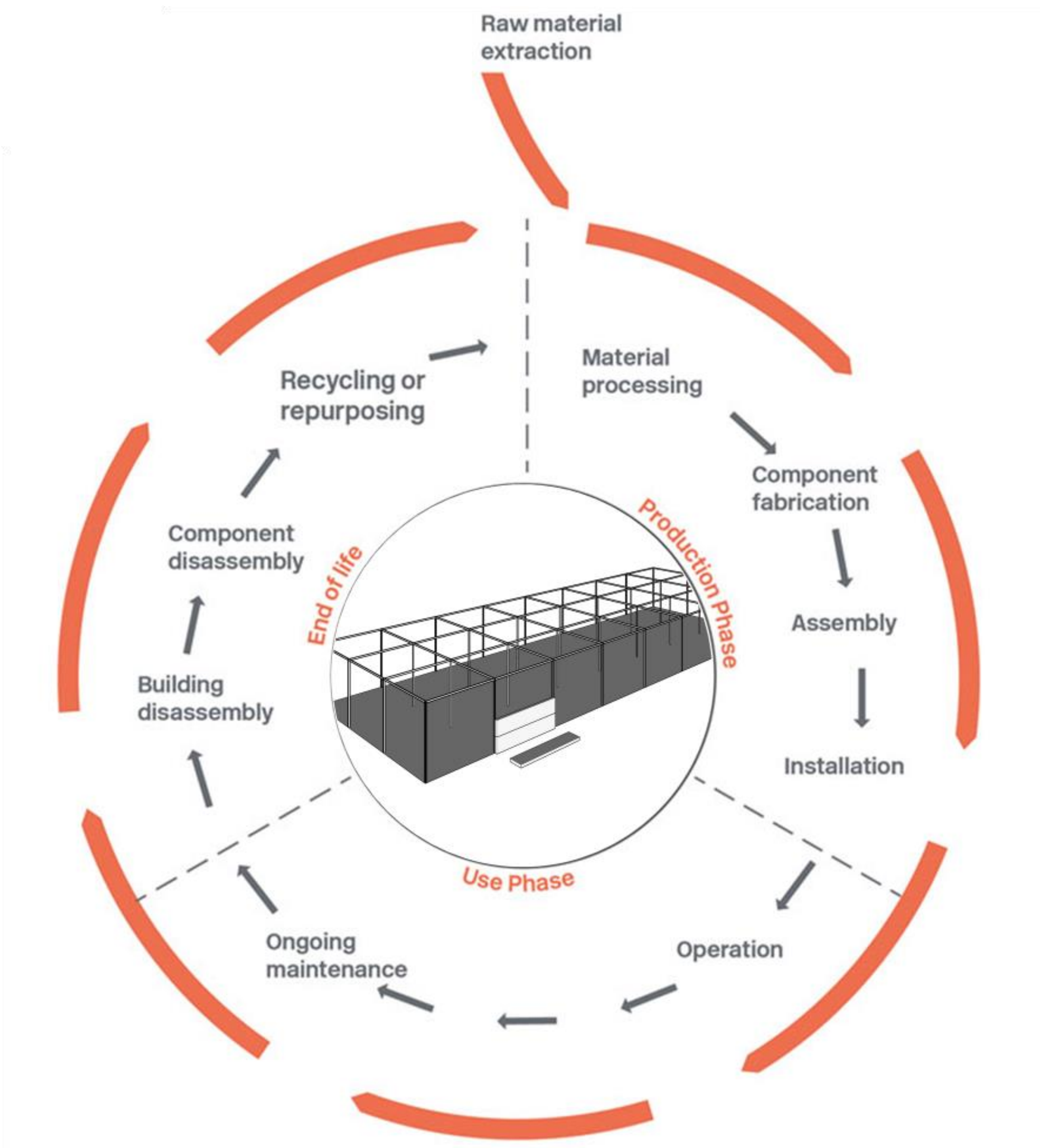
Circular façades

Assessment of an industrial building façade using circularity indicators



Jean-Paul Boertje
Master Thesis
Faculty of Civil Engineering and Geosciences
Delft University of Technology

Circular façades

Assessment of an industrial building façade using circularity indicators

by

J.P.L. Boertje

in partial fulfilment of the requirements for the degree of

Master of Science

in Civil Engineering

Faculty of Civil Engineering and Geosciences
Delft University of Technology
Delft, The Netherlands

September 2020

To be defended publicly on 18-9-2020

Thesis committee

Prof. dr. M. Veljkovic	Delft University of Technology
Dr. ir. R. Abspoel	Delft University of Technology
Ir. S. Pasterkamp	Delft University of Technology
Ir. C. van Zandwijk	CFP Engineering

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Front page: Circular Economy of Façades (O'Callaghan, 2014).

Preface

This thesis has been written as a conclusion of my study at the Faculty of Civil Engineering and Geosciences of Delft University of Technology, in order to obtain a Master of Science (MSc) degree in Civil Engineering.

During my study at Delft University of Technology, my interest for circular economy was sparked by the book Material Matters. In this book a new economic model is introduced, in which consumers no longer own products but use products instead, new business models emerge and waste no longer exists. CFP Engineering gave me the chance to gain more knowledge on this subject, by providing me with an interesting graduation topic: circular façades.

I would like to thank my graduation committee, consisting of prof. dr. M. Veljkovic, dr. ir. R. Abspoel and ir. S. Pasterkamp from Delft University of Technology, and ir. C. van Zandwijk from CFP Engineering, for their help and patience. They have experienced that I am not a student who asks for a lot of feedback, but their guidance was much needed and appreciated during the course of writing this thesis. Their constructive criticism and questions helped me to improve my work and reach a satisfying outcome.

Additionally, I would like to thank my colleagues at CFP Engineering for providing me with information and helping me with their knowledge. I would also like to thank them for their support and the friendly work environment they provided. I would like to thank Cor van Zandwijk in particular, for giving me the opportunity to graduate at his company, and Jan-Willem Duits and Gert-Jan Verweij for offering me their professional opinion about certain structural questions.

Finally, I would like to thank my family and friends for their support during the course of writing this thesis. They encouraged and motivated me throughout the entire project. Especially, I would like to thank my girlfriend, who was always there for me, understanding and supporting me unconditionally.

J.P.L. Boertje
Ridderkerk, September 2020

Abstract

A transition towards a circular economy is proposed by initiators like the Ellen MacArthur Foundation and architect Thomas Rau, in order to preserve and enhance natural capital, optimise resource yields, and minimise system risks. A circular economy seeks to ultimately decouple global economic development from the consumption of non-renewable resources, and will eventually result in an economy of services. In this transition, the construction sector plays a major role because it is responsible for 50% of the total resource use, 40% of demolition waste and 35% of CO_2 emissions.

The design of the façade system of a building which is offered as a service is essential. Assembly and disassembly of components of such a building occurs more often compared to traditional buildings, so the components and elements have to be designed so that they can facilitate this. This is especially true for the components of the façade which, due to the relatively short lifespan of a façade have to be flexible. To help incorporate circular principles in the design, a new method or tool is needed to help making design decisions and compare different alternatives. The main objective of this master thesis is to investigate the suitability of cold-formed steel components for circular façade design and to develop an assessment method to measure the degree of circularity of façades. Current assessment methods for determining the circularity of products either focus on the environmental impact or the flow of materials and protecting existing value, and not on the degree of circularity related to certain design options. Also, there is no method which focusses specifically on façades.

A circular economy is restorative and regenerative, and aims to keep products, components, and materials at their highest utility and value at all times. This is achieved by controlling finite stocks and balancing renewable resource flows, circulating products, components, and materials, and designing out negative externalities. Circular design criteria are derived from the design strategies Design for Disassembly, Design for Adaptability and Modular Design. Currently used façade systems do have the potential to be used in a circular economy, provided that the design criteria for circular use are met.

During the Case Study two designs are proposed: a traditional façade system which uses sandwich panels, and a façade system which uses façade panels designed based on a concept for roof panels developed by CFP Engineering (two alternatives). The aim of this case study is to investigate the suitability of the newly developed façade element for circular façade design. Additionally, it will serve as input for the assessment method which is illustrated later in this thesis, and set boundary conditions for the comparison of the life cycle costs and level of circularity.

The most important design parameters to determine the circularity of a façade system are: the amount of materials used, the possibility for reassembly, the environmental impact of the system, the amount of reused and renewable materials, the availability of information and the amount of toxic materials. These parameters can be measured by calculating the Façade Circularity Indicator which, as the name suggests, cannot be considered an exact value. The Façade Circularity Indicator originates by combining an existing method (Material Circularity Indicator, developed by the Ellen MacArthur Foundation) with research on Design for Disassembly (Durmisevic, 2016). A prerequisite of this method is a Life Cycle Assessment calculation. The method can be used during the design phase to help making design decisions. Based on the Life Cycle Assessment, the environmental costs of the traditional façade system are 22% higher than the environmental costs of the case study alternatives, which makes the traditional façade system less suitable for use in a circular economy. When the mass of the components is used as a weight variable, the Façade Circularity Indicator of the traditional façade system is 9 to 12% lower than that of the case study alternatives. When environmental costs are used as a weight variable, the Façade Circularity Indicator of the traditional façade system is 54 to 60% lower than that

of the case study alternatives. This also indicates that the traditional façade system less suitable for use in a circular economy.

As an overall conclusion, it can be stated that cold-formed components are suitable for use in circular façade design because of their relatively low weight, low life cycle costs and the possibility to (dis)assemble them with relative ease. Furthermore, an indication of level of circularity of façades can be given based on a combination of the Material Circularity Indicator and Design for Disassembly factors.

Samenvatting

Een transitie naar een circulaire economie wordt voorgesteld door initiatiefnemers zoals de Ellen MacArthur Foundation en architect Thomas Rau, met als doel het verbeteren en behouden van het milieu, het optimaliseren van grondstof gebruik en het minimaliseren van economische risico's. Een circulaire economie wil uiteindelijk de wereldwijde economische ontwikkeling loskoppelen van het verbruik van niet hernieuwbare grondstoffen, en zal uiteindelijk resulteren in een economie van diensten. In deze transitie speelt de constructie sector een grote rol, omdat deze verantwoordelijk is voor 50% van het totale grondstofgebruik, 40% van het sloopafval en 35% van de CO_2 uitstoot.

Het ontwerp van het gevelsysteem van een gebouw dat als service wordt aangeboden is essentieel. Montage en demontage van componenten van een dergelijk gebouw komt vaker voor dan traditionele gebouwen, dus de componenten en elementen moeten zo worden ontworpen dat ze dit kunnen faciliteren. Dit geldt met name voor de onderdelen van de gevel die vanwege de relatief korte levensduur van een gevel flexibel moeten zijn. Om circulaire principes in het ontwerp op te nemen, is een nieuwe methode of tool nodig om ontwerpbeslissingen te nemen en verschillende alternatieven te vergelijken. Het hoofddoel van deze thesis is het onderzoeken van de geschiktheid van het gebruik van koud gevormde stalen componenten voor het ontwerpen van circulaire gevels, en het ontwikkelen van een beoordelingsmethode om de mate van circulariteit van gevels te meten. Huidige beoordelingsmethoden voor het bepalen van de circulariteit van producten zijn ofwel gericht op de milieu-impact of de materiaalstroom en het beschermen van bestaande waarde, en niet op de mate van circulariteit die samenhangt met bepaalde ontwerpopties. Ook is er geen methode die zich specifiek op gevels richt.

Een circulaire economie is regeneratief en heeft als doel het te allen tijde behouden van het nut en waarde producten, componenten en materialen. Dit wordt bereikt door de eindige grondstofvoorraden te beheren en aan te vullen met hernieuwbare grondstoffen, producten, componenten en materialen te laten circuleren en negatieve externe effecten te voorkomen. Circulaire ontwerpcriteria zijn afgeleid van de ontwerp strategieën Design for Disassembly, Design for Adaptability en Modular Design. Huidige gevelsystemen kunnen worden gebruikt in een circulaire economie, mits aan deze ontwerpcriteria voor circulair gebruik wordt voldaan.

Tijdens de Case Study worden twee ontwerpen voorgesteld: een traditioneel gevelsysteem dat gebruik maakt van sandwichpanelen, en een gevelsysteem dat gebruik maakt van gevelpanelen die zijn ontworpen op basis van een concept voor dakpanelen dat is ontwikkeld door CFP Engineering (twee varianten). Het doel van deze Case Study is het onderzoeken van de geschiktheid van dit nieuw ontwikkelde element voor het gebruik als een circulair gevelontwerp. Daarnaast zal het dienen als input voor de beoordelingsmethode die later in deze thesis wordt geïllustreerd en stelt het randvoorwaarden voor de vergelijking van de levenscycluskosten en het niveau van circulariteit.

De belangrijkste ontwerpparameters om de circulariteit van een gevelsysteem te bepalen zijn: de hoeveelheid gebruikte materialen, de mogelijkheid tot (de)montage, de milieu-impact van het

systeem, de hoeveelheid hergebruikte en hernieuwbare materialen, de beschikbaarheid van informatie en de hoeveelheid giftige materialen. Deze parameters kunnen worden gemeten door de Façade Circularity Indicator te berekenen die, zoals de naam aangeeft, geen exacte waarde is. De Façade Circularity Indicator komt tot stand door een bestaande methode (Material Circularity Indicator, ontwikkeld door de Ellen MacArthur Foundation) te combineren met onderzoek naar Design for Disassembly (Durmisevic, 2016). Een voorwaarde voor deze methode is een levenscyclusanalyse. De methode kan tijdens de ontwerpfase worden gebruikt om bepaalde ontwerpbeslissingen te nemen. Op basis van de levenscyclusanalyse zijn de milieukosten van het traditionele gevelsysteem 22% hoger dan de milieukosten van de case studie varianten, wat betekend dat het traditionele gevelsysteem minder geschikt is voor het gebruik in een circulaire economie. Wanneer de massa van de componenten wordt gebruikt als een gewogen variabele, is de Façade Circularity Indicator van het traditionele gevelsysteem 9 tot 12% lager dan die van de case studie varianten. Wanneer milieukosten worden gebruikt als een gewogen variabele, is de Façade Circularity Indicator van het traditionele gevelsysteem 54 tot 60% lager dan die van de case studie varianten. Ook dit wijst erop dat het traditionele gevelsysteem minder geschikt is voor het gebruik in een circulaire economie.

Als algemene conclusie kan worden gesteld dat koud gevormde componenten bruikbaar zijn in een circulair gevelontwerp vanwege het relatief lage gewicht, lage levenscycluskosten en de mogelijkheid om ze relatief gemakkelijk te (de)monteren. Verder kan er een indicatie worden gegeven van de mate van circulariteit van gevels op basis van een combinatie van de Material Circularity Indicator en Design for Disassembly factoren.

Table of content

List of Figures

List of Tables

1. Introduction

1.1. Linear and circular economic model

The current economic model can best be described as a linear model of production and consumption. Raw materials are extracted from the earth and processed into products, which are discarded after use. This system is based on consumption instead of the restorative use of resources and causes serious losses along the value chain. Negative consequences of the linear economic model, apart from the economic losses and structural waste, are price- and supply risks. Companies experience an increase in volatile resource prices and supply disruptions. This can hinder economic growth because it increases uncertainty, discourages businesses from investing and it increases the costs of guarding against those risks. The linear economic model also has negative environmental consequences, for example the depletion of finite reserves and the degradation of natural capital. Climate change, loss of biodiversity, land degradation and ocean pollution are examples of this degradation (Ellen MacArthur Foundation, 2015).

A new economic model is proposed by initiators: a circular economic model. The definition of a circular economy by the Ellen MacArthur Foundation, a charity organisation which has played a pioneering role in bringing the transition towards a circular economy under the attention of decision makers in business, government, and academia, is:

A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015).

The objective of the circular economic model is to preserve and enhance natural capital, optimise resource yields, and minimise system risks by managing finite stocks and renewable flows. It seeks to ultimately decouple global economic development from finite resource consumption.

1.2. Circular economy in the construction sector

It is estimated that the construction sector in The Netherlands is responsible for 50% of the total resource use, 40% of the total energy use and 30% of the total water use. Besides, it accounts for 40% of demolition waste and 35% of CO_2 emissions. Construction materials are reused at a large scale, especially in the residential- and utility sector, where 95% of materials is reused. However, this often means reuse at a lower level of utility, for example processing demolition waste into granulate which is then used as foundation material in road construction and hydraulic engineering (Het ministerie van Infrastructuur en Milieu en het ministerie van Economische Zaken, 2016).

According to Thomas Rau, architect and entrepreneur in circular projects, will the implementation of circular economy principles in the construction sector change the way architects, constructors, contractors, and manufacturers work. The focus will shift to designing structures that are easy to repair and disassemble. Furthermore, the aim will become to minimise waste in refurbishment and maximise the reuse potential of constructions. It will also mean a shift to an alternative business model, in which companies will be responsible for their own (raw) materials and use delivery and return logistics to recover their materials and products. In other words: an economy of services (Oberhuber & Rau, 2016).

For the construction sector, this could mean providing a *building as a service*. Instead of a client taking ownership of, and having responsibility over the building, the ownership and responsibility remain with the manufacturer.

This has advantages for manufacturers, clients, and the economy. Waste streams will reduce drastically or may even disappear completely. When a building has served its purpose, the components of the building and its materials will simply return to the material stock of the manufacturer. Because manufacturers have direct ownership over their stock, they are less vulnerable to volatile resource prices and supply disruptions. They will also have more financial security because they are provided with a constant cash flow, instead of receiving one large transaction per project. Because manufacturers will remain responsible for their products, they are incentivised to design buildings which are more durable and of better quality. A negative consequence is that instances of transport will increase. This business model will only help reaching the objective of the circular economy if the positive consequences outweigh the negative consequences.

Clients will not have ownership of the building they are using, so they are not settled with the responsibility over the building when it has served its purpose. The buildings components and materials are returned to the manufacturer, so no utility and value will be lost.

However, there is no generally accepted method or tool available that measures the degree of circularity of façades. This tool can help making design decisions and compare different alternatives, which would assist in transitioning towards a circular economy. In this thesis, such a method is proposed.

1.3. Main objective

The transition from a linear to a circular economy is beneficial in many ways, and although circular design is a hot topic, a lot of progress is still to be made to complete this transition. Circular design principles are implemented at a slow pace because of the conservative nature of the construction sector. To complete the transition, the construction sector must be made more aware of the urgency and their role in this process. To do so, more knowledge about circular design is required.

Pilot projects have been realised where the load bearing structure was carried out using circular design principles (Cobouw, 2020). The next step in this transition is making the building envelope circular as well, for example the roof panel system developed by MBT. MBT is an initiative by CFP Engineering and stands for Modular Building Technology. The system was first used during a pilot project in Enschede, which was realised in October 2019. A complementary façade system would be the subsequent step.

The design of the façade system of a building which is offered as a service is essential. Assembly and disassembly of components of such a building occurs more often compared to traditional buildings, so the components and elements have to be designed so that they can facilitate this. This is especially true for the components of the façade which, due to the relatively short lifespan of a façade (Brand, 1994), has to be flexible. To help incorporate circular principles in the design, a new method or tool is needed to help making design decisions and compare different alternatives.

The main objective of this master thesis is to investigate the suitability of cold-formed steel components for circular façade design and to develop an assessment method to measure the degree of circularity of façades. This objective will be achieved by investigating the definition of a circular façade, designing a circular façade system for an industrial building with cold-formed components based on the concept for roof panels developed by CFP Engineering, and combining existing methods for measuring circularity into a new method. In doing so, more knowledge is acquired about the suitability of cold-formed components, circular façade design and measuring circularity.

1.4. Research questions

The previously stated problem, together with the main objective of this thesis, leads to the following main research question:

Are cold-formed components and connections suitable for circular façade design and how can the degree of circularity of a façade system be assessed?

To answer the main research question, several sub-questions have been formulated. These sub-questions divide this thesis into three parts:

1. Literature study

1. What is the definition of a circular economy and what are its characteristics?
2. What are current assessment methods for determining the degree of circularity?
3. What are the design criteria and strategies when designing a product for circular use?
4. What are current practises in façade design and are these systems and connections suitable for use in a circular economy?

The first phase of this thesis is a Literature study, in which the first 4 sub-questions will be answered. In chapter 2 the term *circular economy* is defined, and the principles on which it is based are explained. Also, the current policies and legislation regarding circular economy in The Netherlands and Europe are discussed. Waste management is an important principle of the circular economy. Chapter 3 lists different strategies for waste management and shows several examples of the application of these strategies. In chapter 4 several methods and tools to assess the circularity and sustainability of products are discussed. Chapter 5 discusses different design criteria which products must meet when they are designed for use in a circular economy.

After investigating circularity in more general terms in chapters 2 to 5, the focus shifts to façade systems in chapter 6, which is the final part of the literature study. The functional lifespan of façades is analysed, as well as the potential to reuse and lease façades. The chapter finishes with an analysis of current practises in façade construction and connections.

The aim of the literature study is to introduce and gain knowledge about the subject of circular economy, which is used during the Case Study and Analysis of Circularity.

2. Case study

5. What is a conceptual design for a cold-formed façade system for an industrial building, using the design criteria for circular use?

The second phase of this thesis is a Case study. In chapter 7 a cold-formed steel façade system is designed using the knowledge obtained in the literature study. Additionally, a traditional façade system is described.

Besides *circular design*, the case study explores the role of cold-formed steel elements in façade design. Formerly, cold-formed steel elements were mainly used in products where saving weight was of great importance, for example aircraft, railway, and motor industries. In buildings, simple cold-formed elements and sheeting were used as non-structural elements. Research performed during the last four decades, as well as improved manufacturing technology, protecting against corrosion, increased material strength and the availability of codes of practise for design, lead to a wider use of cold-formed elements.

The aim of the case study is to investigate the use of cold-formed elements in façade design in combination with large spans. Another aim of the case study is to verify the knowledge and findings obtained during the literature study regarding circular design. Additionally, it will serve as input for the assessment method which is illustrated later in this thesis. In other words, it sets boundary conditions to limit the number of variables.

3. Analysis of Circularity

6. What parameters of the design determine the degree of circularity of the façade system?
7. How can these parameters be combined into an assessment method to measure the level of circularity of façades?
8. Using this method, how does the degree of circularity of the case study design compare to a traditional design?

The third phase of this thesis is the Analysis phase. In this phase sub-questions 6 to 8 are answered.

Chapter 8 contains a Life Cycle Assessment calculation, in which the environmental costs of the materials of the façade systems are calculated. This calculation is a prerequisite of the method which is illustrated in chapter 9, since keeping checks and balances on the environmental impact is essential when designing for circular use. Chapter 9 starts by listing different parameters that determine the level of circularity of façade systems. Then a method for measuring the degree of circularity of façade systems is developed by extending the method of the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015) and combining it with the research of Durmisevic (Durmisevic, 2016) regarding Design for Disassembly. The developed method is then used to measure the degree of circularity of the traditional façade system and the case study variants.

The aim of the Analysis is to verify the knowledge and findings obtained during the literature study, evaluate the case study design, and develop a new method for measuring the circularity of façades.

Literature study

2. The circular economy

In this chapter, different definitions of a circular economy are investigated, and its principles explained. Additionally, current policies and legislation regarding circularity are addressed.

2.1. The definition of circular economy

Circular economy is a fashionable term used in the construction sector over the past few years by architects, engineers, and designers. The definition can be vague at times because it varies, depending on the problem which is addressed, the audience and the scope. Despite the lack of a concrete definition, two interpretations of the concept will be discussed.

2.1.1. Ellen MacArthur Foundation

The first definition is one proposed by the Ellen MacArthur Foundation, which has already been mentioned in the introduction:

A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.

The cycles preserve and enhance natural capital, optimise resource yields, and minimises system risks. This is done by managing resources and renewable flows. The goal of this model is to decouple global economic development from finite resource consumption. A graphic representation of the circular economic model is displayed in Figure 1. The circular economy system is based on three principles:

- Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows. This means using technologies and processes that use resources that are renewable or better performing. It also means encouraging flows of nutrients within the system so that resources can regenerate, for example soil.
- Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles. This can be achieved by designing products that can be remanufactured, refurbished, and recycled. Using “tighter” loops, for example maintenance rather than recycling, is preferred because more embedded energy and value is preserved this way. Also, the system aims to maximise the number of consecutive cycles and time spent in each cycle, by extending product life and optimising reuse.
- Foster system effectiveness by revealing and designing out negative externalities. Land use, air-, water- and noise pollution, and the release of toxic substances are examples of negative externalities (Ellen MacArthur Foundation, 2015).

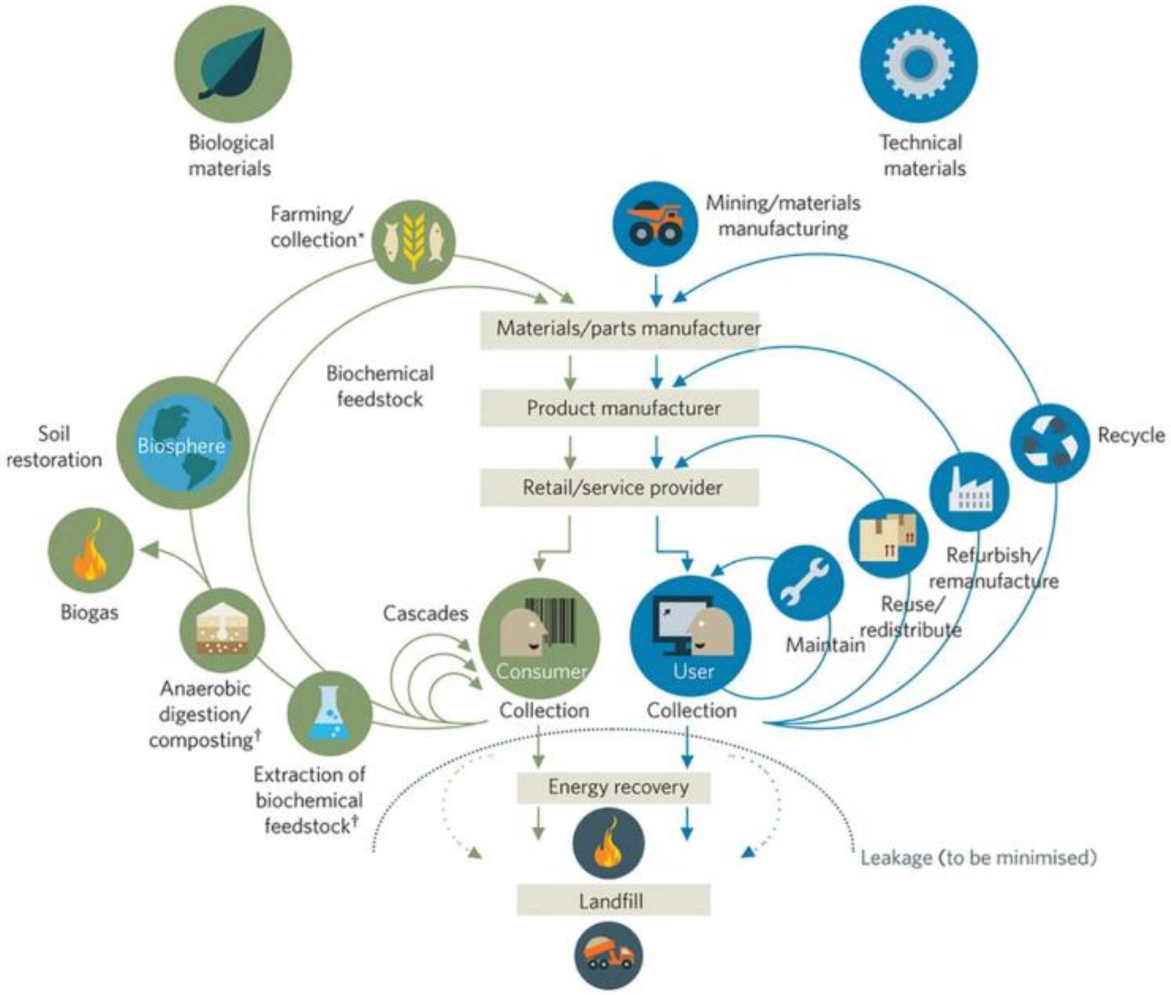


Figure 1: Outline of a circular economy (Ellen MacArthur Foundation, 2015)

2.1.2. Circle Economy

Circle Economy U.A., a non-profit organisation which aims to accelerate the implementation of circular economy, has mapped various definitions of the term, used by 20 organisations working in the field of circular economy (Circle Economy, 2020). The abbreviation U.A. stands for "excluded liability" (in Dutch: "uitgesloten aansprakelijkheid"). According to the organisation, the definition of a circular economy always includes the following elements.

- The prioritization of regenerative resources: instead of using up non-regenerative resources, fossil fuels for example, renewable, reusable, and non-toxic resources should be utilized.
- The preservation and extension of current, in-use resources: maximize the lifespan of resources and giving resources a "second life".
- Using waste streams as a resource: recover secondary resources from waste streams instead of discarding waste without a second thought.
- Rethinking business models: create greater value by changing current business models.
- Designing for the future: use different materials and designs to accommodate future use. This is closely tied with the transformation of business models.
- Incorporation of digital technology: gain insight in resource status through monitoring, using digital, online platforms and technologies.

- Collaboration to create joint value: improve the collaboration of different actors in the supply chain, as well as cooperation between public and private sectors, increasing transparency and creating joint value.

The first three strategies focus on optimising material use and recycling. The other four are enabling strategies. These strategies can be applied to any sector.

It can be concluded that the two definitions share a lot of the same principles, like the use of renewable resources, preserving in-use resources, maximising the lifespan of products, and designing out waste by using it as a resource. In practise a completely circular economy might not be achievable because of barriers which hold back the transition towards a circular economy. Examples of barriers are a lack of knowledge and collaboration, the lack of a consistent regulatory framework and limited funding (Tura, et al., 2019).

2.2. Policy and legislation on circular economy

Policy and legislation help implementing the principles of circular economy in today's society. In this paragraph the legislation in The Netherlands and Europe is discussed, as well as the relevance of the circular economy to the construction sector.

2.2.1. Legislation in Europe

In 2015 the European Commission adopted the Circular Economy Action Plan, with the aim to set the European Union on the course of transitioning to a circular economy, increase global competitiveness, encourage sustainable economic growth and create new jobs (European Commission, 2019). In addition, the plan promotes cooperation between member states, regions, municipalities, businesses, research bodies, citizens, and other stakeholders.

The Circular Economy Action Plan includes 54 measures which aim at "closing the loop" of product lifecycles. These measures regard production, consumption, waste management and the market for secondary raw materials. Five sectors were identified and given priority. These include plastics, food waste, biomass and biobased products, critical raw materials and construction and demolition. The transition towards a circular economy is financially supported by the European Structural and Investment Funds, Horizon 2020, the European Fund for Strategic Investments, and the LIFE programme.

In March 2019, the European commission reported that three years after the adoption of the Circular Economy Action Plan, all 54 measures have been implemented.

Currently, the standard NEN-EN 15804 is used to present environmental information for products and their applications. The aim of this standard is to support scientifically based, fair choices and stimulate the potential for environmental improvement. This standard and other methods and tools used to measure circularity are discussed in chapter 4.

2.2.2. Legislation in The Netherlands

The in the report *Nederland circular in 2050*, the Dutch government published their view on the circular economy (Het ministerie van Infrastructuur en Milieu en het ministerie van Economische Zaken, 2016). The ambition of the Dutch government is, in cooperation with their social partners, to realise a circular economy before 2050, and to realise the intermediate goal of reducing the primary resource use (minerals, fossil fuels and metals) by 50% in 2030. This ambition is similar to that of surrounding countries. To transform the current linear economy to a circular economy, three strategic goals have been formulated:

- Resources in existing cycles are used efficiently. This leads to a reduction in the need of resources.
- When new resources are required, sustainable, renewable, and generally available resources are used instead of non-sustainable and fossil resources.
- New products are developed, in combination with new production methods. Additionally, new ways of consuming are promoted.

To reach these goals, the Dutch government aims to remove laws and regulations which hinder this transformation, as well as provide a legal framework which stimulates innovation, promotes dynamics, and supports investments. Also, the market is directed towards a circular economy by targeted price incentives and regulations, and active support for circular business models is provided. Furthermore, the government provides the infrastructure which supports education, research and spread of knowledge about circular economy. Additionally, international cooperation is stimulated, to decouple resource use and economic growth.

The Dutch government prioritises five themes, which include: biomass and food, plastics, the manufacturing industry, the construction sector, and consumer goods.

2.2.3. Policy in the Dutch construction sector

The Dutch Ministry of Infrastructure and the Environment published their report *Circular economy in the Dutch construction sector* in 2015 (Ministry of Infrastructure and the Environment, 2015). The goal of the report was to investigate the role of the Dutch government in the transition towards a circular construction sector. The report came into existence with the help of frontrunners and organisations in the circular economy sector.

The main challenge are the waste streams produced by the construction sector. One of the conclusions of the report is that the recycling and reuse of construction waste in the Netherlands is at an advanced level. Most of the construction waste is used as foundation material in infrastructure. However, in the construction of residential and non-residential buildings, no more than 3 to 4% of construction materials consist of secondary materials (Ministry of Infrastructure and the Environment, 2015). This means that the construction sector cannot be considered circular.

To transition towards a circular economy, cooperation, knowledge sharing and transparency are at least as important as the design- and technological challenges this transition induces. During the design, all phases of the lifecycle of the structure must be considered.

Some principles of circular economy have already been applied in the Dutch construction sector, in theory and in practice. However, there is still a long way to go before the construction sector can be considered fully circular. One key point to take away from the report is that businesses need to start with experiments and pilot projects to improve knowledge on circular economy. The government can contribute to this by assisting in the development of assessment methods for circular construction.

According to the stakeholders, an important obstacle in the transition towards a circular economy is the fact that the demolition and recycling of constructions is not financed (Ministry of Infrastructure and the Environment, 2015). A structure is built to last an indefinite period of time. When it has served its purpose and the time has come to replace it, either the community or the new investor pay for the demolition and recycling. So, building on a unbuilt lot is cheaper. This causes more buildings to become vacant, puts a brake on urban renewal and leaves a lot of potential building materials unused. They advise the government to develop a clear vision to solve this problem.

The Dutch government prescribes regulations on safety, health, usability, energy efficiency and environment in the Building Decree (*Bouwbesluit*) of 2012 (Dutch National Government, 2020). Starting on the 1st of July 2020, new buildings have to meet strict requirements regarding energy consumption (BENG-requirements). The following calculation methods, checklists and guidelines can be used to check if structures meet the required standards:

- NEN-standards
- Licenced quality declarations
- Equivalent solutions
- Dutch practical guidelines
- Dutch technical arrangements

The requirements for the environmental performance of buildings are expressed in MPG or Environmental Performance Buildings (*MilieuPrestatie Gebouwen*). The MPG gives an indication of the environmental impact of all components and materials applied in a building. Furthermore, the MPG is increasingly used to measure circularity.

2.3. Elaborations

Reducing environmental impact of the construction sector is a goal which should be strived for. Implementing circular principles can help in bringing this goal one step closer. However, one should be critical when putting these principles into practise and assess whether they really help achieving this goal. For example, one should not recycle products for the sake of recycling, but the overall environmental impact should always be considered. A strict hierarchy of waste management strategies (recycle, refurbish, and reuse) is therefore questionable, and should be seen as an indicator rather than something which is always true.

Currently there are policies and regulations in place to help implementing the principles of circular economy in Europe and The Netherlands. In The Netherlands, the Building Decree prescribes that the environmental performance of buildings is measured and expressed in MPG. However, this is not a direct expression of the level of circularity of a building, and it can be argued whether there are better ways to express a buildings level of circularity.

3. Implementation of circular economy principles

This chapter discusses current examples of the implementation of circular economy principles. It starts with a discussion of different strategies for waste management. Next, several examples of current applications of these strategies are discussed.

3.1. Strategies for value creation

The aim of a circular economy is to keep products, components, and materials at their highest utility and value at all times. Proper waste management is one of the policies to reach this goal. Examples of waste management policies are waste prevention, recycling, and recovery of resources. It is argued that there is a certain hierarchy to these strategies (The European Parliament and the council of 19 November 2008, 2008). For example, it is thought to be more desirable to reuse a building, rather than to recycle all its materials, because it requires less energy and new resource input. This is better because all energy sources have some impact on the environmental (climate change, loss of biodiversity, land degradation and ocean pollution), so it is advantageous to use less of it. This hierarchy is illustrated in Figure 2.

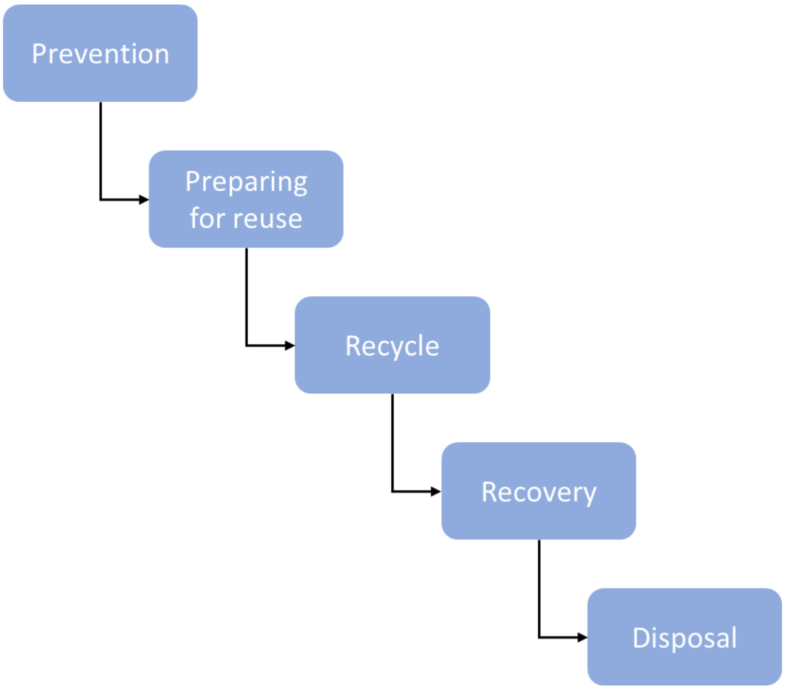


Figure 2: Waste management hierarchy (The European Parliament and the council of 19 November 2008, 2008)

The Delft Ladder (Hendriks & te Dorsthorst, 2001) is another model which describes the different waste management strategies, and ranks them according to favourability from an economic and ecological perspective. There is also a certain hierarchy in the different building levels to which these strategies can be applied, which are construction level, element level and material level. It depends on the following parameters:

1. Construction level

- Technical state of the construction (remaining lifetime). There are different methods to estimate the remaining lifespan of a building. Data is often gathered by performing a health check on the building. This is done using different types of equipment and visual inspection.
- Possibilities to improve current technical state (by repairing damages).
- Flexibility of the construction (with respect to reuse). Flexibility is defined as the ability to change or react with little penalty time, effort, cost or performance. In other words, it describes the ability of a project to cope with changes in the project definition or scope and compensate them with little influences on schedule, costs and quality by appropriate management policies and actions. A way to measure the flexibility of a construction is to analyse the ratio between the renovation costs and the costs of a new construction (Shahu, Pundir, & Ganapathy, 2012).

2. Element level

- Technical state of the elements (remaining lifetime).
- Possibilities to improve current technical state (by repairing damages).
- Possibilities to deconstruct the construction into the different elements (design for deconstruction).

3. Material level

- Possibilities to separate and reuse building materials.

Figure 3: Delft ladder (Hendriks & te Dorsthorst, 2001)

3.2. Examples of circular economy principles

3.2.1. Hoogstraat Rotterdam

The concept of a “Donor Skeleton” was investigated by IMd Raadgevende Ingenieurs, an engineering firm based in Rotterdam, The Netherlands. When a structure serves as a donor skeleton, its load bearing structure can be disassembled and used in another structure. In current practise, these elements would be demolished and turned into debris. The load bearing structure of a construction makes up 60% of the total material mass in a building. Reusing elements like columns, floors and walls significantly reduces the use of primary resources. This would not so much reduce the construction costs, but rather the environmental impact, which could be reduced up to 75% (Glias, 2013).

The application of the principle of the Donor Skeleton was first used on a large scale during the transformation of three buildings on the corner of the Hoogstraat and Vlasmarkt in Rotterdam. The original concrete load bearing structure was demolished and replaced with a steel load bearing structure. For this a total of 27 tonnes of steel was required, which came down to about 100 steel profiles. These profiles originated from different demolished buildings around the Netherlands (IMd Raadgevende Ingenieurs, 2020).

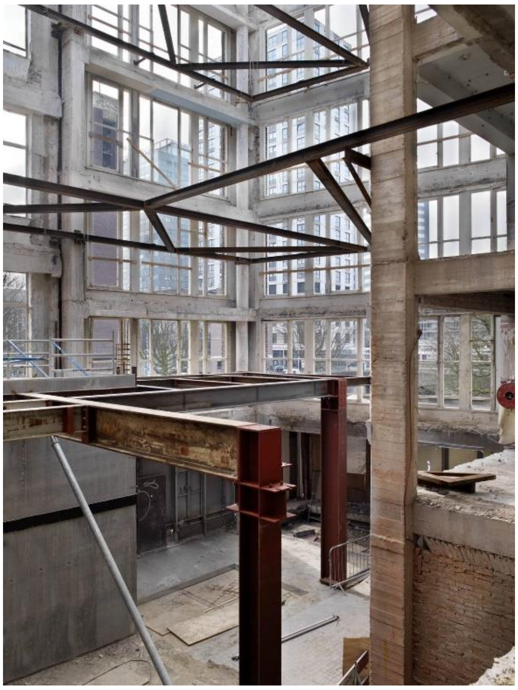


Figure 4: Interior of Hoogstraat 168-172 with the Donor Skeleton clearly visible (IMd Raadgevende Ingenieurs, 2020)

3.2.2. Town hall Brummen

The town hall in the municipality of Brummen was completed in 2013. The structure was commissioned by the municipality and designed by RAU BV. The municipality was in need for a semi-permanent accommodation with a lifespan of at least 20 years. Because the architect did not want to do concessions in terms of quality, a new way of designing and building was introduced: the building was designed as a material depot (Rau BV, 2019).

After the building’s lifespan, all valuable elements and materials are taken back by the suppliers or manufacturers. In the end, more than 90% of the building is realised in components which can be disassembled. This modular design strategy also resulted in a significant reduction of the construction time.

Additionally, the materials that were used in the process are reusable, renewable and of high quality. Materials are used with a holistic view, which means that the material-, component- and product value after 20 years is maximized. For example, this resulted in timber components which were over-dimensioned, because this would improve their usability after 20 years. Because the town hall was designed as a material depot, a material passport was introduced. All elements and details were documented, including their destination in a second life.

Figure 5: Town hall in Brummen (Rau BV, 2019)

3.2.3. Courthouse Amsterdam

The Courthouse in Amsterdam is situated at the Parnassusweg and was designed as a temporary accommodation for the duration of 5 years. The government real estate company (Rijksvastgoedbedrijf), who was the client for the building, aimed for high levels of sustainability. This resulted in a tender for a *Design, Built, Maintain and Remove contract*, and a concept which can be disassembled. After the contract expires, the building can be disassembled and moved to a new location (Bouwen met Staal, 2017).

The building elements have residual value after deconstruction. Also, the waste of materials, which is measured in CO_2-equivalents, is reduced as much as possible. This is especially true for the main structural elements and the skin of the building, which have the highest environmental impact in a construction (about 60%). The building was constructed out of new materials, and the elements return to the supplier after 5 years. Therefore, the building was constructed with dry connections. Other factors that simplify the assembly and disassembly of the construction is the fact that the elements of the construction are relatively small, and the fact that the building is constructed in a fixed grid.

The façade is made of prefabricated timber skeleton elements, which are attached to steel façade columns. The façade cladding consists of open curtain wall profiles made of aluminium, closed façade elements made of aluminium and a perforated plastic façade curtain. The façade curtain will not be reused after deconstruction but recycled instead. A constructive element that will not be recycled is the fire-resistant paint on the steel profiles. After disassembly, the profiles need to be stripped of a layer of paint, because it can get damaged during disassembly and transport. It is also not clear whether the bolts and screws in the connections are reused after disassembly. They are non-uniform and designed without over dimensioning, which causes uncertainties.

Figure 6: Temporary courthouse in Amsterdam (Bouwen met Staal, 2017)

3.2.4. Fokker 7

Fokker 7 is part of a logistical business park located at the former premise of airplane manufacturer Fokker at Schiphol-Oost. The building has been described as the first logistic C2C-building in the world, where C2C stands for “cradle to cradle”. It is an initiative by Brink Staalbouw, a steel construction firm based in The Netherlands, and Nexteria, an institute of knowledge in the circular building industry (Nationale Staalprijs, 2020).

The building is designed to be completely disassembled and reused elsewhere: all connections of the building structure are bolted connections, and all other building components like plating is screwed. Also, the dimensioning of the elements is considered: elements have a limited size so they can be installed and disassembled easier. Installations are not cast in concrete or hidden behind alcoves but left fully in sight to make them accessible for disassembly. The design is made using a BIM-model (Building Information Model) in which all relevant information is captured.

The internal volume of the two-storey industrial building is flexible: the building is realised in a modular way, making it very suitable for multi-tenant use who can divide the space at their own discretion. The project won the Nationale Duurzaamheidsprijs Staal 2016.

Figure 7: Fokker 7 (Nationale Staalprijs, 2020)

3.2.5. Summary of examples

For all projects discussed in this chapter, different waste management policies were applied on different building levels. During the transformation of the three buildings on the corner of Hoogstraat, the structure of another building was reused on element level. The elements that were reused were not originally designed for this purpose but were fitted to realize the ambitions of the developer.

The town hall in Brummen was designed in such a way that elements and materials can be disassembled and reused. Additionally, materials that were used in the process were renewable and of high quality. The building was designed as a material depot because of the client's wishes and the ambitions of the architect.

The temporary courthouse in Amsterdam and the Fokker 7 building were designed so that the complete building could easily be disassembled and moved to a new location. This was done to fulfil the client's needs.

Project	Waste hierarchy level	Building level
Hoogstraat 168-172, Rotterdam	Object renovation Element reuse	Construction level Element level
Town hall, Brummen	Element reuse Material reuse	Element level Material level
Temporary courthouse, Amsterdam	Element reuse	Construction level Element level
Fokker 7, Schiphol-Oost	Element reuse	Construction level Element level

Table 1: Summary examples

3.3. Elaborations

As was discussed in chapter 2, the strict hierarchy of waste management strategies is an indication rather than an exact model. Furthermore, there is no generally accepted methodology for measuring the remaining lifetime and flexibility of a construction, which makes determining the building level on which certain waste management strategies can be applied somewhat subjective.

The concept of the donor skeleton does seem to have potential. According to (Glias, 2013), the reuse of elements results in a 10% cost reduction compared to using new elements with the same dimensions. The deconstruction of the elements which are to be reused account for 57% of their costs. This financial advantage might be an incentive to further explore the donor skeleton concept, in addition to the environmental benefits.

Assessing the structural integrity of the elements which are to be reused is a challenge for which an appropriate solution has yet to be found. Additionally, the concept can be improved by standardising element lengths and connections. This eliminates the need for customising the elements when they are disassembled and prepared for reuse.

The question could be raised whether realising a temporary construction and removing it after the contract with the client has expired (Town hall in Brummen and Temporary courthouse in Amsterdam) is the most appropriate scenario and option to satisfy the needs of the client. In case of the Temporary courthouse, an accommodation with a new function, for example a residential tower, is planned to be raised in its place after disassembly of the temporary construction. Complete reuse of the whole building (object renovation) ranks higher than element reuse from an economic and ecological perspective, and could be favourable. Another option could be the use of Portacabins, which are prefabricated standardised units. They are particularly used when the construction is considered temporary. Both of these options could be favourable compared to the chosen option in terms of environmental costs. In the end these options were rejected, presumably because of the specific requirements of the building regarding appearance and functionality. Also, because these projects are pilot projects, one of their purposes is to gain knowledge about circular design, and some design decisions might prove to be disadvantageous in hindsight. An important lesson taken away from these examples is that all life cycle stages (production, construction, use, and end-of-life) must be taken into account, including instances of transport during or in between these stages.

4. Assessment methods and tools for circularity

Measuring and assessing the circularity of products and services is important when making choices between processes, products, or companies. While there are several methods and tools that assess circularity and sustainability, there is no generally accepted methodology yet. In this chapter, several methods and tools are discussed.

4.1. NEN-EN 15804

The standard NEN-EN 15804 provides core product category rules (PCR) for constructions and services (Normcommissie 351281 Duurzaamheid van bouwwerken, 2019). These rules form a structure to derive, verify and present the Environmental Product Declarations (EPD) of construction products, services, and processes. The core product category rules:

- Define which indicators should be declared, what information should be provided and the way in which the indicators are reported.
- Describe which stages of a product's life cycle should be considered in the EPD and which processes must be included in the life-cycle stages.
- Define rules for the development of scenarios.
- Contain the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment (LCA) which support the EPD.
- Include the rules for reporting environmental and health information that is not covered by an LCA.
- Define the conditions under which construction products can be compared based on the information provided by EPD.

