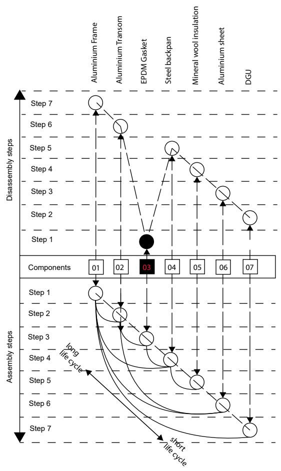

Fig. 59 – Connections, Lime Street (source: Scheldebouw, adapted)

The projects achieve a very similar level in this field, which rather moderate due to many glued and riveted connections which keep the score low.

8. Life Cycle Coordination

Assuming that disassembly mirrors the assembly order, materials of short life-cycles should be assembled last to enable disassembly of them first without interrupting the rest of the system. Further Life Cycle Coordination means that the technical life cycle of materials meets or exceeds their use life cycle, i.e.

materials should last as long as the component is expected to last.




| use life-cycle | | technical life-cycle | | | | | |
|---|---|---|---|---|---|---|---|
| Component: | Years: | 01 | 02 | 03 | 04 | 05 | 06 |
| Aluminium frame | 25 | 75 | | | | | |
| Aluminium transom | 25 | | 75 | | | | |
| EPDM Gaskets | 25 | | | 20 | | | |
| Steel backpan | 25 | | | | 75 | | |
| Mineral wool insulation | 25 | | | | | 75 | |
| Aluminium sheet | 25 | | | | | | 75 |
| DGU | 25 | | | | | | |

source: SBR (2011)

Fig. 60 – Life Cycle Coordination, Lime Street (source: own image)

In all three cases the life cycle is not coordinated in terms of assembly order or in terms of longevity of the element. The gaskets have a relative short life-cycle of 20 years according to SBR (Straub, van Nunen, Janssen, & Liebregts, 2011) and therefore interrupt the assembly / disassembly coordination since they are installed at midpoint during the process but last the shortest time. Further they do not meet the generally estimated life time of a façade being 25 years.

Results calculation Disassembly Potential

The following diagrams show the results of the DP research for each project.

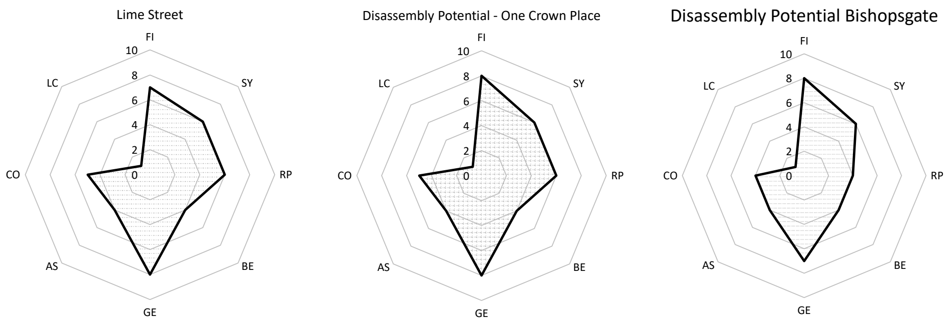



Fig. 61 – Results DP Lime Street, One Crown Place, Bishopsgate (source: own image)

The three projects almost show identical ratings in all aspects. Not a single rating aspect scored fully, leaving room for improvement especially at Base-element, Assembly, Connection and Life-cycle co-ordination.

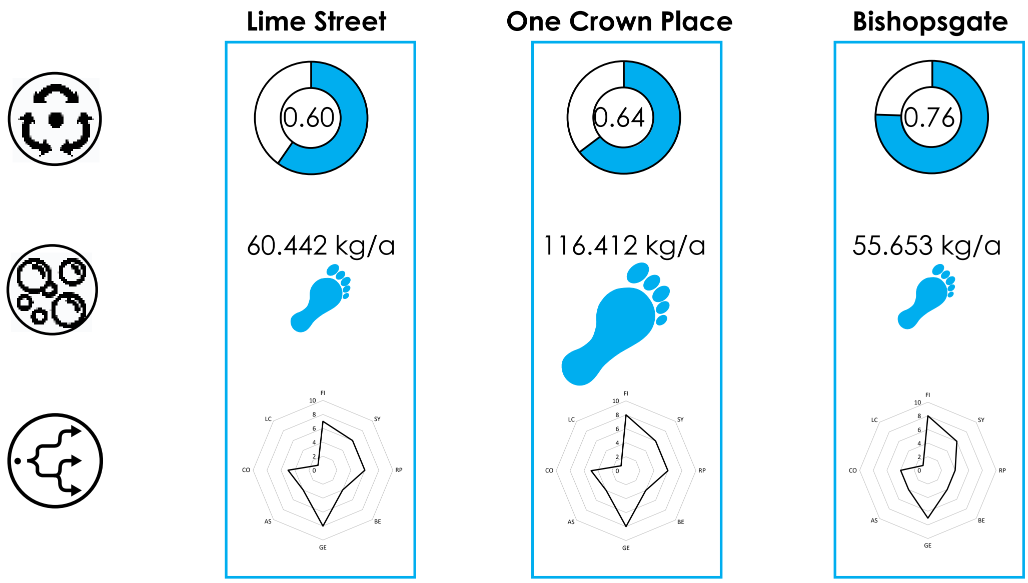
The Functional Decomposition shows that many elements serve two functions, which shows how compact the units are planned. At Systematization the materials for the spandrel panel clearly stand out from the diagram as potential for improvement.

The Relational pattern indicates the dominance of the Aluminium frame within the unit. Almost all items are individually connected to the frame. Since the frame consists of mullions and transoms, in some cases with thermal break, a horizontal link at high level appears in the diagram. The level of the base element can be increased if it does not have to cater as thermal break too, as shown in the Lime Street project. The score of the geometries are moderate and offer a little room for improvement by applying more open interfaces.

The assembly sequence shows once more the important role of the frame and how at various stages connections are made to it. By re-organising the assembly pattern a higher score should be achievable. The connections score very low with all sealants, glue and rivets being applied. Replacing them with more indirect connections via third component should bring the score much higher. The Life-cycle coordination is only scoring low because of EPDM gaskets. Replacing them with a longer life material or reshuffling the assembly order will achieve a higher score.

## 5.6 Conclusions

A summary of all results shows the following picture:




**MCI**
It is notable that Lime Street and One Crown Place rate similarly at the MCI despite One Crown Place having a much higher material usage per m2. Bishopsgate has by far the highest material deployment but achieves the best MCI value thanks to the durability of the system. Not a single material is reused or comes from reused stock. This would probably made for interesting findings.

**$CO_2$**
For the $CO_2$ emissions rating One Crown Place tops the table due to its small unit dimension in combination with a high amount of Aluminium usage. It's emission exceed the emissions of the other two projects by approximately the double. The emission level of Bishopsgate is the lowest, again due to its longevity of 50 years.

**DP**
Lime Street shows the best coverage of all aspects of the Disassembly Potential because of its straightforward construction. One Crown Place covers slightly less fields and the more complicated construction of Bishopsgate scores the least points for disassembly.
The rating system does not feature all conditions or aspects as found during the research. It is not explained into all details and since the application of unexplained aspects might give wrong results the

unexplained rating aspects were left out.
In agreement with Scheldebouw the Rating system is not resulting in single digit but in a graphic display allowing quicker location of strength and weaknesses of a system.
The rating system does not cater for all conditions that appeared during the research. Some rating criteria are open to subjectivity, weakening the meaningfulness of the rating in the end.

**Answers to research questions**

The outcomes of this chapter allow to answer the previously asked research questions.

***What is the current salvage practice of Aluminium facades and to what extent do the materials return to the material stream?***
Regarding the current salvage and recycle praxis a mixed picture appears. In short the metals and glass are recycled at high efficiencies and all other materials are incinerated or become landfill.
While the sloping is undertaken very diligently and all façade material is removed from site, except the mineral wool falls victim to an unavailable recycling infrastructure and is brought to landfill, the materials score very differently regarding recycling. All materials remain for further proceeding, with the economically valuable materials being recycled with high efficiencies, while the others are incinerated or landfilled since they are not worth filtering out of the waste stream. Aluminium returns at the highest fraction to the feedstock. Glass and steel are recycled at high efficiencies but for different reasons are returned at a much smaller fraction into the feedstock. All other materials do not return to form feedstock.

***How do the selected projects of Scheldebouw rate for Circularity and Disassembly Potential?***
The systems rate very differently for circularity and rather close for disassembly.
The Bishopsgate project clearly benefits from the longevity it is planned for, showing the highest MCI level and the lowest $CO_2$ emissions over its 50 years life span. One Crown Place on the other hand scores moderately at MCI but causes the highest emissions over its life time due to its high material employment, especially of Aluminium. Lime Street scores the lowest at the MCI due to a high glazing amount but otherwise it achieves a respectable level or emissions.
Regarding the Disassembly potential the projects show closer results. Lime Street performs the best of the three projects but leaves many opportunities for improvement. The more intricate construction of One Crown Place and Bishopsgate score slightly less.

## DESIGN SECTION

# 6 | NEW SYSTEMS

## IN BRIEF

This chapter starts with outlining design objectives for an amended design based on the results from the previous ratings. It includes a list of strategies for initial improvement of existing systems by simple means of material changes, connection improvement and layout changes without overly changing or affecting the overall design. Thoughts for alternative designs are then formulated based on the results of rating exercise and the proposal is described in more detail.

### DESIGN OBJECTIVES

**General design objectives are developed and checked for their potential for improvement of the existing facade systems.**

### GUIDELINES

**A rating of the improvement measures leads to a collection of guidelines for future facades.**

### NEW DESIGNS

**With the guidelines and the resuslts of the previous research in mind in mind two facade systems are developed.**

# 6. NEW PROPOSED SYSTEMS
## Design Section

## 6.1 Design Objectives

The general design objectives are to increase the MCI value, to lower the emission and to increase the DP. From the previous chapter valuable conclusions can be drawn for the amendment of the current systems or the design of new systems. The following lessons learned should be applied to achieve more circular and demountable systems.

**Design objectives MCI**

General measures to achieve a higher MCI level or in other words a more circular product include:-
- Reduce material deployment.
- Manufacture with materials of high recycled or reused content
- Chose materials with an established recycle infrastructure to prevent landfill or incineration.
- Chose materials with high recycling efficiencies or potential for reuse.
- Manufacture products with a higher utility during user phase i.e. higher

longevity or better performance than industry average.

The review of the MCI results show that some materials feature very low amount of recycled feedstock. The industry offers the same materials with higher feedstock that can be readily applied to reduce the usage of virgin material without change in design.

Metals, especially Aluminium have the highest recycling rate and the highest fraction in feedstock. Its application is beneficial to achieve a good rating. The amount of glazing has a strong impact on the MCI result since it has a low amount of recycled feedstock. Its use should be limited.

The insulation wool is currently not collected at all since no recycling of this product currently exists. An alternative material which is actually recycled would prove beneficial, although due to its limited amount the advantage is tiny.

The previous rating exercise did not feature any material being of reused feedstock or being totally reused after usage. This is another way to reduce the MCI value, since the loss caused by recycling is bypassed.

**Design objectives $CO_2$**

The list of standard steps to reduce emissions reads as below:-
- Reduce material employment, the less material the less emissions.
- Chose materials with low emission levels.
- Chose primary process of little energy requirements.
- Chose materials with high recycled content or better reuse parts.
- Enable positive end of life scenarios like recycling or reuse.
- Chose low emission transport modes e.g. by rail than by air.
- Chose materials with short transport distances.
- Plan for products with a long service life.

With the experience from the emission rating the following steps can be taken to lower emissions of the systems under review:

With glazing being the heaviest item, it lends itself to being reduced.
The most emissions of the facades are caused by the production of Aluminium. One way to reduce the emissions is to choose Aluminium which has a higher recycled content or is completely recycled.

Alternatively Aluminium can be replaced with a material which has a lower emission level e.g. steel although this will result in an increased total weight.
The steel applied to the systems has an extraordinary low recycled content. Steel from a plant with higher scrap metal input will lower emissions.
The transport distances are already relatively low but the steel has to travel the furthest by some distance. Changing to a supplier which is located closer might slightly reduce transport emissions, although the amount of steel used it limited and therefore the effect will be minimal.
The results from the Bishopsgate show that a long product life-span reduces emissions, even if parts need to be replaced after a while. Hence the new design should aim for longevity of the façade.

**Design objectives DP**

In general the actions below lead to a structure with a high MCI rating:-

- Separate functions to achieve functional independence of elements.
- Cluster on component level for higher level of systematization.
- Aim for vertical links to enable a hierarchy without mixing functions.
- Create a base element with intermediary increasing exchangeability.
- Aim for open/linear geometries to ease removability.
- Plan for parallel/open assembly linking less building elements together.
- Chose indirect connections with additional fixings over chemical connections.
- Coordinate materials for functional and technical life cycle.

The results of the DP assessment highlight the main shortcomings of the systems and therefore pinpoint to make the following improvements:-

In all three projects a higher ranking of systematization can be achieved by clustering the materials of the spandrel panels.

The relational pattern or hierarchy, especially of the more complex systems One Crown Place and Bishopsgate, show horizontal connections on various levels. By reorganizing the hierarchy to feature horizontal connections in the lower zone only, a better result can be expected.

The role of the base element can be increased by removing the number of functions it fulfils or making it monofunctional and introducing an intermediary between the systems.

In all three projects the geometries can be improved so that assembly order is be amended to achieve a more parallel assembly routine. The creation of a component from the spandrel panel should be beneficial in this aspect.

Many chemical connections or other direct connections are included in all three projects and are to be replaced with indirect connections via another component.

The life cycle coordination of all three projects should be adapted to feature the gaskets being installed last, so they can be removed first after their technical life cycle. At the same time the material for the gaskets should be utilized which has a technical life cycle matching the use life cycle of the façade.

## 6.2 Improvements

Before designing a new system the question arises what level of circularity and potential of disassembly the amendment of the present system can be achieved. Outlined in the drawing below are various aspects that would increase the performance of the Lime Street system for circularity and disassembly.

# NEW PROPOSED SYSTEMS

## Research Section

These are steps that Scheldebouw can take immediately without much effort or redesign.

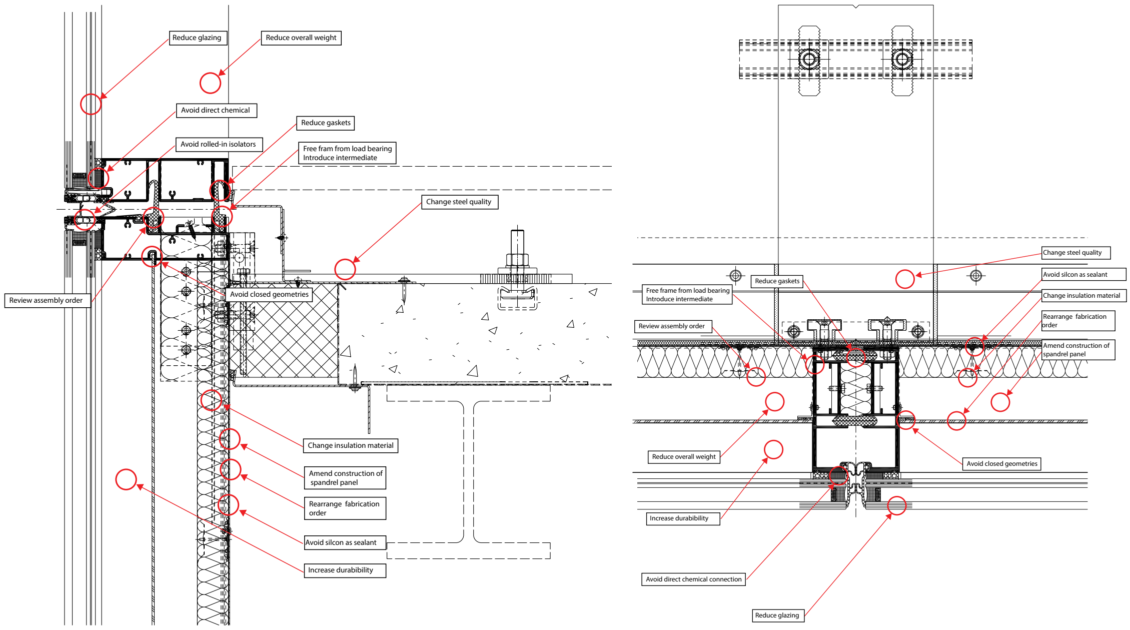



Fig. 62 – Improvement points Lime Street (source: Scheldebouw, adapted)

**Improvement MCI**

Many materials used for the Lime Street project have a limited recycled content in its feedstock. During the research it was discovered that many of the same materials are offered with a higher recycled content. By using the same materials in the version with higher recycling content the overall MCI of the system could be increased by approx. 8% from 0.60 to 0.64 without any change of design.

| Material | Current recycled feedstock | Available recycled feedstock |
|---|---|---|
| Aluminium | 50% (source: Hydro Circal) | 75% (source: Hydro Circal) |
| Steel | 0.8% (source: Arcellor Mittal) | 71.3% (source: Arcellor Mittal) |
| Polyamide | 0% (source: Ensinger) | 100% (source: Insulbar RE) |
| Mineral wool | 2% (source: Rockwool) | 40% (source: Isover) |

Fig. 63 – Improvement material level (source: own image)

| **Step 2: Calculation of Virgin Feedstock** | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | **0.75** | 0 | 1.719 |
| Steel | Technical | **0.713** | 0 | 1.559 |
| Gaskets | Technical | 0 | 0 | 2.988 |
| Insulation | Technical | **0.4** | 0 | 0.399 |
| Sealing | Technical | 0 | 0 | 1.582 |
| Glazing | Technical | 0.053 | 0 | 45.947 |
| Isolator | Technical | **1** | 0 | 0.000 |
| | | | | **54.195** |

Fig. 64 – Calculation with improved recycled content (source: own image)

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.16 | 30 | 1.20 | 0.75 | 0.88 |
| Steel | 0.16 | 30 | 1.20 | 0.75 | 0.88 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.80 | 30 | 1.20 | 0.75 | 0.40 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 0.50 | 30 | 1.20 | 0.75 | 0.63 |
| | | | | **Total MCI** | **0.64** |

Fig. 65 – Calculation with improved recycled content (source: own image)

**Improvement $CO_2$ Emissions**

Several suppliers provide materials with extra high recycled feedstock. Aluminium, Steel and Polyamide are readily available with high recycled content and can be applied without any changes to design and any loss of performance. Aluminium can be ordered with 75% recycled content, steel with 71.3% and Polyamide is available to 100% from recycled material. The high recycled content reduces $CO_2$ emissions caused during production. Since the software does not allow for manual adaption of the recycled content in the database the calculations were done manually.

$$CO_2\text{grade} = \left(\frac{100 \cdot R_F}{100}\right) \cdot CO_{2m} + \left(\frac{R_F}{100}\right) \cdot CO_{2RC} \left[{}^{kg}/_{kg}\right]$$

where:
$CO_2m$ = [$CO_2$ footprint, primary production ] (kg/kg)
$CO_2$ RC = [$CO_2$ footprint, recycling ] (kg/kg)
RF = Recycle Fraction

Fig. 66 – $CO_2$ footprint calculation primary production (source: Granta Design CES EduPack, 2019)

The results of the three materials with higher recycling content leads to a reduction of the overall $CO_2$ footprint in production.

**$CO_2$ Emmission material production original recycled content**

| Material | Total mass(kg) | Recycled % as per CES | $CO_2$ kg/kg | CO2 footprint(kg) |
|---|---|---|---|---|
| Aluminium | 67,840 | 40.5 - 44.7 | 8.62 | 584,974 |
| Glazing | 485,190 | 22.7 - 25.1 | 0.70 | 340,882 |
| Steel | 54,190 | 52.3 - 57.8 | 1.79 | 96,871 |
| Gasket | 29,880 | 0.10 | 3.42 | 102,063 |
| Sealant | 15,820 | 0.10 | 6.51 | 103,022 |
| Mineral wool | 6,660 | 23.8 - 26.3 | 0.87 | 5,814 |
| Isolator | 160 | 0.10 | 6.34 | 1,015 |
| | | | Total | **1,234,641** |

**$CO_2$ Emmission material production increased recycled content**

| Material | Total mass(kg) | Recycled % NEW | $CO_2$ kg/kg | CO2 footprint(kg) |
|---|---|---|---|---|
| Aluminium | 67,840 | 75.00 | 5.53 | 374,816 |
| Glazing | 485,190 | 22.7 - 25.1 | 0.70 | 340,882 |
| Steel | 54,190 | 71.30 | 1.50 | 81,068 |
| Gasket | 29,880 | 0.10 | 3.42 | 102,063 |
| Sealant | 15,820 | 0.10 | 6.51 | 103,022 |
| Mineral wool | 6,660 | 23.8 - 26.3 | 5,813.79 | 5,814 |
| Isolator | 160 | 100.00 | 1.07 | 171 |
| | | | Total | **1,007,836** |

Fig. 67 – $CO_2$ footprint calculation primary production (source: own image)

**$CO_2$ Emission (kg) original vs. increased recycled content**

| | Original recycled content | Increased recycled content |
|---|---|---|
| Material | 1,234,641 | 1,007,836 |
| Manufacture | 429,625 | 429,625 |
| Transport | 117,566 | 117,566 |
| Disposal | 31,452 | 31,452 |
| Total | 1,813,283 | 1,586,478 |
| over 30 years | **60,443** | **52,883** |

Fig. 68 – $CO_2$ Emission (kg) original vs. increased recycled content over full life span (source: own image)

The comparison of the results shows that substantial emissions can be reduced by choosing materials with high recycled content. By applying readily available material options the emissions at production level can be lowered by approx. 18.4%. Over the lifespan of 30 years the reduction including all other material stages amounts to approx. 12.5% per year. As the software comes with a pre-defined set of recycled contents which can not be amended in the used version and do not meet the data as found during the research, the results of the above calculation are to be considered indicative. The exercise deliberately does not take any change of materials into account to prevent design changes due to other masses or performance values.

**Improvement DP**

Some of the potential steps for amending the connection level lead to fundamental changes to the current design e.g. the improvement of the base element to feature an intermediary comes with substantial changes to the design. Other amendments can be made without causing as much deviation to the design or interruption to assembly procedures.

The Systematization of the system can be enhanced by forming the lose parts of the spandrel panel into a component. By doing so the spandrel panel will help the overall system to score better. The DGU is still formed on Element level, but this fact shall be not considered as there seems no other technical solution. The Silicone sits on the Material level and that cannot be changed as long as the façade features structural glazing.

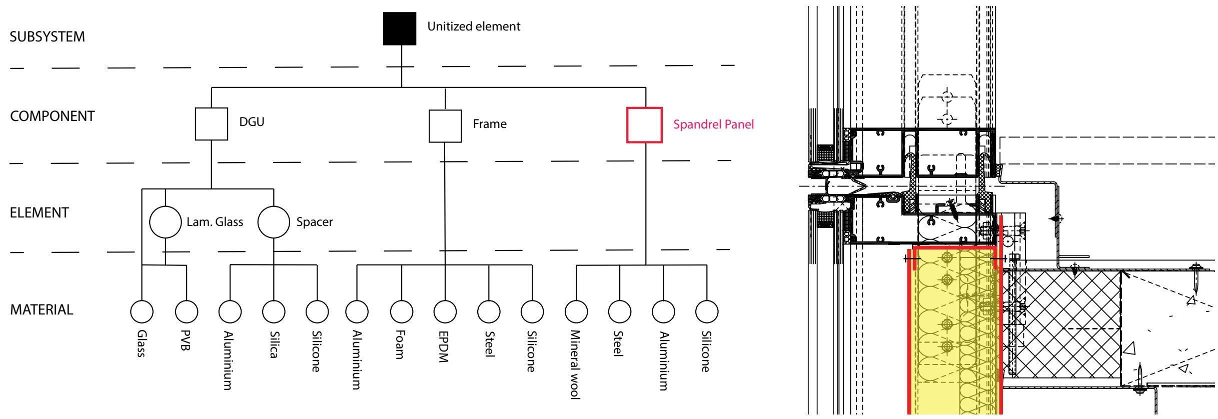
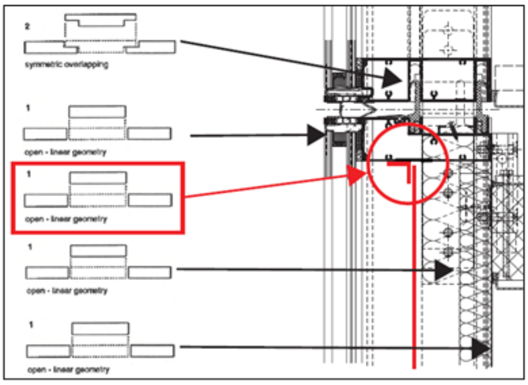



Fig. 69 – Amendment to Systematization via spandrel panel design (source: own image)

Another way for improvement is the closed/integrated geometry in the spandrel panel of Lime Street. By exchanging it to an open/linear geometry enabling easier removal the score increases from 8 to 10.

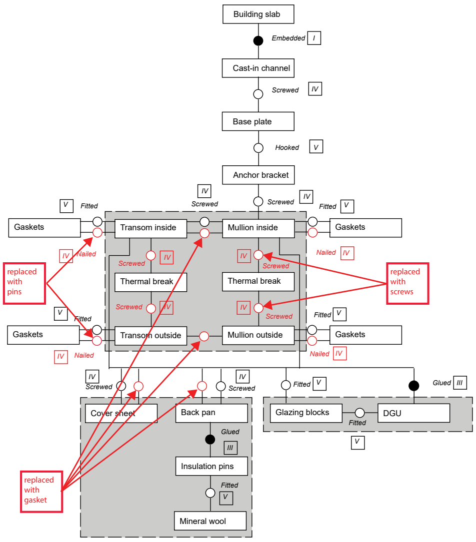



| gp = | 9.5 |
|---|---|

| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

Fig. 70 – Amendment to geometry of spandrel panel (source: own image)

Further the type of connections can be amended. By reducing the number of glued connections, exchanging the rolled-in polyamide webs for screwed-on ones and replacing the silicone seals for EPDM gaskets, the overall score of the connections can be enhanced to 5.




| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 0 | 2 | 0 | |
| III | 2 | 4 | 8 | |
| IV | 13 | 5 | 65 | |
| V | 8 | 6 | 48 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 24 | | 122 | 5.08 |

Fig. 71 – Amendment to Connections of facade unit (source: own image)

With the changes introduced  a slight improvement of the system can be achieved.

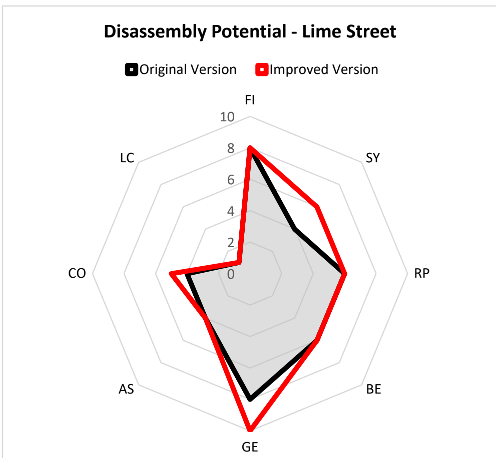



Fig. 72 – Comparison chart – original vs. improved version (source: own image)

### Improvement Layout

Assuming that a client is open for a more dramatic change of the appearance of the façade while unit dimension general amount of daylight provision shall stay the same, the question arises what a reduction of glazed area would lead to.

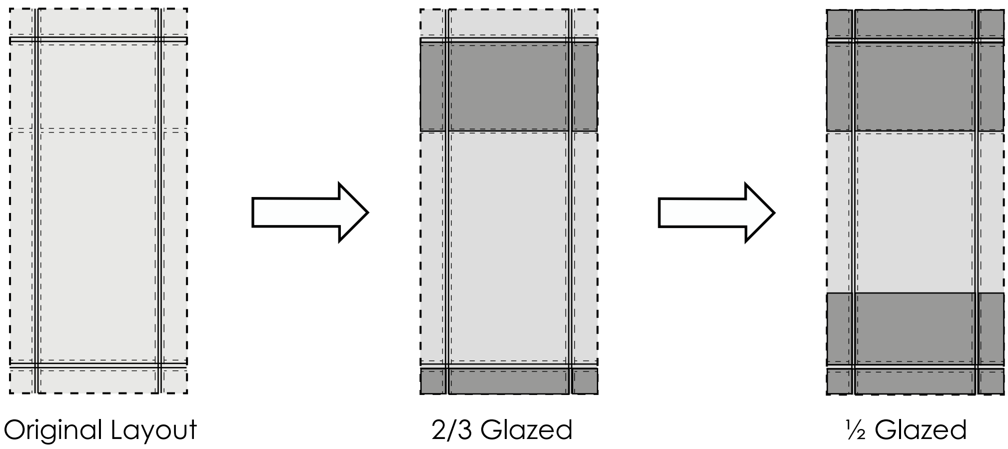



Fig. 73 – Amendment to layout of façade unit from fully glazed to 2/3 glazed to 1/2 glazed façade unit (source: own image)

Layout improvement 1: **2/3 glazed unit**
In accordance with the original's design vision area and spandrel area division the spandrel panel is amended to feature an Aluminium sheet on the outside, as a result the glazing amount of the unit is reduced by 30% and the Aluminium amount is increased by the weight of an Aluminium panel of 1.5 x 1.12 x 0.003m. For convenience all other material amount shall stay the same. Running the MCI calculation with the same data as per the first calculation the material ratios changes follows:

| **Step 1: Calculation of material masses** | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | **0.020** | 2700 | 54.000 | 5.89 | 9.168 | **17.0%** |
| Steel | 0.004 | 8000 | 32.000 | 5.89 | 5.433 | 10.1% |
| Gaskets | 0.011 | 1600 | 17.600 | 5.89 | 2.988 | 5.6% |
| Insulation | 0.056 | 70 | 3.920 | 5.89 | 0.666 | 1.2% |
| Sealing | 0.007 | 1370 | 9.316 | 5.89 | 1.582 | 2.9% |
| Glazing | **0.080** | 2500 | 200.000 | 5.89 | 33.956 | **63.1%** |
| Isolator | 0.000 | 1300 | 0.094 | 5.89 | 0.016 | 0.0% |
| | | | **316.930** | | **53.808** | |

Fig. 74 – Improved layout resulting in different material volumes (source: own image)

By reducing the amount of glazing by a third and adding the 3mm thick Aluminium sheet to the surface of the spandrel area the percentage of Aluminium changes from 10.4 to 17% per m2 average façade and the glazing amount reduces from 73.4 to 63.1%. The total weight is reduced from 66.079 to 53.808kg.

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | Total MCI | 0.61 |

Fig. 75 – MCI result of amended layout (source: own image)

The total MCI changes from 0.6 of the original version to 0.61 for the amended version. Which does not resemble a strong improvement.

Layout improvement 2: **1 / 2 glazed unit**
In this second layout the glazing area is further reduced. An intermediate transom is introduced to form a balustrade and in addition to the overhead spandrel area with Aluminium cover as per Layout 1, the balustrade area is as well transformed into a Aluminium clad spandrel panel. For ease of calculation changes to other materials are not considered for now. The glazing area is only half the size of the original design. The effect on the weight distribution is as follows:

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.025 | 2700 | 67.500 | 5.89 | 11.460 | 24.3% |
| Steel | 0.004 | 8000 | 32.000 | 5.89 | 5.433 | 11.5% |
| Gaskets | 0.011 | 1600 | 17.600 | 5.89 | 2.988 | 6.3% |
| Insulation | 0.056 | 70 | 3.920 | 5.89 | 0.666 | 1.4% |
| Sealing | 0.007 | 1370 | 9.316 | 5.89 | 1.582 | 3.4% |
| Glazing | 0.059 | 2500 | 147.500 | 5.89 | 25.042 | 53.1% |
| Isolator | 0.000 | 1300 | 0.094 | 5.89 | 0.016 | 0.0% |
| | | | 277.930 | | 47.187 | |

Fig. 76 – Improved layout resulting in different material volumes (source: own image)

The Aluminium amounts to 24,3% of the overall façade weight and the glazing is reduced from original 70,3 to 53,1%. The overall weight is reduced from original 66.079 to 47.187kg/m2.

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | Total MCI | 0.62 |

Fig. 77 – MCI result of amended layout (source: own image)

As per the table above the total MCI changes from 0.6 of the original fully glazed version to 0.62 of the half glazed version. The improvement is marginal considering the drastic change in layout.

**Conclusion**

Three different approaches were tested for their impact on increasing circularity or disassembly performance of the Lime Street project:

1. The application of materials with higher recycled content leads to an improvement of the MCI value from 0.6 to 0.64 without any design changes.
2. The application of readily available materials with high recycled content reduces the total $CO_2$ emissions by 12.5% per year over the 30 years life span. The higher recycled content in Aluminium is the main factor for this.

3. The change of the layout to a lower glazing and a higher Aluminium content of the façade unit leads to a marginal improvement from 0.6 to 0.61 of the MCI, this in combination with the original recycled content. Further reduction of the glazed area to only ½ of the original design leads to an increased MCI of 0.62. Since glazing represents the material with the biggest weight per m2 façade and features a modest MCI of 0.62 a very high reduction of its amount is required to lower the MCI. Even reducing the glazed amount by half as per the second layout improvement, achieves only a marginal improvement is. Since the glazing is crucial to allow in light, a strong reduction of it might not be an option.

4. Moderate changes of the construction of the unit results in an improvement of various aspects of Disassembly Potential.

In summary, the choice of materials with high recyclable content has an impact on the overall MCI and a more substantial one on the emission levels. The impact of a layout change does hardly deliver anything and affects the design severely. The slight amendment of the construction to follow principles of DfD without changing the appearance of the design leads to a more worthwhile improvement. Some of the changes are immediately possible but they do not deliver a breakthrough.

## 6.3 Guidelines

A guideline for Scheldebouw to improve the performance of the façade systems can be summarized as below. Some steps lead to a measurable improvement and others affect the outcome only marginally.

**Material Circularity Indicator**
→ Chose materials with a higher recycled feedstock. An improvement of approx. 6% can be achieved without any changes to the design being necessary.
→ Reduce the amount of materials with low recycled content. This applies to Silicone sealants, EPDM gaskets, mineral wool and the Polyamide isolator. Even by halving the amount of these materials the result is a modest increase of approx. 3% of the MCI score only since the four materials amount to little weight in the overall system.
→ Change the steel quality to a steel with higher recycling content. This step has an impact on the systems with a higher steel amount. Its impact can achieve an increase of approx. 3 % at Lime Street but no measurable increase at Bishopsgate.
→ Change the insulation material to one with higher recycling content. This step has hardly any impact at all. An insulation material of 40% recycled content e.g. glass wool achieves no MCI improvement. An insulation material with 100% recycled content delivers approx. 1% MCI increase.
→ Reduce the amount of glazing. This step reduces the overall weight of the systems immensely and comes with a big impact on the layout. However even if the amount of glazing is halved, the effects on the MCI score are minimal since the material still represents the most heaviest item and its overall MCI measures 0.62 only.

→ Produce façades for long life-spans. This is the action delivers the highest score, even if some materials need replacement the total MCI-value will benefit. The overall MCI of the Bishopsgate project exceeds the MCI's of Lime Street and One Crown Place by approx. 21 and 16%.

**$CO_2$ Emissions Calculation**
→ Select materials of high recycled amount. Applying this change to Aluminium, Steel and Polyamide leads to a reduction of emissions of 12.5% for Lime Street.
→ Plan systems for a long use-life cycle. The Bishopsgate features the highest material deployment but through its long life span of 50 years features the lowest emissions per year, even with double the amount of gaskets due to exchange after 25 years. At Bishopsgate the emissions lowered from 92,800 kg/year over 30 years to 55,700 kg/year over 50 years, a drop of 40%.
→ Reduce transport distances. By halving the transport distances for the materials of Lime Street a yearly reduction of approx. 3% can be achieved.
→ Apply other transport modes. Transport by rail reduces the emissions caused by Lime Street by approx. 4%.
→ Reduce the amount of glazing. When halving the amount of glazing at Lime Street project and increasing the amount of Aluminium for spandrel panel cover, the emissions can be reduced by approx. 12% taking the EoLP of Aluminium into account.
→ Reduce the amount of gaskets, sealings, isolators and insulation. A reduction of the materials by 10% delivers a reduction of 1.5% of $CO_2$ emissions.
→ Consider the End of Life Potential when applying materials. Aluminium can redeem 65% of its emissions if the EoLP is taken into account.

**Disassembly Potential**
→ Convert the spandrel panel - currently being built by several lose materials - into a component. This benefits on the Systematization level and increases it from 4 to 6.
→ Improve the hierarchy rating by creating more vertical patterns. The frame cannot be helped to form a horizontal link at high level but this could be ignored since the mullions and transoms form a unit once connected. Especially the spandrel panel allows for a more vertical pattern by allocating the Aluminium sheet to be part of the spandrel panel and not to be fixed to the frame. A score of at least 6 can be achieved by this measure, under the condition that the horizontal connection between mullions and transoms are ignored.
→ Introduce open linear geometry wherever possible. Avoid the very low scoring rolled-in isolators with their closed – integral geometry on two sides. At Lime Street this leads to an increase on the Geometry score from 8 to 10.
→ Free the base element from the bearing function of the frame by introducing another component. This measure improves the score of the Base element from 6 to 8.
→ Reshuffle the assembly sequence and the component relations so that the present interlocking assembly order can be prevented. Avoid current overlaps and intersections by arranging cascading or concurrent sequences. Produce parallel assembly sequence by clustering elements enabling simultaneous installation. Design amendments to the spandrel panel area to allow parallel assembly sequence. The changes will produce an increase for the Assembly Sequence from 4 to at least 6 points.
→ Avoid connections of direct chemical connection, direct connection between two pre-made components and indirect connection with third chemical material. Replace them with higher scoring connection types as indirect connections via independent third components or even better indirect connections with additional fixing devices, allowing replacement of an element without affecting adjoining elements. The steps results in an increase on the Connections scale from 4 to 5, or 6 in the case of glazing held by mechanical means.
→ Make sure all materials meet the expected use life cycle of the façade. Exchange weak materials with more durable ones. Place all materials with short life-cycles at the end of the assembly. This step increases the scoring on the Life-Cycle Coordination from 1 to at least 4.

# NEW PROPOSED SYSTEMS
## Research Section

**Summary**

Summarized the improvement measures are listed as following:

**Improvement steps MCI**

→ Produce façades for long life-spans. Improvement approx. 16 and 21%. ★★★

→ Chose materials with high recycled feedstock.  Improvement approx. 6% ★★☆

→ Change to a steel with higher recycling content. Improvement approx. 0-3 % ★☆☆

→ Change to insulation with high recycling content. Improvement approx. 1% ★☆☆

→ Reduce the amount of glazing. Improvement approx. 1% ★☆☆

**Improvement steps $CO_2$ footprint**

→ Plan systems for a long use-life cycle. Improvement approx. 40%. ★★★

→ Select materials of high recycled amount. Improvement approx. 16% ★★☆

→ Reduce glazing. Improvement approx. 12% ★★☆

→ Reduce transport distances. Improvement approx. 3% ★☆☆

→ Apply other transport modes. Improvement approx. 4%. ★☆☆

**Improvement steps Disassembly Potential**

→ Aligning materials life span with assembly sequence. Improvement approx. 30%. ★★★

→ Converting spandrel panel into component. Improvement approx. 20%. ★★☆

→ Introducing more open linear geometries. Improvement approx. 20%. ★★☆

→ Freeing base element from bearing function. Improvement approx. 20%. ★★☆

→ Avoiding direct or chemical connections. Improvement approx. 20%. ★★☆

## 6.4 Design Approach

The results of the previous exercise in comparison with the MCI of Bishopsgate, shows that a system designed for durability achieves a very high level of Circularity and low levels of emissions. The question arises how a system would score with less material usage, high recycled content and following the principles from DfD from the beginning.

Another aspect that catches the eye is that no system was evaluated for reuse of materials. The recycling efficiencies were researched in detail but the circling of materials for reuse was not computed in any way. The question is how well a system would fare, which was designed with reuse of materials in mind, enabled by principles of disassembly.

The design shall be based on the materials usually applied at Scheldebouw. As per information by Scheldebouw the standard dimension that most of their projects come in are 3.6m x 1.5m h x w which shall be applied to the new design. Standard performance enablers e.g. thermal break shall be incorporated. A complete in-depth review of a new system regarding structural performance or building physics goes beyond the scope of the investigation. The three reviewed projects shall be function as guides regarding profile dimensions and glass built-up. The frame work for the new systems shall be:

- Female/female unitized system
- Thermally broken
- High glazing amount
- 3.6m height and 1.5m width
- Frame-based rectangular unit
- Anchorage via steel brackets and plate fixed to a cast-in channel

## 6.5 Proposed Designs

**Type 1**

The first proposal is designed to enhance the longevity of the system by applying the principles of DfD. It is characterized by a sandwich panel which allows complete exchange and replacement or refurbishment since it can be loosened from the base element. Therefore it enables replacement of gaskets and glazing unit after expiration of their technical life span. The glazing unit is reduced to fit into the sandwich panel and to reduce the overall weight of the system and $CO_2$ footprint. The majority of the connection are produced by applying screws. Profile and glazing thicknesses are based on the ‘Lime Street’ project.

The idea is to develop a large sandwich element that can be easily replaced after several years without removing the frame. After dismantling, the sandwich element can be easily opened to remove the insulation. At the construction site, it is delivered and installed with the frame like a conventional element facade. The proportion of insulating glass has become smaller in order to save weight.
The glass can also be replaced from the inside. Silicone is avoided if possible and replaced with EPDM rubbers if possible. Although they are not better in terms of MCI or $CO_2$, they are at least easier to dismantle. This system is characterized by a longer lifespan. After 25 years, for example, only the seals and glasses could be replaced to allow another 25 years of service.

# NEW PROPOSED SYSTEMS
## Research Section

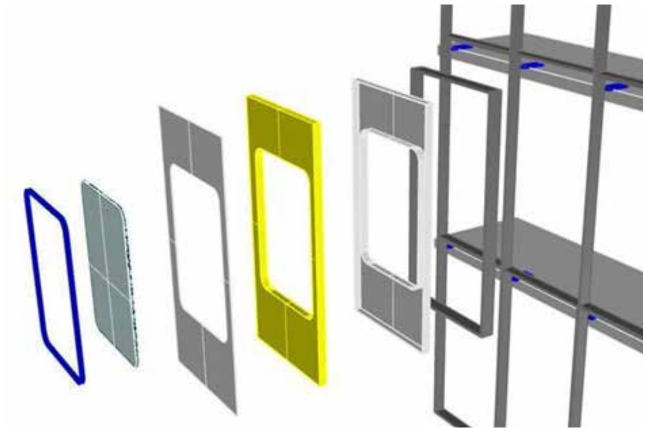


Fig. 78 – Type 1 schematic drawing (source: own image)

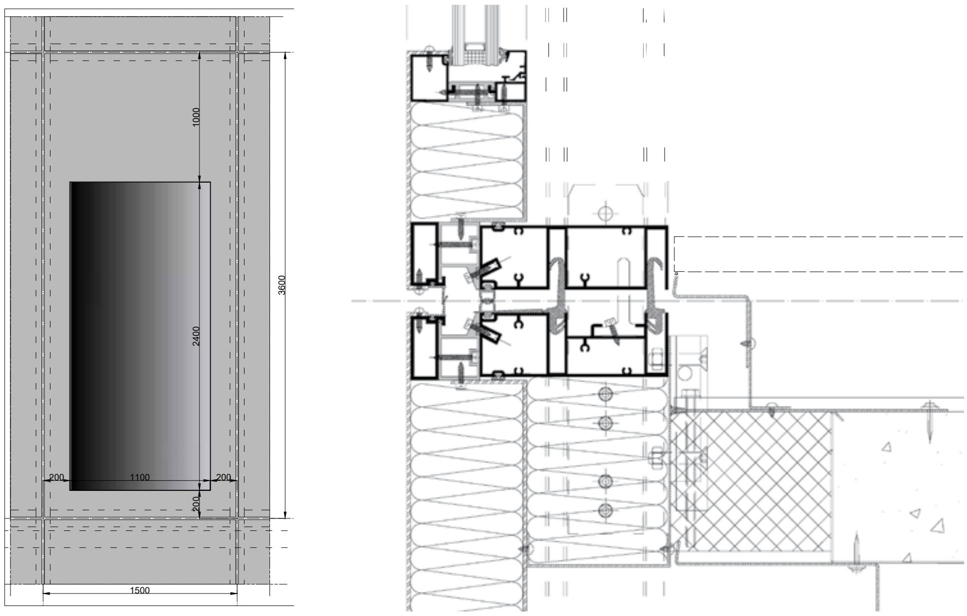



Fig. 79 – Type 1 elevation and vertical section detail n.t.s. (source: own image)

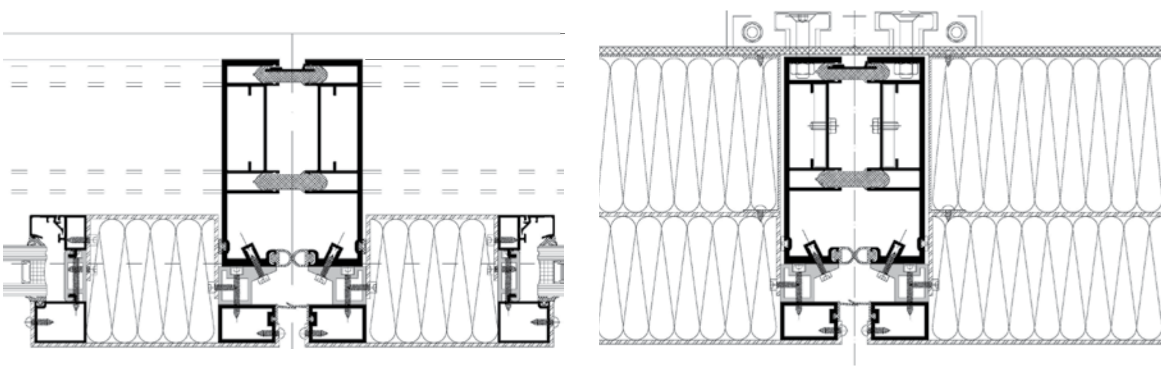


Fig. 80 – Type 1 horizontal detail spandrel area and vision area n.t.s. (source: own image)

**Type 2**

The idea for this type is to create a frame made up of profiles and nodes to enable reuse. The sandwich elements are traditional, but here too the vision panel has become smaller This system is designed to reuse the frame. The nodes can be used in a new design, the frame profiles can be shortened or replaced.

