A SUSTAINABLE AND REUSABLE CONCRETE FACADE SYSTEM

An approach to improve the use of concrete in the Dutch housing market

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COLOPHON

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PREFACE

Since I was little, I had a passion for building and I wanted to start the bachelor study Architecture. Through the years studying Architecture, I became more aware of topics such as sustainability and accompanying problems we are experiencing today. This is why I chose the subject of reuse and sustainability of concrete as my graduation topic. The thesis is meant for people working in the built environment and having the same vision as I have: working towards a more sustainable construction sector.

I would like to start by thanking my family and friends for their continuous support. Most of all, I would like to thank my mentors, who have supported me with their knowledge in the field of design for deconstruction, circularity and prefab concrete, and for their great understanding of the circumstances in which my thesis was made.

I hope you enjoy reading my thesis!

Lieve Croonen
Delft, November 2020

EXECUTIVE SUMMARY

The use of concrete in the construction sector is in need of change. Concrete is one of the most used and energy-demanding materials in the world due to its cement production. It plays a major role in producing CO2 emissions, demolition waste and depletion of materials. Unfortunately, this is not likely to change over time due to its popularity in the construction sector. It is therefore important to think about circularity and lose the loop of these materials by reusing concrete.

Because the Netherlands has the ambition to build 1 million houses by 2030 and concrete is dominant in the Dutch construction environment, it offers the opportunity to tackle the concrete in this sector and to apply concepts such as reuse and standardization. Unfortunately, concrete is currently not being used optimally, while it has a long lifespan and the potential to be reused. However, reusing concrete remains challenging as it is often not designed to be disassembled and reassembled. Also, the focus must be on making the concrete itself more sustainable, by looking at the production process and methods that reduce, capture or store CO2 emissions. In this way, it can bring us a step closer to reduce global warming.

Purpose and methodology
The main goal of this study is to provide a design strategy that gives insight on how to design a sustainable and reusable concrete facade system. This is researched by means of a literature study, analyses of case studies and research through design. This will finally conclude in a final design strategy. The literature study focuses on the concepts of reuse, standardization, modularity and sustainability of concrete, and will conclude in a list of technical and design criteria that form the basis for the design of a sustainable and reusable concrete facade system. Furthermore, two different case studies have been conducted, one of which examines standardization in the current housing market and has to conclude which dimensions are best for a standardized facade system. The other analysis looks at existing modular building systems that are assessed on the basis of the established criteria. The findings of both analyses will be added to the final technical and design criteria. Then the design process can be initiated and this research through design will lead to a final design strategy.

Main findings
To design a sustainable and reusable concrete facade system for the Dutch housing market, strategies have to be used that focus on the aspects *building efficiency, standardization, sustainability and adaptability*. The three main strategies that focus on these aspects and form the final design strategy are: **Rethink, Reduce and Reuse**. The process begins with **Rethink**. Firstly, designing the facade system for repeated use, through *standardization*, and finding the best suitable dimensions for the facade system. Secondly, by increasing its *functional flexibility and adaptability* by designing it for multiple uses and target audiences. Standardization is needed when designing a product for repeated use where repetition provides improved quality, better quality control, faster production time, lower costs, and a safer work environment. The second strategy, **Reduce**, helps the design to reduce waste, material and CO2 emissions. Firstly, by researching how to make concrete more *sustainable*. Secondly, by *building lightweight* through the use of a lightweight shape and material, such as lightweight aggregate concrete. At last, the strategy of **Reuse** will come into play where *modularity* forms the basis for a reusable design that focuses on the *building efficiency* by means of the concept of design for disassembly.

Conclusion
It will all conclude in the final design strategy that consists of a decision chart that guides the architect or client and offers multiple options of building systems. This enables the architect or client to have design freedom while providing an easy guide that helps to choose a building system. In order to successfully implement a sustainable and reusable concrete facade system, it is recommended to present a good business case that focuses on the barrier of reuse and how these can be best resolved.

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INTRODUCTION

This chapter will describe the thoughts behind the topic and its main problem. From the main problem several subproblems can be formulated that will lead to different research and design questions. To answer these questions a fitting methodology approach needs to be used and will be described. Finally the societal and scientific relevance and its importance will be explained.

1.1 Background

For years, mankind has extracted many materials such as oil, gas and coal to meet demands, and at the rate that we are now consuming, many of these materials will disappear in 30-40 years. Materials such as wood and food are renewable, but oil and coal do not have this property and will eventually be exhausted. The demand for these materials will not decrease and as these materials are a big part of the building environment, it is important to think about circularity and close the loop of these materials. A lot of research development is needed to understand the reuse of waste products as well as design tools to work towards a circular economy.