An EPD contains environmental information and information on health-related emissions to indoor air, soil, and water during the use stage of a building. The purpose of an EPD in the construction sector is to provide a basis for assessing the impact on the environment of buildings and construction works. The information in an EPD is expressed in modules. This allows easy organisation and expression of data packages throughout the life cycle of the building or construction. The approach requires that the underlying data should be consistent, reproducible, and comparable.

Figure 8 displays the types of EPD and which modules should be declared with respect to different life cycle stages. All construction products and materials must declare modules A1-A3, modules C1-C4 and module D.

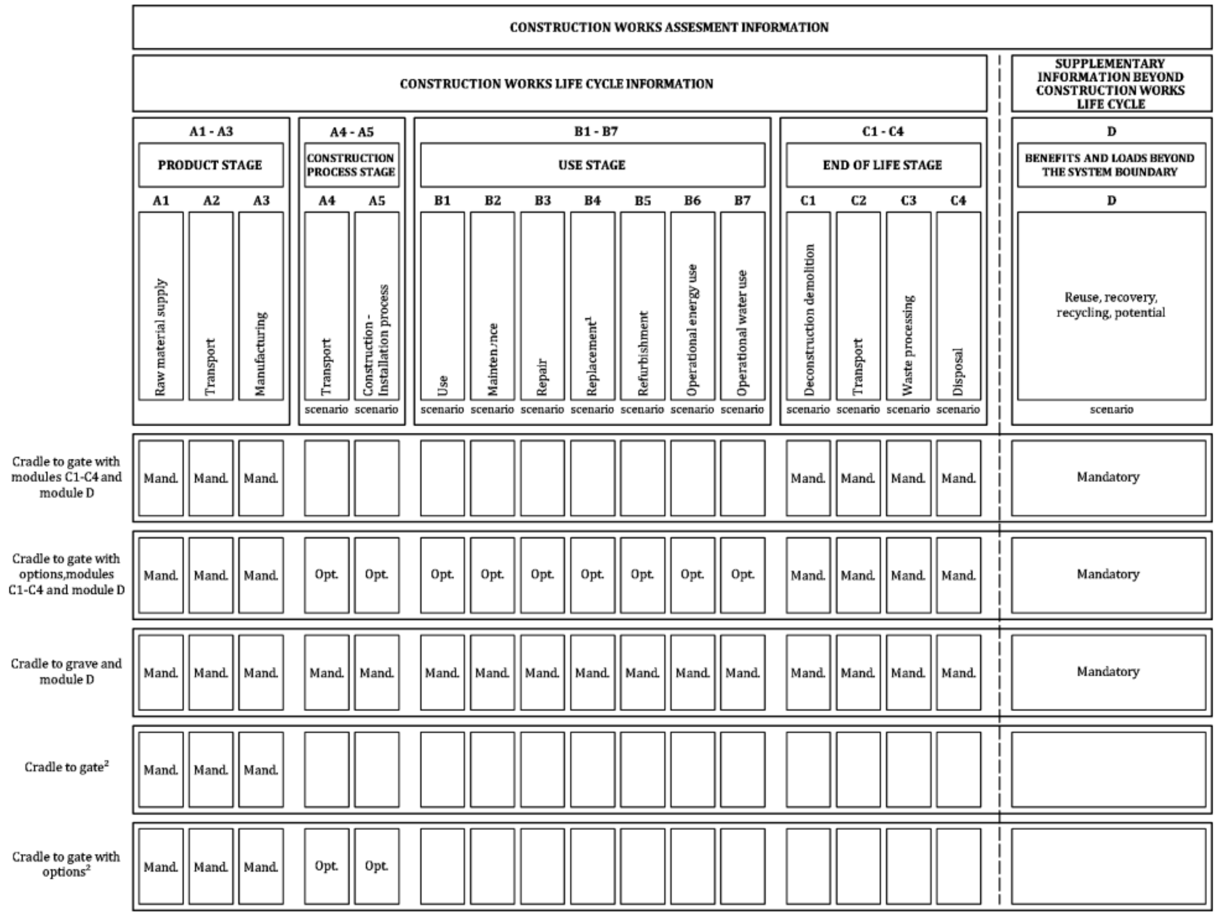


Figure 8: Types of EPD and which modules should be declared with respect to different life cycle stages (Normcommissie 351281 Duurzaamheid van bouwwerken, 2019)

4.2. Determination Method

The Environmental Performance of Buildings and Civil Engineering Works Determination Method (or Determination Method in short) is developed by the Stichting Bouwkwaliteit (Foundation for Building Quality). It has been developed to calculate environmental performance of buildings and civil engineering works over their entire life cycle in terms of the materials used (Stichting Bouwkwaliteit, 2019). The method is based on the NEN-EN 15804 and forms a complete method using the Nationale Milieu Database, or NMD in short (National Environmental Database).

The method closely follows the standard NEN-EN 15804 with some adjustments and additions. The most important additions are:

- Additional indicators regarding human toxicity and ecotoxicity are provided.
- Specific fixed values are prescribed for several processes.
- A specific LCA database is used for raw materials and basic processes.
- Within specific conditions, future scenarios are permitted in the product scenarios.

When calculating the environmental performance of buildings and civil engineering works, choices must be made regarding establishing scenarios and fixed values for the Dutch context and the use of generic data if no manufacturer or sector-specific data is available. The NMD was developed to provide a uniform calculation of the environmental performance of buildings and civil engineering works in the Dutch context. It provides information on products and activities in the form of product cards that refer to environmental profiles.

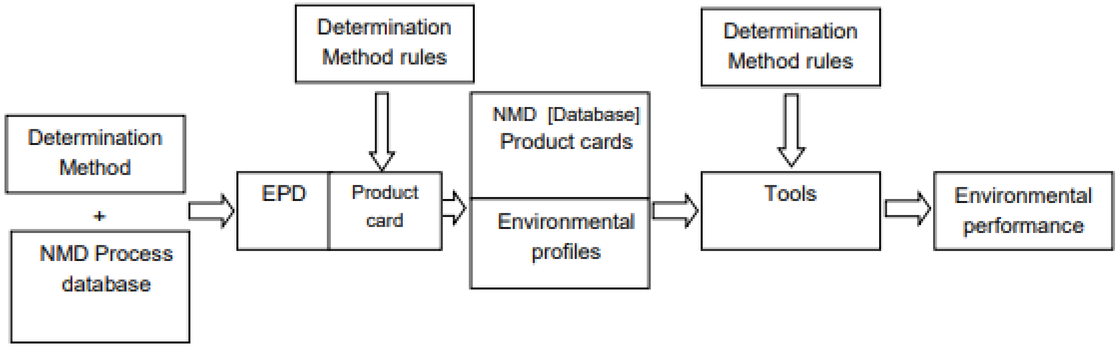


Figure 9: Relation of Determination Method and Environmental Database (Stichting Bouwkwaliteit, 2019)

4.3. Material Circularity Indicator

The Material Circularity Indicator tool is developed by the Ellen MacArthur Foundation and Granta Design (Ellen MacArthur Foundation, 2015). It allows users to identify the circular value of their products and materials and reduce the risks from material price volatility and supply. Additionally, it measures environmental-, regulatory- and supply chain risks.

This is done with the Material Circularity Indicator (MCI), which measures the restorative and regenerative material flows of a product or company, and complementary indicators that allow additional impacts and risks to be considered. In other words, it measures the extent to which the linear flow has been minimised and the restorative flow maximised, and how long and intensively a product is used compared to a similar product.

The methodology includes both the technical and biological cycles of materials. The Material Circularity Indicator tool can be used as a decision-making tool during the design of a product, but it can also be used for internal reporting and procurement decisions.

The MCI is constructed from a combination of three product characteristics: the mass of virgin raw material used during manufacturing, the mass of unrecoverable waste that is attributed to the product, and a utility factor that accounts for the length and intensity of the product's use. The material flow for technical materials is displayed in Figure 10.

A product that is manufactured using only virgin materials and ends up as landfill at the end of its use is considered a fully linear product. A product that is manufactured with no virgin materials, is completely collected for recycling or component reuse, and which has a recycling efficiency of 100% is considered a fully circular product.

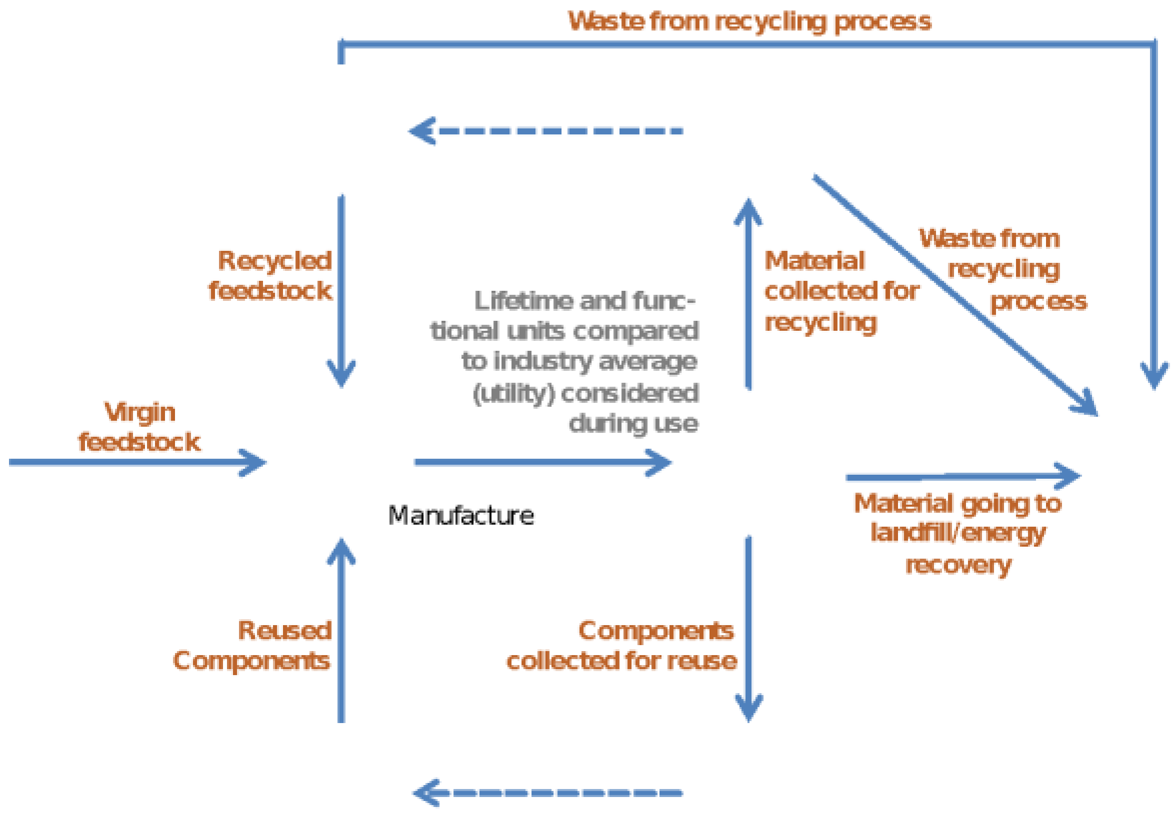


Figure 10: Flow of materials (Ellen MacArthur Foundation, 2015)

4.4. Madaster Circularity Indicator

The Madaster Circularity Indicator is developed by Madaster, which is a registry for materials, to improve the design of buildings in terms of circularity and to increase the circular value of these buildings (Madaster, 2018). The method rates a building with a score from 0 to 100%. This score is determined based on the data the user uploads to Madaster. The level of circularity is measured during three phases: the construction phase, the user phase, and the end-of-life phase.

- Construction phase: the ratio between virgin materials and recycled, reused and renewable materials.
- User phase: the expected lifespan of a product compared to the average lifespan of a comparable product.
- End-of-life phase: the ratio between waste and the reuse or recycling of materials and products produced during the refurbishment or demolition of a building.

The method is based on the Material Circularity Indicator method by the Ellen MacArthur Foundation and has been adjusted to facilitate the ease of use of Madaster users. The Madaster Circularity Indicator is calculated using a weighted average score, which is based on the mass of the applied materials and products. The scores are calculated for different building layers and the building as a whole.

4.5. Level(s) Framework

The Level(s) Framework (European Commission, 2017) is developed as a common European approach to assess the environmental performance of constructions throughout their life cycle, considering relevant resources such as energy, materials, and water. The framework consists of a set of core indicators that are used to assess the environmental performance of constructions. It also allows for other performance aspects to be assessed using indicators for health and comfort, life cycle cost, and potential future risks to performance. All in all, Level(s) provides a language to describe the sustainability of buildings. It contributes to broader European environmental policy objectives. It contains the following elements:

- Macro-objectives: six macro-objectives contribute to EU policy objectives in areas such as energy, material use and waste, water, and indoor air quality.
- Core Indicators: nine common indicators for measuring the performance of buildings which contribute to achieving each macro-objective.
- Life cycle tools: four scenario tools and one data collection tool, together with a simplified Life Cycle Assessment (LCA) methodology that are designed to support a more holistic analysis of the performance of buildings.
- Value and risk rating: a checklist and rating system provides information on the contribution to a property valuation and the reliability of performance assessments made.

The Level(s) framework also aims to promote life cycle thinking. It focusses on a more holistic perspective, with the aim of wider European use of Life Cycle Assessment (LCA) and Life Cycle Costs Assessment (LCCA).

4.6. Platform CB'23

The guide *Measuring circularity in the construction sector* (Platform'23, 2019) is the first step towards an assessment method for the circularity of buildings and infrastructural works. The guide describes a method which defines a fixed set of circularity indicators which are to be used in all measurements, can be integrated in existing tools, and allows for additional circular indicators to be added. This method focusses on protecting existing material stocks, the environment and existing value.

Key points of this method are:

- The circular strategy which is used (for example extending the lifespan of a product or reusing a product) is not of importance.
- The method is applicable at every level and during all phases of the life cycle of a product.
- The method is based on material flows during the life cycle of a product. It is based on existing methods and focusses on the collection of information.

The methods consist of two elements: a list of indicators of the degree of circularity and a report on the adaptive capacity of an object. The circular indicators can be divided into 7 main indicators, which can be divided further into sub-indicators:

- The quantity of materials used
- The quantity of materials available for the next cycle
- The quantity of material lost
- The influence on the quality of the environment
- The quantity of existing value used
- The quantity of value available for next cycle
- The quantity of existing value lost

The report on adaptive capacity is used to gain insight on the extent to which materials, environmental quality and existing value is lost after the life cycle of the object. An object with a high adaptive capacity will be useful for a longer period because most materials and value will be retained after the first life cycle. Additional investments in materials must be considered because this will lead to a lower environmental impact during the construction phase.

The report consists of scenario studies and implications of probable scenarios for the design. Scenario studies include expected developments and the effect of these developments on the supply and demand of the product. The implications of these scenarios deal with how these effects are translated into design decisions.

The design decisions can be subdivided into spatial and technical adaptability. Spatial functional adaptability refers to the resilience of a building to cope with changes in functions and space requirements. Technical adaptability is expressed in how elements, products and materials are assembled: the detachability of connections and physical independence.

4.7. IMPACT Method

The IMPACT-method is developed by TNO (TNO, 2020). IMPACT is an acronym that stands for Integrated Method of sustainable Product Assessment for Circular Transition. It functions as a tool for manufacturers in different sectors to help them make their products more sustainable. The method aims to indicate the circularity of a product with three main parameters:

- The quantity of resources used during the production process.
- The impact of the product of human health and the environment.
- The economic effects of the product.

Especially the first two parameters give a good indication of the sustainability and circularity of a product.

4.8. Circularity Check

The Circularity Check is developed by Ecopreneur (Ecopreneur, 2020). It is primarily intended as a tool for self-evaluation by companies.

It is an online scan tool with a questionnaire of about 60 questions that determines a circularity score for a specific product or service. This is expressed in a percentage which indicates how circular the product or service is. The tool also provides partial scores on design, procurement, manufacturing, delivery, use, recovery, and sustainability.

4.9. Elaborations

The previously discussed circularity assessment models and tools attempt to quantify the level of circularity of construction materials, products, processes and services, buildings and infrastructural works in one way or another.

NEN-EN 15804 and the Determination Method express circularity using an indicator for environmental performance. The methods focus on environmental impact and health-related emissions. However, they neglect the circular principle of circulating products, and preserving existing value.

The Material Circularity Indicator and the Madaster Circularity Indicator measure circularity by examining the flow of materials of a product. The methods focus on material flows, but falls short in investigating the environmental impact of products.

The Level(s) framework focusses on the environmental impact of products, and takes into account relevant resources such as energy, materials and water. Other performance aspects can be assessed using indicators for health and comfort, life cycle cost, and potential future risks to performance. It also aims to promote the circularity principle of circulating products.

The method of Platform CB’23 focusses on protecting existing material stocks, the environment and existing value.

The IMPACT Method takes into account the quantity of resources used during production, impact on human health and the environment and economic effects. However, it also neglects the circularity principle of circulating products and preserving existing value.

The Circularity Check is a questionnaire which focusses on design, procurement, manufacturing, delivery, use, recovery, and sustainability. However, the tool is a *black box*, and provides no information about its inner workings.

It can be concluded that all methods and tools discussed either focus on the environmental impact or the flow of materials and protecting existing value, except for the method of Platform CB’23 which focusses on both. It can also be noted that these methods (with the exception of the Circularity Check) do not really measure the degree of circularity related to certain design options. Although the tools and methods aim to help to make design decisions, they do remain quite general on the subject of design. Also, all methods are intended to measure the circularity of construction materials, products, processes and services, buildings and infrastructural works. None of the methods focus specifically on the façade of a building.

It can be desirable to expand or combine these methods, and create a new method which focusses on environmental impact, circulation of materials and products, and design options. It can also be desirable to develop a method specifically for the façade of a building.

5. Circular design criteria and strategies

To design a circular façade system, certain design criteria must be met. This chapter discusses the origin and reasoning behind these design criteria. The design criteria are derived from different design strategies. The strategies discussed in this thesis are *Design for Disassembly, Design for Adaptability and Modular Design*.

Design for Disassembly is the design of buildings to facilitate future change and the eventual dismantlement for recovery of systems, components, and materials. The design process includes developing the assembly techniques, components, materials, construction techniques and information and management systems to accomplish this goal (Ciarimboli & Guy, 2020).

The purpose of Design for Adaptability is like that of Design for Disassembly: extending the utility and value of buildings. When a design is adaptable, manufacturers can develop upgraded or customized elements. This prevents premature product replacement, which provides economic and environmental benefits.

Modular Design is linked with Design for Adaptability. An optimum life cycle is assumed for the different layers of a building. Layers of a building can be adapted by replacing certain sections with modules, increasing efficiency and reducing construction time (Modular Building Institute, 2020).

The three strategies will be discussed in the following paragraphs.

5.1. Design for Disassembly

The goal of Designing for Disassembly is to maximise economic value and minimise environmental impact. This is achieved though subsequent reusing, repairing, remanufacturing, and recycling of materials. When this is no longer possible, energy can be generated from materials and bio degradation. Design for Disassembly can be described with the following ten key points (Ciarimboli & Guy, 2020):

- Documentation of materials and deconstruction methods: information about materials, elements and components should always be available, as well as a plan for deconstruction when the building has served its lifetime. This will result in a more efficient disassembly- and deconstruction process.
- Use of circular materials: construction materials should be used which have a high quality and will retain their value. Also, the use of toxic and non-biodegradable materials and additives should be avoided.
- Design accessible connections: connections should be designed so that they are visually, physically, and ergonomically accessible. This will increase the efficiency in disassembly and deconstruction and will avoid expensive equipment or extensive health and safety precautions.
- Avoid chemical connections: chemical connections like binders, sealers or glue should be avoided. These connections are difficult to separate and recycle and increase the risk of a negative environmental impact.
- Design bolted, screwed, and nailed connections: standard connections will decrease the use of tools during installation and disassembly. This will increase the efficiency and reduce time and effort.
- Separate mechanical, electrical, and plumbing systems: separating these systems will make it easier to repair, replace, reuse, or recycle them.
- Design to the worker and labour of separation: the labour intensity of workers will be decreased by scaling components and attuning to ease of removal.

- Design to simplicity: designing simple structural systems, simple forms and standard grids will increase the ease of installation and disassembly of elements.
- Design interchangeable components: designing modular components will facilitate reuse.
- Allow for safe deconstruction: allowing for movement and safety of workers, equipment and site access, and ease of materials flow will increase effectiveness and reduce risk during the disassembly of components.

The notion that a buildings transformation capacity, which relies on the disassembly potential, has a direct relation with the sustainability of the building is endorsed by Durmisevic (Durmisevic, 2016). A higher transformation capacity means a less environmental impact and a higher level of sustainability.

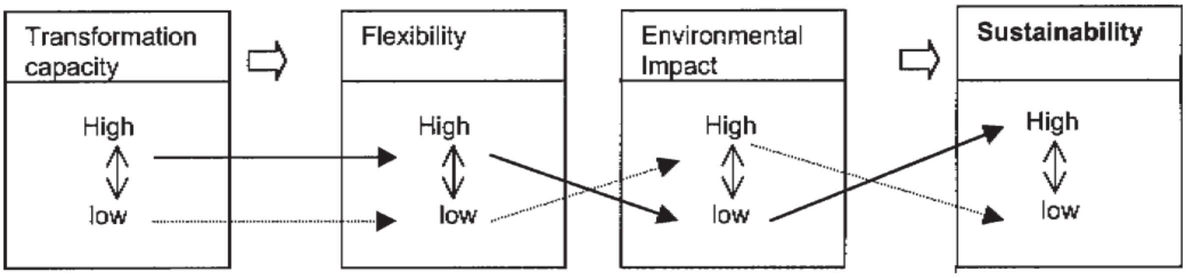


Figure 11: Relation between transformation capacity and sustainability (Durmisevic, 2016)

Based on this notion, buildings can be divided into three categories:

- Buildings with a low disassembly potential. These structures have a standard construction waste stream (70-100% of materials are downcycled and demolished).
- Buildings with a partial disassembly potential (30-70% of materials are downcycled, landfilled or incinerated).
- Building structures with a high disassembly potential (0-30% of materials are downcycled, landfilled or incinerated).

5.2. Design for Adaptability

Design for Adaptability is linked with Design for Disassembly, both aiming to extend the utility and value of buildings. The key points of design for adaptability are (Moffatt & Russell, 2001):

- Independence of parts: integrate systems (or layers) within a building in ways that allow parts to be removed or upgraded without affecting the performance of connected systems.
- Upgradeability of the system: choose systems and components that anticipate and can accommodate potential increased performance requirements.
- Lifetime compatibility: do not encapsulate, or strongly interconnect short lifetime components with those having longer lifetimes. It also may be advantageous to maximize durability of materials in locations where long lifetimes are required, like structural elements and the cladding. Durable claddings and foundations can also facilitate adaptability because it makes conversion of the building more attractive than demolition.
- Record keeping: ensure that information on the building components and systems is available and explicit for future use. It will assist effective decision-making regarding conversion options and prevent costly investigative proceedings.

5.2.1. Independence of parts

Independence of parts is both a key feature of Design for Disassembly and Design for Adaptability. This notion is endorsed by Lichtenberg (Lichtenberg, 2016). The construction sector is known for its slow innovation and its conservative attitude towards new practises. This is caused by the fragmentation and complexity of the construction sector. When innovation is present, it is usually driven by stakeholders who improve their own process or product. Such innovations are relatively small and incremental, and result in incoherent products: stacked innovation to solve sub problems, which is not the most efficient. This innovation by addition results in inefficiency in terms of material use and labour hours. An integral approach, not focussing on one specific bottleneck at the time, but multiple problems at once, could be more efficient from the point of view of the consumer.

Stacked innovation can especially be seen in the way services are installed in buildings. When building services are tolerated on the roof of the building, this is not a major problem. It becomes problematic when services are "hidden" in ceilings and walls. This interweaving of service channels, also called the spaghetti-effect (Van Randen, 1976), results in the fact that service installers must return to the building site multiple times in order to finish their work.

This is also problematic from a financial point of view. Housing has become increasingly more expensive, compared to consumer goods like cars, because of this phenomenon. Additionally, buildings with an interwoven network of services tend to be less flexible. This results in lower efficiency in use of space, vacancy, and premature demolition.

The solution Lichtenberg proposes is based on the principle of building layers (Brand, 1994). These layers should complement each other, for example by integrating prefabricated openings for the installation of services. This can reduce the construction time, installation costs (up to 30%) and material use. This also has a positive effect on the possibility of disassembly.

5.2.2. Documentation and record keeping

For both Design for Disassembly and Design for Adaptability, the monitoring of status and whereabouts of the different components and materials is essential. After the initial use phase, sufficient information should be available to reuse components or materials.

Usually, this information is obtained by investigation and detection methods. This is not very efficient, because these methods can be inaccurate and sometimes require destructive testing. To make the transfer of information more efficient, a material passport is introduced. The material passport includes information about the product, component, or material into itself.

Some initiatives in this field are Madaster and the BIM (Building Information Modelling) 3D design tool (Van Heel, 2017). Both initiatives are based on the same principle: by capturing the physical world in data, it can be stored and organised, remaining available for future use indefinitely. The first building that was built with a material passport was the city hall of Brummen in 2013 (3.2.2).

Alkondor, a company that specialises in façade constructions, developed a so-called Façade Identification System, or FIS. Alkondor engineers its products in a BIM environment, after which relevant information is added to the individual products. During production, the data is attached to the façade elements through a tag or identification document, for example a QR-code or a NFC chip (Alkondor, 2020).

5.3. Modular Design

Modular design is the design of products by assembling components as distinct building blocks that can be integrated to fulfil various customer and engineering requirements (Jiao, Tseng, & Wang, 2018). The concept was introduced, to develop variety in the production of goods. It ensures the modification of modules for them to meet new requirements, without influencing the main structure. Modular design has been deployed in many fields of design and manufacturing, for example building design.

Product architecture and product platform concepts are essential in Modular design. Product architecture is a scheme where physical components are linked to functional elements to form various products (Eppinger & Ulrich, 1995). The product platform is a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced (Lehnerd & Meyer, 2011). Compared to product architecture, the product platform concept focusses more on the physical configuration of components.

A typical process to establish modular product architecture is:

- Develop a conceptual model of components and functions of a product.
- Cluster the elements, regroup components inside of the modules in the model according to assembly precision, function sharing, technological simplicity, localisation of change, accommodating variety, enabling standardisation and portability interfaces.
- Create a geometric layout to better detect interfaces and modules.
- Identify important interactions in the conceptual model to find modules and the persons in charge of the modules.

6. Façade systems

In this chapter façade systems are discussed in more detail. First, the lifespan of façades is analysed. This is relatively short compared to other building layers like the load bearing structure. Also, the leasing- and reuse potential of façades is examined. Then, different façade systems are analysed which are currently used for industrial buildings. The chapter concludes with a discussion of connections used in façade design.

6.1. Functions and lifespan

The façade of a building has multiple functions: it shields the occupants of a building against the elements of nature like wind, rain, extreme temperatures, and humidity. It provides ventilation of the building as well. This reduces the energy which is otherwise needed to heat, cool, and ventilate the interior of the building. Besides protection against the elements, a façade also provides acoustic insulation and security to the occupants of the building. The façade also protects the building itself, adding to the buildings lifespan (De Brito & Flores-Colen, 2010).

Finally, a façade defines the appearance of a building. This means that apart from structural requirements, a façade has aesthetic requirements as well. If the appearance of a façade does not meet these requirements anymore, it is disassembled even though it still meets the structural requirements.

The shearing layers concept was introduced by architect Frank Duffy and was later elaborated by Stewart Brand. It refers to the fact that buildings consist of different layers, each with its own lifespan. The different layers and their lifespan are displayed in Table 2.

Layer	Explanation	Life span
Site	The geographical setting	Eternal
Structure	The foundation and load-bearing elements	30-300
Skin	Exterior surfaces	20
Services	The working guts of a building	7-15
Space plan	Interior layout like walls, ceilings, floors, and doors	3-30
Stuff	Furniture	Daily

Table 2: Shearing layers and their lifespans (Crowther, 2005)

The skin, or façade, is typically the most restructured and demolished subsystem of the total building system. Therefore, it can be seen as the weak link in the building system, and is one of the main sources of waste generation (Deniz & Dogan, 2014). This is often because sustainability and durability of the building skin system is often payed little attention to during the design phase. This means that there is a lot of potential in building skin design and increasing its lifespan and sustainability. Another factor that influences the lifespan of the façade is its appearance. A client can decide that the appearance of a façade does not meet the aesthetic requirements. This can for example be because of fashion trends or visible pollution on the façade.

The fact that façades are often replaced because of their aesthetic features instead of their structural integrity makes them an interesting subject for circular innovations. After all, elements and materials are discarded even though they are still serviceable. Updating the appearance of a façade whilst keeping the rest of the elements and materials of the building at their highest utility is a challenge designers of circular façades are faced with.

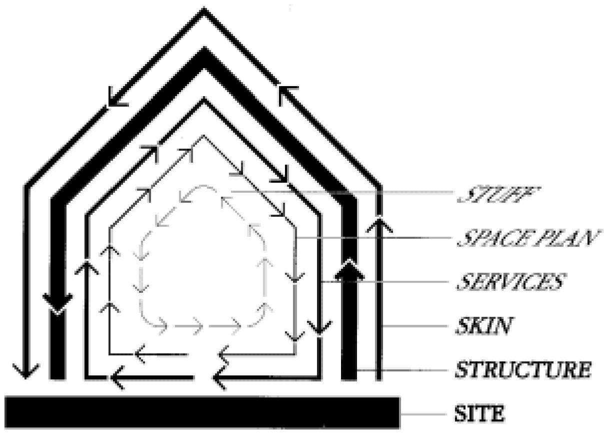


Figure 12: The shearing layers of a building (Li, Zhou, & Wang, 2019)

6.2. Causes for failure

Failure is defined as a condition in which a component does not meet the performance requirement of its designed use (Carper & Feld, 1996). The definition includes several examples such as minor visual faults, or more serious serviceability problems such as excessive deformations, deterioration of materials or leakage. Failures can be characterised in two ways (Gilboa, Puterman, & Shohet, 2002).

- The symptomatic approach: focusses on the results of the failure and the effects of the failure on the building.
- The circumstantial approach: focusses on the failure itself and the mechanism of degradation.

Failure arises when one of the following three phenomenon occurs (Hermans, 1995): (1) changes of material characteristics, (2) changes of shape characteristics, (3) changes of location characteristics. These phenomena are caused by deterioration agents, which can be either chemical, biological, physical, or mechanical. These agents can be found both inside and outside the building structure. Examples of internal sources are:

- Stresses incorporated in materials or components due to the production process.
- Effluent washing out of materials and disrupting other materials.
- Changes due to the combination of incompatible materials.

Examples of external sources are:

- Temperature
- Moisture
- Radiation
- Air pollution
- External loads
- Water or wind flow containing particles
- Effluent caused by transportation of substances from the outside.

The most frequent sources of premature deterioration of façades are: (1) Faulty design; (2) Poor quality of implementation; (3) Poor quality of materials; (4) Adverse climatic or atmospheric conditions; (5) Adverse atmospheric conditions caused by air pollutions; (6) Poor maintenance; (7) Intensive use (Gilboa, Puterman, & Shohet, 2002).

6.3. Reuse and leasing potential

In 2016 researchers from the faculty of Architecture of the TU Delft developed a business concept in which clients do not own structural elements of buildings but instead lease them (Azcarate-Aguerre J. , Façade Leasing pilot project at TU Delft, 2020). Four façade panels were tested at the campus of the TU Delft, varying in the degree of circularity. The final design consisted of robust aluminium panels, to which different modules of climate technology could be added (Redactie Bouwwereld, 2016).

Figure 13: Pilot project TU Delft (Azcarate-Aguerre J. , Façade Leasing pilot project at TU Delft, 2020)

The façades were installed on the faculty of Electrical Engineering, Mathematics and Computer Science on the campus of the TU Delft. The project was used as a case study to investigate new building methods, organization, and cooperation within the construction sector. It forms the basis for further research in building contracts, financial structures, and operational services, to eventually enable the implementation of façade leasing. The concept of façade leasing is because the client does not own the building envelope and its integrated building services but leases them from a service provider through a long-term performance contract. In other words, the client does not buy a product, but hires energy performance and user comfort services. At the end of the contract, the façade elements are returned to the developers, who also perform service and maintenance.

In the master thesis *Façades as a Product-Service System* (Azcarate-Aguerre J. , Façades as a Product-Service System - The potential of new business-to-client relations in the façade industry, 2014), it is concluded that façade leasing is a viable concept, for other industries have used the concept of leasing products and combining products and services for decades. This increases client loyalty, eliminates second-hand markets, and increases the rate of replacement. It also increases the effective use of resources, by conserving material ownership with the manufacturer and binding stakeholders into a shared long-term commitment.

Although structural projects have a longer economic lifespan, a proven system will also work on another timescale. This is only the case when certain design parameters are considered. Technical design requirements include modular design and prefabrication. Façade leasing could not only improve façade design, production, and disposition, it could also improve the communication process between businesses and clients during construction projects.

There are however a lot of uncertain factors that require further research, such as the financial capacity of the service provider, regulations within the manufacturer's jurisdiction and the type of client who would be interested in such a concept. DBFOM (Design Build Finance Operate and Maintain) contracts are increasingly more used and can play a role in the implementation of façade leasing constructions. The main drivers and barriers of the façade leasing concept are displayed in Table 3.

	Drivers	**Barriers**
Client	Outsource non-core processes (e.g., façade maintenance schedules and indoor comfort performance monitoring)	Partial third-party ownership of organisation's real estate
	Accelerate rate and depth of portfolio retrofitting	Possibly high risk-premium while track-record is created
	Stabilise cash-flow, lower upfront capital requirements	Cash-flow based financing limited to relatively large clients
	Improve functional flexibility of portfolio	Contract setup and management costs
Service provider/manufacturer	Access to new service-based markets	R&D investment on system and service integration
	Stabilise cash-flow, reduce impact of real estate cycles	Lower upfront profit
	Higher profit margin for services. Incentivise innovation and quality	Development of new processes required (staff and training)
	Enhance raw material security	Financial model sensitive to global material / commodities market trends
	Gather valuable data on the use, performance, and failure of products. Contributing to updated engineering and manufacturing practices	Data collection and privacy issues

Table 3: Drivers and barriers for façade leasing (Azcarate-Aguerre, den Heijer, Klein, & Vrijhoef, 2018)

6.4. Current façade systems

6.4.1. Masonry

Masonry cladding consists of units, typically bricks which are manufactures off-site, and mortar which is mixed on-site. The bricks are installed on site as well, usually on a concrete foundation or structural steel or concrete beam. Expansion joints are required in the design to avoid cracking, spalling and displacements in the masonry due to moisture and thermal changes (Weber, 2016).

The system can be classified as a modular system: the masonry units are the different modules, which can be laid in different patterns and to various heights. The strength of the cladding is achieved after curing of the mortar. Apart from cladding, masonry can serve as a structural element, for example bearing walls, columns, or pillars. In general, there are two different types of masonry walls: veneer- and structural walls.

Veneer walls function as cladding material only, and only transfer horizontal wind loads to the structure, so lateral support is required. This is typically provided by an interior wall, for example a cold-formed steel frame. Structural masonry walls can be reinforced both vertically and horizontally to achieve flexural resistance. A second layer of masonry is typically added to ensure structural integrity. The layers act as a composite wall or as two individual walls to support the loads.

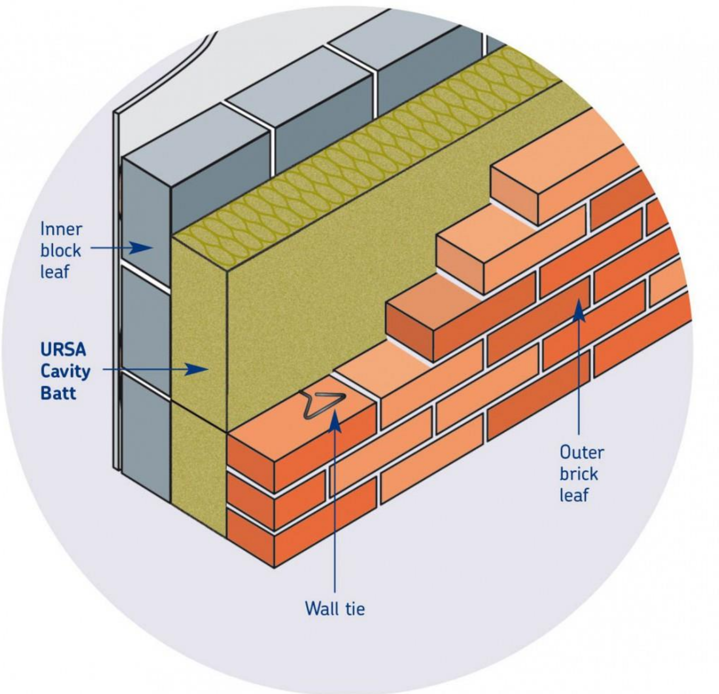


Figure 14: Section of a veneer masonry wall system (Ursa, 2020)

6.4.2. Precast concrete panels

Precast concrete panels can vary in shape and size: they can span one or multiple stories and can include window openings. Cladding can be added, depending on appearance, weatherproofing and other performance criteria. Typically, each precast panel is supported by the building structure using a variety of metal components and anchors. Joints of the precast panels are usually filled with sealant. Precast concrete panel systems are most often constructed as a curtain wall or veneer. They must resist lateral loads such as wind and earthquake loading, as well as vertical loads resulting from self-weight. The loads must be transmitted to the building structure through secondary structural elements (Gaudette, 2016). There are four types of precast panels used as part of a building envelope:

- Cladding or curtain walls: this is the type of precast concrete panel which is most used. They do not transfer vertical loads and are only designed to resist wind and seismic forces and forces required to transfer the weight of the panel to the support. Cladding can be added to these units and they can be removed individually is necessary.
- Load bearing wall units: this type of precast concrete panel does transfer horizontal loads from other elements and cannot be removed without affecting the strength and stability of the building.
- Shear walls: precast concrete shear wall panels provide lateral stability when combined with diaphragm action of the floor construction. The effectiveness depends on the panel-to-panel connection.
- Formwork for cast-in-place concrete: this formwork provides the aesthetics while the cast-in concrete provides the structural component of the system.

Figure 15: Installation of a precast concrete panel (Mishra, 2020)

6.4.3. Metal panels

There exists a wide variety of metal façade panels, usually made of aluminium. Steel, stainless steel, copper or composite materials are also possible, however. Metal panels typically support gravity, seismic and wind loading. The support system of the panels also needs to be able to accommodate tolerances from the main construction and fabrication. They are often screwed or bolted to a metal structure frame. Joint design is essential to the water tightness of the system. Compared to prefabricated concrete panels and masonry cladding, metal panel systems have higher expansion coefficients, which mean more thermal movement. This means that joints should accommodate expansion movements between different parts of the system (Chiropolos, 2016). The most common types of metal panel systems are:

- Lap-seam metal panels: these panels are formed out of metal sheets and are placed ship-lapped with adjacent panels. At the edges, typically sealant tape or gutters are present.
- Composite metal panels: composite panels consist of two sheets of metal with a core material in between. These panels are generally stronger than lap-seam panels and include built-in insulation. Like lap-seam panels, these panels are often ship-lapped with adjacent panels.

Types of composite metal wall panels include foamed-insulation core metal wall panels, laminated-insulation core metal wall panels and honeycomb core metal wall panels.

- Flat plate metal panels: these panels are cold-formed into the desire profile. Stiffeners and support structure can be welded to the flat plate. Flat plate panels have high impact resistance compared to other types of panels.
- Metal faced composite panels: metal faced composite panels consist of metal facings attached to a thin thermoplastic core. Like flat plate metal panels, stiffeners can be attached to the panels, but they are not as impact resistant. The panels are either directly attached to the main structure or to a secondary structure.

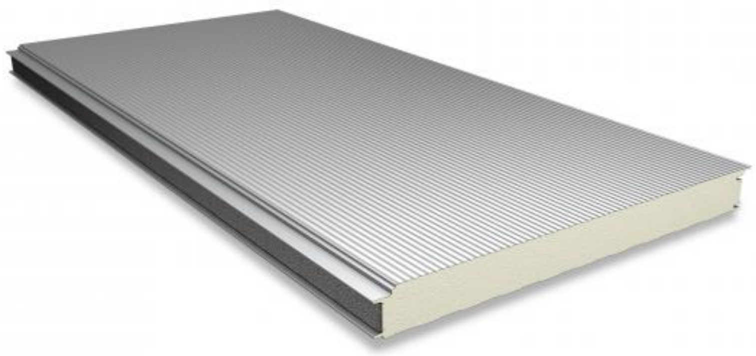


Figure 16: Sandwich panel (Two sheets of metal with a core material in between) (SAB-Profiel BV, 2020)

6.4.4. Structural liner trays

A *liner tray system* consists of liner trays, which are used as main supporting structure and insulation support. Insulation is placed inside the trays, after which they are closed off with a metal cover sheet. Typically, the trays are placed horizontally from column to column, after which the finishing element is placed vertically. The installation of the trays starts from the bottom. The subsequent tray interlocks with the previous one, and this process is repeated.

The trays are typically placed in a two-field span. When window- or door openings are present in the façade, the trays are attached to a secondary support structure. This support structure usually consists of cold-formed steel elements as well. The trays are connected to the supporting structure with shot fired pins or self-drilling screws.

Depending on the manufacturer, the trays can measure up to 20 metres. Spans larger than 7 metres are not common in practice. Large profiles are not desired: because of the increase in weight, the profiles are more difficult to handle. Sometimes the metal plates are perforated to improve their acoustic performance. Sound waves pass through the perforated profiles, after which they are absorbed by the insulation (Industriebouwen, 2020).

Figure 17: Section of a liner tray system (Architectenweb, 2020)

6.4.5. Summary and elaborations on façade systems

	Masonry	Precast concrete panels	Metal panels	Structural liner trays
Thermal performance	Large thermal mass, insulation in wall cavity	Depends on insulation in cavity wall	Depends on insulation in cavity/built in insulation	Depends on insulation in liner tray
Moisture protection	Barrier system with joint seal	Barrier system incorporating a joint seal	Can function as a moist barrier, joints are critical	Can function as a moist barrier, joints are critical
Fire safety	Excellent fire resistance, often used as firewall construction	Connections are damaged easily, so serious hazard for high rise buildings	Not considered a fire safe system, insulation material can be flammable	Not considered a fire safe system, insulation material can be flammable
Acoustics	Heavy mass, good sound insulation	Generally good, however sound can spill through joints	Back-up wall cavity typically provides sound insulation	Liner tray cavity typically provides sound insulation
Maintenance and durability	Little to no maintenance	Attributed to problems during erection, connection to main structure and reinforcement	Dependent on the material, finishing of the metal panels is essential	Usually galvanised
Transfer of vertical loads	Yes	Yes	No	No
Prefabrication	No	Yes	Yes	No
Dry connection to load bearing structure	No	Yes	Yes	Yes
Dry connection between elements	No	Yes	Yes	Yes
Reusable	No	Yes	Yes	Yes

Table 4: Summary of current façade systems

When determining the suitability for use in a circular economy, the following can be concluded about the different façade systems:

- Masonry is very durable and requires little to no maintenance, the most frequent maintenance being the replacement of the sealant in expansion joints and around the perimeter of openings. Repointing the mortar joints in exterior masonry is required between 20 to 30 years after installation. It has a good thermal and acoustic performance, and has an excellent resistance to fire. The system does have a number of drawbacks however. The bricks are installed on-site which is labour intensive and time consuming. Also, the connections between the bricks are wet connections, which makes them difficult to disassemble and reuse.
- Precast concrete panels can be durable provided that the connections are well designed and executed. The design and execution of the connections also influences the acoustic performance and the performance under fire conditions. Concrete panels can be suitable for circular use, because they are prefabricated and have dry connections. Because of their mass, they might be difficult to install.
- The acoustic and thermal performance of metal panel and structural liner tray systems depends on the insulation in the cavity. Both systems use dry connections, making them easy to disassemble. Where metal panels are prefabricated, liner tray systems filled with insulation materials and covered with a finishing element on-site. Protection against corrosion is essential for the durability of metal panels and structural liner trays. The most common finishes include fluoropolymers and powder coatings. A potential problem that can occur is pitting, which happens when metal panels are exposed to weathering and pollution. Contact between different metals can also result in problems, for example due to water runoff or galvanic corrosion. Metals are especially vulnerable when their coating is damaged, for example when the metal and finishing is pierced by a connector.

To create a façade system which is well suited for circular use, it is interesting to look at the strengths and weaknesses of current façade systems. When designing for Disassembly dry connections should be used between the elements, and between the elements and the loadbearing structure. Therefore, masonry can be disregarded as a suitable façade system for circular use.

The element should be easy to disassemble, so the weight of the elements should be reduced as much as possible. Therefore, cold-formed steel (metal panels and liner tray systems) are regarded best suitable. When designing for adaptability, the system should be upgradeable. In case of metal panels and liner tray systems, the thermal and acoustic performance depends on the insulation in the cavity. When insulation material can be added to the cavity, it will improve the thermal and acoustic performance. This is possible for structural liner trays, because the connection between the insulation material and the liner trays is a dry connection, instead of a chemical connection as is the case for metal panels.

A liner tray system does have the drawback of not being prefabricated however. This can be solved by using liner trays in a prefabricated element.

6.5. Connections

6.5.1. Standard connections

6.5.1.1. Welding

Welds can be subdivided into arc welds and resistance welds, but in practise arc welds are generally used. They are made using an electric arc and weld filler material, fusing two elements together. Either cover electrodes or welding wires are used as filler material, which should appropriately match the strength of the base material. The most common weld is the fillet weld, and it is used to connect sheet to sheet of cross-section to cross-section (Yu, 2000).

6.5.1.2. Bolts

Bolts are mechanical fasteners. They are combined with nuts to install them in pre-drilled holes through the elements which are to be connected. The shape of the head of the bolt can vary, for example hexagonal, cup, countersunk or hexagonal flanged, although hexagonal are the most common. The bolt diameter can vary from M5 to M16. The property classes are usually 8.8 or 10.9, but bolts can be larger in diameter. Bolts are usually used to connect thin to thick or thick to thick elements (Yu, 2000).

6.5.1.3. Fired pins

Fired pins are mechanical fasteners. They are driven through the element that is to be fastened and through base material. The maximum thickness of the element that is to be fastened is 3 millimetres. The driving energy of these fastener can either be powder actuated or air driven. Powder actuated fasteners require a thicker base material (minimum of 4 millimetres) because of their firepower. Fired pins are usually used to connect thin to thick elements (Yu, 2000).

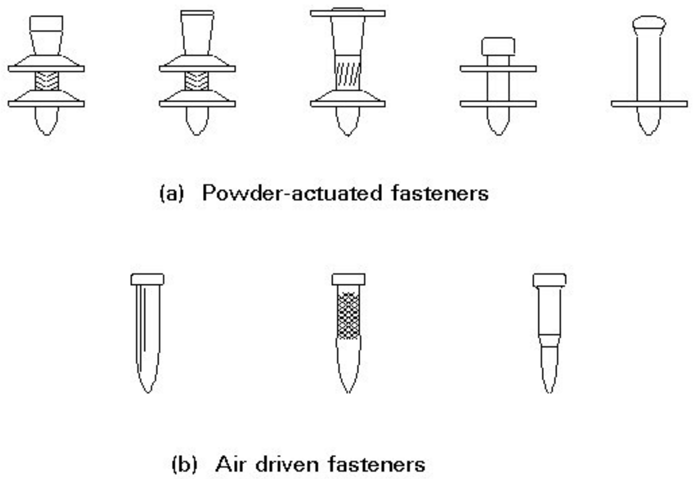


Figure 18: Powder-actuated and air driven fasteners (Yu, 2000)

6.5.1.4. Self-drilling screws

Self-drilling screws are usually combined with washers to improve the load bearing capacity of the fastener and to make the fastener self-sealing. They drill their own hole and form their mating threads in one operation. Self-drilling screws are typically made of heat-treated carbon steel or stainless steel. In both cases they are protected from corrosion with zinc coating. Self-drilling screws are usually used to connect thin to thin or thin to thick elements (Yu, 2000).

6.5.2. Alternative connections

6.5.2.1. Self-tapping screws

Like self-drilling screws, self-tapping screws are usually combined with washers. Unlike self-drilling screws, they tap their counter thread in a pre-drilled hole. They can be subdivided in thread-forming screws and thread-cutting screws. Thread-forming screws are typically used for connecting thin to thin steel sheets, or a thin sheet to a steel base up to 4 millimetres thick. They are usually made of carbon steel or stainless steel with a zinc coating. Thread-cutting screws are typically used for connecting thin sheets to a thicker steel base and are usually made out of case hardened carbon steel with a zinc coating (Yu, 2000).

6.5.2.2. Blind rivets

Blind rivets are used when access to the connection is limited to one side. They are installed in pre-drilled holes and use a locking mechanism which expands the shanks of the rivet. Blind rivets can be further subdivided into pull-system rivets, explosive rivets, and drive-pin rivets. The installation process of a pull-though rivet is displayed in Figure 19. Rivets are usually used to connect thin to thin elements (Yu, 2000).