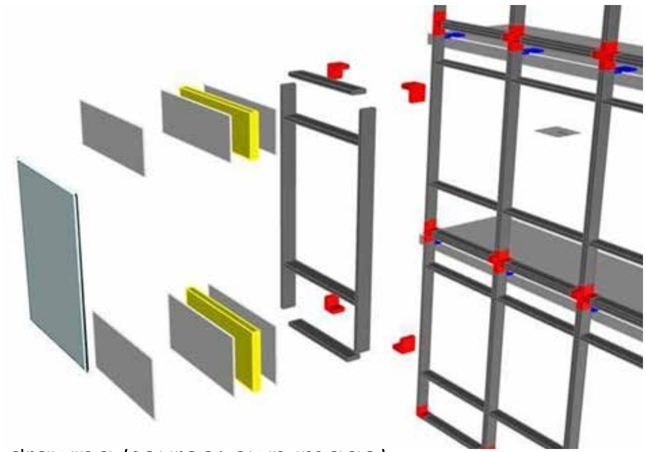


Fig. 81 – Type 2 schematic drawing (source: own image)

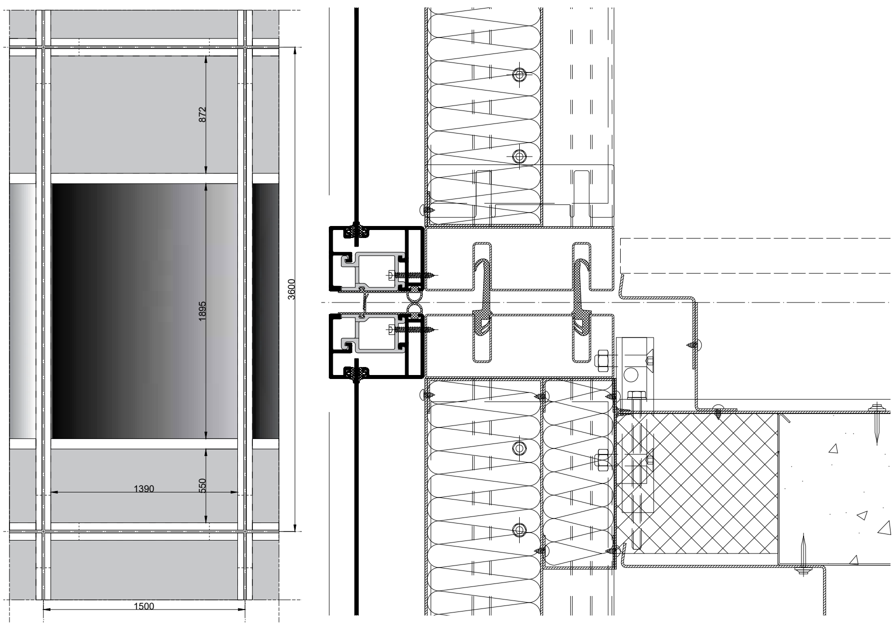



Fig. 82 – Type 2 elevation and vertical section detail n.t.s. (source: own image)

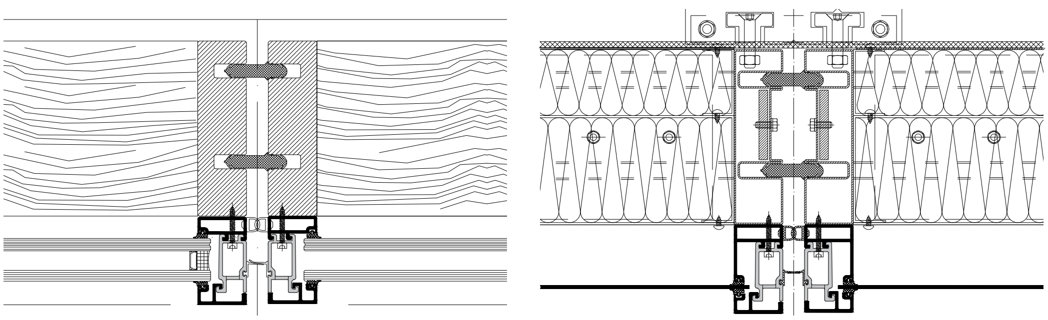


Fig. 83 – Type 2 horizontal detail spandrel area and vision area n.t.s. (source: own image)

**Answers to research questions**

The outcomes of this chapter allow to answer the previously defined research questions:

***Which straightforward measures can be applied to the existing systems and how effective are they?***

There are several measures Scheldebouw can take without amending their design. Regarding the MCI value the most convenient approach is to order materials with high levels of recycled feedstock. These are available on the market now and offer the same performances as the standard materials. Its application betters the MCI performance of the systems by approx. 6%. A far bigger impact makes a design for a longer life-span as the result of Bishopsgate reveals. However, this comes usually with special measures which not easily applicable to all designs.
For the reduction of Carbon Dioxide footprint the application of materials with high recycled share is highly beneficial. For one project it leads to a reduction of approx. 12% in emissions. Similar to the MCI the footprint is heavily reduced if a system reaches a long life span. The Bishopsgate project rates very well on emissions due to its 50 year life span and despite its heavy material deployment. Again, this is not a hasty remedy but a goal set out from the beginning. When accounting for the End of Life Potential of Aluminium it proves beneficial to replace other materials of higher emission levels with Aluminium if applicable. Halving the glazing of Lime Street and replacing it mostly with Aluminium lowered the emissions by approx. 12%
The Disassembly Potential can be increased by various measures but the most prominent standing out are the design of the spandrel panel allowing to higher level of Systematization and to aim for open/linear geometries. Furthermore, a less design intrusive change is the reduction of chemical connections and direct connections between two pre-made components in favour of removable connections. Improvements of the Life-Cycle Coordination prove challenging since materials with short life-cycles i.e. gaskets and glazing tend to be placed in the core of a system, being held in place by other later assembled materials.

***What are potential approaches for a new design of unitized systems?***

The research shows that the Disassembly Potential allows for improvement of especially the systematization of the sandwich panel, the geometries of the interface edges and the type of connections. This forms one approach for a new design of a unitized system. In addition the longevity of the Bishopsgate project proved very beneficial for MCI and carbon footprint but it was achieved with a high amount of materials. A lighter system with the same life-span might even score better. Further the rating system for material circularity encloses a cycle for reuse of material. The materials of the reviewed systems do not use any material of reused feedstock or allow for their reuse. Since the effect of this cycle is not explored a design allowing for disassembly for subsequent reuse of materials makes an interesting approach for a new system. In any case materials of high recycled feedstock should be applied to allow a comparison with standard material selection. The material selection should resemble the presently used materials in order not to drift off into another specialized field, the material selection.

## DESIGN SECTION

# 7 | ANALYSIS NEW SYSTEMS

## IN BRIEF

This chapter contains the analyses of the newly developed systems for circularity and disassembly. To allow a comparison with the existing projects the new designs are subjected to the same rating procedures. The material volumes have been computed in the same manner as with the existing facades. With the help of the material volumes first the MCI and then the carbon footprint are calculated. For the computation of the Disassembly Potential the same routine as for the three existing structures was applied.

### MATERIAL CIRCULARITY

**The material circularity is calculated as per the previous set-out calculation method. Materials with high recycled content are applied to bring the value up.**

### CARBON FOOTPRINT

**The emission levels are computed by using the EduPack of Granta Design in combination with hand calculations.**

### DISASSEMBLY POTENTIAL

**The systems are rated for their disassembly performance as outlined before.**

# 7. ANALYSIS PROPOSED SYSTEMS
## Design Section

## 7.1 Rating Circularity

High levels of material recycled content as available were calculated with. The same connections and technique for fixing the panels to the concrete slab were considered. The following tables form a part of the calculation only. Please see Appendix B for the material take-off list and the full calculation.

**Rating Circularity Type 1**

As per the design the numbers of the material deployment reflect the reduction of the vision panel in comparison with the existing systems and the increase of spandrel panel area. This approach makes the system lighter than any of the previously reviewed systems, namely approx. 54kg/m2. In comparison the other projects feature heavier weights: Lime Street 66kg/m2, One Crown Place 73kg/m2 and Bishopsgate 85kg/m2. While the amount of glazing is rather low, Aluminium accounts for more than a third of all material.

| **Step 1: Calculation of material masses** | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.037 | 2700 | 98.691 | 5.4 | 18.276 | 33.9% |
| Steel | 0.002 | 8000 | 14.234 | 5.4 | 2.636 | 4.9% |
| Gaskets | 0.009 | 1600 | 15.005 | 5.4 | 2.779 | 5.1% |
| Insulation | 0.218 | 70 | 15.255 | 5.4 | 2.825 | 5.2% |
| Sealing | 0.002 | 1370 | 2.329 | 5.4 | 0.431 | 0.8% |
| Glazing | 0.055 | 2500 | 136.406 | 5.4 | 25.260 | 46.8% |
| Isolator | 0.007 | 1300 | 9.448 | 5.4 | 1.750 | 3.2% |
| | | | **291.368** | | **53.957** | |

Fig. 84 –Type 1 Calculation material masses (source: own image)

The selection of materials with hi9gh recycled content lead to low Linear Flow Indexes, especially for the metals which have the highest recycled feedstock and best recycling rates. The lifespan is set to 50 years which is supported with an exchange of gaskets and glazing after 25 years to enable the system to last another 25 years. The extra material was added in the material take-off. The utility factor lies at 2.0 since a 50 years life span is the double of the industry standard.

| **Step 4: Calculation of MCI-value** | | | | | | |
|---|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value | |
| Aluminium | 0.16 | 50 | 2.00 | 0.45 | 0.93 | |
| Steel | 0.18 | 50 | 2.00 | 0.45 | 0.92 | |
| Gaskets | 1.00 | 50 | 2.00 | 0.45 | 0.55 | **1x replacement** |
| Insulation | 0.80 | 50 | 2.00 | 0.45 | 0.64 | |
| Sealing | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| Glazing | 0.51 | 50 | 2.00 | 0.45 | 0.77 | **1x replacement** |
| Isolator | 0.50 | 50 | 2.00 | 0.45 | 0.78 | |
| | | | | **Total MCI** | **0.81** | |

Fig. 85 –Type 1 Calculation MCI-value (source: own image)

With the individual MCI values of the materials very high, the total MCI – under taking into consideration the percentage share of each material in the build-up – is the lowest of the projects, at 0.81.

**Rating Circularity Type 2**

The rating of the second system distinguishes the two different material cycles for steel. The corner pieces are designed for reuse, the other steel goes through the standard recycling process. This system is the lightest of all systems with approx. 45 kg/m2. The timber was computed with a density of 450kg/m3, an average value for timber with medium strength.

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.01466 | 2700 | 39.570 | 5.4 | 7.328 | 16.3% |
| Steel for Reuse | 0.00146 | 8000 | 11.671 | 5.4 | 2.161 | 4.8% |
| Steel for Recycle | 0.00174 | 8000 | 13.896 | 5.4 | 2.573 | 5.7% |
| Gaskets | 0.00896 | 1600 | 14.332 | 5.4 | 2.654 | 5.9% |
| Insulation | 0.20588 | 70 | 14.412 | 5.4 | 2.669 | 5.9% |
| Sealing | 0.00170 | 1370 | 2.329 | 5.4 | 0.431 | 1.0% |
| Glazing | 0.05462 | 2500 | 136.548 | 5.4 | 25.287 | 56.3% |
| Isolator | 0.00737 | 1300 | 9.581 | 5.4 | 1.774 | 4.0% |
| Timber | 0.09017 | 450 | 40.577 | 5.4 | 7.514 | 16.7% |
| | | | **242.338** | | **44.877** | |

Fig. 86 –Type 2 Calculation material masses (source: own image)

The steel of the corner pieces and the timber of the profiles are designed to be reused completely which is mirrored in their Linear Flow Indexes. But while the LFI of steel is low due to its high recycled feedstock, the timber is computed as from 100% virgin material. This leads to the timber having a mediocre MCI value for the material only. The lifespan of the system is limited in this case to 30 years, leading to a utility factor of 1.2 only.

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.16 | 30 | 1.20 | 0.75 | 0.88 |
| Steel for Reuse | 0.14 | 30 | 1.20 | 0.75 | 0.89 |
| Steel for Recycle | 0.18 | 30 | 1.20 | 0.75 | 0.87 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.80 | 30 | 1.20 | 0.75 | 0.40 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 0.50 | 30 | 1.20 | 0.75 | 0.63 |
| Timber | 0.50 | 30 | 1.20 | 0.75 | 0.63 |
| | | | | **Total MCI** | **0.69** |

Fig. 87 –Type 2 Calculation MCI-value (source: own image)

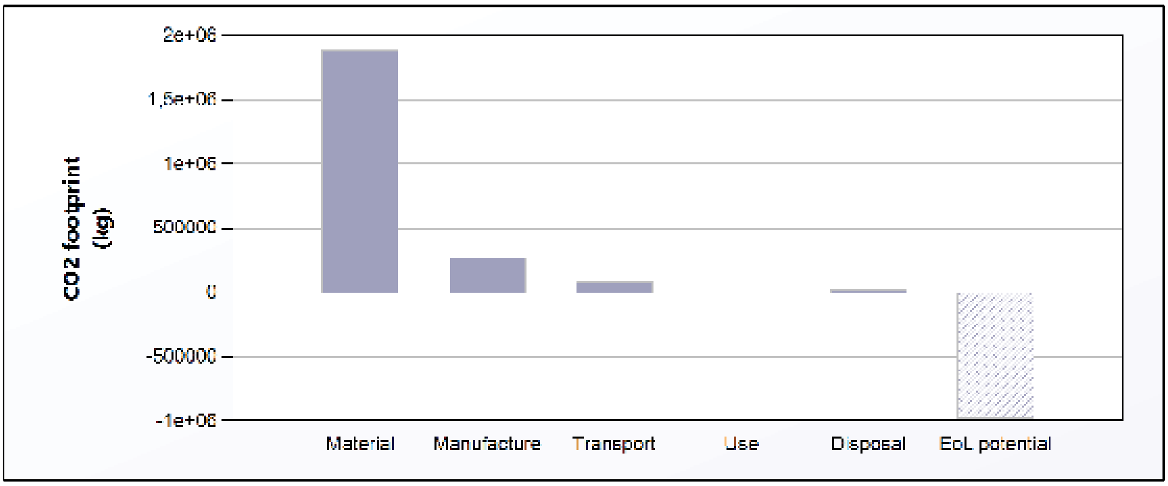
The resulting overall MCI of 0.69 is not very high when considering the high recycled material amount and the reuse of all timber and parts of steel.

## 7.2 Rating Emissions

The carbon footprint of the new systems were computed with the same production emissions, manufacturing processes and transport distances as entered for the existing three projects. As the computer software does not allow to enter amended recycled contents, the numbers were calculated by hand, following the formula for $CO_2$ emission grade during material production described by the software manual. In this way the benefits of materials with high recycled content could be determined.

**Rating Emissions Type 1**

The initial calculation of the $CO_2$ emissions for Type 1 indicates a low result with standard recycle contents as per software. The annual environmental burden over is 50 year product life is 45.416 $CO_2$ kg/kg, the lowest value so far. This is without taking EoLP into consideration.




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 50 year product life):** | 4,54e+04 |

Fig. 88 –Type 1 Overall $CO_2$ emission (source: own image)

As per previous results the Aluminium accounts for the highest emissions of all materials, with the bulk of it coming from the manufacturing process. At the same time it offers the highest End-of-Life Potential from all materials.

| | Material | Manufacture | Transport | Disposal | End of Life P. |
|---|---|---|---|---|---|
| **Aluminium** | 1,444,843 | 59,793 | 5,093 | 8,210 | -997,989 |
| **Glazing** | 162,709 | 160,150 | 5,485 | 11,348 | -40,236 |
| **Steel** | 43,207 | 5,375 | 39,962 | 1,184 | -24,221 |
| **Gasket** | 87,000 | 35,292 | 9,795 | 891 | 60,151 |
| **Sealant** | 25,723 | 4,087 | 1,175 | 138 | 6,964 |
| **Mineral wool** | 22,609 | 0 | 8,228 | 363 | 0 |
| **Isolator** | 101,733 | 7,434 | 18,414 | 561 | 21,619 |

Fig. 89 –Type 1 - $CO_2$ emissions per stage (source: own image)

The following graph highlights the dominance of Aluminium for the emission level.

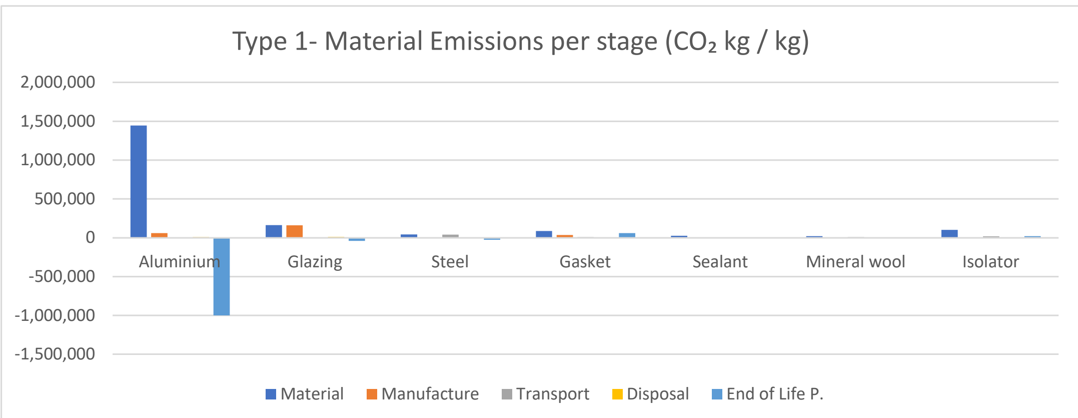



Fig. 90 –Type 1 - $CO_2$ emissions per stage (source: own image)

By following the formula below provided by the software developer the actual $CO_2$ grade for the materials with high recycled content is computed.

$$CO_2\text{grade} = \left(\frac{100 \cdot R_F}{100}\right) \cdot CO_{2m} + \left(\frac{R_F}{100}\right) \cdot CO_{2RC} \left[{}^{kg}/_{kg}\right]$$

Fig. 91 –Type 1 - Formula $CO_2$ emission grade Material Production (source: CES Granta Design)

| Component | Material | $CO_2$ Primary Pro | $CO_2$ Recycling kg/kg | |
|---|---|---|---|---|
| Aluminium | Aluminum, 6060, T4 | 13.700 | 2.800 | |
| Glazing | Soda lime - 0080 | 0.796 | 0.556 | |
| Steel | Coated steel, steel, galv | 3.160 | 0.826 | |
| Gasket | Ethylene propylene (die | 3.590 | - | |
| Sealant | Silicone, phenyl-type (P | 6.840 | - | |
| Mineral wool | T-glass | 0.917 | 0.459 | source: assumed 50% |
| Isolator | PA6 (25% glass fiber) | 6.660 | 1.066 | source: Ensinger |
| | | source: CES | | |

Fig. 92 –Type 1 - $CO_2$ emissions Primary Production vs Recycling (source: own image)

The $CO_2$ footprints for primary production and for recycling were taken from the software's database as available. For mineral wool a 50% difference between primary ans recycling emissions were assumed as no data was found and the primary process is generally not repeated for recycling. The recycling emission for the polyamide isolator stems from a supplier, Ensinger.

| Component | Material | Total mass (kg) | $CO_2$ Primary Prod. kg/ | $CO_2$ Recycling kg/kg | NEW Recycled % | $CO_2$ grade kg/kg | New Material $CO_2$ footprint |
|---|---|---|---|---|---|---|---|
| Aluminium | Aluminum, 6060, T4 | 167,560 | 13.70 | 2.80 | 75.00 | 5.53 | 925,769 |
| Glazing | Soda lime - 0080 | 231,590 | 0.80 | 0.56 | 5.30 | 0.78 | 181,400 |
| Steel | Coated steel, steel, galv | 24,170 | 3.16 | 0.83 | 71.30 | 1.50 | 36,155 |
| Gasket | Ethylene propylene (die | 25,470 | 3.59 | 0.00 | 0.00 | 3.59 | 91,436 |
| Sealant | Silicone, phenyl-type (P | 3,950 | 6.84 | 0.00 | 0.00 | 6.84 | 27,018 |
| Mineral wool | T-glass | 25,900 | 0.92 | 0.46 | 40.00 | 0.73 | 19,005 |
| Isolator | PA6 (25% glass fiber) | 16,040 | 6.66 | 1.07 | 100.00 | 1.07 | 17,099 |

Fig. 93 –Type 1 – New material $CO_2$ emission footprint Material Production (source: own image)

After applying the new recycled fraction the new material $CO_2$ footprint is calculated which is in cases considerably lower than the previous one. Aluminium remains the material with the highest emissions but covers almost of its environmental burden with its EoLP, as per table below.

| | Material | Manufacture | Transport | Disposal | End of Life Pote |
|---|---|---|---|---|---|
| Aluminium | 925769 | 59793 | 5093 | 8210.44 | -997989 |
| Glazing | 181400 | 160150 | 5485 | 11347.91 | -40236 |
| Steel | 36155 | 5375 | 39962 | 1184.33 | -24221 |
| Gasket | 91436 | 35292 | 9795 | 891.45 | 60151 |
| Sealant | 27018 | 4087 | 1175 | 138.25 | 6964 |
| Mineral wool | 19005 | 0 | 8228 | 362.60 | 0 |
| Isolator | 17099 | 7434 | 18414 | 561.40 | 21619 |
| | 1297882 | 272131 | 88152 | 22696 | -973712 |

Fig. 94 –Type 1 - $CO_2$ emissions per stage with higher recycling content (source: own image)

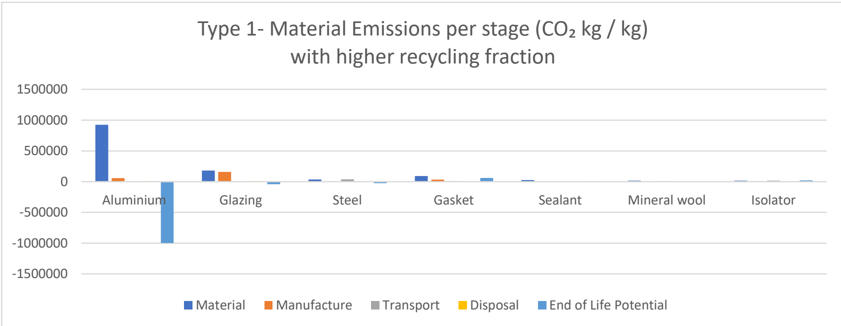



Fig. 95 –Type 1 - $CO_2$ emissions per stage with higher recycling content (source: own image)

Taking the new values for the calculation lowers the $CO_2$ footprint even further to 33.617kg per year over the 50 years life span, see table below.

$CO_2$ Emission level with higher recycling content

| | $CO_2$ Emission |
|---|---|
| Material | 1,297,882 |
| Manufacture | 272,131 |
| Transport | 88,152 |
| Disposal | 22,696 |
| Total | 1,680,862 |
| divided by use life of 50 years | **33,617** |

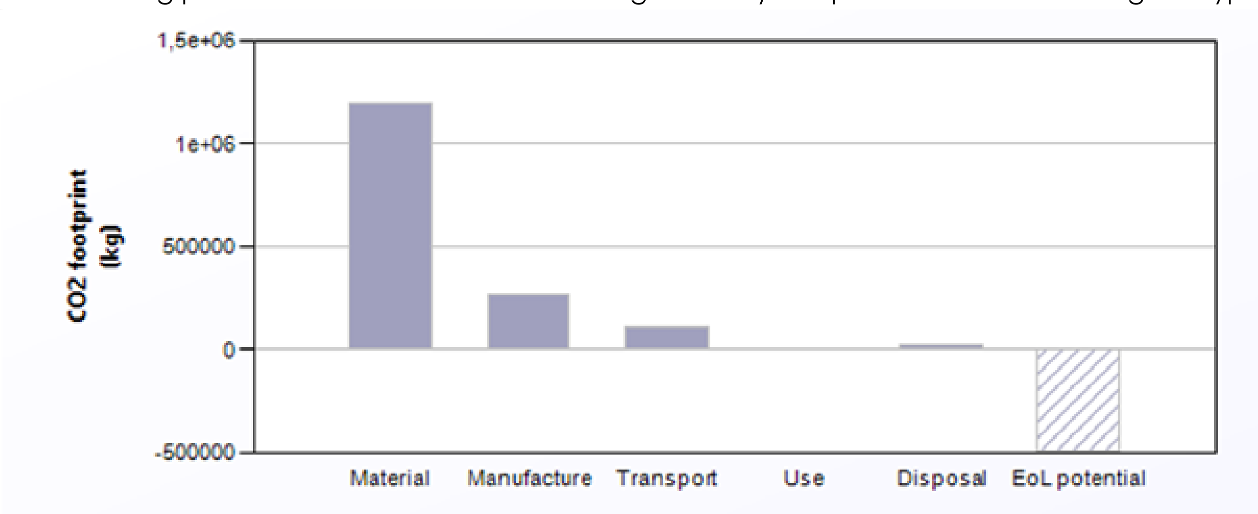
$CO_2$ Emission level with EoLP

| | $CO_2$ Emission |
|---|---|
| Material | 1,297,882 |
| Manufacture | 272,131 |
| Transport | 88,152 |
| Disposal | 22,696 |
| EoLP | -973,712 |
| Total | 707,150 |
| divided by use life of 50 years | **14,143** |

Fig. 96 –Type 1 Overall $CO_2$ emissions with high recycle content (source: own image)

**Rating Emissions Type 2**

The initial rating procedure calculates 52.961 $CO_2$ kg over 30 years product life for the design of Type 2.




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 30 year product life):** | 52961.033 |

Fig. 97 –Type 2 Overall $CO_2$ emission (source: own image)

Despite its reduced share of approx. 16% of all materials Aluminium is still the main emission driver.

| | Material | Manufacture | Transport | Disposal | End of Life P. |
|---|---|---|---|---|---|
| Aluminium | 631882 | 26150 | 5394 | 3591 | -436456 |
| Glazing | 177660 | 174866 | 5809 | 12391 | -43933 |
| Steel for reuse | 38631 | 4806 | 19319 | 303 | -38631 |
| Steel for recycle | 45996 | 5722 | 23003 | 1261 | -25785 |
| Gasket | 90655 | 36775 | 10373 | 929 | 62678 |
| Sealant | 28067 | 4459 | 1245 | 151 | 7599 |
| Mineral wool | 23299 | 0 | 8714 | 374 | 0 |
| Isolator | 112515 | 8222 | 19502 | 621 | 23910 |
| Timber | 45293 | 0 | 19804 | 1052 | -45293 |

Fig. 98 –Type 2 - $CO_2$ emissions per stage (source: own image)

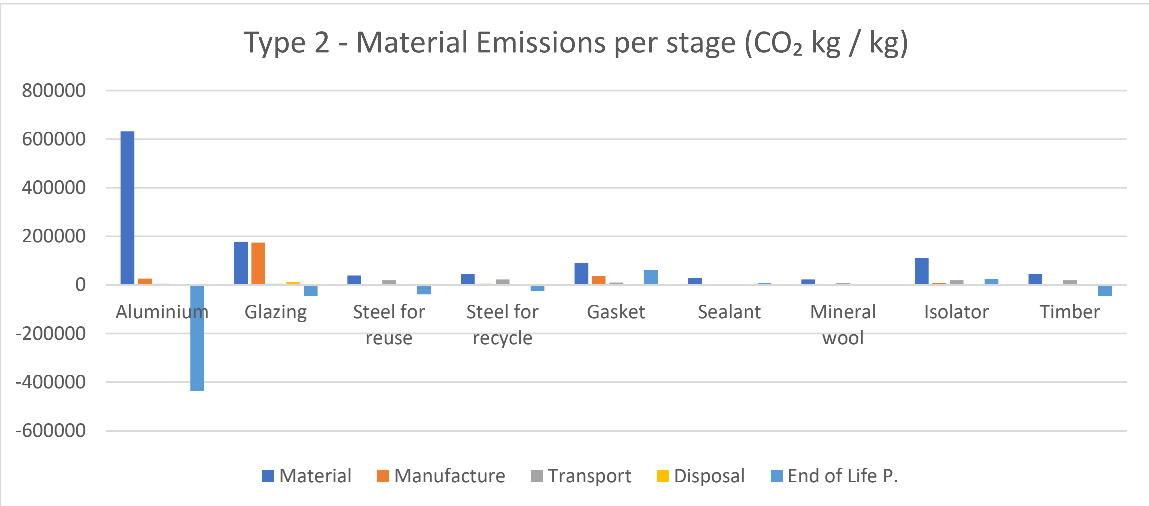



Fig. 99 –Type 2 - $CO_2$ emissions per stage (source: own image)

By applying the higher recycled content of the materials the emission levels are calculated again as per table below.

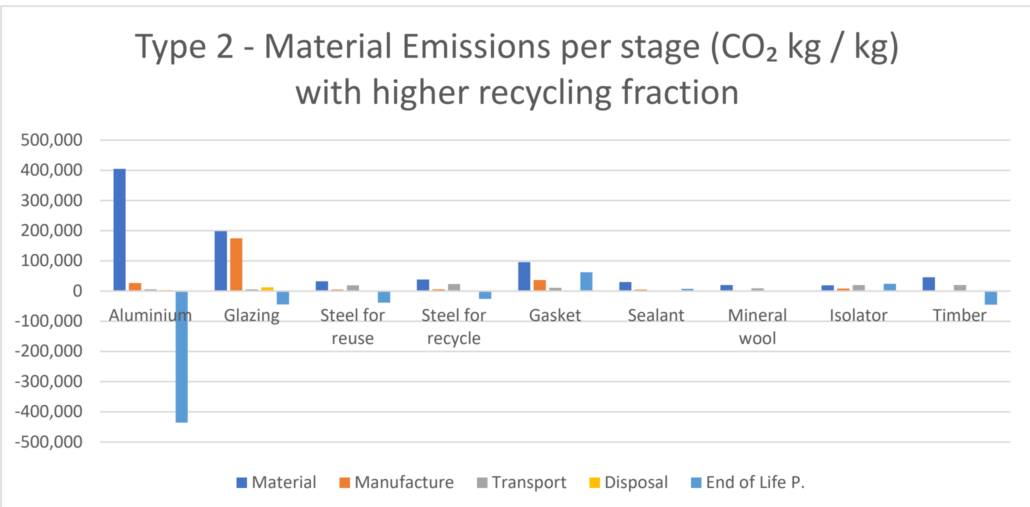



Fig. 100 –Type 2 - $CO_2$ emissions per stage with higher recycling content (source: own image)

| | Material | Manufacture | Transport | Disposal | End of Life P. |
|---|---|---|---|---|---|
| Aluminium | 404,872 | 26,150 | 5394 | 3,591 | -436,456 |
| Glazing | 198,068 | 174,866 | 5809 | 12,391 | -43,933 |
| Steel for reuse | 32,325 | 4,806 | 19319 | 303 | -38,631 |
| Steel for recycle | 38,488 | 5,722 | 23003 | 1,261 | -25,785 |
| Gasket | 95,278 | 36,775 | 10373 | 929 | 62,678 |
| Sealant | 29,480 | 4,459 | 1245 | 151 | 7,599 |
| Mineral wool | 19,585 | 0 | 8714 | 374 | 0 |
| Isolator | 18,911 | 8,222 | 19502 | 621 | 23,910 |
| Timber | 45,293 | 0 | 19804 | 1,052 | -45,293 |

Fig. 101 –Type 2 - $CO_2$ emissions per stage with higher recycling content (source: own image)

When calculating the overall emissions again but this time with the higher recycled content the result shows that the Type 2 design produces 40.787 kg $CO_2$ per year of its 30 years life span.

$CO_2$ Emission level with higher recycling content

| | $CO_2$ Emission |
|---|---|
| Material | 882,300 |
| Manufacture | 260,999 |
| Transport | 59,638 |
| Disposal | 20,671 |
| Total | 1,223,609 |
| divided by use life of 30 years | **40,787** |

$CO_2$ Emission level with EoLP

| | $CO_2$ Emission |
|---|---|
| Material | 882,300 |
| Manufacture | 260,999 |
| Transport | 59,638 |
| Disposal | 20,671 |
| EoLP | -495,910 |
| Total | 727,699 |
| divided by use life of 30 years | **24,257** |

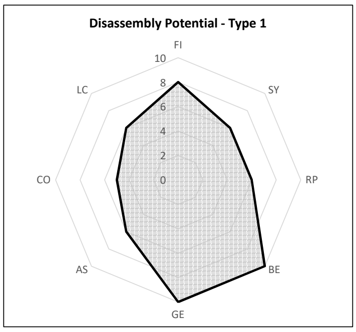
Fig. 102 –Type 2 Overall $CO_2$ emissions with high recycle content (source: own image)

## 7.3 Rating Disassembly

The rating of the DP follows the same pattern as used for the three existing projects. The new systems are checked for their performance on eight disassembly aspects as outlined by Durmisevic. For the complete evaluation please refer to appendix B.

**Rating Disassembly Type 1**

The new Type 1 design scores especially high on the Base Element and the Geometry. It fares better on Life-Cycle Coordination since its gaskets and glazing unit can be installed last and therefore replaced first again. This is based on the assumption that the fitting of the glazing beads does not count as installation step because they are designed for easy installation and removal by simply clicking them in.



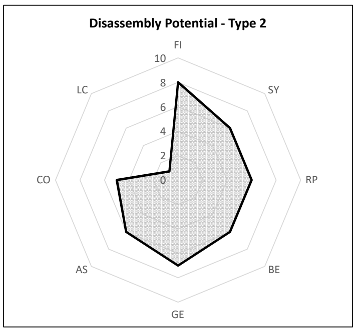

**Type 1 - Disassembly Potential - Results**

| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 6 |
| Base element specification | BE | 10 |
| Geometry of product edges | GE | 10 |
| Assembly sequence | AS | 6 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 6 |

Fig. 103 –Type 2 – Disassembly Potential result chart and list (source: own image)

#### Rating Disassembly Type 2

The rating of the Type 2 design shows a less impressive result. Except the Functional Independence no other rating aspect scored 8 or higher. Especially the Life Cycle Coordination scores very low as the materials with the lowest life span, namely gaskets and glazing are not assembled at the end and hence the disassembly of them causes complicated removal procedures of several components. The more traditional design of the glazing and spandrel covers being held in place by a cover profile leads to a reduced score in Geometry. The Base Element does not reach its fullest potential as no intermediary element is introduced.



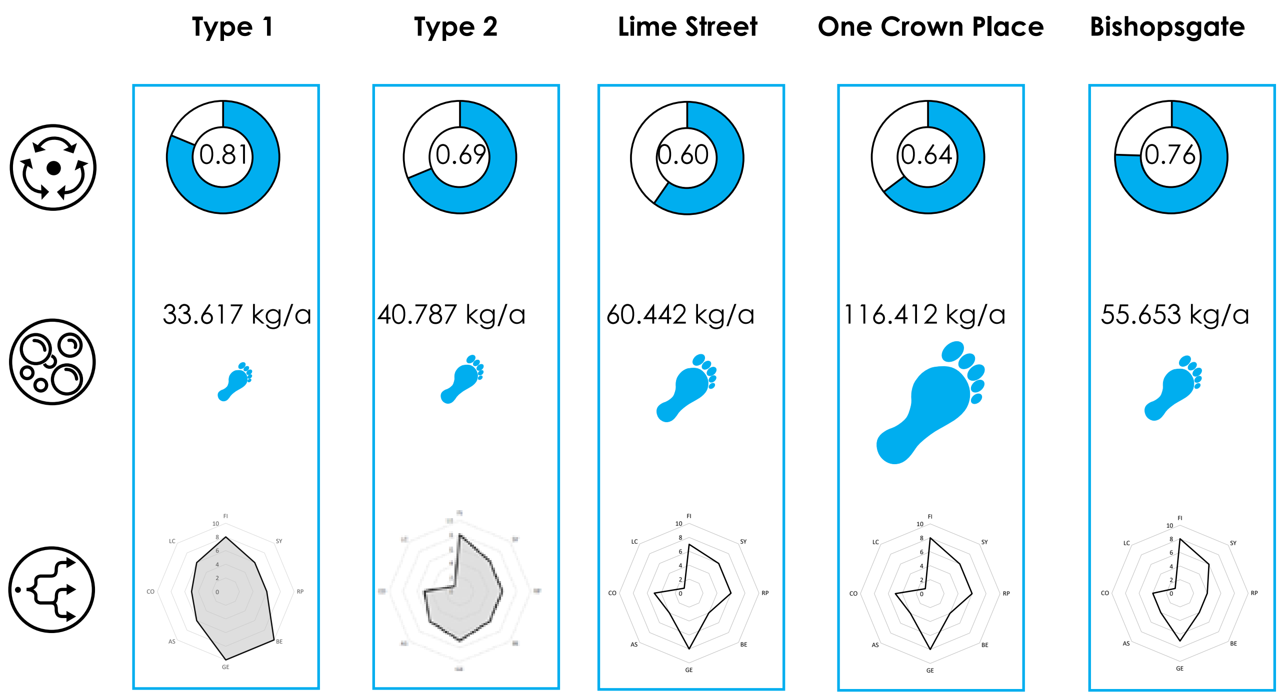

**Type 2 - Disassembly Potential - Results**

| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 6 |
| Base element specification | BE | 6 |
| Geometry of product edges | GE | 7 |
| Assembly sequence | AS | 6 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 1 |

Fig. 104 –Type 2 – Disassembly Potential result chart and list (source: own image)

## 7.4 Comparison

A comparison of all systems is as follows:



**MCI**

The design of the first type delivers the highest MCI value of 0.81, closely followed by the design of Bishopsgate with 0.76. In both cases the systems were designed for a life span of 50 years, which produces high individual MCI values of the materials. In the case of Type 1 a material exchange of glazing unit and gaskets has been considered in the calculation by doubling their original material mass. Further readily available materials with high levels of recycled feedstock have been applied and the amount of glazing was reduced since it features a mediocre individual MCI value and by its high weight has a negative impact on the overall MCI. In the case of Bishopsgate the gaskets were calculated double for later replacement only and standard recycling rates were considered.

**$CO_2$**

In terms of $CO_2$ emissions the new designs of Type 1 and Type 2 clearly achieve the best results with 33.617 kg/a and 40.787 kg/a respectively. This is owed mainly to a long life span of Type 1 and to usage of materials with low emission levels i.e. timber at Type 2. In addition materials with high recycled feedstock amounts have been adopted which proved beneficial for the result. One Crown Place produces the highest emissions annually of 116.412kg which stems to a great deal from its high amount of Aluminium. The results do not integrate the End-of-Life Potential of the materials which of which systems with a high amount of Aluminium benefit since Aluminium has the highest EoLP of the involved materials.

**DP**

The Disassembly Potential of the new design Type 1 is the highest of all five systems. Its design scores especially with its Base Element and the Geometry of the interface edges. Further it scores high on the Life Cycle Coordination since it allows easy access and replacement of quicker deteriorating materials i.e. gaskets and glazing. The designs of Type 2 and Lime Street are the scoring second best for DP with Type 2 scoring better at Assembly while Lime Street achieves a higher rating for Geometry. No system scores well for Life-Cycle Coordination since the limited life span of gaskets and glazing compromise the results.

**Answers to research sub-questions**

The outcomes of this chapter allow to answer the previously defined research sub-question:

***How do the new designs rate regarding Circularity performance and Disassembly Potential?***

The design of Type 1 rates highest in terms of Circularity and DP. The approach to produce a product with high disassembly potential in combination with a long life span results in the best circularity and emission levels of all reviewed systems. Even the additional material allowing for the exchange of gaskets and glazing one time during the 50 years does not affect the result too much. The application of materials with a high recycled content contributes immensely to the result, the following of the principles for DP enables exchange of materials with short life-cycles and overall exchange for exchangeability and independence.

The results of the Type 2 are much lower in comparison. The reuse of some of the materials does not lead to a higher overall circularity rating. The Disassembly Potential is not higher than with present systems since the design was orientated more on traditional systems. The main aspect of this type was to review if in how far a design for reuse can contribute to circularity. The implemented MCI does not reward the application of materials from biological cycles as their feedstock are tagged of 100% virgin origin. Materials with an established recycle infrastructure as Aluminium and Steel fare much better in this aspect and feature a much better individual MCI value. The level of emissions were considerably low though for a system of only 30 years life span so in this aspect the system recorded well.

RESULTS

# 8 | THE BROADER PICTURE

## IN BRIEF

The eighth chapter describes the current state of Circularity and Disassembly in construction and other industries to provide an overview of hurdles encountered in other industries how they are handled elsewhere and which lessons can be learned from it.

### BROADER VIEW

**The Broader View offers a chance to step back from the topic for a moment and see what in other fields happens regarding circularity and disassembly.**

### HVAC AND CIRCULARITY

**In another research two projects are compared regarding the circularity of their HVAC systems.**

### BUSINESS EXAMPLE

**A successful business for the re-manufacturing of automobile parts is an exemplary case for circularity.**

# 8. THE BROADER PICTURE
## RESULTS

### 8.1 Circularity and Disassembly in Construction

Similar to the building envelope the mechanical and electrical services of a building comprise of very expensive and probably even more complex systems. Croxford et al. conducted a study with the focus on circular building services comparing a standard building following current legislation and a project designed for assessing present methods of applying circular strategies to construction and building components. They were particularly interested in the building services since they bundle various characteristics making them ideal for Circular Economy models: they are often tailor-made solutions with high upfront costs, outdating very fast, prone to failure and need constant care and attention (maintenance). (Croxford, Mendoza, Portal, & Rovas, 2018)

The standard building was equipped with the usually applied service package comprising a complicated air-conditioning controllable by the user, a central HVAC system with chilled beam units, a modern high voltage transformer for combining LED lights into the chilled beams, 'genderneutral' toilets, a centralised domestic hot water system, a fire-dedicated core and other fire-safety services. This building is considered 'permanently' and the structure and services were planned accordingly.

The design of the Circular Building was aimed at showcasing modern circular strategies to construction and building components. The building was equipped with materials and technology supporting circular economy aspects. Accoya timber on the outside, digital material passports, BIM supported planning, a 3D printed Mechanical Ventilation with Heat Recovery system, cardboard ducts, a DC power grid supported by a saline battery, plug-and-play power connections, recyclable LED lighting and a virtual controls system with wireless data monitoring. This building was designed as a test laboratory on circularity and planned on a temporary basis with the aim to disassemble it later.

Despite the different nature and permanence the two buildings the assessed for their circularity performance and guidelines are formulated on the design and procurement of circular building services. The following results are stated:
1. Any service that can be avoided helps to increase the overall circularity of the building, even if it means that other parts of the structure need to be expanded slightly e.g. to expand thermal mass to save on mechanical ventilation.
2. Durable materials and mechanisms are to be selected to prolong the life span of the services. Products of high grade with little need for maintenance are to be selected with a preference for products guaranteeing long life usage. Methods for this are modular units, uniformity and planning for removal of units or parts to enable repair or renovation. Components designed for easy disassembly ask for considerably less effort to modify into reusable and recyclable components than components designed as fixed units allowing energy-intensive end-of-life options only.
3. Digital technologies e.g. 3D printing, automation and BIM are to be applied to enhance efficient usage of resource. In this context falls data collection for later use by facility management and for reverse logistics. Strategies allowing for low tech solutions consisting of sustainable materials also makes sense.
4. A key aspect to implant the above mentioned procurement measures into the supply chain is changing the business models from product to service. Thereby manufacturers maintain ecological responsible for their product instead of transferring it to consumers. This step allows to join economic with environmental advantages  and improves efficient resource usage.
5. The choice of products meeting aspects of circularity is still relatively restricted. In addition checking certificates and LCA's of products and materials turn out to be lengthy processes. As a result the decision for circular products and services is to be taken early during the design stage and circular designs are to be adapted to circular materials and services available.

The authors conclude their research with identifying three main aspects to achieve a circular project: Firstly durability and resilience of used products, enabling straightforward disassembly to recover com-

ponents or materials at their highest value. Secondly, information through digital technology, allowing a life-cycle management of buildings with a digital copy by all stakeholders being integrated in this methodology
And thirdly, the product as a service business model shift with service contracts retaining ownership and 'ecological responsibility' on the supplier's side. (Croxford, Mendoza, Portal, & Rovas, 2018)

## 8.2 Circularity and Disassembly other industries

An industry which realized in parts the characteristics of the Circular Economy is the automotive industry. Repair and remanufacture cycles of automotive parts have been established probably since cars exist. The Ellen McArthur Foundation reports of a French company that was established in 1949 solely for the remanufacturing of automotive parts.

With the current resources of raw materials dwindling, safeguarding future supply became a strategic focus for the car industry. As an example for a material that will be in the new future hard to gain lead is mentioned with 60% of the global supply going into car manufacturing and the reserves to deplete in 2030. (Ellen MacArthur Foundation, 2020) But there is another reason why the car industry is interested in protecting their material supply. Since the start of the millennium the prices for materials and energy saw a sharp increase (Ecorys, 2012).

Further pressure to change their linear economic model came from the introduction of the directive 2000/53/EC of the European Parliament which dictates the car industry to prevent waste and to support the reuse, recycling and recovery of end-of life vehicles (European Commission, 2020). With more than 12 million vehicles being scrapped every year in the European Union, the savings on raw materials which are millions of tonnes are extremely high. Recycling of cars turned into a multimillion business.

Remanufacturing at the French plant on the other hand means making the part as good as new. Since its founding the company continuously grew and broadened their product range. There are several advantages of the business model. The parts are approx. 30-50% less expensive than new ones while they come with the same guarantee and pass the same quality tests as new parts. The commercial proposition consists of enabling repair of older cars of reduced value with part which is relative to the life-span of the repaired vehicle at an affordable price. This allows the continued use of the vehicle and in some case prevents the cars to become total losses if repair is more than the market value. Further the plant created several hundred jobs for skilled workers, providing employment and income in the region since shipping remanufactured parts is not lucrative due to transport costs.

Finally, another huge advantage of the remanufacturing process is the savings on raw materials and energy. The difference in consumption between a remanufactured part and a new part can be summarized as follows: 80% less energy consumption, 88% less water consumption, 92% less chemical products usage and 70% less waster production. Due to a strict material reusage concept no waste is sent to landfill.

## 8.3 Outlook

In the past facades have been designed to achieve stipulated thermal and structural performances and to meet daylight factors and air- and water tightness. With growing environmental awareness the performance requirements were regularly increased until they are at a level now where further performance increment is difficult to achieve and to justify. Hence the focus shifted from the performance to the environmental burden building components resemble. This has been translated by the legislator into a new regulation.

With the introduction of the ‘Milieu Prestatie Gebouwen’ (MPG) in the Netherlands the environmental impact of the materials used in a building another performance aspect is added to the list. It applies to new office buildings (larger than 100 m²) and new-build homes. As of 1 January 2018, the maximum limit for the MPG is 1.0.