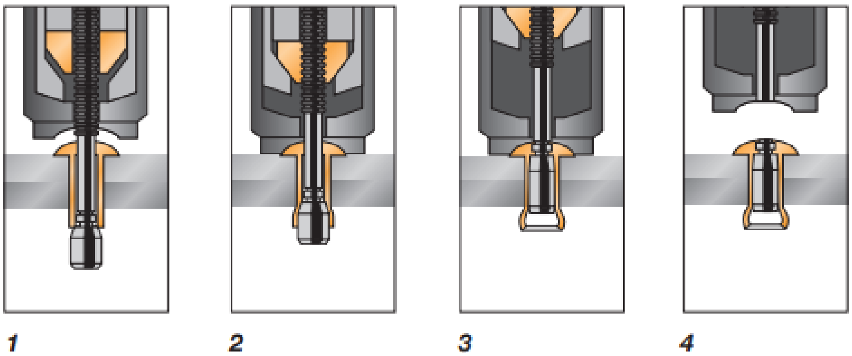


Figure 19: Installation of a blind rivet (Onkenhout Access & Fastening Solutions, 2020)

6.5.2.3. Press joints

Press-joint are relatively new. To make a press joint, a tool which consists of a punch and expanding die is needed. The process is illustrated in Figure 20. The advantages of this technique are that no additional material is required for the connection, it does not damage protective coating, and the connection can be made watertight and is fast and efficient.

It is also possible to press joints with added material, which are so called self-piercing rivets. A semi-tubular rivet is pressed into the two materials to join them, creating an interlocked friction joint. The rivet pierces the upper layers of the material and spreads under the influence of a die. The lower layer of the material is not pierced, so the joint is air- and watertight. Press joints are usually used to connect thin to thin elements (Yu, 2000).

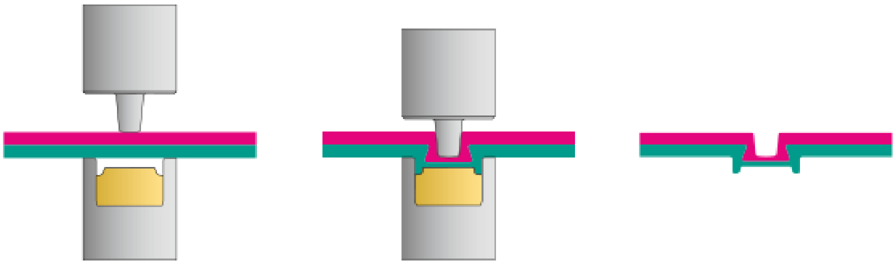


Figure 20: Formation of a press joint (Tox Pressotechnik, 2020)

6.5.2.4. Adhesive bonding

Adhesive bonding is sometimes used in combination with mechanical fasteners to ensure good resistance against shear- and peeling forces. Adhesive bonds are usually weak to pealing forces, so the mechanical fasteners come into effect when the capacity of the adhesive connection has been exceeded. Adhesives that are used can be categorised into epoxy adhesive types and acrylic adhesive types. Epoxy adhesives will harden under elevated temperatures, whereas acrylic adhesives are more flexible. Advantages of adhesive connections are a uniform distribution of forces and high resistance to cyclic loading. Disadvantages are the strict surface requirement and the fact that there is hardening time (Yu, 2000).

6.5.3. Summary and elaborations on connections

Connection	**Type**	**Fastened elements**	**Tolerance**	**Demountable**
Welding	Direct integral connection	Steel (thin-thin or thick-thick)	Medium	No
Bolts	Direct connection with additional fixing devices	Steel (thin-thick or thick-thick)	High	Yes
Fired pins	Direct connection with additional fixing devices	Steel (thin-thick)	High	Yes
Self-drilling screws	Direct connection with additional fixing devices	Steel (thin-thin or thin-thick)	Medium	Yes
Self-tapping screws	Direct connection with additional fixing devices	Steel (thin-thin or thin-thick)	Medium	Yes
Blind rivets	Direct connection with additional fixing devices	Steel (thin-thin)	Medium	Yes
Press joints	Direct integral connection	Steel (thin-thin)	Medium	No
Adhesive bonding	Direct chemical connection	Steel, wood	No	No

Table 5: Summary connections

When designing for disassembly, the connections used have to meet the certain design criteria. First of all, the connections should be visually, physically, and ergonomically accessible. This will increase the efficiency during disassembly and deconstruction and will avoid expensive equipment or extensive health and safety precautions. Furthermore, chemical connections like binders, sealers or glue should be avoided. These connections are difficult to separate and recycle and increase the risk of a negative environmental impact. Welded connections are not demountable and should also be avoided.

Bolted, screwed, and nailed connections are suitable for reuse in a circular façade system. These are standard connections that will decrease the use of tools during installation and disassembly. Standardising connections will increase the efficiency and reduce time and effort. While increasing the number of connections increases the labour time and effort during (dis)assembly, it will also increase the flexibility of the component making it suitable for reuse or recycling.

Connection types with high tolerances are preferred because this will also increase the efficiency during (dis)assembly. Fired pins can therefore be suitable. However, by firing the pins through the fastened material, it gets damaged and cannot be reused. This problem can be resolved if the component through which the pin is fired, can easily be replaced.

Case study

7. Design of a circular façade system

In this chapter, a structural design for a circular façade system is proposed. The aim of the case study is to investigate the use of cold-formed elements in façade design in combination with large spans. Another aim of the case study is to verify the knowledge and findings obtained during the literature study regarding circular design. Additionally, it will serve as input for the assessment method which is illustrated later in this thesis. In other words, it sets boundary conditions to limit the number of variables.

The chapter starts with an overview of the setting and a short description of a traditional façade system. What follows is an outline of the new design, from here on referred to as the *circular façade system*. A distinction is made between two alternatives of the circular façade system: alternative 1 makes use of a trapezoidal sheet to support the insulation, alternative 2 makes use of liner trays. The basic concept of the circular façade system will be explained with schematic figures. The chapter continues with an overview of all components of the circular façade element. Details on these calculations can be found in the Appendices. Finally, the overall stability of the façade system and the flow of forces within the system will be explained

During the design process, the following is assumed:

- Circular design: the circular façade system is designed taking into account the design strategies and criteria which are discussed in chapter 5.
- Consequence class: the consequence class is assumed to be CC1. The consequence class of a construction is defined based on the consequences of failure or malfunctioning of that construction. When the consequence class of a construction is defined as CC1, it means that the consequences are small with respect to the loss of human lives, and economic, social, or environmental consequences. Because the façade is designed for an industrial hall, CC1 is sufficient.
- The reference period of the building is 50 years.

7.1. Setting

The circular façade system is designed for a hypothetical industrial building. The building is a simple rectangular box consisting of multiple spans in longitudinal direction, with intermediate columns supporting the spans. The building only has one building level, namely the ground floor. An impression of the geometry of the industrial hall is displayed in Figure 21.

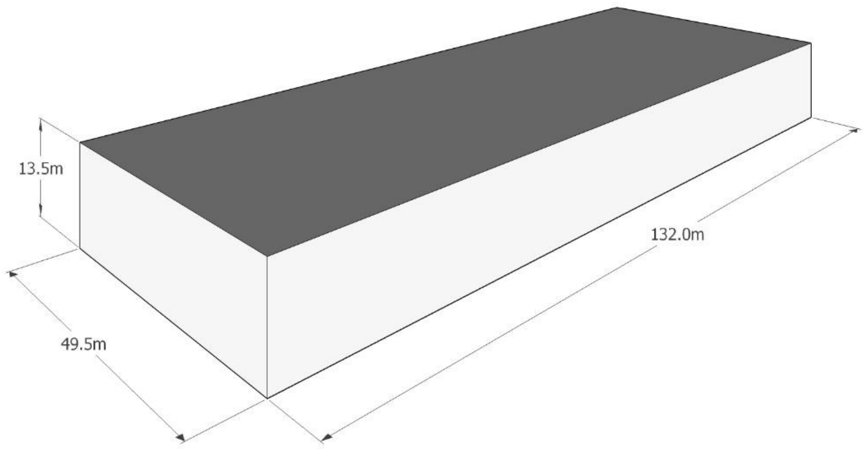


Figure 21: Overview of the industrial hall

7.2. Traditional façade system

The load bearing structure of the traditional façade system has a grid size of 5,5 m. The façade contains the following elements:

- Columns: IPE 400 (S355), with a length of 13,5 m (c.t.c. 5,5 m).
- Main girders (green): cold-formed C-profiles (S350), spanning horizontally between the columns (c.t.c. 1,75 m), with:
  - Height of the web (h_w) 250 mm.
  - Length of the flange (b) 50 mm.
  - Length of the lip (c) 15 mm.
  - Thickness of the profile (t) 2 mm.
- Sandwich panels: SAB W 100.1000 SL, with a length of 10,5 m and a width of 1 m, spanning vertically in between the main girders. Where the two face sheets primarily resist the in-plane bending, the core material mainly resists shear loads.

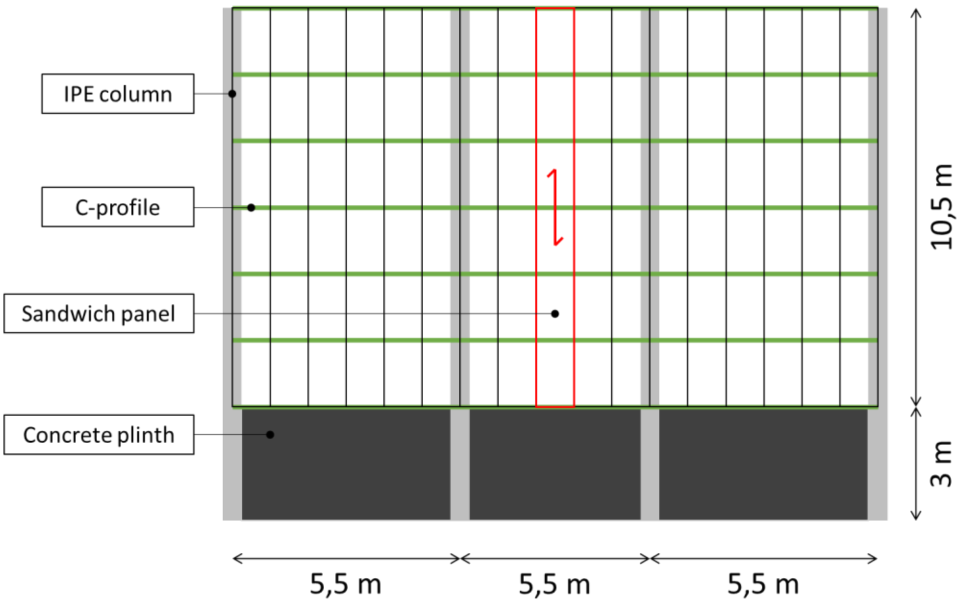


Figure 22: Schematic overview of the traditional façade system

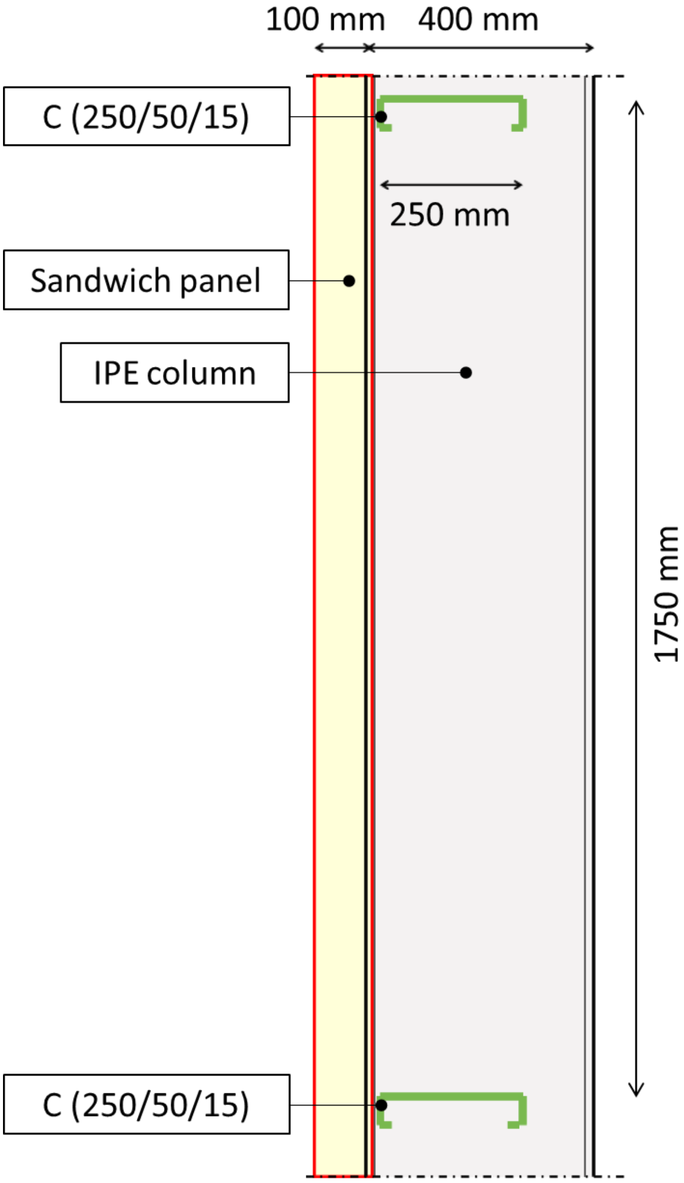


Figure 23: Vertical section traditional façade system

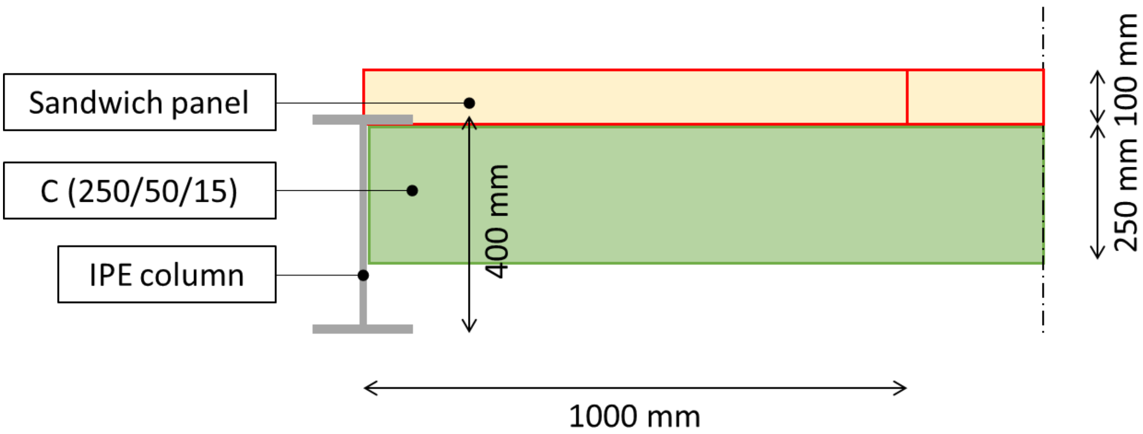


Figure 24: Horizontal section traditional façade system (width of one sandwich panel is 1000 mm)

The calculation of the traditional façade system is displayed in Appendix N.

7.3. Concept overview

The circular façade system has a grid size of 16,5 m, which is three times larger than the grid size of the traditional façade system. By reducing the number of columns, it is attempted to reduce the amount of material as much as possible. The columns are not made of cold-formed steel but hot-rolled steel profiles. This is because cold-formed sections are sensitive to buckling, and during construction the columns are not always supported by the façade elements while they still have to support the load of the roof. Hot-rolled steel profiles are less sensitive to buckling which allows for a more flexible construction sequence.

The reduction of the number columns does lead to an increase in element size, which span from column to column, which conflicts with the design criteria of designing elements to the worker and labour of separation, and decreases the flexibility of the element. It does however decrease the total number of elements, which could reduce the assembly time, and number of connections. The elements do have to be (dis)assembled using lifting equipment.

The circular façade system can be classified as a combination of a unitised façade system and a horizontal stick or *transom* system (Beurskens & Bakx, 2015). A unitised façade system is a system in which prefab elements are used to close the building envelope. These elements typically span between building levels. Transom systems consist of horizontal girders spanning in between the columns of the load bearing structure.

The circular façade system consists of prefab elements, which span between the columns of the structure, combining the two systems. The prefab elements function as the secondary structure, carrying horizontal (wind)loads to the load bearing structure. The prefab elements contain insulation material as well. On-site, finishing elements are installed in front of the prefab elements to enclose them. These finishing elements span vertically. A schematic overview of the circular façade system is displayed in Figure 25, Figure 26 and Figure 27.

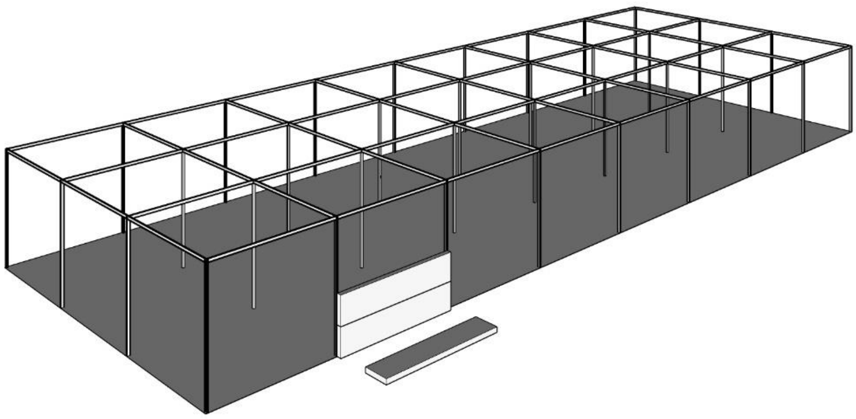


Figure 25: Load bearing structure with prefab elements

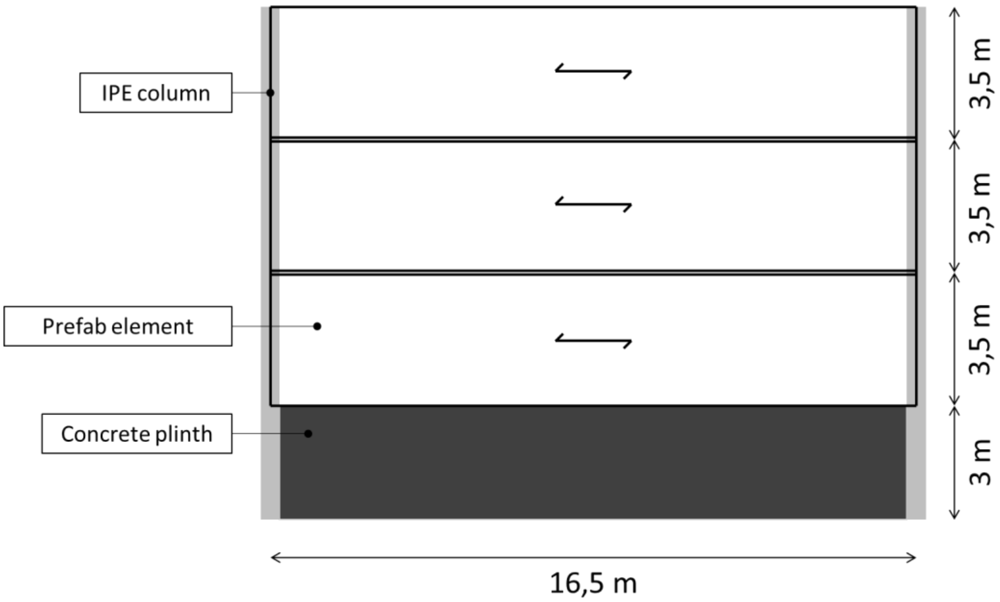


Figure 26: Schematic front view prefab elements

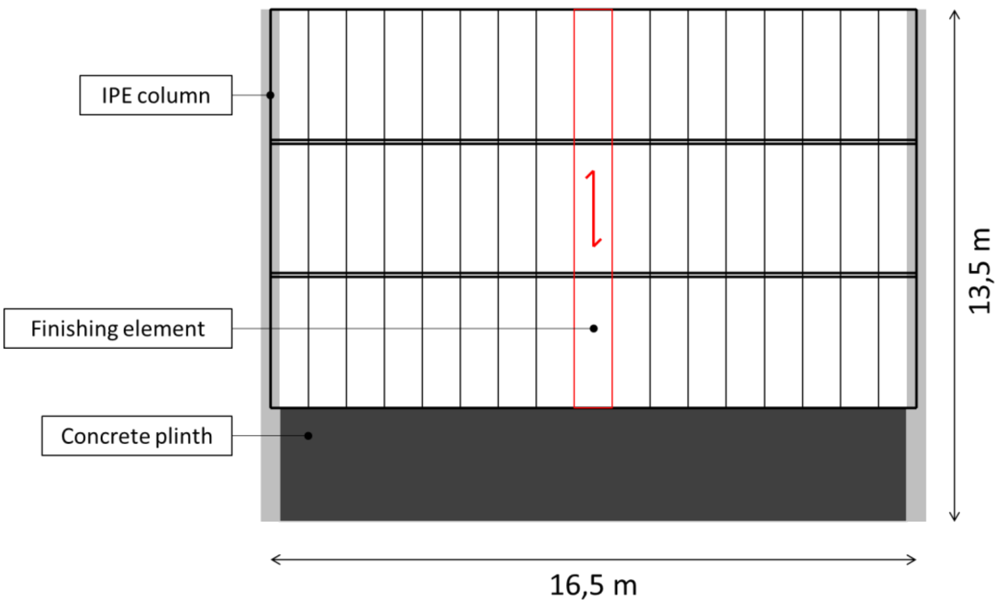


Figure 27: Schematic front view finishing elements

7.4. Design choices

In this paragraph, the design choices are explained and linked to the different strategies discussed in chapter 5.

- Cold-formed steel: cold-formed steel is a material which is particularly suitable for circular use: currently about 50% of feedstock is derived from recycled sources, and 99% of the mass is recycled at the end of its use or going into components reuse. The use of circular materials is derived from the strategy Design for Disassembly.
- Powder coated steel: to extend the lifespan of cold-formed steel it is protected with a powder coating. The powder coating can be damaged during transportation or installation. Small damaged areas can be rectified on-site by manually applying a new polyurethane topcoat. Retaining the value of construction materials is derived from the strategy Design for Disassembly.
- Prefabricated element and standard grid: elements are prefabricated and placed in a standard grid. They have a simple form, resulting in a simple structural system which eases the (dis)assembly of elements. This is derived from the design strategy Design for Disassembly.
- Optimising material use: the use of the materials is optimised, which means the amount of material is reduced as much as possible. This is not directly linked to one of the previously discussed design strategies, but is something that is deduced from one of the principles of circular economy, namely preserving and enhancing natural capital by controlling finite stocks of material. This is not only attempted by reducing the number of columns, but also by the use of slender, cold-formed elements. The reduction of the number columns does lead to an increase in element size, which conflicts with the design criteria of designing elements to the worker and labour of separation (Design for Disassembly).
- Interchangeable components: the components of the façade system are easily detached from one another, resulting in improved interchangeability of components. When components do not meet certain structural or aesthetic requirements anymore, they can be replaced while leaving the rest of the system intact. This is derived from the design strategy Design for Disassembly.
- Upgradeable insulation: the amount of insulation material is not fixed and can be increased, depending on the regulations on thermal and acoustic performance. The upgradeability of the insulation is derived from the design strategy Design for Adaptability.
- Separate services: mechanical, electrical, and plumbing systems are not integrated in the structural system of the façade, which allows for easier repairing, replacing, reusing, or recycling. This is derived from the design strategy Design for Disassembly.
- External finishing element: the façade system makes use of an external façade element. The skin of a building has a shorter lifecycle than the secondary structure, in this case the prefabricated element. By aligning the lifecycles of the different elements, unnecessary disassembly and deconstruction of elements is avoided. Lifetime compatibility is derived from the design strategy Design for Adaptability.
- Appropriate connections: the connections used are assessable, non-chemical and bolted, screwed, or nailed. This is derived from the design strategy Design for Disassembly.

7.5. Components of the element

In this paragraph, the different components of the element are discussed. An overview of the elements of alternative 1 and 2 is shown in Figure 28 to Figure 39.

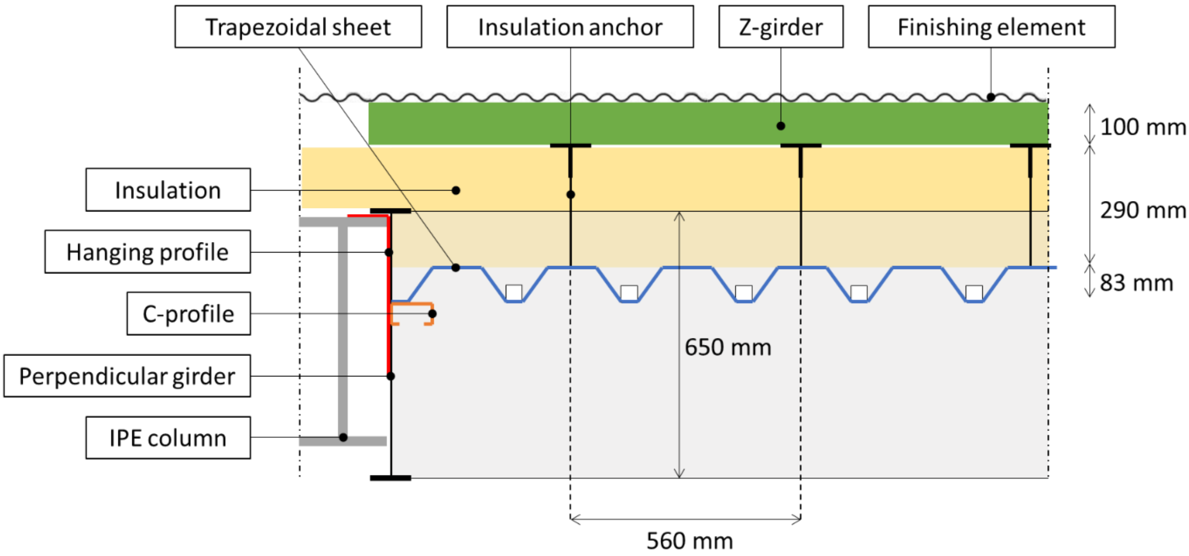


Figure 28: Horizontal section case study alternative 1

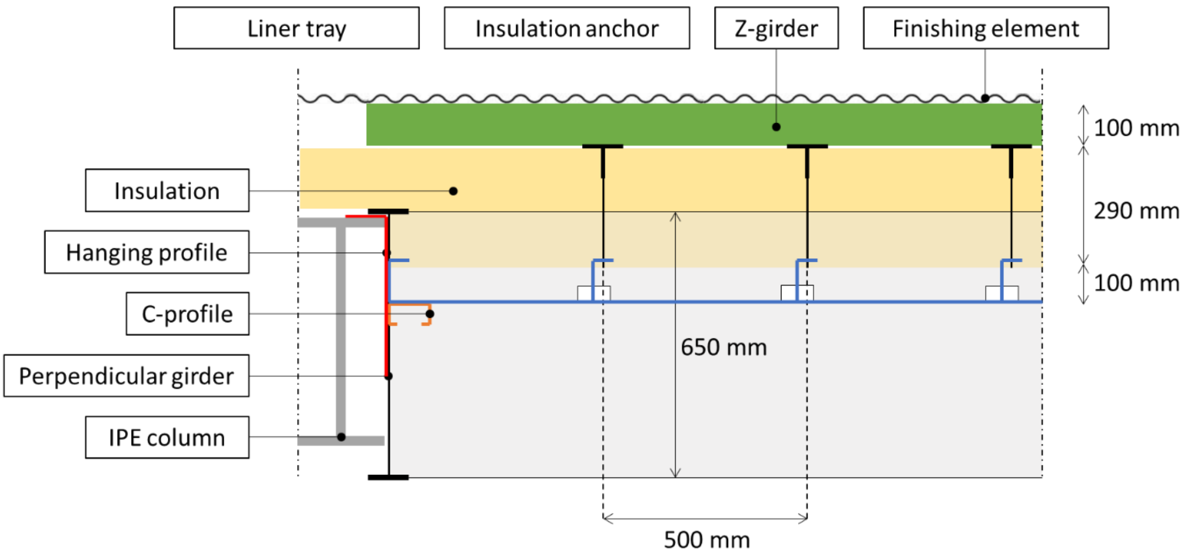


Figure 29: Horizontal section case study alternative 2

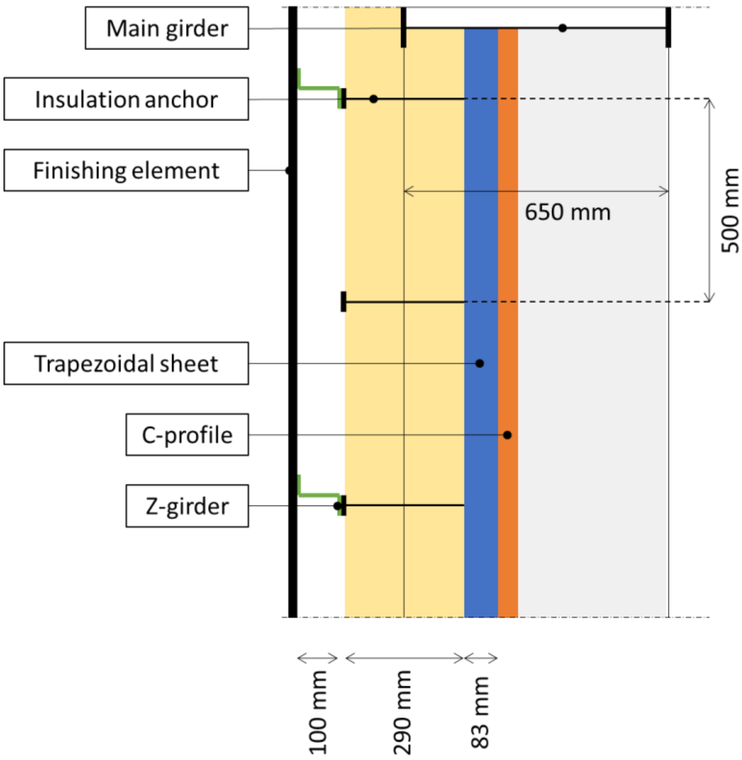


Figure 30: Vertical section case study alternative 1

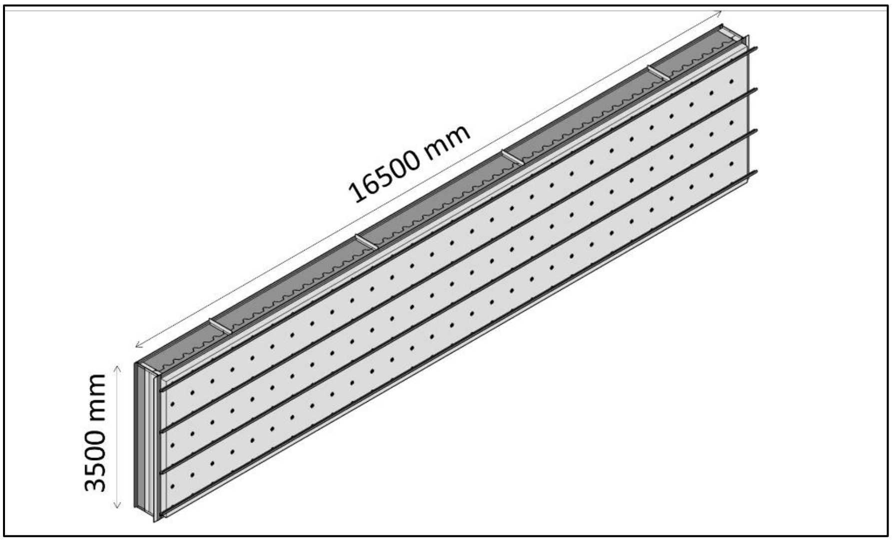


Figure 31: Isometric view of element

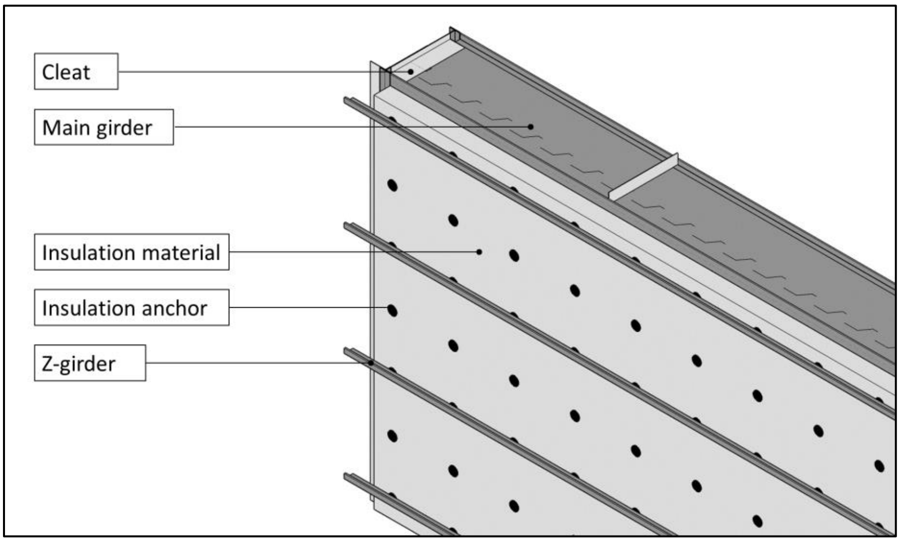


Figure 32: Isometric view of element zoomed in

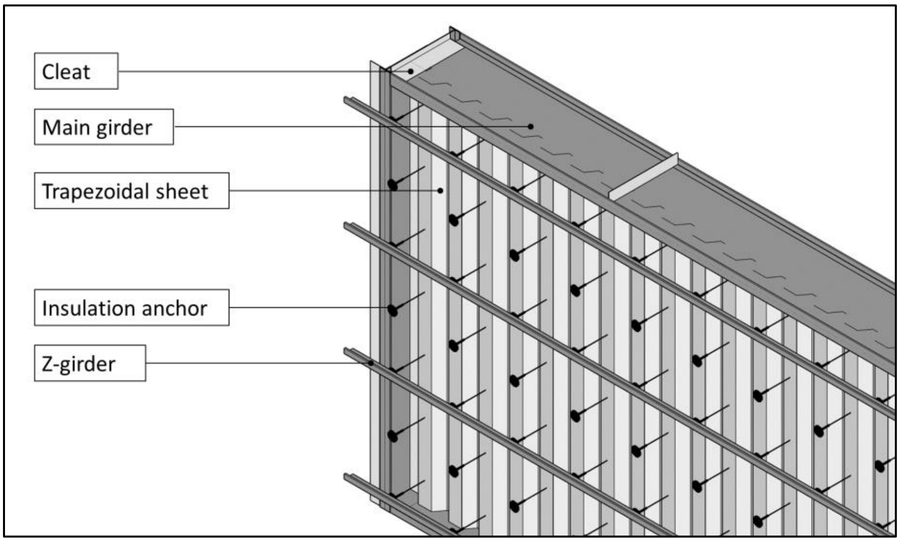


Figure 33: Isometric view of element zoomed in, without insulation

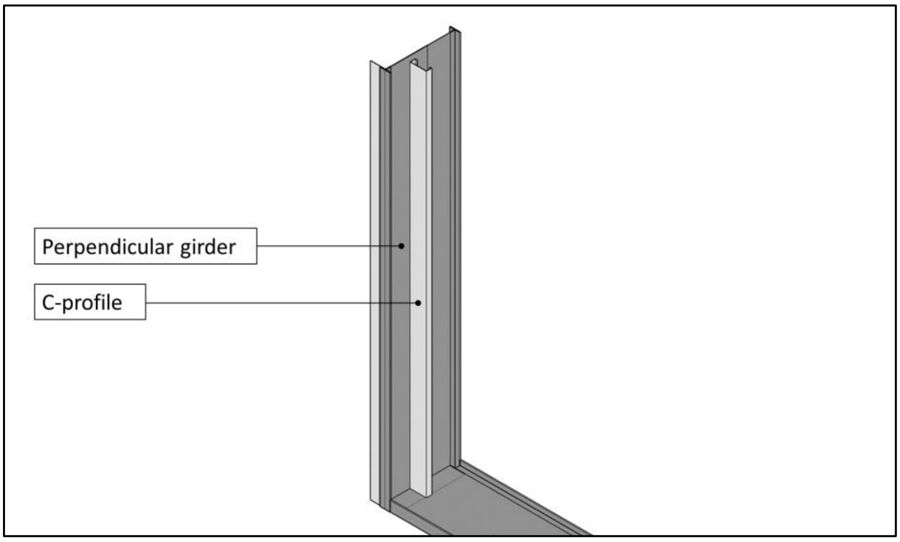


Figure 34: Isometric view of element zoomed in, without trapezoidal sheet

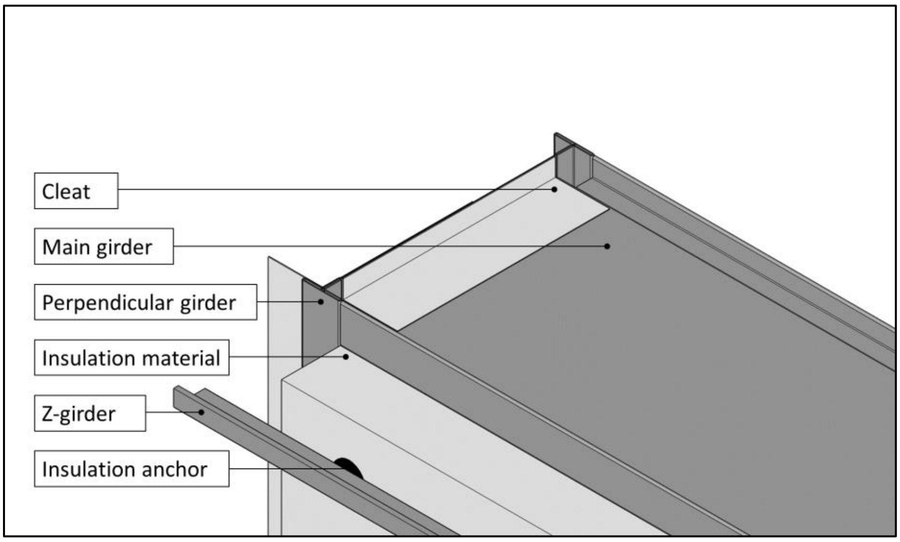


Figure 35: Isometric view of element zoomed in on connection between main- and perpendicular girder

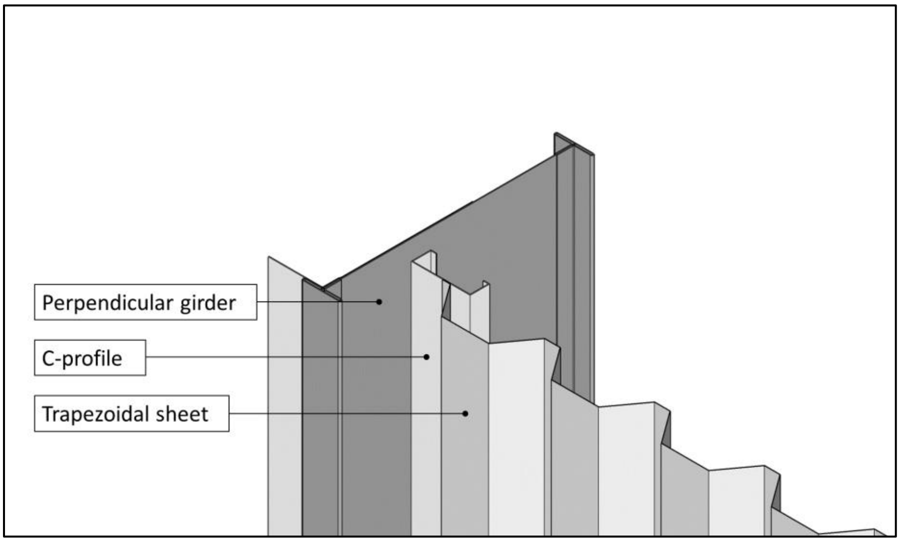


Figure 36: Isometric view of element zoomed in, without main girder

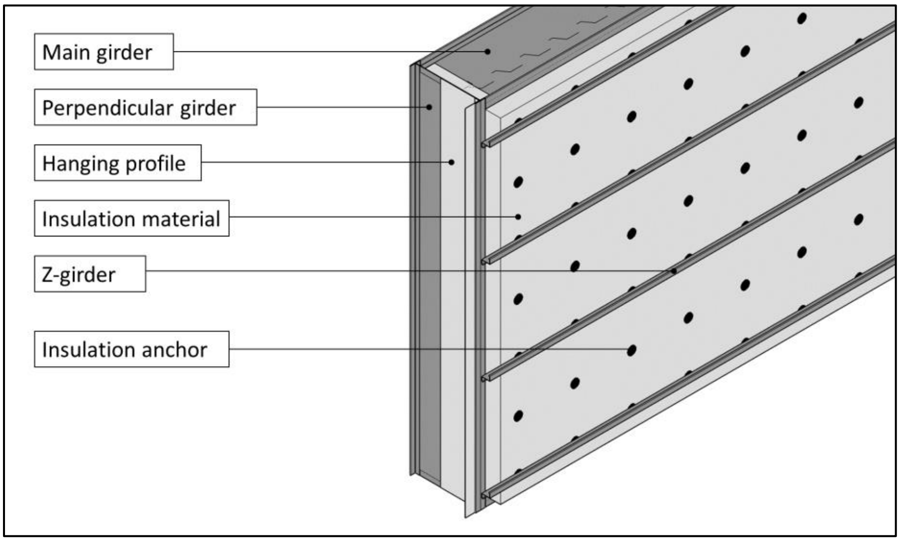


Figure 37: Isometric view of element zoomed in

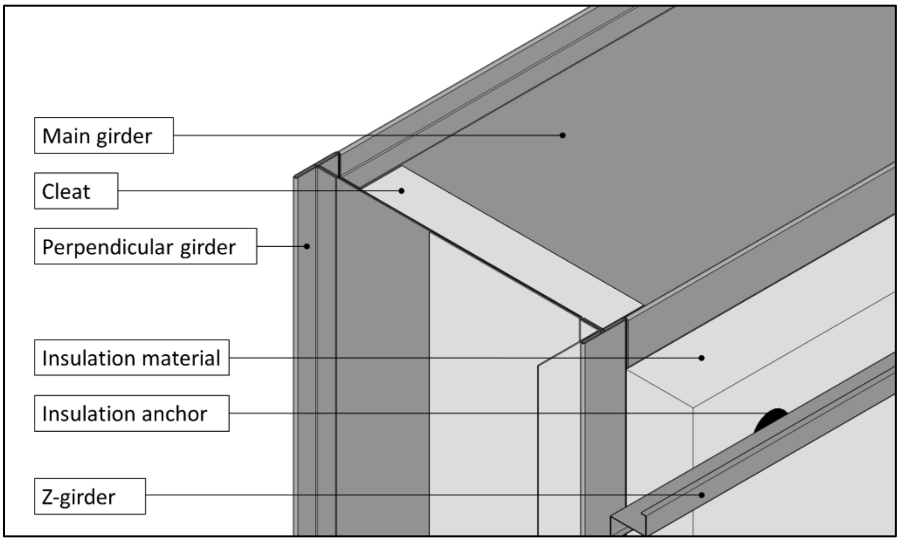


Figure 38: Isometric view of element zoomed in on hanging profile

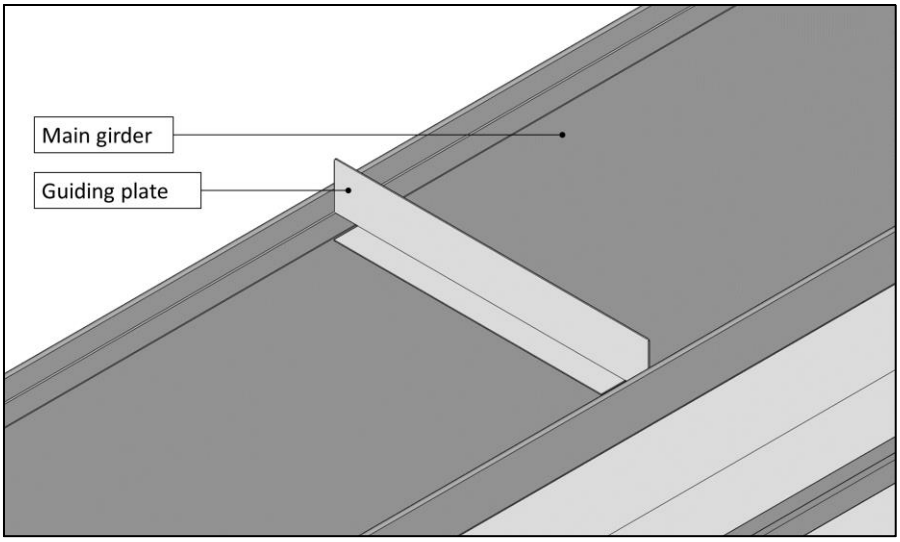


Figure 39: Isometric view of element zoomed in on guiding plate

The element consists of the following components:

- Main- and perpendicular girders: the main girders of the prefab elements are cold-formed I-sections. The main girders are connected to each other at both ends. These perpendicular girders are the same type of I-sections. The I-sections are made up of three parts: one web and two flanges. The flanges are connected to the web with blind rivets.
- Trapezoidal sheet: the trapezoidal sheet spans between the two main girders of the prefab element (alternative 1) and supports the insulation material. Additionally, the sheet functions as a support for the girders against lateral torsional buckling and helps to realise diaphragm action to transfer the load due to self-weight to the load bearing structure. Parallel to the main girder, the trapezoidal sheet is supported by support lips. The support lips are cut out of the web of the main girder and bend inwards. Perpendicular to the main girder, the trapezoidal sheet is supported by a C-profile.
- Liner tray: the other option for a profile spanning between the main girders to support insulation material is the liner tray (alternative 2). Like the trapezoidal sheet, it functions as a support for the girders against lateral torsional buckling and helps to realise diaphragm action. The liner trays are supported in the same way as the trapezoidal sheet.
- C-profile: the C-profiles are placed parallel to the perpendicular girders on the inside of the element. They support the trapezoidal sheet or liner trays.
- Cleat: The webs of the main girder and the perpendicular I-section are connected to each other with a cleat.
- Hanging profile: the element is connected to the main structure by means of a hanging profile. This L-shaped profile is attached to the web of perpendicular I-section. It connects the element to the outside flange of the hot-rolled column of the load bearing structure (for example an IPE profile).
- Insulation material: the insulation material is fastened to the trapezoidal sheet or liner trays with insulation anchors.
- Insulation anchors: the insulation anchors fasten the insulation material to the trapezoidal sheet or liners trays. Additionally, the anchors are connected to the Z-girders.
- Z-girders: the Z-girders span in horizontal direction and support the finishing elements which are installed on-site. They are connected to the insulation anchors.

Now, each component is discussed separately.

7.5.1. Main- and perpendicular girders

The I-section (which make up the main- and perpendicular girders of the element) consists of a web plate with flanges at the top and bottom. Both are made of cold-formed steel (S350). The flanges are fastened to the web with blind rivets.

The properties of the web (thickness and height) are determined by optimising the ratio between the two. Due to confidentiality, only the outcome of this process is included in this thesis. More information about this process can be provided in consultation with CFP Engineering. During the optimisation process, the following assumptions were made:

- The properties of the main girder are determined. For the perpendicular girder, the same profile is used.
- The I-section is optimised when an increase in material only marginally increases the maximum span of the I-section.
- The aim of the optimisation of the I-section is to maximise the span. This is because an increase in span means an increase in element size, and an increase in element size means that the

same façade area can be covered with less elements. This conflicts with the design criteria *scaling components and attuning to ease of removal* (Design for Disassembly). It does (in theory) decrease the number of elements and thus de number of actions during assembly and disassembly.

- The aim is to at least reach a span of 15 meters. However, the height of the I-section is limited. This is because I-profiles which are too high result in a reduced effective floor area of a building.
- During the optimisation of the I-profiles, it is assumed that lateral torsional buckling is prevented, since the trapezoidal sheet or liner trays in between the main girders will provide support. Additionally, the elements will be placed directly on top of each other which means that the elements will also support each other.
- The dimensions of the flanges of the I-sections are fixed. These dimensions are based on the flanges of the I-section developed by CFP Engineering.
- The maximum allowable deflection of the façade (δ_{max}) is assumed to be 1/150.

A unity check for the main girders is performed for the bending moment in y-direction (around the global z-axis), the shear force in y-direction and the maximum displacement in y-direction. The results of the optimisation can be found in Appendix B. The optimisation results in a profile with a height of 650 mm and a web thickness of 2,2 mm, which is displayed in Figure 60.

The perpendicular girder is disregarded during this calculation. This element is loaded by a torsional bending moment due to the offset between the point of connection of hanging profile to the load bearing structure and the web of the perpendicular girder. The resistance to this bending moment is provided by cooperation between the hanging profile, perpendicular girder and C-profile. Determining the level of cooperation between these profiles lays outside the scope of this thesis.

7.5.2. Trapezoidal sheet and liner trays

The insulation material which is placed inside the façade element must be supported in vertical and horizontal direction. To support the insulation material, it is fastened with insulation anchors to insulation support profiles, of which two possibilities are investigated. The first option is a trapezoidal sheet, the second option is a liner tray, both spanning between the two main girders in vertical direction. Both profiles are S350. In order to investigate the suitability of the both profiles, their resistance to wind loading is investigated, which can be found in Appendix C and Appendix D. A unity check is performed the bending moment in y-direction (around the global x-axis), the shear force in y-direction and the displacement in y-direction.

The resistance to punching shear to both elements has not been taken into account. When the insulation anchors transfer the load perpendicularly to the trapezoidal sheet or liner tray, the local stresses in the thin sheet (0,75 mm) may exceed the maximum punching shear stress. This can be solved by locally increasing the thickness of the sheet, which leads to a better introduction of forces. Locally increasing the thickness of the sheeting may decrease the level of circularity however.

For the trapezoidal sheet, the type SAB 85R/1120, which is displayed in Figure 40, is used. This type of sheeting is normally used as roof sheeting (SAB-Profiel BV, 2020).

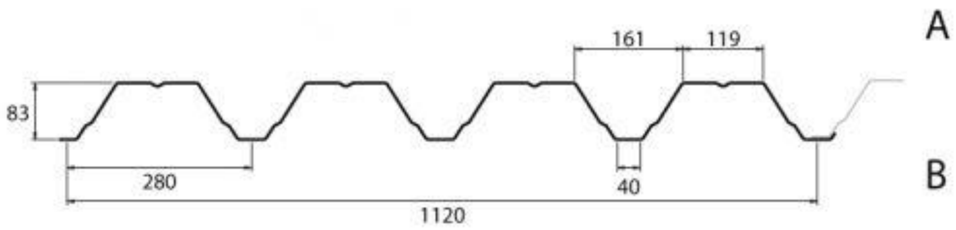


Figure 40: SAB 85R/1120 (SAB-Profiel BV, 2020)

For the liner tray, the type SAB B90/500, which is displayed in Figure 41, is used. The liner trays are placed vertically instead of horizontally, which is normally the case (SAB-Profiel BV, 2020).

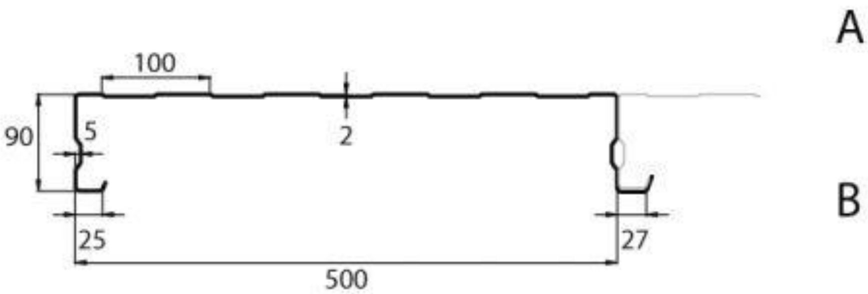


Figure 41: SAB B90/500 (SAB-Profiel BV, 2020)

7.5.3. Support lips

Both the trapezoidal sheet and the liner trays are supported by a lip which is cut from the web of the I-section and bent inwards. The trapezoidal sheet is supported every 280 mm, which is the distance between two troughs. The liner trays are supported every 500 mm, which is the width of one liner tray, so every tray is supported at all four corners. The width of the lip supporting the trapezoidal sheet is 50 mm, the length is 48 mm. The width of the lip supporting the liner trays is 100 mm, the length is 48 mm.

The trapezoidal sheet and liner trays are fastened to the support lip by means of a self-tapping screw, which is placed through a pre-drilled hole in the support lip and drilled through the trapezoidal sheet or liner tray (from the side of the support lip). The calculation of the connection in both alternatives can be found in Appendix E and Appendix F.

For both types support lips, a unity check is performed for shear, tension, and combined shear and tension on the self-tapping screw. Resulting deformations of the web of the main girders is not taken into account. The flow of forces is illustrated in Figure 46.

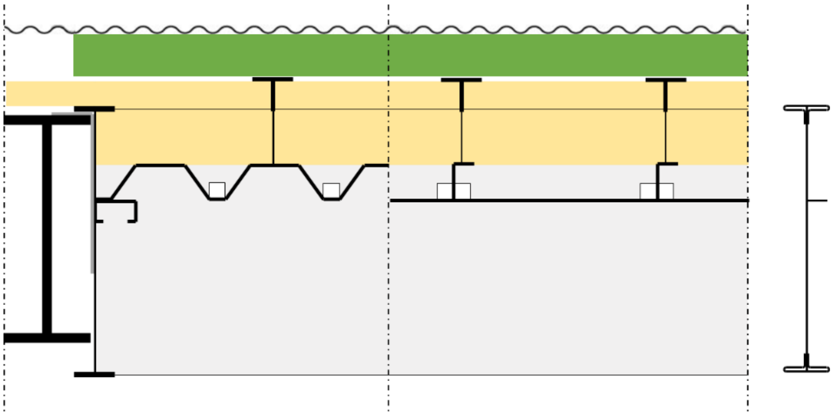


Figure 42: Support lip location (lefthand side: horizontal section; righthand side: vertical section of the main girder only)

7.5.4. Cleat

The cleats connect the main girders to the perpendicular girders. In the calculation the cleat is divided in two parts: part 1 is the part which is connected to the main girder, part 2 is the part which is connected to the perpendicular girder. Both parts are connected to the respective elements with blind rivets. The cleat is an L-profile measuring 48 by 140 mm with a thickness of 2 mm. The calculation can be found in Appendix G.

For both parts of the cleat, a unity check is performed where the distance between the centre of the holes and the end distance of the holes is checked, the tensile resistance and the resistance of the net section is checked, and the bearing capacity and shear resistance per blind rivet and of the total connection is checked.

7.5.5. Hanging profile

The hanging profile connects the prefab element to the load bearing structure. It is connected to the perpendicular girder of the element. The hanging profile is an L-profile measuring 140 by 390 mm with a thickness of 2 mm. In total, the hanging profile is connected to the element with 26 blind rivets. The calculation of this connection can be found in Appendix H.

A unity check is performed for the part of the hanging profile which is attached to the perpendicular girder. The bearing capacity and shear resistance per blind rivet and of the total connection is checked.

The hanging profile is connected to the main structure by means of shot fired pins. The shot fired pins are shot through the flange of the hanging profile and the flange of the column which is part of the load bearing structure. The calculation can be found in Appendix I.

For this part of the hanging profile, the distance between the centre of the holes and the end distance of the holes is checked, and the bearing capacity and shear resistance per shot fired pin is checked.

7.5.6. Z-girders

The Z-girders span in horizontal direction and support the finishing elements which are installed on-site. They are connected to the insulation anchors. Per element, four Z-girders are present (c.t.c. 1 m). The profiles have a web height of 100 mm, the length of the flange is 50 mm and the length of the lip is 15 mm. The profile has a thickness of 2 mm.

The Z-girders are connected to the insulation anchors with a bolted connection. The bolt is installed through a pre-drilled hole in the girder and fastens itself in a helicoil which is present in the insulation anchor.

Because of the amount of supports, the internal forces in the profile (bending moments and shear forces) will be minimal, so the profile will not be analysed. The calculation of the resistance of the insulation anchors can be found in Appendix J.

7.5.7. Connection between the elements

During installation, the elements are *stacked* on top of each other, after which the hanging profiles are attached to the main structure. The main girders of the element support each other using a *guiding plate*. The guiding plates are attached to the web of the main girder by blind rivets. Per element, four guiding plates are present (c.t.c. 3300 mm, end distance 1650 mm).

7.5.8. Finishing element

To seal the element and the insulation material, the element is covered by a finishing element. This finishing element is a sinusoidal sheet which spans vertically, in this case a SAB 18/988 (see Figure 43).

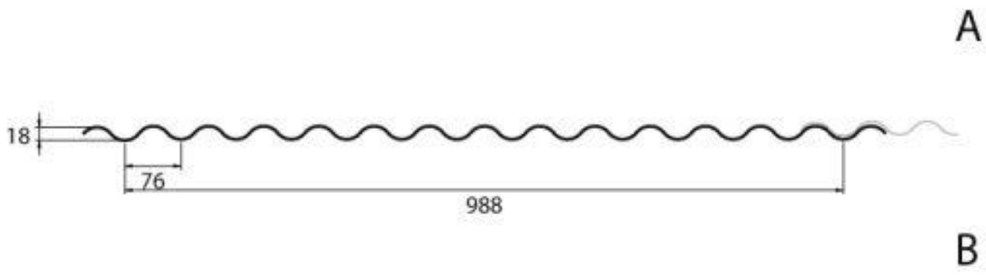


Figure 43: SAB 18/988 (SAB-Profiel BV, 2020)

7.6. Stability and flow of forces

The two primary loads acting on the façade are the self-weight of the façade itself in vertical direction and the wind load in horizontal direction. The calculation of the magnitude of both loads can be found in Appendix A.

The load on the façade elements due to self-weight is transferred to the load bearing structure by diaphragm action in the façade elements. To investigate the possibility of diaphragm action in the elements, the publication *RMBS 2000 Richtlijnen voor toepassing van metalen beplating als schijfconstructie* is used (Bouwen met Staal, 2004). The calculation of the diaphragm action and shear forces in the façade elements can be found in Appendix M.

The conclusion of this calculation is that the self-weight of the elements can be transferred to the load bearing structure by diaphragm action in the trapezoidal sheet elements (alternative 1). For the liner tray elements (alternative 2) the same is concluded, although this is an estimation.

The load on the façade due to wind (pressure) is transferred from the finishing element to the main girders of the façade elements via the Z-girders, insulation anchors and trapezoidal sheet. The main girders transfer the loads horizontally to the load bearing structure. This is illustrated in Figure 45, where the red arrows represent normal forces and blue arrows represent bending in the y-direction (around the z-axis).

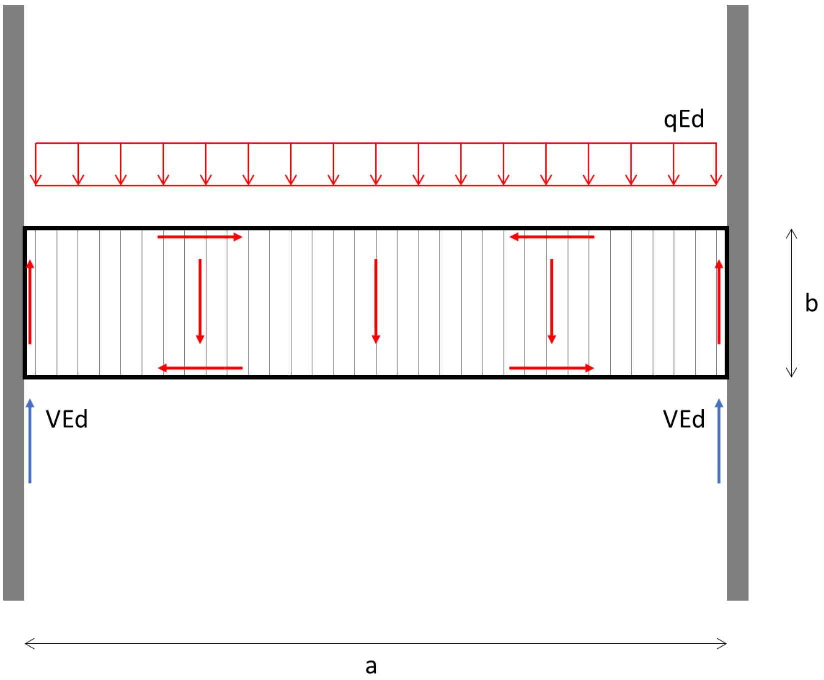


Figure 44: Diaphragm action in one prefab element

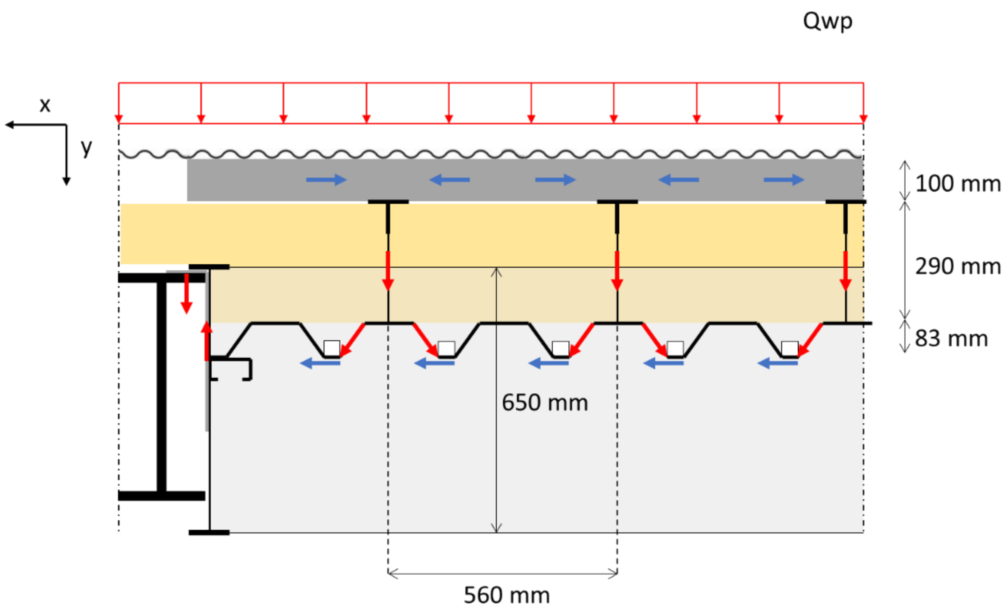


Figure 45: Load path wind pressure (horizontal section)

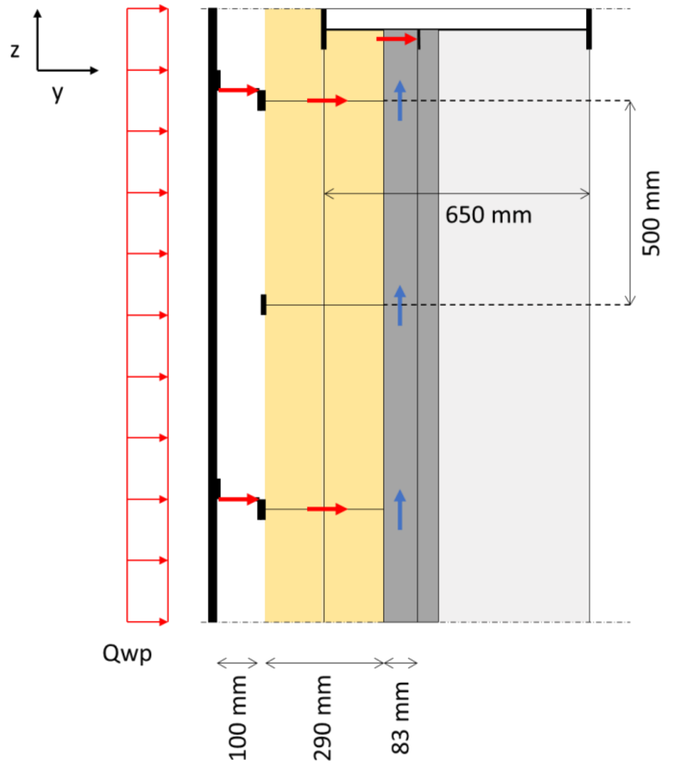


Figure 46: Load path wind pressure (vertical section)

7.7. Plinth

One of the disadvantages of a façade system using cold-formed elements, is the fact that these elements are sensitive to impact loads, which are likely to occur in an industrial building. Better suited to withstand the impact of such loads, are materials like concrete. Therefore, in this design a concrete plinth is introduced to withstand impact loads. The height of this plinth is 3 m.

This has an additional benefit. A façade usually contains openings like door- and window openings. The concrete plinth will include these openings, so the integrity of the prefabricated cold-formed elements will not be compromised by openings. However, industrial doors (with a height up to 5 m) will not completely fit in the concrete plinth.

The concrete plinth is discussed in Appendix L.

Analysis of Circularity

8. Life Cycle Assessment

A Life Cycle Assessment (LCA) is a methodology for assessing the environmental impact during all stages of the life cycle of a product, process, or service. Two types can be distinguished (Vogtlander, 2012):

- A classic Life Cycle Assessment is used to investigate the environmental impact of the production of plastics, metals, chemicals, and energy, starting from scratch. This can require a lot of time and resources.
- A *Fast Track* Life Cycle Assessment is used when comparing design alternatives. The input of the Fast Track LCA is the output of the calculation of the classic LCA. When the required input data are available, this will take significantly less time.

In this thesis, a Fast Track Life Cycle Assessment is chosen to compare a traditional façade system to the two alternatives designed in the case study. The goal is to gain insight on their impact on the environment. The results are used to determine the level of circularity of the façade systems.

8.1. System boundaries

8.1.1. Elements

Because the LCA is used to compare the environmental impact of multiple façade systems, only the elements that are linked to the façade of the building are considered. These elements include:

- The columns in the façade. The columns of the traditional façade system are of the type IPE 400, and have a centre to centre distance of 5,5 m. The columns of the case study alternatives are of the type IPE 550 and have a centre to centre distance of 16,5 m. The internal columns of the building are not considered.
- The secondary structure supporting the finishing elements. The secondary structure of the traditional façade system consists of cold-formed C-profiles with a height of 250 mm and a thickness of 2 mm. The secondary structure of the case study alternatives consists of the various cold-formed elements which are discussed in the case study (chapter 7)
- The insulation material. The insulation material of the traditional façade system is PIR insulation inside the sandwich panel. The insulation material of the case study alternatives is the mineral wool placed within the cavity.
- The finishing elements. The finishing elements of the traditional façade system are the sandwich panels. The finishing element of the cases study alternatives is a sinusoidal sheeting profile (SAB 18/988).

The rest of the building is assumed to be similar for both the traditional façade system and the alternatives designed in the case study and are therefore not considered in the LCA. These parts include:

- The foundation.
- Part of the load bearing structure which is not present in the façade (roof, internal columns).
- The plinth.

8.1.2. Life cycle stages

The life cycle stages that are included in the LCA are based on the life cycle stages identified in NEN-EN 15804 (4.1). These stages include:

- Production stage (A1-A3)
- Construction stage (A4-A5)
- Use stage (B1-B7)
- End-of-life stage (C1-C4)
- Benefits and loads beyond the system boundary (Reuse and/or recycling potential) (D)

An overview of the different life cycle stages and their processes is displayed in Table 6. NEN-EN 15804 prescribes that all construction products and materials shall declare modules A1-A3 (production), modules C1-C4 (end-of-life) and module D (benefits and loads beyond the system boundary) in the Environmental Product Declaration of a product. Other modules can be included but are not mandatory.

Life cycle stage	Process	Module code
Production stage	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
Construction process stage	Transport	A4
	Construction and installation process	A5
Use stage	Use	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-life stage	Deconstruction or demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4
Benefits and loads beyond the system boundary	Reuse, recovery, and recycling potential	D

Table 6: Life cycle stages and processes

In the LCA performed in this thesis, the life cycle stages which are different for the traditional façade system and the alternatives of the case study are considered, which are:

- Production stage (A1-A3)
- Construction process stage (A4)
- End-of-life stage (C2-C4)
- Benefits and loads beyond the system boundary (Reuse and/or recycling potential) (D)

The use stage (B1-B7) is not considered since it is assumed that there will be no difference between the use stages of the different façade systems during their life cycle (B1). Other processes, like maintenance, repair and refurbishment are considered by investigating different scenario's.

8.1.3. Assembly and disassembly process

According to NEN-EN 15804, all construction products and materials must declare modules A1-A3, C1-C4 and D. This is in accordance with an article published in *Building and Environment* (Althaus & Kellenberger, 2009), in which it is concluded that transport of construction materials should be taken into account when calculating the environmental impact of a construction.

The influence of the construction and disassembly process (A5 and C1), excluding the transportation of materials, equipment, construction crew and temporary heating, is less than 8% of the total of the environmental impact of the construction (Althaus & Kellenberger, 2009). It is concluded that it is admissible that, to simplify the calculation, the influence of the construction process is neglected. This will also be done in this thesis, due to a limited time frame.

8.1.4. Transport

For the comparison of different alternatives, the transportation of the materials from the manufacturing site to the construction site and the needed additional materials with a high environmental impact should be taken into account for the LCA (Althaus & Kellenberger, 2009).

According to the Determination Method (Stichting Bouwkwaliteit, 2019), the following transport distances have to be taken into account for a single journey to the construction site (A4), when produced in The Netherlands:

- For bulk material: 50 km
- For other materials, products, and elements: 150 km

Since the transport to the construction site only includes prefabricated elements, a transport distance of 150 km is considered. No transport distances are prescribed for the transport of (raw) materials during the production stage (A2). In this thesis, a transport distance of 50 km is considered, which is in line with the transport distance of bulk material during the construction process stage.

A single journey from the construction site to the waste processing location is assumed to be 50 km. This is the transport distance prescribed in the Determination Method for transport from the location of disassembly or demolition to the waste deposition location. The same distance is considered as the transport distance from the construction site to the manufacturer's storage location.

The calculation of the environmental costs per tonne-kilometre (tkm) is € 0,016. The derivation of this parameter is displayed in Appendix O.

8.1.5. Scenario's

The life cycle scenarios of the traditional façade system and the alternatives of the case study are displayed in Figure 47, Figure 48 and Figure 49. Two possible scenarios are investigated. Both scenarios are investigated for the traditional façade system as well as the case study alternatives, to get a sense of the effects of the different scenario's. It should be noted that in reality, a circular business model would not be applied to a traditional façade system and Figure 48 is purely hypothetical.

In the first scenario, a traditional business model is assumed. During the total reference period, the load bearing structure remains unchanged, while the secondary structure is renewed every 50 years and the finishing elements are renewed every 20 years. At the end of the reference period all layers have come to their end-of-life, and their waste is processed.

In the second scenario, a circular business model (*building as a service*) is assumed. It is assumed that every 20 years, the manufacturer will return the components of the industrial building to its storage location and reuse the components at a different location if possible. At the end of the reference period all layers have come to their end-of-life, and their waste is processed.

By retuning the secondary structure to the storage location after 20 years, the manufacturer does not have to produce a new secondary structure, but can reuse it. This will save costs for the manufacturer and reduce the impact on the environment.

Different life cycle lengths are assumed for the different layers of the building:

- The length of the life cycle of the load bearing structure (columns) is assumed to be 100 years. This is assumed since the lifespan of the structure is 30-300 years according to Brand (Brand, 1994), as is mentioned in paragraph 6.1.
- The length of the life cycle of the secondary structure (prefabricated elements or main girders) is assumed to be 50 years. This is assumed since the façade system designed in the case study is designed for a lifespan of 50 years.
- The length of the life cycle of the finishing elements is assumed to be 20 years. This is assumed since this is the lifespan of the skin of a building is 20 years according to Brand.

The total reference period which is considered during the Life Cycle Assessment is 100 years. In Table 12, Table 15, and Table 18 it can be seen which layer contains which elements.

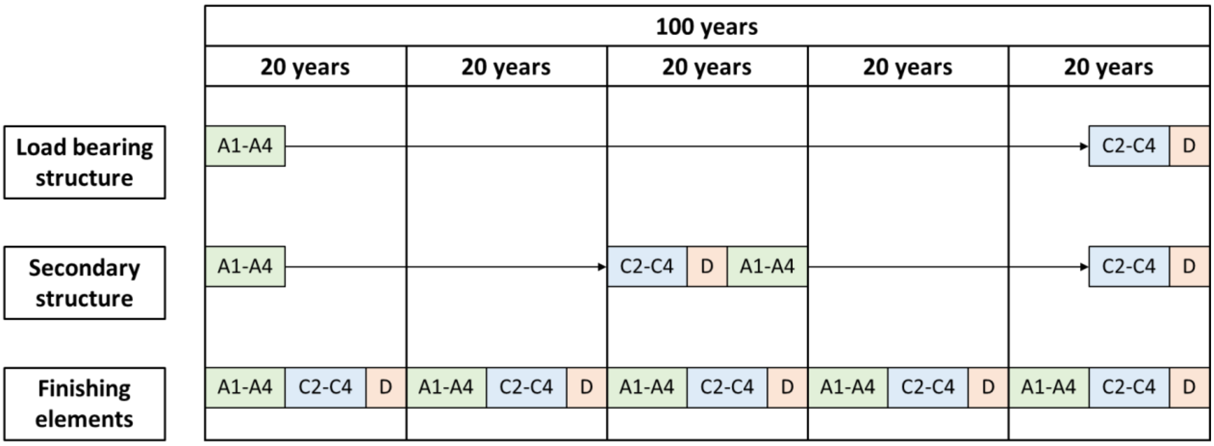


Figure 47: Scenario 1 (traditional business model) for all façade systems

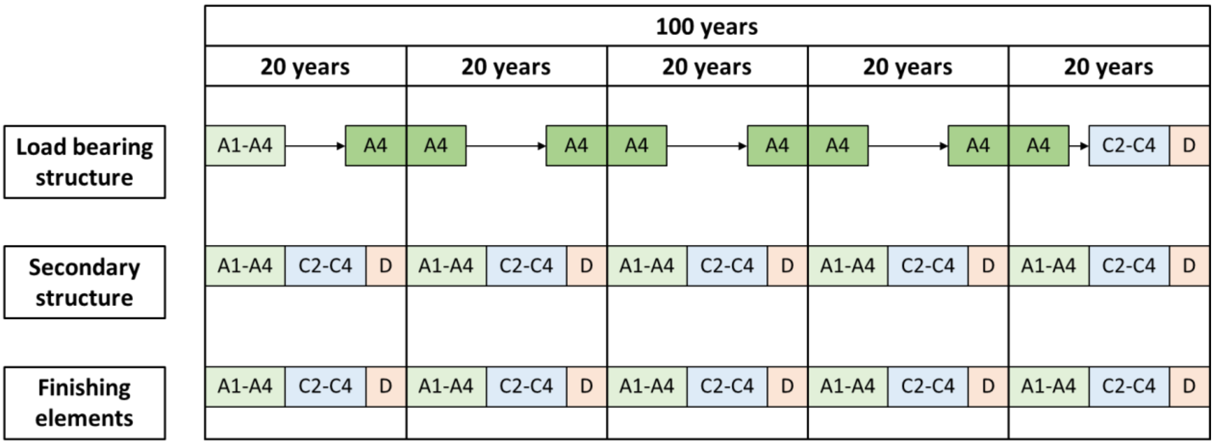


Figure 48: Scenario 2 (circular business model) for traditional façade system

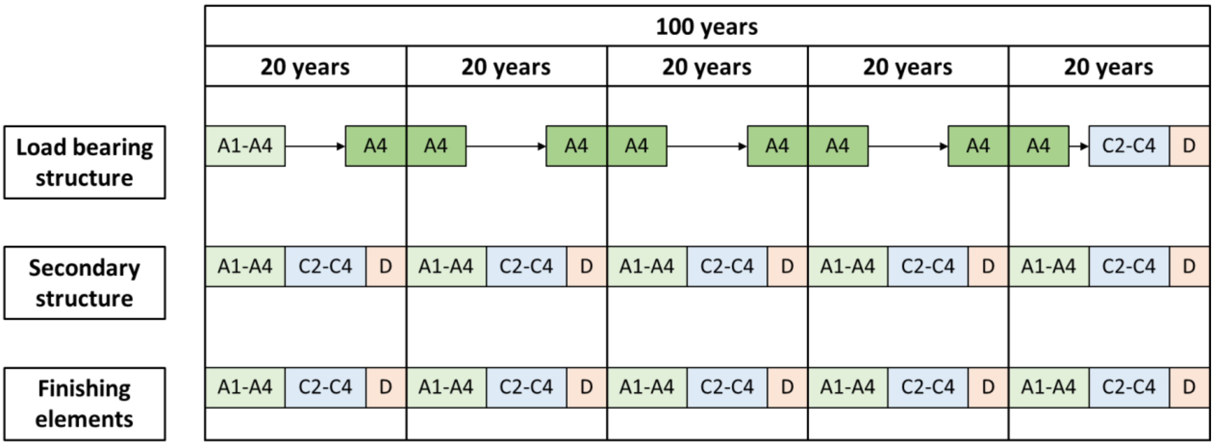


Figure 49: Scenario 2 (circular business model) for case study alternatives

8.2. Quantification of materials

Element	Type	Length	Component	Weight		% of total weight
		m		kg/m	kg/m²	
Column	IPE 400	13,5		67,6	21,1	55,9
Main girder	C 250.50.15 - 2	16,5		5,7	3,8	10,1
Sandwich panel	SAB W 100.1000 SL	3,5	Inside plate		3,3	8,8
			Outside plate		5,7	15,2
			PIR insulation		3,8	10,1
Total weight per m²					37,7	

Table 7: Material quantification traditional façade

Element	Type	Length	Weight		% of total weight
		m	kg/m	kg/m²	
Column	IPE 550	13,5	108	16,8	29,4
Main girder	I 650.98.2,2 - 2	16,5	19,7	11,3	19,7
Perpendicular girder	I 650.98.2,2 - 2	3,5	19,7	2,4	4,2
Perpendicular support	C 100.50.15 - 2	3,4	3,6	0,4	0,7
Trapezoidal sheet	SAB 85R/1120 - 0,75	3,4		7,9	13,8
Insulation material	Knauf 432 KD - 240			5,8	10,1
Cleat	L 48.140 - 2	0,5	3	0,1	0,2
Hanging profile	L 140.390 - 2	3,5	8,3	1,0	1,8
Z-Girder	Z 100.50.15 - 2	16,5	3,6	4,1	7,2
Sinusoidal sheet	SAB 18/988 - 0,75			7,5	13,0
Total weight per m²				57,2	

Table 8: Material quantification case study alternative 1

Element	Type	Length	Weight		% of total weight
		m	kg/m	kg/m²	
Column	IPE 550	13,5	108	16,8	28,9
Main girder	I 650.98.2,2 - 2	16,5	19,7	11,3	19,4
Perpendicular girder	I 650.98.2,2 - 2	3,5	19,7	2,4	4,1
Perpendicular support	C 100.50.15 - 2	3,4	3,6	0,4	0,7
Liner tray	SAB B90/500 - 0,75	3,4		8,8	15,2
Insulation material	Knauf 432 KD - 240			5,8	9,9
Cleat	L 48.140 - 2	0,5	3	0,1	0,2
Hanging profile	L 140.390 - 2	3,5	8,3	1,0	1,7
Z-Girders	Z 100.50.15 - 2	16,5	3,6	4,1	7,1
Sinusoidal sheet	SAB 18/988 - 0,75			7,5	12,8
Total weight per m²				58,2	

Table 9: Material quantification case study alternative 2

8.3. Calculation

8.3.1. Method and data

In order to calculate the environmental impact of the façade systems, the Determination Method (paragraph 4.2) is used. The input for this method is data from the National Environmental Database. This database contains information on the environmental impact of materials and commonly used structural elements. In the database, the environmental impact per unit is given for the different life cycle stages discussed in paragraph 8.1.2. The environmental impact can be divided into different environmental effect categories, shown in Table 10. The different categories are expressed in different equivalent units, for example CO_2 equivalent.

Per environmental effect category a certain weight factor is assigned. This weight factor translates the equivalent unit for each effect category to an equivalent cost in price per kilogram (€/kg). The monetary value per impact category expresses the amount of money needed to mitigate the effect of one kilogram of the environmental effect category. The total equivalent costs per unit is obtained by adding all the equivalent costs per category, so:

$$Virtual\ costs\ per\ effect\ catgory = equivalent\ unit\ material * weight\ factor$$

$$Virtual\ costs\ per\ unit\ material = \sum Virtual\ costs\ per\ effect\ category$$

Environmental effect category	**Equivalent unit**	**Weight factor (€/kg eq)**	
Exhaustion abiotic raw materials	Sb eq	€ 0,16	Raw materials
Exhaustion fossil energy carriers	Sb eq	€ 0,16	
Climate change	CO_2 eq	€ 0,05	Emissions
Affecting ozone layer	CFK-11 eq	€ 30	
Photochemical oxidant formation	C_2H_4 eq	€ 2	
Acidification	SO_2	€ 4	
Eutrophication	PO_4 eq	€ 9	
Human toxicity	1,4-DCB eq	€ 0,09	
Fresh water aquatic ecotoxicity	1,4-DCB eq	€ 0,03	
Marine aquatic ecotoxicity	1,4-DCB eq	€ 0,0001	
Terrestrial ecotoxicity	1,4-DCB eq	€ 0,06	

Table 10: Environmental effect categories with equivalent unit and weight factor (Stichting Bouwkwaliteit, 2019)

The environmental costs per kg of the production and waste processing of different materials used in both the traditional façade system and the case study alternatives are displayed in Table 11. The calculation of these data is displayed in Table 47 and Table 48 in Appendix O.

Material	**Unit**	**Environmental costs per unit production (€/unit)**	**Environmental costs per unit waste processing (€/unit)**
Steel (heavy)	kg	0,068	-0,035
Steel (light-weight)	kg	0,167	-0,098
Steel (medium)	kg	0,178	-0,099
PUR	kg	0,378	0,007
Glass wool	kg	0,191	0,001

Table 11: Environmental production- and waste processing costs (Nationale Milieu Database, 2020)

It can be noted that in Table 11, the environmental costs per unit for waste processing for some materials is negative. This is because of the assumption that steel is recycled which reduces the impact on the environment.

8.3.2. Results

In Table 12 to Table 20 the results of the calculation of the environmental costs of the traditional façade system and the cases study alternatives are displayed. The system boundaries, material bill and calculation method described in paragraphs 8.1 to 8.3 is used during the calculation.

Layer	**Element**	**Component**	**Weight**	**Σ**	**Environmental costs (€/m²)**	
			kg/m²	kg/m²	Scenario 1	Scenario 2
Load bearing structure	Column		21,07	21,07	0,77	1,16
Secondary structure	Main girder		3,80	3,80	0,56	1,39
Finishing element	Finishing element	Inside plate	3,32		1,37	1,37
		Outside plate	5,72	12,84	2,37	2,37
		PIR Insulation	3,80		7,39	7,39
Total per m²			37,7		12,46	13,68

Table 12: Environmental costs traditional façade

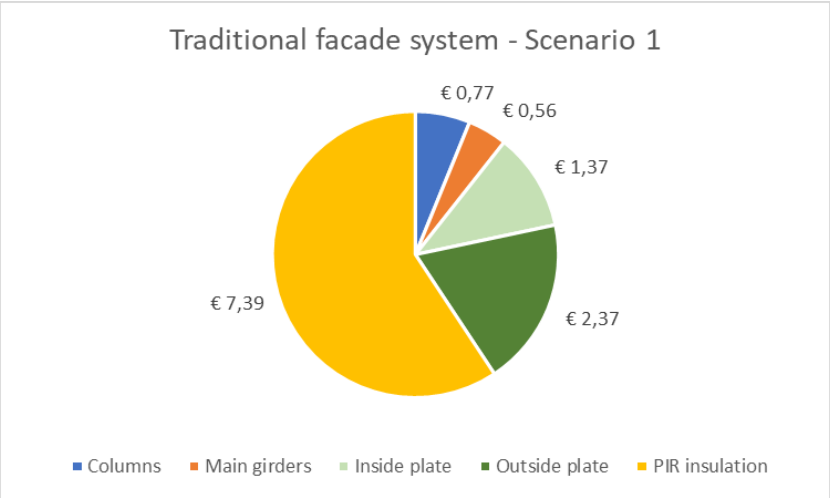


Table 13: Environmental costs traditional façade scenario 1

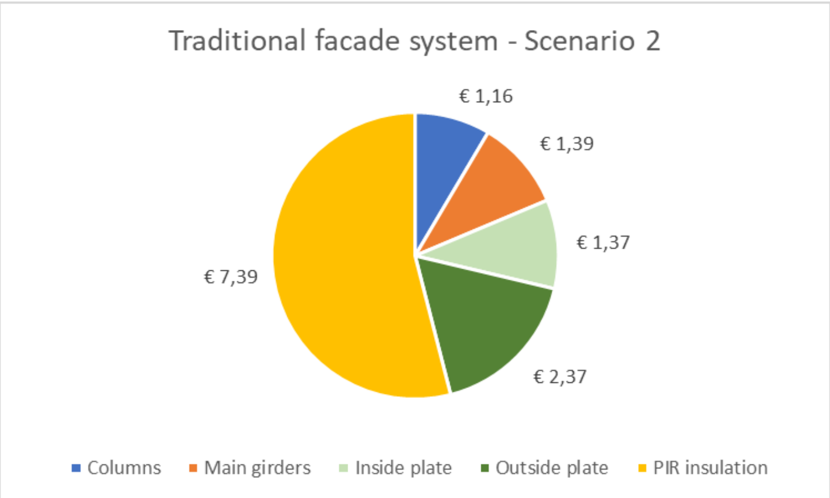


Table 14: Environmental costs traditional façade scenario 2

Layer	Element	Weight	Σ	Environment costs (€/m²)	
		kg/m²	kg/m²	Scenario 1	Scenario 2
Load bearing structure	Column	16,8	16,8	0,62	0,93
Secondary structure	Main girder	11,3	32,95	1,65	1,86
	Perpendicular girder	2,4		0,35	0,39
	Perpendicular support	0,4		0,06	0,07
	Trapezoidal sheet	7,89		1,31	1,45
	Insulation material	5,76		2,25	2,36
	Cleat	0,1		0,02	0,02
	Hanging profile	1,0		0,15	0,17
	Z-Girders	4,1		0,60	0,68
Finishing element	Sinusoidal sheet	7,45	7,45	3,08	3,08
Total per m²		57,2		10,08	11,01

Table 15: Environmental costs case study alternative 1

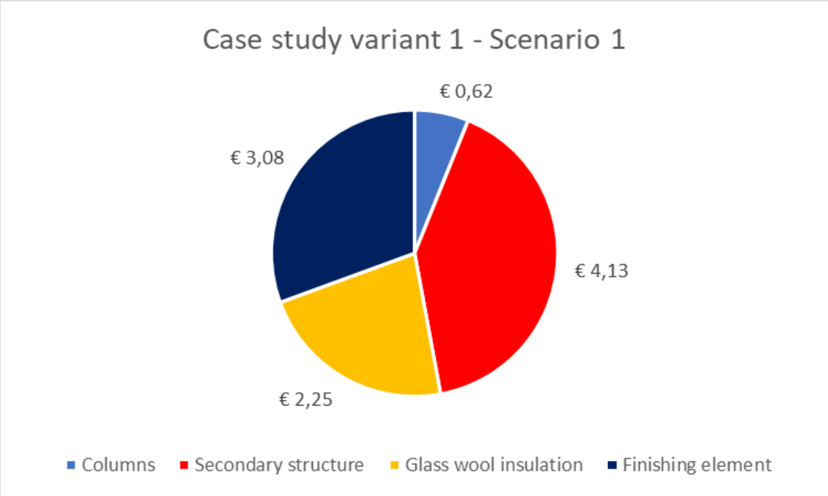


Table 16: Environmental costs case study alternative 1 scenario 1

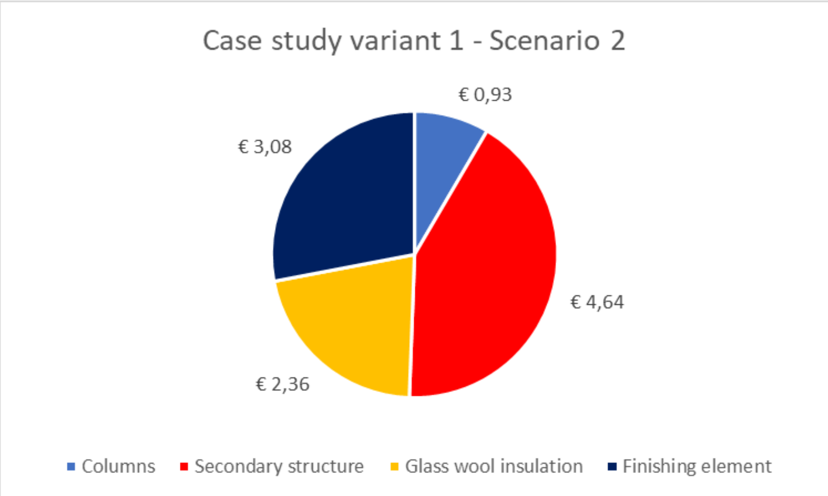


Table 17: Environmental costs case study alternative 1 scenario 2

Layer	Element	Weight	Σ	Environmental costs (€/m²)	
		kg/m²	kg/m²	Scenario 1	Scenario 2
Load bearing structure	Column	16,8	16,8	0,62	0,93
Secondary structure	Main girder	11,3	33,89	1,65	1,86
	Perpendicular girder	2,4		0,35	0,39
	Perpendicular support	0,4		0,06	0,07
	Liner tray	8,83		1,46	1,63
	Insulation material	5,76		2,25	2,36
	Cleat	0,1		0,02	0,02
	Hanging profile	1,0		0,15	0,17
	Girders	4,1		0,60	0,68
Finishing element	Sinusoidal sheet	7,45	7,45	3,08	3,08
Total per m²		58,2		10,23	11,18

Table 18: Environmental costs case study alternative 2

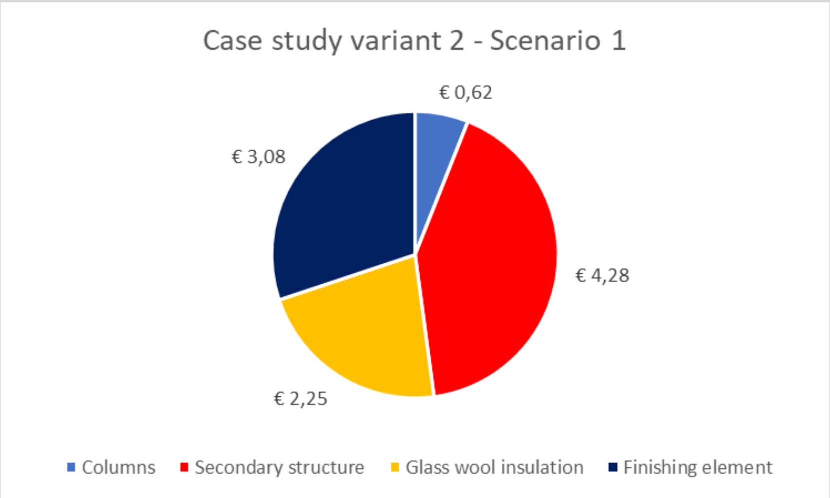


Table 19: Environmental costs case study alternative 2 scenario 1

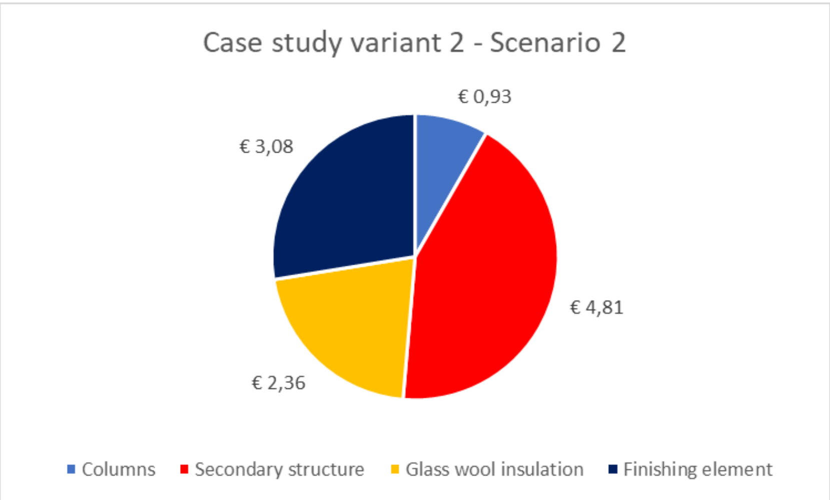


Table 20: Environmental costs case study alternative 2 scenario 2

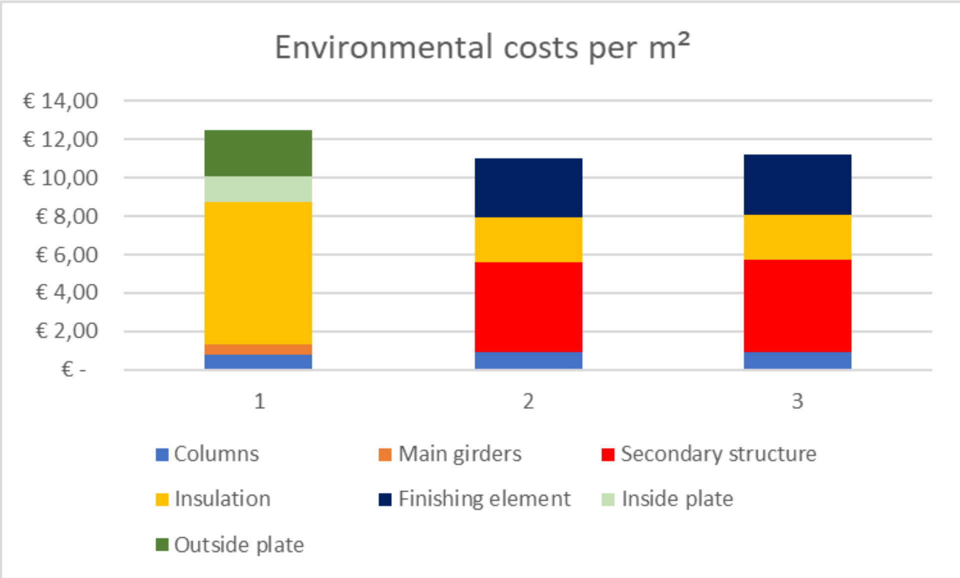


Table 21: Environmental costs per m² (1: Traditional façade – scenario 1; 2: Alternative 1 – scenario 2; 3: Alternative 2 – scenario 2)

8.4. Summary of Life Cycle Assessment results

Based on the results of the calculation of the environmental impact, displayed in Table 12 to Table 20, the following can be concluded:

- In scenario 1, the environmental costs of the traditional façade system are 12,46 €/m^2, compared to 10,08 €/m^2 for case study alternative 1 and 10,23 €/m^2 for case study alternative 2. In scenario 2, the environmental costs of the case study alternatives are 11,01 €/m^2 for case study alternative 1 and 11,18 €/m^2 for case study alternative 2 (difference of 22%). This is displayed in Table 12, Table 15, and Table 18. It should be noted that in reality, scenario 2 does not apply to the traditional façade.
- Between the case study alternatives the difference is very small, the only difference being the trapezoidal sheet used in case study alternative 1 instead of liner trays in case study alternative 2, which have a slightly higher mass per square meter compared to the trapezoidal sheet.
- The mass per square meter of the traditional façade is 35% lower than the case study alternatives (Table 7, Table 8, and Table 9). So creating larger spans by removing columns will increase the total mass of the façade, because the elements in between the columns are required to be heavier (when spanning horizontally from column to column).
- The traditional façade system has a smaller span and thus more columns compared to the case study alternatives (4 columns per 16,5 m compared to 2 columns per 16,5 m). The environmental costs of the columns of the traditional façade system are 0,77 €/m^2 in scenario 1, compared to 0,93 €/m^2 for the columns of the case study alternatives in scenario 2.
- The environmental costs of the main girders of the traditional façade system are 0,56 €/m^2 (scenario 1), compared to 6,39 €/m^2 for case study alternative 1 and 6,54 €/m^2 for case study alternative 2 (scenario 1). In scenario 2, the environmental costs of the case study alternatives are 7,00 €/m^2 and 7,18 €/m^2 respectively.
- As can be seen in Table 12, Table 15, and Table 18, the environmental costs of the PIR insulation of the traditional façade system are 7,39 €/m^2 (scenario 1), compared to the environmental costs of glass wool of 2,25 €/m^2 (scenario 1) or 2,36 €/m^2 (scenario 2) used in the case study alternatives. The impact of the PIR insulation on the total environmental costs is 54%. The impact of glass wool on the total environmental costs is 22%.
- The primary difference between the environmental costs of the traditional façade system and the cases study alternatives is the impact of the insulation material, which is illustrated by Table 21. On the one hand this is due to the production and waste processing costs (1,46 €/m^2 for PIR insulation, 0,59 €/m^2 for glass wool, Table 11). Another factor is the fact that the PIR insulation is chemically attached to the plates of the sandwich panel. The relatively short life cycle of the finishing elements result in a short life cycle of the PIR insulation as well. This is in contrast with the glass wool used in the case study alternatives. There, the insulation is mechanically attached to the secondary structure with a relatively long lifecycle. An additional advantage of this configuration is that the insulation material can easily be added or removed if necessary. This is not the case for sandwich panels, which need the PIR insulation for resistance against bending so it cannot be removed.

8.5. Discussion of Life Cycle Assessment

The Life Cycle Assessment is used to compare a traditional façade system to two alternatives designed in the case study and gain insight on their impact on the environment. It is a simplified calculation of the environmental impact of the façade systems. During the calculation, a number of boundary conditions, assumptions, and simplification have been made which affect the outcome of the calculation.