Considering that improvement in the other aspects have reached already levels in which further advancements become questionable of their benefit compared to effort required, the ecological footprint might become more important. In addition to presently required performances future facades will be rated more strictly on their environmental burden.

## 8.4 Summary

The comparison of the two projects with different approaches towards HVAC implementation showed which lessons have been learned about the implementation of Circular Economy in other key construction industries. While some findings have been already highlighted in this study, among them the important role of disassembly, one of the key aspects was to transform the existing business from a product to a performance model.

The review of the French remanufacturing plant explained how successful Circular business models can work and how beneficial they are for the local economy and local economy. With the legislation starting to regulate the environmental performance of building products, the advantages of the Circular Economy are more and more shifting into focus.

In summary it can be said that businesses in the future will be successful if they manage offer their services based on the principles of the Circular Economy, with Design for Disassembly being a key aspect to achieve this.

RESULTS

# 9 | CONCLUSION

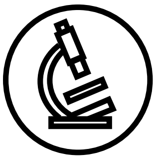
## IN BRIEF

This chapter concludes the research by answering the research and design question. It contains suggestions for further research and ends with the reflection of the research process.

### RESULTS

**After the new designs have been evaluated the main research and the design question are answered.**

### FURTHER RESEARCH



**During the research several questions came up which could not be answered and would make interesting new research topics.**

### REFLECTION

**Finally a brief essay on the research process, the gained knowledge and a discussion of the challenges encountered is added.**

# 9. CONCLUSION
## RESULTS

## 9.1 Answer to Research Question

At the begin of the research the main problem was described as that the current design of facades does not consider the end of life of facades which leads to demolition and subsequently loss of material and energy. Design for Disassembly was regarded as a contributor for the reduction of material and energy losses caused by demolition. As a result the main research question was asked:

***To what extent can Design for Disassembly contribute to optimize the facades of Scheldebouw for Circularity?***

The terms Circularity and Disassembly were defined and rating systems for both reviewed and chosen. Subsequently three projects of Scheldebouw examined for their potential for circularity and disassembly. The findings were compared and suggestions formulated for the design of new improved systems. When these new systems were subjected to the same valuation method it showed that they reached at least in one case a higher level of circularity and disassembly. This design aimed at prolonging the life span of the system by allowing easy replacement of components following the principles of Design for Disassembly. Therefore the Design for Disassembly contributed immensely to the system's high rating for Circularity and the main research question is answered.
The second system was designed with aspects of disassembly in mind allowing for reuse of the system's frame. It achieved a good level of circularity but did not accomplish well on the disassembly aspect for its design was more based on a traditional design. It uncovered however that the reuse loop does not necessarily be the best option for achieving high circularity grades. Especially biological materials do not turn out well since their feedstock is considered 100% virgin which leads to a low grade of circularity for the particular material.
By improving disassembly, choosing material with high recycled content and established recycling infrastructure to increase MCI's and reducing emissions the facades become more circular. But the steps are not sufficient to make it circular in the end. Scheldebouw will have to review its overall business model if they want to truly offer a circular product.

## 9.2 Answer to Design Question

The design question asked previously was:

***How does a standard façade of Scheldebouw look like when optimized for Disassembly and Circularity?***

The unitized facades of Scheldebouw are frame-based and this approach was taken over in the new design Type 1 which was successfully optimized for disassembly to reach higher levels of circularity. The main design features of the type were a Base Element which allows removal of a sandwich panel for exchange or renovation. The glazing sits in the sandwich panel and can be replaced by unclicking glazing beads located on the inside of the building. Once the glazing is taken out from the sandwich element free access to the window gaskets is enabled so that replacement can take place. Further main improvements were the Connections which were modified to removable connections, omitting most of chemical and direct connections between pre-made components.
Materials with high recycled feedstock are used and the overall weight of the system is reduced by limiting the vision panel since it represents the heaviest item of the unitized element.

## 9.3 Further Research

The following topics and issues were encountered during the research and recognized as important factors on the way to achieving circular or demountable façade systems:

Local production and application vs. global market
The three existing systems reviewed shared materials sourced worldwide, manufacture in the Netherlands, shipping to UK and assembly in London. The emission and other environmental burdens were not considered in this research. With growing pressure for more circular products this globally operating system will be more scrutinized as it comes with long transport ways and therefore emissions. There might be a point when locally produced systems will score higher in circularity against systems produced far away and transported over long distances to their destinations.

Improvement of recycled glazing amount required
Current architecture features high amount of glazing. It allows natural light to get into the building and establishes connections into the environment. The reviewed facades feature almost complete glazing on the outside. As the research showed the recycled content of float glass is low at 5.3% since a higher amount results in unacceptable contamination of the material (Kurian, 2020). With the MCI of glazing of a modest 0.62 in combination with its high application in façade units it hinders the effort to achieve a high MCI for the overall façade. Without progress to increase the recycled content of glazing modern facades of today with their high focus on transparency are stuck at modest levels of MCI. Progress in recycling or production techniques has to be made to change the situation. Otherwise research on alternative materials for glazing might lead to the same result.

Improvement of life span of gaskets
From the research it was learned that gaskets turned out to be of material with the shortest life span, often leading to discoordination between assembly and disassembly sequences and shortening the overall life span of a façade system. While the glazing is considered to be lasting 30 years, the SBR considers 20 years for the life-span of gaskets. Further research for gaskets which can last at least as last as the glazing could lead to overall improvements on facades.

Different material selection to be checked
The research considers the standard material selection of Scheldebouw as applied in the reviewed projects. To achieve higher levels of circularity the complete material selection should be reviewed again. Insulation from cellulose, glazing from polycarbonate or acryl, frames in timber or steel, the complete material palette should be searched through for more circular materials. Another research on other materials might lead to better results in terms of circularity, emissions or disassembly.

## 9.4 Reflection

**Graduation process**

1. How is your graduation topic positioned in the studio?

Facades form a crucial part of the built environment. They have to fulfil multiple functions, feature a high level of building technology and tend to be very cost intensive. Previous courses of my study examined facades in detail and highlighted the importance of sustainability. The graduation topic offered a chance to combine knowledge gained from previous courses to achieve a highly technological façade system with an improved level of sustainability level. The cooperation with an industry leader made the opportunity even more attractive. Further it allowed me to familiarize myself with the Circular Economy, an economic model of growing importance.

2. How did the research approach work out (and why or why not)? And did it lead to the results you aimed for?

# CONCLUSION
## Results

The approach was based on the research structure outlined in the manual for the Building Technology graduation studio. The procedure consisted of formulating a research problem first followed by literature research on the topic and its framework. A comparison of existing measuring systems was followed by the selection of the most appropriate for the rating procedure ahead. The company was examined to gain more understanding of their business model and fabrication procedures. Three sample projects were analysed by applying the selected rating systems and the collected data was used to formulate design guidelines for the subsequent design research. Two new designs were developed and subjected to the same rating procedure. The results were vetted to close the research question formulated at the begin of the research. In my opinion the research approach was conclusively built-up. The analysis of the company did not deliver substantial new insights but rounded the picture. Time constrains prevented the previously envisaged amendment of the two new designs which would probably helped to gain more convincing results.
The research lead to results but there were no particular aims set out consciously at the begin of the process.  It was expected that DfD is beneficial for producing circular products but the was no defined degree of improvement targeted upfront.

3. What is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

The research was not undertaken to support a particular research program of the department. The research however produced findings which might be helpful for the 'FacadeReLog' workshop which focuses on the reverse logistics for the recovery of metals in the facade industry. The examination of the recycling process of the façade elements showed in detail the flow of involved materials. The new designs indicated ways for companies to extend the service-lives of their products. The conducted expert interviews helped to gain insight in most advanced technologies for regaining materials and highlighted hurdles to the Circular Built Environment.

4. How are research and design related?

The design is directly related to the outcomes of the research. It follows the guidelines stipulated as consequences of the research findings. Further it incorporates existing and fundamental working practices in order to maintain relevance for the company. The design of the second façade type was following an inquisitive nature to evaluate potential of another material circle, reuse instead of the standard recycle procedure. Strictly speaking it was not necessary for answering the research and design questions but it was interesting discourse.

5. Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

The rating systems were at times challenging since they were not clearly defined and allowed subjectivity to
influence the outcome of the assessment. The question was if to enter data which turns the result in a favourable direction or to remain neutral and enter data which leads to a vague result. I decided to analyse and interpret data as objective as possible and to accept results which were less absolute.

**Societal impact**

1. To what extent are the results applicable in practice?

The results should be highly applicable in practice since they were developed in coordination with the company and follow their common practice. The developed guidelines allow the company to choose between slight amendments to their current design e.g. by opting for materials with higher recycling

# CONCLUSION
## Results

content or reducing glued connections and more effective measure which have a stronger impact on the design e.g. the introduction of an intermediary at the base element.

2. To what extent has the projected innovation been achieved?

Rather than a truly innovative product the research produced directions the company can develop further to improve their product for circularity via DfD. The research displayed the shortcomings of the currently used systems. It further showed that with little effort the company can make progress towards circularity. The developed solution can be adopted by the company to raise the circularity of their products to a much higher level.

3. Does the project contribute to sustainable development?

The research showed ways to improve the circularity of facades systems. Circular building elements follow the principles of CE which represents a more resource effective and efficient economic system with a focus on reducing, slowing and stopping material and energy flows (Ellen McArthur Foundation, 2013) . Hence it can be concluded that the project does help to produce sustainable development.

4. What is the impact of your project on sustainability (people, planet, profit/prosperity)?

The results of the research show that façade systems can be improved for circularity by applying principles of DfD. Considering that Scheldebouw produces approx. 80.000m2 of unitized facades per year a very positive impact can be deducted if the findings of the research are applied to future façade systems.

5. What is the socio-cultural and ethical impact?

Considering 'socio-cultural' as a term standing for common traditions, habits, patterns and beliefs present in a population group, the improved façade systems might change the assumption that circular building products have to look radical different from conventional facades or that unitized facades can not be more circular than they are right now. It might lead to the company offering more circular products and clients opting for façade designs and making more truthful, fair, honest or ethical decisions for their project.

6. What is the relation between the project and the wider social context?

The Circular Economy shows a way out of the problems mankind produced by its irresponsible squandering of resources. Design for Disassembly can contribute to reduce energy and resource consumption by fostering longevity of products, reuse of components or recycling. While other industries e.g. the car industry progressed in this field and benefitted from returning old products back into the material flow, the construction industry lacks behind. This research aimed to contribute to the ongoing discussion of transforming buildings to comply with principles of Circular Economy. This happens with the intention to conserve our environment to the benefit of our society.

7. How does the project affect architecture / the built environment?

The research showed that facades can be improved for circularity by applying principles of DfD. Clients and architects are therefore able to ask for a higher performance in terms of Circularity and Scheldebouw can offer suitable solutions. The result was achieved however by changing the layout and aesthetic of the standard fully glazed elements. Until glazing production does not enable a significant rise in recycled content, the usage of all glazed facades compromises circularity and has to be avoided.

## 9.5 Discussion

While working with the rating systems several shortcomings came to light which had a strong influence on the result of the research. In order to state the issues encountered and to highlight potential weaknesses in the calculations the rating systems are commented individually below:

**Material Circularity Indicator by Ellen McArthur Foundation**

The assessment is based on a reduced scheme consisting of a straight process and consumption string representing the linear economy and two return loops representing the recycling and reuse processes. Various waste routes lead from the consumer and the recycling stations to landfill and incineration.
The scheme proves too simple when trying to reflect the reality onto it. It holds spaces for the manufacturer and consumer but it does not hold enough slots when more than two stations are involved in the recycling process. Further it is not quite clear where a company like Scheldebouw sits in the scheme. It does not receive raw materials as indicated as flow to the 'manufacturer' in the scheme. Any waste produced during manufacturing is not accounted for in the scheme either, so there is a waste flow missing. The recycling loop features waste flows at each recycling station, however he reuse loop does not feature any waste flows, which is not understandable as any material primed for reuse will be checked for fitness of purpose and most likely some material will be sorted out on the way, sent to recycling or landfill. Another issue is that the calculation model does not consider materials which have zero efficiency at the recycling used to produce recycled feedstock for a product (EF). This can happen for materials which are not recycled at all e.g. silicone, EPDM gaskets or Polyamide. Entering this info into the calculation leads to an error. The issue was bypassed by entering the material masses to the waste flow from consumer.

**CES EduPack by Granta Design**

To compensate for shortcomings of the MCI the carbon dioxide emissions were computed with the student version of the CES EduPack. The database of the software is extensive and the procedure straightforward. Some deficiencies have an impact on the results though. The database has limitations when it comes to hybrid materials. Common building materials e.g. mineral wool which consist of several individual materials are not included in the database. To circumvent the issue other materials were chosen which represent the main ingredient of the hybrid material and feature similar emissions. There remains the possibility that inaccuracies are included in the calculation unintentionally. Further the database is found on worldwide data meaning that values are not necessarily matching the actual numbers encountered during the research. This aspect was already highlighted in chapter 5.4. The recycling data as per database was not meeting the data found out during the research. This issue was bypassed by hand calculation to achieve the values for the higher recycling content but again mistakes might slip in by doing so. Further the accuracy of the other data, e.g. production emissions, was trusted since otherwise one benefit of using of the computer namely speed becomes obsolete and all calculations and data has to be researched laboriously. The End of Life Potential was indicated by the software but not considered in the results of the yearly emission levels. Gervasio and Dimova reviewed the EoLP and recommended its inclusion in Life Cycle Calculations as it enables to close the loop for materials with potential for reuse, recycling and recovery (Gervasio & Dimova, 2018). In the current calculations especially facades with a high Aluminium content would benefit since Aluminium features the highest EoLP of the materials reviewed.

**Disassembly Potential by Elma Durmisevic**

After reviewing various rating systems for disassembly the assessment by Durmisevic was chosen as it is more suitable for building components than the other systems which are based on electrical appliances. However the comparison revealed shortcomings of the DP. The rating of Durmisevic covers the widest range of aspects of the systems reviewed but it neglects movements to be made, actions to be performed and time required to do the disassembly. While these aspects might be admittingly easier to establish for mass products than for customized building components they allow for economical evaluation which is one of the biggest factors when deciding between demolition or disassembly. Further practical issues when dealing with building components are not taking into consideration e.g. the weight of the components. The disassembly exercise showed that the disassembly of heavy building elements ask for extra effort from the disassembly crew and slow down the exercise considerably. As previously mentioned the assessment method was not performed until the end which accumulates in a single digit to indicate the ability of a building element for transformation and exchange because the single digit does not indicate where the strengths and weaknesses of a system lie and hinder quick comparison. In addition the explanation of the evaluation of the eight disassembly aspects is not clearly described in the document, with low printing quality and unexplained additional sub aspects not being beneficial either.

## 9.6 Relevance

The research showed that the currently applied design strategies of Scheldebouw do not score well regarding circularity. It further demonstrated that the circularity performance of façade units can be increased, especially by applying DfD for the improvement of the longevity of the systems.

The question arises in how far the research results are relevant for Scheldebouw and how their current business model is affected.

The awareness of the benefits by applying the principles of the circular economy has been growing for some time now. Various national and international institutes are working on formulating measuring methods for the construction sector e.g. Nederland Circulair in 2050, the global ISO committee 'Circular Economy' and the European Committee for Standardization 'CEN/CLC/JTC 10 - Energy-related products - Material Efficiency Aspects for Ecodesign'.

The new rating systems can make use of existing databases e.g. the life time estimation of the Stichting Bouwkwaliteit (SBK) and the EBP or ECI as per per 'Bepaling Milieuprestatie Gebouwen'. So the basis of the calculation models does not have to be established but is readily available, albeit some amendments to the existing database are suggested.

The MCI method as used in this research was identified for various shortcomings e.g. the missing measurement of production waste, the missing attention to toxicity of materials and the non-consideration of biological materials. These issues have been addressed and modifications of the MCI are under review.

The current phase of initial experimentation, discussion and reviewing of preliminary calculation models is about to close soon with a generally accepted formulation of its framework, an agreement on the measuring procedures and the collection of the necessary data. In the next phase the focus will lie on the points of value creation, financing and the necessary assurances e.g. the legal framework. It is expected that the development of the circular construction will increase sharply within the next phase which is considered to be completed by 2030 (Platform CB'23, 2019).

The above states that progress on measuring the circularity of constructions are well underway and that the legislation set out already targets ( Ministerie van Infrastructuur en Waterstaat, 2020). This combination will lead to pressure on manufacturers and construction companies to deliver.

# CONCLUSION
## Results

The research shows that slight amendments to the existing design strategy have a positive effect on the MCI performance and that these first improvements can be achieved easily. It proved however as well that only radical design changes bring the systems close to achieving higher levels of circularity, in the research case by using DfD to increase the longevity of the systems.

The decisive step for Scheldebouw is the change from a linear to a circular business model which represents a total different way of producing and consuming goods and services. The type of hurdles this step encounters can be divided into 4 categories: cultural, technological, market and regulatory (Kirchherr, et al., 2017).

In a research from the University of Utrecht the main hurdles for businesses to switch to CE were surveyed with the support of 153 businesses, 55 government officials and 47 other experts.

It was found that the cultural attitude towards the circular economy can be considered the most pressing issue, with almost half of the respondents citing lacking consumer interest, the current company culture and the operating within a linear system as main barriers. The mind-set is to rather stick to the current business models even if CE actions had already been tried. IN most companies the idea of the CE remains as an idea in the research or environmental department, other department with more power show little interest and rather delve in the day to day business.

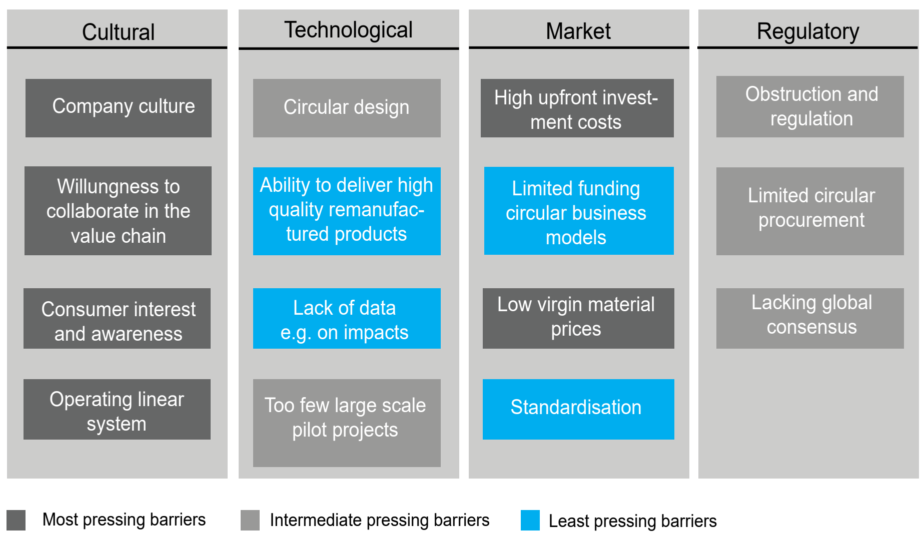



Fig. 105 – Circular Economy Barriers (source: Kirchherr, et al., 2017)

On a second rank as barrier to the introduction of CE stands the relative low virgin materials. It is expected that they will lead to products in the CE to be more expensive and hence companies offering products and services on CE basis not being able to be competitive. Further high upfront investments are making potential companies to shy away from the transition to CE.

On the plus side the technological transition to produce a circular product is not considered a big issue. While the design needs adaption or a total make-over the study found that there is general confidence that this can be done. The second issue mentioned was the lack of large scale test projects which would if successful consolidate the benefits of the transition to CE.

Regarding the regulatory aspect the biggest hindrance was identified as obstructing laws and regulations. For example can specific purity standards hinder the application of recycled content for a product.

## 9.7 Proposals

The results of the investigation can be summarized in an action plan for Scheldebouw, which can be classified according to changes for the products, the service or the entire business model. Some of the measures are relatively simple and quick to implement, while others have a fundamental impact on the business model.

**Changes at product level**

The list of the following changes starts with simple steps which can be initiated without affecting the design of the facades and have minor influence on its costs. The improvements towards circularity are limited but worth the little effort required.

1. Applying material with recycled feedstock content, during the research it was found that some of Scheldebouw's current suppliers offer their materials in a version with high recycled content.
2. Reviewing the market for alternative suppliers offering materials with high recycled content and for suppliers which are closer located in order to reduce transport emissions.
3. Checking the material deployment to meet the minimal requirements in order to prevent any material usage which is not required.

The following steps have a direct impact on the design and will have to be agreed upon with the client. Their effect on the circularity performance of the product is immense as per the previous undertaken research.

4. Incorporating disassembly features into the design which allow pure material separation after the facades service life.
5. Aiming for application of materials and components with long life cycles and durability while allowing replacement of materials with short life cycles by applying the principles of Design for Disassembly.
6. Enhance adaptive capacity of the façade units for potential future changes by producing a high systematization of the spandrel panel and a providing a base element with intermediate.
7. Omitting fixed connections i.e. sealants, which leads to the excluding of structural glazing.

**Changes at service level**

While the services of Scheldebouw were not part of the research the gained knowledge during the research allow for conclusions on potential changes to the company's service package. Again, some of the measures are simply to achieve while others touch on the very business model of the company.

1. Incorporating the gained knowledge about circularity performance of systems and advising the customers accordingly.
2. Establishing circularity passports for every new design and sharing openly environmental impact studies.
3. Including services and solutions for the end of the façade units. This might be as simple as providing disassembly manuals and BIM data or as fundamental as a buy back guarantee.
4. Distinguishing Scheldebouw by offering extra expertise and services on circular construction.

# CONCLUSION
## Results

**Changes at business level**

Some changes to the business approach of Scheldebouw touches on the very core of its company set-up. Other steps have fundamental impact on the whole set-up of the company and its value proposition.

1. Becoming an early adopter by undertaking small-scale projects as an experiment to test the processes of circular economy and construction.
2. Getting involved into the debate and forming of the methods to calculate and measure circularity. Since there is currently no normed or statutory measurement of circularity and with the debate and method finding ongoing there is now the chance the co-create future rating instruments and procedures for circularity.
3. Training staff about the circular economy and construction by running internal workshops and competitions. Collecting the ideas that stem from highly skilled staff and funnelling it into new designs.
4. Shifting from the business of product sales to leasing performances. The ultimate step is to transfer from the model of the linear economy to the model of the circular economy.

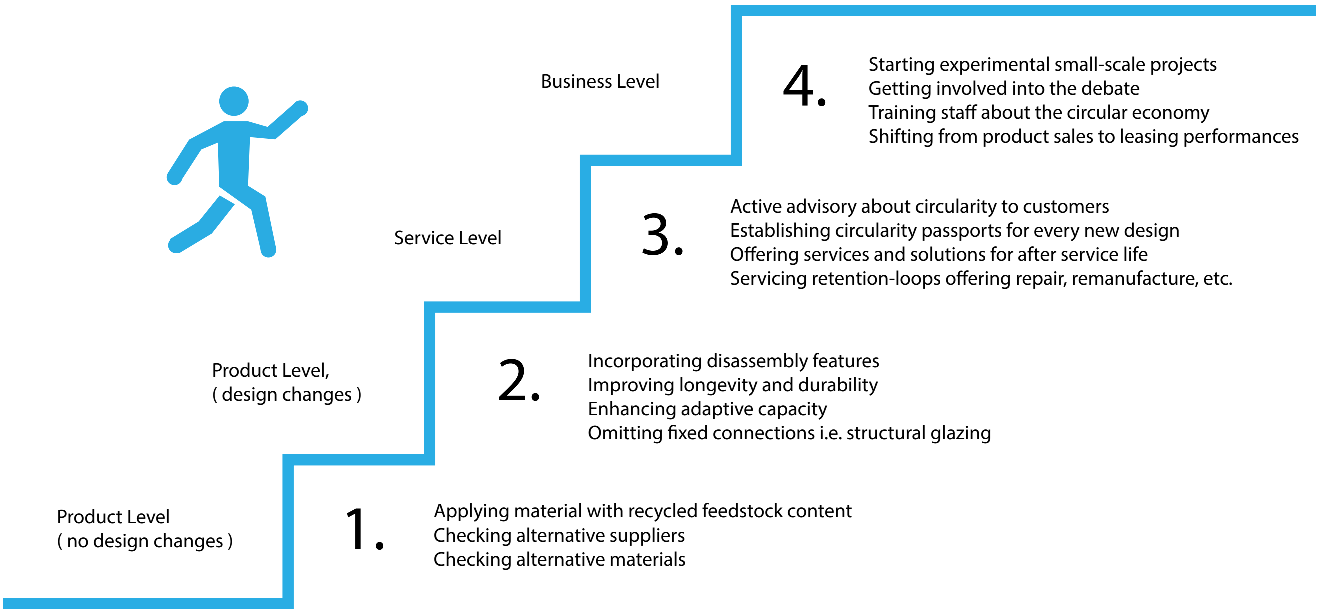



Fig. 106 – Stepped approach to circularity (source: own)

The initial steps to achieve circular products and services are easy to take, they do not jeopardize ongoing business but their effect the circular performance of the simple steps are very limited. These steps can be considered sufficient to familiarize with the topic. Any further measures will have an effect on the operation, strategy and structure of the company. But only then a truly circular product can be achieved. The question is how serious the company is regarding applying the principles of the circular economy. The good news they do not have to jump from one economic model to the other but Scheldebouw can create and follow a stepped transition with small scale projects as test projects.

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# APPENDIX
## Supplementary information

# Appendix A

## Specialists' interviews

# Aluminium recycled content - Hydro

19.02.2020

Telephone Interview with Hilbrand Kamphuis, Sales Engineer, Hydro Extrusion Hoogezand BV

Hans Gamerschlag: Hilbrand Kamphuis, can you explain what Hydro does?

Hilbrand Kamphuis: Our Aluminium production location in Hoogezand specializes in extruding long lengths and precision profiles. As a “one stop shop” we have the possibility to anodize, powder coat, insulate and cut the profiles to size.

Hans Gamerschlag: Who are your clients?

Hilbrand Kamphuis: We sell our products to many industry sectors. One of the main industries using our profiles is the construction sector. But further we sell to Electronic Industry, Transport, Industrial design, Solar energy and General Construction. Scheldebouw is one of our clients.

Hans Gamerschlag: Please explain me about how much recycled content is in your Aluminium?

Hilbrand Kamphuis: We noticed that consumers became increasingly climate-conscious and hence we designed new products to help our customers to achieve their sustainability goals, the Hydro Circal and Hydro Reduxa. We can also ensure that the products are developed in an environmentally friendly manner.

Hans Gamerschlag: Ok, sounds good. Please explain.

Hilbrand Kamphuis: Hydro CIRCAL is made from 75% recycled post-consumer scrap. By using recycled content, we reduce energy consumption and are still able to deliver a high quality product. The scrap percentage varies based on customer specifications, but we always guarantee a CO2 footprint lower than 2.3 kg CO2 per 1 kg Aluminium produced for Hydro CIRCAL 75R.

Hans Gamerschlag: And the other?

Hilbrand Kamphuis: Hydro REDUXA is our series of low carbon aluminium. By using renewable energy sources such as hydropower, we are reducing the carbon footprint per kg of aluminium to less than a quarter of the global average. The result is aluminium with one of the lowest carbon footprints yet. Since February we press here the alloy Reduxa.

Hans Gamerschlag: Very good. But how about the projects that have been built already? How much was the recycling content a few years ago?

Hilbrand Kamphuis: Looking into our books I can say that a few years ago we had a lower scrap content, the then "regular" Aluminium had a scrap share of approximately 50%.

Hans Gamerschlag: Ok, that was not so good then.

Hilbrand Kamphuis: Back then the demand was not there as it is now. We upgraded our products in the meanwhile.

Hans Gamerschlag: Do you have other sustainable products?

Hilbrand Kamphuis: Yes, we offer in combination with our low Carbon Aluminium profiles a recently developed Polyamide strip from 100% recycled material. This is another way we can offer our customers to reduce their environmental impact. Let me add that the material is not yet always available though.

Hans Gamerschlag: That’s great news. But what about the pricing?

Hilbrand Kamphuis:  I got to admit, the current Prices for recycled or "green" Aluminium and polyamide are somewhat higher. But this is will change once it becomes the standard choice.

Hans Gamerschlag: Thank you for the information.

Hilbrand Kamphuis: Welcome, anytime. I am glad I could help.

# Steel recycled content – ArcelorMittal

26.02.2020

Telephone Interview with Ing. Tim Meert, Technical Manager, ArcelorMittal Europe - Long products

Hans Gamerschlag: Mr. Meert, can you explain what ArcelorMittal does?

Tim Meert: ArcelorMittal is the largest steel producer in the world, producing 96 million tons of steel in 2018. The company has at least 6 sites in 27 countries and employs some 200,000 people worldwide. In Belgium, the company has offices in Ghent, Geel, Genk and Liège.

Hans Gamerschlag: Who are your clients?

Tim Meert: Our material covers a broad range of applications as you can imagine. Steel is used everywhere. To name the main sectors: Automotive and mobility, Construction, Energy, Packaging, Appliances and Transport.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Tim Meert: Very, but this depends on the clients wishes. Theoretically we can make steel from 100% recycled content. We recently developed a new composition called Histar. Our Histar quality is a more sustainable quality because the values in the EPD are based on Electric Arc Furnace only and not on a mix with Blast Furnace.

Hans Gamerschlag: What does the sustainability have to do with the furnace?

Tim Meert: Some furnaces work with a higher scrap content than others.

Hans Gamerschlag: So what recycling content is in your products?

Tim Meert: The crap content is subject to the type of steel and furnace between 4.8 – 95%.

Hans Gamerschlag: That’s a big range. That is the total scrap content, right? What is the post-consumer content?

Tim Meert: That’s right. The post-consumer content lies between 0.8 and 71.3%.

Hans Gamerschlag: The brackets of a unitized façade, which post-consumer content do they have?

Tim Meert: For strips and small corners, most of the material comes from Dabrowa, Poland. They have a Blast Furnace which can take up to 5% scrap content only. The post-consumer scrap content there is 0.8%.

Hans Gamerschlag: That is pretty bad. How could Scheldebouw get steel with higher recycling content?

Tim Meert: The steel has to be ordered specifically with a higher recycling content. I can send you our latest document regarding the share recycled steel from our various rolling mills. You see, our Histar steel is produced in Differdange, where they have an Electric Arc Furnace. For now it is for beams larger than HEA 300 / IPE550.

Hans Gamerschlag: Ok. Thank you! That was very helpful.

Tim Meert: You’re welcome. Glad I could help.

# Polyamide recycled content – Technische Profielen Produktie BV

16.03.2020

Telephone Interview with Hans Brokking, Algemeen Directeur, Technische Profielen Produktie BV

Hans Gamerschlag: Mr. Brokking can you explain what Ensinger does?

Hans Brokking: Technische Profielen Produktie B.V. (TPP) is a specialist in the manufacturing of rubber sealing gaskets which are applied to many different constructions and purposes. Examples are gaskets for greenhouses, caravans, aluminium façade systems, etc.

Hans Gamerschlag: Do you count Scheldebouw to your customers?

Hans Brokking: We have a very good relationship with Scheldebouw.We delivered material for some of their most prestigious projects.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Hans Brokking: We aim at high levels of sustainability for our products. For example: waste from our TPE extrusion process is 100% returned to our production process.

Hans Gamerschlag: And how about EPDM gaskets?

Hans Brokking: We are currently carrying out a project in which we have a total of 1,000 kg of waste from our EPDM production de-vulcanized and will be returned to our production process. We do this by means of mixing de-vulcanized material into our compounds. The project we carry out will initially only be used for internal testing purposes. We do this to first determine what percentage of de-vulcanized material we can mix back to the maximum and what the influence is on the mechanical and optical properties of the finished product. Once we have gathered and mastered that knowledge sufficiently, we will share these results with a select number of our customers. After acceptance by these customers we will commercialize this 'greener compound'.

Hans Gamerschlag: Ok. How high is the recycling content in your EPDM gaskets at the moment?

Hans Brokking: At the moment we do not yet use recycled material in our EPDM sealing profiles.

Hans Gamerschlag: Understood. Ok, that info helps me further.

Hans Brokking: You are welcome. I wish you good luck for your study.

# Polyamide recycled content – Technoform

17.03.2020

Telephone Interview with Alexander Ott, Technoform Bautec Kunststoffprodukte GmbH

Hans Gamerschlag: Mr. Spronken, can you explain what Technoform does?

Alexander Ott: Technoform is a global family business, with 14 production sites worldwide. We extrude plastic profiles and tubes in Europe, America and Asia-Pacific. Technoform has 45 factories and sales offices and more than 1,500 employees.

Hans Gamerschlag: Who are your clients?

Alexander Ott: Technoform offers products to several industries. From automotive and aviation to marine and medical engineering. The façade industry is one of our big clients.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Alexander Ott: Our product form crucial insulation elements helping to create thermal breaks and therefore reducing energy consumption and lowering CO2-emissions considerably.

Hans Gamerschlag: Fine, how high is the recycling content in your product?

Alexander Ott: For unitized systems our current material has a recycled content of 15%.

Hans Gamerschlag: Ok, you say that is the current material. Are you working on another more sustainable material?

Alexander Ott: However, a project group is currently working on the introduction of Post Consumer Recycled material. The first series of tests have already been carried out here. The challenge lies on the one hand in the guaranteed availability and on the other hand in the material certification. Once this is done, the proportion of recycled material will increase again.

Hans Gamerschlag: Ok. Thank you very much for the support.

Alexander Ott: Welcome. Feel free to contact me for further info.

# Float glass recycled content – AGC Glass Europe

20.02.2020

Telephone Interview with Deepthi Kurian, Chemical Compliance consultant, AGC Glass Europe

Hans Gamerschlag: Ms. Kurian, can you explain what AGC Glass does?

Deepthi Kurian: We here at AGC Glass Europe produce, process and distribute flat glass for the building industry e.g. external glazing and interior decorative glass, the automotive industry and various other sectors as transport, solar power and high-tech applications.

Hans Gamerschlag: Who are your clients?

Deepthi Kurian: We have clients in many sectors. The building industry is probably our biggest client.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Deepthi Kurian: We work continuously to make our product more sustainable. What speaks for glass that it is very durable and can last decades if handled properly. Further it has a very established recycling infrastructure. Glass is endlessly recyclable like no other product. Our main objective is to use as much glass cullet as possible in our production processes. The use of cullet avoids CO2 emissions, since cullet requires less energy to melt and replaces carbonated raw materials.

Hans Gamerschlag: What is cullet?

Deepthi Kurian: Glass that is crushed and ready to be re-melted is called cullet.

Hans Gamerschlag: So how much is the post-consumer content in your float glass?

Deepthi Kurian: Based on 2018 values, 5.3% is the average external recycled content within AGC Glass Europe. Please take a look at our 'Recycled content declaration' online. We have new calculations going on now to make the new Recycled content declaration based on 2019 values, but not finished yet.

Hans Gamerschlag: That is not very high. Can the recycled content be increase?

Deepthi Kurian: That is not so easy. The cullet used in our own production process has to meet stringent specifications, and so we also actively seek out alternative routes for cullet that we cannot recycle in our own products.

Hans Gamerschlag: OK, I understand. One more question, I heard that coated glass can not be recycled. Is that correct?

Deepthi Kurian: no, that is not correct. Coating does not have effects on the recycling potential. It is laminated glass that needs to be treated before it can go back to the furnace.

Hans Gamerschlag: Great info. Thank you for helping me out.

Deepthi Kurian: You are most welcome. Good luck with your studies!

# Mineral wool recycled content – Rockwool B.V.

17.03.2020

Telephone Interview with Hans Spronken, Manager Public Affairs & Technical Support, ROCKWOOL B.V.

Hans Gamerschlag: Mr. Spronken, can you explain what Rockwool does?

Hans Spronken: Rockwool B.V. is part of the Rockwool Group. As a Benelux organization with 1 factory and 1,200 employees, we supply advanced insulation systems for buildings.

Hans Gamerschlag: Who are your clients?

Hans Spronken: Our products are applied over many sectors. Rockwool is used for thermal insulation, as sound barrier and to achieve fire resistance. The list of sectors we sell to is very long. The construction sector is the most important sector for us.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Hans Spronken: We believe it is important to make better use of our planet's resources, such as stone. Rock wool is a sustainable material: it is produced sustainably, is made from sustainable raw materials and literally contributes to the creation of sustainable buildings. Thanks to our recyclable products, we can use a circular business model.

Hans Gamerschlag: So how high is the recycling content in your product?

Hans Spronken: We have our own ROCKWOOL recycling plant. There we recycle old mineral wool for the production of new stone wool on the line. Waste from the production process is also used in the recycling plant. Therefore, new products consist of up to 50 % out of recycled resources.

Hans Gamerschlag: That is the total recycling content, I guess. How much is the post-consumer content?

Hans Spronken: ROCKWOOL insulation products include 25-55% recycled material. We have a special line that applies 34% of recycled materials and 66% consists of other raw materials. At this line the pre-consumer recycled content can go up to 36% and the post-consumer recycled content is 2%.

Hans Gamerschlag: Is there any chance to get the post-consumer recycled content higher?

Hans Spronken: We are offering 100% recycled Rockwool material. But that is not standard material yet and can be ordered on request as of now.

Hans Gamerschlag: That's great.

Hans Spronken: Please refer for more info to our website, we have lots of info there.

Hans Gamerschlag: Thank you very much for the info. This helps me to progress.

Hans Spronken: I was glad to help. Success with your study.

# Demolition and recycling procedure curtain walls

20.03.2020

Telephone Interview with Axel Hendriks, Commercial Directeur or Beelen NEXT - Beelen Sloopwerken

Q: How do you approach the demolition of a curtain wall?

A: At first we check what we have in front of us. What materials are used, how are they connected, what is the easiest way for removal? Secondly we check the financial aspect of the project. What values do the materials have and how can we separate them in a timely manner. Which components are easy to remove and carry high material value.

And important in this context is to examine which elements or components can be salvaged for reuse. Reuse does not often produce any financial advantage for us but is often wished for by the customer for sustainability reasons.

While looking at technical and financial issues we never have to forget to put health and safety aspects for our team as a priority. Demolition work can be very dangerous and lead to accidents if it is undertaken light-hearted and without previous examination of structure, material state and connection quality.

Q: Which elements of a façade can be reused?

A: In theory a whole façade could be reused or salvaged in a way that allows for repair and subsequent reuse. However the facades that we demolish these days were built many years ago and therefore they do not meet today's rules and regulations regarding building physical aspects e.g. thermal conductivity and sound reduction.

We demolish for example a lot of old windows with double glazing. These days the double glazing from 25 years ago is not sufficient to comply with the current requirements. In this case we check if the old double glazing can be exchanged for new higher performing double glazing or even triple glazing. If the windows allow for this flexibility of replacing the glazing we salvage them in a way which enables reuse. If not we salvages them for recycling only.

Q: You mentioned previously that the connections of the materials are important. Can you explain this in more detail?

A: Connections between components are important to us since they determine how easy a component can be disassembled. The loosening of connections have a direct impact on how much time is spend to recover an element or component and hence affects the financial return. Further some connections allow the use of small machinery while others ask for the operation of heavy equipment, resulting in a different health and safety environment. The removal of some connections causes a lot of dirt and dust e.g. separating reinforcement irons from concrete. In this case we undertake special steps to protect the adjacent neighbourhood and to reduce the impact of the demolition work as far as possible.

When it comes to the connections of curtain walls the most critical connections are ones where glue or structural silicone was applied. These connections take a lot of effort to lose and require a lot of time to take apart. In addition the separated materials always have remains of the glue sticking to them preventing mono-material recycling.

Q: What happens to the materials after demolition?

A: The whole curtain wall of a building is demolished and introduced to recycling. That means if not some components can be salvaged for reuse. All glazing is separated and collected for transport to a dedicated recycling plant for float glass. There the old glazing is further separated and treated before recycling.

The Aluminum elements are put aside and cut into shorter pieces for better handling. The they are transported to an Aluminium smeltery for recovery. However it needs to be mentioned that the profiles still feature the rubbers, silicone blobs and thermal breaks. If the profiles undergo another stripping process to achieve a higher purity for its raw materials is to discussed with the smeltery.

Regarding mineral wool Rockwool has a limited recycling program for stone wool. In practice, however, rock wool is often dumped. There are no recycling options at all for glass wool. This is therefore also dumped or sent to incinerators.

# Polyamide recycled content – Ensinger Plastics

25.03.2020

Telephone Interview with Severin Hoppmann, Project Manager Application Technology insulbar®

Division Building Products, Ensinger GmbH

Hans Gamerschlag: Mr. Hoppmann, can you explain what Ensinger does?

Severin Hoppmann: Ensinger is a world leader in the field of engineering plastics, excelling in both the manufacture of semi-finished stock shapes and profiles and in the machining of plastic materials. Our headquarter is based in Nufringen in Germany.

Hans Gamerschlag: Who are your clients?

Severin Hoppmann: We serve several industries from Aerospace, Building, Food, Mechanical, Medical, Oil & Gas to Semiconductor industry.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Severin Hoppmann: The profiles are highly heat-insulating, enable Uf values at passive house level and thus save energy. Insulbar RE made from recycled polyamide ensures maximum sustainability. Insulbar insulating bars are continuously developed further and always correspond to the current state of the art.

Hans Gamerschlag: Ok. How high is the recycling content in your products?

Severin Hoppmann: I am afraid purchasing specifications etc. have been declared a trade secret and therefore I am unfortunately unable to give you exact dates. But I will send our EPD to you, I think the data from them can be used well for your work. The two materials of interest to you are our standard material TECATHERM 66 GF the material TECATHERM 66 GF RE, a material that consists of 100% pure polyamide recycling. Which is recycling pure waste products from other industries.

Hans Gamerschlag: Interesting. So, some of your material is made from 100% recycled content. And about some of your material you can not say of much recycling content is has?

Severin Hoppmann: Yes. I am afraid we have our company policies.

Hans Gamerschlag: Well, ok then. Thank you for your time.

Severin Hoppmann: Certainly. Anytime. Good luck!

# Recycling procedure float glass

26.03.2020

Telephone Interview with Daniele Modesti, Technical Manager / Plant Manager Lommel a.i. of Maltha Glasrecycling

Hans Gamerschlag: Ms. Modesti, where do you get the float glass for recycling from?

Daniele Modesti: We recycle exclusive float glass on our plant in Lommel. This includes insulating glass. We receive the float glass from collecting services as Vlakglas Recycling Nederland or direct from Demolition companies.

Float glass, such as windows, wire and insulating glass, car windows and mirrors, comes from greenhouses, buildings and cars. Float glass is supplied from recycling schemes, environmental streets, construction companies, greenhouses, glaziers and specialized collectors from the automotive industry.

Hans Gamerschlag: What are the main issues when recycling float glass?

Daniele Modesti: Float glass is used in environments other than hollow glass. As a result, float glass has other types of contamination, which requires a different processing process. For example, float glass itself may contain metal and / or foil. Along with the glass, metal waste, debris, wood, plastic and rubber is often also included.

Hans Gamerschlag: So, tell me about the contaminations.

Daniele Modesti: The pollution can be sorted into categories:

Ceramic Stone and Porcelain comes in through people being lazy or unaware. Containers stand isolated at locations and it is quite easy to throw in your construction rubble, a broken coffee bag or others. This can lead to 2-5% contamination in the container and is very difficult to sort out.

Iron pollution stems often from renovation works (especially old buildings / houses) where old metal window frames were used. There are restrictions to put them in containers but this is not always followed. Contamination can be up to 1% in some cases.

More and more iron ends up in the recycling due to the evolution of car windows. Think especially of the trunk lids that consist entirely of glass mounted on a steel frame.

Non-iron metals, so Aluminium, lead, or other alloys end up being mixed with float glass to. In some deliveries we find between 2-5% contamination with this metals. Certainly there are the Aluminium strips of double glazing. Previously they were made from lead. This also comes to us from renovation

We even have organic contamination like wood and paper or cardboard. The wood comes from timber frames. The paper and cardboard comes from improper use of the containers. We find between 2-3% contamination in some deliveries.

Recently we see as well an increase in plastics between the collected float glass. This comes as either Polycarbonate or PVB's. They can account for 8-12% in some deliveries. Where are they from? The PCB is regularly placed between laminated glass to make the glass even stronger without loss of transparency. The PVB is the well-known foil between laminated glass. Think of car windows, you will see them the fastest.

Hans Gamerschlag: How do you deal with these contaminations?

Daniele Modesti: We have our own method of separation for every type of pollution. We use all kinds of detection methods: light, X-ray, UV, laser, magnetic, eddy current, density etc. Regarding the numbers, they are percentages on an annual basis of pollution over our total processed glass regardless of the type or origin of the glass

Hans Gamerschlag: What happens to the recycled materials?

Daniele Modesti: The iron is sold, there is a good recycling market for this material. The Ceramic Stone and Porcelain goes completely into landfill for the time being, but tests are underway to use it in other markets. The organic material is as much separated as possible for recycling. A minimal amount, the one usually contaminated with glass, goes to landfill. The Plastics are separated as good as possible for recycling. A small amount, the one usually contaminated with glass, goes to landfill as well. The PVB goes completely to landfill but there are tests are ongoing to use it again.

Hans Gamerschlag: And how high is your recycling efficiency for the float glass in the end?

Daniele Modesti: Depending on the quality of the float glass coming in for recycling, we strive for the highest possible output of clean recycled glass, in Lommel we aim for recuperation of approximately 90% for the float glass and to be able to return it to the glass industry. We are proud at Maltha upon our good cooperation with the flat glass industry, which has led to the use of the end products of the glass recycling as fully-fledged raw materials in this industry.

Hans Gamerschlag: Thank you Ms. Modesti, that was very helpful info.

Daniele Modesti: My pleasure. You are welcome.

# Silicone recycled content – Sika

31.03.2020

Telephone Interview with Martin Woldorf, Sales Manager North/West, Sika Deutschland GmbH

Hans Gamerschlag: Mr. Woldorf, can you please explain what Sika does?

Martin Woldorf: Sika is a Swiss international company with a global local presence in 84 countries and more than 16,000 employees. With its process materials for sealing, gluing, damping, reinforcing and protecting load-bearing structures, Sika strives for the leadership position or a strong second place in its clearly defined target markets.

Hans Gamerschlag: Who are your clients?

Martin Woldorf: The business activity of Sika is situated in 7 target markets: finishing & renovation, sealing & bonding, roof systems, auxiliary materials, industry, floor systems and waterproofing.

Hans Gamerschlag: Please explain me about how your sustainable your material is?

Martin Woldorf: Our sustainability principles form the basis for environmentally conscious strategic management. Our product range meets the prevailing environmental standards. We reduce our dependence on crude oil and other scarce materials. We are reducing our contribution to global warming. We continuously improve our production process and reduce our environmental footprint. We provide solutions for more efficient use of energy and resources.