One of the boundary conditions is the reference period of 100 years. However, this reference period might be too short to prove the difference in environmental impact between the façade systems. Another factor which does affect the outcome of the environmental impact calculation is the composition of the different scenarios, which is uncertain. The same is true for the life cycle of the different materials and layers of the façade systems.

The assembly and disassembly process are not considered in order to simplify the calculation and since it has a small effect on the outcome. If a more accurate calculation is desired, it is recommended that this process is considered however.

The foundation, roof construction and plinth are not considered during the calculation, because these are assumed to be the same for the different façade systems. However, if the load bearing structure is different (less columns in the case study alternatives), it is likely that these parts of the building are different as well. Another *material* which is not considered is the powder coating of all cold-formed elements, but this only has a marginal effect on the environmental impact.

Because the environmental impact is calculated per span, the calculation of the effect of the load bearing structure might be inaccurate. When calculating the environmental impact per span, the number of columns in the case study alternatives is halved with respect to the traditional façade system. However, when calculating the environmental impact for the whole building, the number of columns in the case study alternatives is only one third compared to the traditional façade system.

The transport distances which are considered are prescribed by the Determination Method. In reality, these distances may differ from these values.

9. Development of an assessment model for circularity

In this chapter, an assessment model for measuring the circularity of façades is developed by extending the method of the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2015) and combining it with the research of Durmisevic (Durmisevic, 2016) regarding Design for Disassembly. In chapter 4 it was concluded that current methods either focus on environmental impact or flow of materials, and design is neglected in almost all methods. Also, methods specifically for measuring the circularity of façades do not exist at the moment. It can therefore be desirable to expand or combine current methods, and create a new method which focusses on environmental impact, circulation of materials, and design, specifically for the façade of an industrial building.

The assessment model is meant as an instrument to indicate the level of circularity of façades during the design phase. As a point of reference, the definition of a circular economy by the Ellen MacArthur Foundation is used:

A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015).

This system is based on three principles:

- Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.
- Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.
- Foster system effectiveness by revealing and designing out negative externalities.

The aim is to develop an assessment model that can measure the circularity of façades based on these three principles. The Ellen MacArthur Foundation differentiates between a technical and biological cycle. This assessment model will only consider the technical cycle. This is because materials which are most used in façade construction (concrete and steel) are technical materials instead of biological.

9.1. Key Performance Indicators

The Key Performance Indicators (KPI's) of the circularity of façades are identified based on the report *A framework for circular buildings – indicators for possible inclusion in BREEAM* (Bamberger, et al., 2018). The report identifies seven areas, on which a circular building has a positive impact:

- Materials
- Energy
- Water
- Biodiversity and ecosystems
- Human culture and society
- Health and wellbeing
- Multiple forms of value

Furthermore, the report identifies four design strategies: reduce, synergise, supply, and manage. These four design strategies are deduced from the seven general strategies for circularity identified by Circle Economy (paragraph 2.1.2).

- Reduce: instead of finding a sustainable supply of materials, energy, or water, it is best to design a system with a low demand for these resources. For example, up to 75% of energy used in the built environment could be saved through smarter design (Bamberger, et al., 2018).

- Synergise: when the demand for materials, energy and water has been reduced, local synergies should be identified that can satisfy these demands, for example the reuse of heat or waste flows.
- Supply: the remaining resource- and functional demands should be supplied using clean, renewable, or recycled sources of supply.
- Manage: the system can only function well if information is shared and data is transparent. Feedback about how the system operates also helps the system to function better.

For this thesis, the impact area *Materials* is the most relevant, since typically a façade neither uses energy or water, nor has a minimal impact on biodiversity and ecosystems and human culture and society. Façades can affect health and wellbeing (for example the use of non-toxic materials) and other forms of value (it influences the aesthetic value of a building). The most essential sub-strategies for designing a circular façade are listed in Table 22.

Impact area	Strategy	Sub-strategy	Design strategies
Material	Optimise material use	Reduce amount of materials	Reduce
Material	Optimise material use	Design for reassembly	
Material	Optimise material use	Checks and balances on environmental impact (*)	
Material	Reutilisation	Maximise amount of reused materials	Synergise
Material	Circular materials	Maximise amount of renewable materials	Supply
Material	Knowledge development and sharing	Increase availability of information	Manage
Health and wellbeing	Avoid toxic materials and pollution	Building design embodies no or minimal toxicity	Reduce

Table 22: Sub-strategies prioritised by experts (Bamberger, et al., 2018)

(*) It should be noted that the sub-strategy of *checks and balances on environmental impact* is a prerequisite for all the other sub-strategies. This is because reducing the environmental impact is the purpose of circular design, so it is always necessary to use this sub-strategy. Therefore, a Life Cycle Assessment is performed in chapter 8.

For every sub-strategy, indicators are proposed through which the sub-strategies can be assessed. The sub-strategies and proposed indicators are listed in Table 23. It can be concluded that all essential sub-strategies and indicators are either linked to material use, the design of the connections and the availability of information. Based on these findings, a framework for a new assessment model is proposed.

Sub-strategy	Indicator
Reduce amount of materials	Possibilities for refurbishment
	Possibilities of minimising the square meters of development
	Possibilities of minimising total material mass
Design for reassembly	Demountability of connections used during installation
	Demountability of connections through which the façade is assembled
	Accessibility of connections used during installation
Checks and balances on environmental impact	LCA calculation compared to similar systems
	LCA calculation of all material options
Maximise amount of reused materials	Mass of the reused materials
	Origin of materials used
Maximise amount of renewable materials	Mass of recyclable materials used in the technical cycle
	Mass of biobased materials used in the biological cycle
Increase availability of information	Composition and maintenance of a material passport
	Availability of the material passport for every stakeholder
	Demolition specification or disassembly guidelines
Embodiment of no or minimal toxicity	No materials from the C2C (Cradle to Cradle) Banned List of Chemical Materials are used
	No VOC emission (Volatile Organic Compound)

Table 23: Indicators for each sub-strategy (Bamberger, et al., 2018)

9.2. Framework

From the analysis of the KPI's, it is concluded that to evaluate the circularity of a façade, three main indicators must be investigated:

- The circularity of materials
- The circularity of the design
- The availability of information

The Material Circularity Indicator (MCI) assesses the material input, the utility, and the material output of a façade. This is a theoretical value which can be calculated according to the method developed by the Ellen MacArthur Foundation.

The Design Circularity Indicator (DCI) assesses the design of the façade, including the connections between different components and materials. The design options are analysed based on the principles of Design for Disassembly.

The overall indicator of the circularity of the façade, or Façade Circularity Indicator (FCI), is calculated by weighting the DCI of every component of the façade. A schematisation of a conceptual framework of the assessment model is displayed in Figure 50, where:

- LFI_c is the Linear Flow Index per component
- X_c is the utility of a component
- MCI_c is the Material Circular Indicator per component
- G_i is the weight-factor per option

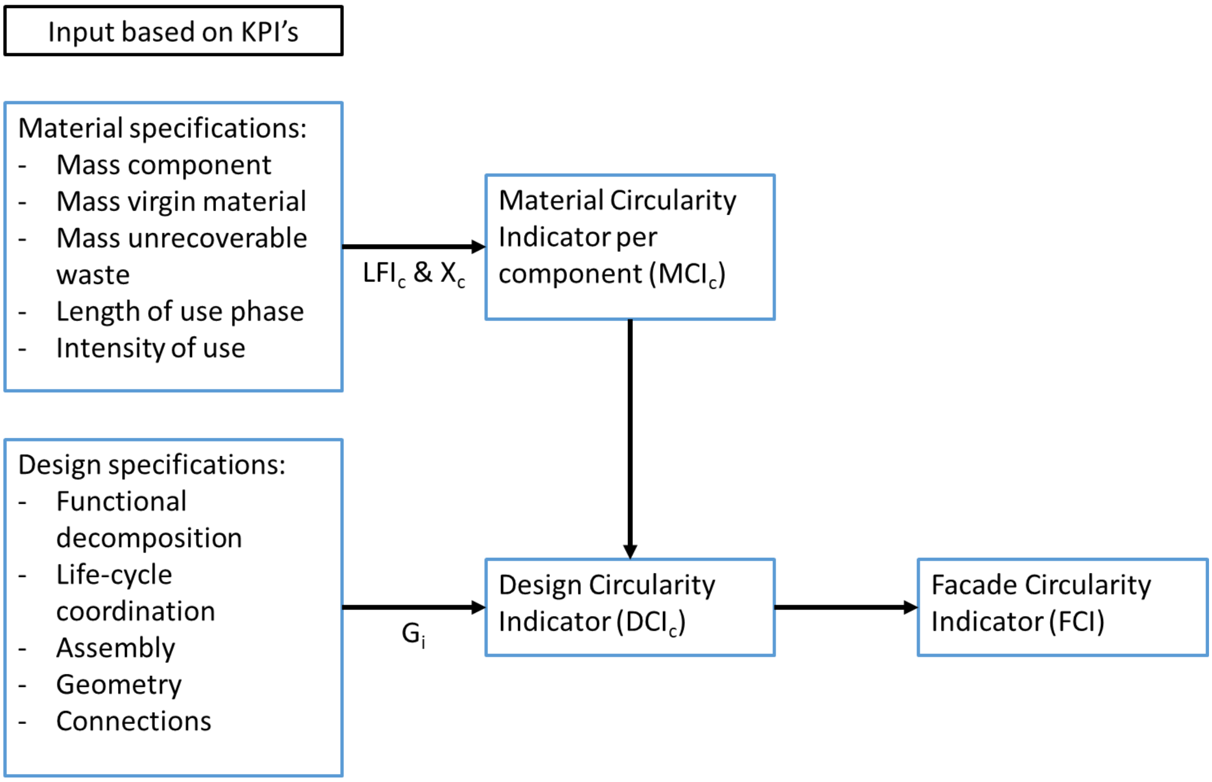


Figure 50: Framework assessment model

9.3. Material Circularity Indicator

The Material Circularity Indicator (MCI) is based on the tool of the Ellen MacArthur Foundation. The tool measures the extent to which linear flow has been minimised and restorative flow maximised, and how long and intensively a product, in this case a façade, is used compared to a similar product. To determine the MCI of a façade, it is necessary to have detailed information about its components and materials. The flow of materials is displayed in Figure 51.

The MCI is calculated using three characteristics of the components material as input: the mass (V) of virgin raw material used in the manufacturing process, the mass (W) of unrecoverable waste that is attributed to the product, and a utility factor (X) that accounts for the length and intensity of the product's use (Ellen MacArthur Foundation, 2015). Table 24 displays the meaning of the different variables influencing the MCI.

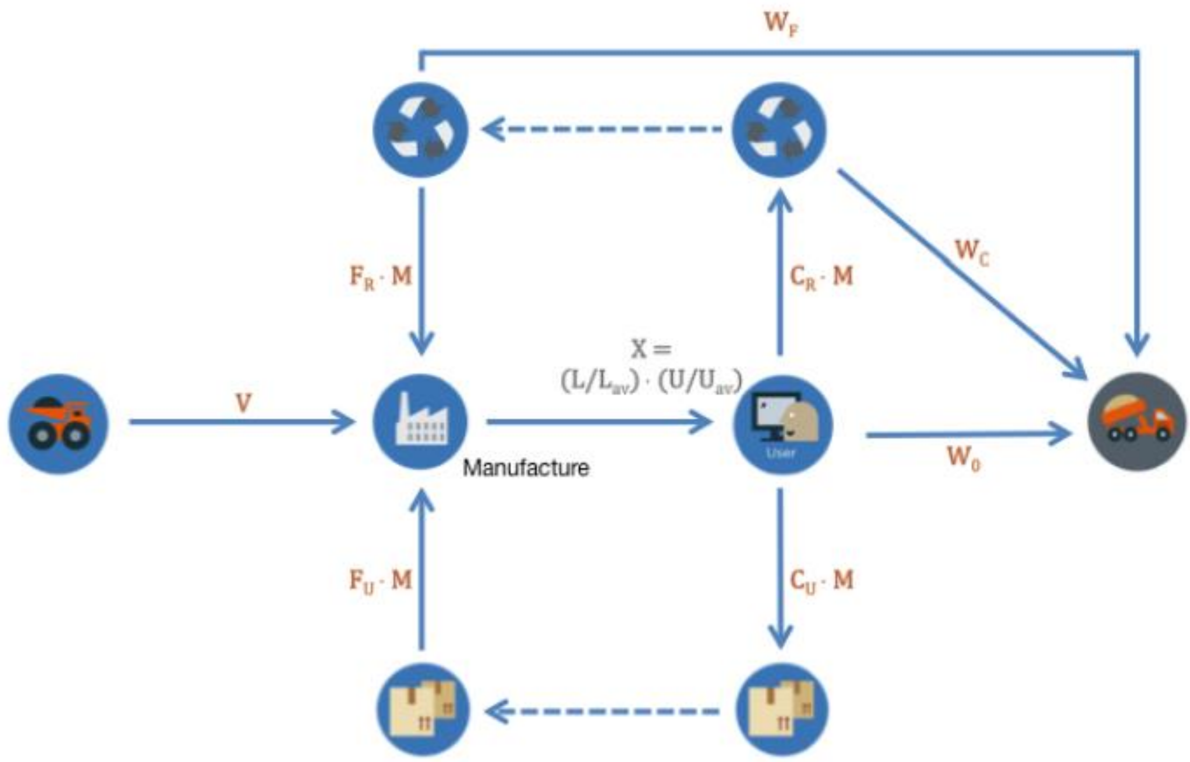


Figure 51: Flow of materials (Ellen MacArthur Foundation, 2015)

Symbol	Definition
V	Mass of virgin material
F_R	Fraction of feedstock derived from recycled sources
F_U	Fraction of feedstock derived from reused sources
M	Mass of the finished product
C_R	Fraction of the mass of the product being collected for recycling at the end of its use phase
C_U	Fraction of the mass of the product going into component reuse
W_0	Amount of waste going to landfill or energy recovery
W_C	Quantity of waste generated in the recycling process
W_F	Waste generated to produce any recycled content used as feedstock
E_C	Efficiency of the recycling process used for recycling the product at the end of its use phase
E_F	Efficiency of the recycling process used to produce the recycled feedstock
X	Utility of a product
L	Lifetime of a product
L_{av}	Lifetime of an industry-average product of the same type
U	Number of functional units achieved during the use of a product
U_{av}	Number of functional units achieved during the use of an industry-average product of a similar type

Table 24: Definitions of variables (Ellen MacArthur Foundation, 2015)

All materials that are part of a façade are either virgin feedstock (V), recycled feedstock (F_R) or reused feedstock (F_U). The virgin feedstock is calculated using:

$$V = M * (1 - F_R - F_U) \tag{9.1}$$

The destination of a material after its useful life cycle is called the material output. The material output can be divided into three categories: materials that go to landfill or energy recovery, waste generated during the recycling process and waste generated to produce recycled content which is used as feedstock.

The amount of waste going to landfill or energy recovery (W_0) is calculated with:

$$W_0 = M * (1 - C_R - C_U) \tag{9.2}$$

The amount of waste generated in the recycling process (W_C) is calculated with:

$$W_C = M * (1 - E_C) * C_R \tag{9.3}$$

The amount of waste generated to produce any recycled content used as feedstock (W_F) is:

$$W_F = M * \frac{(1 - E_F) * F_R}{E_F} \tag{9.4}$$

The amount of unrecoverable waste is (W):

$$W = W_0 + \frac{W_F + W_C}{2} \tag{9.5}$$

The Linear Flow Index (LFI) measures the proportion of materials flowing in a linear fashion. In other words, the proportion of materials sourced from virgin materials and ending up as unrecoverable waste. The LFI of a façade component is calculated by dividing the amount of material flowing in a linear fashion by the total mass flow:

$$LFI_c = \frac{V + W}{2 * M + \frac{W_F - W_C}{2}} \tag{9.6}$$

The utility (X) of a product consists of two components: the length of the product's use phase (lifetime) and the intensity of use (functional units). The component representing the length of the use phase accounts for a change in the waste stream in each amount of time for products that have a longer or shorter lifetime than the industry average.

The component representing the intensity of use reflects the extent to which a product is used to its full capacity. In this thesis, both the U and U_{av} are assumed to be 1, since the façade system which are compared will be used the same number of "functional units". The utility of a façade component is calculated using:

$$X_c = \left(\frac{L}{L_{av}}\right) * \left(\frac{U}{U_{av}}\right) \tag{9.7}$$

Finally, the Material Circularity Indicator of a component of a facade is calculated by considering the Linear Flow Index and a factor F(X), which is a function of the component's utility. The equation is:

$$MCI = 1 - LFI * F(X) \tag{9.8}$$

The value of MCI cannot be negative. The function F is chosen in such a way that improvement of the utility of a product, for example by using it longer, has the same impact on the MCI as the reuse of components that leads to the same amount of reduction in the use of virgin materials and production of unrecoverable waste. This function has the form:

$$F(X) = \frac{a}{X} \tag{9.9}$$

A fully linear product has a Linear Flow Index of 1 (LFI = 1). When this products utility equals the industry average (X = 1), "a" should be set to 0,9 to ensure an MCI of 0,1 (Ellen MacArthur Foundation, 2015). So F(X) is:

$$F(X) = \frac{0{,}9}{X} \tag{9.10}$$

MCI decreases as the utility of a product is lower than the industry average. This means that when a fully linear product (LFI_c = 1) has a utility which is lower than the industry average (X < 1), the MCI approaches 0.

This allows the MCI to differentiate between a fully linear product with a utility value equal to 1 (X = 1, with MCI = 0,1), and fully linear product with a utility value lower than 1 (X < 1, with 0 < MCI < 1). Therefore, the MCI of a fully linear product with a utility of 1 (X = 1) has been chosen to be 0,1 instead of 0 (Ellen MacArthur Foundation, 2015).

The MCI of each component of a façade can thus be calculated with the formula:

$$MCI_c = 1 - LFI_c * \frac{0{,}9}{X_c} \tag{9.11}$$

9.4. Design Circularity Indicator

The Design Circularity Indicator (DCI) describes the level of circularity of different design decisions in façade design. The different components of the façade are analysed based on the principles of Design for Disassembly (Durmisevic, 2016). The goal of Design for Disassembly is to maximise economic value and minimise environmental impact. This is achieved through subsequent reusing, repairing, remanufacturing, and recycling of materials.

The parameters used to assess Design for Disassembly in this thesis are based on the model of Durmisevic and specified for façade design. This model differentiates between material levels decomposition, technical decomposition, and physical decomposition. These three design domains can be further divided into Design for Disassembly aspects. An overview of the design domains, Design for Disassembly aspects and determining factors are displayed in Table 25.

Design domain	Design for Disassembly aspects	Determining factors
Material levels decomposition	Functional decomposition	Functional separation
		Functional dependence
	Systematisation	Structure of material levels
		Type of clustering
Technical decomposition	Base elements	Type of base element
	Life cycle coordination	Use life cycle coordination
		Technical life cycle coordination
		Coordination of life cycle and size
	Relational pattern	Type of relational pattern
Physical decomposition	Assembly process	Assembly direction
		Assembly sequences
	Geometry	Geometry of product edge
		Standardisation of product edge
	Connections	Type of connections
		Accessibility to fixings
		Tolerance
		Morphology of joints

Table 25: Determining factors per aspect of Design for Disassembly (Durmisevic, 2016)

Two sets of grading factors are used. This is done because the grading factors are so called *fuzzy variables* which contain a lot of uncertainties. By using two sets of grading factors, the influence of certain grading factors can be demonstrated, and a range rather than an exact value is obtained.

The first set is based on the model of Durmisevic, and is labelled the *original* set of grading factors. These grading factors are chosen so that options resulting in a fully linear material flow during the recycling process receive a grade between 0,1 and 0,3. Options resulting in a predominantly linear material flow during the recycling process receive a grade between 0,4 and 0,6. Options resulting in a minimally linear material flow during the recycling process receive a grade between 0,7 and 1. In paragraph 5.1, these categories are expressed as buildings with a low disassembly potential, buildings with a partial disassembly potential and buildings with a high disassembly potential.

The second set of grading factors are based on a survey amongst colleagues at CFP Engineering, who have graded the Design for Disassembly aspects to the best of their knowledge, using their experience in the construction environment. This set of grading factors is labelled *alternative* set of grading factors. Both sets of weight factors are displayed in Table 26.

The DCI of each component of a façade is calculated with the formula:

$$DCI_c = \frac{1}{n} * \sum_{i=1}^{n} MCI_c * G_i \tag{9.12}$$

Where n is the number of determining factors per component and G_i is the grading factor of each option. There are 14 determining factors listed in Table 26, so n is 14. The options per determining factor and their grade expressing their disassembly potential are displayed in Table 26. The grading per component is shown in Table 52 to Table 57 in Appendix Q.

Design for disassembly aspects	Determining factors	Options	Original grading factors (G_i)	Alternative grading factors (G_i)
Functional decomposition	Functional separation	Separation of functions	1	1
		Integration of functions with the same life cycle into one element	0,5	0,3
		Integration of functions with different life cycles into one element	0,1	0,2
	Functional autonomy	Modular zoning	1	1
		Planned interpenetrating for different solution (overcapacity)	0,8	1
		Planned interpenetrating for one solution	0,4	0,8
		Unplanned interpenetrating	0,2	0,6
		Total dependence	0,1	0,2
Life-cycle coordination	Technical life cycle of components in relation to assembly sequence (1) Assembled first (2) Assembled second	Long life cycle (1) / Long life cycle (2)	1	1
		Long life cycle (1) / Short life cycle (2)	0,8	0,9
		Short life cycle (1)/ Short life cycle (2)	0,4	0,2
		Short life cycle (1) / Long life cycle (2)	0,1	0,1
	Life cycle of components and elements in relation to the size	Big element / Long life cycle	1	1
		Small element / Long life cycle	1	0,8
		Small element / Short life cycle	0,6	0,8
		Big element / Short life cycle	0,1	0,3
Assembly	Assembly direction based on assembly type	Parallel assembly	1	0,9
		Sequential sequence base element	0,1	0,5
Geometry	Type	Unitised façade system	1	0,6
		Vertical stick system	0,8	0,6
		Horizontal stick system	0,8	0,6
	Position relative to building structure	In front of building structure	1	0,9
		Aligned with building structure	0,5	0,4
		Behind building structure	0,1	0,6
	Geometry horizontal edge	Open linear	1	0,9
		Symmetrical overlapping	0,8	0,7
		Overlapping on one side	0,7	0,9
		Unsymmetrical overlapping	0,4	0,6
		Closed – Integrated on one side	0,2	0,6
		Closed – Integrated on two sides	0,1	0,2

	Geometry of vertical edge	Open linear	1	0,9
		Symmetrical overlapping	0,8	0,4
		Overlapping on one side	0,7	0,9
		Unsymmetrical overlapping	0,4	0,6
		Closed – Integrated on one side	0,2	0,6
		Closed – Integrated on two sides	0,1	0,1
	Separation of finishing	Finish with separable capping element	1	0,8
		Wet paint finish	0,5	0,1
		Powder coat finish	0,5	0,1
		No finish	0,1	0,8
	Standardisation of product edge	Prefabricated	1	0,8
		Half-standardised	0,5	0,5
		Made on site	0,1	0,2
Connections	Type of connection	External connection with additional parts (EA)	1	0,8
		Direct connection with additional fixing devices (DA)	0,8	0,8
		Direct integral connection with inserts (PIN)	0,6	0,6
		Direct integral connection (DI)	0,5	0,5
		Internal connection with additional parts (IA)	0,4	0,5
		Filled soft chemical connection (SC)	0,2	0,2
		Filled hard chemical connection (HC)	0,1	0,1
		Direct chemical connection (DC)	0,1	0,1
	Accessibility of connections	Accessible (A)	1	0,9
		Accessible with an additional operation which causes no damage (ND)	0,8	0,7
		Accessible with an additional operation which causes repairable damage (RD)	0,6	0,6
		Accessible with an additional operation which causes partly repairable damage (PRD)	0,4	0,3
		Not accessible (NA)	0,1	0,1
	Tolerances	High tolerance (HT)	1	0,8
		Minimum tolerance (MT)	0,5	0,5
		No tolerance (NT)	0,1	0,1

Table 26: Options per determining factor (Durmisevic, 2016)

9.4.1. Functional separation

There are four main building functions: supporting, enclosing, servicing, and partitioning. These can be further divided into sub-systems like foundation, floor, façade, roof, etc. Each sub-system can accommodate multiple functions. For example, a façade can support loads and enclose a space. Different functions can have different life cycles, for example because of new user requirements. Therefore, separating functions is considered more circular than integrating functions.

9.4.2. Functional autonomy

Functional autonomy describes the dependency of components with different functions which are interwoven with each other. This means that the relocation or resizing of one component influences other components that have other functions.

9.4.3. Life-cycle coordination

Elements with a long lifecycle and that have a great dependency during assembly should be installed first and disassembled last. The opposite is true for elements with a short life cycle. This results in a situation where, when an element with a short life cycle needs to be replaced, elements with a long lifecycle do not have to be disassembled as well.

Additionally, it is preferable if elements with a short life cycle have a smaller size, which makes them easier to disassemble and replace.

9.4.4. Assembly

There are two assembly sequences: parallel and sequential. Parallel assembly only depends on the type of connection between the elements. In sequential assembly, each element is fixed by a new element, so they are linear dependent on each other. This makes parallel assembly faster than sequential assembly.

9.4.5. Geometry

The three façade types regarded in this thesis are, ranked from circular to linear: unitised façade systems, mullion stick systems and transom stick systems. Unitised façade systems consist of prefabricated elements, which reduce the assembly and disassembly time on site. Stick systems consist of individual components which increases the assembly and disassembly time on site. For all three types, it is possible to change the finishing without replacing the whole façade, making them adaptable and easy to disassemble.

The position of the façade in relation to the main building structure is also relevant when considering Design for Disassembly. Façades which are placed in front of the building structure are more easily disassembled or adapted, compared to façades aligned with the building structure and façades placed behind the building structure.

The geometry of the horizontal and vertical edges of the components and elements influences the assembly and disassembly process as well. Elements and components with open, linear edges are considered the more circular than elements and components with overlapping edges. Closed integral edges are considered the least circular of the options.

The finishing of the façade influences the life cycle of the façade, as well as the disassembly process. Finishing can either be a separable capping element, or a wet paint or powder coat finish.

9.4.6. Type of connection

There are three types of connections: direct (integral), indirect (accessory), and filled. Integral connections are connections where the shape of the edges of the components form the complete connection. This can either be overlapped or interlocked.

Accessory connections are connections in which additional parts are used to form a connection. There are two types of accessory connections: internal and external.

Filled connections are connections between two components that are filled on site with chemical material.

9.5. Façade Circularity Indicator

The Façade Circularity Indicator (FCI) is calculated by adding the DCI's of all façade components and weighing them. This can either be done using the mass (in kg) of the components, or the environmental costs (in €/m^2) of the components as a weight variable.

The most straight forward weight variable is the mass of the different components and the total mass of the façade system. Mass is an adequate weight variable, because generally, the impact on the environment in terms of material use, and thus on the level of circularity of a façade system, is higher for heavier elements. Also, the disassembly of heavy components is usually more difficult, reducing the level of circularity of the façade system.

An alternative option is to use the environmental costs per square meter and the total environmental costs per square meter of the façade system as a weight variable. By weighing the components according to their environmental costs, a more accurate representation of the impact on the environment in terms of material use is obtained.

When using mass as weight variable, the equation to calculate the total Façade Circularity Indicator is:

$$FCI = \frac{1}{M} * \sum_{k=1}^{l} DCI_c * M_c \qquad (9.13)$$

Where M is the total mass of the façade and M_c is the mass per façade component, so:

$$M = \sum_{k=1}^{l} M_c \qquad (9.14)$$

When using environmental costs as weight variable, the equation to calculation the total Façade Circularity Indicator is:

$$FCI = \frac{1}{EC} * \sum_{k=1}^{l} DCI_c * EC_c \qquad (9.15)$$

Where EC is the total environmental costs of the façade and EC_c is the environmental costs per façade component, so:

$$EC = \sum_{k=1}^{l} EC_c \qquad (9.16)$$

The value of the FCI ranges from 0 to 1, where 0 means that the façade can be considered fully linear, and 1 means that the façade can be considered fully circular.

9.6. Prerequisites

The Façade Circularity Indicator describes the circularity of facades in terms of materials and design. However, from the analyses of the KPI's it can be concluded that these indicators do not fully measure the circularity of a façade. As noted before, *checks and balances on environmental impact* is a prerequisite for all the other sub-strategies. This is done with a Life Cycle Assessment calculation.

Other indicators that do influence the level of circularity are:

- Knowledge development and sharing: it is essential to keep track of products and materials to increase the reuse potential. This information can be stored in a material passport. Data transparency and knowledge sharing is another import factor in this process. Finally, information feedback on how the system works once it is in use, can further help to increase the efficiency of the system.
- The use of toxic materials and pollution: health and wellbeing relate to the construction-, use- and demolition phase of a façade. The use of toxic or polluting materials should be avoided during the construction and demolition phase to decrease health risks and preserving the environment. During the use phase, indoor air quality and access to natural light are important health-related factors to consider.

9.7. Results

In this paragraph, the façade assessment model is validated by calculating the Façade Circularity Indicator of a traditional façade system, and the two alternatives designed in the case study. By validating the model in this way, a better understanding of the model is gained, and assumptions can be re-examined, which can help to improve the model.

The bill of materials used during the validation of the FCI is corresponding to the bill of materials used in the Life Cycle Assessment calculation which is presented in paragraph 8.2.

9.7.1. Material Circularity Indicator

During the calculation of the MCI several assumptions are made regarding the fractions of different mass streams, the efficiency of different processes and lifespan and intensity of use of different elements. The justification of parameters used in the calculation of the MCI is presented in Table 27.

Parameter	Material/element	Value	Justification/Source
F_R	Steel (heavy)	0,5	(Reck, Müller, Rostkowski, & Graedel, 2008)
	Steel (light-weight)	0,5	
	Steel (medium)	0,5	
	PIR insulation	0,0	
	Glass wool	0,7	(Krijgsman & Marsidi, 2019)
F_U	All materials	0	All materials assumed to have no previous lifecycle
C_R	Steel (heavy)	0,51	(Stichting Bouwkwaliteit, 2019)
	Steel (light-weight)	0,87	
	Steel (medium)	0,87	
	PIR insulation	0,1	
	Glass wool	0,1	
C_U	Steel (heavy)	0,49	(Stichting Bouwkwaliteit, 2019)
	Steel (light-weight)	0,12	

	Steel (medium) PIR insulation Glass wool	0,12 0,0 0,0	
E_C	Steel (heavy) Steel (light-weight) Steel (medium) PIR insulation Glass wool	0,92 0,92 0,92 0,30 0,99	(Broadbent, 2016) (NVPU, 2020) (Isover, 2020)
E_F	All materials	Corresponding to E_C	A closed loop is assumed
L	Load bearing structure Secondary structure Finishing element	100 50 20	(Brand, 1994)
L_{av}	All materials	Corresponding to L	Assumed to be the same for all alternatives
U	All materials	1	Assumed to be the same for all alternatives
U_{av}	All materials	Corresponding to U	Assumed to be the same for all alternatives

Table 27: Justification MCI parameters

The calculation of the MCI of the traditional façade system and the two case study alternatives is displayed in Appendix P.

9.7.2. Design Circularity Indicator

When calculating the DCI of the façade systems, certain weight factors (G_i) are assigned to the different elements. The weight factors are based on the principles of Design for Disassembly. The justification of parameters used in the calculation of the DCI is presented in this paragraph.

9.7.2.1. Functional separation

All elements (columns, secondary structure, insulation material, finishing element) only perform one function (either load carrying vertical and horizontal loads, insulating, or finishing). The only exception are the components which make up the sandwich panels (traditional façade system), which perform both the functions insulating and finishing. The life cycles of these functions are assumed to be different (50 years for insulation, 20 years for finishing).

9.7.2.2. Functional autonomy

None of the façade elements are interpenetrated by components having different functions, making them independent to one another. The only exception are the main girders (of both the traditional façade system and the case study alternatives), which are provided with a free zone which allows for unplanned interpenetration of services (in future designs this can be planned interpenetrations with premade holes).

9.7.2.3. Life cycle of components in relation to assembly sequence

The load bearing structure (in all façade systems) is installed first and has a relatively long lifecycle (100 years). The secondary structure is installed second (for the traditional façade system this only includes the main girders, for the case study alternatives the entire element) which has a long lifecycle as well (50 years). The finishing elements (sandwich panels or sinusoidal sheet) are installed last and have a relatively short life cycle (20 years).

9.7.2.4. Life cycle of components in relation to size
The load bearing structure (in all façade systems) is relatively big and has a long lifecycle. The secondary structure (in all façade systems) is also relatively big and has a long lifecycle. The finishing elements (in all façade systems) are relatively small and have a relatively short life cycle.

9.7.2.5. Assembly direction
The columns of the load bearing structure (in all façade systems) can be installed in parallel sequence. The same is true for the main girders of the traditional façade system. The secondary structure of the case study alternatives and the finishing elements of all façade systems are installed sequentially.

9.7.2.6. Geometry type
The geometry type of the columns (in all façade systems) is not relevant, so they will just receive a score of 1. The secondary structure of the traditional façade system is considered a *horizontal stick system*. The finishing elements of the case study alternatives are considered a *vertical stick system*. The finishing elements of the traditional façade system and the secondary structure of the case study alternatives are considered a *unitised façade system*.

9.7.2.7. Position relative to building structure
The position relative to the building structure of the columns (in all façade systems) is not relevant since it is part of the building structure. The position relative to the building structure of all other elements is in front of the building structure, except for the secondary structure of the traditional façade system, which is in line with the building structure.

9.7.2.8. Geometry horizontal edge
The geometry of the horizontal edge of all elements is considered open linear, with two exceptions: the horizontal edge of the PIR insulation is considered closed (integrated on two sides) since the foam is chemically attached to the inside and outside plate (see paragraph 9.7.2.12). The horizontal edge of the main girders of the traditional façade system is considered closed (integrated on two sides) as well, since they are connected to the webs of the columns and cannot be moved horizontally freely. The horizontal edge of the main girders of the case study alternatives systems is considered unsymmetrical overlapping since the stacked façade elements overlap each other on the horizontal edge.

9.7.2.9. Geometry vertical edge
The geometry of the vertical edge of all elements is considered open linear, with two exceptions: the vertical edge of the PIR insulation is considered closed (integrated on two sides). The vertical edge of the finishing elements (in case of the traditional façade system this is excluding the PIR insulation) are considered unsymmetrical overlapping, since they overlap each other on the vertical edge.

9.7.2.10. Separation of finishing
The columns of all façade systems are protected with a powder coat finish. The finishing of the traditional façade is not considered separable since the complete sandwich panel would have to be removed. However, the main girders and inner- and outer plates are protected with a powder coat finish. The finishing elements of the case study alternatives are considered separable.

9.7.2.11. Standardisation of product edge
All elements are prefabricated. There is however one exception: the glass wool which covers the outside of the columns (in case of the case study alternatives) is cut to size on site.

9.7.2.12. Type, accessibility, and tolerances of connections
The components which comprise the different façade systems are all interconnected. To grade the type of connection of each component, the lowest scoring grade per component is counted. The

connections and grading is displayed in Figure 52 and Figure 53. The meaning of the symbols are displayed in Table 26.

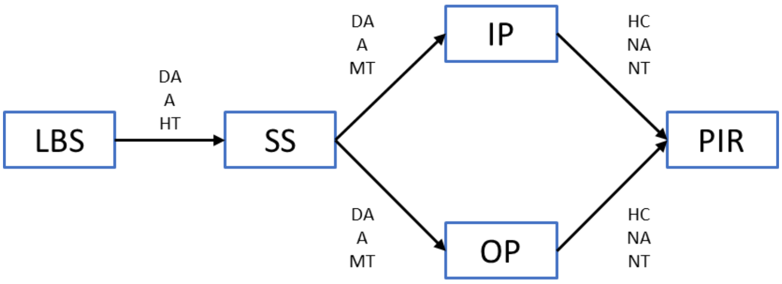


Figure 52: Connection diagram traditional facade

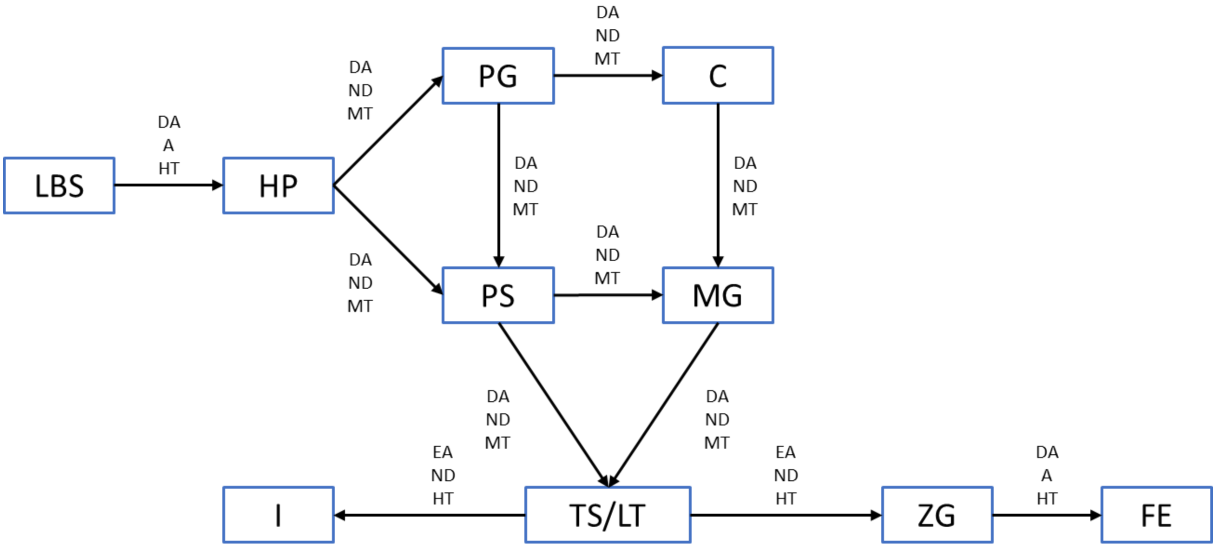


Figure 53: Connection diagram case study alternatives

The calculation of the DCI of the traditional façade system and the two case study alternatives is displayed in Table 52 to Table 57 in Appendix Q.

9.7.3. Façade Circularity Indicator

The FCI of the traditional façade system and the case study alternatives is displayed in Appendix R.

	Element	Component	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
			Original DfD factors			Alternative DfD factors		
Scenario				1	2		1	2
Load bearing structure	Column	-	0,401	0,044	0,061	0,350	0,039	0,053
Secondary structure	Main girder	-	0,058	0,026	0,059	0,053	0,024	0,054
Finishing element	Sandwich panel	Inside plate	0,038	0,048	0,044	0,037	0,047	0,043
		Outside plate	0,066	0,083	0,075	0,064	0,081	0,073
		PIR Insulation	0,005	0,032	0,029	0,005	0,031	0,028
Total			0,569	0,233	0,267	0,510	0,221	0,251

Table 28: FCI traditional facade system

	Element	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
		Original DfD factors			Alternative DfD factors		
Scenario			1	2		1	2
Load bearing structure	Column	0,211	0,044	0,061	0,184	0,038	0,053
Secondary structure	Main girder	0,113	0,094	0,097	0,113	0,094	0,097
	Perpendicular girder	0,027	0,022	0,023	0,025	0,021	0,022
	Perpendicular support	0,005	0,004	0,004	0,005	0,004	0,004
	Trapezoidal sheet	0,089	0,084	0,085	0,084	0,079	0,080
	Insulation material	0,041	0,091	0,087	0,038	0,084	0,081
	Cleat	0,001	0,001	0,001	0,001	0,001	0,001
	Hanging profile	0,011	0,009	0,010	0,011	0,009	0,009
	Z-Girders	0,046	0,039	0,040	0,044	0,036	0,038
Finishing element	Sinusoidal sheet	0,079	0,186	0,171	0,078	0,183	0,168
Total		0,624	0,574	0,578	0,582	0,549	0,552

Table 29: FCI case study alternative 1

	Element	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
		Original DfD factors			Alternative DfD factors		
Scenario			1	2		1	2
Load bearing structure	Column	0,208	0,043	0,060	0,181	0,038	0,052
Secondary structure	Main girder	0,111	0,092	0,095	0,111	0,092	0,095
	Perpendicular girder	0,027	0,022	0,023	0,025	0,021	0,021
	Perpendicular support	0,005	0,004	0,004	0,004	0,004	0,004
	Liner tray	0,098	0,092	0,094	0,093	0,087	0,089
	Insulation material	0,040	0,089	0,086	0,037	0,083	0,080
	Cleat	0,001	0,001	0,001	0,001	0,001	0,001
	Hanging profile	0,011	0,009	0,010	0,011	0,009	0,009
	Z-Girders	0,046	0,038	0,039	0,043	0,036	0,037
Finishing element	Sinusoidal sheet	0,078	0,184	0,168	0,077	0,180	0,165
Total		0,624	0,575	0,579	0,583	0,550	0,553

Table 30: FCI case study alternative 2

9.8. Summary of FCI results

Based on the results of the calculation of the Façade Circularity Indicator displayed in Table 28 to Table 30, the following can be concluded:

- Regardless of which weighted variable is used, the difference between the case study alternatives is negligible.
- When using the mass as a weight variable, the FCI of the traditional façade is 9% to 12% lower compared to the FCI of both case study alternatives, depending on the set of DfD factors that is used. Heavy elements (for example columns) have a large impact on the outcome of the FCI calculation when mass is used as weight variable. For example, the columns of the traditional façade system account for approximately 70% of the total FCI.
- When using environmental costs as a weight variable, the FCI of the traditional façade is 60% lower compared to the FCI of both case study alternatives in scenario 1 and 55% lower in scenario 2, regardless of which set of DfD factors is used. The influence of the steel elements (light, medium and heavy) decreases because of their relatively low environmental cost. The influence of the insulation materials increases but is still marginal because of their low MCI and DCI score.
- Using the alternative DfD factors, the FCI of the traditional façade system is 5 to 10% lower compared to when the original DfD factors are used. For the case study alternatives this difference is 4 to 7%. This means that, although we are dealing with *fuzzy variables* and the exact value of the grading factors cannot be determined, there is an overall consensus about which design options are considered more or less circular than others.
- In short, it can be concluded that the case study alternatives can be considered more circular than the traditional façade system, regardless of which weighted variable (mass or environmental cost) or set of DfD factors is used.

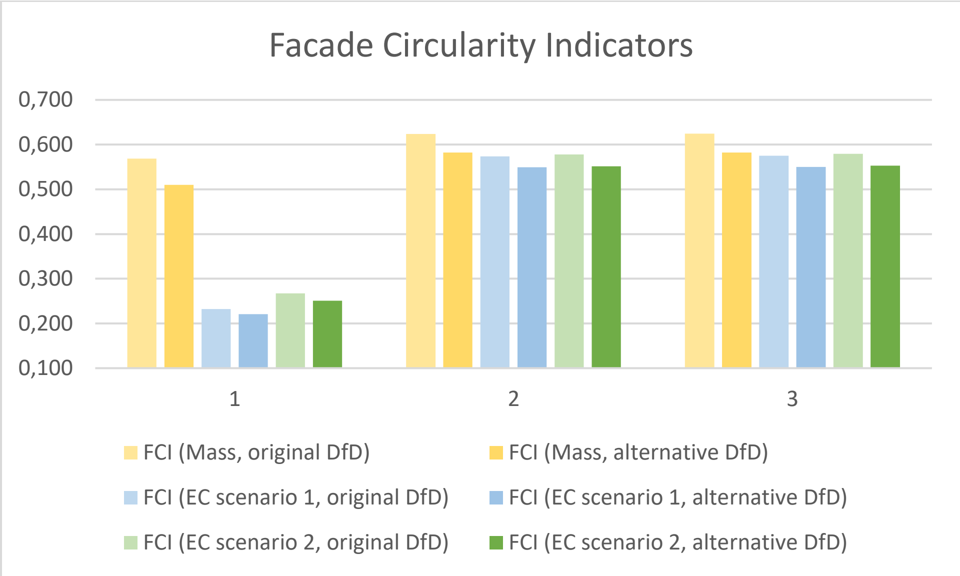


Table 31: Comparison of the Facade Circularity Indicators (1: Traditional façade; 2: Alternative 1; 3: Alternative 2)

9.9. Discussion of FCI calculation

The goal of this chapter was to illustrate an assessment model that can measure the circularity of façades by extending the method of the Ellen MacArthur Foundation and combining it with the research of Durmisevic regarding Design for Disassembly. The assessment model is meant as an instrument to measure the circularity of façades during the design phase.

During the calculation of the MCI a number of assumptions are made regarding the source of feedstock and recycling rate and efficiency during waste processing. These assumptions are based on literature but can differ in practise. Also, no distinction is made between upcycling, recycling and downcycling of materials. During the calculation it is assumed that the length and intensity of use of the traditional façade system and the case study alternatives are equal. In reality, these parameters can be different. All these assumptions cause a relatively high value of the MCI. When the variables are obtained with more certainty, more accurate values of the MCI can be obtained. As of now, the outcome of the MCI calculation is only an indication of the circular use of the materials.

During the calculation of the DCI the two sets of grading factors result in a range rather than an exact value. It is found that both sets of grading factors agree on some level about the degree of circularity of certain design options. In this thesis it is assumed that all options are of equal importance, but in reality, some options are more important than others. In future research this can be included by adding a weight factors per design option.

Using mass as a weight variable emphasises the reduction of materials in order to reduce the total weight of the façade. Using environmental costs as a weight variable emphasises the use of materials with a low environmental cost. Both strategies are important in circular façade design, although checks and balances on the environmental impact can be regarded as the more important of the two since it is the prerequisite of the calculation method. Future research might reveal more appropriate weight factors that could be used.

10. Conclusions and recommendations

10.1. Conclusions

The main objective of this master thesis is to investigate the suitability of cold-formed steel components for circular façade design and to develop an assessment method to measure the circularity of façades. In doing so, more knowledge is acquired about the suitability of cold-formed components, circular façade design and measuring circularity.

The main research question *Are cold-formed components and connections suitable for circular façade design and how can the degree of circularity of a façade system be assessed* is considered to be answered when all sub questions have been answered.

From the literature study it is concluded that current assessment methods for determining the circularity of products either focus on the environmental impact or the flow of materials and protecting existing value, and not on the degree of circularity related to certain design options. Also, there is no method which focusses specifically on façades.

From the case study it is concluded that cold formed steel elements are usable in façade design, as they are already used in practise. In the case study design, all structural criteria were met. All components of the prefabricated elements are detachable from one another, improving their reusability. Because of practical considerations, the case study design does not fully consist of cold formed steel elements. A concrete plinth was added to the design because of its high resistance to impact loads.

From the analysis of circularity it is concluded that the most important design parameters to determine the circularity of a façade system are: the amount of materials used, the possibility for reassembly, the environmental impact of the system, the amount of reused and renewable materials, the availability of information and the amount of toxic materials. These parameters can be measured by calculating the Façade Circularity Indicator. The Façade Circularity Indicator consists of a Material Circularity Indicator and a Design Circularity Indicator. A prerequisite of this method is a Life Cycle Assessment calculation. Due to uncertainty of the variables, the MCI, DCI and FCI are merely and indicator of circularity and cannot be considered exact values. The method can however be used during the design phase to help making certain design decisions.

Based on the LCA, the environmental costs per square meter of the traditional façade system are 22% higher than the environmental costs of the case study alternatives, which means that a traditional façade system is less suitable for use in a circular economy. The difference in environmental costs is in large part due to the high environmental costs of the PIR insulation inside the sandwich panel.

The FCI gives an indication for the level of circularity of a façade system between the values 0 and 1, with 0 meaning that the design is not circular at all and 1 meaning the design in fully circular. When the mass of the components is used as a weight variable, the Façade Circularity Indicator of the traditional façade system is 9 to 12% lower than that of the case study alternatives, so it is considered slightly less circular. This relatively small difference is due to the fact that heavy elements (for example columns) have a large impact on the outcome of the FCI calculation, and lighter components such as the PIR insulation have a small impact.

When environmental costs are used as a weight variable the Façade Circularity Indicator of the traditional façade system is 54 to 60% lower than that of the case study alternatives. This means that the traditional façade system is considered significantly less circular in this case. This relatively large difference is due to the fact that components with a high environmental cost per square meter (insulation material) have a larger impact on the outcome of the FCI calculation, and components with a low environmental cost per square meter (light-weight steel, columns) have a smaller impact.

	LCA	LCA	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI(EC)
	(€/m²)	(€/m²)	(-)	(-)	(-)	(-)	(-)	(-)
DfD factors			**Original**			**Alternative**		
Scenario	1	2	-	1	2	-	1	2
Traditional	12,46	13,68	0,569	0,233	0,267	0,510	0,221	0,251
Case study alternative 1	10,08	11,01	0,624	0,574	0,578	0,582	0,549	0,552
Case study alternative 2	10,23	11,18	0,624	0,575	0,579	0,583	0,550	0,553

Table 32: Summary LCA and FCI

As an overall conclusion, it can be stated that cold-formed components are suitable for circular façade design because of their relatively low weight, low life cycle costs and the possibility to (dis)assemble them with relative ease. The difference between the case study alternatives is negligible, both alternatives can potentially be used in a circular economy. Furthermore, the circularity of façades can be assessed by a combination of the Material Circularity Indicator and Design for Disassembly factors. However, a lot of uncertain variables are used during this calculation that have a large effect on the outcome of the Façade Circularity Indicator.

10.2. Recommendations

Based on the research conducted during this thesis, a number of recommendations are given. These recommendations can be used in future research about the use of cold-formed components in circular façade design and measuring the degree of circularity of façades.

10.2.1. Structural aspects

The design of the circular façade system developed in the case study can potentially be used in a circular economy. The difference between the use of a trapezoidal sheet and liner trays is negligible. However, more research about the structural behaviour of the element is necessary and the design can be improved as well.

The resistance to torsional moment taken up by cooperation of the hanging profile, perpendicular girder and C-profile must be examined further to ensure the safety of the façade element. The behaviour of the main girders, in particular the introduction of the forces into the web of the main girder through the support lips, is another part of the structure which has to be further examined. Finite Element Software may be required for this. The introduction of force via the insulation anchors into the trapezoidal sheet or liner tray also has to be carefully examined. The problem which the high stresses can cause may be solved by locally increasing the thickness of the sheet, which leads to a better introduction of forces.

The shot fired pins used to assemble the façade elements to the loadbearing structure do have the drawback of damaging the elements through which they are shot. This is solved for the façade element, which has a hanging profile which is easily replaced. The columns of the loadbearing structure are permanently damaged however. A new type of connection may solve this problem.

Columns in a façade have a relatively high MCI and DCI score. Creating larger spans by removing them will increase the total mass of the façade, because the elements in between the columns are required to be heavier (when spanning horizontally from column to column). When designing circular façade systems, smaller spans are advisable because this will reduce the total mass of the façade and result in smaller elements, which can be handled more easily during (dis)assembly. The (dis)assembly sequence of the façade elements is another determining factor which has to be further improved upon in future design.

Furthermore, in order to improve knowledge development and sharing, it is advised to keep track of products and materials to increase the reuse potential. This information can be stored in a material passport.

10.2.2. Circular aspects

The scenarios used in the Life Cycle Assessment contain a lot of assumptions, for example regarding the life cycle of different components and materials, and transport differences. This results in the fact that the outcome of the LCA cannot be regarded as an exact value and merely as an indicator. The accuracy of the LCA can be improved by considering (dis)assembly of components. Also, extending the boundaries of the LCA, and considering the complete load bearing structure and foundation, can result in a more holistic view of the environmental impact.

During the calculation of the Material Circularity Indicator, no difference is made between upcycling, recycling and downcycling of materials. In order to increase the accuracy of the MCI, these waste management strategies should be differentiated in the calculation.

In order to improve the calculation of the Design Circularity Indicator, the grading factors should be further investigated. Although researchers and professionals working the construction sector generally agree about the degree of circularity of certain design options, a definitive set of grading factors could give the calculation of the Design Circularity Indicator more credibility. Also, the design options should be weighted according to their importance and impact on the overall circularity.

Future research might reveal more appropriate weight factors that could be used to improve the calculation of the Façade Circularity Indicator. A parametric study is advised to investigate the effect of different weight factors.

Bibliography

Alkondor. (2020). *Geveltoepassingen*. Opgehaald van http://www.alkondor.nl/geveltoepassingen/

Althaus, H.-J., & Kellenberger, D. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*.

Architectenweb. (2020). *Binnendozen met dichtband van SAB-profiel*. Opgehaald van https://architectenweb.nl/producten/product.aspx?ID=13931

Azcarate-Aguerre, J. (2014). *Façades as a Product-Service System - The potential of new business-to-client relations in the façade industry.*

Azcarate-Aguerre, J. (2020). *Façade Leasing pilot project at TU Delft*. Opgehaald van https://www.tudelft.nl/en/architecture-and-the-built-environment/research/projects/green-building-innovation/facade-leasing/facade-leasing-pilot-project-at-tu-delft/

Azcarate-Aguerre, J. F., den Heijer, A., Klein, T., & Vrijhoef, R. (2018). Façade Leasing: Drivers and barriers to the delivery of integrated Façades-as-a-Service. *Real Estate Research Quarterly*.

Bamberger, M., Blok, M., Faes, K., Hoek, J., Klubbinga, B., Van Noort, E., . . . Roemers, G. (2018). *A framework for circular buildings.*

Beurskens, P., & Bakx, M. (2015). *Built-to-rebuild - The development of a framework for buildings according to the circular economy.*

Bouwen met Staal. (2004). *Richtlijnen metalen beplating als schijfconstructie (RMBS 2000).*

Bouwen met Staal. (2017). Rechtbank met restwaarde. *Bouwen met Staal*.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built.* Viking Press.

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *The International Journal of Life Cycle Assessment*.

Carper, K. L., & Feld, J. (1996). *Construction Failure.* John Wiley & Sons Inc.

CFP Engineering. (2019). *Testrapport spouwankers.*

Chiropolos. (2016). *Panelized Metal Wall Systems*. Opgehaald van http://www.wbdg.org/guides-specifications/building-envelope-design-guide/wall-systems/panelized-metal-wall-systems

Ciarimboli, N., & Guy, B. (2020). *DfD Design for Disassembly in the built environment*. Opgehaald van https://www.lifecyclebuilding.org/docs/DfDseattle.pdf

Circle Economy. (2020). *Making sense of the circular economy: the 7 key elements*. Opgehaald van https://www.circle-economy.com/circular-economy/7-key-elements

Cobouw. (2020). Circulair en losmaakbaar bouwen hoeft niet ingewikkeld te zijn. *Cobouw*.

Crowther, P. (2005). Design for disassembly - Themes and principles. *RAIA/BDP Environment Design Guide*.

De Brito, J., & Flores-Colen, I. (2010). Discussion of proactive maintenance strategies in Façades - coatings of social housing. *Journal of Building Appraisal*.

Deniz, O., & Dogan, E. (2014). Building Façade System for Deconstruction. *Journal of Sustainable Architecture and Civil Engineering*.

Durmisevic, E. (2016). *Transformable building structures: design for dissassembly as a way to introduce sustainable engineering to building design & construction.*

Dutch National Government. (2020). *Bouwbesluit 2012*. Opgehaald van https://www.rijksoverheid.nl/onderwerpen/bouwregelgeving/bouwbesluit-2012

Ecopreneur. (2020). *Circularity Check*. Opgehaald van https://ecopreneur.eu/circularity-check-landing-page/

EJOT. (2020). *EJOT self-tapping screw JZ3-6.3*. Opgehaald van https://www.ejot.com/Building-Fasteners/Products/Self-tapping-Screws/JZ3-6-3/p/JZ3-6_3-3111111311

Ellen MacArthur Foundation. (2015). *Circularity Indicators - An Approach to Measuring Circularity.*

Ellen MacArthur Foundation. (2015). *Towards a circular economy: business rationale for an accelerated transition.*

Eppinger, S., & Ulrich, K. (1995). Product design and development. In S. Eppinger, & K. Ulrich, *Product design and development.*

European Commission. (2017). *Level(s) - A common EU framework of core sustainability indicators for office and residential buildings.*

European Commission. (2019). *Report on the implementation of the Circular Economy Action Plan.*

Gaudette, P. E. (2016). *Precast Concrete Wall Systems*. Opgehaald van http://www.wbdg.org/guides-specifications/building-envelope-design-guide/wall-systems/precast-concrete-wall-systems

Gilboa, E., Puterman, M., & Shohet, I. M. (2002). Deterioration patterns of building cladding components for maintenance management. *Construction Management and Economics*.

Glias, A. (2013). *The Donor Skelet: Designing with reused structural concrete elements.*

Hendriks, C., & te Dorsthorst, B. (2001). Re-use of constructions at different levels: construction, element or material.

Hermans, M. (1995). *Deterioration characteristics of building components: a data collecting model to support performance management.*

Het ministerie van Infrastructuur en Milieu en het ministerie van Economische Zaken. (2016). *Nederland circular in 2050.*

Hilti. (2017). *Threaded stud fastning to steel*. Opgehaald van https://www.hilti.nl/medias/sys_master/documents/h9a/ha4/9533687005214/X-EM6H-X-EW6H-X-EF7H-X-EM8H-X-EM10H-EW10H-Data-Sheet-Technical-information-ASSET-DOC-2597824.pdf

IMd Raadgevende Ingenieurs. (2020). *Winkelpanden Hoogstraat 168-172*. Opgehaald van https://imdbv.nl/Projecten/Hergebruik/Winkelpanden-Hoogstraat-168_172

Industriebouwen. (2020). *Wat is een binnendoos*. Opgehaald van https://industriebouwen.be/industriebouw/structuurelementen/wandbekleding/binnendoos/

Isover. (2020). *Milieuvriendelijk geproduceerd*. Opgehaald van https://www.isover.nl/over-isover/milieuvriendelijk-geproduceerd

Jiao, R. J., Tseng, M. M., & Wang, Y. (2018). Modular Design. In R. J. Jiao, M. M. Tseng, & Y. Wang, *CIRP Encyclopedia of Production Engineering.*

Krijgsman, R., & Marsidi, M. (2019). *Decarbonisation options for the Dutch glass wool industry.*

Lehnerd, A. P., & Meyer, M. H. (2011). The Power of Product Platforms. In A. P. Lehnerd, & M. H. Meyer, *The Power of Product Platforms.*

Li, G., Zhou, J., & Wang, L. (2019). A Hierarchical Approach for the Sustainability of Residential Building Regeneration. *Open Journal of Social Sciences*, 269-280.

Lichtenberg, J. (2016). *De diffusie van Slimbouwen.*

Madaster. (2018). *Toelichting Madaster Circulariteit Indicator.*

Ministry of Infrastructure and the Environment. (2015). *Circular economy in the Dutch construction sector .*

Mishra, G. (2020). *Precast Concrete Cladding - Types, Loads, Features and Construction*. Opgehaald van https://theconstructor.org/concrete/precast-concrete-cladding-types-loads-construction/6338/

Modular Building Institute. (2020). *What is Modular Construction*. Opgehaald van http://modular.org/HtmlPage.aspx?name=why_modular

Moffatt, S., & Russell, P. (2001). *Assessing Buildings for Adaptability.*

Nationale Milieu Database. (2020). *Inzage in Nationale Milieudatabase B&U*. Opgehaald van https://www.milieudatabase.nl/viewNMD/

Nationale Staalprijs. (2020). *Bedrijfsgebouw Fokker 7*. Opgehaald van https://www.nationalestaalprijs.nl/project/bedrijfsgebouw-fokker-7

Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies. (2011). *National Annex to NEN-EN 1991-1-4+A1+C2.*

Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies. (2011). *NEN-EN 1991-1-4+A1+C2.*

Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies. (2011). *NEN-EN 1993-1-3 Ontwerp en berekeningen van staalconstructies.*

Normcommissie 351281 Duurzaamheid van bouwwerken. (2019). *NEN-EN 15804+A2 Duurzaamheid van bouwerken - Milieuverklaringen van producten - Basisregels voor de productgroep bouwproducten.*

NVPU. (2020). *Is PU isolatiemateriaal recyclebaar?* Opgehaald van https://www.nvpu.nl/is-pu-isolatiemateriaal-recyclebaar/

Oberhuber, S., & Rau, T. (2016). *Material Matters.* Bertram + de Leeuw Uitgevers.

O'Callaghan, E. (2014). *Circular economy of facades*. Opgehaald van https://igsmag.com/press-releases/eckersley-ocallaghan/climate-friday-circular-economy-of-facades/

Onkenhout Access & Fastening Solutions. (2020). *Blindklinknagels zware belasting M-Lok*. Opgehaald van https://www.onkenhout.nl/pdf/Blindklinknagels_multigrip_MLok_aluminium/134/t/p

Platform'23. (2019). *Core method for measuring circularity in the construction sector.*

Rau BV. (2019). *Gemeentehuis Brummen*. Opgehaald van https://www.rau.eu/portfolio/gemeentehuis-brummen/

Reck, B. K., Müller, D. B., Rostkowski, K., & Graedel, T. (2008). Antropogenic nickel cycle: insights into use, trade, and recycling. *Environ Sci Technol*.

Redactie Bouwwereld. (2016). Test met geveltypes op TU Delft. pp. https://www.bouwwereld.nl/bouwkennis/test-geveltypes-op-tu-delft/.

Redactie Bouwwereld. (sd). *Test met geveltypes op TU Delft.* Opgehaald van https://www.bouwwereld.nl/bouwkennis/test-geveltypes-op-tu-delft/

SAB-Profiel BV. (2020). *SAB 18/988*. Opgehaald van https://www.sabprofiel.nl/producten/gevelplaten-gevelprofielen/golfplaten-golfprofielen/sab-18-988.html

SAB-Profiel BV. (2020). *SAB 85R/1120*. Opgehaald van https://www.sabprofiel.nl/producten/dakplaten-dakprofielplaten/warmdakplaten/sab-85r-1120.html

SAB-Profiel BV. (2020). *SAB B90/500*. Opgehaald van https://www.sabprofiel.nl/producten/binnendozen/sab-b90-500.html

SAB-Profiel BV. (2020). *SAB WB 60-80-100-120*. Opgehaald van https://www.sabprofiel.nl/producten/sandwichpanelen/gevelpanelen/sab-wb-60-80-100-120.html

Shahu, R., Pundir, A. K., & Ganapathy, L. (2012). Measuring flexibility degree of building construction projects - A case study. *International Journal of Social Science and Interdisciplinary Research*.

Stichting Bouwkwaliteit. (2019). *Determination Method - Environmental performance buildings and civil engineering works.*

The European Parliament and the council of 19 November 2008. (2008). *Directive 2008/98/EC on waste and repealing certain Directives.*

TNO. (2020). *Nieuwe methode helpt bedrijven om producten circular te maken*. Opgehaald van https://www.tno.nl/nl/tno-insights/artikelen/nieuwe-methode-helpt-bedrijven-om-producten-circulair-te-maken/

Tox Pressotechnik. (2020). *Tox Round Joint Joining System*. Opgehaald van https://uk.tox-pressotechnik.com/applications/clinching/sheet-metal-clinching-shapes/tox-round-joint/

Tura, N., Hanski, J., Ahola, T., Stahle, M., Piiparinen, S., & Valkokari, P. (2019). Unlocking circular business: a framework of barriers and drivers. *Journal of Cleaner Production*.

Ursa. (2020). *Masonry Cavity Walls*. Opgehaald van https://www.ursa-uk.co.uk/applications/masonry-cavity-walls

Van Heel, P. (2017). *Madaster: bouwsteen voor circulaire economie*. Opgehaald van https://insights.abnamro.nl/2017/06/madaster-bouwsteen-voor-circulaire-economie/

Van Randen, A. (1976). *De bouw zit in de knoop.*

Vogtlander, J. (2012). *LCA: A practical guide for students, designers and business managers.*

Weber, R. A. (2016). *Masonry Wall Systems*. Opgehaald van https://www.wbdg.org/guides-specifications/building-envelope-design-guide/wall-systems/masonry-wall-systems

Yu, W.-W. (2000). *Cold-Formed Steel Design.* John Wiley & Sons Inc.

Appendices

Appendix A

Loads on a façade

Self-weight

The only vertical load which acts on the façade is the self-weight of the façade element. A simplified version of the self-weight of the façade element is presented in Table [] and Table [], only taking into account the main girders, Z-girders, finishing element and trapezoidal sheets (alternative 1) or liner trays (alternative 2).

Element	Weight (kN/m)	No. per façade element	Total weight (kN/m)
Main girder	0,197	2	0,39
Trapezoidal sheet	0,276	1	0,28
Z-girder	0,029	4	0,12
Finishing element	0,261	1	0,26
Total			**1,05**

Table 33: Simplified self-weight case study alternative 1

Element	Weight (kN/m)	No. per façade element	Total weight (kN/m)
Main girder	0,197	2	0,39
Liner tray	0,309	1	0,31
Z-girder	0,029	4	0,12
Finishing element	0,261	1	0,26
Total			**1,08**

Table 34: Simplified self-weight case study alternative 2

$$q_{g1;k} = 1{,}05 \frac{kN}{m}$$

$$q_{g1;d} = \gamma_g * q_{g1;k} = 1{,}1 * 1{,}05 = 1{,}16 \frac{kN}{m}$$

$$q_{g2;k} = 1{,}08 \frac{kN}{m}$$

$$q_{g2;d} = \gamma_g * q_{g2;k} = 1{,}1 * 1{,}08 = 1{,}19 \frac{kN}{m}$$

Wind loads

To determine the wind load, the location of the structure must be considered. This method differentiates three areas in the Netherlands, as is displayed in Figure 54. Besides the wind area, the roughness of the surrounding terrain also plays a role in determining the wind load. In Table 35, the values of the wind thrust are summarised.

In this thesis a wind thrust is considered which corresponds with a structure located in wind area 2, with an unbuilt surrounding. This is chosen because it represents a value which is adequate for most of The Netherlands. Only coastal areas and areas in the province of Noord-Holland have a higher representative value for the wind load. An advantage of this design choice is that it avoids over-dimensioning, while still being sufficient for most standard projects.

The façade should be able to be applied to a building of at least 15 meters. This means a wind thrust of 0,976 kN/m^2 is considered.

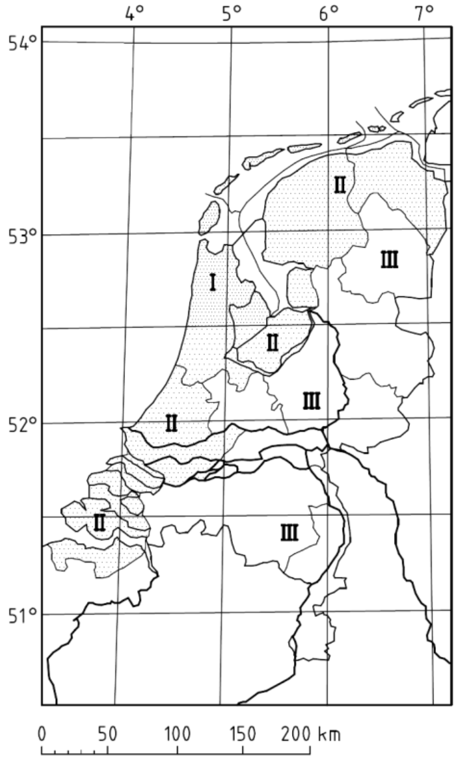


Figure 54: Wind areas in The Netherlands (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011)

Height (m)	**Wind thrust (kN/m²)**		
	Wind area 1	Wind area 2	Wind area 3
1	0,71	0,60	0,49
2	0,71	0,60	0,49
3	0,71	0,60	0,49
4	0,71	0,60	0,49
5	0,784	0,657	0,541
6	0,843	0,707	0,582
7	0,895	0,749	0,617
8	0,94	0,787	0,648
9	0,981	0,822	0,676
10	1,018	0,853	0,702
11	1,052	0,881	0,725
12	1,083	0,907	0,747
13	1,112	0,932	0,767
14	1,139	0,954	0,786
15	1,165	0,976	0,804

Table 35: Wind load per meter height (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011)

The values of the wind thrust are based on the location of the structure, and do not consider the geometry and the orientation of the structure. Table 36 provides wind pressure coefficients which consider both. The wind zones are based on the wind zones displayed in Figure 55.

Zone	A		B		C		D		E	
h/d	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
≤ 0,25	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

Table 36: Wind pressure coefficients (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011)

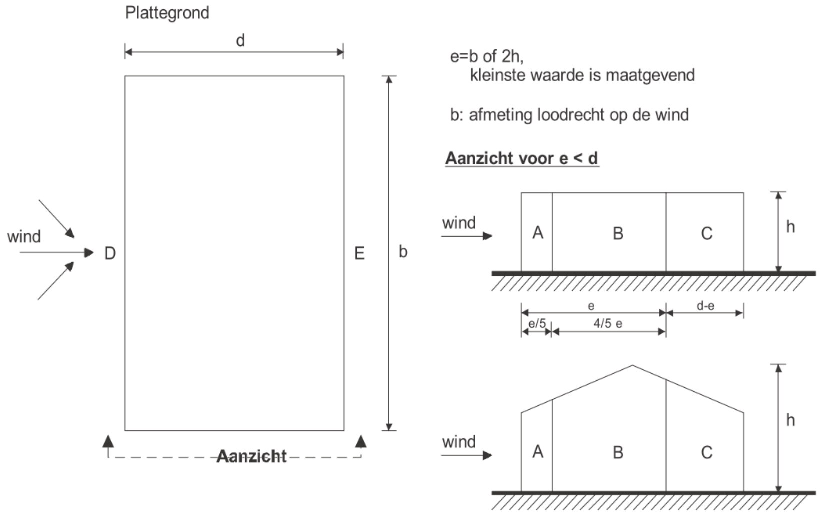


Figure 55: Wind zones on a building's façade (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011)

Wind suction

The wind pressure coefficients of zone A are normative for wind suction. Global effects are considered instead of local effects, because the façade elements have an area larger than 10 m^2. This leads to negative external pressure coefficient ($C_{pe,10}$) of -1,2. This is combined with a positive internal wind pressure coefficient ($C_{pi,10}$) of +0,2. To combine these two coefficients, the absolute value of the two coefficients are added, leading to a $C_{pc,10}$ of 1,4. The wind load per square meter becomes:

$$Q_{ws;k} = q_p * C_{pc,10} = 0{,}976 * 1{,}4 = 1{,}37 \frac{kN}{m^2}$$

$$Q_{ws;d} = Q_{ws;k} * \gamma_q = 1{,}37 * 1{,}35 = 1{,}85 \frac{kN}{m^2}$$

$$q_{ws;d} = Q_{ws;d} * \frac{b}{2} = 1{,}85 * \frac{3{,}5}{2} = 3{,}24 \frac{kN}{m}$$

Wind pressure

The wind pressure coefficients of zone D are normative for wind pressure, which has a positive external pressure coefficient ($C_{pe,10}$) of +0,8. This is combined with a negative internal wind pressure coefficient ($C_{pi,10}$) of -0,3. This leads to a $C_{pc,10}$ of 1,1. The wind load per square meter becomes:

$$Q_{wp;k} = q_p * C_{pc,10} = 0{,}976 * 1{,}1 = 1{,}08 \frac{kN}{m^2}$$

$$Q_{wp;d} = Q_{wp;k} * \gamma_q = 1{,}08 * 1{,}35 = 1{,}43 \frac{kN}{m^2}$$

$$q_{wp;d} = Q_{wp;d} * \frac{b}{2} = 1{,}43 * \frac{3{,}5}{2} = 2{,}49 \frac{kN}{m}$$

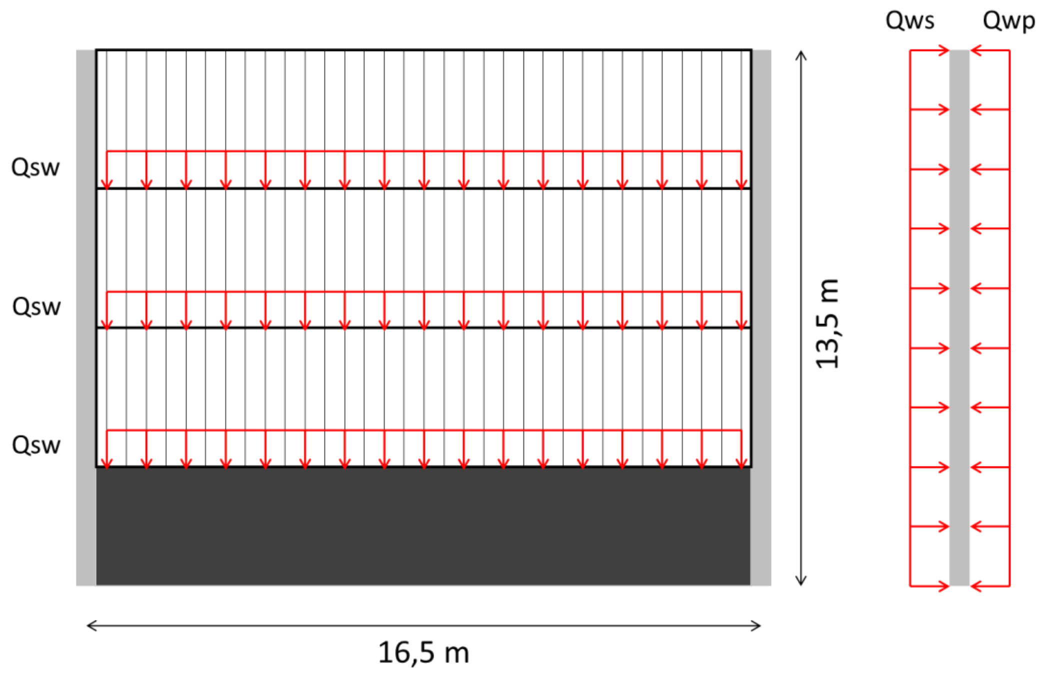


Figure 56: Schematisation of self-weight (left) and wind loads (right)

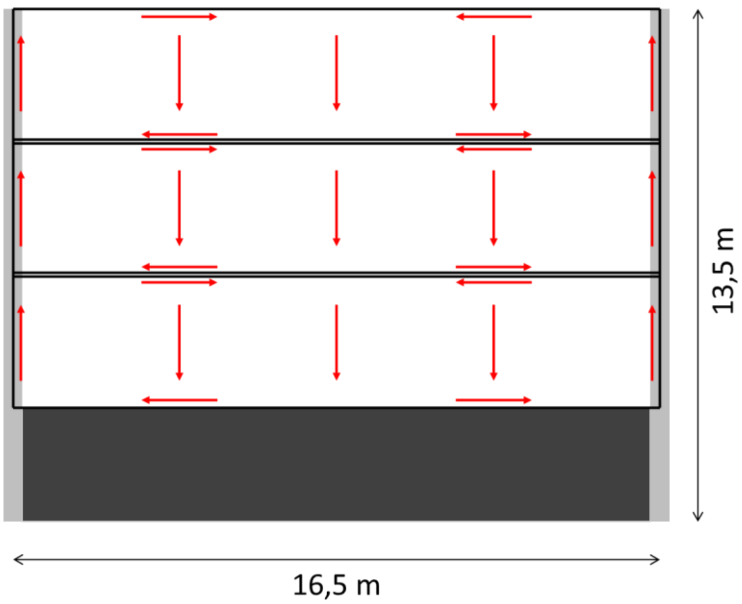


Figure 57: Flow of self-weight forces (diaphragm action)

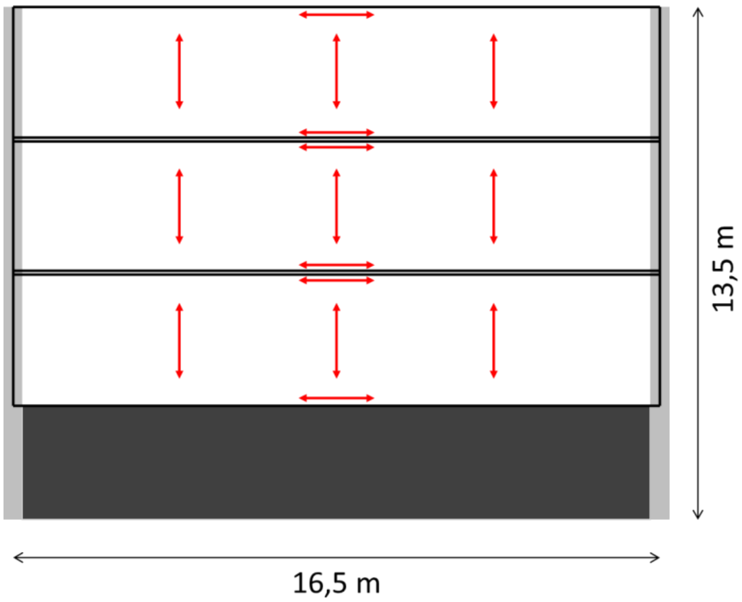


Figure 58: Flow of wind forces

Appendix B

I-section

During the optimisation of the I-section, the maximum span for different profile heights and web thicknesses are calculated. The span is modelled as a simply supported beam.

Loads

The normative load on the main girder is the load due to wind suction. The magnitude of this uniformly distributed load is:

$$q_{ws;d} = 3{,}24 \frac{kN}{m}$$

Effects

The maximum bending moment in the span is:

$$M_{Ed} = \frac{1}{8} * q_{ws;d} * a^2$$

The maximum shear force in the span is:

$$V_{Ed} = \frac{1}{2} * q_{ws;d} * a$$

The maximum deflection in the span is:

$$\delta_{max} = \frac{5}{384} * \frac{q_{ws;d} * a^4}{E * I}$$

Resistance

The aim of the optimisation of the I-section is to determine the optimal web thickness (t_w) for a certain profile height (h) and fixed flange dimensions. The profiles are optimised in terms of moment capacity, shear capacity and maximum deflection. The results are displayed in Table 37 and Figure 59.

	Web thickness t_w (mm)										
	2,0	2,1	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,0
Profile type	Span (m)										
I.300.98.2	9,81	9,92	10,02	10,13	10,24	10,35	10,46	10,57	10,66	10,69	10,72
I.350.98.2	10,86	10,98	11,10	11,22	11,34	11,46	11,58	11,71	11,83	11,95	12,07
I.400.98.2	11,85	11,98	12,12	12,25	12,38	12,52	12,65	12,79	12,93	13,06	13,20
I.450.98.2	12,79	12,94	13,09	13,24	13,38	13,53	13,68	13,83	13,98	14,13	14,28
I.500.98.2	13,70	13,86	14,02	14,19	14,35	14,51	14,67	14,83	14,99	15,16	15,32
I.550.98.2	14,58	14,75	14,93	15,11	15,28	15,46	15,63	15,81	15,98	16,15	16,33
I.600.98.2	13,89	15,62	15,81	16,00	16,19	16,38	16,56	16,75	16,94	17,13	17,32
I.650.98.2	12,44	14,40	16,56	16,87	17,07	17,28	17,48	17,68	17,88	18,08	18,28
I.700.98.2	11,26	13,04	14,99	17,13	17,94	18,16	18,37	18,58	18,80	19,01	19,22
I.750.98.2	10,29	11,91	13,69	15,64	17,77	19,02	19,25	19,47	19,70	19,93	20,15

Table 37: Maximum span per profile type with varying web thickness

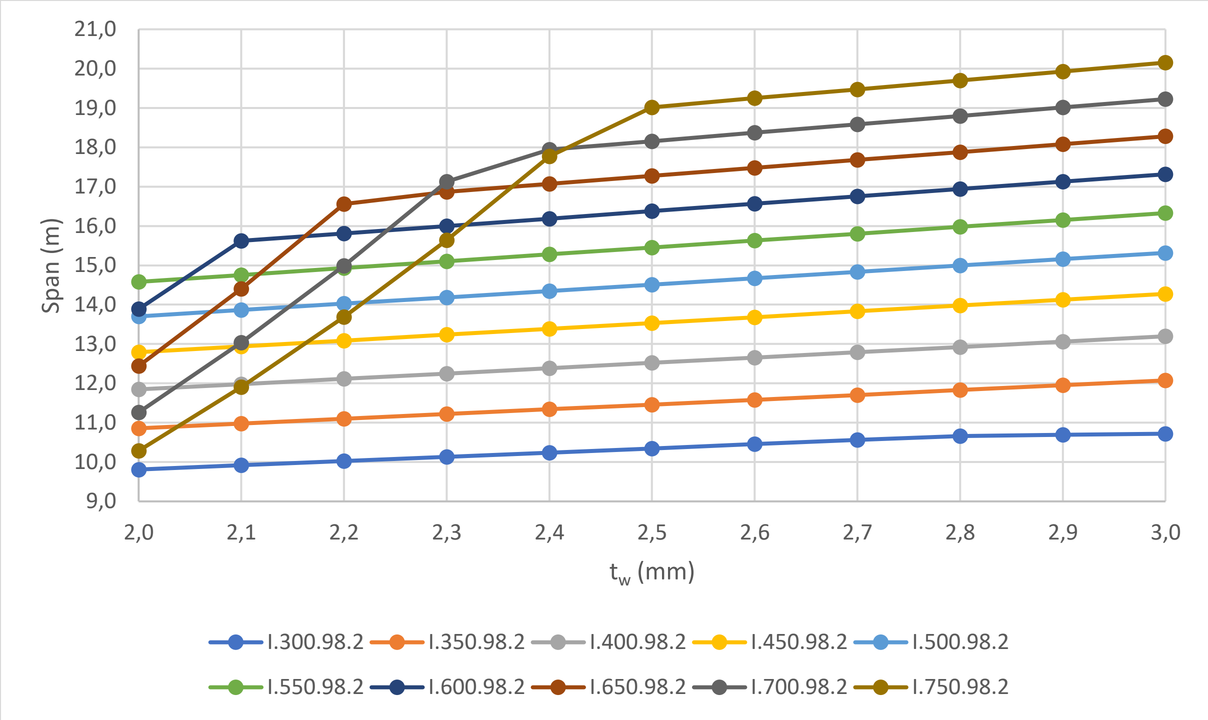


Figure 59: Maximum span per profile type with varying web thickness

From this Table 37 and Figure 59, it is concluded that:

- For profiles with a height of 550 mm or smaller (h ≤ 550 mm) is the maximum deflection normative in all cases. This can be seen in the graphs of Figure 59, since these graphs are completely linear. This means that increasing the thickness of the web (t_w) will have a small effect on the maximum span of the profile. For example, a profile with a height of 550 mm and a web thickness of 2 mm has a maximum span of 14,58 m, whereas a profile with the same height and a web thickness of 3 mm has a maximum span of 16,33 m. An increase in web thickness by 50%, increases the maximum span with only 12%.
- For profiles with a height larger 550 mm (h > 550 mm), other failure mechanisms play a role. This can be seen in the graphs of Figure 59, since they are not linear. This is because when the web is too thin, the profile fails due to shear force. When the thickness of the web increases the graphs become linear again, which means that the maximum deflection becomes normative. A profile with a height of 650 mm and a web thickness of 2 mm has a maximum span of 12,44 m, whereas a profile with the same height and a web thickness of 2,2 mm has a maximum span of 16,56 m. An increase of the web thickness of 10%, increases the maximum span with 33%.
- The *tipping point* between the two linear parts of the graphs can be regarded as the optimal web thickness of the profile. Increasing the web thickness beyond this point will only marginally increase the maximum span of the profile.
- The value of the tipping point increases as the height of the profiles increases. For example, the tipping point of a profile with a height of 650 mm is 2,2 mm, whereas the tipping point of a profile with a height of 750 mm is 2,5 mm. This is because slender profiles are more sensitive to failure due to shear.
- The maximum value of the tipping point is 2,5 mm. This means that, for these profile heights, increasing the web thickness beyond this point will have a marginal effect on the maximum span.

- For the rest of this case study, a profile height of 650 mm and a web thickness of 2,2 mm is chosen. The properties are of the I-section are displayed in Table 38 and Figure 60.

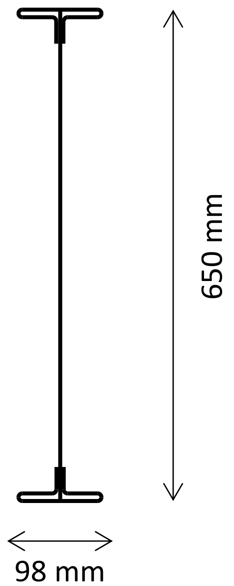


Figure 60: I-section

Parameter	Value
f_y (N/mm^2)	350
E (N/mm^2)	210000
h (mm)	650
b_f (mm)	98
h_f (mm)	50
t_f (mm)	2,0
M_{Rd} (kNm)	112
V_{Rd} (kN)	26,7

Table 38: I-section properties

Appendix C

Trapezoidal sheet

The calculation of the shear resistance of the trapezoidal sheet are based on EN1993-1-3 art. 6.1.7.3. (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011). For the calculation of the bending moment resistance and the deflection of the trapezoidal sheet, the model of a simply supported beam is assumed with a width of 1 m. First, the loads are described, and the effects are calculated, then the resistance to shear and bending, and the deflection of the profile is calculated.

Loads

The primary load on the trapezoidal sheet is wind load, which causes wind pressure and suction on the façade. These forces are represented by the surface loads Q_{wp} and Q_{ws}. For the calculation of the shear resistance of the profile, the surface loads are simplified to line loads in horizontal direction. The wind suction per meter (in transverse direction of the profile) is:

$$q_{ws;sheet;k} = Q_{ws;k} * b = 1{,}37 * 3{,}5 = 4{,}8\ kN/m$$

$$q_{ws;sheet;d} = Q_{ws;d} * b = 1{,}85 * 3{,}5 = 6{,}5\ kN/m$$

The wind pressure per meter (in transverse direction of the profile) is:

$$q_{wp;sheet;k} = Q_{wp;k} * b = 1{,}08 * 3{,}5 = 3{,}8\ kN/m$$

$$q_{wp;sheet;d} = Q_{wp;d} * b = 1{,}43 * 3{,}5 = 5{,}0\ kN/m$$

For the calculation of the bending moment resistance and maximum deflection, the surface loads are simplified to line loads in vertical direction. The wind suction per meter (in longitudinal direction of the profile) is:

$$q_{ws;trough;k} = Q_{ws;k} * d = 1{,}37 * 0{,}28 = 0{,}38\ kN/m$$

$$q_{ws;trough;d} = Q_{ws;d} * d = 1{,}85 * 0{,}28 = 0{,}52\ kN/m$$

The wind pressure per meter (in longitudinal direction of the profile) is:

$$q_{wp;trough;k} = Q_{wp;k} * d = 1{,}08 * 0{,}28 = 0{,}30\ kN/m$$

$$q_{wp;trough;d} = Q_{wp;d} * d = 1{,}43 * 0{,}28 = 0{,}40\ kN/m$$

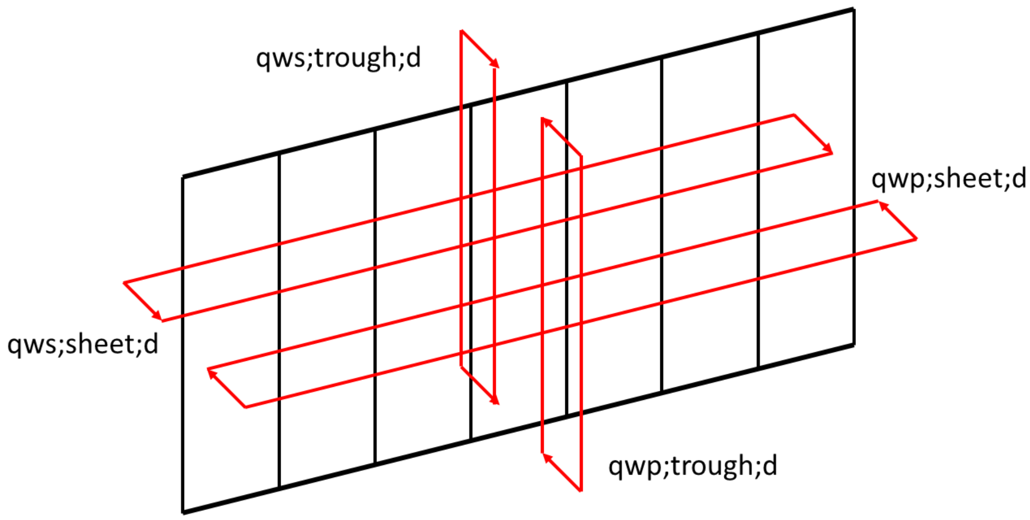


Figure 61: Schematisation of loads

Effects

The effective shear forces (in transverse direction of the profile) are:

$$V_{ws;sheet;Ed} = \frac{q_{ws;sheet;d}}{2} = \frac{6{,}5}{2} = 3{,}3\ kN/m$$

$$V_{wp;sheet;Ed} = \frac{q_{wp;sheet;d}}{2} = \frac{5{,}0}{2} = 2{,}5\ kN/m$$

The effective bending moments (in longitudinal direction of the profile) are:

$$M_{ws;sheet;Ed} = \left(\frac{1}{8}\right) * q_{ws;trough;d} * b^2 = \left(\frac{1}{8}\right) * 0{,}52 * 3{,}5^2 = 0{,}79\ kNm$$

$$M_{wp;sheet;Ed} = \left(\frac{1}{8}\right) * q_{wp;trough;d} * b^2 = \left(\frac{1}{8}\right) * 0{,}40 * 3{,}5^2 = 0{,}61\ kNm$$

The maximum displacements (in longitudinal direction of the profile) are:

$$\delta_{ws;sheet} = \frac{5}{384} * \frac{Q_{ws;k} * b^4}{E * (I_{eff}{}^{-} * 10^4)} = \frac{5}{384} * \frac{1{,}37 * 3500^4}{210000 * (886 * 10^3)} = 14{,}4\ mm$$

$$\delta_{wp;sheet} = \frac{5}{384} * \frac{Q_{wp;k} * b^4}{E * \left(I_{eff}{}^{+} * 10^4\right)} = \frac{5}{384} * \frac{1{,}08 * 3500^4}{210000 * (849 * 10^3)} = 11{,}8\ mm$$

With I_{eff}^- and I_{eff}^+ being the effective moments of inertia in upward (suction) and downward (pressure) direction.

Resistance

Shear

In order to determine the local transverse resistance of an unstiffened web of cross-sections with two or more stiffened webs, the following conditions must be satisfied (Normcommissie 351 001 Technische Grondslagen voor Bouwconstructies, 2011):

- The clear distance d_c from the bearing length for the support reaction or local load to a free end, is at least 40 millimetres.
- The cross-section satisfies the following criteria:

$$\frac{r}{t} = \frac{5}{0{,}75} = 6{,}67 \leq 10$$

$$\frac{h_w}{t} = \frac{83}{0{,}75} = 111 \leq 200\sin(\Phi) = 200 * \sin(53{,}9) = 161{,}6$$

$$45° \leq 53{,}9° \leq 90°$$

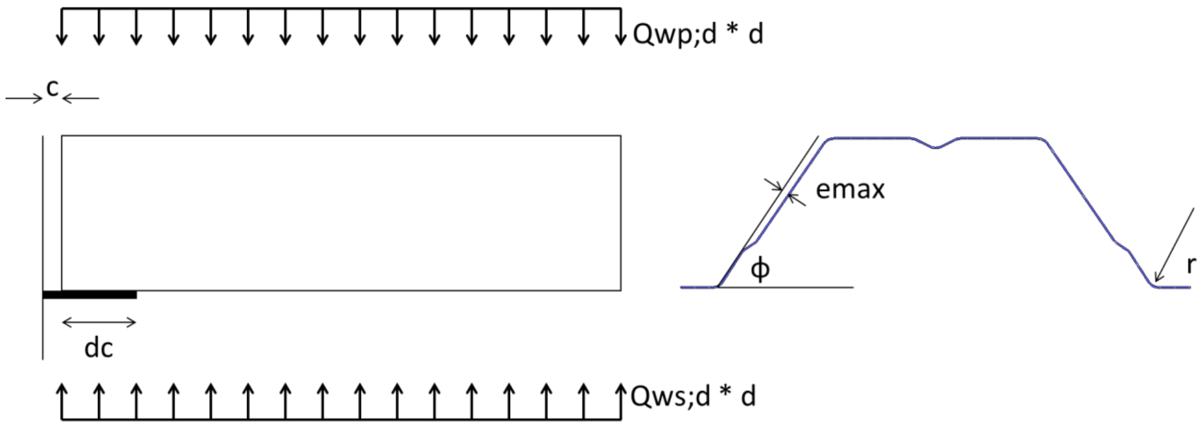


Figure 62: Parameters trapezoidal sheet calculation

When both conditions are satisfied, the local transverse resistance $R_{w,Rd}$ per web of the cross-section can be determined. Here, the profile is regarded as category 1, because the distance from the support to the end of the sheet (*c*) satisfies:

$$c \leq 1{,}5 * h_w = 1{,}5 * 83 = 124{,}5\ mm$$

This leads to the following values for α and l_a:

$$\alpha = 0{,}075$$

$$l_a = 10\ mm$$

$$R_{w,Rd} = \alpha * t^2 * \sqrt{f_{yb} * E} * \left(1 - 0{,}1 * \sqrt{\frac{r}{t}}\right) * \left(0{,}5 + \sqrt{0{,}02 * \frac{l_a}{t}}\right) * \frac{2{,}4 + \left(\frac{\Phi}{90}\right)^2}{\gamma_{m;1}}$$

$$= 0{,}075 * 0{,}75^2 * \sqrt{320 * 210000} * \left(1 - 0{,}1 * \sqrt{\frac{5}{0{,}75}}\right) * \left(0{,}5 + \sqrt{0{,}02 * \frac{10}{0{,}75}}\right)$$

$$* \frac{2{,}4 + \left(\frac{53{,}9}{90}\right)^2}{1{,}0} = 719\ N$$

Because the web is stiffened with longitudinal stiffeners, the local transverse resistance can be increased with a factor $\kappa_{a;s}$ if the following condition is satisfied:

$$2 < \frac{e_{max}}{t} < 12$$

where e_{max} is the larger eccentricity of the folds relative to the system line of the web. In this case

$$2 < \frac{e_{max}}{t} = \frac{5}{0{,}75} = 6{,}67 < 12$$

is satisfied. The factor $\kappa_{a;s}$ can be calculated with:

$$\kappa_{a;s} = 1{,}45 - 0{,}05 * \frac{e_{max}}{t} = 1{,}45 - 0{,}05 * \frac{5}{0{,}75} = 1{,}12$$

which satisfies the condition that:

$$\kappa_{a;s} \leq 0,95 + 35000 * t^2 * \frac{e_{min}}{{b_d}^2 * s_p} = 0,95 + 35000 * 0,75^2 * \frac{5}{40^2 * 21,6} = 3,80$$

The total transverse resistance per meter is:

$$R_{Rd} = \frac{\kappa_{a;s} * R_{w;Rd} * 2}{280} = \frac{1,12 * 719 * 2}{280} = 5,8\ \frac{kN}{m}$$

The unity check is a check of the wind pressure per meter and the resistance per meter. The wind suction per meter is checked, as this would result in tension in the web.

$$uc = \frac{5,0}{5,8} = 0,86$$

Bending moment

The bending moment resistances of the profile are:

$$M_{ws;sheet;Rd} = \frac{{I_{ef}}^{-} * 280}{z_{top}} * f_y = \frac{886 * 280}{37,8} * 320 = 2,1\ kNm$$

$$M_{wp;sheet;Rd} = \frac{{I_{ef}}^{+} * 280}{z_{bottom}} * f_y = \frac{849 * 280}{45,2} * 320 = 1,7\ kNm$$

The unity check of the bending moment resistance of the wind suction is:

$$uc = \frac{M_{ws;sheet;Ed}}{M_{ws;sheet;Rd}} = \frac{0,79}{2,1} = 0,38$$

The unity check of the bending moment resistance of the wind pressure is:

$$uc = \frac{M_{wp;sheet;Ed}}{M_{wp;sheet;Rd}} = \frac{0,61}{1,7} = 0,36$$

Deflection

The maximum allowable deflection of the profile is:

$$\delta_{max} = \frac{l}{150} = \frac{3500}{150} = 23,3\ mm$$

The unity check of the maximum negative displacements:

$$uc = \frac{\delta_{ws;sheet}}{\delta_{max}} = \frac{14,4}{23,3} = 0,62$$

The unity check of the maximum positive displacements:

$$uc = \frac{\delta_{wp;sheet}}{\delta_{max}} = \frac{11,8}{23,3} = 0,51$$

With all unity checks lower than 1, this means that a trapezoidal sheet of the type SAB – 85R/1120 – 0,75 can be applied.

Appendix D

Liner tray

For the calculations of the shear- and bending moment resistance and the deflection of the liner tray, the model of a simply supported beam is assumed. First, the loads are described, and the effects are calculated, then the resistance to shear and bending, and the deflection of the profile is calculated.