Hans Gamerschlag: Ok. How high is the recycling content in your products Sikasil WS 605S and Sikasil SG-500?

Martin Woldorf: ok, to make it short: Our Sikasil WS 605S and Sikasil SG-500 products contain 0% recycled content.

Hans Gamerschlag: How come there is no recycled material in the sealants?

Martin Woldorf: There is research going on how to recycle silicone and in theory it is possible. There is no established return infrastructure for the material.

Hans Gamerschlag: Well, that was helpful. Thank you for your time Mr. Woldorf.

Martin Woldorf: Welcome. Feel free to contact me for further info.

# Recycling procedure metals – Goudsmit B.V.

20.04.2020

Telephone Interview with Fabian van den Braak, Sales Support Engineer Magnetic Recycling at Goudsmit B.V.

Hans Gamerschlag: Mr. van den Broek , can you explain what Gousdmit does?

Fabian van den Braak: Goudsmit Magnetics has been a leading international producer of magnetic systems for various applications since 1959. Goudsmit has production facilities in China and the Czech Republic, sales channels in France, Germany and England and various agencies, Goudsmit's magnets and magnetic systems are finding their way around the world.

Hans Gamerschlag: Who are your clients?

Fabian van den Braak: Goudsmit Magnetics supplies magnets for the automotive, food, recycling, metal, pharmaceutical, offshore, chemical and aerospace industries.

Hans Gamerschlag: Please explain how the general recycling procedure for Aluminium frames looks like.

Fabian van den Braak: After the façades have been removed, the elements are cut to length with scissors that fit into the shredder. At the recycling company, the shortened profiles are poured into the shredder with an excavator and shredded into small parts.

A wind shifter filters out light parts as foils, insulation wool, silicon, polyamides, rubbers.

Then an upper band magnetic separator sorts out all magnetic metals as iron and steel.

In another step remaining non-metallic parts such as silicones, EPDM seals and polyamides are recognized and sorted using an eddy current separator.

Hans Gamerschlag: What happens next?

Fabian van den Braak: Further methods exist to analyse and sort different Aluminium alloys using X-ray fluorescence or LIBS (laser-induced degradation spectroscopy) technology.

Hans Gamerschlag: Please explain what an upper band magnetic separator is.

Fabian van den Braak: Overbelt magnets are for mounting above conveyor belts in the bulk loading of recycling industry. They remove ferrous particles from raw materials automatically and continuously.

Hans Gamerschlag: And what is an eddy current separator?

Fabian van den Braak: Non-ferrous separators or Eddy current separators remove non-ferrous metal parts such as copper and aluminum in a continuous process. For the recovery (recycling) or removal of metals. At this stage, all ferrous metal parts are already filtered out through the overband magnet. At this stage, the plastic, rubbers and silicon particles can be separated from the Aluminium.

Hans Gamerschlag: How efficient are the various steps?

Fabian van den Braak: Regarding the wind shifter I don’t know because this is not our product.

The overband magnet depending on the type of magnet, layer thickness, belt speed, belt width and grain size, can filter 70-90% of all ferrous particles from the waste stream. This percentage can be increased to 95% by coordinating all factors, but our company has no influence on the circumstances.

The  efficiency of the Eddy current separator depends on various factors such as bandwidth, belt speed and grain size. Furthermore, even spread and layer thickness play an important role to increase efficiency, especially with smaller grain size.

The type of magnetic roller has a major influence on the design. A 12-magnet coil is not as efficient as a 22-magnet coil. The separation efficiency of this step is 85%, which means that 85% of the Aluminum is sorted in this step.

Hans Gamerschlag: What happens to plastics, silicone and rubber?

Fabian van den Braak: I presume they are incinerated or dumped. But there is another aspect that is important. We distinguish between two types of customers.

At the first customer type, all materials are separated as much as possible to receive high purity materials that can be sold to smelters who are in turn interested in pure materials to protect their furnaces from contaminants.

The second type of your customers is only interested in separating the iron from the waste stream to sell it and sends all the leftover material to incineration, which is beneficial for the embodied energy of the materials. Aluminuim is sorted out in the form of slag after the combustion process.

Hans Gamerschlag: So, can I summarize that 85% of Aluminium is recycled, up to 95% of the iron and steel and that 100% of sealants, rubbers and plastics are incinerated or landfilled?

Fabian van den Braak: Generally speaking yes. This applies to the first customer type only, who is interested in separating as far as possible. This is the majority of our customers though. Sometimes they run the materials twice through the process with two machines set one after the other. This results in even higher levels of purity but it costs more energy and money. It is rather the exception.

Hans Gamerschlag: Thank you for the conversation.

Fabian van den Braak: You are welcome.

# Recycling procedure metals - Redwave

21.04.2020

Telephone Interview with Thomas Diesenreiter, Sales Engineer REDWAVE XRF/C

Hans Gamerschlag: Mr. Diesenreiter, can you please explain what Redwave does?

Thomas Diesenreiter: Redwave manufactures advanced optical sorting machines and complete plant solutions for getting the highest recycling rates and maximum profit.

Hans Gamerschlag: Who are your clients?

Thomas Diesenreiter: Our clients are private sorting companies and municipalities. We sell our products worldwide. We have clients in The Netherlands too.

Hans Gamerschlag: Please explain how the general recycling procedure for Aluminium frames looks like.

Thomas Diesenreiter: After dismantling the facades, the elements are cut to the length that fits into the shredder using scissors. This already happens at the shredder's storage bin.

In the recycling company, the shortened profiles are put into the shredder with a material handler and shredded into small parts. A fraction <100mm is usually generated here, since it is easier to handle in the further system.

Then a wind shifter is usually integrated in the shredder, which separates the material into heavy fraction (metals) and light fraction (plastics). The heavy fraction is usually further processed, the light fraction goes to the combustion as far as we know.

Hans Gamerschlag: What is a wind shifter, please?

Thomas Diesenreiter: A windshifter is used to separate light from heavy materials with the use of an air stream.

Hans Gamerschlag: How does the process go further?

Thomas Diesenreiter: An overbelt magnetic separator, usually from barium ferrite, sorts out all magnetic metals e.g. iron and steel. If necessary, stainless steel can be removed separately using a neodymium magnet, since it is not attracted to a normal barium ferrite magnet.

The remaining fraction is separated via an eddy current separator into non-ferrous metal as Aluminium, zinc, copper, brass, etc. and "fluff" as insulated cables, stainless steel, plastic, non-metal parts such as silicone, EPDM seals and polyamides, Rubber, wood, etc.

The non-ferrous metals "ZORBA" can then be divided into individual fractions e.g. pure Zn, pure Cu, pure brass, etc. with the help of sensor-based sorting technology e.g. REDWAVE XRF / C by using air pressure nozzles.

Hans Gamerschlag: What is 'ZORBA'?

Thomas Diesenreiter: 'ZORBA' is a mix of metals. It still contain heavy metals called 'ZEBRA' and Aluminium called 'TWITCH'.

Hans Gamerschlag: What happens next?

Thomas Diesenreiter: If necessary Various Aluminium alloys from the Aluminium mix (“TWITCH”) are analysed and sorted out using our REDWAVE XRF / C applying X-ray technology or LIBS technology using Laser induced breakdown spectroscopy.

Hans Gamerschlag: And the iron, what happens to it?

Thomas Diesenreiter: The iron separated by a magnet is melted down again. Here too, a high degree of purity is not achieved.

Hans Gamerschlag: How efficient are the various steps?

Thomas Diesenreiter: For our sorting machines, we guarantee the efficiency of product output and product purity of approx. 93% -99.5% depending on the task, composition of the input material, throughput and customer requirements for operating the system.

Unfortunately, we cannot answer how high the general recycling rates and efficiency are. These are values that you should contact the recycler (such as HKS, Galloo, etc.).

Hans Gamerschlag: So the metals are separated very well. But what happens to plastics, silicone and rubber?

Thomas Diesenreiter: To our knowledge, there is currently no recycling of the materials silicone, polyamide and EPDM. On the one hand, this has to do with the heavy soiling and the adherence to other parts (one would have to separate it from composite parts by type), on the other hand, these plastics can only be used in downcycling, for which, to our knowledge, “cleaner” sources ( such as production waste) is a mix of contaminated light fractions.

Hans Gamerschlag: To your knowledge, what happens to the non-metal materials?

Thomas Diesenreiter: The separate EPDM seals and polyamides can be used to manufacture inferior goods, e.g. Fillers or are burned (which in our experience is mostly true). The silicone burns as it melts as far as it sticks to the metal.

Unfortunately, we do not know exactly how much of the originally added silicones, EPDM and polyamides are sorted out by means of air classifiers (light fraction). Depending on the setting, however, with certainty> 95%. The rest ends up in the Eddy Current Drop, i.e. the fluff or sticks to metal parts (= composite pieces).

Unfortunately we do not know to what extent these silicones, EPDM and polyamides can be separated from each other and whether this makes economic sense.

Hans Gamerschlag: So, please let me summarize to check if I understand correctly. In the first step an air classifier sorts out 95% of all silicon, EPDM rubbers and Polyamides. These ones are burned to your knowledge.  In the second step a minimum 93% of all steel, stainless steel and iron are sorted out.

Thomas Diesenreiter: …using a Barium Ferrit Magnet for iron and steel and a Neodym Magnet for stainless steel.

Hans Gamerschlag: In the third step at least 93% of all non-iron metals i.e. Aluminium are sorted out via an Eddy Current Separator. ‘Fluff’ is the name of all the materials other than non-iron metals material at this process step. And then you offer systems which allow further separation of non-iron materials ‘ZORBA’ into pure Zinc, Copper, messing, brass and Aluminium, again at a recycling efficiency of at least 93%. In one last step the Aluminium alloys ‘TWITCH’ can be sorted into individual packages via spectroscopy, again with minimum 93% efficiency. Is that a good summary?

Thomas Diesenreiter: Yes, but keep in mind that all components must be optimally adjusted, that responsibility lies with the operator in the end.

Hans Gamerschlag: How common are the high end sorting machines, the x-ray and spectroscopy machines at the scrap metal businesses?

Thomas Diesenreiter: They are less present since they are relatively recent technologies, but we assume that what the Eddy Current was 10 years ago , XRF based sorting will be in 2 years from now.

Hans Gamerschlag: Thank you for the conversation.

Thomas Diesenreiter: My pleasure, I hope I could bring some light in the matter.

# Sustainability, Design and Sales at Scheldebouw

03.03.2020

Interview with Patrick Eichhorn, Design & Engineering, Scheldebouw B.V.

**Sustainability**

Hans Gamerschlag: The sustainability of building products is increasingly important to planner and owners. Several rating systems do exist outlining the sustainability level of a building and its components. Does Scheldebouw produce any calculations about the sustainability of their products?

Patrick Eichhorn: To date Scheldebouw provided information about the systems for other specialists to undertake BREEAM or LEED calculations. In this context they provide BoQ's, material specifications and further relevant data to enable specialist engineers to conduct e.g. life cycle assessments. Scheldebouw themselves did not undertake any calculations regarding sustainability performance of their products yet but they noticed that the topic becomes more important to planners, clients and municipalities. Hence, Scheldebouw might find themselves soon in the position to have to perform sustainability calculations in the nearby future as part of their service.

Hans Gamerschlag: The façade systems do not last forever. Does Scheldebouw take the end-of life and dismantling of their products into design considerations?

Patrick Eichhorn: Scheldebouw recognizes the limited life span of its products, especially in comparison to the superstructure. A potential total dismantling of the their facades Scheldebouw does not take into consideration at the design stage though. There are aspects acknowledged that ask for a partly dismantling of the façade in order to guarantee its constant effectiveness e.g. repair and maintenance work. So are for example all facades designed with the potential of re-glazing in mind. Further any components that are subject to movements e.g. blinds, fins and motors are being placed accessible enabling easy repair or replacement. Cleaning procedures often ask for accessibility and part-dismantling which result in openable façade sections or glazing which allows removal from inside. In summary, while the ease and speed of assembly is a key factor to produce the façade units, their total dismantling and general end of life scenario is not taken into consideration.

Hans Gamerschlag: Durability of buildings can be enhanced by applying better quality components. Does Scheldebouw consider their products of a higher quality than the ones of their competitors? Does that affect their products' life span?

Patrick Eichhorn: We at Scheldebouw consider durability as one of the keys aspects of a façade and apply high quality materials and components to our products. We always provide our customers with value for their investments and the longer a façade lasts, the more value can be gained from it. Certainly there are limits as well since the budget of our clients has limits and we stand in competition with other companies. Considering the quality our competitors deliver we consider our product's quality slightly superior for various reasons: we have all engineering in house giving us an advantage over companies who rely on outside expertise. Secondly the many years of experience of a well-rehearsed team and thirdly an inhouse test center, allowing us to test what we developed and omitting weak points.

**Design**

Hans Gamerschlag: The design of a new project has to be started by someone from Scheldebouw. Who produces the initial design?

Patrick Eichhorn: The initial design steps are undertaken by the acquisition team which generally consists of a lead concept designer (LCD), a representative of the tender department and a representative of the sales department. Each team member has a specific role and together they ensure to find the optimal solution for the requested building envelope. The role of the lead designer is to formulate an initial design based on the project requirements in order to form a discussion basis with the client. The representative of the tender department provides input regarding procurement, bidding procedure, time frames and resource handling. The sales person produces the cost structure and payment terms. Further it strengthens the relationship with the customer and focuses on meeting the customer's needs. The composition of the team is subject to the size and nature of the project in question. Bigger projects might require more team representatives in order to handle the workload.

Hans Gamerschlag: Computer programs form crucial instruments of design and evaluation of façade proposals. What software packages are applied by Scheldebouw and at what stages?

Patrick Eichhorn: In many aspects Scheldebouw uses typical software programs for design, procurement and production. The design of the projects is in many cases started in 2D in AutoCad and then transferred to Revit for enhanced 3D modelling and obtaining an initial BoQ. In the next step for production AutoCad Inventor is applied which translates the data from Revit into a machine readable version for the CNC machine. The procurement department makes use of PMF, an inhouse software especially designed for Permasteelisa's procurement processes. SAP is applied by the sales and logistic departments for controlling and monitoring suppliers, processes, budgets, approvals, and payments.

Hans Gamerschlag: Building owners and main contractor want to make the most of the money they are spending on building components and often ask subcontractors for lower pricing. What is Scheldebouw's approach to value-engineering?

Patrick Eichhorn: Designing with delivering value is a core character of Scheldebouw. Typical measures to produce value for money are standardisation of solutions, efficient profiling to reduce material usage and an economic application of accessories. Further steps include the meeting of specifications while not exceeding them, the choice of system suppliers of doors or windows where required and a streamlined production and installation process.

Hans Gamerschlag: One decisive factor for the design of especially tall buildings is the wind force. How are wind loads calculated?

Patrick Eichhorn: Wind load calculations are in general provided by specialist consultants e.g. Arup, Wintech, JBS etc. In special cases, when for example a tower is of outstanding dimensions the data is computed by wind tunnel testing, which delivers the most accurate results. The data is then applied to out designs in order to provide products of sufficient strength to withstand the wind forces. It has the most impact on the dimension of mullions and transoms but affects as well the glass built-up and the design to achieve sufficient air- and wind tightness of the system.

Hans Gamerschlag: Another important aspect, especially at high buildings is the risk of water- and air ingress. Can air- and water tightness actually be calculated and how is it designed for?

Hans Gamerschlag: Rather than the performance architects and owners are often concerned about the looks of façade which includes the colour coating of the profiles. What coatings do you recommend and why?

Patrick Eichhorn: The surface treatment of the product is at the discretion of the owner. Generally speaking for Aluminium profiles there are three finishes. Powder coating , anodizing and wet painting. Our preferred option is powder coating since it offers many surface colours and qualities, is relatively budget friendly and can be repaired in case a scratch is made.

Hans Gamerschlag: Considering that Design for Disassembly has to unravel what was done previously at the assembly stage, how are the connections designed and when do you opt for assembly via rivets, screws, glue or clips?

Patrick Eichhorn: Connections are designed with various aspects in mind. Firstly the connection has to cater the structural load it has to cater for. Secondly the connection type has to be quick to apply e.g. rivets are quicker than screws. Thirdly the connections can be sealing as well as it is often with glue the case. The application of various connection methods has developed over time. We often apply techniques which proved the test of time.

Hans Gamerschlag: The aim of Design for Disassembly is to enable component and material reuse or recycling. How does recycling or reuse of facades take place at the moment?

Patrick Eichhorn: To make it sort: we do not use recycled or used material in our projects. The client's brief does not ask for it. Furthermore, who could guarantee us that they will last as long as new materials. The risk will be on us.

Hans Gamerschlag: When it comes to selecting materials for the systems, are the materials applied in accordance to their life expectancy (life cycle coordination)?

Patrick Eichhorn: As mentioned previously we at Scheldebouw aim for durable systems with materials which are proven and tested. The majority of the materials have a long life span. The materials do not have all the same life expectancy however. Some materials unfortunately do not last as long as for example the Aluminium frames. The gaskets are the first that spring to my mind. When exposed to UV light they can show to deteriorate after 20 to 25 years, subject to climate of the region and orientation of the façade.

**Sales**

Hans Gamerschlag: As other companies your group relies upon a constant supply of projects. How does Scheldebouw acquire new projects?

Patrick Eichhorn: The market Scheldebouw operates in is relatively small and the customers, suppliers and other key players know each other very well. Scheldebouw gets involved at early project stages and offers its expertise to owners and designers in the form of a pre-construction services agreement (PCSA) which allows Scheldebouw to carry out services before entering into a formal building contract. The PCSA contract has the benefit for the customer that he receives Scheldebouw's full support and expertise at an early stage of the project while on the other hand Scheldebouw is financially rewarded for their input and enabled to shape the design and specifications in a beneficial way for the subsequent bidding process.

Hans Gamerschlag: Winning new projects relies on various aspects. Pricing is sometimes the most important for a client. How are Scheldebouw's prices being established?

Patrick Eichhorn: The sales department is in charge of producing the product and service pricing. Various factors are being included in their considerations. The material and labour costs for the units are to be calculated based on BoQ and assembly procedures required to manufacture the façade which is determined by its complexity. The material prices changes continuously e.g. the price for Aluminium and other metals which are traded at the London Metal Exchange (LME) and are subject to global demand changes. Further the logistics and transport modes affect the pricing. The situation on site plays an important role too. Can any material be stored on site or does it have to be delivered just in time, without any interims storage. Lastly commercial aspects as competition offers, profit margins and factory workload influence the final pricing.

Hans Gamerschlag: Another point for a good relationship with a potential client is a clear communication policy. Does Scheldebouw provide one contact person for a client from start to end? How does Scheldebouw support their customers?

Patrick Eichhorn: The lead concept designer (LCD) is the contact person for the client from start to completion of a project. The position is very broad and comprises all aspects ranging from initial design to handover procedures. On several fields he/she is supported by other specialists from sales or tender department. Once the design is approved the role of the LCD decreases and the role of the sales and tender department become more important. However the LCD remains in constant contact with the client to ensure a smooth installation phase and to handle any upcoming design- and detail issues.

Hans Gamerschlag: You are not the only company in your field. Who are Scheldebouw's biggest competitors?

Patrick Eichhorn: Scheldebouw, being part of the Permasteelisa group, focuses on a certain sales territory and does not intervene in sales areas of other Permasteelisa members e.g Gartner from Germany. This agreement ensures that inhouse competition between members of the group is prevented. Competition from outside comes mainly from the Italian Focchie Group, another leading company in the curtain walling sector. Furthermore, at small projects of up to 8000m2 façade area, system providers e.g. Schüco or Reynaers team up with smaller fabricators to bid for the façade packages. In this cases Scheldebouw has good chances to win on price because they can offer a more budget friendly package since they do not have to pay the overheads of a system provider.

Hans Gamerschlag: If costs is one of the most decisive factor to win or lose a project the question arises what are the highest cost factors for Scheldebouw?

Patrick Eichhorn: The highest cost factor is formed by the materials, therefore efficient material usage and clever material selection is vital for pricing and competitiveness. Further the installation costs are substantial and have to be considered carefully. Questions of logistics, storage and installation sequences are crucial to be established at an early stage in order to prevent later surprises, meaning financial losses.

Hans Gamerschlag: With the prices for materials being so important did Scheldebouw ever consider to establish a disassembly line in order to retain the valuable materials from facades they installed years ago?

Patrick Eichhorn: We at Scheldebouw acknowledge that resources are limited and that the question of material reuse becomes more important in the future. While we continuously optimize our façade performances and longevity e.g. with the closed cavity concept we recognise that they are not designed with material recycling and reuse in mind. To date there is little incentive to disassemble old façade systems for material reuse and hence Scheldebouw did not actively ponder to set up a disassembly line. This step might become feasible in the future on basis either by legislative or commercial reasons.

# 11. Appendix B

## Calculations and drawings

# MCI Calculation - project: Lime Street , London

**Material volume and weight**

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium profiles** | Mullion | 2 | 4.005 | 8.01 | 0.0011370 | 0.00911 | 2700 | 24.590 | 5.89 | 4.175 |
| | Sunshade track | 2 | 2.850 | 5.70 | 0.0000373 | 0.00021 | 2700 | 0.574 | 5.89 | 0.097 |
| | Interlock | 1 | 4.005 | 4.01 | 0.0000264 | 0.00011 | 2700 | 0.285 | 5.89 | 0.048 |
| | Transom top | 1 | 1.600 | 1.60 | 0.0002510 | 0.00040 | 2700 | 1.084 | 5.89 | 0.184 |
| | Transom intermediate | 1 | 1.500 | 1.50 | 0.0001520 | 0.00023 | 2700 | 0.616 | 5.89 | 0.105 |
| | Transom bottom | 1 | 1.600 | 1.60 | 0.0002720 | 0.00044 | 2700 | 1.175 | 5.89 | 0.199 |
| | Dowel | 2 | 0.265 | 0.53 | 0.0000759 | 0.00004 | 2700 | 0.109 | 5.89 | 0.018 |
| | Glass support | 2 | 0.100 | 0.20 | 0.0000440 | 0.00001 | 2700 | 0.024 | 5.89 | 0.004 |
| | Angle profile 20x20x3 | 4 | 0.100 | 0.40 | 0.0000189 | 0.00001 | 2700 | 0.020 | 5.89 | 0.003 |
| | | | | | | 0.01055 | | **28.477** | | **4.835** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium sheet** | Backpan | 1 | 1.013 | 1.398 | 0.003 | 0.00425 | 2700 | **11.471** | 5.89 | **1.948** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steel** | Spandrel sheet | 1 | 1.034 | 1.429 | 0.0015 | 0.00222 | 8000 | 17.731 | 5.89 | 3.010 |
| | Spandrel sheet | 2 | 1.500 | 0.180 | 0.0015 | 0.00081 | 8000 | 6.480 | 5.89 | 1.100 |
| | Bracket | 1 | 0.400 | 0.200 | 0.012 | 0.00096 | 8000 | 7.680 | 5.89 | 1.304 |
| | | | | | | | | **31.891** | | **5.414** |
| | | | | | | `` | | | | |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **EPDM Gasket** | Gasket interlock mullion mi | 1 | 4.225 | 4.225 | 0.000624 | 0.003 | 1600 | 4.218 | 5.89 | 0.716 |
| | Gasket interlock mullion ba | 1 | 4.225 | 4.225 | 0.000487 | 0.002 | 1600 | 3.292 | 5.89 | 0.559 |
| | Gasket interlock transom fr | 1 | 1.700 | 1.700 | 0.000585 | 0.001 | 1600 | 1.591 | 5.89 | 0.270 |
| | Gasket interlock transom ba | 1 | 1.700 | 1.700 | 0.000488 | 0.001 | 1600 | 1.327 | 5.89 | 0.225 |
| | Gasket mullion closure | 2 | 4.225 | 8.450 | 0.000248 | 0.002 | 1600 | 3.353 | 5.89 | 0.569 |
| | Gasket transom closure mic | 1 | 1.700 | 1.700 | 0.000120 | 0.000 | 1600 | 0.326 | 5.89 | 0.055 |
| | Gasket transom closure fro | 2 | 1.700 | 3.400 | 0.000050 | 0.000 | 1600 | 0.272 | 5.89 | 0.046 |
| | Gasket SSG mullion | 2 | 4.120 | 8.240 | 0.000123 | 0.001 | 1600 | 1.622 | 5.89 | 0.275 |
| | Gasket SSG transom | 2 | 1.725 | 3.450 | 0.000094 | 0.000 | 1600 | 0.519 | 5.89 | 0.088 |
| | Gasket closure glass | 2 | 1.800 | 3.600 | 0.000063 | 0.000 | 1600 | 0.363 | 5.89 | 0.062 |
| | Gasket intermediate transor | 1 | 1.700 | 1.700 | 0.000054 | 0.000 | 1600 | 0.147 | 5.89 | 0.025 |
| | | | | | | | | **17.031** | | **2.891** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Silicone** | Sealant | 1 | 6.800 | 6.800 | 0.001 | 0.007 | 1370 | **9.316** | 5.89 | **1.582** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Glass** | DGU | 1 | 3.875 | 1.475 | 0.02 | 0.11431 | 2500 | **285.781** | 5.89 | **48.520** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral wool** | Spandrel panel insulation | 1 | 1.005 | 1.400 | 0.040 | 0.056 | 70 | **3.940** | 5.89 | **0.669** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Polyamide** | Thermal break | 2 | 1.500 | 3.000 | 0.000024 | 0.000072 | 1370 | **0.099** | 5.89 | **0.017** |

# MCI Calculation - project: One Crown Place , London

**Material volume and weight**

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium profiles** | Mullion split | 2 | 3.20 | 6.40 | 0.001037 | 0.00664 | 2700 | 17.919 | 1.82 | 9.846 |
| | Mullion intermedi | 1 | 3.20 | 3.20 | 0.000889 | 0.00284 | 2700 | 7.681 | 1.82 | 4.220 |
| | Transom interme | 1 | 0.57 | 0.57 | 0.000889 | 0.00051 | 2700 | 1.368 | 1.82 | 0.752 |
| | Transom top | 1 | 0.57 | 0.57 | 0.001074 | 0.00061 | 2700 | 1.653 | 1.82 | 0.908 |
| | Transom bottom | 1 | 0.57 | 0.57 | 0.001185 | 0.00068 | 2700 | 1.824 | 1.82 | 1.002 |
| | Intermediate Trar | 1 | 0.57 | 0.57 | 0.001296 | 0.00074 | 2700 | 1.995 | 1.82 | 1.096 |
| | Bead profile | 2 | 1.00 | 2.00 | 0.000241 | 0.00048 | 2700 | 1.301 | 1.82 | 0.715 |
| | Vent Frame profi | 1 | 3.20 | 3.20 | 0.000852 | 0.00273 | 2700 | 7.361 | 1.82 | 4.045 |
| | Louvre profile | 1 | 0.57 | 0.57 | 0.001333 | 0.00076 | 2700 | 2.051 | 1.82 | 1.127 |
| | Nosing profile | 1 | 0.57 | 0.57 | 0.002 | 0.00114 | 2700 | 3.078 | 1.82 | 1.691 |
| | | | | | | **0.01712** | | **46.232** | | **25.402** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (n | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium sheet** | Backpan | 1 | 0.57 | 0.5 | 0.003 | **0.00086** | 2700 | **2.309** | 1.82 | **1.268** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (n | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steel** | Spandrel sheet | 1 | 0.57 | 0.502 | 0.0015 | **0.00043** | 8000 | 3.434 | 1.82 | 1.887 |
| | Bracket | 1 | 0.320 | 0.270 | 0.01 | **0.00086** | 8000 | 6.912 | 1.82 | 3.798 |
| | | | | | | | | **10.346** | | **5.684** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **EPDM Gasket** | Gasket mullion cl | 4 | 3.2 | 12.800 | 0.00006 | 0.001 | 1600 | 1.229 | 1.82 | 0.675 |
| | Gasket mullion cl | 2 | 3.2 | 6.400 | 0.000012 | 0.000 | 1600 | 0.123 | 1.82 | 0.068 |
| | Gasket glass ext | 4 | 3.2 | 12.800 | 0.00007 | 0.001 | 1600 | 1.434 | 1.82 | 0.788 |
| | Gasket glass inte | 4 | 3.2 | 12.800 | 0.000133 | 0.002 | 1600 | 2.724 | 1.82 | 1.497 |
| | Gasket transom | 2 | 0.6 | 1.200 | 0.000197 | 0.000 | 1600 | 0.378 | 1.82 | 0.208 |
| | Gasket transom | 4 | 0.6 | 2.400 | 0.000012 | 0.000 | 1600 | 0.046 | 1.82 | 0.025 |
| | Gasket transom | 2 | 0.6 | 1.200 | 0.00007 | 0.000 | 1600 | 0.134 | 1.82 | 0.074 |
| | Gasket transom | 2 | 0.6 | 1.200 | 0.000133 | 0.000 | 1600 | 0.255 | 1.82 | 0.140 |
| | Gasket transom | 2 | 0.6 | 1.200 | 0.000062 | 0.000 | 1600 | 0.119 | 1.82 | 0.065 |
| | | | | | | **0.004** | | **6.442** | | **3.540** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Silicone** | Sealant | 1 | 1.820 | 1.820 | 0.001 | **0.002** | 1370 | **2.493** | 1.82 | **1.370** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (n | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Glass** | Spandrel panel | 1 | 0.447 | 0.505 | 0.02 | 0.005 | 2500 | 11.287 | 1.82 | 6.202 |
| | Vision panel | 1 | 2.563 | 0.505 | 0.016 | 0.021 | 2500 | 51.773 | 1.82 | 28.446 |
| | | | | | | **0.025** | | **63.059** | | **34.648** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (n | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral wool** | Spandrel panel ir | 2 | 0.500 | 0.500 | 0.040 | **0.020** | 70 | **1.400** | 1.82 | **0.769** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | nel dimension (n | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Polyamide** | Thermal break | 4 | 3.200 | 12.800 | 0.000074 | 0.000947 | 1370 | 1.298 | 1.82 | 0.713 |
| | | 4 | 0.57 | 2.280 | 0.000074 | 0.000169 | 1370 | 0.231 | 1.82 | 0.127 |
| | | | | | | **0.001116** | | **1.529** | | **0.840** |

# MCI Calculation - project: Bishopsgate , London

**Material volume and weight**

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium profile** | Mullion split Left | 1 | 3.90 | 3.90 | 0.001632 | 0.00636 | 2700 | 17.185 | 5.7 | 3.015 |
| | Mullion split Righ | 1 | 3.90 | 3.90 | 0.001637 | 0.00638 | 2700 | 17.238 | 5.7 | 3.024 |
| | Mullion closure | 1 | 3.90 | 3.90 | 0.000101 | 0.00039 | 2700 | 1.064 | 5.7 | 0.187 |
| | Mullion window | 2 | 3.20 | 6.40 | 0.000549 | 0.00351 | 2700 | 9.485 | 5.7 | 1.664 |
| | Transom top | 1 | 1.60 | 1.60 | 0.002101 | 0.00336 | 2700 | 9.075 | 5.7 | 1.592 |
| | Transom interme | 1 | 1.50 | 1.50 | 0.001124 | 0.00169 | 2700 | 4.554 | 5.7 | 0.799 |
| | Transom bottom | 1 | 1.60 | 1.60 | 0.002022 | 0.00324 | 2700 | 8.736 | 5.7 | 1.533 |
| | Transom window | 2 | 0.75 | 1.50 | 0.000549 | 0.00082 | 2700 | 2.223 | 5.7 | 0.390 |
| | Transom door | 1 | 0.20 | 0.20 | 0.000833 | 0.00017 | 2700 | 0.450 | 5.7 | 0.079 |
| | Transom blind | 1 | 1.50 | 1.50 | 0.000731 | 0.00110 | 2700 | 2.962 | 5.7 | 0.520 |
| | | | | | | **0.02703** | | **72.972** | | **12.802** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (r | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium sheet** | Backpan | 1 | 1.407 | 0.585 | 0.003 | **0.00247** | 2700 | **6.667** | 5.7 | **1.170** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (r | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steel** | Spandrel sheet | 1 | 1.480 | 0.620 | 0.002 | **0.001376** | 8000 | 11.011 | 5.7 | 1.932 |
| | Bracket | 1 | 0.340 | 0.230 | 0.015 | **0.001173** | 8000 | 9.384 | 5.7 | 1.646 |
| | | | | | | | | **20.395** | | **3.578** |

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| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **EPDM Gasket** | Gasket interlock | 1 | 4.100 | 4.100 | 0.000492 | 0.002 | 1600 | 3.228 | 5.7 | 0.566 |
| | Gasket mullion c | 2 | 4.100 | 8.200 | 0.000156 | 0.001 | 1600 | 2.047 | 5.7 | 0.359 |
| | Gasket mullion c | 6 | 4.100 | 24.600 | 0.000077 | 0.002 | 1600 | 3.031 | 5.7 | 0.532 |
| | Gasket mullion c | 1 | 4.100 | 4.100 | 0.000015 | 0.000 | 1600 | 0.098 | 5.7 | 0.017 |
| | Gasket mullion S | 2 | 4.000 | 8.000 | 0.000156 | 0.001 | 1600 | 1.997 | 5.7 | 0.350 |
| | Gasket window c | 2 | 3.350 | 6.700 | 0.000082 | 0.001 | 1600 | 0.879 | 5.7 | 0.154 |
| | Gasket SSG | 2 | 3.350 | 6.700 | 0.000070 | 0.000 | 1600 | 0.750 | 5.7 | 0.132 |
| | Gasket interlock | 1 | 1.800 | 1.800 | 0.000608 | 0.001 | 1600 | 1.751 | 5.7 | 0.307 |
| | Gasket transom | 1 | 1.800 | 1.800 | 0.000158 | 0.000 | 1600 | 0.455 | 5.7 | 0.080 |
| | Gasket transom | 2 | 1.800 | 3.600 | 0.000161 | 0.001 | 1600 | 0.927 | 5.7 | 0.163 |
| | Gasket transom | 2 | 1.700 | 3.400 | 0.000156 | 0.001 | 1600 | 0.849 | 5.7 | 0.149 |
| | Gasket transom | 2 | 1.410 | 2.820 | 0.000080 | 0.000 | 1600 | 0.361 | 5.7 | 0.063 |
| | Gasket transom | 2 | 1.400 | 2.800 | 0.000070 | 0.000 | 1600 | 0.314 | 5.7 | 0.055 |
| | | | | | | **0.010** | | **16.686** | | **2.927** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Silicone** | Sealant | 1 | 4.500 | 4.500 | 0.00100 | **0.005** | 1370 | **6.165** | 5.7 | **1.082** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (r | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Glass** | SGU | 1 | 3.74 | 1.44 | 0.01200 | 0.0646 | 2500 | 161.568 | 5.7 | 28.345 |
| | DGU | 1 | 3.055 | 1.4 | 0.01800 | 0.0770 | 2500 | 192.465 | 5.7 | 33.766 |
| | | | | | | **0.14161** | | **354.033** | | **62.111** |

| Material | Part | Amount | Length (m) | Width (m) | hickness (r | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral wool** | Spandrel panel ir | 1 | 1.420 | 0.380 | 0.12000 | **0.065** | 70 | **4.533** | 5.7 | **0.795** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | nsity (kg/r | Mass (kg) | el dimension | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Polyamide** | Thermal break | 4 | 3.80 | 15.200 | 0.00006 | 0.00091 | 1370 | 1.249 | 5.7 | 0.219 |
| | Thermal break | 4 | 1.50 | 6.000 | 0.00009 | 0.00054 | 1370 | 0.740 | 5.7 | 0.130 |
| | | | | | | **0.00145** | | **1.989** | | 0.349 |

# MCI Calculation - Type 1

**Material volume and weight**

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium profiles** | Mullion | 2 | 3.600 | 7.20 | 0.0016800 | 0.01210 | 2700 | 32.659 | 5.4 | 6.048 |
| | Mullion outer profile | 2 | 3.600 | 7.20 | 0.0004000 | 0.00288 | 2700 | 7.776 | 5.4 | 1.440 |
| | Window profile inside vert. | 2 | 2.500 | 5.00 | 0.0001940 | 0.00097 | 2700 | 2.619 | 5.4 | 0.485 |
| | Glazing bead vertical | 2 | 2.500 | 5.00 | 0.0001090 | 0.00055 | 2700 | 1.472 | 5.4 | 0.273 |
| | Window profile outside vert. | 2 | 2.500 | 5.00 | 0.0002820 | 0.00141 | 2700 | 3.807 | 5.4 | 0.705 |
| | Gasket cover | 1 | 3.6 | 3.6 | 0.00009 | 0.000324 | 2700 | 0.8748 | 5.4 | 0.162 |
| | Transom top | 1 | 1.390 | 1.39 | 0.0016980 | 0.00236 | 2700 | 6.373 | 5.4 | 1.180 |
| | Transom bottom | 1 | 1.390 | 1.39 | 0.0016090 | 0.00224 | 2700 | 6.039 | 5.4 | 1.118 |
| | Transom outer | 2 | 1.390 | 2.78 | 0.0004900 | 0.00136 | 2700 | 3.678 | 5.4 | 0.681 |
| | Window profile inside horiz. | 2 | 1.390 | 2.78 | 0.0001940 | 0.00054 | 2700 | 1.456 | 5.4 | 0.270 |
| | Glazing bead horizontal | 2 | 1.390 | 2.78 | 0.0001090 | 0.00030 | 2700 | 0.818 | 5.4 | 0.152 |
| | Window profile outs. horiz. | 2 | 1.390 | 2.78 | 0.0002820 | 0.00078 | 2700 | 2.117 | 5.4 | 0.392 |
| | | | | | | **0.02581** | | **69.688** | | **12.905** |

| Material | Part | Amount | | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium sheet** | Outer | 1 | | 2.76 | 0.003 | 0.00828 | 2700 | 22.356 | 5.4 | 4.140 |
| | Inner | 1 | | 1.231 | 0.002 | 0.00246 | 2700 | 6.647 | 5.4 | 1.231 |
| | | | | | | **0.01074** | | **29.003** | | **5.371** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steel** | Spandrel sheet bottom | 1 | 1.39 | 0.18 | 0.0015 | 0.00038 | 8000 | 3.002 | 5.4 | 0.556 |
| | Spandrel sheet inner | 1 | 1.480 | 0.200 | 0.0015 | 0.00044 | 8000 | 3.552 | 5.4 | 0.658 |
| | Bracket | 1 | 0.400 | 0.200 | 0.012 | 0.00096 | 8000 | 7.680 | 5.4 | 1.422 |
| | | | | | | **0.00178** | | **14.234** | | **2.636** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **EPDM Gasket** | Interlock mullion back | 1 | 3.600 | 3.600 | 0.000504 | 0.002 | 1600 | 2.903 | 5.4 | 0.538 |
| | Interlock mullion front | 1 | 3.600 | 3.600 | 0.000638 | 0.002 | 1600 | 3.675 | 5.4 | 0.681 |
| | Lips mullion front | 2 | 3.600 | 7.200 | 0.000100 | 0.001 | 1600 | 1.152 | 5.4 | 0.213 |
| | Mullion closure front | 2 | 3.600 | 7.200 | 0.000046 | 0.000 | 1600 | 0.530 | 5.4 | 0.098 |
| | Mullion closure sandwich | 2 | 3.500 | 7.000 | 0.000027 | 0.000 | 1600 | 0.302 | 5.4 | 0.056 |
| | Glazing outer vertical | 2 | 2.400 | 4.800 | 0.000051 | 0.000 | 1600 | 0.392 | 5.4 | 0.073 |
| | Glazing inner vertical | 2 | 2.400 | 4.800 | 0.000056 | 0.000 | 1600 | 0.430 | 5.4 | 0.080 |
| | Interlock transom back | 1 | 1.500 | 1.500 | 0.000483 | 0.001 | 1600 | 1.159 | 5.4 | 0.215 |
| | Interlock transom front | 1 | 1.500 | 1.500 | 0.000595 | 0.001 | 1600 | 1.428 | 5.4 | 0.264 |
| | Transom closure front | 2 | 1.500 | 3.000 | 0.000480 | 0.001 | 1600 | 2.304 | 5.4 | 0.427 |
| | Transom closure sandwich | 2 | 1.500 | 3.000 | 0.000046 | 0.000 | 1600 | 0.221 | 5.4 | 0.041 |
| | Glazing outer horizontal | 2 | 1.100 | 2.200 | 0.000051 | 0.000 | 1600 | 0.180 | 5.4 | 0.033 |
| | Glazing innner horrizontal | 2 | 1.100 | 2.200 | 0.000056 | 0.000 | 1600 | 0.197 | 5.4 | 0.037 |
| | Slab connection | 1 | 1.500 | 1.500 | 0.000055 | 0.000 | 1600 | 0.132 | 5.4 | 0.024 |
| | | | | | | **0.009** | | **15.005** | | **2.779** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Silicone** | Sealant | 1 | 1.700 | 1.700 | 0.001 | **0.002** | 1370 | **2.329** | 5.4 | **0.431** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Glass** | DGU | 1 | 2.425 | 1.125 | 0.02 | **0.05456** | 2500 | **136.406** | 5.4 | **25.260** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral wool** | Sandwich panel | 1 | 1 | 1.91051 | 0.1 | 0.191051 | 70 | 13.37357 | 5.4 | 2.476587 |
| | | 1 | 1.400 | 0.160 | 0.120 | 0.027 | 70 | 1.882 | 5.4 | 0.348 |
| | | | | | | **0.218** | | **15.255** | | **2.825** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Polyamide** | Thermal break mullion | 2 | 3.600 | 7.200 | 0.000477 | 0.003434 | 1370 | 4.705 | 5.4 | 0.871 |
| | Thermal break transom | 2 | 1.500 | 3.000 | 0.000513 | 0.001539 | 1370 | 2.108 | 5.4 | 0.390 |
| | Thermal break window vert. | 2 | 2.500 | 5.000 | 0.000310 | 0.001550 | 1370 | 2.124 | 5.4 | 0.393 |
| | Thermal break window horiz. | 2 | 1.200 | 2.400 | 0.000310 | 0.000744 | 1370 | 1.019 | 5.4 | 0.189 |
| | | | | | | **0.007267** | | **9.956** | | **1.844** |

# MCI Calculation - Type 2

**Material volume and weight**

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium profiles** | Mullion adapter | 2 | 3.600 | 7.20 | 0.000432 | 0.003 | 2700 | 8.398 | 5.4 | 1.555 |
| | Mullion cover | 2 | 3.600 | 7.20 | 0.000281 | 0.002 | 2700 | 5.463 | 5.4 | 1.012 |
| | Transom adaptor 1 | 2 | 1.390 | 2.78 | 0.000481 | 0.001 | 2700 | 3.610 | 5.4 | 0.669 |
| | Transom adaptor 2 | 2 | 1.390 | 2.78 | 0.000595 | 0.002 | 2700 | 4.466 | 5.4 | 0.827 |
| | Transom cover 1 | 2 | 1.390 | 2.78 | 0.000309 | 0.001 | 2700 | 2.319 | 5.4 | 0.430 |
| | Transom cover 2 | 1 | 1.390 | 1.39 | 0.000465 | 0.001 | 2700 | 1.745 | 5.4 | 0.323 |
| | | | | | | **0.010** | | **26.002** | | **4.815** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aluminium sheet** | Spandrel sheet outer 1 | 1 | 1.418 | 0.578 | 0.003 | 0.002 | 2700 | 6.639 | 5.4 | 1.229 |
| | Spandrel sheet outer 2 | 1 | 1.418 | 0.905 | 0.002 | 0.003 | 2700 | 6.930 | 5.4 | 1.283 |
| | | | | | | **0.005** | | **13.569** | | **2.513** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steel for Reuse** | Mullion cornerpiece | 4 | 0.260 | 1.04 | 0.000868 | 0.00090 | 8000 | 7.222 | 5.4 | 1.337 |
| | Transom cornerpiece | 4 | 0.200 | 0.8 | 0.000869 | 0.00056 | 8000 | 4.449 | 5.4 | 0.824 |
| | | | | | | 0.00146 | | **11.671** | | **2.161** |

| **Steel for Recycle** | | Amount | Length (m) | Width (m) | Thickness (m) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sandwich cassette lower | 1 | 0.797 | 1.636 | 0.0015 | 0.00196 | 8000 | 15.647 | 5.4 | 2.898 |
| | Sandwich cover lower | 1 | 0.555 | 1.39 | 0.0015 | 0.00116 | 8000 | 9.257 | 5.4 | 1.714 |
| | Sandwich cassette upper | 1 | 1.126 | 1.636 | 0.0015 | 0.00276 | 8000 | 22.106 | 5.4 | 4.094 |
| | Sandwich cover upper | 1 | 0.880 | 1.390 | 0.0015 | 0.00183 | 8000 | 14.678 | 5.4 | 2.718 |
| | Sandwich cassette slab | 1 | 0.114 | 1.562 | 0.0015 | 0.00027 | 8000 | 2.137 | 5.4 | 0.396 |
| | Sandwich cover slab | 1 | 0.164 | 1.390 | 0.0015 | 0.00034 | 8000 | 2.736 | 5.4 | 0.507 |
| | Bracket | 1 | 0.400 | 0.200 | 0.0015 | 0.00012 | 8000 | 0.960 | 5.4 | 0.178 |
| | | | | | | **0.008** | | **67.520** | | **12.504** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **EPDM Gasket** | Interlock mullion back | 1 | 3.600 | 3.600 | 0.000638 | 0.002 | 1600 | 3.675 | 5.4 | 0.681 |
| | Interlock mullion front | 1 | 3.600 | 3.600 | 0.000638 | 0.002 | 1600 | 3.675 | 5.4 | 0.681 |
| | Lips mullion front | 2 | 3.600 | 7.200 | 0.000100 | 0.001 | 1600 | 1.152 | 5.4 | 0.213 |
| | Closure mullion front | 2 | 3.600 | 7.200 | 0.000047 | 0.000 | 1600 | 0.541 | 5.4 | 0.100 |
| | Interlock transom back | 1 | 1.500 | 1.500 | 0.000484 | 0.001 | 1600 | 1.162 | 5.4 | 0.215 |
| | Interlock transom front | 1 | 1.500 | 1.500 | 0.000595 | 0.001 | 1600 | 1.428 | 5.4 | 0.264 |
| | Lips transom front | 2 | 1.500 | 3.000 | 0.000100 | 0.000 | 1600 | 0.480 | 5.4 | 0.089 |
| | Closure transom front | 2 | 1.500 | 3.000 | 0.000047 | 0.000 | 1600 | 0.226 | 5.4 | 0.042 |
| | Glazing outer horizontal | 2 | 1.410 | 2.820 | 0.000039 | 0.000 | 1600 | 0.176 | 5.4 | 0.033 |
| | Glazing inner horizontal | 2 | 1.410 | 2.820 | 0.000039 | 0.000 | 1600 | 0.176 | 5.4 | 0.033 |
| | Glazing outer vertical | 2 | 1.915 | 3.830 | 0.000039 | 0.000 | 1600 | 0.239 | 5.4 | 0.044 |
| | Glazing inner vertical | 2 | 1.915 | 3.830 | 0.000039 | 0.000 | 1600 | 0.239 | 5.4 | 0.044 |
| | Spandrel outer horizontal | 4 | 1.410 | 5.640 | 0.000039 | 0.000 | 1600 | 0.352 | 5.4 | 0.065 |
| | Spandrel inner horizontal | 4 | 1.410 | 5.640 | 0.000039 | 0.000 | 1600 | 0.352 | 5.4 | 0.065 |
| | Spandrel outer vertical | 2 | 1.456 | 2.912 | 0.000039 | 0.000 | 1600 | 0.182 | 5.4 | 0.034 |
| | Spandrel inner vertical | 2 | 1.456 | 2.912 | 0.000039 | 0.000 | 1600 | 0.182 | 5.4 | 0.034 |
| | Slab connection | 1 | 1.500 | 1.500 | 0.000040 | 0.000 | 1600 | 0.096 | 5.4 | 0.018 |
| | | | | | | **0.009** | | **14.332** | | **2.654** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Silicone** | Sealant | 1 | 1.700 | 1.700 | 0.001 | **0.002** | 1370 | **2.329** | 5.4 | **0.431** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Glass** | DGU | 1 | 1.93 | 1.415 | 0.02 | **0.055** | 2500 | **136.548** | 5.4 | **25.287** |

| Material | Part | Amount | Length (m) | Width (m) | Thickness (m) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral wool** | Sandwich panel upper | 1 | 1.390 | 0.876 | 0.097 | 0.118 | 70 | 8.268 | 5.4 | 1.531 |
| | Sandwich panel lower | 1 | 1.390 | 0.552 | 0.097 | 0.074 | 70 | 5.210 | 5.4 | 0.965 |
| | Sandwich panel slab | 1 | 1.390 | 0.160 | 0.060 | 0.013 | 70 | 0.934 | 5.4 | 0.173 |
| | | | | | | **0.206** | | **14.412** | | **2.669** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Polyamide** | Thermal break mullion | 2 | 3.600 | 7.200 | 0.000501 | 0.004 | 1370 | 4.942 | 5.4 | 0.915 |
| | Thermal break transom 1 | 2 | 1.428 | 2.856 | 0.000539 | 0.002 | 1370 | 2.109 | 5.4 | 0.391 |
| | Thermal break transom 2 | 2 | 1.428 | 2.856 | 0.000555 | 0.002 | 1370 | 2.172 | 5.4 | 0.402 |
| | Separation plate mullion | 2 | 3.600 | 7.200 | 0.000050 | 0.000 | 1370 | 0.493 | 5.4 | 0.091 |
| | Sepration plate transom | 4 | 1.390 | 5.560 | 0.000050 | 0.000 | 1370 | 0.381 | 5.4 | 0.071 |
| | | | | | | **0.007** | | **10.096** | | **1.870** |

| Material | Part | Amount | Length (m) | Total length (m) | Area (m2) | Volume (m3) | Density (kg/m3) | Mass (kg) | Panel dimension (m2) | kg/m2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Timber** | Mullion | 2 | 3.343 | 6.686 | 0.006503 | 0.043 | 450 | 19.566 | 5.4 | 3.623255 |
| | Transom 1 | 2 | 1.390 | 2.780 | 0.007877 | 0.022 | 450 | 9.854 | 5.4 | 1.824838 |
| | Transom 2 | 2 | 1.390 | 2.780 | 0.008919 | 0.025 | 450 | 11.158 | 5.4 | 2.066235 |
| | | | | | | **0.090** | | **40.577** | | **7.514** |