Loads

The primary load on the liner tray wind load, which causes wind pressure and suction on the façade. For the calculation of the shear- and bending moment resistance and the maximum deflection of the profile, the surface loads are simplified to line loads in vertical direction. The wind suction per profile (in longitudinal direction) is:

$$q_{ws;tray;k} = Q_{ws;k} * w_{tray} = 1{,}37 * 0{,}500 = 0{,}69\ kN/m$$

$$q_{ws;tray;d} = Q_{ws;d} * w_{tray} = 1{,}85 * 0{,}500 = 0{,}93\ kN/m$$

The wind pressure per profile (in longitudinal direction) is:

$$q_{wp;tray;k} = Q_{wp;k} * w_{tray} = 1{,}08 * 0{,}500 = 0{,}54\ kN/m$$

$$q_{wp;tray;d} = Q_{wp;d} * w_{tray} = 1{,}43 * 0{,}500 = 0{,}72\ kN/m$$

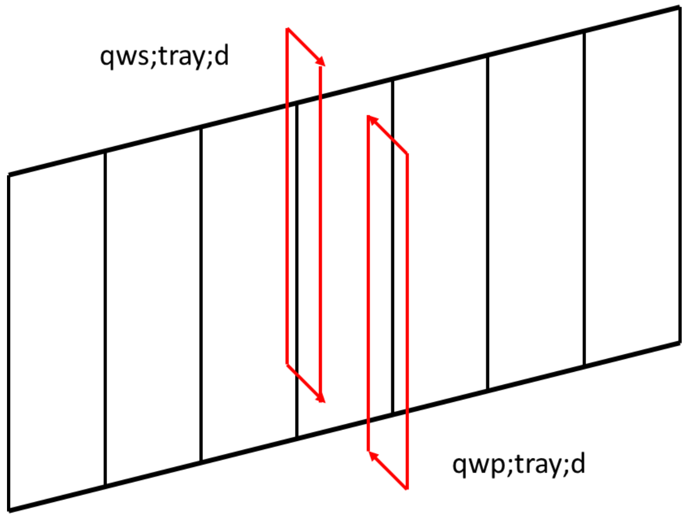


Figure 63: Schematisation of loads

Effects

The effective shear forces are:

$$V_{ws;tray;Ed} = \left(\frac{1}{2}\right) * q_{ws;tray;d} * b = \left(\frac{1}{2}\right) * 0{,}93 * 3{,}5 = 1{,}63\ kN$$

$$V_{wp;tray;Ed} = \left(\frac{1}{2}\right) * q_{wp;tray;d} * b = \left(\frac{1}{2}\right) * 0{,}72 * 3{,}5 = 1{,}26\ kN$$

The effective bending moments are:

$$M_{ws;tray;Ed} = \left(\frac{1}{8}\right) * q_{ws;tray;d} * b^2 = \left(\frac{1}{8}\right) * 0{,}93 * 3{,}5^2 = 1{,}42\ kNm$$

$$M_{wp;tray;Ed} = \left(\frac{1}{8}\right) * q_{wp;tray;d} * b^2 = \left(\frac{1}{8}\right) * 0{,}72 * 3{,}5^2 = 1{,}10\ kNm$$

The maximum displacements are:

$$\delta_{ws;tray} = \frac{5}{384} * \frac{q_{ws;tray;k} * b^4}{E * I_{eff}^{\ -}} = \frac{5}{384} * \frac{0{,}69 * 3500^4}{210000 * 71{,}1 * 10^4} = 9{,}0\ mm$$

$$\delta_{wp;tray} = \frac{5}{384} * \frac{q_{wp;tray;k} * b^4}{E * I_{eff}^{\ +}} = \frac{5}{384} * \frac{0{,}54 * 3500^4}{210000 * 101{,}2 * 10^4} = 5{,}0\ mm$$

With I_{eff}^- and I_{eff}^+ being the effective moments of inertia in upward (suction) and downward (pressure) direction.

Resistance

The resistances of the profile are derived from Figure 64, the product sheet of the profile.

$$M_{ws;tray;Rd} = 4{,}24\ kNm/m$$

$$M_{wp;tray;Rd} = 3{,}36\ kNm/m$$

$$V_{ws;tray;Rd} = 8{,}75\ kN/m$$

$$V_{wp;tray;Rd} = 6{,}04\ kN/m$$

$$\delta_{max} = \frac{l}{150} = \frac{3500}{150} = 23{,}3\ mm$$

The unity check of the bending moment resistance of the wind suction is:

$$uc = \frac{M_{ws;tray;Ed}}{M_{ws;tray;Rd}} = \frac{1{,}42}{4{,}24 * 0{,}500} = 0{,}67$$

The unity check of the bending moment resistance of the wind pressure is:

$$uc = \frac{M_{wp;tray;Ed}}{M_{wp;tray;Rd}} = \frac{1{,}10}{3{,}36 * 0{,}500} = 0{,}65$$

The unity check of the shear resistance of the wind suction is:

$$uc = \frac{V_{ws;tray;Ed}}{V_{ws;tray;Rd}} = \frac{1{,}63}{8{,}75 * 0{,}500} = 0{,}37$$

The unity check of the shear resistance of the wind pressure is:

$$uc = \frac{V_{wp;tray;Ed}}{V_{wp;tray;Rd}} = \frac{1{,}26}{6{,}04 * 0{,}500} = 0{,}42$$

The unity check of the maximum negative displacements:

$$uc = \frac{\delta_{ws;tray}}{\delta_{max}} = \frac{9{,}0}{23{,}3} = 0{,}39$$

The unity check of the maximum positive displacements:

$$uc = \frac{\delta_{wp;tray}}{\delta_{max}} = \frac{5{,}0}{23{,}3} = 0{,}21$$

With all unity checks lower than 1, this means that a liner tray of the type SAB B90/500 – 0,75 can be applied.

Nenn-blech-dicke t_N [mm]	Feld-moment $M_{F,k}$ [kNm/m]	Endauflagerkräfte: Trag-fähigkeit $R^T_{A,K}$ [kN/m]	Endauflagerkräfte: Gebrauchs-tauglichkeit $R^G_{A,K}$ [kN/m]	Elastisch aufnehmbare Schnittgrößen an Zwischenauflagern 2): $M^0_{B,k}$ [kNm/m]	$R^0_{B,k}$ [kN/m]	maximales Stütz-moment max $M_{B,k}$ [kNm/m]	maximale Zwischen-auflager-kraft max $R_{B,k}$ [kN/m]	Reststützmomente 3): min l [m]	max l [m]	max $M_{R,K}$ [kNm/m]
	4) $b_A + ü = 40$ mm			5) Zwischenauflagerbreite $b_B = 100$ mm; ε = 1						
0,70	3,66	7,56		3,04	71,59	2,86	12,79			
0,75	4,24	8,75		3,52	93,28	3,31	14,80			
0,88	5,40	11,65		4,84	149,68	4,58	20,77			
1,00	6,48	14,32		6,05	201,75	5,76	26,28			
1,13	7,36	16,26		6,90	229,07	6,54	29,84			
1,25	8,17	18,05		7,63	254,29	7,26	33,12			
	4),6) $b_A + ü \geq 40$ mm			6) Zwischenauflagerbreite $b_B \geq 300$ mm; ε = 1						
0,70	3,66	7,56		3,26	∞	3,26	19,15			
0,75	4,24	8,75		3,77	∞	3,77	22,16			
0,88	5,40	11,65		5,15	∞	5,15	30,37			
1,00	6,48	14,32		6,43	∞	6,43	37,95			
1,13	7,36	16,26		7,30	∞	7,30	43,09			
1,25	8,17	18,05		8,10	∞	8,10	47,83			

Stahlkern- Nennstreckgrenze $f_{y,k}$ = **320 N/mm²** | Abstand der Befestigungen $a_1 \leq 621$ mm **A)**

Charakteristische Werte für Widerstandsgrößen bei nach unten gerichteter und andrückender Flächenlast 1)

Reststützmomente 3): $M_{R,K} = 0$ für l < min l

$$M_{R,K} = \frac{l - \min l}{\max l - \min l} \cdot \max M_{R,K}$$

$M_{R,K}$ = max M_R für l > max l

Nenn-blech-dicke t_N [mm]	Maßgebende Querschnittswerte: Eigen-last g [kN/m²]	Trägheits-momente 7) $I^+_{ef,k}$ [cm⁴/m]	$I^-_{ef,k}$ [cm⁴/m]	Quer-schnitts-fläche A_g [cm²/m]	Grenzstützweiten L_{gr} 8), Einfeldträger: während der Montage [m]	nach der Montage [m]	Feld-moment $M_{F,k}$ [kNm/m]	Endauf-lager $R_{A,k}$ [kN/m]	Zwischenauflager 2), ε = 1: $M^0_{B,k}$ [kNm/m]	$R^0_{B,k}$ [kN/m]	max $M_{B,k}$ [kNm/m]	max $R_{B,k}$ [kN/m]
0,70	0,0824	87,4	61,4	10,50			2,90	5,22	5,41	20,84	3,89	13,05
0,75	0,0883	101,2	71,1	11,25			3,36	6,04	6,26	29,19	4,61	15,10
0,88	0,1036	118,4	84,5	13,20			4,49	8,32	7,28	50,91	5,80	20,80
1,00	0,1178	134,2	96,8	15,00			5,53	10,42	8,23	70,95	6,90	26,06
1,13	0,1331	152,4	109,9	16,95			6,28	11,84	9,34	80,56	7,83	29,59
1,25	0,1473	169,1	122,0	18,75			6,97	13,14	10,37	89,42	8,70	32,85

Columns $M_{F,k}$ to max $R_{B,k}$: Charakteristische Werte der Widerstandsgrößen bei nach oben gerichteter und abhebender Flächenlast 9)

1) An den Stellen von Linienlasten quer zur Spannrichtung und von Einzellasten ist der Nachweis nicht mit dem Feldmoment $M_{F,k}$ sondern mit dem Stützmoment $M_{B,k}$ für die entgegengesetzte Lastrichtung zu führen.
2) Interaktionsbeziehung für $M_{B,k}$ und $R_{B,k}$ gemäß Abschnitt 3.2.4.5.2.
3) Sind keine Werte für die Reststützmomente angegeben, ist beim Tragsicherheitsnachweis $M_{R,K} = 0$ zu setzen, oder für M_B ein Nachweis mit $\gamma_M = 1,1$ nach der Elastizitätstheorie zu führen. (l = kleinere der benachbarten Stützweiten).
4) b_A+ü = Endauflagerbreite + Profilüberstand.
5) Für kleinere Zwischenauflagerbreiten b_B als angegeben müssen die charakteristischen Werte der Widerstandsgrößen linear im entsprechenden Verhältnis reduziert werden. Für b_B < 10 mm z. B. bei Rohren, dürfen die Werte für b_B = 10 mm eingesetzt werden.
6) Bei Auflagerbreiten, die zwischen den aufgeführten Auflagerbreiten liegen, dürfen die aufnehmbaren Tragfähigkeitswerte jeweils linear interpoliert werden.
7) Effektive Trägheitsmomente für Lastrichtung nach unten (+) bzw. nach oben (-).
8) Maximale Stützweiten, bis zu denen die Kassettenprofiltafel ohne lastverteilende Maßnahmen begangen werden kann.
9) Verbindung mit der Unterkonstruktion in jedem anliegenden Gurt mit mindestens 2 Verbindungselementen.
A) Für dreischalige Konstruktionen mit Befestigung der Außenschale über Hutprofile mit einer Höhe von höchstens 40 mm, im Abstand von 1000 mm werden die in de Tabelle aufgetragenen Werte wie folgt abgemindert:
- die Zwischenauflagerwerte für Windsog mit 25%.

Firma **SAB-profiel bv** Produktieweg 2 3400 MG IJsselstein Niederlande	Querschnitts – und charakteristische Widerstandswerte des Stahlkassettenprofils **SAB 90/500**	**Typenblatt 1** zur statischen Berechnung Nr. 061130

Stand: 03. 09. 2007

Figure 64: Product sheet SAB B90/500

Appendix E

Support lip trapezoidal sheet

The trapezoidal sheet is fastened to the support lip by means of a self-tapping screw, which is placed through a pre-drilled hole in the support lip and drilled through the trapezoidal sheet from the side of the support lip. The dimensions of the support lip are displayed in Figure 66. Dimensions on the self-tapping screw (JZ3-6,3 xL) are displayed in Figure 65.

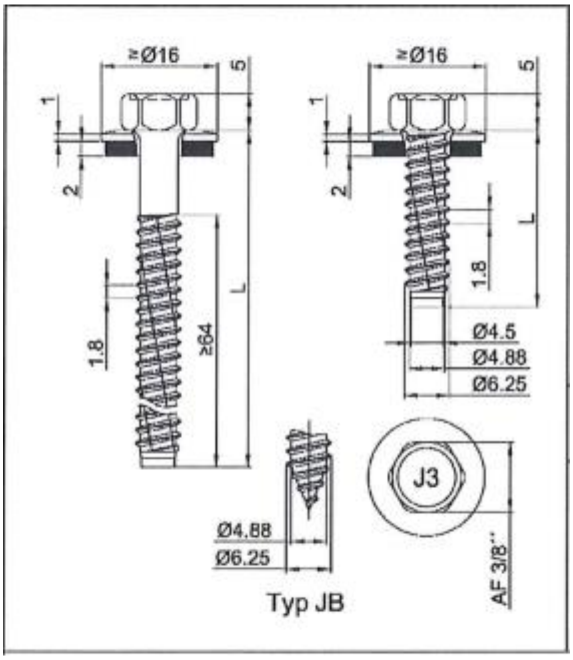


Figure 65: JZ3-6,3 xL (EJOT, 2020)

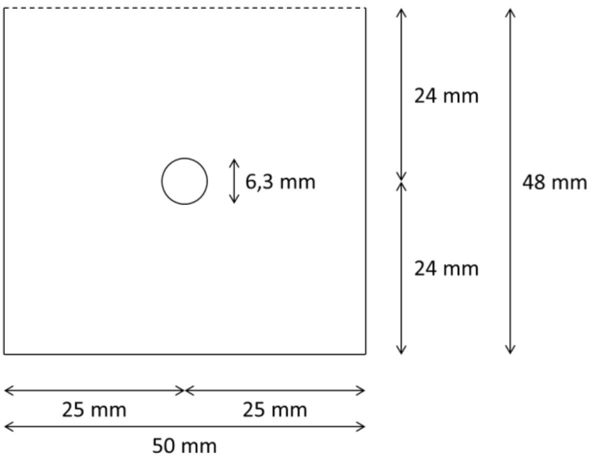


Figure 66: Dimensions support lip

Loads

The normative load on the support lip is wind suction, which acts in horizontal direction. When this surface load is simplified to a line load per trough, the magnitude is:

$$q_{ws;trough;k} = 0{,}38\ kN/m$$

Additionally, the self-weight of a segment of the element acts on the support lip in vertical direction. This self-weight is comprised of the weight of the trapezoidal sheet itself, the Z-girders, and the finishing element. The self-weight per support lip is:

$$F_{s;sw;k} = \frac{(G_t + G_z + G_f) * d}{2} = \frac{(0{,}28 + 0{,}12 + 0{,}26) * 0{,}280}{2} = 0{,}09\ kN$$

With G_t, G_z and G_f being the self-weight per meter of the trapezoidal sheet, Z-girders and finishing element.

Effects

The tensile force per support lip is:

$$F_{t;ws;k} = \frac{q_{ws;trough;k} * (b - b_f)}{2} = \frac{0{,}38 * (3500 - 100)}{2} = 0{,}65\ kN$$

$$F_{t;ws;d} = F_{t;ws;k} * \gamma_q = 0{,}65 * 1{,}35 = 0{,}88\ kN$$

The shear force per support lip is:

$$F_{s;sw;d} = F_{s;sw;k} * \gamma_q = 0{,}09 * 1{,}35 = 0{,}12\ kN$$

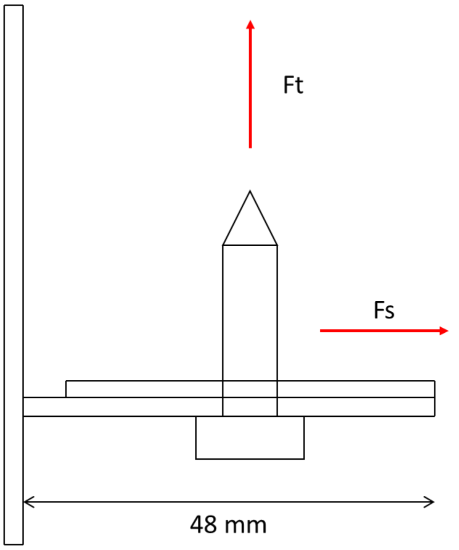


Figure 67: Effects on self-tapping screw

Resistance

For the bearing capacity of the connection, the capacity of the trapezoidal sheet is normative, since the thickness of the trapezoidal sheet (t_t = 0,75 mm) is lower that the thickness of the support lip (t = 2,2 mm):

$$F_{b;Rd} = \frac{\alpha * f_u * d * t_t}{\gamma_{m2}} = \frac{1{,}1 * 390 * 6{,}3 * 0{,}75}{1{,}25} = 1{,}63\ kN$$

The shear capacity of the self-tapping screw is:

$$F_{v;Rd} = \frac{\alpha_v * 0{,}25 * \pi * (d - 0{,}938194 * s)^2 * f_{ub}}{\gamma_{m2}} = \frac{0{,}50 * 0{,}25 * \pi * (6{,}3 - 0{,}938194 * 0{,}69)^2 * 515}{1{,}25} = 5{,}17\ kN$$

The pull capacity of the self-tapping screw is:

$$F_{t;Rd} = \frac{k_2 * f_{ub} * 0{,}25 * \pi * (d - 0{,}938194 * s)^2}{\gamma_{m2}}$$
$$= \frac{0{,}9 * 515 * 0{,}25 * \pi * (6{,}3 - 0{,}938194 * 0{,}69)^2}{1{,}25} = 9{,}31\ kN$$

The pull through capacity (static) of the support lip is:

$$F_{p1;Rd} = \frac{d_w * t * f_u}{\gamma_{m2}} = \frac{16 * 2{,}2 * 390}{1{,}25} = 10{,}98\ kN$$

The pull through capacity (dynamic) of the support lip is:

$$F_{p2;Rd} = \frac{F_{p1;Rd}}{2} = \frac{10{,}98}{2} = 5{,}49\ kN$$

The pull-out capacity of the self-tapping screw is:

$$F_{O;Rd} = \frac{0{,}65 * d * t_t * f_u}{\gamma_{m2}} = \frac{0{,}65 * 6{,}3 * 0{,}75 * 390}{1{,}25} = 0{,}96\ kN$$

In tension, the pull-out capacity of the self-tapping screw is normative. In shear, the bearing capacity of the trapezoidal sheet is normative.

$$uc = \frac{F_{v;Ed}}{F_{v;Rd}} = \frac{0{,}12}{1{,}63} = 0{,}07$$

$$uc = \frac{F_{t;Ed}}{F_{O;Rd}} = \frac{0{,}88}{0{,}96} = 0{,}92$$

For combined shear and tension, the unity check becomes:

$$\frac{F_{v;Ed}}{F_{v;Rd}} + \frac{F_{t;Ed}}{1{,}4 * F_{O;Rd}} = \frac{0{,}12}{1{,}63} + \frac{0{,}88}{1{,}4 * 0{,}96} = 0{,}73$$

Appendix F

Support lip liner tray

The liner trays are fastened to the support lip in a way similar to the fastening of the trapezoidal sheet to the support lip. Instead of the trough of the trapezoidal sheet, the liner trays are connected to the support lips at every corner of the profile. The dimensions of the support lip can be found in Figure 68. The self-tapping screws are of the same type as the self-tapping screws used for the trapezoidal sheet (Figure 65).

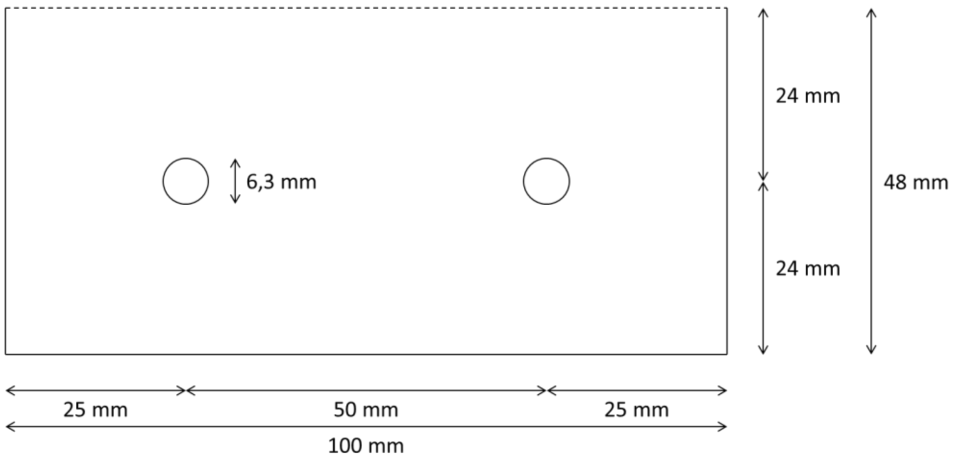


Figure 68: Dimensions support lip

Loads

The normative load on the support lip is wind suction, which acts in horizontal direction. When this surface load is simplified to a line load per liner tray, the magnitude is:

$$q_{ws;tray;k} = 0{,}69\ kN/m$$

Additionally, the self-weight of a segment of the element acts on the support lip in vertical direction. This self-weight is comprised of the weight of the liner tray itself, the Z-girders, and the finishing element. The self-weight per support lip is:

$$F_{s;sw;k} = \frac{\left(G_t + G_z + G_f\right) * 0{,}5}{2} = \frac{(0{,}31 + 0{,}12 + 0{,}26) * 0{,}5}{2} = 0{,}17\ kN$$

$$F_{s;sw;d} = F_{s;sw;k} * \gamma_q = 0{,}17 * 1{,}35 = 0{,}23\ kN$$

With G_t, G_z and G_f being the self-weight per meter of the trapezoidal sheet, Z-girders and finishing element.

Effects

The tensile force per support lip is:

$$F_{t;ws;k} = \frac{q_{ws;tray;k} * (b - b_f)}{2} = \frac{0{,}69 * (3500 - 100)}{2} = 1{,}16\ kN$$

$$F_{t;ws;d} = F_{t;ws;k} * \gamma_q = 1{,}16 * 1{,}35 = 1{,}57\ kN$$

This force is taken up by two screws per support lip. The tensile force per screw is:

$$F_{t;ws;d} = \frac{1{,}57}{2} = 0{,}79\ kN$$

The shear force per support lip is:

$$F_{s;sw;d} = F_{s;sw;k} * \gamma_q = 0{,}17 * 1{,}35 = 0{,}23\ kN$$

The shear force per screw is:

$$F_{s;sw;d} = \frac{0{,}23}{2} = 0{,}12\ kN$$

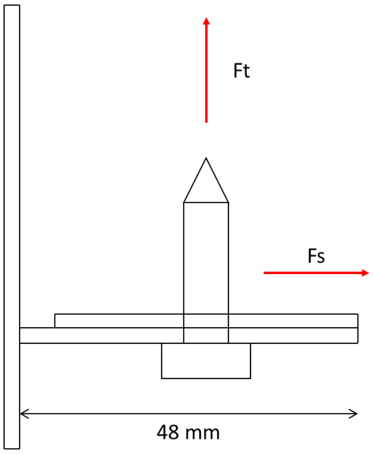


Figure 69: Effects on self-tapping screw

Resistance

The capacity of the self-tapping screws is similar to the self-tapping screws used to connect the trapezoidal sheet to the support lips, since the same screws are used, and the liner trays have the same thickness as the trapezoidal sheet.

In tension, the pull-out capacity of the self-tapping screw is normative. In shear, the bearing capacity of the liner tray is normative.

$$uc = \frac{F_{v;Ed}}{F_{v;Rd}} = \frac{0{,}12}{1{,}63} = 0{,}07$$

$$uc = \frac{F_{t;Ed}}{F_{O;Rd}} = \frac{0{,}79}{0{,}96} = 0{,}82$$

For combined shear and tension, the unity check becomes:

$$\frac{F_{v;Ed}}{F_{v;Rd}} + \frac{F_{t;Ed}}{1{,}4 * F_{O;Rd}} = \frac{0{,}12}{1{,}63} + \frac{0{,}79}{1{,}4 * 0{,}96} = 0{,}66$$

Appendix G

Cleat

In this calculation the cleat is divided in two parts: part 1 is the part which is connected to the main girder, part 2 is the part which is connected to the perpendicular girder. An overview of the dimensions of the two parts are displayed in Figure 70 and in Table 39.

The cleat is fastened to both girders by means of a blind rivet, which is placed through pre-drilled holes in the cleat and girders. Details on the blind rivets are displayed in Table 39 as well (Onkenhout Access & Fastening Solutions, 2020).

	Parameter	Value
Cleat	f_y	350 N/mm^2
	f_u	420 N/mm^2
	t_c	2 mm
Blind rivet	d	6,4 mm
	d_0	6,9 mm
	f_{ub}	510 N/mm^2
	$F_{u;Rd}$	6,56 kN
Part 1	p_1	50 mm
	p_2	90 mm
	e_1	20 mm
	e_2	20 mm
	No. of blind rivets	22
Part 2	e_1	20 mm
	e_2	24 mm
	p_1	50 mm
	No. of blind rivets	11

Table 39: Parameters cleat calculation

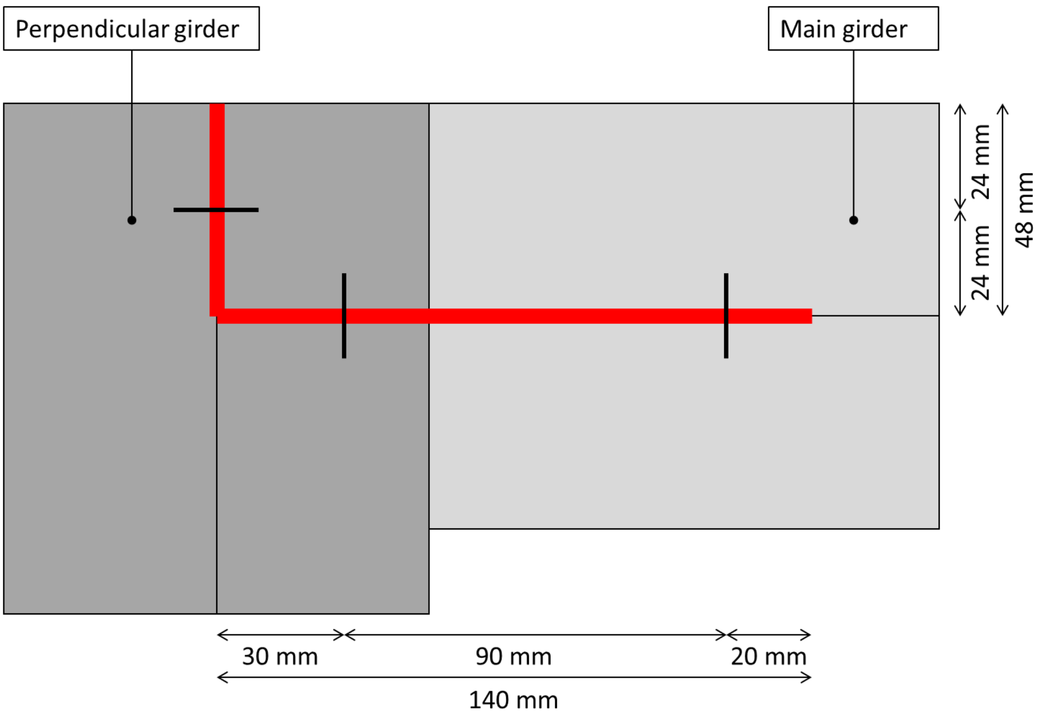


Figure 70: Dimensions cleat

Loads

The normative load on the cleat is wind suction. The load because of wind suction is:

$$V_{ws;Ed} = (q_{ws;d} * a)/2 = (3{,}24 * 16{,}5)/2 = 26{,}7\ kN$$

Effects

To perform a unity check for part 1 of the cleat, the forces in the outmost blind rivet of the rivet-group (point A) is calculated. This is the blind rivet which must resist the highest forces. The force in this point consists of a shear force, and a force due to a bending moment caused by eccentricity. The magnitude of this bending moment is:

$$M_{e;Ed} = V_{ws;Ed} * e = 26{,}7 * \left(30 + \frac{90}{2}\right) = 2002{,}5\ kNmm$$

This bending moment is divided over all the blind rivets in the group. The magnitude of the shear force per rivet depends on the distance of the rivet to the centre of the group. The distances to the centre of the group are displayed in Table 40.

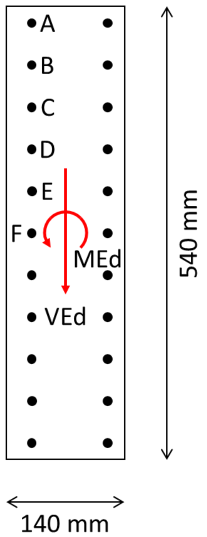


Figure 71: Effects on part 1

Point	**Distance to centre (i)**	**Distance to centre squared (i^2)**
	mm	mm^2
A	254	64525
B	205	42025
C	157	24525
D	110	12025
E	67	4525
F	45	2025

Table 40: Distance from blind rivet to the centre of the rivet group

Due to symmetry the total sum of i^2 is obtained by:

$$\sum i^2 = 4 * i_1^2 + 4 * i_2^2 + 4 * i_3^2 + 2 * i_4^2$$
$$= 4 * 64525 + 4 * 42025 + 4 * 24525 + 4 * 12025 + 4 * 4525 + 2 * 2025$$
$$= 598600\ mm^2$$

The shear force in point A (normative because of the largest distance) due to the bending moment is:

$$V_{ws;e;Ed} = (M_{e;Ed} * \frac{p_2}{2}) / \sum i^2 = (2002{,}5 * \frac{90}{2})/598600 = 0{,}15\ kN = 150\ N$$

The total shear force in point A is:

$$V_{A;Ed} = \frac{V_{ws;Ed}}{22} + V_{ws;e;Ed} = \frac{26{,}7}{22} + 0{,}15 = 1{,}36\ kN$$

For part 2, the force in all the blind rivets is equal since the force in these points only consists of a shear force. The magnitude of this force is:

$$V_{G;Ed} = \frac{V_{ws;Ed}}{11} = \frac{26{,}7}{11} = 2{,}43\ kN$$

Resistance

For part 1 of the cleat, the following calculations apply:

Check distance between centre of the holes:

$$p_1 = 50\ mm > 3 * d = 3 * 6{,}4 = 19{,}2\ mm$$

$$p_2 = 90\ mm > 3 * d = 3 * 6{,}4 = 19{,}2\ mm$$

Check end distance of the holes:

$$e_1 = e_2 = 20\ mm > 1{,}5 * d = 1{,}5 * 6{,}4 = 9{,}6\ mm$$

The tension resistance of the connected parts is:

$$N_{t;Rd} = \frac{f_y * A_g}{\gamma_{m;0}} = \frac{350 * 2 * 140}{1} = 98\ kN$$

The resistance of the net section is:

$$F_{n;Rd} = A_{net} * \frac{f_u}{\gamma_{m;2}} = (140 - 2 * 6{,}9) * 2 * \frac{420}{1{,}25} = 84{,}8\ kN$$

The bearing resistance per blind rivet is:

$$F_{b;Rd} = \frac{\alpha * f_u * d * t_c}{\gamma_{m;2}} = \frac{2{,}01 * 420 * 6{,}4 * 2}{1{,}25} = 8{,}64\ kN$$

with α equal to:

$$\alpha = 3{,}6 * \sqrt{\frac{t_c}{d}} = 3{,}6 * \sqrt{\frac{2}{6{,}4}} = 2{,}01$$

The total bearing resistance is:

$$F_{b;Rd;total} = 8{,}64 * 22 = 190{,}1\ kN$$

The shear resistance per blind rivet is:

$$F_{u;Rd} = 6{,}56\ kN$$

The total shear resistance is:

$$F_{u;Rd;total} = F_{u;Rd} * number\ of\ rivets = 6{,}56 * 22 = 144{,}3\ kN$$

The normative resistance of the total connection is $F_{n;Rd}$ = 84,8 kN

The unity check becomes:

$$uc = \frac{V_{Ed}}{V_{b;Rd}} = \frac{26,7}{84,8} = 0,31$$

The normative resistance of point A of the connection is $F_{u;Rd}$ = 6,56 kN

The unity check becomes:

$$uc = \frac{V_{Ed}}{F_{u;Rd}} = \frac{1,36}{6,56} = 0,21$$

For part 2 of the cleat, the following calculations apply:

Check distance between centre of the holes:

$$p_1 = 50\ mm > 3 * d = 3 * 6,4 = 19,2\ mm$$

Check end-distance of the holes:

$$e_1 = 24\ mm > 1,5 * d = 1,5 * 6,4 = 9,6\ mm$$

The tension resistance of the connected parts is:

$$N_{t;Rd} = \frac{f_y * A_g}{\gamma_{m;0}} = \frac{350 * 2 * 50}{1} = 35\ kN$$

The resistance of the net section is:

$$F_{n;Rd} = A_{net} * \frac{f_u}{\gamma_{m;2}} = (50 - 6,9) * 2 * \frac{420}{1,25} = 29,0\ kN$$

The bearing resistance per blind rivet is:

$$F_{b;Rd} = \frac{\alpha * f_u * d * t_c}{\gamma_{m;2}} = \frac{2,01 * 420 * 6,4 * 2}{1,25} = 8,64\ kN$$

The total bearing resistance is:

$$F_{b;Rd;total} = F_{b;Rd} * number\ of\ rivets = 8,64 * 11 = 95,0\ kN$$

The shear resistance per blind rivet is:

$$F_{u;Rd} = 6,56\ kN$$

The total shear resistance is:

$$F_{u;Rd;total} = F_{u;Rd} * number\ of\ rivets = 6,56 * 11 = 72,2\ kN$$

The normative resistance of the total connection is $F_{n;Rd}$ = 29,0 kN

The unity check becomes:

$$uc = \frac{V_{Ed}}{F_{n;Rd}} = \frac{26,7}{29,0} = 0,92$$

The normative resistance of one rivet is $F_{u;Rd}$ = 6,56 kN

The unity check becomes:

$$uc = \frac{V_{Ed}}{F_{u;Rd}} = \frac{2,43}{6,56} = 0,37$$

Appendix H

Hanging profile

The hanging profile is connected to the web of the perpendicular I-section by a total of 26 rivets. They arranged in two horizontal rows of 8 rivets with a centre to centre distance of 500 mm, and additional blind rivets at both ends. This is illustrated in Figure 72 and Table 41.

	Parameter	Value
Hanging profile	f_{yr}	350 N/mm^2
	f_u	420 N/mm^2
	t	2 mm
Blind rivet	d	6,4 mm
	d_0	6,9 mm
	f_{ub}	510 N/mm^2
	$F_{u;Rd}$	6,56 kN
Connection	p_1	300 mm
	p_2	500 mm
	e_1	20 mm
	e_2	20 mm
	No. of rivets	26

Table 41: Parameters hanging profile calculation

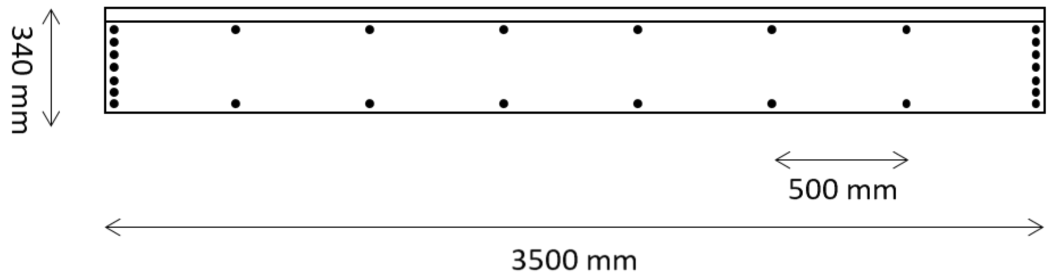


Figure 72: Hanging profile

Loads

The load because of self-weight is:

$$V_{sw;Ed} = \frac{Q_{g2;d} * a}{2} = \frac{1{,}19 * 16{,}5}{2} = 9{,}8\ kN$$

Here, self-weight of alternative 2 is used since the self-weight of both alternatives is similar (alternative 2 is only slightly heavier). The load because of wind suction (normative) is:

$$V_{ws;Ed} = \frac{q_{ws;d} * a}{2} = \frac{3{,}24 * 16{,}5}{2} = 26{,}7\ kN$$

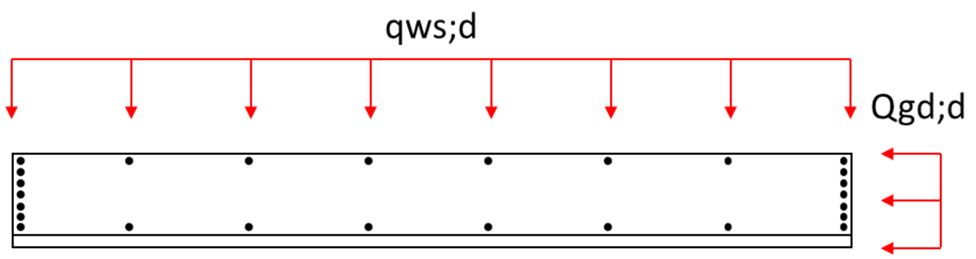


Figure 73: Loads on hanging profile

Effects

The shear force per blind rivet because of self-weight is:

$$F_{s;sw;Ed} = \frac{V_{sw;Ed}}{number\ of\ rivets} = \frac{9{,}8}{26} = 0{,}38\ kN$$

This force acts vertically. The load due to wind suction causes a shear- and tensile force on the blind rivets. The shear force per blind rivet because of wind suction is:

$$F_{s;ws;Ed} = \frac{2 * V_{ws;Ed}}{number\ of\ rivets} = \frac{2 * 26{,}7}{26} = 2{,}05\ kN$$

This force acts horizontally. Adding these two shear forces results in a total shear force of:

$$F_{s;Ed} = \sqrt{F_{s;sw;Ed}^2 + F_{s;ws;Ed}^2} = \sqrt{0{,}38^2 + 2{,}05^2} = 2{,}08\ kN$$

Additionally, the load due to wind suction causes a bending moment, which in its turn causes compression- and tension forces in the blind rivets. It is assumed that these forces are taken up by the 16 blind rivets with the largest distance to the centre of the group

The distance from top of L-profile (which is connected to the load bearing structure) to centre of the group is:

$$e_{rg} = 50 + 20 + (3 * 50) = 220\ mm$$

The distance from the point of connection to the main structure to the web of the L-profile is approximately 60 mm ("x"). Tensile force per blind rivet due to the resulting bending moment is:

$$F_{t;Ed} = \frac{2 * V_{Ed} * \left(\frac{x}{e_{rg}}\right)}{number\ of\ rivets} = \frac{2 * 26{,}7 * \left(\frac{60}{220}\right)}{16} = \ 0{,}91\ kN$$

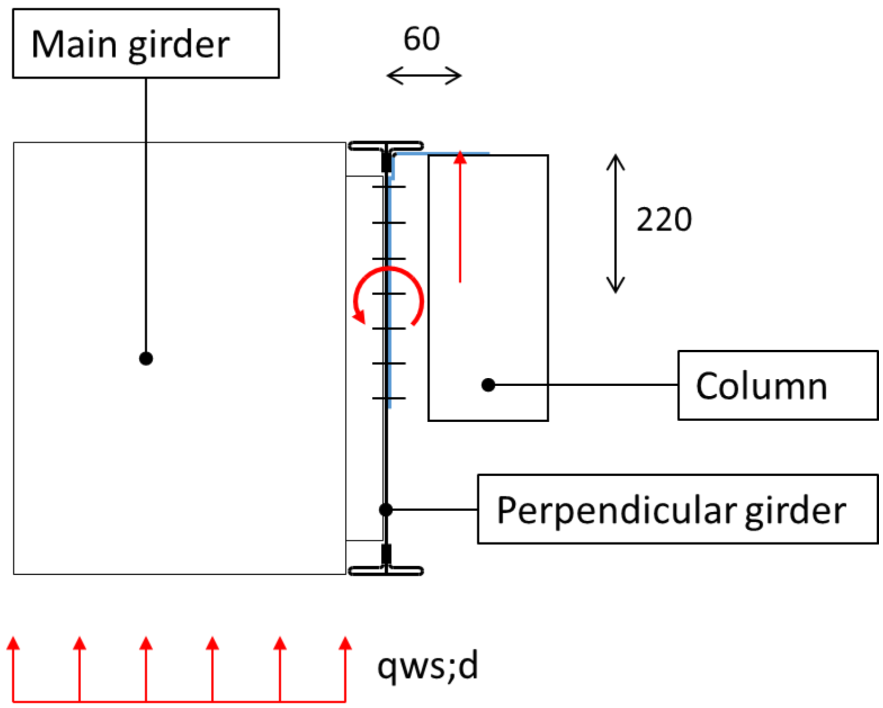


Figure 74: Effects on hanging profile

Resistance

The bearing capacity per blind rivet is:

$$F_{b;Rd} = \frac{\alpha * f_u * d * t_c}{\gamma_{m;2}} = \frac{2{,}01 * 420 * 6{,}4 * 2}{1{,}25} = 8{,}64\ kN$$

The total bearing capacity is:

$$F_{b;Rd;total} = F_{b;Rd} * number\ of\ rivets = 8{,}64 * 26 = 225\ kN$$

The shear capacity per blind rivet is:

$$F_{u;Rd} = 6{,}56\ kN$$

The total shear capacity is:

$$F_{u;Rd;total} = F_{u;Rd} * number\ of\ rivets = 6{,}56 * 26 = 171\ kN$$

The tensile capacity per rivet is:

$$F_{p;Rd} = 2{,}22\ kN$$

The unity check for combined shear and tension on one rivet becomes:

$$uc = \frac{V_{1;Ed}}{F_{u;Rd}} + \frac{F_{t;Ed}}{F_{p;Rd}} = \frac{2{,}08}{6{,}56} + \frac{0{,}91}{2{,}22} = 0{,}73$$

Appendix I

Connection to load bearing structure

The hanging detail is connected to the load bearing structure using shot fired pins of the type Hilti X-EM10H P10 (Hilti, 2017). Details are found in Table 42 and Figure 75.

	Parameter	Value
Hanging profile	f_{yr}	350 N/mm^2
	f_u	420 N/mm^2
	t	2 mm
Hilti X-EM10H P10	Shank d_s	4,5 mm
	Shank L_s	12 mm
	N_{rec}	2,4 kN
	V_{rec}	2,4 kN
Connection	p_1	125 mm
	e_1	62 mm
	e_2	80 mm
	No. of connectors	28

Table 42: Calculation parameters connection to load bearing structure

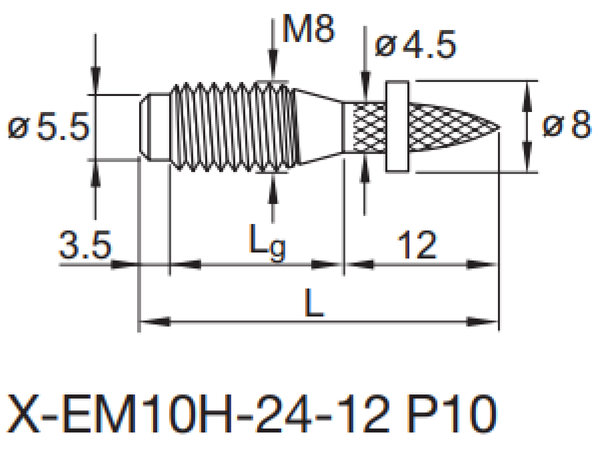


Figure 75: Hilti X-EM10H P10

Loads

The load because of self-weight is:

$$V_{sw;Ed} = \frac{Q_{g2;d} * a}{2} = \frac{1{,}19 * 16{,}5}{2} = 9{,}8\ kN$$

The load because of wind suction is:

$$q_{ws;d} = \frac{Q_{ws;d} * a}{2} = \frac{1{,}85 * 16{,}5}{2} = 15{,}3\ kN/m$$

Effects

The shear force per connector because of self-weight is:

$$F_{s;sw;Ed} = \frac{V_{sw;Ed}}{number\ of\ connectors} = \frac{9{,}8}{28} = 0{,}35\ kN$$

This force acts vertically.

The tensile force per connector because of wind suction is:

$$F_{t;ws;Ed} = \frac{q_{ws;d} * 3{,}5}{number\ of\ connectors} = \frac{15{,}3 * 3{,}5}{28} = 1{,}91\ kN$$

This force acts horizontally.

Resistance

The minimum edge and distance spacing of the connectors are 15 millimetres (Hilti, 2017).

Check distance between centre of the connectors:

$$p_1 = 125\ mm > 15\ mm$$

Check end distance of the connectors:

$$e_1 = 62\ mm > 15\ \ mm$$

The bearing capacity per connector is:

$$F_{b;Rd} = \frac{\alpha * f_u * d * t_c}{\gamma_{m;2}} = \frac{1 * 420 * 4{,}5 * 2}{1{,}25} = 3{,}0\ kN$$

The shear capacity per connector is:

$$V_{rec} = 2{,}4\ kN$$

The tensile capacity per connectors is:

$$N_{Rec} = 2{,}4\ kN$$

The unity check for combined shear and tension is:

$$uc = \frac{F_{s;sw;Ed}}{V_{rec}} + \frac{F_{t;ws;Ed}}{N_{rec}} = \frac{0{,}35}{2{,}4} + \frac{1{,}91}{2{,}4} = 0{,}94$$

Appendix J

Insulation anchors

In case study alternative 1 the insulation anchors are connected at every other trough, which means every 560 mm in horizontal direction. In case study alternative 2 the insulation anchors are connected at every web of the liner trays, which means every 500 mm in horizontal direction. The distance between insulation anchors in vertical direction is 500 mm in both case study alternatives. The insulation anchors consist of a plastic insulation plug with an integrated helicoil, and a stainless-steel anchor which is drilled through the glass wool and the trapezoidal sheet or liner tray. A picture of the insulation plug is displayed in Figure 76.

Figure 76: Insulation plug

Loads

The normative wind load on the anchors is:

$$Q_{ws;d} = 1{,}85\ \frac{kN}{m^2}$$

Effects

The effective area per anchor for case study alternative 1 is:

$$A_{eff} = 560 * 500 = 0{,}28\ m^2$$

The tensile force per anchor is:

$$F_{Ed;t} = A_{eff} * Q_{ws;d} = 0{,}28 * 1{,}85 = 0{,}52\ kN$$

The effective area per anchor for case study alternative 2 is:

$$A_{eff} = 500 * 500 = 0{,}25\ m^2$$

The tensile force per anchor is:

$$F_{Ed;t} = A_{eff} * Q_{ws;d} = 0{,}25 * 1{,}87 = 0{,}47\ kN$$

Resistance

The tensile resistance per insulation anchor is (CFP Engineering, 2019):

$$F_{t;anchor} = 550\ N$$

$$uc1 = \frac{0{,}52}{0{,}55} = 0{,}95$$

$$uc2 = \frac{0{,}47}{0{,}55} = 0{,}85$$

Appendix K

Finishing element

The sinusoidal sheet finishes the element and seals the insulation material in between the trapezoidal sheet or liner trays, and itself. Figure 77 displays a horizontal section of case study alternative 1 and 2. The finishing elements are connected to the horizontal Z-girders with a self-tapping screw every 500 mm in horizontal direction. The length of every finishing element is 10,5 m (the height of three prefab elements) and the width is 988 mm (standard width of a SAB 18/988 profile).

These self-tapping screws resist horizontal (wind)loads. To resist vertical (self-weight)loads, the bottom of every finishing element is fastened to the concrete plinth.

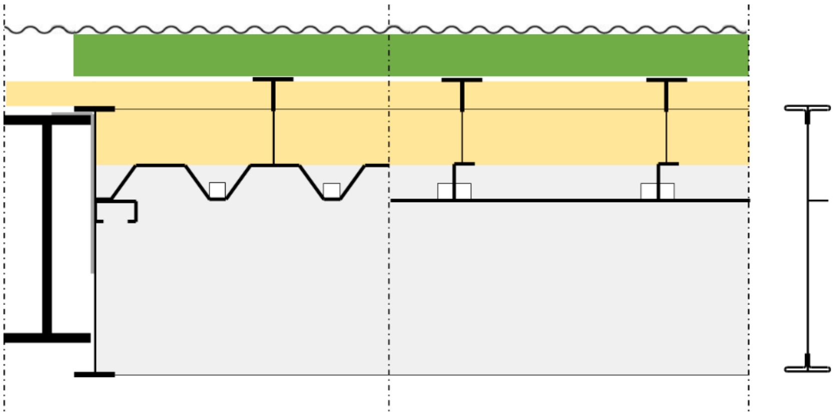


Figure 77: Horizontal section of the façade element (alternative 1 on the left, alternative 2 on the right)

Appendix L

Plinth

A concrete core insulated wall is used as the plinth of the façade. The height of this plinth is 3 m. Figure 78displays a section of the core insulated wall. It consists of:

- A structural panel which is connected to the foundation and the columns of the load bearing structure.
- An architectural panel which is attached to the structural panel with thermal anchors.
- Insulation material in between the two panels.

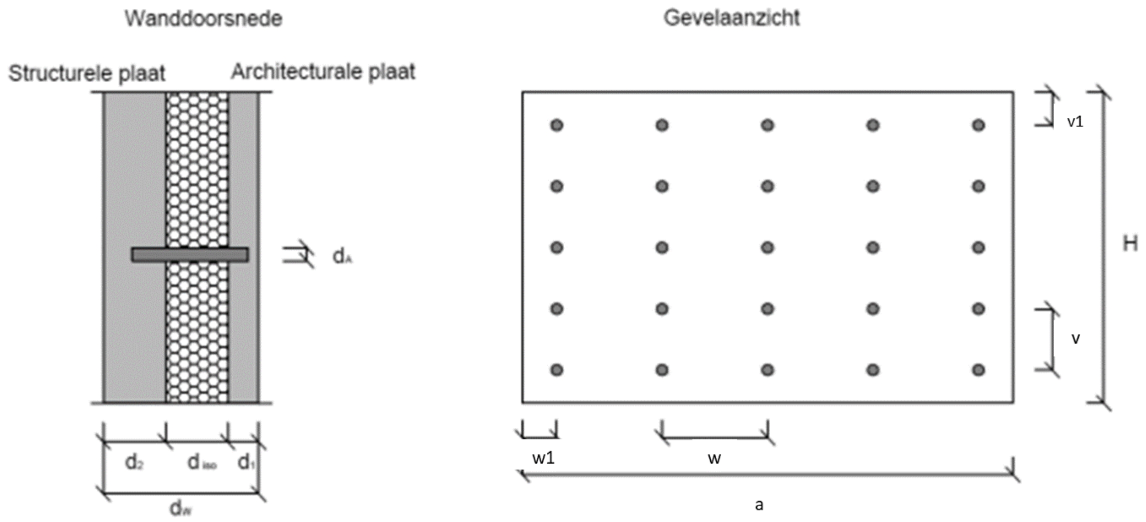


Figure 78: Core insulated wall

The parameters of the core insulated wall are displayed in Table 43.

Parameter	Length (mm)
d_a	12
d_1	90
d_{iso}	100
d_2	150
d_w	340
w	400
w_1	200
v	400
v_1	200
a	16500
H	3000

Table 43: Dimensions of the core insulated wall

Both architectural and structural panels are reinforced with a reinforcement mesh B500 Ø 10 mm. Properties of the concrete and reinforcement is displayed in Table 44.

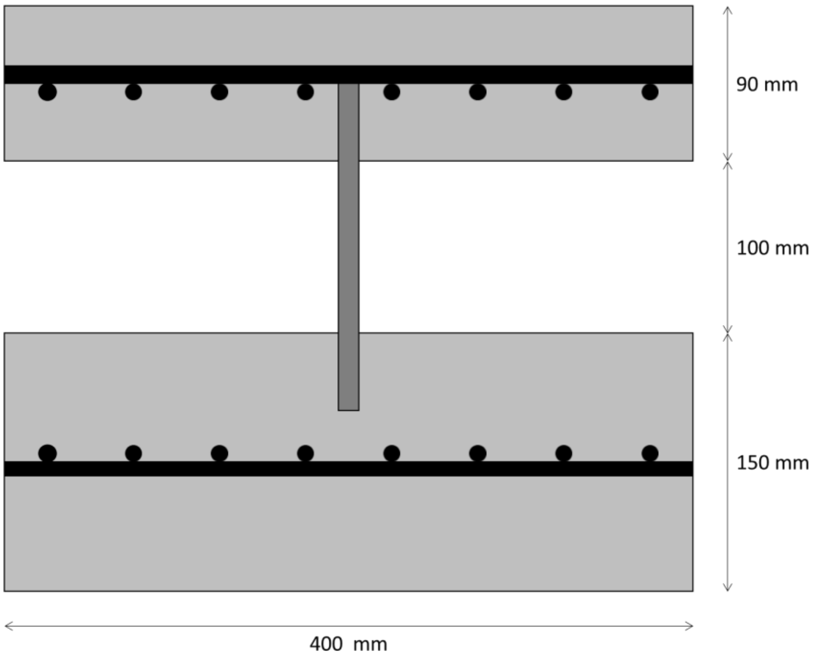


Figure 79: Wall segment (h=400 mm)

	Parameter	Value
Reinforcement (B500)	d_r	10 mm
	f_{yd}	435 N/mm^2
	c.t.c. 1	50 mm
	c.t.c. 2	100 mm
	c_1	35 mm
	c_2	65 mm
Concrete (C30/37)	f_{ck}	30 N/mm^2
	f_{cd}	20 N/mm^2
	E_{cm}	32837 N/mm^2
	f_{ctd}	1.35 N/mm^2
	ρ_{min} (%)	0,151
	$\rho_{w,min}$ (%)	0,088

Table 44: Concrete and reinforcement properties

Loads

The normative load on the plinth is wind suction. Per segment with a height of 400 mm, the characteristic load per meter is:

$$q_{ws;k} = Q_{ws;k} * 400 * 10^{-3} = 1{,}37 * 400 * 10^{-3} = 0{,}55 \frac{kN}{m}$$

Effects

The maximum bending moment in the middle of the span is:

$$M_{Ed} = \frac{1}{8} * q_{ws;k} * a^2 = \frac{1}{8} * (1{,}35 * 0{,}55) * 16{,}5^2 = 25{,}3\ kNm$$

The maximum deflection is:

$$\delta_{max} = \frac{l}{150} = \frac{16500}{150} = 110\ mm$$

Resistance

The distance from the outside pane of the architectural panel to the normal force centre is:

$$z_c = \frac{400 * 90 * 45 + 400 * 150 * 265}{400 * 90 + 400 * 150} = 183\ mm$$

In this calculation, the thermal anchors are not considered when calculating the moment of inertia of the segment. The moment of inertia of the wall when no composite action is assumed is:

$$I_{ync} = \frac{1}{12} * 400 * 90^3 + \frac{1}{12} * 400 * 150^3 = 136800000\ mm^4$$

The moment of inertia of the wall when full composite action is assumed is:

$$I_{yc} = \frac{1}{12} * 400 * 90^3 + 400 * 90 * 138^2 + \frac{1}{12} * 400 * 150^3 + 400 * 150 * 82^2$$
$$= 1225800000\ mm^4$$

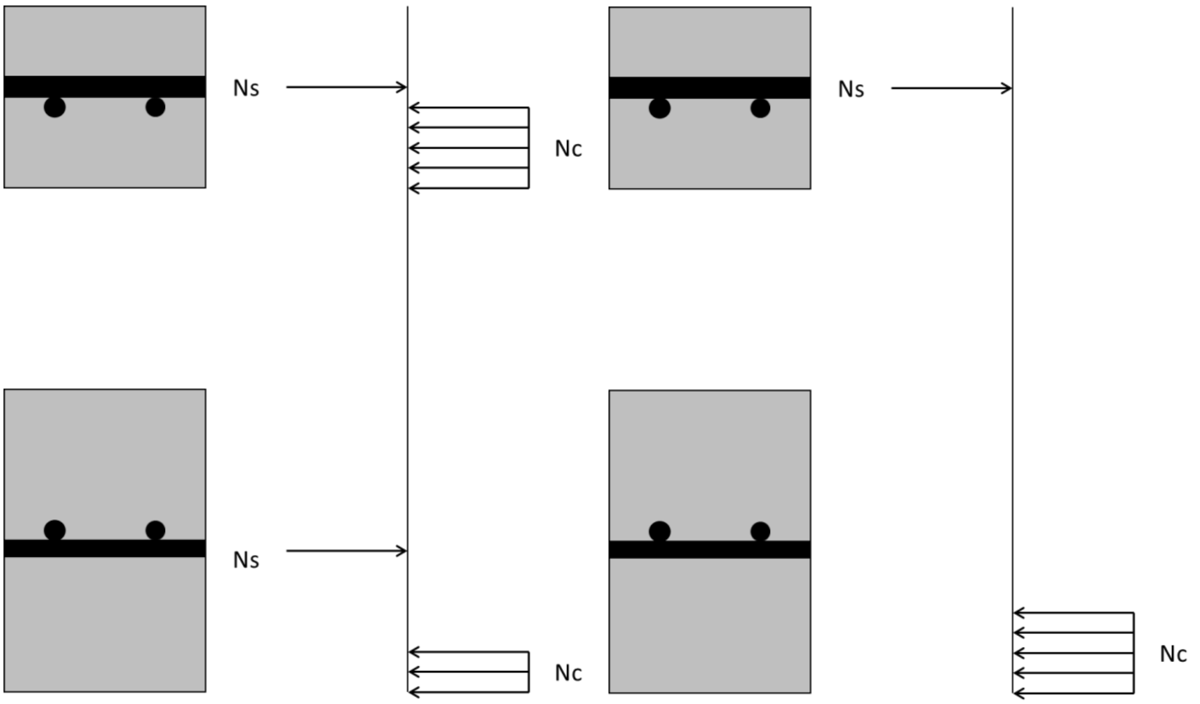


Figure 80: Composite (right) and non-composite behaviour (left)

First, the bending moment resistance of the panel is calculated assuming non-composite behaviour. The horizontal forces in both upper (1) and lower (2) cross section must be in equilibrium, so:

$$N_{c1} = N_{s1}$$

$$N_{c2} = N_{s2}$$

The tensile force in the longitudinal reinforcement in the architectural panel is:

$$N_{s1} = A_{s1} * f_y = 785 * 435 = 273319\ N = 273.3\ kN$$

With the area of the reinforcement:

$$A_{s1} = \frac{1}{4} * \pi * d_r^2 * \frac{400}{c.t.c.} = \frac{1}{4} * \pi * 10^2 * \frac{400}{50} = 628\ mm^2$$

The compression force in the architectural panel is:

$$N_{c1} = f_{cd} * \alpha * h * x_{u1}$$

This means that the height of the compressive area must be at least:

$$x_{u1} = \frac{N_{s1}}{f_{cd} * \alpha * h} = \frac{273319}{20 * 0,75 * 400} = 45,6\, mm$$

This will not fit into the architectural panel, because:

$$x_{u1} = 45,6\, mm < c_1 = 35\, mm$$

So, the height of the compressive area is taken as 35 mm.

$$M_{Rd,1} = N_{s1} * z_1 = 273319 * 36.0 * 10^{-6} = 9,8\, kNm$$

With z_1 being the internal lever arm, in this case:

$$z_1 = c_1 + (3 * d_r/2) - 0.4 * x_{u1} = 35 + (3 * 10/2) - 0,4 * 35 = 36,0\, mm$$

The tensile force in the longitudinal reinforcement in the structural panel is:

$$N_{s2} = A_{s2} * f_y = 314 * 435 = 136659\, N = 136,7\, kN$$

With the area of the reinforcement:

$$A_{s2} = \frac{1}{4} * \pi * d_r^2 * \frac{400}{c.t.c.} = \frac{1}{4} * \pi * 10^2 * \frac{400}{100} = 314\, mm^2$$

The compression force in the structural panel is:

$$N_{c2} = f_{cd} * \alpha * h * x_{u2}$$

This means that the height of the compressive area must be at least:

$$x_{u2} = \frac{N_{s2}}{f_{cd} * \alpha * h} = \frac{136659}{20 * 0,75 * 400} = 22,8\, mm$$

This will fit into the structural panel, because:

$$x_{u2} = 22,8\, mm < c_2 = 65\, mm$$

$$M_{Rd,2} = N_{s2} * z_2 = 136659 * 60,9 * 10^{-6} = 8,3\, kNm$$

With z_2 being:

$$z_2 = c_2 + \left(\frac{d_r}{2}\right) - 0.4 * x_{u2} = 65 + (\frac{10}{2}) - 0,4 * 22,8 = 60,9\, mm$$

The moment resistance of the wall is the combined moment resistance of the two panels:

$$M_{Rd,totaal} = M_{Rd,1} + M_{Rd,2} = 9,8 + 8,3 = 18,2\, kNm$$

$$uc = \frac{M_{Ed}}{M_{Rd,totaal}} = \frac{25,3}{18,2} = 1,39$$

The deflection of the wall becomes:

$$\delta = \frac{5}{384} * \frac{q_{ws;k} * a^4}{E_c * I_{y1}} = \frac{5}{384} * \frac{0{,}55 * 16500^4}{33000 * 136800000} = 118\,mm$$

$$uc = \frac{\delta}{\delta_{max}} = \frac{118}{110} = 1{,}07$$

This means that when the wall is non-composite, it will not suffice.

Now, the bending moment resistance of the panel is calculated, assuming full-composite behaviour. The horizontal forces in both upper and lower cross section must be in equilibrium, so:

$$N_c = N_s$$

The tensile force in the longitudinal reinforcement in the architectural panel is:

$$N_s = A_s * f_y = 628 * 435 = 273319\,N = 273{,}3\,kN$$

With the area of the reinforcement:

$$A_s = \frac{1}{4} * \pi * d_r^2 * \frac{400}{c.t.c.} = \frac{1}{4} * \pi * 10^2 * \frac{400}{50} = 628\,mm^2$$

The compression force in the structural panel is:

$$N_c = f_{cd} * \alpha * h * x_u$$

This means that the height of the compressive area must be at least:

$$x_u = \frac{N_s}{f_{cd} * \alpha * h} = \frac{273319}{20 * 0{,}75 * 400} = 45{,}6\,mm$$

This will not fit into the architectural panel, because:

$$x_{u1} = 45{,}6\,mm < c_1 = 35\,mm$$

So, the height of the compressive area is taken as 35 mm.

$$M_{Rd} = N_s * z = 273319 * 286 * 10^{-6} = 78{,}2\,kNm$$

With z being:

$$z = d_1 + d_{iso} + d_2 - c_1 - \left(\frac{d_r}{2}\right) - 0.4 * x_u = 90 + 100 + 150 - 35 - (\frac{10}{2}) - 0{,}4 * 35 = 286\,mm$$

$$uc = \frac{M_{Ed}}{M_{Rd}} = \frac{25{,}3}{78{,}2} = 0{,}32$$

The deflection of the wall becomes:

$$\delta = \frac{5}{384} * \frac{q_{ws;k} * a^4}{E_c * I_{y2}} = \frac{5}{384} * \frac{0{,}55 * 16500^4}{33000 * 1225800000} = 13\,mm$$

This means that when the wall is full-composite, it will suffice. In reality, the behaviour of the wall is partially composite. To calculate the behaviour under partially composite action, it is assumed that the composite action gradient K is 0,5. The formula for K is:

$$\mathrm{K} = \frac{I_\kappa - I_{NC}}{I_C - I_{NC}}$$

$$M_K = \frac{M_\kappa - M_{NC}}{M_C - M_{NC}}$$

The moment of inertia of the wall under partially composite action becomes:

$$I_\kappa = I_{NC} * \left(K * (I_C - I_{NC})\right) = 136800000 + \left(0{,}5 * (1225800000 - 136800000)\right) = 681300000\ mm^4$$

The bending moment resistance under partially composite action is:

$$M_\kappa = M_{NC} * \left(\kappa * (M_C - M_{NC})\right) = 18{,}2 + \left(0{,}5 * (78{,}2 - 18{,}2)\right) = 48{,}2\ kNm$$

$$uc = \frac{25{,}3}{48{,}2} = 0{,}52$$

The deflection of the wall becomes:

$$\delta = \frac{5}{384} * \frac{q_{ws\prime k} * a^4}{E_c * I_\kappa} = \frac{5}{384} * \frac{0{,}55 * 16500^4}{33000 * 681300000} = 24\ mm$$

$$uc = \frac{24}{110} = 0{,}22$$

This means that when the grade of composite action is 50%, it will suffice.

Appendix M

Diaphragm action

The diaphragm action in the façade element is analysed by calculating the elements resistance to shear force. The publication *RMBS 2000 Richtlijnen voor toepassing van metalen beplating als schijfconstructie* is used for this calculation (Bouwen met Staal, 2004). First the resistance and deflection of a single element of case study alternative 1 is calculated. Then the resistance of a single element of case study alternative 2 is estimated.

Case study alternative 1

In Table 45, the calculation parameters for the calculation of the diaphragm action are displayed.

Symbol	Value	Unit
a	16500	mm
A	2509	mm^2
b	3500	mm
d	280	mm
E	210	kN/mm^2
$F_{p;u;d}$	3,50	kN
$F_{s;u;d}$	1,84	kN
$F_{sc;u;d}$	3,50	kN
h	83	mm
K_1	0,108	
R	119	mm
n_b	1	
n_f	5	
n_p	2	
n_s	9	
n_{sc}	9	
n'_{sc}	9	
n_{sh}	15	
p	280	mm
s_p	0,15	mm/kN
s_s	0,25	mm/kN
s_{sc}	0,15	mm/kN
t	0,75	mm
$f_{y;d}$	0,32	kN/mm^2
α_1	1,00	
α_2	1,00	
α_3	1,00	
α_4	1,30	
β_1	1,13	
β_2	1,25	
β_3	1,00	

Table 45: Calculation parameters diaphragm action

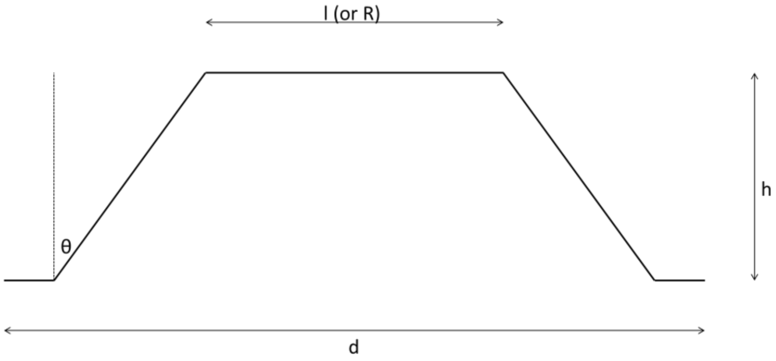


Figure 81: Parameters trapezoidal sheet

$$F_{p;u;d} = 1{,}9 * f_t * d_n * t = 1{,}9 * 0{,}39 * 6{,}3 * 0{,}75 = 3{,}50\ kN$$

$$F_{s;u;d} = 2{,}9 * \left(\frac{t}{d_n}\right)^{0,5} * f_t * d_n * t = 2{,}9 * \left(\frac{0{,}75}{6{,}3}\right)^{0,5} * 0{,}39 * 6{,}3 * 0{,}75 = 1{,}84\ kN$$

$$\frac{l}{d} = \frac{119}{280} = 0{,}425$$

$$\frac{h}{d} = \frac{83}{280} = 0{,}30$$

Interpolation between the values for l/d = 0,40 and l/d = 0,50 results in:

$$K_1 = 0{,}093 + (0{,}151 - 0{,}093) * 0{,}25 = 0{,}108$$

$$n_s = n_{sc} = n'_{sc} = \left(\frac{h_e}{h.o.h.}\right) - 1 = \left(\frac{3500}{3500}\right) - 1 = 9$$

Loads

The load that must be resisted by diagram action is the self-weight of the panel. The magnitude of this load is:

$$q_{g1;d} = 1{,}16 \frac{kN}{m}$$

Effects

The magnitude of the shear force caused by this load is:

$$V_{h;Ed} = 0{,}5 * q_{g1;d} * \frac{a * n}{1000} = 0{,}5 * 1{,}16 * \left(\frac{16500 * 1}{1000}\right) = 9{,}6\ kN$$

Resistance

The capacity of the longitudinal seam is:

$$V_{u;d1} = n_s * F_{s;u;d} + \frac{\beta_1}{\beta_3} * n_p * F_{p;u;d} = 9 * 1{,}84 + \frac{1{,}13}{1{,}0} * 2 * 3{,}50 = 24{,}5\ kN$$

The capacity of the shear panel is:

$$V_{u;d2} = n_{sc} * F_{sc;u;d} = 9 * 3{,}50 = 31{,}5\ kN$$

$$V_{v;u;d} = \min\left(V_{u;d1}; V_{u;d2}\right) = \min(24{,}5; 31{,}5) = 24{,}5\ kN$$

The capacity of the connection of the sheeting (shear + prying force) is:

$$\frac{0{,}6 * b * F_{p;u;d}}{p * \alpha_3} = \frac{0{,}6 * 3500 * 3{,}50}{280 * 1{,}0} = 26{,}3\ kN \geq V_{u;d}$$

The capacity of the connection between the end support and sheeting is:

$$\frac{0{,}9 * t * \sqrt{t} * b * f_{y;d}}{\sqrt{d}} = \frac{0{,}9 * 0{,}75 * \sqrt{0{,}75} * 3500 * 0{,}320}{\sqrt{280}} = 39{,}1\ kN \geq V_{v;u;d}$$

The shear capacity of the longitudinal seam is normative, so:

$$V_{u;d} = 24{,}5\ kN$$

The unity check is:

$$uc = \frac{V_{h;Ed}}{V_{u;d}} = \frac{9{,}6}{24{,}5} = 0{,}39$$

Deflection

The total deformation of the element is due to multiple factors. The factor of contribution of bending deformation of the trapezoidal sheet is:

$$c_{1,1} = \frac{a * d^2 * \sqrt{d} * \alpha_1 * \alpha_4 * K}{E * t^2 * \sqrt{t} * b^2} = \frac{16500 * 280^2 * \sqrt{280} * 1{,}0 * 1{,}3 * 0{,}108}{210 * 0{,}75^2 * \sqrt{0{,}75} * 3500^2} = 2{,}425$$

The factor of contribution of shear strain of the trapezoidal sheet is:

$$c_{1,2} = \frac{2 * a * \alpha_2 * (1 + \upsilon) * \left(1 + \left(2 * \frac{h}{d}\right)\right)}{E * t * b} = \frac{2 * 16500 * 1{,}0 * (1 + 0{,}3) * \left(1 + \left(2 * \left(\frac{83}{280}\right)\right)\right)}{210 * 0{,}75 * 3500} = 0{,}124$$

The factor of contribution of slip of the connection between the trapezoidal sheet and the main girder is:

$$c_{2,1} = \frac{2 * a * s_p * p * \alpha_3}{b^2} = \frac{2 * 16500 * 0{,}15 * 280 * 1{,}0}{3500^2} = 0{,}113$$

The factor of contribution of slip of the connection between the different segments of the trapezoidal sheeting is:

$$c_{2,2} = \frac{s_s * s_p * (n_{sh} - 1)}{n_s * s_p + \beta_1 * s_s} = \frac{0{,}25 * 0{,}15 * (15 - 1)}{9 * 0{,}15 + 1{,}13 * 0{,}25} = 0{,}322$$

The factor of contribution of slip of the connection between the trapezoidal sheeting and the element is:

$$c_{2,3} = \frac{4 * (n + 1) * s_{sc}}{n^2 * n'_{sc}} = \frac{4 * (1 + 1) * 0{,}15}{1^2 * 9} = 0{,}133$$

The factor of contribution of axial strain in the girders is:

$$c_3 = \frac{n^2 * a^3 * \alpha_3}{4{,}8 * E * A * b^2} = \frac{1^2 * 16500^3 * 1{,}0}{4{,}8 * 210 * 2509 * 3500^2} = 0{,}145$$

The total flexibility due to shear is:

$$c' = c_{1,1} + c_{1,2} + c_{2,1} + c_{2,2} + c_{2,3} = 2{,}425 + 0{,}124 + 0{,}113 + 0{,}322 + 0{,}133 = 3{,}117$$

The total flexibility of the element is:

$$c = c' + c_3 = 3{,}117 + 0{,}145 = 3{,}262$$

The deflection of the element is:

$$\delta = \left(\frac{a}{1000} * q_{Ed}\right) * \frac{n^2}{8} * c = \left(\frac{16500}{1000} * 1{,}16\right) * \left(\frac{1^2}{8} * 3{,}262\right) = 7{,}8\, mm$$

Case study alternative 2

The diaphragm action of liner trays which span vertically is not covered in the RMBS 2000, so a simplified calculation of a single panel is made, disregarding the factors α and β.

Loads

The load that must be resisted by diagram action is the self-weight of the panel. The magnitude of this load is:

$$q_{g2;d} = 1{,}19 \frac{kN}{m}$$

Effects

The magnitude of the shear force caused by this load is:

$$V_{h;Ed} = 0{,}5 * q_{g2;d} * \frac{a * n}{1000} = 0{,}5 * 1{,}19 * \left(\frac{16500 * 1}{1000}\right) = 9{,}8\, kN$$

Resistance

The capacity of the longitudinal seam is:

$$V_{u;d1} = n_s * F_{s;u;d} + n_p * F_{p;u;d} = 9 * 1{,}84 + 2 * 3{,}50 = 23{,}6\, kN$$

The capacity of the shear panel is:

$$V_{u;d2} = n_{sc} * F_{sc;u;d} = 9 * 3{,}50 = 31{,}5\, kN$$

$$V_{v;u;d} = \min(V_{u;d1}; V_{u;d2}) = \min(23{,}6; 31{,}5) = 23{,}6\, kN$$

The capacity of the connection of the liner trays (shear + prying force) is:

$$\frac{0{,}6 * b * F_{p;u;d}}{p} = \frac{0{,}6 * 3500 * 3{,}50}{280} = 26{,}3\, kN \geq V_{u;d}$$

The capacity of the connection between the end support and liner tray is:

$$\frac{0{,}9 * t * \sqrt{t} * b * f_{y;d}}{\sqrt{d}} = \frac{0{,}9 * 0{,}75 * \sqrt{0{,}75} * 3500 * 0{,}320}{\sqrt{280}} = 39{,}1 \geq V_{v;u;d}$$

The unity check is:

$$uc = \frac{V_{h;Ed}}{V_{u;d}} = \frac{9{,}8}{23{,}6} = 0{,}42$$

Appendix N

Traditional façade system

Sandwich panel

SAB W 100.1000 SL – Double span of 3,5 m (2 x 1,75 m)

- Wind pressure of 1,45 kN/m^2: maximum span of 5,75 m
- Wind suction of 1,85 kN/m^2: maximum span of 4,54 m

Main girder

C 250.50.15 – 2 – c.t.c. 1,75 m

- W_y = 43969 mm^3
- I_y = 6037361 mm^4

Loads

$$q_{Ed} = Q_{ws;d} * c.t.c. = 1{,}85 * 1{,}75 = 3{,}24 \frac{kN}{m}$$

$$V_{Ed} = \frac{1}{2} * q * l = \frac{1}{2} * 3{,}24 * 5{,}5 = 8{,}9\ kN$$

$$M_{Ed} = \frac{1}{8} * q * l^2 = \frac{1}{8} * 3{,}24 * 5{,}5^2 = 12{,}3\ kNm$$

$$\delta = \frac{5}{384} * \frac{q * l^4}{E * I_y} = \frac{5}{384} * \frac{(1{,}37 * 1{,}75) * 5500^4}{210000 * 6037361} = 22{,}5\ mm$$

Resistance

$$V_{Rd} = 9{,}6\ kN$$

$$M_{Rd} = W_y * f_y = 43969 * 350 = 15{,}4\ kNm$$

$$\delta_{max} = \frac{l}{150} = \frac{5500}{150} = 36{,}7\ mm$$

$$uc = \frac{V_{Ed}}{V_{Rd}} = \frac{8{,}9}{9{,}6} = 0{,}93$$

$$uc = \frac{M_{Ed}}{M_{Rd}} = \frac{12{,}3}{15{,}4} = 0{,}80$$

$$uc = \frac{\delta}{\delta_{max}} = \frac{22{,}5}{36{,}7} = 0{,}61$$

Column

IPE 400 – c.t.c. 5,5 m

- W_y = 1156*10^3 mm^3
- I_y = 23128*10^4 mm^4

Loads

$$q_{Ed} = Q_{ws;d} * c.t.c. = 1{,}85 * 5{,}5 = 10{,}18 \frac{kN}{m}$$

$$V_{Ed} = \frac{1}{2} * q * l = \frac{1}{2} * 10{,}18 * 13{,}5 = 68{,}7\ kN$$

$$M_{Ed} = \frac{1}{8} * q * l^2 = \frac{1}{8} * 10{,}18 * 13{,}5^2 = 231{,}9\ kNm$$

$$\delta = \frac{5}{384} * \frac{q * l^4}{E * I} = \frac{5}{384} * \frac{(1{,}37 * 5{,}5) * 13500^4}{210000 * 231280000} = 67{,}1\ mm$$

Resistance

$$\begin{aligned} A_v &= \max\left(A - 2 * b * t_f + (t_w + 2 * r) * t_f, 1.2 * t_w * h_w\right) \\ &= \max(8446 - 2 * 180 * 13{,}5 + (8{,}6 + 2 * 21) * 13{,}5\ ;\ 1{,}2 * 8{,}6 * 400) \\ &= \max(4269; 4128\ ) = 4269\ mm^2 \end{aligned}$$

$$V_{Rd} = A_v * \frac{f_{yd}}{\sqrt{3}} = 4269 * \frac{355}{\sqrt{3}} = 875\ kN$$

$$M_{Rd} = W_{y;e} * f_y = 1156000 * 355 = 410{,}4\ kNm$$

$$\delta_{max} = \frac{l}{150} = \frac{13500}{150} = 90{,}0\ mm$$

$$uc = \frac{M_{Ed}}{M_{Rd}} = \frac{231{,}9}{410{,}4} = 0{,}57$$

$$uc = \frac{V_{Ed}}{V_{Rd}} = \frac{68{,}7}{875} = 0{,}08$$

$$uc = \frac{\delta}{\delta_{max}} = \frac{67{,}1}{90} = 0{,}75$$

Appendix O

Life Cycle Assessment

Transport												
	Exhaustion abiotic raw materials (Sb eq)	Exhaustion fossil energy carriers (Sb eq)	Climate change (CO_2 eq)	Affecting ozone layer (CFK-11 eq)	Photochemical oxidant formation (C_2H_4 eq)	Acidification (SO_2 eq)	Eutrophication (PO_4 eq)	Human toxicity (1,4-DCB eq)	Fresh water aquatic ecotoxicity (1,4-DCB eq)	Marine aquatic ecotoxicity (1,4-DCB eq)	Terrestrial ecotoxicity (1,4-DCB eq)	Total
Weight factor (€/kg)	0,16	0,16	0,05	30	2	4	9	0,09	0,03	1 E-04	0,06	
Transport 900t (kg/tkm)	3,75 E-07	9,72 E-04	1,32 E-01	2,43 E-08	7,77 E-05	5,71 E-04	1,14 E-04	5,27 E-02	1,55 E-03	5,58 E+00	1,87 E-04	
Environmental costs (€/tkm)	6,00 E-08	1,56 E-04	6,58 E-03	7,29 E-07	1,55 E-04	2,28 E-03	1,03 E-03	4,74 E-03	4,64 E-05	5,58 E-04	1,12 E-05	0,016

Table 46: Environmental costs transport

Production												
	Exhaustion abiotic raw materials (Sb eq)	Exhaustion fossil energy carriers (Sb eq)	Climate change (CO_2 eq)	Affecting ozone layer (CFK-11 eq)	Photochemical oxidant formation (C_2H_4 eq)	Acidification (SO_2)	Eutrophication (PO_4 eq)	Human toxicity (1,4-DCB eq)	Fresh water aquatic ecotoxicity (1,4-DCB eq)	Marine aquatic ecotoxicity (1,4-DCB eq)	Terrestrial ecotoxicity (1,4-DCB eq)	Total
Weight factor (€/kg)	0,16	0,16	0,05	30	2	4	9	0,09	0,03	1 E-04	0,06	
329 Steel (heavy) (kg/kg)	-1,34 E-07	5,21 E-03	9,08 E-01	1,55 E-08	3,30 E-04	3,38 E-03	3,74 E-04	3,33 E-02	3,02 E-03	6,34 E+00	4,68 E-04	
Environmental costs (€/kg)	-2,14 E-08	8,34 E-04	4,54 E-02	4,65 E-07	6,60 E-04	1,35 E-02	3,37 E-03	3,00 E-03	9,06 E-05	6,34 E-04	2,81 E-05	0,068
330 Steel (light-weight) (kg/kg)	2,31 E-06	1,35 E-02	2,50 E+00	1,96 E-08	1,17 E-03	6,63 E-03	6,11 E-04	5,24 E-02	4,53 E-03	1,06 E+01	9,95 E-04	
Environmental costs (€/kg)	3,70 E-07	2,16 E-03	1,25 E-01	5,88 E-07	2,34 E-03	2,65 E-02	5,50 E-03	4,72 E-03	1,36 E-04	1,06 E-03	5,97 E-05	0,167
331 Steel (medium) (kg/kg)	2,44 E-07	1,40 E-02	2,59 E+00	1,02 E-08	1,23 E-03	6,63 E-03	6,00 E-04	1,16 E-01	2,92 E-03	1,33 E+01	9,99 E-04	
Environmental costs (€/kg)	3,90 E-08	2,24 E-03	1,30 E-01	3,06 E-07	2,46 E-03	2,65 E-02	5,40 E-03	1,04 E-02	8,76 E-05	1,33 E-03	5,99 E-05	0,178
208 PUR (kg/kg)	5,41 E-06	4,28 E-02	4,48 E+00	4,81 E-08	3,76 E-03	1,83 E-02	2,35 E-03	4,18 E-01	3,74 E-02	5,64 E+01	6,92 E-03	
Environmental costs (€/kg)	8,66 E-07	6,85 E-03	2,24 E-01	1,44 E-06	7,52 E-03	7,32 E-02	2,11 E-02	3,76 E-02	1,12 E-03	5,64 E-03	4,15 E-04	0,378
074 Glass wool (kg/kg)	5,50 E-06	1,05 E-02	1,20 E+00	2,51 E-07	9,55 E-04	8,92 E-03	2,81 E-03	6,73 E-01	2,27 E-02	4,78 E+01	4,81 E-03	
Environmental costs (€/kg)	8,80 E-07	1,68 E-03	5,99 E-02	7,53 E-06	1,91 E-03	3,57 E-02	2,53 E-02	6,05 E-02	6,80 E-04	4,78 E-03	2,89 E-04	0,191

Table 47: Environmental costs production

Waste processing												
	Exhaustion abiotic raw materials (Sb eq)	Exhaustion fossil energy carriers (Sb eq)	Climate change (CO_2 eq)	Affecting ozone layer (CFK-11 eq)	Photochemical oxidant formation (C_2H_4 eq)	Acidification (SO_2)	Eutrophication (PO_4 eq)	Human toxicity (1,4-DCB eq)	Fresh water aquatic ecotoxicity (1,4-DCB eq)	Marine aquatic ecotoxicity (1,4-DCB eq)	Terrestrial ecotoxicity (1,4-DCB eq)	Total
Weight factor (€/kg)	0,16	0,16	0,05	30	2	4	9	0,09	0,03	1 E-04	0,06	
329 Steel (heavy) (kg/kg)	9,55 E-08	-2,72 E-03	-5,12 E-01	-3,72 E-09	-1,84 E-04	-1,51 E-03	-1,53 E-04	-8,85 E-03	-1,87 E-03	-1,78 E+00	-1,40 E-04	
Environmental costs (€/kg)	1,53 E-08	-4,35 E-04	-2,56 E-02	-1,12 E-07	-3,68 E-04	-6,04 E-03	-1,38 E-03	-7,97 E-04	-5,61 E-05	-1,78 E-04	-8,40 E-06	- 0,035
330 Steel (light-weight) (kg/kg)	-2,15 E-06	-8,13 E-03	-1,64 E+00	5,16 E-09	-8,32 E-04	-3,06 E-03	-1,75 E-04	5,64 E-03	-2,10 E-03	1,11 E+00	3,87 E-05	
Environmental costs (€/kg)	-3,44 E-07	-1,30 E-03	-8,20 E-02	1,55 E-07	-1,66 E-03	-1,22 E-02	-1,58 E-03	5,08 E-04	-6,30 E-05	1,11 E-04	2,32 E-06	- 0,098
331 Steel (medium) (kg/kg)	-2,89 E-07	-8,14 E-03	-1,66 E+00	7,00 E-09	-8,79 E-04	-2,96 E-03	-1,96 E-04	3,39 E-03	-9,23 E-04	1,65 E+00	1,38 E-04	
Environmental costs (€/kg)	-4,62 E-08	-1,30 E-03	-8,30 E-02	2,10 E-07	-1,76 E-03	-1,18 E-02	-1,76 E-03	3,05 E-04	-2,77 E-05	1,65 E-04	8,28 E-06	- 0,099
020 PUR (stort) (kg/kg)	1,19 E-08	1,08 E-04	1,07 E-01	2,60 E-09	2,46 E-05	5,73 E-05	3,50 E-05	6,84 E-03	5,19 E-03	5,34 E+00	1,70 E-05	
Environmental costs (€/kg)	1,90 E-09	1,72 E-05	5,37 E-03	7,80 E-08	4,92 E-05	2,29 E-04	3,15 E-04	6,15 E-04	1,56 E-04	5,34 E-04	1,02 E-06	0,007
013 Glass wool (stort) (kg/kg)	4,61 E-09	6,65 E-05	4,30 E-03	1,70 E-09	4,66 E-06	3,16 E-05	6,68 E-06	1,90 E-03	4,62 E -05	1,55 E-01	4,38 E-06	
Environmental costs (€/kg)	7,38 E-10	1,06 E-05	2,15 E-04	5,10 E-08	9,32 E-06	1,26 E-04	6,01 E-05	1,71 E-04	1,39 E-06	1,55 E-05	2,63 E-07	0,001

Table 48: Environmental costs waste processing

Appendix P

Material Circularity Indicator

Component	M	F_R	F_U	V	C_R	C_U	E_C	E_F	W_0	W_C	W_F	W	LFI_c	L	L_{av}	U	U_{av}	X_c	MCI_c
	(kg)	(-)	(-)	(kg)	(-)	(-)	(-)	(-)	(kg)	(kg)	(kg)	(kg)	(-)	(yrs)	(yrs)	(-)	(-)	(-)	(-)
Column	3650	0,5	0	1825	0,51	0,49	0,92	0,92	0	157	168	162	0,27	100	100	1	1	1	0,755
Main girder	658	0,5	0	329	0,87	0,12	0,92	0,92	7	48	30	46	0,29	50	50	1	1	1	0,742
Inside plate	576	0,5	0	288	0,87	0,12	0,92	0,92	6	42	26	40	0,29	20	20	1	1	1	0,742
Outside plate	992	0,5	0	496	0,87	0,12	0,92	0,92	10	73	46	69	0,29	20	20	1	1	1	0,742
PIR Insulation	658	0,0	0	658	0,1	0	0,30	0,30	593	46	0	616	0,98	20	20	1	1	1	0,114

Table 49: Material Circularity Indicator traditional facade

Component	M	F_R	F_U	V	C_R	C_U	E_C	E_F	W_0	W_C	W_F	W	LFI_c	L	L_{av}	U	U_{av}	X_c	MCI_c
	(kg)	(-)	(-)	(kg)	(-)	(-)	(-)	(-)	(kg)	(kg)	(kg)	(kg)	(-)	(yrs)	(yrs)	(-)	(-)	(-)	(-)
Column	2916	0,5	0	1458	0,51	0,49	0,92	0,92	0	125	134	130	0,27	100	100	1	1	1	0,755
Main girder	1950	0,5	0	975	0,87	0,12	0,92	0,92	20	143	90	136	0,29	50	50	1	1	1	0,742
Perpendicular girder	414	0,5	0	207	0,87	0,12	0,92	0,92	4	30	19	29	0,29	50	50	1	1	1	0,742
Perpendicular C-profile	73	0,5	0	37	0,87	0,12	0,92	0,92	1	5	3	5	0,29	50	50	1	1	1	0,742
Trapezoidal sheet	1367	0,5	0	683	0,87	0,12	0,92	0,92	14	100	63	95	0,29	50	50	1	1	1	0,742
Insulation material	998	0,7	0	299	0,1	0	0,99	0,99	898	1	7	902	0,60	50	50	1	1	1	0,459
Cleat	19	0,5	0	10	0,87	0,12	0,92	0,92	0	1	1	1	0,29	50	50	1	1	1	0,742
Hanging profile	174	0,5	0	87	0,87	0,12	0,92	0,92	2	13	8	12	0,29	50	50	1	1	1	0,742
Girders	713	0,5	0	356	0,87	0,12	0,92	0,92	7	52	33	50	0,29	50	50	1	1	1	0,742
Sinusoidal sheet	1291	0,5	0	645	0,87	0,12	0,92	0,92	13	95	59	90	0,29	20	20	1	1	1	0,742

Table 50: Material Circularity Indicator case study alternative 1

Component	M	F_R	F_U	V	C_R	C_U	E_C	E_F	W_0	W_C	W_F	W	LFI_c	L	L_{av}	U	U_{av}	X_c	MCI_c
	(kg)	(-)	(-)	(kg)	(-)	(-)	(-)	(-)	(kg)	(kg)	(kg)	(kg)	(-)	(yrs)	(yrs)	(-)	(-)	(-)	(-)
Column	2916	0,5	0	1458	0,51	0,49	0,92	0,92	0	125	134	130	0,27	100	100	1	1	1	0,755
Main girder	1950	0,5	0	975	0,87	0,12	0,92	0,92	20	143	90	136	0,29	50	50	1	1	1	0,742
Perpendicular girder	414	0,5	0	207	0,87	0,12	0,92	0,92	4	30	19	29	0,29	50	50	1	1	1	0,742
Perpendicular C-profile	73	0,5	0	37	0,87	0,12	0,92	0,92	1	5	3	5	0,29	50	50	1	1	1	0,742
Liner tray	1530	0,5	0	765	0,87	0,12	0,92	0,92	15	112	70	107	0,29	50	50	1	1	1	0,742
Insulation material	998	0,7	0	299	0,1	0	0,99	0,99	898	1	7	902	0,60	50	50	1	1	1	0,459
Cleat	19	0,5	0	10	0,87	0,12	0,92	0,92	0	1	1	1	0,29	50	50	1	1	1	0,742
Hanging profile	174	0,5	0	87	0,87	0,12	0,92	0,92	2	13	8	12	0,29	50	50	1	1	1	0,742
Girders	713	0,5	0	356	0,87	0,12	0,92	0,92	7	52	33	50	0,29	50	50	1	1	1	0,742
Sinusoidal sheet	1291	0,5	0	645	0,87	0,12	0,92	0,92	13	95	59	90	0,29	20	20	1	1	1	0,742

Table 51: Material Circularity Indicator case study alternative 2

Appendix Q

Design circularity Indicator

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	1	1	1	1	1	0,5	1	0,8	1	1	0,717
Main girder	1	0,2	1	1	1	0,8	0,5	0,1	1	0,5	1	0,8	1	1	0,578
Inside plate	0,1	1	0,8	0,6	0,1	1	1	1	0,4	0,5	1	0,1	0,1	0,5	0,435
Outside plate	0,1	1	0,8	0,6	0,1	1	1	1	0,4	0,5	1	0,1	0,1	0,5	0,435
PIR Insulation	0,1	1	0,8	0,6	0,1	1	1	0,1	0,1	0,5	1	0,1	0,1	0,1	0,054

Table 52: Design Circularity Indicator traditional façade with original DfD factors

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	0,9	0,6	0,9	0,9	0,9	0,1	0,8	0,8	0,9	0,8	0,626
Main girder	1	0,6	1	1	0,9	0,6	0,4	0,2	0,9	0,1	0,8	0,8	0,9	0,8	0,530
Inside plate	0,2	1	0,9	0,8	0,5	0,6	0,9	0,9	0,6	0,1	0,8	0,1	0,1	0,5	0,424
Outside plate	0,2	1	0,9	0,8	0,5	0,6	0,9	0,9	0,6	0,1	0,8	0,1	0,1	0,5	0,424
PIR Insulation	0,2	1	0,9	0,8	0,5	0,6	0,9	0,2	0,1	0,1	0,8	0,1	0,1	0,1	0,052

Table 53: Design Circularity Indicator traditional façade with alternative DfD factors

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	1	1	1	1	1	0,5	1	0,8	1	1	0,717
Main girder	1	0,2	1	1	0,1	1	1	0,4	1	1	1	0,8	0,8	0,5	0,572
Perpendicular girder	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Perpendicular C-profile	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Trapezoidal sheet	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Insulation material	1	1	1	1	0,1	1	1	1	1	1	0,5	1	0,8	1	0,407
Cleat	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Hanging profile	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Girders	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Sinusoidal sheet	1	1	0,8	0,6	0,1	0,8	1	1	0,4	1	1	0,8	1	1	0,609

Table 54: Design Circularity Indicator case study alternative 1 with original DfD factors

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	0,9	0,6	0,9	0,9	0,9	0,1	0,8	0,8	0,9	0,8	0,626
Main girder	1	0,6	1	1	0,5	0,6	0,9	0,6	0,9	0,8	0,8	0,8	0,8	0,5	0,572
Perpendicular girder	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Perpendicular C-profile	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Trapezoidal sheet	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Insulation material	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,5	0,8	0,8	0,8	0,377
Cleat	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Hanging profile	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Girders	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Sinusoidal sheet	1	1	0,9	0,8	0,5	0,6	0,9	0,9	0,6	0,8	0,8	0,8	0,9	0,8	0,599

Table 55: Design Circularity Indicator case study alternative 1 with alternative DfD factors

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	1	1	1	1	1	0,5	1	0,8	1	1	0,717
Main girder	1	0,2	1	1	0,1	1	1	0,4	1	1	1	0,8	0,8	0,5	0,572
Perpendicular girder	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Perpendicular C-profile	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Liner tray	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Insulation material	1	1	1	1	0,1	1	1	1	1	1	0,5	1	0,8	1	0,407
Cleat	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Hanging profile	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Girders	1	1	1	1	0,1	1	1	1	1	1	1	0,8	0,8	0,5	0,647
Sinusoidal sheet	1	1	0,8	0,6	0,1	0,8	1	1	0,4	1	1	0,8	1	1	0,609

Table 56: Design Circularity Indicator case study alternative 2 with original DfD factors

	Functional decomposition		Life cycle coordination		Assembly	Geometry						Connections			
	Functional separation	Functional autonomy	Life cycle of components irt assembly sequence	Life cycle of components irt size	Assembly direction	Type	Position relative to building structure	Geometry horizontal edge	Geometry vertical edge	Separation of finishing	Standardisation of product edge	Type of connection	Accessibility of connections	Tolerances	DCI_c
Column	1	1	1	1	0,9	0,6	0,9	0,9	0,9	0,1	0,8	0,8	0,9	0,8	0,626
Main girder	1	0,6	1	1	0,5	0,6	0,9	0,6	0,9	0,8	0,8	0,8	0,8	0,5	0,572
Perpendicular girder	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Perpendicular C-profile	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Liner tray	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Insulation material	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,5	0,8	0,8	0,8	0,377
Cleat	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Hanging profile	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Girders	1	1	1	1	0,5	0,6	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,5	0,609
Sinusoidal sheet	1	1	0,9	0,8	0,5	0,6	0,9	0,9	0,6	0,8	0,8	0,8	0,9	0,8	0,599

Table 57: Design Circularity Indicator case study alternative 2 with alternative DfD factors

Appendix R

Façade Circularity Indicator

	Element	Component	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
			Original DfD factors			Alternative DfD factors		
Scenario				1	2		1	2
Load bearing structure	Column	-	0,401	0,044	0,061	0,350	0,039	0,053
Secondary structure	Main girder	-	0,058	0,026	0,059	0,053	0,024	0,054
Finishing element	Sandwich panel	Inside plate	0,038	0,048	0,044	0,037	0,047	0,043
		Outside plate	0,066	0,083	0,075	0,064	0,081	0,073
		PIR Insulation	0,005	0,032	0,029	0,005	0,031	0,028
Total			0,569	0,233	0,267	0,510	0,221	0,251

Table 58: Facade Circularity Indicator traditional façade

	Element	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
		Original DfD factors			Alternative DfD factors		
Scenario			1	2		1	2
Load bearing structure	Column	0,211	0,044	0,061	0,184	0,038	0,053
Secondary structure	Main girder	0,113	0,094	0,097	0,113	0,094	0,097
	Perpendicular girder	0,027	0,022	0,023	0,025	0,021	0,022
	Perpendicular support	0,005	0,004	0,004	0,005	0,004	0,004
	Trapezoidal sheet	0,089	0,084	0,085	0,084	0,079	0,080
	Insulation material	0,041	0,091	0,087	0,038	0,084	0,081
	Cleat	0,001	0,001	0,001	0,001	0,001	0,001
	Hanging profile	0,011	0,009	0,010	0,011	0,009	0,009
	Z-Girders	0,046	0,039	0,040	0,044	0,036	0,038
Finishing element	Sinusoidal sheet	0,079	0,186	0,171	0,078	0,183	0,168
Total		0,624	0,574	0,578	0,582	0,549	0,552

Table 59: Facade Circularity Indicator case study alternative 1

	Element	FCI (M)	FCI (EC)	FCI (EC)	FCI (M)	FCI (EC)	FCI (EC)
		Original DfD factors			Alternative DfD factors		
Scenario			1	2		1	2
Load bearing structure	Column	0,208	0,043	0,060	0,181	0,038	0,052
Secondary structure	Main girder	0,111	0,092	0,095	0,111	0,092	0,095
	Perpendicular girder	0,027	0,022	0,023	0,025	0,021	0,021
	Perpendicular support	0,005	0,004	0,004	0,004	0,004	0,004
	Liner tray	0,098	0,092	0,094	0,093	0,087	0,089
	Insulation material	0,040	0,089	0,086	0,037	0,083	0,080
	Cleat	0,001	0,001	0,001	0,001	0,001	0,001
	Hanging profile	0,011	0,009	0,010	0,011	0,009	0,009
	Z-Girders	0,046	0,038	0,039	0,043	0,036	0,037
Finishing element	Sinusoidal sheet	0,078	0,184	0,168	0,077	0,180	0,165
Total		0,624	0,575	0,579	0,583	0,550	0,553

Table 60: Facade Circularity Indicator case study alternative 2