# MCI Calculation - project: Lime Street , London

**Feedstock, Waste, LFI and MVI value**

## Original Calculation

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.015 | 2700 | 40.500 | 5.89 | 6.876 | 10.4% |
| Steel | 0.004 | 8000 | 32.000 | 5.89 | 5.433 | 8.2% |
| Gaskets | 0.011 | 1600 | 17.600 | 5.89 | 2.988 | 4.5% |
| Insulation | 0.056 | 70 | 3.920 | 5.89 | 0.666 | 1.0% |
| Sealing | 0.007 | 1370 | 9.316 | 5.89 | 1.582 | 2.4% |
| Glazing | 0.114 | 2500 | 285.775 | 5.89 | 48.519 | 73.4% |
| Isolator | 0.000 | 1300 | 0.094 | 5.89 | 0.016 | 0.0% |
| | | | **389.205** | | **66.079** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0 | 3.438 |
| Steel | Technical | 0.008 | 0 | 5.389 |
| Gaskets | Technical | 0 | 0 | 2.988 |
| Insulation | Technical | 0.02 | 0 | 0.652 |
| Sealing | Technical | 0 | 0 | 1.582 |
| Glazing | Technical | 0.053 | 0 | 45.947 |
| Isolator | Technical | 0 | 0 | 0.016 |
| | | | | **60.013** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | 1 | 0 | 0.000 |
| Insulation | 0 | 0 | 0.666 |
| Sealing | 1 | 0 | 0.000 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | 1 | 0 | 0.000 |
| | | | **0.666** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 0.756 |
| Steel | 1 | 0.93 | 0.380 |
| Gaskets | 1 | **0.95** | 0.149 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **0.95** | 0.079 |
| Glazing | 1 | 0.9 | 4.852 |
| Isolator | 1 | **0.95** | 0.001 |
| | | | **6.218** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.070 |
| Steel | 0.92 | 0.05 | 0.024 |
| Gaskets | **0** | **0** | 0.000 |
| Insulation | **0** | **0.02** | 0.000 |
| Sealing | **0** | **0** | 0.000 |
| Glazing | 0.83 | 0.053 | 0.527 |
| Isolator | **0** | **0** | 0.000 |
| | | | **0.620** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Total unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 0.756 | 0.070 | 0.413 |
| Steel | 0.000 | 0.380 | 0.024 | 0.202 |
| Gaskets | 0.000 | 0.149 | 0.000 | 0.075 |
| Insulation | 0.666 | 0.000 | 0.000 | 0.666 |
| Sealing | 0.000 | 0.079 | 0.000 | 0.040 |
| Glazing | 0.000 | 4.852 | 0.527 | 2.689 |
| Isolator | 0.000 | 0.001 | 0.000 | 0.000 |
| | | | | **4.085** |

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | **0.78** |
| Steel | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Gaskets | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | **0.26** |
| Sealing | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | **0.62** |
| Isolator | 0.52 | 30 | 1.20 | 0.75 | **0.61** |
| | | | | Total MCI | **0.63** |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: One Crown Place , London

**Feedstock, Waste, LFI and MVI value**

## Original Calculation

| **Step 1: Calculation of material masses** | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.018 | 2700 | 48.600 | 1.82 | 26.703 | 36.5% |
| Steel | 0.001 | 8000 | 9.600 | 1.82 | 5.275 | 7.2% |
| Gaskets | 0.004 | 1600 | 6.442 | 1.82 | 3.540 | 4.8% |
| Insulation | 0.020 | 70 | 1.400 | 1.82 | 0.769 | 1.1% |
| Sealing | 0.002 | 1370 | 2.493 | 1.82 | 1.370 | 1.9% |
| Glazing | 0.025 | 2500 | 63.059 | 1.82 | 34.648 | 47.4% |
| Isolator | 0.001 | 1300 | 1.451 | 1.82 | 0.797 | 1.1% |
| | | | 133.046 | | **73.102** | |

| **Step 2: Calculation of Virgin Feedstock** | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0% | 13.352 |
| Steel | Technical | 0.008 | 0% | 5.233 |
| Gaskets | Technical | 0 | 0% | 3.540 |
| Insulation | Technical | 0.02 | 0% | 0.754 |
| Sealing | Technical | 0 | 0% | 1.370 |
| Glazing | Technical | 0.053 | 0% | 32.812 |
| Isolator | Technical | 0 | 0% | 0.797 |
| | | | | **57.856** |

| **Step 3.1: Calculation of waste going to landfill or incineration W0** | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling CR | Fraction collected for Reuse CU | Unrecoverable Waste W0 for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | 1 | 0 | 0.000 |
| Insulation | 0 | 0 | 0.769 |
| Sealing | 1 | 0 | 0.000 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | 1 | 0 | 0.000 |
| | | | **0.769** |

| **Step 3.2: Calculation of waste generated during recycling Wc** | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling CR | Efficency of recycling process EC | Unrecoverable Waste WC for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 2.937 |
| Steel | 1 | 0.93 | 0.369 |
| Gaskets | 1 | **0.95** | 0.177 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **0.95** | 0.069 |
| Glazing | 1 | 0.9 | 3.465 |
| Isolator | 1 | **0.95** | 0.040 |
| | | | **7.057** |

| **Step 3.3: Calculation of waste generated for feedstock production Wf** | | | |
|---|---|---|---|
| Material | Efficency of recycling process EF for feedstock | Fraction of feedstock from recycling FR | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.272 |
| Steel | 0.92 | 0.05 | 0.023 |
| Gaskets | **0** | **0** | 0.000 |
| Insulation | **0** | **0.02** | 0.000 |
| Sealing | **0** | **0** | 0.000 |
| Glazing | 0.83 | 0.053 | 0.376 |
| Isolator | **0** | **0** | 0.000 |
| | | | **0.672** |

| **Step 3.4: Calculation of overall amount of unrecoverable waste W** | | | | |
|---|---|---|---|---|
| Material | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | waste generated for feedstock production Wf | Unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 2.937 | 0.272 | 1.605 |
| Steel | 0.000 | 0.369 | 0.023 | 0.196 |
| Gaskets | 0.000 | 0.177 | 0.000 | 0.088 |
| Insulation | 0.769 | 0.000 | 0.000 | 0.769 |
| Sealing | 0.000 | 0.069 | 0.000 | 0.034 |
| Glazing | 0.000 | 3.465 | 0.376 | 1.920 |
| Isolator | 0.000 | 0.040 | 0.000 | 0.020 |
| | | | | **4.633** |

| **Step 4: Calculation of MCI-value** | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| | | | | **Total MCI** | **0.67** |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: Bishopsgate , London

**Feedstock, Waste, LFI and MVI value - Original calculation**

## Original Calculation

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.029 | 2700 | 78.300 | 5.70 | 13.737 | 16.1% |
| Steel | 0.003 | 8000 | 24.000 | 5.70 | 4.211 | 4.9% |
| Gaskets | 0.010 | 1600 | 16.686 | 5.70 | 2.927 | 3.4% |
| Insulation | 0.065 | 70 | 4.533 | 5.70 | 0.795 | 0.9% |
| Sealing | 0.005 | 1370 | 6.165 | 5.70 | 1.082 | 1.3% |
| Glazing | 0.142 | 2500 | 354.033 | 5.70 | 62.111 | **72.9%** |
| Isolator | 0.001 | 1300 | 1.888 | 5.70 | 0.331 | 0.4% |
| | | | 485.604 | | **85.194** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0% | 6.868 |
| Steel | Technical | 0.008 | 0% | 4.177 |
| Gaskets | Technical | 0 | 0% | 2.927 |
| Insulation | Technical | 0.02 | 0% | 0.779 |
| Sealing | Technical | 0 | 0% | 1.082 |
| Glazing | Technical | 0.053 | 0% | 58.819 |
| Isolator | Technical | 0 | 0% | 0.331 |
| | | | | **74.984** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | 1 | 0 | 0.000 |
| Insulation | 0 | 0 | 0.795 |
| Sealing | 1 | 0 | 0.000 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | 1 | 0 | 0.000 |
| | | | **0.795** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 1.511 |
| Steel | 1 | 0.93 | 0.295 |
| Gaskets | 1 | **0.95** | 0.146 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **0.95** | 0.054 |
| Glazing | 1 | 0.9 | 6.211 |
| Isolator | 1 | **0.95** | 0.017 |
| | | | **8.234** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.140 |
| Steel | 0.92 | 0.05 | 0.018 |
| Gaskets | **0** | **0** | 0.000 |
| Insulation | **0** | **0.02** | 0.000 |
| Sealing | **0** | **0** | 0.000 |
| Glazing | 0.83 | 0.053 | 0.674 |
| Isolator | **0** | **0** | 0.000 |
| | | | **0.833** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| Material | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 1.511 | 0.140 | 0.826 |
| Steel | 0.000 | 0.295 | 0.018 | 0.157 |
| Gaskets | 0.000 | 0.146 | 0.000 | 0.073 |
| Insulation | 0.795 | 0.000 | 0.000 | 0.795 |
| Sealing | 0.000 | 0.054 | 0.000 | 0.027 |
| Glazing | 0.000 | 6.211 | 0.674 | 3.443 |
| Isolator | 0.000 | 0.017 | 0.000 | 0.008 |
| | | | | **5.329** |

| Step 4: Calculation of MCI-value | | | | | | |
|---|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value | |
| Aluminium | 0.29 | 50 | 2.00 | 0.45 | 0.87 | |
| Steel | 0.52 | 50 | 2.00 | 0.45 | 0.76 | |
| Gaskets | 0.52 | 25 | 1.00 | 0.90 | 0.53 | replacement after 25 years |
| Insulation | 0.99 | 50 | 2.00 | 0.45 | 0.55 | |
| Sealing | 0.52 | 50 | 2.00 | 0.45 | 0.77 | |
| Glazing | 0.51 | 50 | 2.00 | 0.45 | 0.77 | |
| Isolator | 0.52 | 50 | 2.00 | 0.45 | 0.77 | |
| | | | | Total MCI | 0.78 | |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: Lime Street , London

**Feedstock, Waste, LFI and MVI value**

## Amended Waste Flow

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.015 | 2700 | 40.500 | 5.89 | 6.876 | 10.4% |
| Steel | 0.004 | 8000 | 32.000 | 5.89 | 5.433 | 8.2% |
| Gaskets | 0.011 | 1600 | 17.600 | 5.89 | 2.988 | 4.5% |
| Insulation | 0.056 | 70 | 3.920 | 5.89 | 0.666 | 1.0% |
| Sealing | 0.007 | 1370 | 9.316 | 5.89 | 1.582 | 2.4% |
| Glazing | 0.114 | 2500 | 285.775 | 5.89 | 48.519 | 73.4% |
| Isolator | 0.000 | 1300 | 0.094 | 5.89 | 0.016 | 0.0% |
| | | | **389.205** | | **66.079** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0 | 3.438 |
| Steel | Technical | 0.008 | 0 | 5.389 |
| Gaskets | Technical | 0 | 0 | 2.988 |
| Insulation | Technical | 0.02 | 0 | 0.652 |
| Sealing | Technical | 0 | 0 | 1.582 |
| Glazing | Technical | 0.053 | 0 | 45.947 |
| Isolator | Technical | 0 | 0 | 0.016 |
| | | | | **60.013** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | **0** | **0** | 2.988 |
| Insulation | 0 | 0 | 0.666 |
| Sealing | **0** | **0** | 1.582 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | **0** | **0** | 0.016 |
| | | | **5.251** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 0.756 |
| Steel | 1 | 0.93 | 0.380 |
| Gaskets | 1 | **1** | 0.000 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **1** | 0.000 |
| Glazing | 1 | 0.9 | 4.852 |
| Isolator | 1 | **1** | 0.000 |
| | | | **5.989** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.070 |
| Steel | 0.92 | 0.05 | 0.024 |
| Gaskets | **1** | **1** | 0.000 |
| Insulation | **1** | **0.02** | 0.000 |
| Sealing | **1** | **1** | 0.000 |
| Glazing | 0.83 | 0.053 | 0.527 |
| Isolator | **1** | **1** | 0.000 |
| | | | **0.620** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Total unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 0.756 | 0.070 | 0.413 |
| Steel | 0.000 | 0.380 | 0.024 | 0.202 |
| Gaskets | 2.988 | 0.000 | 0.000 | 2.988 |
| Insulation | 0.666 | 0.000 | 0.000 | 0.666 |
| Sealing | 1.582 | 0.000 | 0.000 | 1.582 |
| Glazing | 0.000 | 4.852 | 0.527 | 2.689 |
| Isolator | 0.016 | 0.000 | 0.000 | 0.016 |
| | | | | **8.556** |

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | **Total MCI** | **0.60** |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: One Crown Place , London

**Feedstock, Waste, LFI and MVI value**

## Amended Waste Flow

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.018 | 2700 | 48.600 | 1.82 | 26.703 | 36.5% |
| Steel | 0.001 | 8000 | 9.600 | 1.82 | 5.275 | 7.2% |
| Gaskets | 0.004 | 1600 | 6.442 | 1.82 | 3.540 | 4.8% |
| Insulation | 0.020 | 70 | 1.400 | 1.82 | 0.769 | 1.1% |
| Sealing | 0.002 | 1370 | 2.493 | 1.82 | 1.370 | 1.9% |
| Glazing | 0.025 | 2500 | 63.059 | 1.82 | 34.648 | 47.4% |
| Isolator | 0.001 | 1300 | 1.451 | 1.82 | 0.797 | 1.1% |
| | | | 133.046 | | **73.102** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0% | 13.352 |
| Steel | Technical | 0.008 | 0% | 5.233 |
| Gaskets | Technical | 0 | 0% | 3.540 |
| Insulation | Technical | 0.02 | 0% | 0.754 |
| Sealing | Technical | 0 | 0% | 1.370 |
| Glazing | Technical | 0.053 | 0% | 32.812 |
| Isolator | Technical | 0 | 0% | 0.797 |
| | | | | **57.856** |

| Step 3.1: Calculation of waste going to landfill or incineration W0 | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling CR | Fraction collected for Reuse CU | Unrecoverable Waste W0 for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | 0 | 0 | 3.540 |
| Insulation | 0 | 0 | 0.769 |
| Sealing | 0 | 0 | 1.370 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | 0 | 0 | 0.797 |
| | | | **6.476** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling CR | Efficency of recycling process EC | Unrecoverable Waste WC for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 2.937 |
| Steel | 1 | 0.93 | 0.369 |
| Gaskets | 1 | 1 | 0.000 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | 1 | 0.000 |
| Glazing | 1 | 0.9 | 3.465 |
| Isolator | 1 | 1 | 0.000 |
| | | | **6.771** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process EF for feedstock | Fraction of feedstock from recycling FR | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.272 |
| Steel | 0.92 | 0.05 | 0.023 |
| Gaskets | 1 | 1 | 0.000 |
| Insulation | 1 | 0.02 | 0.000 |
| Sealing | 1 | 1 | 0.000 |
| Glazing | 0.83 | 0.053 | 0.376 |
| Isolator | 1 | 1 | 0.000 |
| | | | **0.672** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| Material | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | waste generated for feedstock production Wf | Unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 2.937 | 0.272 | 1.605 |
| Steel | 0.000 | 0.369 | 0.023 | 0.196 |
| Gaskets | 3.540 | 0.000 | 0.000 | 3.540 |
| Insulation | 0.769 | 0.000 | 0.000 | 0.769 |
| Sealing | 1.370 | 0.000 | 0.000 | 1.370 |
| Glazing | 0.000 | 3.465 | 0.376 | 1.920 |
| Isolator | 0.797 | 0.000 | 0.000 | 0.797 |
| | | | | **10.197** |

| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.29 | 30 | 1.20 | 0.75 | 0.78 |
| Steel | 0.52 | 30 | 1.20 | 0.75 | 0.61 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.99 | 30 | 1.20 | 0.75 | 0.26 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| | | | | **Total MCI** | **0.64** |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: Bishopsgate , London

**Feedstock, Waste, LFI and MVI value**

## Amended Waste Flow

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.029 | 2700 | 78.300 | 5.70 | 13.737 | 16.1% |
| Steel | 0.003 | 8000 | 24.000 | 5.70 | 4.211 | 4.9% |
| Gaskets | 0.010 | 1600 | 16.686 | 5.70 | 2.927 | 3.4% |
| Insulation | 0.065 | 70 | 4.533 | 5.70 | 0.795 | 0.9% |
| Sealing | 0.005 | 1370 | 6.165 | 5.70 | 1.082 | 1.3% |
| Glazing | 0.142 | 2500 | 354.033 | 5.70 | 62.111 | **72.9%** |
| Isolator | 0.001 | 1300 | 1.888 | 5.70 | 0.331 | 0.4% |
| | | | 485.604 | | **85.194** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | 0.5 | 0% | 6.868 |
| Steel | Technical | 0.008 | 0% | 4.177 |
| Gaskets | Technical | 0 | 0% | 2.927 |
| Insulation | Technical | 0.02 | 0% | 0.779 |
| Sealing | Technical | 0 | 0% | 1.082 |
| Glazing | Technical | 0.053 | 0% | 58.819 |
| Isolator | Technical | 0 | 0% | 0.331 |
| | | | | **74.984** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | **0** | **0** | 2.927 |
| Insulation | 0 | 0 | 0.795 |
| Sealing | **0** | **0** | 1.082 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | **0** | **0** | 0.331 |
| | | | **5.135** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 1.511 |
| Steel | 1 | 0.93 | 0.295 |
| Gaskets | 1 | **1** | 0.000 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **1** | 0.000 |
| Glazing | 1 | 0.9 | 6.211 |
| Isolator | 1 | **1** | 0.000 |
| | | | **8.017** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | 0.5 | 0.140 |
| Steel | 0.92 | 0.05 | 0.018 |
| Gaskets | **1** | **1** | 0.000 |
| Insulation | **1** | **0.02** | 0.000 |
| Sealing | **1** | **1** | 0.000 |
| Glazing | 0.83 | 0.053 | 0.674 |
| Isolator | **1** | **1** | 0.000 |
| | | | **0.833** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| Material | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 1.511 | 0.140 | 0.826 |
| Steel | 0.000 | 0.295 | 0.018 | 0.157 |
| Gaskets | 2.927 | 0.000 | 0.000 | 2.927 |
| Insulation | 0.795 | 0.000 | 0.000 | 0.795 |
| Sealing | 1.082 | 0.000 | 0.000 | 1.082 |
| Glazing | 0.000 | 6.211 | 0.674 | 3.443 |
| Isolator | 0.331 | 0.000 | 0.000 | 0.331 |
| | | | | **9.560** |

| Step 4: Calculation of MCI-value | | | | | | |
|---|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value | |
| Aluminium | 0.29 | 50 | 2.00 | 0.45 | 0.87 | |
| Steel | 0.52 | 50 | 2.00 | 0.45 | 0.76 | |
| Gaskets | 1.00 | 25 | 1.00 | 0.90 | 0.10 | replacement after 25 years |
| Insulation | 0.99 | 50 | 2.00 | 0.45 | 0.55 | |
| Sealing | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| Glazing | 0.51 | 50 | 2.00 | 0.45 | 0.77 | |
| Isolator | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| | | | | **Total MCI** | **0.76** | |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - project: Type 1

**Feedstock, Waste, LFI and MCI value**

## Amended Waste Flow

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.037 | 2700 | 98.691 | 5.4 | 18.276 | 33.9% |
| Steel | 0.002 | 8000 | 14.234 | 5.4 | 2.636 | 4.9% |
| Gaskets | 0.009 | 1600 | 15.005 | 5.4 | 2.779 | 5.1% |
| Insulation | 0.218 | 70 | 15.255 | 5.4 | 2.825 | 5.2% |
| Sealing | 0.002 | 1370 | 2.329 | 5.4 | 0.431 | 0.8% |
| Glazing | 0.055 | 2500 | 136.406 | 5.4 | 25.260 | 46.8% |
| Isolator | 0.007 | 1300 | 9.448 | 5.4 | 1.750 | 3.2% |
| | | | **291.368** | | **53.957** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | **0.75** | 0 | 4.569 |
| Steel | Technical | **0.713** | 0 | 0.757 |
| Gaskets | Technical | 0 | 0 | 2.779 |
| Insulation | Technical | **0.4** | 0 | 1.695 |
| Sealing | Technical | 0 | 0 | 0.431 |
| Glazing | Technical | 0.053 | 0 | 23.922 |
| Isolator | Technical | **1** | 0 | 0.000 |
| | | | | **34.152** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel | 1 | 0 | 0.000 |
| Gaskets | **0** | **0** | 2.779 |
| Insulation | 0 | 0 | 2.825 |
| Sealing | **0** | **0** | 0.431 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | **0** | **0** | 1.750 |
| | | | **7.785** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 2.010 |
| Steel | 1 | 0.93 | 0.185 |
| Gaskets | 1 | **1** | 0.000 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | **1** | 0.000 |
| Glazing | 1 | 0.9 | 2.526 |
| Isolator | 1 | **1** | 0.000 |
| | | | **4.721** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | **0.75** | 0.280 |
| Steel | 0.92 | **0.713** | 0.163 |
| Gaskets | **1** | 0 | 0.000 |
| Insulation | **1** | **0.4** | 0.000 |
| Sealing | **1** | 0 | 0.000 |
| Glazing | 0.83 | 0.053 | 0.274 |
| Isolator | **1** | **1** | 0.000 |
| | | | **0.717** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Total unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 2.010 | 0.280 | 1.145 |
| Steel | 0.000 | 0.185 | 0.163 | 0.174 |
| Gaskets | 2.779 | 0.000 | 0.000 | 2.779 |
| Insulation | 2.825 | 0.000 | 0.000 | 2.825 |
| Sealing | 0.431 | 0.000 | 0.000 | 0.431 |
| Glazing | 0.000 | 2.526 | 0.274 | 1.400 |
| Isolator | 1.750 | 0.000 | 0.000 | 1.750 |
| | | | | **10.504** |

| Step 4: Calculation of MCI-value | | | | | | |
|---|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value | |
| Aluminium | 0.16 | 50 | 2.00 | 0.45 | 0.93 | |
| Steel | 0.18 | 50 | 2.00 | 0.45 | 0.92 | |
| Gaskets | 1.00 | 50 | 2.00 | 0.45 | 0.55 | **1x replacement** |
| Insulation | 0.80 | 50 | 2.00 | 0.45 | 0.64 | |
| Sealing | 1.00 | 50 | 2.00 | 0.45 | 0.55 | |
| Glazing | 0.51 | 50 | 2.00 | 0.45 | 0.77 | **1x replacement** |
| Isolator | 0.50 | 50 | 2.00 | 0.45 | 0.78 | |
| | | | | **Total MCI** | **0.81** | |

**0 = complete linear product**
**1 = complete circular product**

# MCI Calculation - Type 2

**Feedstock, Waste, LFI and MCI value**

## Amended Waste Flow

| Step 1: Calculation of material masses | | | | | | |
|---|---|---|---|---|---|---|
| Material | Volume (m3) | Density (kg/m3) | Mass (kg) | Unit area (m2) | Total (kg/m2) | % |
| Aluminium | 0.01466 | 2700 | 39.570 | 5.4 | 7.328 | 16.3% |
| Steel for Reuse | 0.00146 | 8000 | 11.671 | 5.4 | 2.161 | 4.8% |
| Steel for Recycle | 0.00174 | 8000 | 13.896 | 5.4 | 2.573 | 5.7% |
| Gaskets | 0.00896 | 1600 | 14.332 | 5.4 | 2.654 | 5.9% |
| Insulation | 0.20588 | 70 | 14.412 | 5.4 | 2.669 | 5.9% |
| Sealing | 0.00170 | 1370 | 2.329 | 5.4 | 0.431 | 1.0% |
| Glazing | 0.05462 | 2500 | 136.548 | 5.4 | 25.287 | 56.3% |
| Isolator | 0.00737 | 1300 | 9.581 | 5.4 | 1.774 | 4.0% |
| Timber | 0.09017 | 450 | 40.577 | 5.4 | 7.514 | 16.7% |
| | | | **242.338** | | **44.877** | |

| Step 2: Calculation of Virgin Feedstock | | | | |
|---|---|---|---|---|
| Material | Cycle | Recycled Feedstock Fr | Reused Feedstock | Virgin Material (kg) |
| Aluminium | Technical | **0.75** | 0 | 1.832 |
| Steel for Reuse | Technical | **0.713** | 0 | 0.620 |
| Steel for Recycle | Technical | **0.713** | 0 | 0.739 |
| Gaskets | Technical | 0 | 0 | 2.654 |
| Insulation | Technical | **0.4** | 0 | 1.601 |
| Sealing | Technical | 0 | 0 | 0.431 |
| Glazing | Technical | 0.053 | 0 | 23.946 |
| Isolator | Technical | 1 | 0 | 0.000 |
| Timber | Biological | 0 | 0 | 7.514 |
| | | | | **31.824** |

| Step 3.1: Calculation of waste going to landfill or incineration Wo | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Fraction collected for Reuse Cu | Unrecoverable Waste Wo for Landfill or Incineration (kg) |
| Aluminium | 1 | 0 | 0.000 |
| Steel for Reuse | 0 | 1 | 0.000 |
| Steel for Recycle | 1 | 0 | 0.000 |
| Gaskets | 0 | 0 | 2.654 |
| Insulation | 0 | 0 | 2.669 |
| Sealing | 0 | 0 | 0.431 |
| Glazing | 1 | 0 | 0.000 |
| Isolator | 0 | 0 | 1.774 |
| Timber | 0 | 1 | 0.000 |
| | | | **7.528** |

| Step 3.2: Calculation of waste generated during recycling Wc | | | |
|---|---|---|---|
| Material | Fraction collected for Recycling Cr | Efficency of recycling process Ec | Unrecoverable Waste Wc for Landfill or Incineration (kg) |
| Aluminium | 1 | 0.89 | 0.806 |
| Steel for Reuse | 0 | 0.93 | 0.000 |
| Steel for Recycle | 1 | 0.93 | 0.180 |
| Gaskets | 1 | 1 | 0.000 |
| Insulation | 0 | 0 | 0.000 |
| Sealing | 1 | 1 | 0.000 |
| Glazing | 1 | 0.9 | 2.529 |
| Isolator | 1 | 1 | 0.000 |
| Timber | 0 | 0 | 0.000 |
| | | | **3.515** |

| Step 3.3: Calculation of waste generated for feedstock production Wf | | | |
|---|---|---|---|
| Material | Efficency of recycling process Ef for feedstock | Fraction of feedstock from recycling Fr | Unrecoverable Waste Wf for Landfill or Incineration (kg) |
| Aluminium | 0.98 | **0.75** | 0.112 |
| Steel for Reuse | 1 | **0.713** | 0.000 |
| Steel for Recycle | 0.92 | **0.713** | 0.160 |
| Gaskets | 1 | 0 | 0.000 |
| Insulation | 1 | **0.4** | 0.000 |
| Sealing | 1 | 0 | 0.000 |
| Glazing | 0.83 | 0.053 | 0.274 |
| Isolator | 1 | 1 | 0.000 |
| Timber | 1 | 0 | 0.000 |
| | | | **0.546** |

| Step 3.4: Calculation of overall amount of unrecoverable waste W | | | | |
|---|---|---|---|---|
| | Waste going to landfill of incineration Wo | Waste generated during recycling Wc | Waste generated for feedstock production Wf | Total unrecoverable Waste W for Landfill or Incineration (kg) |
| Aluminium | 0.000 | 0.806 | 0.112 | 0.459 |
| Steel for Reuse | 0.000 | 0.000 | 0.000 | 0.000 |
| Steel for Recycle | 0.000 | 0.180 | 0.160 | 0.170 |
| Gaskets | 2.654 | 0.000 | 0.000 | 2.654 |
| Insulation | 2.669 | 0.000 | 0.000 | 2.669 |
| Sealing | 0.431 | 0.000 | 0.000 | 0.431 |
| Glazing | 0.000 | 2.529 | 0.274 | 1.402 |
| Isolator | 1.774 | 0.000 | 0.000 | 1.774 |
| Timber | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | **9.559** |

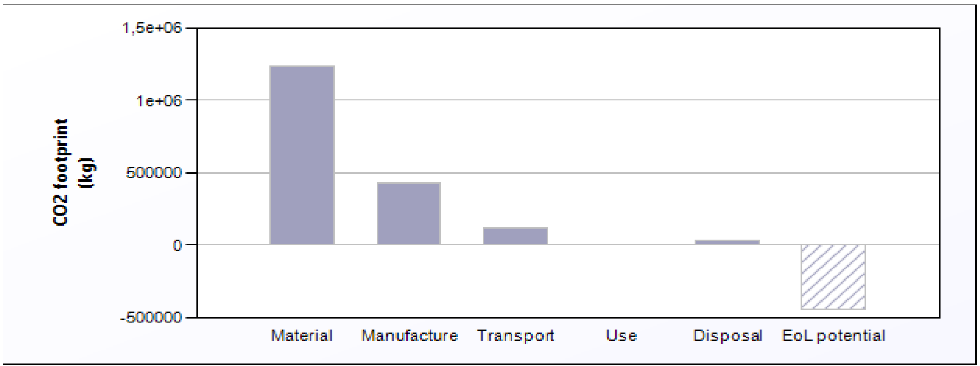
| Step 4: Calculation of MCI-value | | | | | |
|---|---|---|---|---|---|
| Component | Linear Flow Index | Lifespan (a) | Utility Factor X (a / 25) | F(X) | MCI-value |
| Aluminium | 0.16 | 30 | 1.20 | 0.75 | 0.88 |
| Steel for Reuse | 0.14 | 30 | 1.20 | 0.75 | 0.89 |
| Steel for Recycle | 0.18 | 30 | 1.20 | 0.75 | 0.87 |
| Gaskets | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Insulation | 0.80 | 30 | 1.20 | 0.75 | 0.40 |
| Sealing | 1.00 | 30 | 1.20 | 0.75 | 0.25 |
| Glazing | 0.51 | 30 | 1.20 | 0.75 | 0.62 |
| Isolator | 0.50 | 30 | 1.20 | 0.75 | 0.63 |
| Timber | 0.50 | 30 | 1.20 | 0.75 | 0.63 |
| | | | | **Total MCI** | **0.69** |

**0 = complete linear product**
**1 = complete circular product**

# Eco Audit Report
## Lime Street, London

Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 30 year product life):** | 60442.777 |

## Detailed breakdown of individual life phases

### Material:

Summary

| Component | Material | Recycled content* | Part mass | Qty. | Total mass (kg) | CO2 footprint | % |
|---|---|---|---|---|---|---|---|
| **Aluminium** | Aluminum, 6060, T4 | Typical % | 6.78 | 10000 | 67840.00 | 584973.64 | 47.4 |
| **Glazing** | Soda lime - 0080 | Typical % | 48.52 | 10000 | 485190.00 | 340881.59 | 27.6 |
| **Steel** | Coated steel, steel, galvanized | Typical % | 5.42 | 10000 | 54190.00 | 96871.46 | 7.8 |
| **Gasket** | Ethylene propylene (diene) (EPDM/EPM, unreinforced) | Virgin (0%) | 2.99 | 10000 | 29880.00 | 102063.27 | 8.3 |
| **Sealant** | Silicone, phenyl-type (PVMQ, heat cured 10-30% fumed | Virgin (0%) | 1.58 | 10000 | 15820.00 | 103022.09 | 8.3 |
| **Mineral wool** | T-glass | Virgin (0%) | 0.67 | 10000 | 6660.00 | 5813.79 | 0.5 |
| **Isolator** | PA6 (25% glass fiber) | Virgin (0%) | 0.02 | 10000 | 160.00 | 1014.79 | 0.1 |
| Total | | | | **70000** | **659740.00** | **1.23E+006** | **100** |

*Typical: Includes 'recycle fraction in current supply'

### Manufacture:

Summary

| Component | Process | Amount processed | CO2 footprint | % |
|---|---|---|---|---|
| **Aluminium** | Extrusion, foil rolling | 67840.00 kg | 24208.32 | 5.6 |
| **Glazing** | Glass molding | 485190.00 kg | 335521.00 | 78.1 |
| **Steel** | Forging | 54190.00 kg | 12050.86 | 2.8 |
| **Gasket** | Polymer molding | 29880.00 kg | 41402.94 | 9.6 |
| **Sealant** | Polymer molding | 15820.00 kg | 16367.59 | 3.8 |
| **Isolator** | Polymer extrusion | 160.00 kg | 74.16 | 0.0 |
| Total | | | **429624.88** | **100** |

### Transport:

Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (m) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Transport Aluminium** | 26 tonne (3 axle) truck | 130000.00 | 6792.68 | 5.8 |
| **Transport Glazing** | 26 tonne (3 axle) truck | 140000.00 | 7315.20 | 6.2 |
| **Transport Steel** | 26 tonne (3 axle) truck | 1.02E+006 | 53296.44 | 45.3 |
| **Transport Gaskets** | 26 tonne (3 axle) truck | 250000.00 | 13062.85 | 11.1 |
| **Transport Sealing** | 26 tonne (3 axle) truck | 30000.00 | 1567.54 | 1.3 |
| **Transport Mineral Wool** | 26 tonne (3 axle) truck | 210000.00 | 10972.80 | 9.3 |
| **Transport Isolator** | 26 tonne (3 axle) truck | 470000.00 | 24558.16 | 20.9 |
| Total | | **2.25E+006** | **117565.67** | **100** |

### Breakdown by components

| Component | Mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| **Aluminium** | 67840.00 | 12089.09 | 10.3 |
| **Glazing** | 485190.00 | 86460.86 | 73.5 |
| **Steel** | 54190.00 | 9656.66 | 8.2 |
| **Gasket** | 29880.00 | 5324.62 | 4.5 |
| **Sealant** | 15820.00 | 2819.12 | 2.4 |
| **Mineral wool** | 6660.00 | 1186.81 | 1.0 |
| **Isolator** | 160.00 | 28.51 | 0.0 |
| Total | **659740.00** | **117565.67** | **100** |

## Use:

Summary

### Relative contribution of static and mobile modes

| Mode | CO2 footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 0.00 | |
| Total | **0.00** | **100** |

## Disposal:

Summary

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | 3324.16 | 10.6 |
| **Glazing** | Recycle | 23774.31 | 75.6 |
| **Steel** | Recycle | 2655.31 | 8.4 |
| **Gasket** | Combust | 1045.80 | 3.3 |
| **Sealant** | Combust | 553.70 | 1.8 |
| **Mineral wool** | Landfill | 93.24 | 0.3 |
| **Isolator** | Downcycle | 5.60 | 0.0 |
| Total | | **31452.12** | **100** |

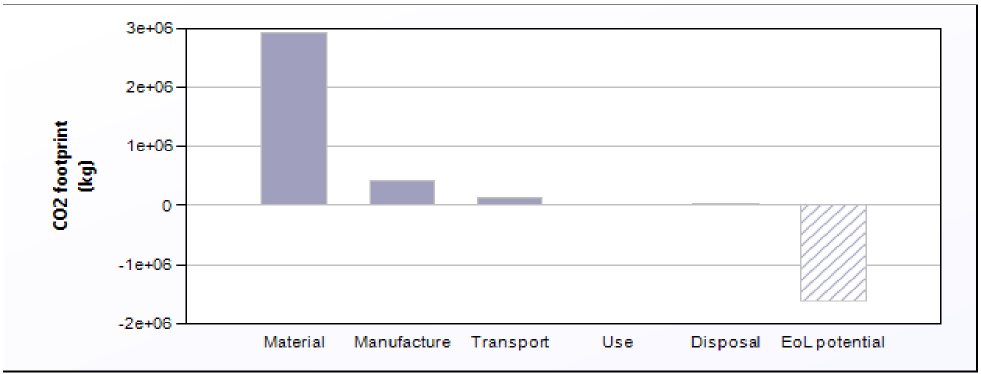
## EoL potential:

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | -404055.67 | 90.9 |
| **Glazing** | Recycle | -84295.43 | 19.0 |
| **Steel** | Recycle | -54304.81 | 12.2 |
| **Gasket** | Combust | 70566.04 | -15.9 |
| **Sealant** | Combust | 27891.60 | -6.3 |
| **Mineral wool** | Landfill | 0.00 | 0.0 |
| **Isolator** | Downcycle | -121.77 | 0.0 |
| Total | | **-444320.03** | **100** |

## Notes:

Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 30 year product life):** | 116411.636 |

## Detailed breakdown of individual life phases

## Material:

Summary

| Component | Material | Recycled content* | Part mass | Qty. | Total mass (kg) | CO2 footprint | % |
|---|---|---|---|---|---|---|---|
| **Aluminium** | Aluminum, 6060, T4 | Typical % | 26.67 | 10000 | 266700.00 | 2.30E+006 | 79.0 |
| **Glazing** | Soda lime - 0080 | Typical % | 34.65 | 10000 | 346480.00 | 243427.63 | 8.4 |
| **Steel** | Coated steel, steel, galvanized | Typical % | 5.68 | 10000 | 56840.00 | 101608.67 | 3.5 |
| **Gaskets** | Ethylene propylene (diene) (EPDM/EPM, unreinforced) | Virgin (0%) | 3.54 | 10000 | 35400.00 | 120918.34 | 4.2 |
| **Sealing** | Silicone, phenyl-type (PVMQ, heat cured 10-30% fumed | Virgin (0%) | 1.37 | 10000 | 13700.00 | 89216.35 | 3.1 |
| **Mineral wool** | T-glass | Virgin (0%) | 0.77 | 10000 | 7690.00 | 6712.92 | 0.2 |
| **Isolator** | PA6 (25% glass fiber) | Virgin (0%) | 0.80 | 10000 | 7970.00 | 50549.15 | 1.7 |
| Total | | | | **70000** | **734780.00** | **2.91E+006** | **100** |

*Typical: Includes 'recycle fraction in current supply'

## Manufacture:

Summary

| Component | Process | Amount processed | CO2 footprint | % |
|---|---|---|---|---|
| **Aluminium** | Extrusion, foil rolling | 266700.00 kg | 95170.39 | 23.0 |
| **Glazing** | Glass molding | 346480.00 kg | 239599.57 | 57.8 |
| **Steel** | Forging | 56840.00 kg | 12640.18 | 3.1 |
| **Gaskets** | Polymer molding | 35400.00 kg | 49051.68 | 11.8 |
| **Sealing** | Polymer molding | 13700.00 kg | 14174.21 | 3.4 |
| **Isolator** | Polymer extrusion | 7970.00 kg | 3694.02 | 0.9 |
| Total | | | **414330.04** | **100** |

## Transport:

Summary

### Breakdown by transport stage

| Stage name | Transport type | Distance (km) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Transport Aluminium** | 26 tonne (3 axle) truck | 130000.00 | 7565.29 | 5.8 |
| **Transport Glazing** | 26 tonne (3 axle) truck | 140000.00 | 8147.24 | 6.2 |
| **Transport Steel** | 26 tonne (3 axle) truck | 1.02E+006 | 59358.47 | 45.3 |
| **Transport Gaskets** | 26 tonne (3 axle) truck | 250000.00 | 14548.64 | 11.1 |
| **Transport Sealing** | 26 tonne (3 axle) truck | 30000.00 | 1745.84 | 1.3 |
| **Transport Mineral Wool** | 26 tonne (3 axle) truck | 210000.00 | 12220.86 | 9.3 |
| **Transport Isolator** | 26 tonne (3 axle) truck | 470000.00 | 27351.45 | 20.9 |
| Total | | **2.25E+006** | **130937.80** | **100** |

### Breakdown by components

| Component | Mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| **Aluminium** | 266700.00 | 47525.94 | 36.3 |
| **Glazing** | 346480.00 | 61742.74 | 47.2 |
| **Steel** | 56840.00 | 10128.89 | 7.7 |

| | | | |
|---|---|---|---|
| **Gaskets** | 35400.00 | 6308.28 | 4.8 |
| **Sealing** | 13700.00 | 2441.34 | 1.9 |
| **Mineral wool** | 7690.00 | 1370.36 | 1.0 |
| **Isolator** | 7970.00 | 1420.25 | 1.1 |
| Total | **734780.00** | **130937.80** | **100** |

## Use:

Summary

### Relative contribution of static and mobile modes

| Mode | $CO_2$ footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 0.00 | |
| Total | **0.00** | **100** |

## Disposal:

Summary

| Component | End of life option | $CO_2$ footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | 13068.30 | 37.4 |
| **Glazing** | Recycle | 16977.52 | 48.6 |
| **Steel** | Recycle | 2785.16 | 8.0 |
| **Gaskets** | Combust | 1239.00 | 3.5 |
| **Sealing** | Combust | 479.50 | 1.4 |
| **Mineral wool** | Landfill | 107.66 | 0.3 |
| **Isolator** | Downcycle | 278.95 | 0.8 |
| Total | | **34936.09** | **100** |

## EoL potential:

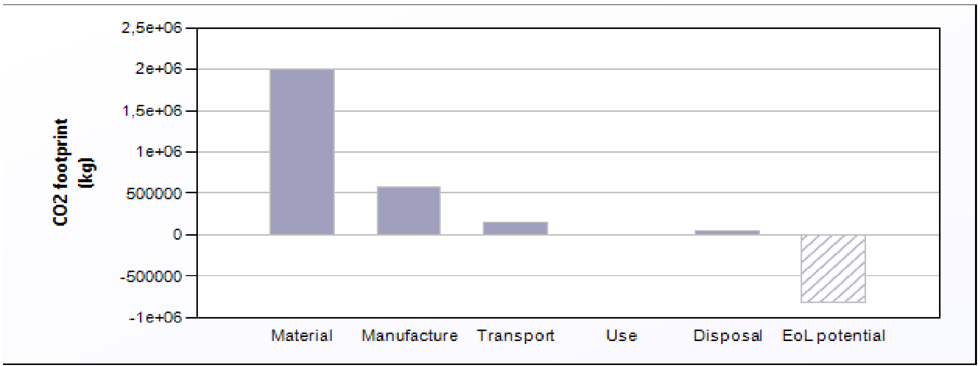
| Component | End of life option | $CO_2$ footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | -1.59E+006 | 99.0 |
| **Glazing** | Recycle | -60196.37 | 3.8 |
| **Steel** | Recycle | -56960.42 | 3.6 |
| **Gaskets** | Combust | 83602.33 | -5.2 |
| **Sealing** | Combust | 24153.92 | -1.5 |
| **Mineral wool** | Landfill | 0.00 | 0.0 |
| **Isolator** | Downcycle | -6065.90 | 0.4 |
| Total | | **-1.60E+006** | **100** |

## Notes:

Summary

Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| Equivalent annual environmental burden (averaged over 50 year product life): | 55653.150 |

## Detailed breakdown of individual life phases

### Material:

Summary

| Component | Material | Recycled content* | Part mass | Qty. | Total mass (kg) | CO2 footprint | % |
|---|---|---|---|---|---|---|---|
| **Aluminium** | Aluminum, 6060, T4 | Typical % | 13.97 | 10000 | 139720.00 | 1.20E+006 | 60.1 |
| **Glazing** | Soda lime - 0080 | Typical % | 62.11 | 10000 | 621110.00 | 436375.37 | 21.8 |
| **Steel** | Coated steel, steel, galvanized | Typical % | 3.58 | 10000 | 35780.00 | 63961.26 | 3.2 |
| **Gaskets** | Ethylene propylene (diene) (EPDM/EPM, unreinforced) | Virgin (0%) | 5.85 | 10000 | 58540.00 | 199959.30 | 10.0 |
| **Sealing** | Silicone, phenyl-type (PVMQ, heat cured 10-30% fumed | Virgin (0%) | 1.08 | 10000 | 10820.00 | 70461.38 | 3.5 |
| **Mineral wool** | T-glass | Virgin (0%) | 0.80 | 10000 | 7950.00 | 6939.89 | 0.3 |
| **Isolator** | PA6 (25% glass fiber) | Virgin (0%) | 0.33 | 10000 | 3310.00 | 20993.44 | 1.0 |
| Total | | | | **70000** | **877230.00** | **2.00E+006** | **100** |

*Typical: Includes 'recycle fraction in current supply'

### Manufacture:

Summary

| Component | Process | Amount processed | CO2 footprint | % |
|---|---|---|---|---|
| **Aluminium** | Extrusion, foil rolling | 139720.00 kg | 49858.29 | 8.6 |
| **Glazing** | Glass molding | 621110.00 kg | 429513.07 | 73.9 |
| **Steel** | Forging | 35780.00 kg | 7956.82 | 1.4 |
| **Gaskets** | Polymer molding | 58540.00 kg | 81115.41 | 14.0 |
| **Sealing** | Polymer molding | 10820.00 kg | 11194.52 | 1.9 |
| **Isolator** | Polymer extrusion | 3310.00 kg | 1534.15 | 0.3 |
| Total | | | **581172.26** | **100** |

### Transport:

Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (m) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Transport Aluminium** | 26 tonne (3 axle) truck | 130000.00 | 9031.96 | 5.8 |
| **Transport Glazing** | 26 tonne (3 axle) truck | 140000.00 | 9726.73 | 6.2 |
| **Transport Steel** | 26 tonne (3 axle) truck | 1.02E+006 | 70866.15 | 45.3 |
| **Transport Gaskets** | 26 tonne (3 axle) truck | 250000.00 | 17369.15 | 11.1 |
| **Transport Sealing** | 26 tonne (3 axle) truck | 30000.00 | 2084.30 | 1.3 |
| **Transport Mineral Wool** | 26 tonne (3 axle) truck | 210000.00 | 14590.09 | 9.3 |
| **Transport Isolator** | 26 tonne (3 axle) truck | 470000.00 | 32654.01 | 20.9 |
| Total | | **2.25E+006** | **156322.39** | **100** |

### Breakdown by components

| Component | Mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| **Aluminium** | 139720.00 | 24898.10 | 15.9 |
| **Glazing** | 621110.00 | 110681.80 | 70.8 |
| **Steel** | 35780.00 | 6376.00 | 4.1 |
| **Gaskets** | 58540.00 | 10431.83 | 6.7 |
| **Sealing** | 10820.00 | 1928.12 | 1.2 |
| **Mineral wool** | 7950.00 | 1416.69 | 0.9 |
| **Isolator** | 3310.00 | 589.84 | 0.4 |
| Total | **877230.00** | **156322.39** | **100** |

## Use:

Summary

### Relative contribution of static and mobile modes

| Mode | CO2 footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 0.00 | |
| Total | **0.00** | **100** |

## Disposal:

Summary

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | 6846.28 | 16.4 |
| **Glazing** | Recycle | 30434.39 | 73.0 |
| **Steel** | Recycle | 1753.22 | 4.2 |
| **Gaskets** | Combust | 2048.90 | 4.9 |
| **Sealing** | Combust | 378.70 | 0.9 |
| **Mineral wool** | Landfill | 111.30 | 0.3 |
| **Isolator** | Downcycle | 115.85 | 0.3 |
| Total | | **41688.64** | **100** |

## EoL potential:

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | -832173.61 | 101.3 |
| **Glazing** | Recycle | -107909.75 | 13.1 |
| **Steel** | Recycle | -35855.81 | 4.4 |
| **Gaskets** | Combust | 138250.87 | -16.8 |
| **Sealing** | Combust | 19076.31 | -2.3 |
| **Mineral wool** | Landfill | 0.00 | 0.0 |
| **Isolator** | Downcycle | -2519.21 | 0.3 |
| Total | | **-821131.21** | **100** |

## Notes:

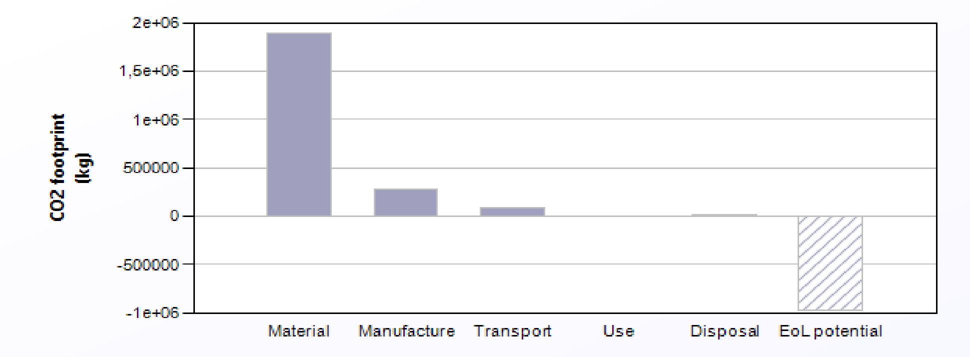
Summary

CES 2019 EDUPACK

# Eco Audit Report
# Type 1 - Sandwich Panel

Summary

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 50 year product life):** | 45416.072 |

## Detailed breakdown of individual life phases

### Material:

Summary

| Component | Material | Recycled content* | Part mass | Qty. | Total mass (kg) | CO2 footprint | % |
|---|---|---|---|---|---|---|---|
| **Aluminium** | Aluminum, 6060, T4 | Typical % | 16.76 | 10000 | 167560.00 | 1.44E+006 | 76.5 |
| **Glazing** | Soda lime - 0080 | Typical % | 23.16 | 10000 | 231590.00 | 162708.98 | 8.6 |
| **Steel** | Coated steel, steel, galvanized | Typical % | 2.42 | 10000 | 24170.00 | 43206.92 | 2.3 |
| **Gasket** | Ethylene propylene (diene) (EPDM/EPM, unreinforced) | Virgin (0%) | 2.55 | 10000 | 25470.00 | 86999.72 | 4.6 |
| **Sealant** | Silicone, phenyl-type (PVMQ, heat cured 10-30% fumed | Virgin (0%) | 0.40 | 10000 | 3950.00 | 25722.96 | 1.4 |
| **Mineral wool** | T-glass | Virgin (0%) | 2.59 | 10000 | 25900.00 | 22609.19 | 1.2 |
| **Isolator** | PA6 (25% glass fiber) | Virgin (0%) | 1.60 | 10000 | 16040.00 | 101732.55 | 5.4 |
| Total | | | | **70000** | **494680.00** | **1.89E+006** | **100** |

*Typical: Includes 'recycle fraction in current supply'

### Manufacture:

Summary

| Component | Process | Amount processed | CO2 footprint | % |
|---|---|---|---|---|
| **Aluminium** | Extrusion, foil rolling | 167560.00 kg | 59792.84 | 22.0 |
| **Glazing** | Glass molding | 231590.00 kg | 160150.27 | 58.9 |
| **Steel** | Forging | 24170.00 kg | 5374.97 | 2.0 |
| **Gasket** | Polymer molding | 25470.00 kg | 35292.27 | 13.0 |
| **Sealant** | Polymer molding | 3950.00 kg | 4086.73 | 1.5 |
| **Isolator** | Polymer extrusion | 16040.00 kg | 7434.38 | 2.7 |
| Total | | | **272131.45** | **100** |

### Transport:

Summary

**Breakdown by transport stage**

| Stage name | Transport type | Distance (m) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Transport Aluminium** | 26 tonne (3 axle) truck | 130000.00 | 5093.23 | 5.8 |
| **Transport Glazing** | 26 tonne (3 axle) truck | 140000.00 | 5485.01 | 6.2 |
| **Transport Steel** | 26 tonne (3 axle) truck | 1.02E+006 | 39962.23 | 45.3 |
| **Transport Gaskets** | 26 tonne (3 axle) truck | 250000.00 | 9794.66 | 11.1 |
| **Transport Sealing** | 26 tonne (3 axle) truck | 30000.00 | 1175.36 | 1.3 |
| **Transport Mineral Wool** | 26 tonne (3 axle) truck | 210000.00 | 8227.52 | 9.3 |
| **Transport Isolator** | 26 tonne (3 axle) truck | 470000.00 | 18413.97 | 20.9 |
| Total | | **2.25E+006** | **88151.98** | **100** |

### Breakdown by components

| Component | Mass (kg) | $CO_2$ footprint (kg) | % |
|---|---|---|---|
| **Aluminium** | 167560.00 | 29859.19 | 33.9 |
| **Glazing** | 231590.00 | 41269.34 | 46.8 |
| **Steel** | 24170.00 | 4307.09 | 4.9 |
| **Gasket** | 25470.00 | 4538.75 | 5.1 |
| **Sealant** | 3950.00 | 703.89 | 0.8 |
| **Mineral wool** | 25900.00 | 4615.38 | 5.2 |
| **Isolator** | 16040.00 | 2858.33 | 3.2 |
| Total | **494680.00** | **88151.98** | **100** |

## Use:

Summary

### Relative contribution of static and mobile modes

| Mode | $CO_2$ footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 0.00 | |
| Total | **0.00** | **100** |

## Disposal:

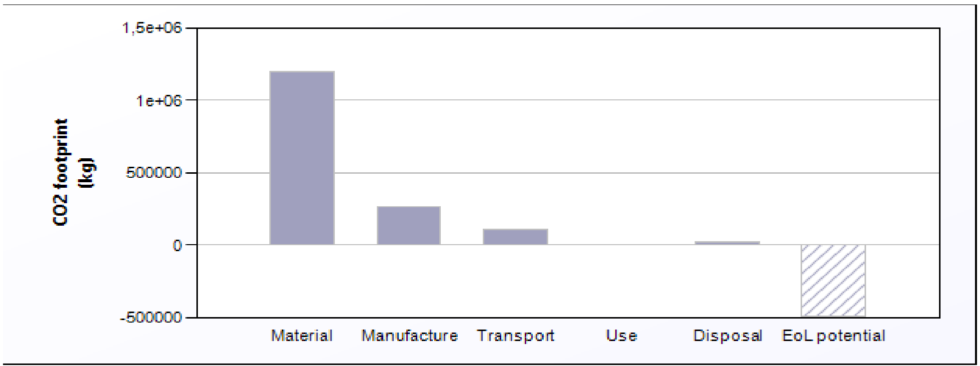
Summary

| Component | End of life option | $CO_2$ footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | 8210.44 | 36.2 |
| **Glazing** | Recycle | 11347.91 | 50.0 |
| **Steel** | Recycle | 1184.33 | 5.2 |
| **Gasket** | Combust | 891.45 | 3.9 |
| **Sealant** | Combust | 138.25 | 0.6 |
| **Mineral wool** | Landfill | 362.60 | 1.6 |
| **Isolator** | Combust | 561.40 | 2.5 |
| Total | | **22696.38** | **100** |

## EoL potential:

| Component | End of life option | $CO_2$ footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | -997988.91 | 102.5 |
| **Glazing** | Recycle | -40235.74 | 4.1 |
| **Steel** | Recycle | -24221.21 | 2.5 |
| **Gasket** | Combust | 60151.17 | -6.2 |
| **Sealant** | Combust | 6964.09 | -0.7 |
| **Mineral wool** | Landfill | 0.00 | 0.0 |
| **Isolator** | Combust | 21618.96 | -2.2 |
| Total | | **-973711.64** | **100** |

## CO2 Footprint Analysis




| | CO2 (kg/year) |
|---|---|
| **Equivalent annual environmental burden (averaged over 30 year product life):** | 52961.033 |

## Detailed breakdown of individual life phases

### Material:

Summary

| Component | Material | Recycled content* | Part mass | Qty. | Total mass (kg) | CO2 footprint | % |
|---|---|---|---|---|---|---|---|
| **Aluminium** | Aluminum, 6060, T4 | Typical % | 7.33 | 10000 | 73280.00 | 631881.90 | 52.9 |
| **Glazing** | Soda lime - 0080 | Typical % | 25.29 | 10000 | 252870.00 | 177659.74 | 14.9 |
| **Steel for reuse** | Coated steel, steel, galvanized | Typical % | 2.16 | 10000 | 21610.00 | 38630.60 | 3.2 |
| **Steel for recycling** | Coated steel, steel, galvanized | Typical % | 2.57 | 10000 | 25730.00 | 45995.62 | 3.9 |
| **Gasket** | Ethylene propylene (diene) (EPDM/EPM, unreinforced) | Virgin (0%) | 2.65 | 10000 | 26540.00 | 90654.59 | 7.6 |
| **Sealant** | Silicone, phenyl-type (PVMQ, heat cured 10-30% fumed | Virgin (0%) | 0.43 | 10000 | 4310.00 | 28067.33 | 2.4 |
| **Mineral wool** | T-glass | Virgin (0%) | 2.67 | 10000 | 26690.00 | 23298.81 | 2.0 |
| **Isolator** | PA6 (25% glass fiber) | Virgin (0%) | 1.77 | 10000 | 17740.00 | 112514.68 | 9.4 |
| **Timber** | Poplar (l) | Virgin (0%) | 7.51 | 10000 | 75140.00 | 45292.78 | 3.8 |
| Total | | | | **90000** | **523910.00** | **1.19E+006** | **100** |

*Typical: Includes 'recycle fraction in current supply'

### Manufacture:

Summary

| Component | Process | Amount processed | CO2 footprint | % |
|---|---|---|---|---|
| **Aluminium** | Extrusion, foil rolling | 73280.00 kg | 26149.55 | 10.0 |
| **Glazing** | Glass molding | 252870.00 kg | 174865.92 | 67.0 |
| **Steel for reuse** | Forging | 21610.00 kg | 4805.67 | 1.8 |
| **Steel for recycling** | Roll forming | 25730.00 kg | 5721.88 | 2.2 |
| **Gasket** | Polymer molding | 26540.00 kg | 36774.90 | 14.1 |
| **Sealant** | Polymer molding | 4310.00 kg | 4459.19 | 1.7 |
| **Isolator** | Polymer extrusion | 17740.00 kg | 8222.32 | 3.2 |
| Total | | | **260999.43** | **100** |

### Transport:

Summary

#### Breakdown by transport stage

| Stage name | Transport type | Distance (m) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Transport Aluminium** | 26 tonne (3 axle) truck | 130000.00 | 5394.18 | 4.8 |
| **Transport Glazing** | 26 tonne (3 axle) truck | 140000.00 | 5809.11 | 5.1 |
| **Transport Steel** | 26 tonne (3 axle) truck | 1.02E+006 | 42323.55 | 37.4 |
| **Transport Gaskets** | 26 tonne (3 axle) truck | 250000.00 | 10373.42 | 9.2 |
| **Transport Sealing** | 26 tonne (3 axle) truck | 30000.00 | 1244.81 | 1.1 |

| | | | | |
|---|---|---|---|---|
| **Transport Mineral Wool** | 26 tonne (3 axle) truck | 210000.00 | 8713.67 | 7.7 |
| **Transport Isolator** | 26 tonne (3 axle) truck | 470000.00 | 19502.03 | 17.2 |
| **Transport Timber** | Rail freight | 1.50E+006 | 19803.80 | 17.5 |
| Total | | **3.75E+006** | **113164.56** | **100** |

### Breakdown by components

| Component | Mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| **Aluminium** | 73280.00 | 15828.48 | 14.0 |
| **Glazing** | 252870.00 | 54619.92 | 48.3 |
| **Steel for reuse** | 21610.00 | 4667.76 | 4.1 |
| **Steel for recycling** | 25730.00 | 5557.68 | 4.9 |
| **Gasket** | 26540.00 | 5732.64 | 5.1 |
| **Sealant** | 4310.00 | 930.96 | 0.8 |
| **Mineral wool** | 26690.00 | 5765.04 | 5.1 |
| **Isolator** | 17740.00 | 3831.84 | 3.4 |
| **Timber** | 75140.00 | 16230.24 | 14.3 |
| Total | **523910.00** | **113164.56** | **100** |

## Use:

Summary

### Relative contribution of static and mobile modes

| Mode | CO2 footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 0.00 | |
| Total | **0.00** | **100** |

## Disposal:

Summary

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | 3590.72 | 17.4 |
| **Glazing** | Recycle | 12390.63 | 59.9 |
| **Steel for reuse** | Reuse | 302.54 | 1.5 |
| **Steel for recycling** | Recycle | 1260.77 | 6.1 |
| **Gasket** | Combust | 928.90 | 4.5 |
| **Sealant** | Combust | 150.85 | 0.7 |
| **Mineral wool** | Landfill | 373.66 | 1.8 |
| **Isolator** | Combust | 620.90 | 3.0 |
| **Timber** | Reuse | 1051.96 | 5.1 |
| Total | | **20670.93** | **100** |

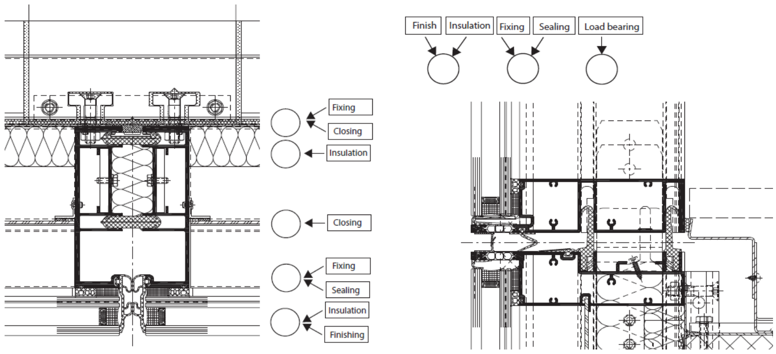
## EoL potential:

| Component | End of life option | CO2 footprint | % |
|---|---|---|---|
| **Aluminium** | Recycle | -436456.36 | 88.0 |
| **Glazing** | Recycle | -43932.86 | 8.9 |
| **Steel for reuse** | Reuse | -38630.60 | 7.8 |
| **Steel for recycling** | Recycle | -25784.51 | 5.2 |
| **Gasket** | Combust | 62678.13 | -12.6 |
| **Sealant** | Combust | 7598.79 | -1.5 |
| **Mineral wool** | Landfill | 0.00 | 0.0 |
| **Isolator** | Combust | 23910.24 | -4.8 |
| **Timber** | Reuse | -45292.78 | 9.1 |
| Total | | **-495909.95** | **100** |

# Lime Street, London - Disassembly Potential

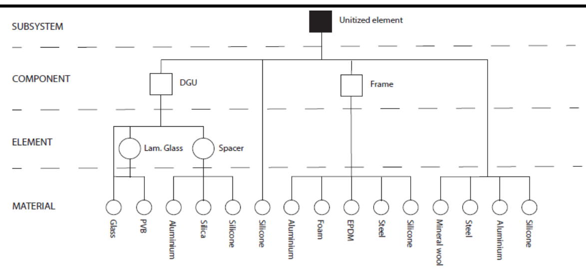
## Functional decomposition

| 1. Functional Independence | Points |
|---|---|
| Total or unplanned integration | 10 |
| Planned interpenetration | 8 |
| Unplanned interpenetration | 2 |
| Total separation/autonomy | 1 |



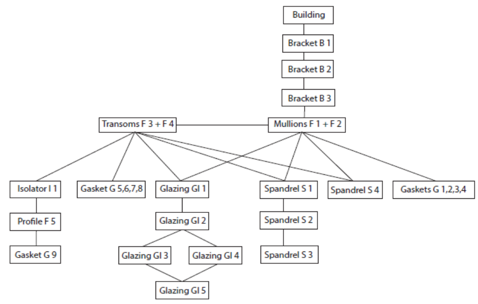

## Functional decomposition

| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



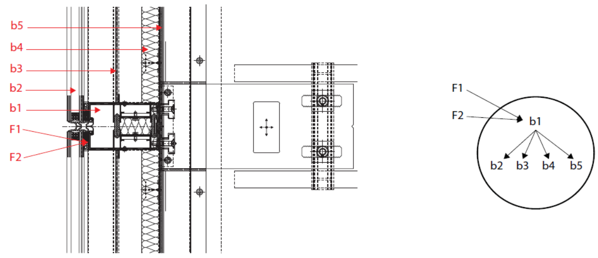

## Technical Decomposition

| 3. Relational Pattern / Hierachy | Points |
|---|---|
| Vertical throughout the schema | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone | 4 |
| Horizontal in upper zone | 1 |




## Technical Decomposition

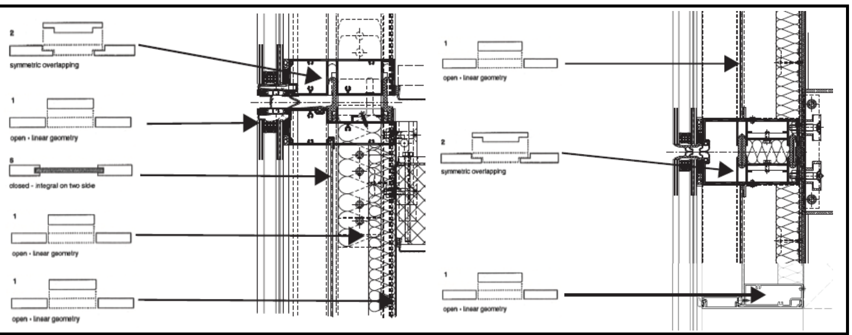
| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions (BE and one building funct | 4 |
| No base element | 1 |




## Technical Decomposition

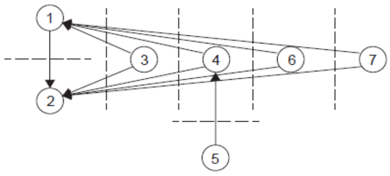
| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

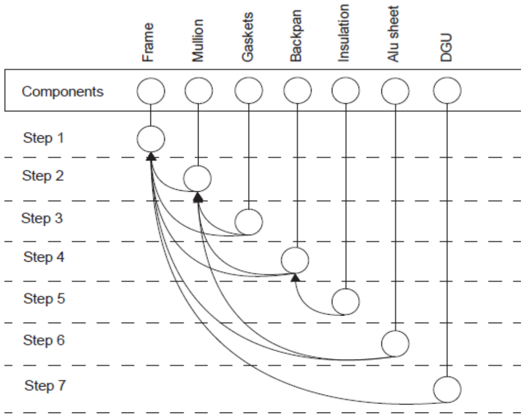
| gp=[gp1 + gp2 + ...gp(n)] / n | |
|---|---|
| gp = [1+2*8+5*10] /8 | |
| gp = | 8.38 |



## Physical Decomposition

| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |

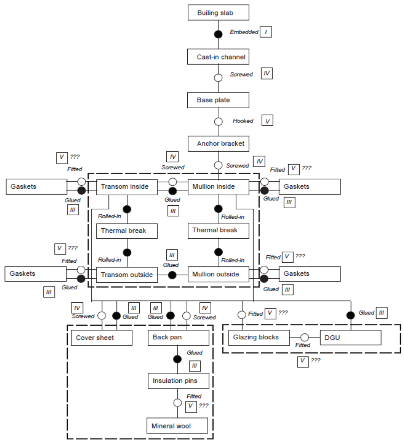



## Physical Decomposition

| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |

| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 0 | 2 | 0 | |
| III | 10 | 4 | 40 | |
| IV | 5 | 5 | 25 | |
| V | 8 | 6 | 48 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 24 | | 114 | 4.75 |



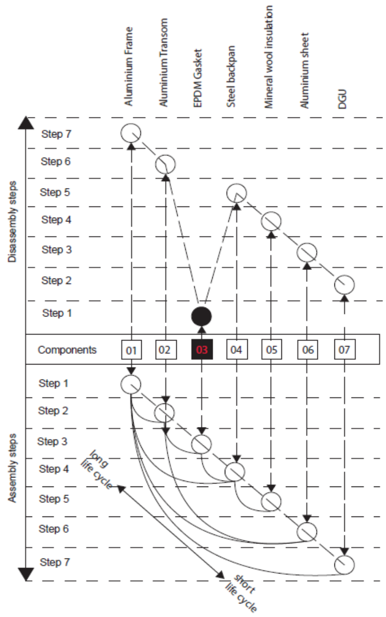

## Physical Decomposition

| 8. Life Cycle Coordination | Points |
|---|---|
| Use life cycle and technical life cycle coord. | 10 |
| Use life cycle without technical life cycle coord. | 6 |
| Technical life cycle, no use life cycle coord. | 4 |
| No technical life cycle, no use life cycle coord. | 1 |

use life-cycle / technical life-cycle

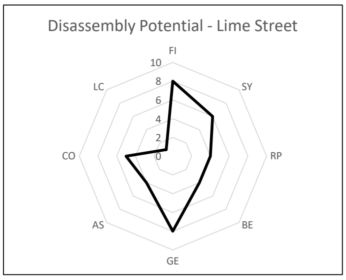
| Component: | Years: | 01 | 02 | 03 | 04 | 05 | 06 | 07 |
|---|---|---|---|---|---|---|---|---|
| Aluminium frame | 25 | 75 | | | | | | |
| Aluminium transom | 25 | | 75 | | | | | |
| EPDM Gaskets | 25 | | | 20 | | | | |
| Steel backpan | 25 | | | | 75 | | | |
| Mineral wool insulation | 25 | | | | | 75 | | |
| Aluminium sheet | 25 | | | | | | 75 | |
| DGU | 25 | | | | | | | 30 |

source: SBR (2011)




## Lime Street, London - Disassembly Potential - Results

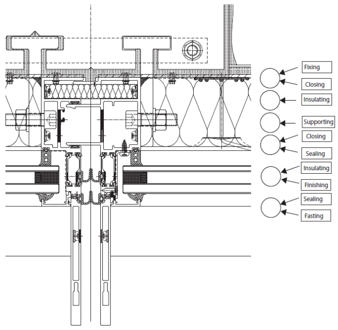
| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 4 |
| Base element specification | BE | 4 |
| Geometry of product edges | GE | 8 |
| Assembly sequence | AS | 4 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 1 |

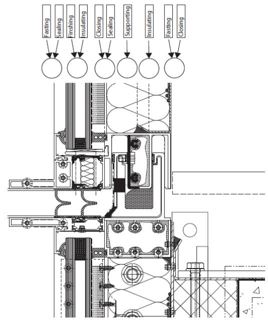


# One Crown Place, London - Disassembly Potential

## Functional decomposition

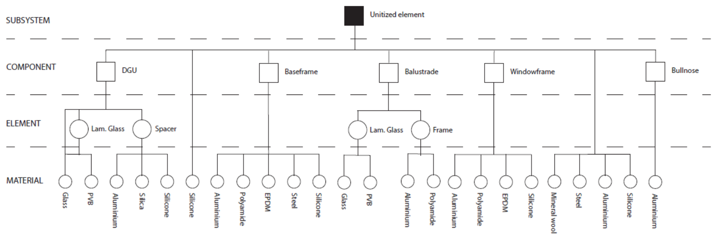
| 1. Functional Independence | Points |
|---|---|
| Total or unplanned integration | 10 |
| Planned interpenetration | 8 |
| Unplanned interpenetration | 2 |
| Total separation/autonomy | 1 |





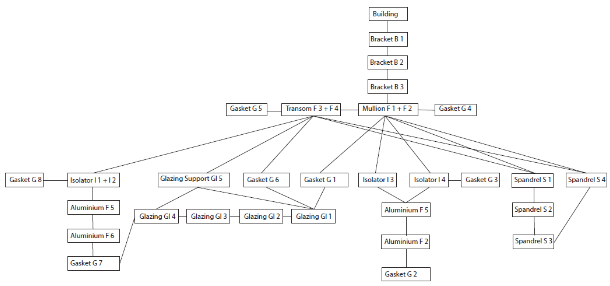
## Functional decomposition

| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



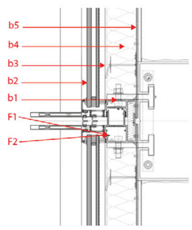
## Technical Decomposition

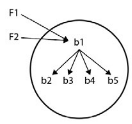
| 3. Relational Pattern / Hierachy | Points |
|---|---|
| Vertical throughout the schema | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone | 4 |
| Horizontal in upper zone | 1 |



## Technical Decomposition

| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions (BE and one building functi | 4 |
| No base element | 1 |

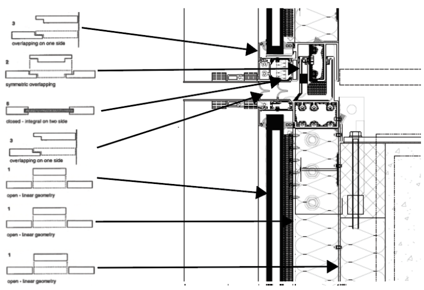


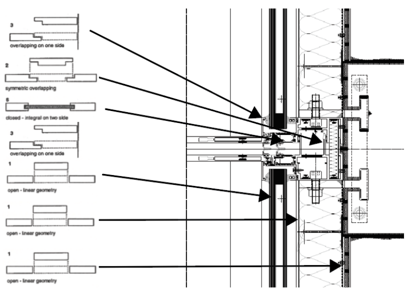


## Technical Decomposition

| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

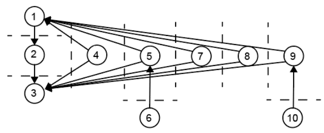
| | |
|---|---|
| gp=[gp1 + gp2 + ...gp(n)] / n | |
| gp = [6*10+2*8+4*6+2*1] / 14 | |
| gp = | 7,285 |

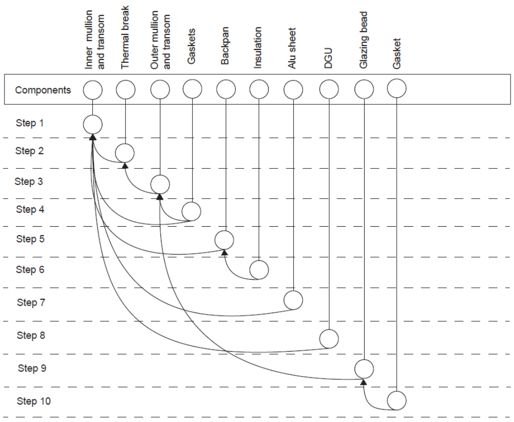




## Physical Decomposition

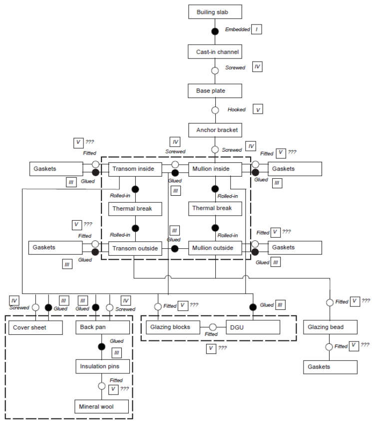
| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |






| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |

| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 0 | 2 | 0 | |
| III | 10 | 4 | 40 | |
| IV | 5 | 5 | 25 | |
| V | 10 | 6 | 60 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 26 | | 126 | 4.85 |



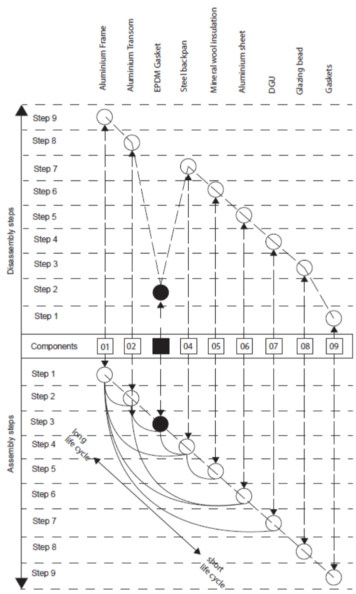

## Physical Decomposition

| 8. Cife Cycle Coordination | Points |
|---|---|
| Use life cycle and technical life cycle coord. | 10 |
| Use life cycle without technical life cycle coord. | 6 |
| Technical life cycle, no use life cycle coord. | 4 |
| No technical life cycle, no use life cycle coord. | 1 |

use life-cycle / technical life-cycle

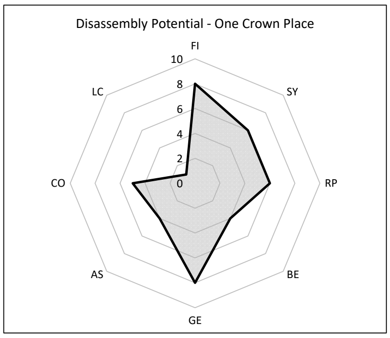
| Component: | Years: | 01 | 02 | ■ | 04 | 05 | 06 | 07 | 08 | 09 |
|---|---|---|---|---|---|---|---|---|---|---|
| Aluminium frame | 25 | 75 | | | | | | | | |
| Aluminium transom | 25 | | 75 | | | | | | | |
| EPDM Gaskets | 25 | | | 20 | | | | | | |
| Steel backpan | 25 | | | | 75 | | | | | |
| Mineral wool insulation | 25 | | | | | 75 | | | | |
| Aluminium sheet | 25 | | | | | | 75 | | | |
| DGU | 25 | | | | | | | 30 | | |
| Glazing bead | 25 | | | | | | | | 75 | |
| EPDM Gasket | 25 | | | | | | | | | 20 |

source: SBR (2011)




## One Crown Place, London - Disassembly Potential - Results

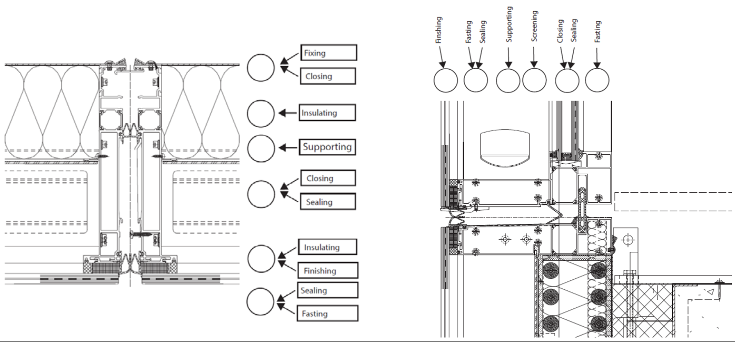
| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 6 |
| Base element specification | BE | 4 |
| Geometry of product edges | GE | 8 |
| Assembly sequence | AS | 4 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 1 |



# Bishopsgate, London - Disassembly Potential

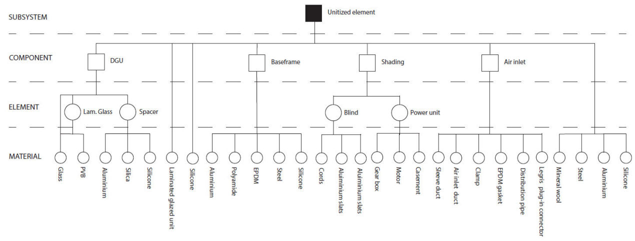
## Functional decomposition

| 1. Functional Independence | Points |
|---|---|
| Total or unplanned integration | 10 |
| Planned interpenetration | 8 |
| Unplanned interpenetration | 2 |
| Total separation/autonomy | 1 |



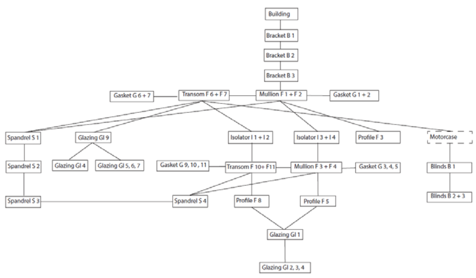

## Functional decomposition

| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



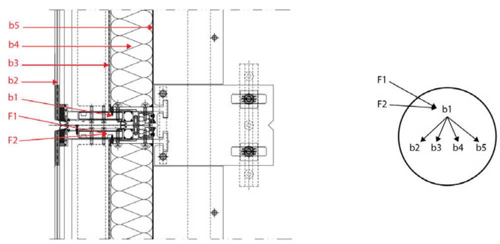

## Technical Decomposition

| 3. Relational Pattern / Hierachy | Points |
|---|---|
| Vertical throughout the schema | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone | 4 |
| Horizontal in upper zone | 1 |




## Technical Decomposition

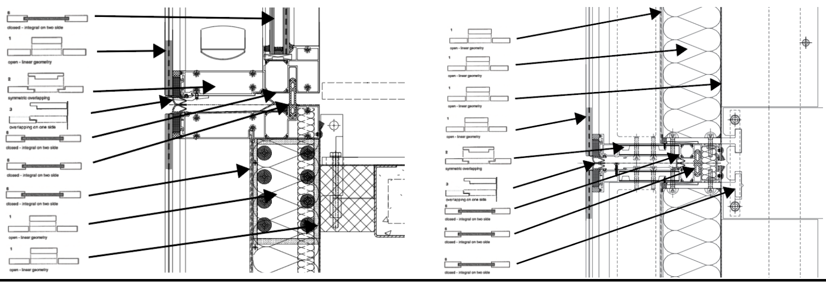
| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions (BE and one building functi | 4 |
| No base element | 1 |




## Technical Decomposition

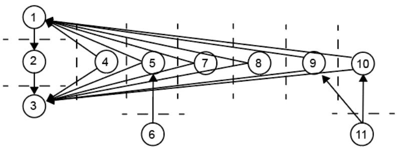
| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

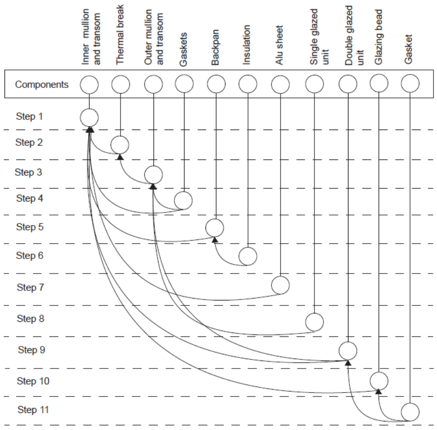
| | |
|---|---|
| gp=[gp1 + gp2 + ...gp(n)] / n | |
| gp = [7*1+2*7+2*8+7*10] /18 | |
| gp = | 5.94 |



## Physical Decomposition

| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |

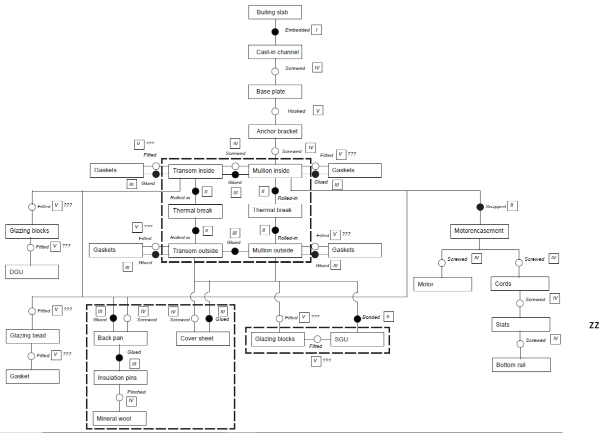





## Physical Decomposition

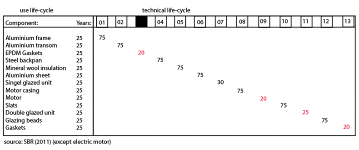
| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |

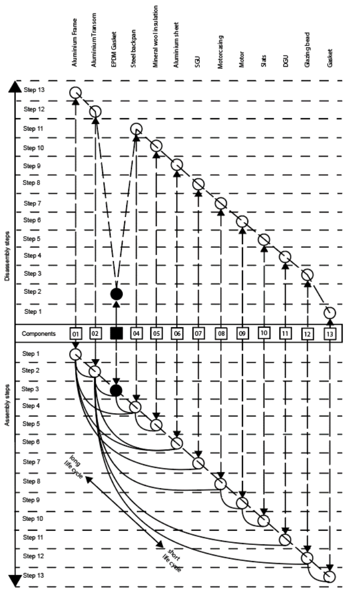
| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 6 | 2 | 12 | |
| III | 10 | 4 | 40 | |
| IV | 9 | 5 | 45 | |
| V | 12 | 6 | 72 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 38 | | 170 | 4.47 |




## Physical Decomposition

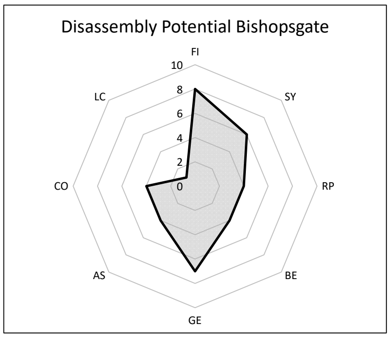
| 8. Life Cycle Coordination | Points |
|---|---|
| Use life cycle and technical life cycle coord. | 10 |
| Use life cycle without technical life cycle coord. | 6 |
| Technical life cycle, no use life cycle coord. | 4 |
| No technical life cycle, no use life cycle coord. | 1 |




## Bishopsgate, London - Disassembly Potential - Results

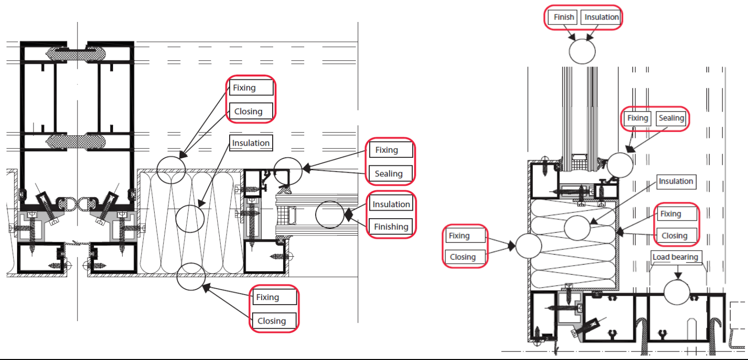
| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 4 |
| Base element specification | BE | 4 |
| Geometry of product edges | GE | 7 |
| Assembly sequence | AS | 4 |
| Connections | CO | 4 |
| Life cycle co-ordination of materials and functions | LC | 1 |



# Type 1 - Disassembly Potential

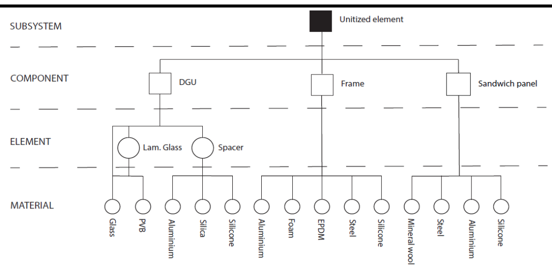
## Functional decomposition

| 1. Functional Independence | Points |
|---|---|
| Total separation/autonomy of functions | 10 |
| Planned integration of functions | 8 |
| Unplanned integration of functions | 2 |
| Total integration of functions | 1 |



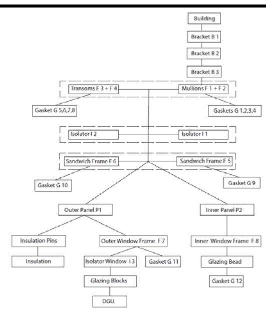

## Functional decomposition

| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



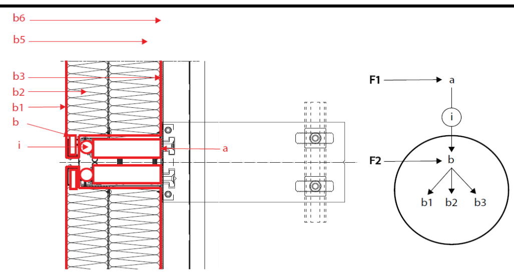

## Technical Decomposition

| 3. Relational Pattern / Hierachy | Points |
|---|---|
| Vertical throughout the schema | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone | 4 |
| Horizontal in upper zone | 1 |



## Technical Decomposition

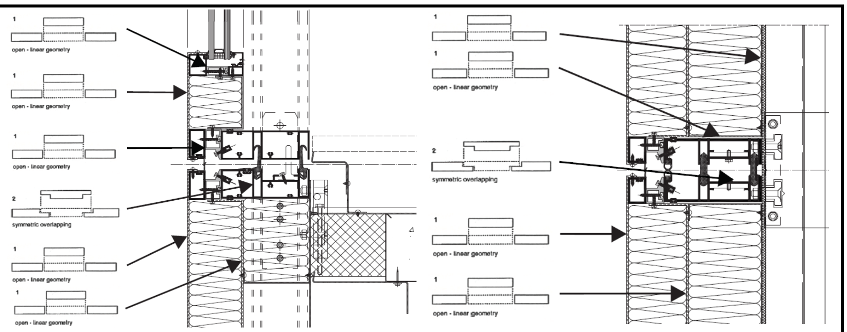
| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions  (BE and one building functi | 4 |
| No base element | 1 |




## Technical Decomposition

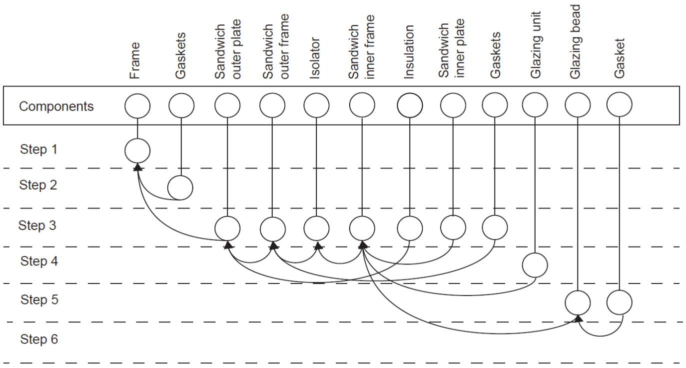
| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

| gp=[gp1 + gp2 + ...gp(n)] / n | |
|---|---|
| gp = [2*8+9*10] /11 | |
| gp = | 9.63 |



## Physical Decomposition

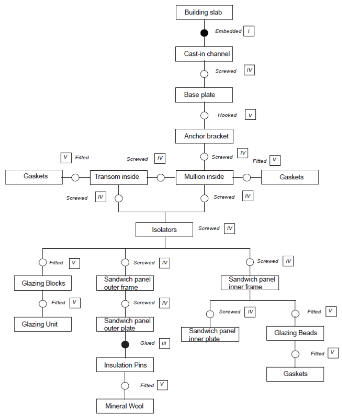
| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |




## Physical Decomposition

| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |

| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 0 | 2 | 0 | |
| III | 1 | 4 | 4 | |
| IV | 10 | 5 | 50 | |
| V | 8 | 6 | 48 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 20 | | 103 | 5.15 |

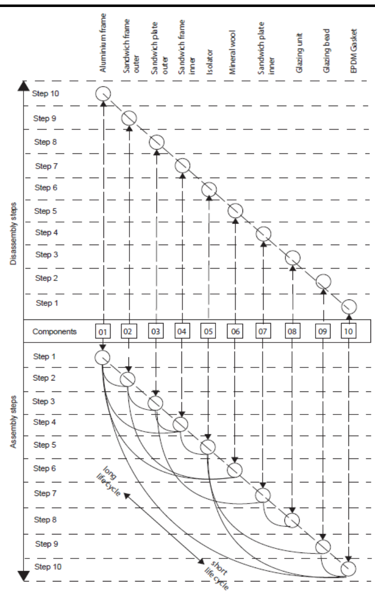



## Physical Decomposition

| 8. Life Cycle Coordination | Points |
|---|---|
| Assembly / Disassembly coordination + Use life cycle and Technical life cycle coordination | 10 |
| Assembly / Disassembly coordination + NO Use life cycle and Technical life cycle coordination | 6 |
| NO Assembly / Disassembly coordination + Use life cycle and Technical life cycle coordination | 4 |
| NO Assembly / Disassembly coordination + NO Use life cycle and Technical life cycle coordination | 1 |

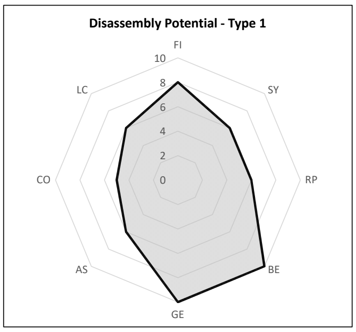
| use life-cycle | | technical life-cycle | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Component: | Years: | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 |
| Aluminium frame | 50 | 75 | | | | | | | | | |
| Sandwich frame outer | 50 | | 75 | | | | | | | | |
| Sandwich plate outer | 50 | | | 75 | | | | | | | |
| Isolator | 50 | | | | 75 | | | | | | |
| Sandwich frame inner | 50 | | | | | 75 | | | | | |
| Mineral wool insulation | 50 | | | | | | 75 | | | | |
| Sandwich plate inner | 50 | | | | | | | 75 | | | |
| Glazing unit | 50 | | | | | | | | 2 x 30 | | |
| Glazing bead | 50 | | | | | | | | | 30 | |
| EPDM gasket | 50 | | | | | | | | | | 2 x 20 |

source: SBR (2011)




## Type 1 - Disassembly Potential - Results

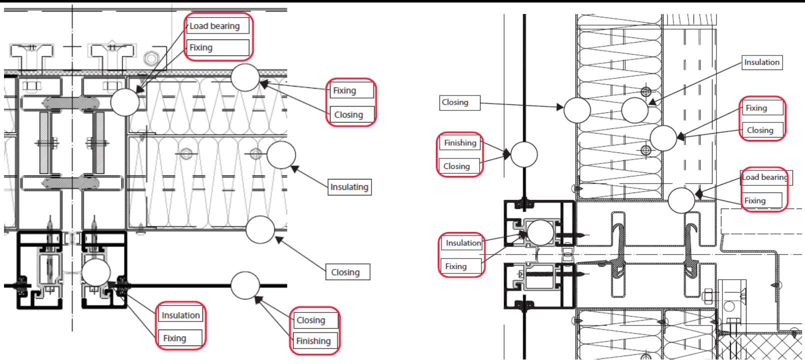
| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 6 |
| Base element specification | BE | 10 |
| Geometry of product edges | GE | 10 |
| Assembly sequence | AS | 6 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 6 |



# Type 2 - Disassembly Potential

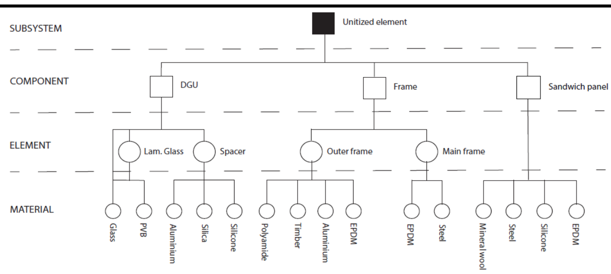
## Functional decomposition

| 1. Functional Independence | Points |
|---|---|
| Total separation/autonomy of functions | 10 |
| Planned integration of functions | 8 |
| Unplanned integration of functions | 2 |
| Total integration of functions | 1 |



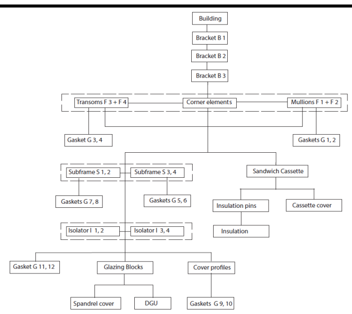

## Functional decomposition

| 2. Systematisation | Points |
|---|---|
| Grouping on system level | 10 |
| Grouping on component stage | 6 |
| Grouping on system, element or material level | 4 |
| No grouping | 1 |



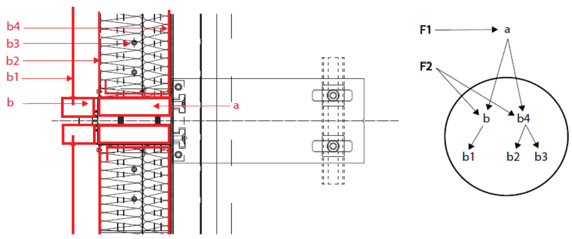

## Technical Decomposition

| 3. Relational Pattern / Hierachy | Points |
|---|---|
| Vertical throughout the schema | 10 |
| Horizontal in lower zones | 6 |
| Horizontal between upper and lower zone | 4 |
| Horizontal in upper zone | 1 |




## Technical Decomposition

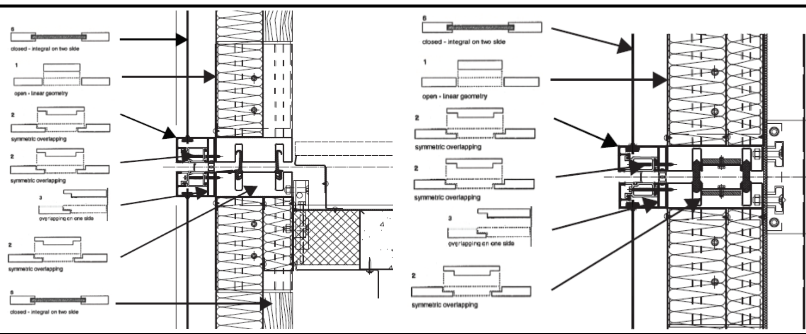
| 4. Base Element | Points |
|---|---|
| Base element with intermediary between two clusters | 10 |
| Base element on two levels | 6 |
| Element with two functions  (BE and one building functi | 4 |
| No base element | 1 |




## Technical Decomposition

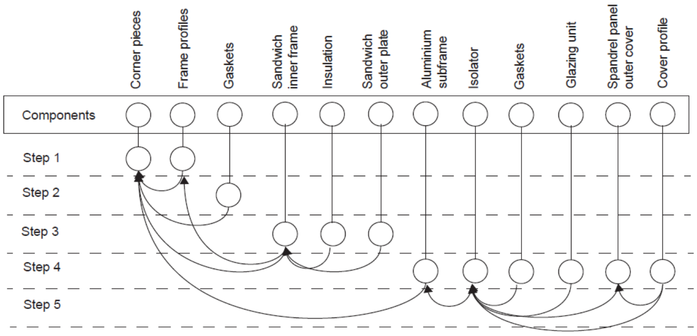
| 5. Geometry | Points |
|---|---|
| Open/linear geometry | 10 |
| Symmetrical overlapping | 8 |
| Overlapping on one side | 7 |
| Unsymmetrical overlapping | 4 |
| Insert on one side | 2 |
| Insert on two sides | 1 |

| | |
|---|---|
| gp=[gp1 + gp2 + ...gp(n)] / n | |
| gp = [2*10+6*8+2*7+3*1] /13 | |
| gp = | 6.54 |



## Physical Decomposition

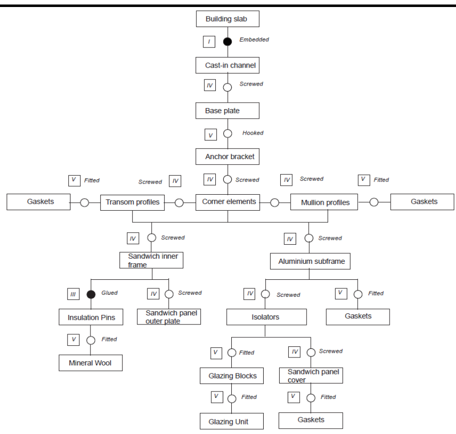
| 6. Assembly Sequence | Points |
|---|---|
| Parallel/open assembly | 10 |
| Stuck assembly | 6 |
| Base element in stuck assembly | 4 |
| Sequential base element | 1 |




## Physical Decomposition

| 7. Connections | Points |
|---|---|
| Indirect with additional fixing device | 10 |
| Indirect via independent third component | 8 |
| Indirect via dependent third component | 6 |
| Direct with additional fixing device | 5 |
| Indirect with third chemical material | 4 |
| Direct between two pre-made components | 2 |
| Direct chemical connection | 1 |

| type | number | value | result | average |
|---|---|---|---|---|
| I | 1 | 1 | 1 | |
| II | 0 | 2 | 0 | |
| III | 1 | 4 | 4 | |
| IV | 9 | 5 | 45 | |
| V | 8 | 6 | 48 | |
| VI | 0 | 8 | 0 | |
| VII | 0 | 10 | 0 | |
| total | 19 | | 98 | 5.16 |

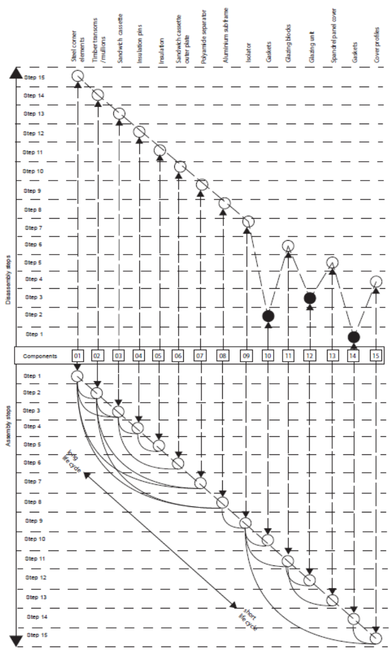



## Physical Decomposition

| 8. Life Cycle Coordination | Points |
|---|---|
| Assembly / Disassembly coordination + Use life cycle and Technical life cycle coordination | 10 |
| Assembly / Disassembly coordination + NO Use life cycle and Technical life cycle coordination | 6 |
| NO Assembly / Disassembly coordination + Use life cycle and Technical life cycle coordination | 4 |
| NO Assembly / Disassembly coordination + NO Use life cycle and Technical life cycle coordination | 1 |

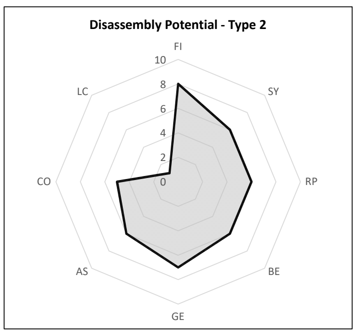
use life-cycle / technical life-cycle

| Component: | Years: | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Steel corner elements | 30 | 75 | | | | | | | | | | | | | | |
| Timber transoms / mullions | 30 | | 75 | | | | | | | | | | | | | |
| Sandwich cassette | 30 | | | 75 | | | | | | | | | | | | |
| Insulation pins | 30 | | | | 75 | | | | | | | | | | | |
| Insulation | 30 | | | | | 75 | | | | | | | | | | |
| Sandwich cassette outer plate | 30 | | | | | | 75 | | | | | | | | | |
| Polyamide separator | 30 | | | | | | | 75 | | | | | | | | |
| Aluminium subframe | 30 | | | | | | | | 75 | | | | | | | |
| Isolator | 30 | | | | | | | | | 75 | | | | | | |
| Gaskets | 30 | | | | | | | | | | 20 | | | | | |
| Glazing blocks | 30 | | | | | | | | | | | 75 | | | | |
| Glazing unit | 30 | | | | | | | | | | | | 30 | | | |
| Spandrel panel cover | 30 | | | | | | | | | | | | | 75 | | |
| Gaskets | 30 | | | | | | | | | | | | | | 20 | |
| Cover profiles | 30 | | | | | | | | | | | | | | | 75 |

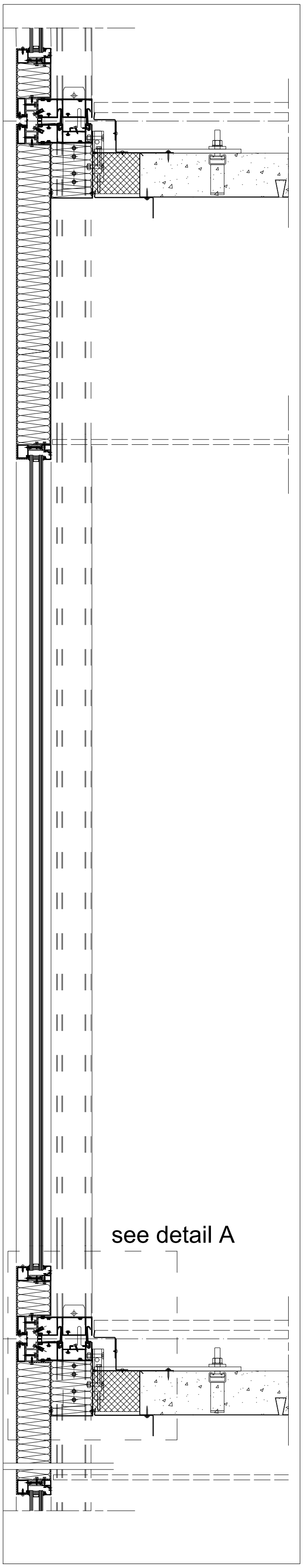


## Type 2 - Disassembly Potential - Results

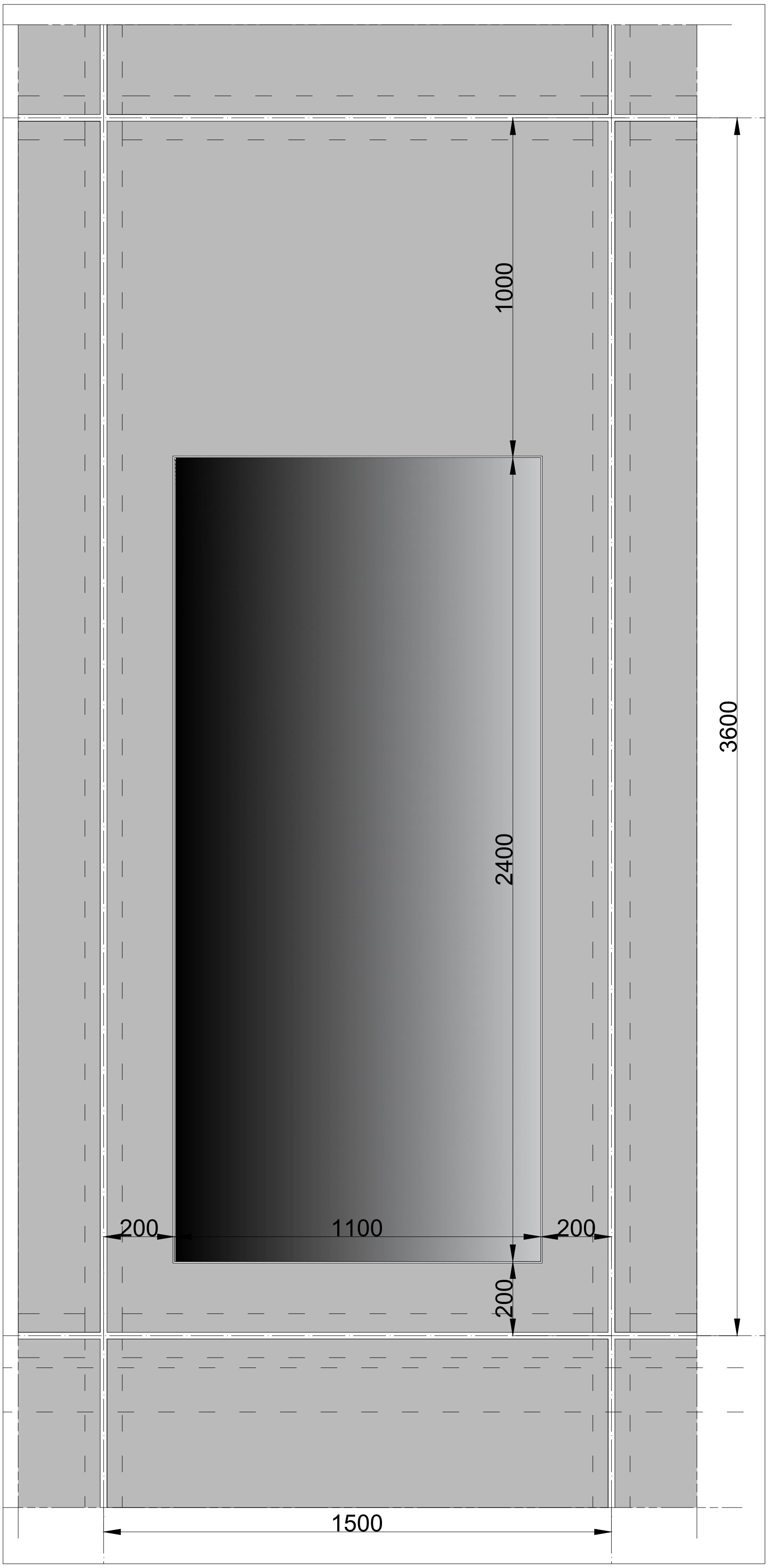
| Criteria | | Points |
|---|---|---|
| Functional Independence | FI | 8 |
| Systematization | SY | 6 |
| Relational patterns | RP | 6 |
| Base element specification | BE | 6 |
| Geometry of product edges | GE | 7 |
| Assembly sequence | AS | 6 |
| Connections | CO | 5 |
| Life cycle co-ordination of materials and functions | LC | 1 |



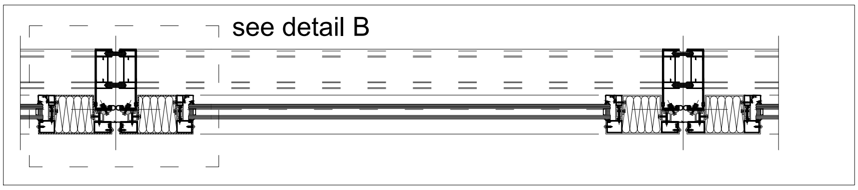
# Proposal Type 1




Vertical section 1:20

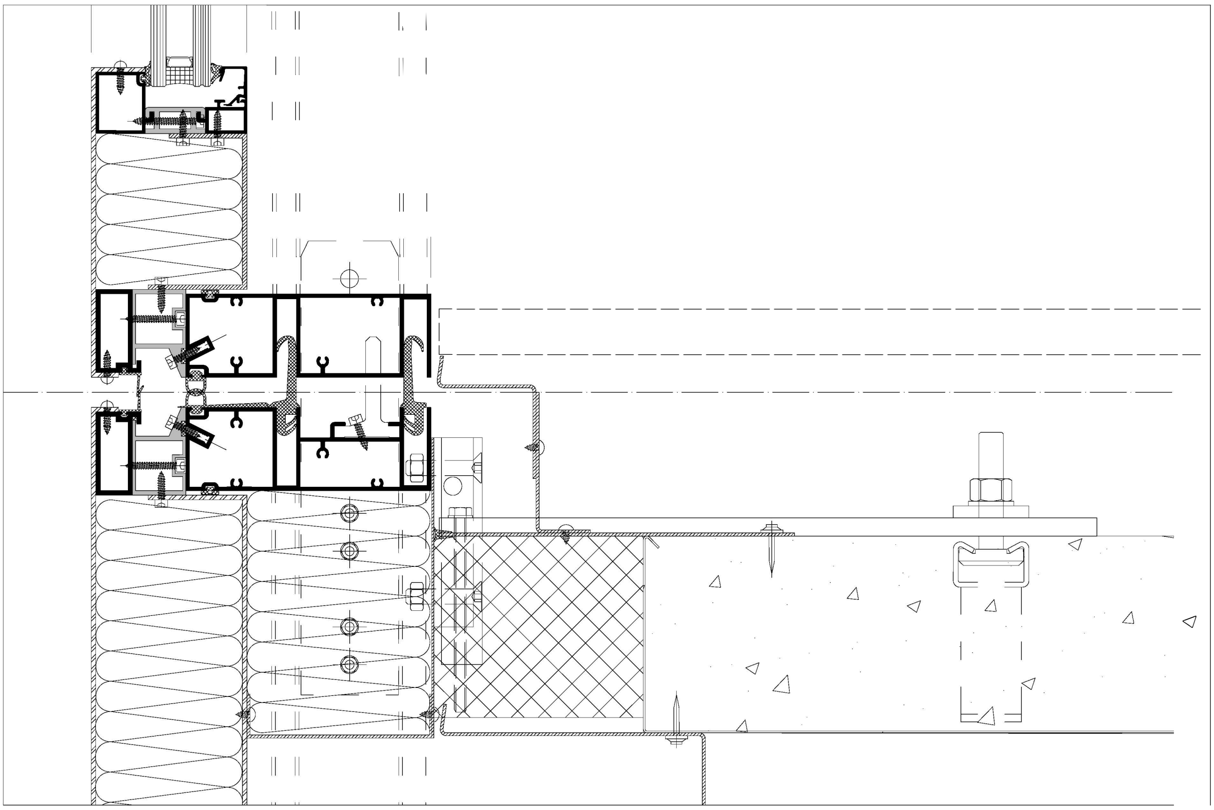



Elevation 1:20

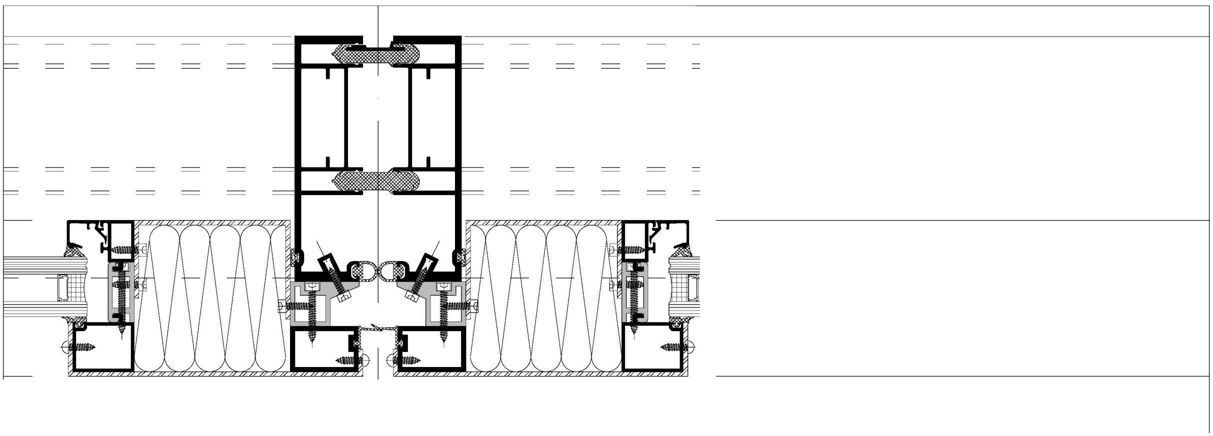



Horizontal section 1:20

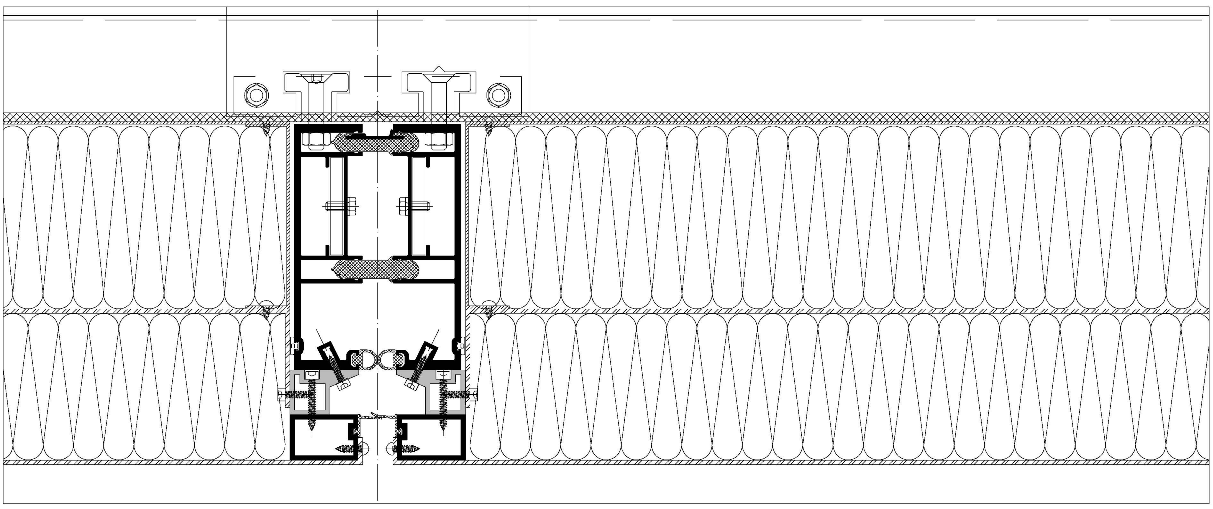
# Proposal Type 1



Vertical detail A 1:5

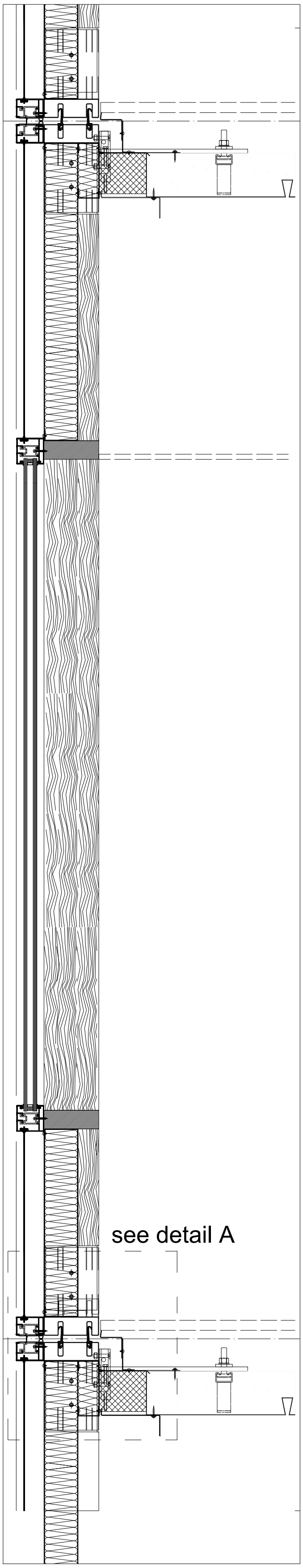


Vertical detail B 1:5

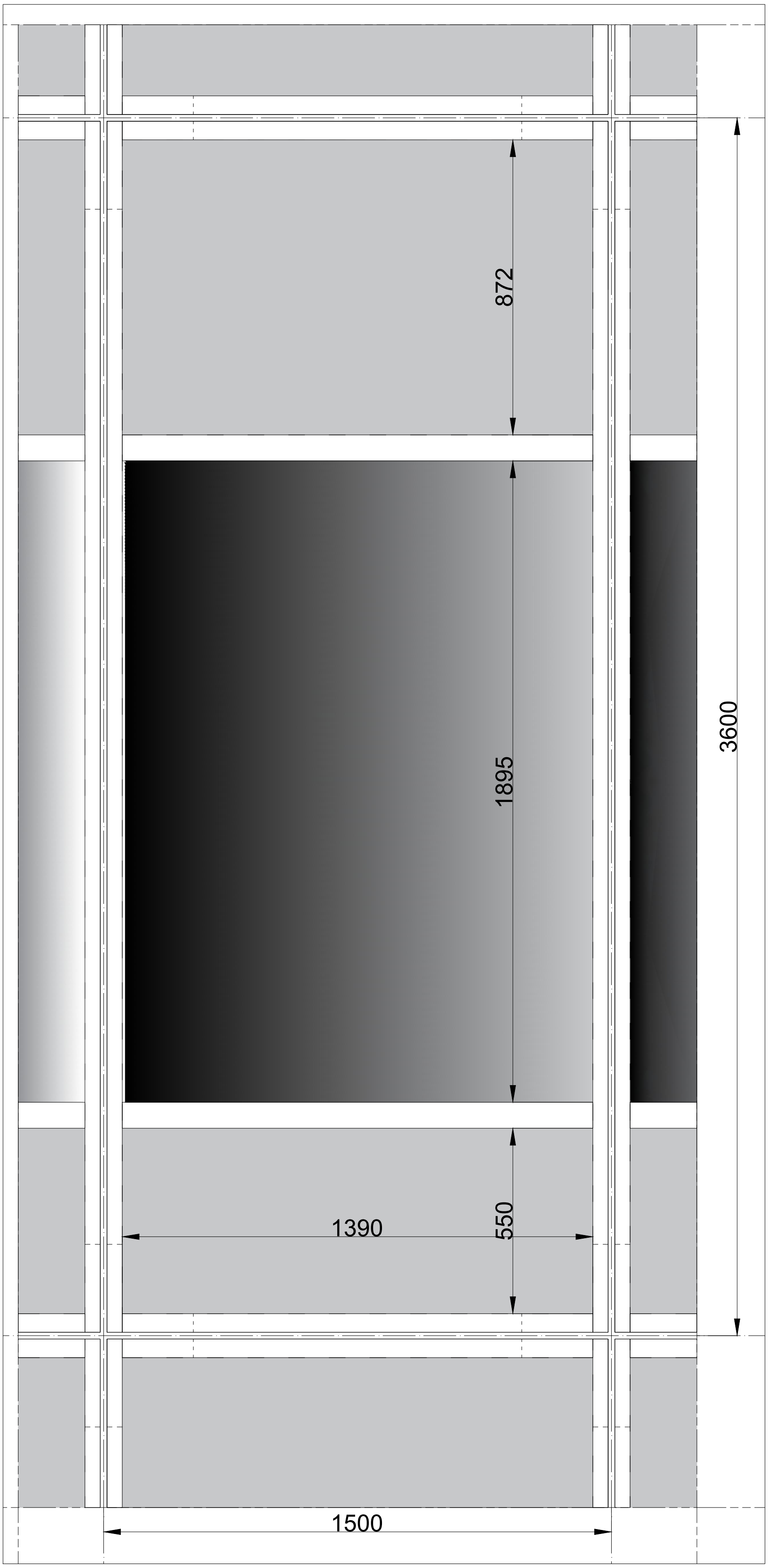


Horizontal detail C 1:5

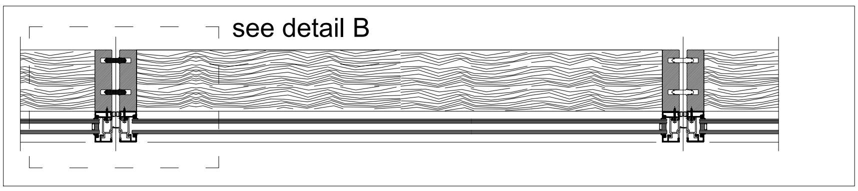
# Proposal Type 2




Vertical section scale 1:20

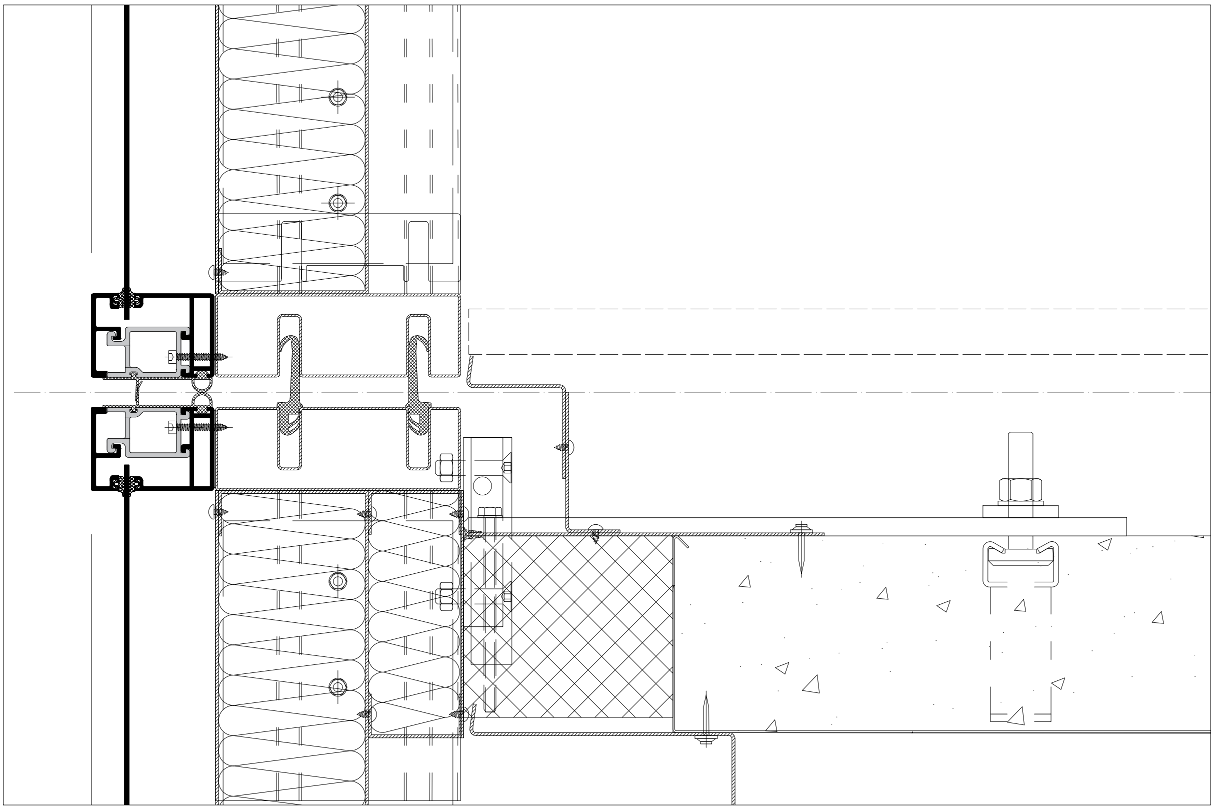



Elevation scale 1:20

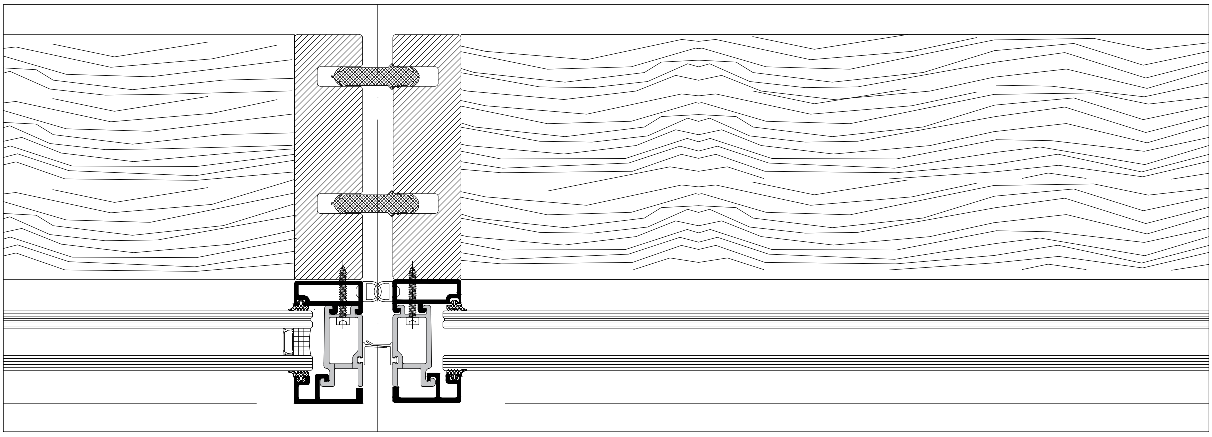



Horizontal section scale 1:20

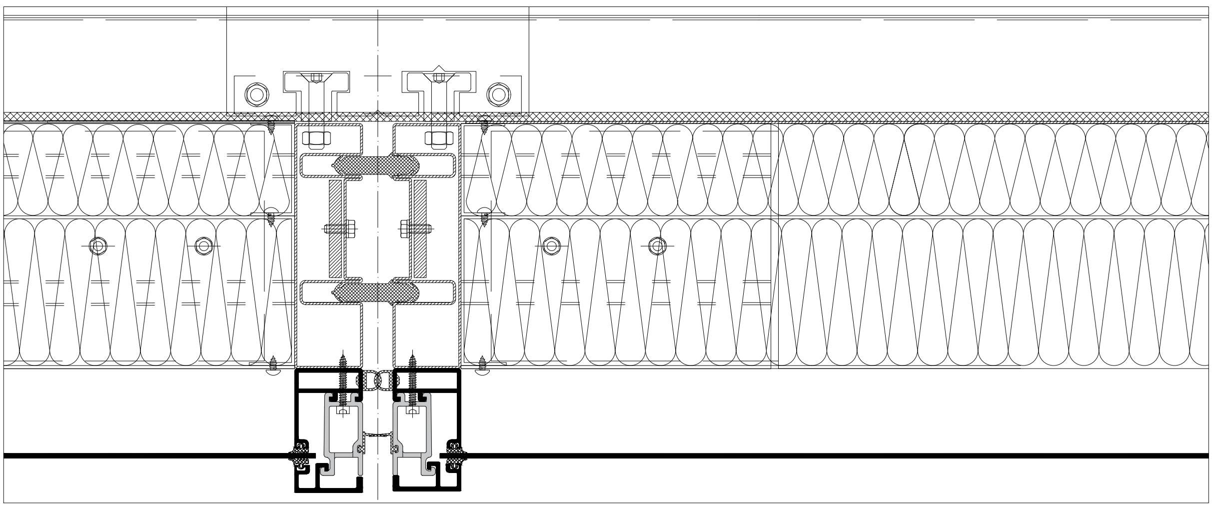
# Proposal Type 2



Detail A scale 1:5



Detail B scale 1:5



Detail C scale 1:5

# 11. Appendix C

## Assembly and disassembly practice

# Assembly process

To gain more insight in the production process the assembly process of a unit for a project in London is documented. The unit consists of an Aluminium frame, a fixed and openable glazing insert, a glazed balustrade with Terracotta fins and an Aluminium bullnose. The production adheres to traditional assembly line procedures with each operator being in charge of certain manufacturing steps.

Date: 22.01.2020
Time: 12.00h – 16.00h
Location: Scheldebouw, Middelburg
Project sample: One Crown Place, London UK
System: female-female
Dimensions: 3.21 x 1.80m

1. Pre-assembly

The profiles are already fitted with thermal isolator in place by the Aluminium extruding company and prepared inhouse via CNC machine for length angles, cut outs and holes. All profiles are already organized with barcode stickers for continuous identification.
Firstly gaskets are inserted into the groves with the help of a hand hold roller. Rockwool pieces are fitted into the ends of the profiles to reduce acoustic transmission. Further foam pieces are inserted into profiles to prevent later applied silicone to protrude too far into the profiles. A metal lightning conductor is applied to bridge the PVC thermal insulator rolled between inner and outer Aluminium profile. An anchor bracket from stainless steel and its matching counter plate is fixed on mullion profiles. The counter plates are positioned inside the profiles and fixed with a little screw to prevent them from sliding out of position in case the bracket needs replacement.
All screws are fixed with adhesive (Loctite 243) to lock the threads against loosening due to transport vibrations. All small screws are fitted with a torx head (hexalobular internal). The big screws for the anchor bracket are fitted with hexagon socket heads.

Fig. X – Pre-assembly (source: own image)

2. Assembly

At this station the frame is assembled. At first the edges of the prepared mullions and transoms are freed from dust and fat with a spiritus based cleaner (Dow Corning Dowsil R-40). Then the cut edges of the profiles are covered generously covered with black silicone Dow Corning 791. A one component, neutral curing silicone seal for use with general glazing and sealing of curtain and other facades which allows for movement allowance of up to 50%. The transom and mullion profiles are assembled vis screws into the screwports of the profiles. Any excessive silicone pressed out of the joints is removed by spatula and the joints are cleaned with a cloth netted with Dowsil R-40.
At this station a stainless steel window-washpoint is fixed as well to some of the frames. It helps later to fix the building maintenance cradle.

Fig. X – Assembly of the frame (source: own image)

3. Table 1

After the initial assembly of the frame in the previous step it is now checked to feature the necessary squareness by measuring the diagonal. If necessary the frame is amended to form a perfect square. A preformed backpan from 2mm galvanized steel is inserted in the spandrel panel section and fixed with stainless steel blind rivets. Blind rivets are generally used to connect profiled sheets with each other, with edge stiffening plates or other cold profiles. The necessary holes were inserted during the CNC machining of the profiles. The heads of the rivets are covered with dots of silicone to increase air tightness. The upfolded edges of the backpan are covered all around with a strip of silicone, with special attention to the corners.
At this table the outer frame of the openable elements are inserted. They were pre-assembled beforehand, apart from this assembly line. Their frames are mitred cut and connected via aluminium cleats. Before the cleats are inserted a two component glue SikaForce-7720 L45 is applied.  After that the corners are nailed for additional strength.
Prior inserting the outer frames the outer gaskets are inserted in the main frame. The outer frame of the openable element is fixed via stainless steel screws with hex-key heads into the base frame. The hollow space between outer frame and basic frame is filled with a foam element.

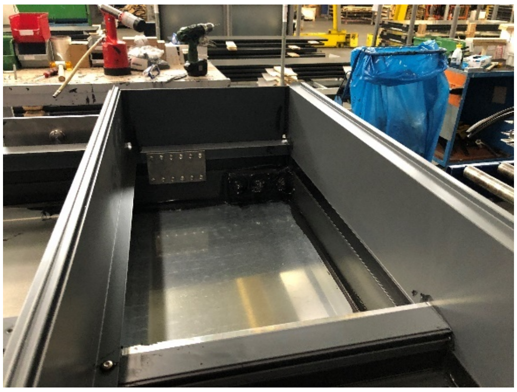


Fig. X – Installation of backpan (source: own image)

4. Table 2

At this station the openable element, also pre-assembled beforehand in a different location in the factory, is lifted into place via suction cup crane and the hinges are connected to inner and outer frame. Fixing blocks are screws into the outer frame of the openable element vis stainless steel screws with hex-key heads.
Further the insulation pins are fixed with hot glue SikaMelt 9285 MC - HP PSA Hot Melt 280ml to the inside face of the backpan. The glue used is resin based and applied via a pneumatic heavy duty

hotmelt glue gun. The insulation pins hold the insulation in place, preventing it from sagging to the floor resulting in uninsulated areas.

5. Table 3

Rockwool is pressed in the spandrel panels at this station. The insulation package consists of two layers placed above each other so that the seams are offset from each other preventing potential cold bridges. The rockwool is secured by thin stainless steel discs sticked upon the insulation pins.

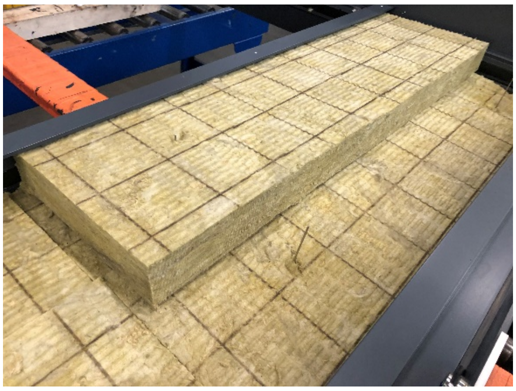


Fig. X – Installation of mineral wool (source: own image)

6. Table 4

All glazing is incorporated at this station. The double glazed units are lifted in place and supporting blocks from PVC are placed around to allow ventilation around the glazing unit. The glazing units are secured via glazing beads and glazing gaskets.
The spandrel panel is closed from the outside by applying a powdercoated Aluminium sheet. Before insertion silicone is added all around with special attention paid to the corner situations. The plate is fixed from outside with visible stainless steel screws featuring hex-key heads. The screws with covered in the following steps with terracotta strips. In addition powdercoated aluminium transoms are screwed upon the outer frame.

Fig. X – Installation of glazing and closure of backpan (source: own image)

7. Table 5

The French balcony also pre-assembled beforehand in a different location in the factor is fixed on top of the openable element with the help of the previously added distance blocks. All glazing surfaces are cleaned.

8. Table 6

All remaining gaskets are added in this station and surplus strips are cut off. Firstly the receiving grooves are cleaned from debris and fat. Then the gaskets are pulled into the groves and cut to length. Ventilation holes are cut into the lip gaskets to prevent any moisture built-up in the frame.

Fig. X – Installation of last gaskets (source: own image)

9. Table 7

At this table all the terracotta elements are fixed. Firstly the various elements are chosen ac-cording to applied barcode and matching colour shade. Since terracotta is a type of earthen-ware which is a clay-based unglazed or glazed ceramic slight colour changes can occur. The terracotta profiles received earlier clips which were attached via low modulus silicone sealant Dowsil 791 FoilPack 600ml Black or Dowsil 896 600ml Black Panel Fix. Via hooks the terracotta is placed onto the previously assembled. The terracotta profiles are fixed in the following or-der, first the vertical fins, then the cover panel, then the side panels.

Fig. X – Installation of Terracotta (source: own image)

10. Table 8

At the last station the bullnose is fixed. Previously it was assembled separately from two profiles and two panels. The assembled panel is hooked onto a groove of the mainframe which will carry the vertical loads. Fixing screws on the underside secure the bullnose against uplift.

Fig. X – Installation of bullnose (source: own image)

11. Final quality control and packaging
A final quality control takes place in the form of a visual inspection before the elements are loaded onto a crat and covered with a PVC film.

Findings
Several items reach the assembly line in a pre-assembled state already.
The assembly takes place in a traditional assembly line work, where every employee fulfils a limited number of working steps.
Three types of adhesives are used in the assembly and applied generously.
The number of various screw types is high, the number of screw head types is limited to two.
The assembly sequence is clearly defined and can not be freely modified.
The waste production during assembly is limited.
The quality of the units are high, there are few units with quality defects.
Heavy items i.e. the glazing units are lifted in via crane.

# Disassembly exercise

For better understanding of the hurdles for disassembly a façade unit was dismantled in Scheldebouw's production plant. The element in question was a test sample of the project Lillie Square in London, UK. It had been exposed to the elements for some time so that its insulation was thoroughly wet and moss had started to grow on it. It had been stored horizontally so that no moisture could flow out. Not all cover elements were still in place but there were sufficient elements still in place to simulate all steps required for a disassembly.

Date: 22.01.2020
Time: 10.00h – 16.00h
Location: Scheldebouw, Heerlen
Project sample: Lillie Square, London UK
System: female-female
Dimensions: 4,72 x 2.99m

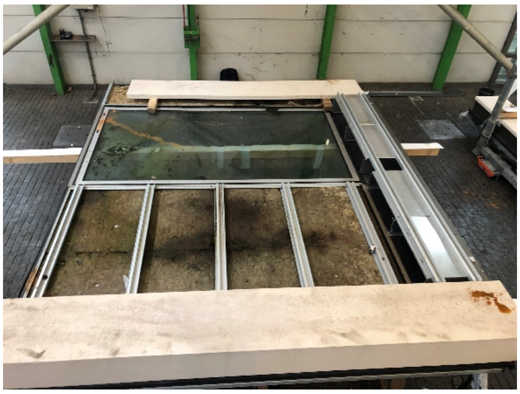


Fig. X – Element prior disassembly (source: own image)

Step 1 – Removal of GRC elements

The first step was to remove the last added elements of the system, the glass fiber reinforced concrete elements (GRC). The disassembly started with unscrewing the fasteners which were securing the element against sliding sideways. The screws to be unfastened were featuring Torx and Philips heads. Then the element was pushed via hammer blows slowly sideways so that the fasteners disengaged from the internal hooks. In the end the system could be lifted with the help of suction cups  from the unitized element. The gaskets fixed to the GRC element were glued on and disintegrated at the attempt to remove them.

Fig. X – Removal of GRC elements (source: own image)

Step 2- Removing Aluminium subframe

In the following step the Aluminium subframe was removed. At first it appeared to be fixed via rivets on the main frame and initially the rivets were removed which proved a very time-consuming process. However at closer inspection it was established that the subframe was as a whole screwed onto the mainframe. Hence by removing the Torx screws the whole subframe could be removed as one component. Since the subframe was considered to exist from the same material, and the removal of the rivets was slow, further disassembly was refrained from. Notable was that the location of the screws was very difficult to access with the drill, an extension shaft was required.

Fig. X – Removal of GRC elements (source: own image)

Step 3 – Removal siderails

After the removal of the subframe further aluminium rails were to be removed to allow access to other fixings. The siderails were physically fixed with Torx screws which could be easily removed. IN addition the rails were sticked to the mainframe by silicone glue which had to be loosened by applying force via a crowbar and cutting it with a carpet knive. The work turned out very laborious due to the glue.

Step 4 – Removal steel cases

Several stainless steel cases were fixed upon an underlying Aluminium sheet to receive exhaust air from inside the building i.e. bad and kitchen, and to channel it through gratings toward the outside. Originally the steel cases were covered with GRC elements and Aluminium gratings but these were missing at the sample. The steel cases were fixed with Torx screws to key-hole slots. After removing the screws the boxes did not slide out since they were glued in addition to the underlying Aluminium sheet. With the deployment of the crowbar, a big screwdriver and a carpet knife the glue connection could be slowly cancelled. Big chunks of glue remained on the steel cases and the Aluminium plate.

Fig. X – Removal of steel boxes (source: own image)

Step 5 – Removal Aluminium plate

Screws and rivets were used to fix the Aluminium plate to the mainframe. The screws were fast removed with the cordless drill. Following the rivets were drilled open, some rivets had to be removed using a hammer and a chisel. The Aluminium plate was not glued to the main frame, which made removal easier.

Step 6 – Removal gaskets

In the next step the main- and the lip gaskets were removed. The majority could be removed easily out of their groves by hand. However in places they were glued onto the main Aluminium frame and there the gaskets broke when pulling them off the frame. Removing the remaining spots of rubber gaskets proved very difficult and laborious so it was decided to refrain from it.

Step 7 – Removal insulation

Once all covers were taken off the removal the insulation could start. The insulation was held in place with insulation pins protruding through the insulation and secured with thin metal discs on top, locking in the insulation in between. The removal of the securing discs was possible by hand via lifting them from the pins. Afterwards the insulation could be removed by hand. Since it was very wet it broke into small pieces which made the process very tedious. The insulation pins could not be taken off the backpan as they were glued on with resin.

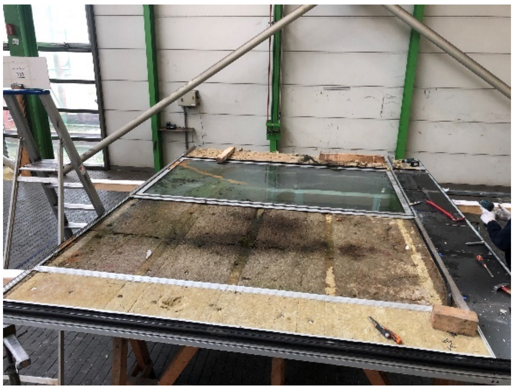


Fig. X – Removal of mineral wool (source: own image)

Step 8 – Removal steel backpan

In order to gain access to the backpan the whole frame needed to be turned around. The mild steel sheets were fixed to the main frame by numerous rivets and glue. The disengagement of the rivets took place again by firstly drilling off the screw heads and secondly cutting off resistant rivets with hammer and chisel. To retrieve the panel it was put under tension with a suction cup glass lifter and then the glue could be cut off from below the frame.

Step 9 – Removing glazing unit

At first the glazing gaskets were pulled out by hand so that the glazing beads could be clicked out. Both actions proved to be very straightforward. Since the sample was used for waterproofing tests the gap between double glazed unit and aluminium frame was filled with silicone. It had to be cut in and then the glass could be evacuated with the suction cup glass lifter.

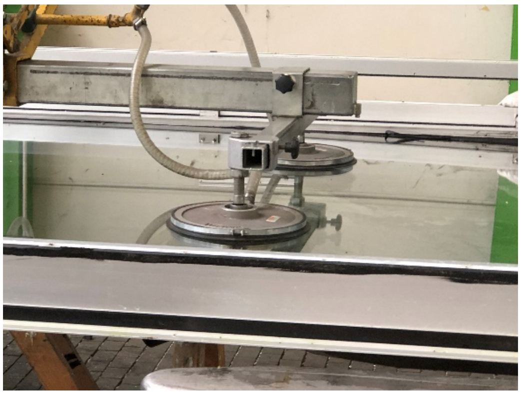


Fig. X – Removal of glazing element (source: own image)

Step 10 – Removal fixed frame

To take out the frame of the fixed glazing a lot of effort had to be taken. Unscrewing the fixing clips was quickly done with the battery drill. Then the generously applied silicone in the gad had to be taken out with the carpet knife and chisel. An underlying foamstrip appeared which was taken out the same. Plastic aluminium plates were pressed out with the chisel. Using a lifting jack from below the frame in combination with blows from the hammer, the glazing from could be forced out of the main frame.

Step 11 – Removal anchor plate

The anchor plate could be easily unscrewed with a hex-key. No glue was used here.

Fig. X – Removal of anchor plate (source: own image)

Step 12 – Removal alignment brackets

The alignment brackets are set into an outer groove of the main frame. Their torx screws were loosened with the battery drill and then shifted sideways with light hammer blows until they were free from the groove.

Step 13 – Removal remaining gaskets

Any remaining gaskets were removed by hand. Again, at places where the gaskets were glued to the frame they broke off. Complete removal was not possible.

Step 14 – Disassemble frame

The frame was held by several screws through the mullions into the screw ports of the transoms. Further silicon was applied to the cut sections. In order to disassemble the mainframe all backpans had to be removed which was laborious due to the many rivets. Due to time constraints this action could not take place anymore but the necessary steps were obviously to loosen the torx screws and driving the profiles apart with hammer blows.

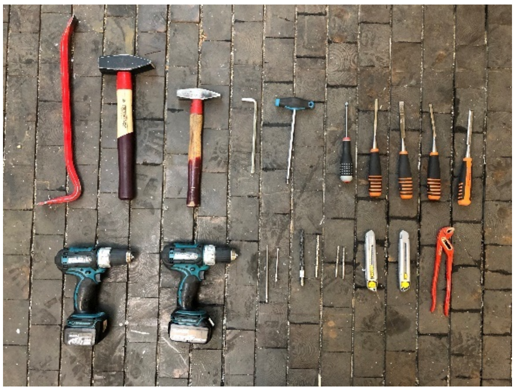


Fig. X – Used tools (source: own image)

## Summary

The disassembly procedure took approximately six hours. In the opinion of the craftsmen the disassembly took longer than the assembly. The application of hand tools and power equipment was manageable. The main challenges that prevented fast progress were glued connections. Their strength was surprisingly high. The riveted connections and the sheer number of them were exhausting. The backpans were fixed with several hundreds of them to the frame. Since the reverse logistic was unknown, the correct sequence of disassembly steps needed to be discussed first before applying. The weight of the GRC elements and of the glazing unit asked for careful handling which slowed down the disassembly process. The overall size of the element resulted in much time spend on walking around the sample. Several foam pieces came to the light after removing sealants. When pulling them, they broke very easily and it took a good time to remove them. The fact that most of the insulation was very wet was very detrimental to the removal process. All screwed connection on the other hand were very simple and quick to be loosened. Gaskets which were not glued in could be removed effortlessly. The lightweight materials as Aluminium, Rockwool, Rubber and Plastics were handy to remove. Any usage of the lifter crane slowed down the logistics immensely.

# 11. Appendix D

## Product information

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# Material Data Sheet

## Aluminium alloy

Materials Services
Technology, Innovation
& Sustainability



| Material designation: | EN-Material No. | DIN-Material No. |
|---|---|---|
| | EN AW-6060<br>[EN AW-Al MgSi] | 3.3206 |

### Scope

This data sheet applies to cold drawn and extruded rod/bar, tubes and profiles made of aluminium-silicon alloy EN AW-6060.

### Application

Among the heat treatable aluminium alloys the material EN AW-6060 shows medium mechanical properties and a good atmospheric and seawater corrosion resistance. The material is good weldable and is used for example in the automotive and railway industry.
The alloy EN AW-6060 is heat treatable and it is suitable for decorative anodizing.

### Chemical composition in %

| Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 0.30–0.6 | 0.10–0.30 | ≤ 0.10 | ≤ 0.10 | 0.35–0.6 | ≤ 0.05 | ≤ 0.15 | ≤ 0.10 | Rest |

Others[a]: Each: max. 0.05 % Total[b]: max. 0.15 %

[a] „Others" includes listed elements for which no specific limit is shown as well as unlisted metallic elements. The producer may analyze samples for trace elements not specified in the registration or specification. However, such analysis is not required and may not cover all metallic „Other" elements. Should any analysis by the producer or the purchaser establish that an „Others" element exceeds the limit of „Each" or that the aggregate of several „Others" elements exceeds the limit of „Total", the material shall be considered non-conforming.

[b] The sum of those "Others" metallic elements 0,010 % or more each, expressed to the second decimal place before determining the sum.

### Mechanical properties at room temperature (cold drawn rod/bar and tube)

| Temper | Dimensions | | | Yield strength | Tensile strength | Elongation | | Hardness[1)] |
|---|---|---|---|---|---|---|---|---|
| | D[a)] | S[b)] | t[c)] | $R_{p0,2}$ | $R_m$ | A | $A_{50}$ | |
| | [mm] | [mm] | [mm] | [N/mm²] | [N/mm²] | [%] | [%] | HBW |
| T4 | -<br>≤ 80 | -<br>≤ 80 | ≤ 5<br>5 < t ≤ 20 | ≥ 65<br>≥ 65 | ≥ 130<br>≥ 130 | ≥ 12<br>≥ 15 | ≥ 10<br>≥ 13 | 50<br>50 |
| T6 | ≤ 80 | ≤ 80 | ≤ 20 | ≥ 160 | ≥ 215 | ≥ 12 | ≥ 10 | 75 |

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Chairman of the Supervisory Board: Guido Kerkhoff
Executive Board: Joachim Limberg (Chairman), Markus Bistram, Hans-Josef Hoss, Dr. Klaus Keysberg
Commercial Register: Essen HRB 22760, Vat-No.: DE811154735

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## Mechanical properties at room temperature (extruded rod/bar and tube)

| Temper | Dimensions | | | Yield strength | Tensile strength | Elongation | | Hardness[1] |
|---|---|---|---|---|---|---|---|---|
| | D[a] [mm] | S[b] [mm] | t[c] [mm] | $R_{p0,2}$ [N/mm²] | $R_m$ [N/mm²] | A [%] | $A_{50}$ [%] | HBW |
| T4 | ≤ 150 | ≤ 150 | ≤ 15 | ≥ 60 | ≥ 120 | ≥ 16 | ≥ 14 | 50 |
| T5 | ≤ 150 | ≤ 150 | ≤ 15 | ≥ 120 | ≥ 160 | ≥ 8 | ≥ 6 | 60 |
| T6 | ≤ 150 | ≤ 150 | ≤ 15 | ≥ 150 | ≥ 190 | ≥ 8 | ≥ 6 | 70 |
| T64 | ≤ 50 | ≤ 50 | ≤ 15 | ≥ 120 | ≥ 180 | ≥ 12 | ≥ 10 | 60 |
| T66 | ≤ 150 | ≤ 150 | ≤ 15 | ≥ 160 | ≥ 215 | ≥ 8 | ≥ 6 | 75 |

## Mechanical properties at room temperature (extruded profiles)

| Temper | Wall thickness | Yield strength | Tensile strength | Tensile strength | | Hardness[1] |
|---|---|---|---|---|---|---|
| | t [mm] | $R_{p0,2}$ [N/mm²] | $R_m$ [N/mm²] | A [%] | $A_{50}$ [%] | HBW |
| T4 | ≤ 25 | ≥ 60 | ≥ 120 | ≥ 16 | ≥ 14 | 50 |
| T5 | ≤ 5<br>5 < t ≤ 25 | ≥ 120<br>≥ 100 | ≥ 160<br>≥ 140 | ≥8<br>≥ 8 | ≥ 6<br>≥ 6 | 60<br>60 |
| T6 | ≤ 5<br>5 < t ≤ 25 | ≥ 150<br>≥ 140 | ≥ 190<br>≥ 170 | ≥ 8<br>≥ 8 | ≥ 6<br>≥ 6 | 70<br>70 |
| T64 | ≤ 15 | ≥ 120 | ≥ 180 | ≥ 12 | ≥ 10 | 60 |
| T66 | ≤ 5<br>5 < t ≤ 25 | ≥ 160<br>≥ 150 | ≥ 215<br>≥ 195 | ≥ 8<br>≥ 8 | ≥ 6<br>≥ 6 | 75<br>75 |

[1] For information only
[a] D = Diameter for round bar
[b] S = Width across flats for square and hexagonal bar, thickness for rectangular bar
[c] t = Wall thickness for tubes

## Reference data for some physical properties (for guidance only)

| Density at 20 °C [kg/dm³] | Electrical conductivity [MS/m] | Thermal conductivity [W/m•K] | Specific heat capacity [J/kg•K] | Young's modulus [MPa] | Shear modulus [MPa] |
|---|---|---|---|---|---|
| 2.70 | 34–38 | 200–220 | 898 | 69500 | 26100 |

Mean linear thermal expansion coefficient [$10^{-6}$ $K^{-1}$]

| -50–20 °C | 20–100 °C | 20–200 °C | 20–300 °C |
|---|---|---|---|
| 21.8 | 23.4 | 24.5 | 25.6 |

## Guidelines on the temperatures for hot forming and heat treatment

| Annealing | | |
|---|---|---|
| Temperature | Time to heat up | Cooling conditions |
| 360–400 °C | 1.0–2.0 h | ≤ 30 °C/h to 250 °C, below 250 °C on air |

| Precipitation heat treatment | | | |
|---|---|---|---|
| Solution heat treatment | Quenching | Natural ageing | Artificial ageing |
| 525–540 °C | Water, air | 5–8 days | Temperature: 155–190 °C<br>Time: 4–16 h |

## Processing/Welding

The material is good weldable with the conventional processes (MIG and TIG). As welding filler metal is SG-AlMg5, SG-AlSi and SG-AlMg3 recommended. In annealed temper there may arise some difficulties during machining (for example ribbon or thread chips). The machinability improves with the grade of ageing.

## Remarks

According to EN 602 the use of the material is allowed for the contact with food.
For decorative anodizing the material EN AW-6060 should be selected as anodizing quality acc. to DIN 17611 for quality reasons.

## Editor

thyssenkrupp Materials Services GmbH
Technology, Innovation & Sustainability (TIS)
thyssenkrupp Allee 1
45143 Essen
Germany

## Reference

| | |
|---|---|
| DIN EN 485-2 : 2016-10 | Beuth Verlag GmbH, Postfach, D-10772 Berlin |
| DIN EN 573-3 : 2013-12 | |
| DIN EN 754-2 : 2017-02 | |
| DIN EN 755-2 : 2016-10 | |
| Aluminium-Werkstoff-Datenblätter | Aluminium-Verlag Marketing & Kommunikation GmbH |
| Aluminiumtaschenbuch Band 1 – 3 | D-40003 Düsseldorf |

## Important Note

Information given in this data sheet about the condition or usability of materials respectively products are no warranty for their properties, but act as a description.
The information, we give on for advice, comply to the experiences of the manufacturer as well as our own. We cannot give warranty for the results of processing and application of the products.

ROCKWOOL

| EN15804 Core EPD | Alle rechten voorbehouden | March 17, 2020 |
|---|---|---|

| | |
|---|---|
| **Bedrijfsinformatie** | ROCKWOOL B.V.<br>Postbus 1160<br>6040 KD Roermond<br>tel. ++31 (0) 475 35 35 35<br>fax. ++31 (0) 475 35 34 84 |
| **Product** | **Spouw- en vliesgevelplaten 433SIL000 RockFit Premium** |
| **Standaard** | Fabrikant eigenverklaring gebaseerd op het EN15804 format — **Type** Wieg-tot-graf |
| **Datum van uitgifte** | 17-3-2020 — **Verzamelperiode** 2017 |
| **Geldig tot:** | 16-3-2025 |
| | Gegevens op dit certificaat zijn opgesteld door The Right Environment met gebruik van SimaPro, gebaseerd op de EN15804 EPD standaard, het is geverifieerd volgens de MRPI® toetsing door een onafhankelijke derde partij |

**Producteenheid Omschrijving** — **1 m2 Spouw- en vliesgevelplaten 433SIL000**

| Dikte | Gewicht | Bekleding | Resin |
|---|---|---|---|
| 40 mm | 2,80 kg/m2 | | 3,1% |

| | |
|---|---|
| **Representatief voor** | ROCKWOOL producten geproduceerd in de Benelux |
| **Opmerkingen** | Isolatieproducten verlagen het energieverbruik in gebouwen. De besparing leidt tot vele malen grotere milieubesparing dan de belasting van isolatieproducten. Een goede prestatie van het gebouw tijdens het gebruik is dus belangrijker dan de verschillen in de milieubelasting van isolatieproducten. De vergelijking op basis van EPDs kan niet los worden gezien van de prestatie van het gebouw. Daarom moet voor een vergelijking altijd gekeken worden naar de prestatie van producten in een gebouw, en over de hele levensduur van een gebouw. De milieuprestatie kan niet los worden gezien van de daarbij bijbehorende functionele prestaties zoals isolatie, brandwerendheid, akoestisch comfort en andere producteigenschappen zoals die door de EN15804 en de CE-markering worden gedefinieerd. |

## Bewijs van verificatie

EN15804 dient als "core PCR"

Geverifieerde verklaring van een onafhankelijke derde partij volgens de ISO 14025

**o** Intern **x** Extern

Onafhankelijke derde partij SGS Search Consultancy

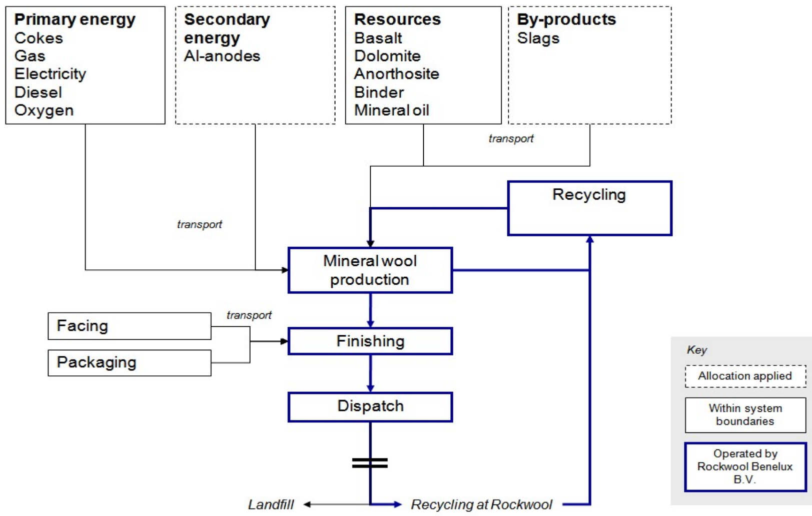
In het algemeen, een vergelijking of evaluatie van EPD data is alleen mogelijk als alle onderliggende en gepresenteerde data zijn opgesteld conform de EN 15804 en als de bouwcontext en/of de productspecifieke prestatiekenmerken in beschouwing worden genomen. EPDs zijn mogelijk niet vergelijkbaar als de eisen uit 15804 sectie 5.3 niet zijn gevolgd, de EPDs de gebouwde omgeving niet beschouwen, en andere regels niet vergelijkbaar zijn (bijvoorbeeld de achtergrondgegevens, aannames over metingen, het type EPD, de productlevensduur en de systeemgrenzen en functionaliteit).

## Deklaratie van materiaalsamenstelling

| | |
|---|---|
| **Referentie** | Alle informatie in relatie tot inhoud en veiligheid van onze producten kan worden verkregen door contact op te nemen met onze technische ondersteuning. |
| **Veiligheidsblad** | Minerale wol vezels worden gesponnen uit gesmolten mineralen gebaseerd op vulkanisch gesteente, zoals diabaas of basalt, van gerecyclede minerale wol en andere secundaire minerale grondstoffen. Afhankelijk van het specifieke product betreft het losse vezels of met hars verbonden vezels. ROCKWOOL minerale wol bevat geen hoog risico stoffen zoals opgenomen op de lijst van de European Chemicals Agency. ROCKWOOL minerale wol is veilig voor gebruik en draagt het EUCEB label. Als meer informatie wordt gewenst, neem a.u.b. contact op met ROCKWOOL. |
| **Stoffen relevant voor REACH (Registation, Evaluation and Authorisation of CHemicals)** | Alle informatie in relatie tot inhoud en veiligheid van onze producten kan worden verkregen door contact op te nemen met onze technische ondersteuning. ROCKWOOL producten bevatten geen stoffen in de categorie "high concern". |

## Systeemgrenzen en procesboom

De procesboom voor minerale wol (alle grondstoffen <1%wt zijn niet weergegeven)
Opmerking: de aanleg en gebruiksfase zijn niet beoordeeld



ROCKWOOL

| Milieu ingrepen | | Productie | Levering | Installatie | Gebruik en onderhoud | Einde toepassing | | | | Module D |
|---|---|---|---|---|---|---|---|---|---|---|
| **Milieuprofiel** | Eenheid | A1, A2, A3 | A4 | A5 | B1 – B7 | C1 | C2 | C3 | C4 | D |
| Klimaatverandering | kg CO2 | 2,56E+00 | 8,75E-02 | 9,65E-02 | MND | MND | 6,12E-02 | 0,00E+00 | 3,05E-03 | -5,77E-03 |
| Ozonlaagaantasting | kg CFK-11 | 1,17E-07 | 1,58E-08 | 5,39E-10 | MND | MND | 1,13E-08 | 0,00E+00 | 8,17E-10 | -3,41E-10 |
| Verzuring | kg SO2 | 1,77E-02 | 3,30E-04 | 3,33E-04 | MND | MND | 2,66E-04 | 0,00E+00 | 1,69E-05 | -9,76E-05 |
| Vermesting | kg PO43- | 3,52E-03 | 5,79E-05 | 6,66E-05 | MND | MND | 4,86E-05 | 0,00E+00 | 3,15E-06 | -8,69E-06 |
| Fotochemische oxydantvorming | kg ethene | 7,51E-04 | 1,46E-05 | 1,38E-05 | MND | MND | 1,07E-05 | 0,00E+00 | 6,60E-07 | -5,12E-06 |
| Uitputting, abiotische grondstoffen (ecxl. fossiele energiedragers) | kg Sb | 1,93E-06 | 3,52E-07 | 4,20E-08 | MND | MND | 1,74E-07 | 0,00E+00 | 6,52E-09 | -1,07E-08 |
| Uitputting, fossiele energiedragers | MJ | 3,53E+01 | 1,30E+00 | 3,09E-01 | MND | MND | 9,32E-01 | 0,00E+00 | 6,71E-02 | -7,13E-01 |
| **Grondstoffen inzet** | | | | | | | | | | |
| Energie, vernieuwbaar, gebruikt als brandstof | MJ, ncw | 1,18E+00 | 1,34E-02 | -6,51E-01 | MND | MND | 8,39E-03 | 0,00E+00 | 6,19E-04 | -1,19E-02 |
| Energie, vernieuwbaar, gebruikt in materiaal | MJ, ncw | 8,51E+00 | 6,80E-03 | 2,23E-01 | MND | MND | 4,66E-03 | 0,00E+00 | 2,98E-04 | -2,03E-01 |
| Energie, vernieuwbaar, totaal | MJ, ncw | 9,69E+00 | 2,02E-02 | -4,28E-01 | MND | MND | 1,30E-02 | 0,00E+00 | 9,18E-04 | -2,15E-01 |
| Energie, niet vernieuwbaar, brandstof | MJ, ncw | 3,61E+01 | 1,33E+00 | 3,09E-01 | MND | MND | 9,49E-01 | 0,00E+00 | 6,86E-02 | -7,95E-01 |
| Energie, niet vernieuwbaar, in materiaal | MJ, ncw | 4,64E-01 | 0,00E+00 | -1,78E-02 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Energie, niet vernieuwbaar, totaal | MJ, ncw | 3,66E+01 | 1,33E+00 | 2,92E-01 | MND | MND | 9,49E-01 | 0,00E+00 | 6,86E-02 | -7,95E-01 |
| Inzet van secundair materiaal | kg | 1,80E+00 | 0,00E+00 | 0,00E+00 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Inzet van vernieuwbare secundaire brandstof | MJ | 0,00E+00 | 0,00E+00 | 0,00E+00 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Inzet van niet vernieuwbare secundaire brandstof | MJ | 2,16E-01 | 0,00E+00 | 4,32E-03 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Inzet van water | m3 | 4,06E-02 | 2,75E-04 | 6,32E-04 | MND | MND | 1,95E-04 | 0,00E+00 | 5,34E-05 | -2,56E-04 |
| **Afval** | | | | | | | | | | |
| Gevaarlijk afval, stort | kg | 2,37E-02 | 0,00E+00 | 4,74E-04 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Niet gevaarlijk afval, stort | kg | 1,90E-01 | 5,20E-02 | 6,21E-03 | MND | MND | 5,79E-02 | 0,00E+00 | 2,82E-01 | -8,03E-04 |
| Radioaktief afval, stort | kg | 7,72E-05 | 9,85E-06 | 4,87E-08 | MND | MND | 6,96E-06 | 0,00E+00 | 4,96E-07 | -2,83E-07 |
| **Andere uitgaande stromen** | | | | | | | | | | |
| Componenten voor hergebruik | kg | 0,00E+00 | 0,00E+00 | 0,00E+00 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Materiaal voor recycling | kg | 1,06E-01 | 0,00E+00 | 1,57E-02 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 5,06E-03 |
| Materiaal voor energieterugwinning | kg | 0,00E+00 | 0,00E+00 | 4,76E-02 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Geexporteerde electrische energie | MJ | 0,00E+00 | 0,00E+00 | 6,71E-02 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| Geexporteerde thermische energie | MJ | 0,00E+00 | 0,00E+00 | 1,31E-01 | MND | MND | 0,00E+00 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| **Aanvullende transparantieparameters** (niet verplicht in EN 15804, maar onderdeel van concept ISO 21930) | | | | | | | | | | |
| Biogene koolstofinhoud van hernieuwbare materialen | kg CO2 | -5,7E-02 | 0,0E+00 | 1,0E-01 | MND | MND | 0,0E+00 | 0,0E+00 | 0,0E+00 | 0,0E+00 |

## [A4] Transport naar de bouwplaats

| Parameter | | |
|---|---|---|
| Brandstoftype | l/100km | 1 liter diesel per 3 km; 150 km, vrachtwagen |
| Afstand | km | |
| Capaciteitsbenuttingsgraad | % | diesel consumptie is voor een gemiddeld belading, 30% komt leeg terug, 70% wordt benut voor andere lading/transport. |
| Dichtheid | kg/m3 | Volumegebaseerd, gemiddeld 105 m3 per vrachtwagen |
| Volume capaciteit | | Sommige poducten zijn gecompacteerd, dit is niet meegenomen, derhalve is een factor 1 toegepast voor alle producten. |

## [A5] Installatie van het product in het gebouw

| Parameter | |
|---|---|
| Materiaal nodig voor de installatie | Niet gedeclareerd |
| Directe emissions naar lucht, grond en water | Geen |
| Andere hulpmiddelen | Geen |
| Benodigde energie | Handmatige installatie, dus geen electriciteitsverbruik |
| Installatieafval | Snijafval is gedeclareerd |
| Afval dat de bouwplaats verlaat voor verbranding als afval | Verpakking en snijafval |
| Directe emissions naar lucht, grond en water | Gelijk aan het onderstaande |

## [B1-7] Gebruiksfase

**Niet gedeclareerd**

## [C] Einde toepassing

| Processen | | | |
|---|---|---|---|
| Verzameling | apart verzameld | kg | 2,52 |
| | gemengd bouwafval | kg | 0,28 |
| Hergebruik | voor hergebruik | kg | 0,00 |
| | voor recycling | kg | 2,52 |
| | voor energieterugwinning | kg | 0,00 |
| Stort | Verpakking en snijafval | kg | 0,00 |
| | produkt of materiaal voor de stort | kg | 0,28 |
| Aanvullende aannames voor scenario ontwikkeling | Geen | | |

## Binnenklimaat

| | |
|---|---|
| **Aandachtspunten** | Er zij geen emissiegerelateerde effecten op het binnenklimaat door het gebruik van dit product. |

| Normative references | |
|---|---|
| **Insulation properties** | EN13162+A1:2015 Thermal insulation products for buildings. Factory made mineral wool (MW) products. Specification, 4.2.1<br>EN12667:2000 Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance<br>EN12939:2001 Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Thick products of high and medium thermal resistance |
| **Glowing combustion** | EN13162+A1:2015 Thermal insulation products for buildings. Factory made mineral wool (MW) products. Specification, 4.3.15 |
| | |

**ncv** net calorische waarde **MND** Module niet gedeclaree **NR** Niet relevant

Ensinger

# TECATHERM 66 GF

## 1. Bezeichnung und Zusammensetzung

TECATHERM 66 GF
Polyamid 66 mit 25±2,5% (Masseanteil) Glasfasern, schwarz
Bezeichnung: Thermoplast ISO 1874-PA 66-HI,EC2L,,GF25,
Dichte: 1,32±0,02 g/cm$^3$

## 2. Mechanische Eigenschaften

| trocken (DAM), Mittelwerte bei 23°C | | | spritzgegossene Probekörper * |
|---|---|---|---|
| Zugfestigkeit | ISO 527 | MPa | ≥ 110 |
| Zugmodul | ISO 527 | MPa | ≥ 6000 |
| Bruchdehnung | ISO 527 | % | ≥ 2,5 |
| Schlagzähigkeit | ISO 179 | kJ/m$^2$ | ≥ 35 |

*** Für Profile sind keine allgemeingültigen Angaben möglich, da die Werte auch von der jeweiligen Profil-Geometrie (Dicke, Höhe, etc.) und der spezifischen, ebenfalls geometrieabhängigen Glasfaserorientierung beeinflusst werden!**

## 3. Thermische Eigenschaften

| | | |
|---|---|---|
| Wärmeleitfähigkeit | DIN 52612 | ~ 0,3 W/m·K |
| Thermischer Längenausdehnungskoeffizient (trocken und in Längsrichtung) | | 2,5 - 3 ∗ 10$^{-5}$/K |
| Schmelztemperatur | ISO 3146 | > 250° C |
| Anwendungstemperaturbereiche | bei 5 000 h<br>bei 20 000 h | 115° C<br>105° C |
| Wärmeformbeständigkeitstemperatur (1,8 MPa) | DIN EN ISO 75 | ≥ 230° C |





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Ensinger

# TECATHERM 66 GF RE

## 1. Bezeichnung und Zusammensetzung

TECATHERM 66 GF RE
Rezykliertes Polyamid 66 mit 25±2,5% (Masseanteil) Glasfasern, schwarz
Bezeichnung: Thermoplast ISO 1874-PA 66-HI,EC2HL,,GF 25,
Dichte: 1,32±0,02 g/cm$^3$

## 2. Mechanische Eigenschaften

| trocken (DAM), Mittelwerte bei 23°C | | | spritzgegossene Probekörper * |
|---|---|---|---|
| Zugfestigkeit | ISO 527 | MPa | ≥ 110 |
| Zugmodul | ISO 527 | MPa | ≥ 6000 |
| Bruchdehnung | ISO 527 | % | ≥ 2,5 |
| Schlagzähigkeit | ISO 179 | kJ/m$^2$ | ≥ 35 |

*** Für Profile sind keine allgemeingültigen Angaben möglich, da die Werte auch von der jeweiligen Profil-Geometrie (Dicke, Höhe, etc.) und der spezifischen, ebenfalls geometrieabhängigen Glasfaserorientierung beeinflusst werden!**

## 3. Thermische Eigenschaften

| | | |
|---|---|---|
| Wärmeleitfähigkeit | DIN 52612 | ~ 0,3 W/m·K |
| Thermischer Längenausdehnungskoeffizient (trocken und in Längsrichtung) | | 2,5 - 3 $*$ 10$^{-5}$/K |
| Schmelztemperatur | ISO 3146 | > 250° C |
| Anwendungstemperaturbereiche | bei 5 000 h<br>bei 20 000 h | 115° C<br>105° C |
| Wärmeformbeständigkeitstemperatur (1,8 MPa) | DIN EN ISO 75 | ≥ 230° C |

Diese Angaben basieren auf unseren jetzigen Kenntnissen. Die Beschaffenheit, die Handelsfähigkeit und die Eignung der Produkte für einen konkreten Einsatz werden damit nicht rechtlich verbindlich zugesichert oder garantiert. Technische Änderungen vorbehalten.

66D6_Werkstoff_Richtwerte_RE_2013-11-12

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BUILDING TRUST

PRODUCTINFORMATIEBLAD

# Sikasil® SG-500

## HOOGWAARDIGE 2-COMPONENTEN SILICONEN STRUCTURELE BEGLAZINGSLIJM, CE GEMARKEERD

### TYPISCHE PRODUCT DATA (RAADPLEEG HET VEILIGHEIDSINFORMATIEBLAD VOOR MEER WAARDEN)

| Eigenschappen | | Sikasil® SG-500 (A) | Sikasil® SG-500 (B) |
|---|---|---|---|
| Chemische basis | | 2-componenten siliconen | |
| Kleur (CQP001-1) | gemengd | Wit / licht grijs | Zwart / donker grijs |
| | | Zwart / grijs S6 | |
| Uithardingsmechanisme | | Polycondensatie | |
| Uithardingstype | | Neutral | |
| Soortelijke massa (niet uitgehard) | | 1,4 kg/l | 1,1 kg/l |
| | gemengd | 1,4 kg/l | |
| Mengverhouding | A:B bij volume | 10:1 | |
| | A:B bij gewicht | 13:1 | |
| Viscositeit (CQP029-5_ISO 3219) | | 1 100 Pa·s | 300 Pa·s |
| Consistentie | | Pasteus | |
| Verwerkingstemperatuur | Omgeving | 5 – 40 °C | |
| Snap time (CQP554-1) | | 50 minuten [A] | |
| Kleefvrij tijd (CQP019-3) | | 240 minuten [A] | |
| Hardheid Shore A (CQP023-1 /ISO 7619-1) | | 45 | |
| Treksterkte (CQP036-1 / ISO 527) | | 2,2 MPa | |
| E- modulus (CQP036-1 / ISO 527) | | 1,1 MPa | |
| 12,5 % modulus (CQP036-1 / ISO 37) | | 0,3 MPa | |
| Rek bij breuk (CQP036-1 / ISO527 ) | | 300 % | |
| Verderscheur weerstand (CQP045-1 / ISO 34) | | 6 N/mm | |
| Doorlaatbaarheid van waterdamp (EN 1279-4) | | 19 g $H_2O$ / $m^2$·24 uur·2 mm | |
| Thermische bestendigheid (CQP 513-1) | 4 uur | 200 °C | |
| | 1 uur | 220 °C | |
| Temperatuursbestendigheid (CQP513-1) | | -40 – 150 °C | |
| Houdbaarheid (CQP016-1) | | 15 maanden [B] | 12 maanden [B] |

CQP = Corporate Quality Procedure A) 23 °C / 50 % r. l. B) Opslag onder 25 °C

### BESCHRIJVING

Sikasil® SG-500 is een 2-componenten, hoge modulus, neutraal uithardende siliconen constructielijm. Het wordt hoofdzakelijk voor structurele beglazingstoepassingen toegepast. Het voldoet aan EOTA ETAG 002 en voorzien van het CE-keurmerk.

### PRODUCTEIGENSCHAPPEN

- Voldoet aan de eisen van EOTA ETAG 002 (draagt de ETA norm), EN 15434 en ASTM C 1184
- Structurele afdichtkit voor in structurele beglazings samenstellingen volgens ETAG 002, Onderdeel 1 Editie november 1999 (revisie maart 2012) gebruikt als EAD, ETA-03/0038 uitgegeven door Technical Assessment Body Deutsches Institut für Bautechnik, DoP 15754339, gecertificeerd door aangemelde certificeringsinstantie 0757, certificaat voor constante prestatie 0757-CPR- 596-7110761-4-4 en voorzien van CE keurmerk
- Ontworpen trekstrerkte voor dynamische belastingen: σdes = 0,14 MPa (ETA)
- SNJF-VEC erkend (code product: 2433)
- Certificering brandveiligheid (DIN 4102-B1)
- Uitstekend UV- en weersbestendig

## TOEPASSINGSGEBIEDEN
Sikasil® SG-500 is ideaal voor structurele beglazing en andere veeleisende industriële toepassingen. Dit product is alleen geschikt voor gebruik door ervaren professionals. Voer vooraf altijd tests uit met de werkelijk ondergronden en onder de plaatselijke omstandigheden voor goede hechting en materiaal compatibiliteit.

## UITHARDINGSMECHANISME
Sikasil® SG-500 vangt aan met uitharden onmiddellijk nadat de twee componenten gemengd zijn. De reactiesnelheid hangt voornamelijk af van de temperatuur: hoe hoger de temperatuur, des te sneller het uithardingsproces verloopt. Verwarming boven 50°C wordt afgeraden, omdat dit kan leiden tot de vorming van luchtbellen. De verwerkingstijd in de menger, d.w.z. de tijd die het materiaal in de menger kan blijven zonder doorstroming of doorspoeling van het product, is beduidend korter dan de hierboven aangegeven Snap time. Neem voor meer informatie contact op met Technical Service van Sika Nederland B.V..

## VERWERKINGSMETHODE
### Ondergrondvoorbehandeling
Oppervlakken moeten schoon, droog en vrij van vet, olie en stof zijn. Oppervlaktebehandeling hangt af van de specifieke aard van de ondergrond en is cruciaal voor een duurzame hechting.

### Toepassing
De optimale temperatuur voor het substraat en afdichtingskit ligt tussen 15 °C en 25 °C. Voordat u Sikasil® SG-500 kunt verwerken dient u eerst beide componenten homogeen en vrij van luchtbellen te mengen in de juiste aangegeven verhouding, met een nauwkeurigheid van ± 10%. De meeste in de handel verkrijgbare meet- en mengapparaten zijn geschikt. Neem voor specifiek advies voor het kiezen van de juiste pompsysteem contact op met Technical Service van Sika Industrie. Component A van Sikasil® SG-500 is stabiel in de lucht, terwijl component B daarentegen vochtgevoelig is en daarom maar kort aan de lucht blootgesteld mag worden. De voegen moeten de juiste afmeting hebben. Als basis voor de berekening van de benodigde voegafmetingen dienen de technische waarden van de lijm, de aangrenzende bouwmaterialen, de blootstelling van de bouwelementen, hun constructie en omvang alsmede de externe belastingen in acht worden genomen.

### Bewerking en afgladden
Bewerking en afgladden moeten worden uitgevoerd binnen de snap time van de lijm. Druk bij het afgladden van de vers aangebrachte Sikasil® SG-500 de lijm op de voegranden aan, zodat het hechtoppervlak goed bevochtigd wordt.Gebruik geen afgladmiddelen.

### Verwijderen
Niet-uitgeharde Sikasil® SG-500 kan van gereedschappen en apparatuur worden verwijderd met Sika® Remover-208 of een ander geschikt oplossmiddel. Wanneer Sikasil® SG-500 eenmaal uitgehard is, kan het alleen nog mechanisch worden verwijderd. Herbruikbare, meestal van metaal, statische mengers kunnen met Sika® Mixer Cleaner worden schoongemaakt. Handen en onbedekte huid moeten onmiddellijk worden gereinigd met Sika® Cleaner-350H tissues of een geschikte industriële handreiniger en water. Gebruik geen oplosmiddelen op de huid!

### Overschilderen
SikaSil® SG-500 kan niet worden overschilderd

### Verwerkingslimieten
Aanbevolen oplossingen van Sika voor structurele lijmen en ruiten lijmen zijn over het algemeen compatibel met elkaar. Deze oplossingen bestaan uit producten zoals Sikasil® SG, IG, WS en WT series. Neem voor specifieke informatie, aangaande het compatibiliteit tussen verschillende Sikasil® producten en andere Sika producten, contact op met Technical Service van Sika Nederland B.V. Om uit te sluiten dat materialen Sikasil® SG-500 beïnvloeden, dienen materialen zoals pakkingen, stelblokken, afdichtkitten etc., die in direct of indirect contact komen met Sikasil® SG-500, voor aanvang van de applicatie goedgekeurd te zijn door Sika. Bij gebruik van twee of meer verschillende reactieve afdichtkitten moet de eerste volledig zijn uitgehard, voordat de volgende afdichtkit wordt aangebracht. Bovengenoemde Sika proces materialen mogen alleen gebruikt worden bij structurele beglazing of ruitverlijming na een gedetailleerde inspectie en schriftelijke toestemming van de corresponderende projectgegevens door Technical Service van Sika Nederland B.V..

## AANVULLENDE INFORMATIE
De information in dit document dient als algemene richtlijn. Advies voor specifieke applicaties is beschikbaar op via Technical Service van Sika Nederland B.V.
Op verzoek zijn kopieën van de volgende publicaties verkrijgbaar:
- Veiligheidsinformatiebladen
- Verwerkingsrichtlijn “Structural Silicon Glazing with Sikasil SG Adhesives

## VERPAKKINGSGEGEVENS
Sikasil® SG-500 (A)

| | |
|---|---|
| Vat | 26 kg<br>260 kg |

Sikasil® SG-500 (B)

| | |
|---|---|
| Vat | 20 kg |

Sikasil® SG-500 (A+B)

| | |
|---|---|
| Dual patroon | 490 ml |

## BASIS PRODUCTWAARDEN
Alle technische gegevens in dit productinformatieblad zijn gebaseerd op laboratoriumtesten. Gegevens kunnen wijzigen, afhankelijk van de omstandigheden.

## GEZONDHEIDS- EN VEILIGHEIDSINFORMATIE
Voor informatie en advies over de veilige hantering, opslag en afvoer van chemische producten, dient de gebruiker het meest recente veiligheidsinformatieblad te raadplegen, betreffende de fysieke, ecologische, toxicologische en ander veiligheidsgerelateerde gegevens.

## WETTELIJKE BEPALINGEN
De informatie, en met name de aanbevelingen met betrekking tot de toe-passing en het eindgebruik van Sika producten, wordt in goed vertrouwen verstrekt op basis van de huidige kennis en ervaring van Sika met producten die op de juiste wijze zijn opgeslagen, behandeld en toegepast onder normale omstandigheden. In de praktijk zijn de verschillen in materialen, onderlagen en werkelijke omstandigheden ter plaatse zodanig dat er geen garantie kan worden ontleend met betrekking tot verhandelbaarheid of geschiktheid voor een bepaald doel, noch enige aansprakelijkheid voortvloeiend uit enige juridische relatie, op basis van deze informatie, of uit enige schriftelijke aanbevelingen of enig ander advies dat wordt gegeven. De gebruiker van het product dient geschiktheid van het product te testen voor de beoogde toepassing. Sika houdt zich het recht voor om producteigenschappen te wijzigen. De eigendomsrechten van derden dienen te worden gerespecteerd. Alle bestellingen worden aanvaard onder de huidige verkoop- en leveringsvoorwaarden. Gebruikers dienen altijd de meest recente uitgave van het productinformatieblad te raadplegen voor het betreffende product; exemplaren hiervan worden op verzoek verstrekt.



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# Sikasil® SG-500

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## Detailed description

Two-component, high-modulus, neutral-curing structural silicone adhesive.

### Features and benefits:

- High mechanical strength.
- UV, weathering and Ozone resistant.
- Bonds well to a variety of substrates.

### Applications:

For professional use only. Suitable for a range of demanding industrial applications, including:

- Structural glazing.
- Bonding of solar modules.

Consult manufacturer for information regarding suitable preparation and application methods for this product.

## Product guidance - As Standard

### Material:

2-C silicone.

### Colour (when mixed):

Black and/or Grey.

### Technical characteristics:

- Density: ~1.37 kg/L (mixed).
- Fire rated to EN 11925-2 / DIN 4102-B1.
- Snap time (CQP 554-1): ~50 minutes (23°C/ 50% r.h.).
- Tack-free time (CQP 019-1): ~240 minutes (23°C/ 50% r.h.).
- Shore A hardness (CQP 023-1/ ISO 868): ~45.
- Tensile strength (CQP 036-1/ ISO 37):~ 2.2 MPa.
- Elongation at break (CQP 036-1/ ISO 37): ~300 %.
- Tear propagation resistance (CQP 045-1/ ISO 34): ~6.0 N/mm.
- 12.5% modulus (CQP 036-1/ ISO 37): ~0.3 MPa.
- 100% modulus (CQP 036-1/ ISO 37): ~1.1 N/mm².
- Movement capability (ASTM C 719): ±12.5 %.
- Application temperature: 5 –40°C.
- Service temperature: -40°C to +150 °C.