The construction sector in Europe is responsible for 38 percent of the total waste production, 40 percent of the CO2 emissions and 50 percent of all-natural resources *(Durmisevic, Beurskens, Adrosevic, & Westerdijk, 2017, p. 274)(Figure 1)*. The consumption, there is now a shortage in the housing market and due to the high expected population growth, 822 thousand people between 2018 and 2035, the plan is to build 1 million homes before 2030 (*ABF Research, 2018; Van Wijnen, 2019)*. Besides, many homes will have to be demolished or replaced due to higher demands placed on the built environment by the government and may, therefore, be higher than based on trends *(ABF Research, 2018)*. It is important to tackle this sector now that a lot of new construction is being produced. In recent years, several companies (Smartcrusher with Smartbreak, Smartliberator, New Horizon, etc.) are already busy thinking about how concrete can best be reused to reduce the environmental impact of it. For example, they came up with a new technique to make concrete fully circular by breaking the concrete in a way that all the materials can be reused again and no waste

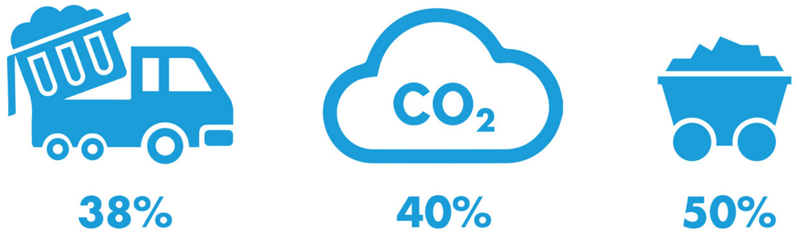


Figure 1: Total waste production, CO2 emissions and use of all-natural resources in the construction sector in Europe. Source: (own ill.)

demand for raw materials for building assignments, a large amount of (demolition) waste from the construction industry, and the impact of the construction sector on greenhouse gas emissions require a more efficient and sustainable approach with building materials.

Concrete is one of the most energy-demanding materials in the world due to its cement production that contributes to 7% of the total CO2 emissions worldwide *(Jonkers, Thijssen, Muyzer, Copuroglu, & Schlangen, 2010; Şanal, 2018)*. In the Netherlands, concrete is dominant as a material in the built environment and provides the most construction and demolition waste *(Durmisevic, 2010)*. In 2010, the housing market was responsible for 28,5% and the utility market for 30% of all the used concrete in the Netherlands. Although the utility market has a larger share in concrete

is created. Although new technology helps to reduce the environmental impact of concrete production, it still needs a lot of optimization on material and product levels to become fully circular.

1.2 Problem

Unfortunately, concrete is not used optimally, while it has a long life span and therefore a high potential to be reused on a product level. to be reused on a product level. Though the direct reuse of concrete always remains a challenge: it is often not designed to be dismantled and therefore when trying to dismantle, reuse cannot be guaranteed to be of high-quality. Demolition is still often a safer and cheaper option to choose. It is a shame because concrete is the second most-consumed material in the Netherlands after water *(Bakker & Hu, 2015*) and can become more durable and reusable if it is designed for dis- and reassembly. With the aim of 1 million houses by 2030, this market must be tackled precisely for reusability and standardization *(Mandshanden & Koops, 2019)*. Especially apartment buildings, as space in the cities becomes scarce, more will be built in height as well as utility buildings being transformed into houses *(CBS, 2019)*. Reusability can be a problem in the housing sector as people have different needs when it comes to their homes. Flexible dimensions must be found that meet these various requirements and guarantee structural safety so it can ultimately contribute to a reusable and sustainable design.

To further improve a sustainable design the focus most lie on a broader mindset that combats global warming. Right now most strategies are focusing on CO2-mitigation at national levels which instead needs to be shifted towards solutions that reduce global warming on a larger scale and in collaboration with other countries such as carbon-capturing in concrete production *(Bryan & Ben Salamah, 2018)*. As concrete is the second most used material in the Netherlands, starting to design sustainable concrete elements that capture and store CO2, can bring us a step closer to reduce global warming.

1.3 Objectives

The main objective of the graduation project is to provide insight on how a concrete façade system is made for the Dutch housing market that is reusable and sustainable. The goal is to contribute to the ambition of reducing the CO2 emissions in the building industry and therefore being an example of how new designs and techniques focusing on this subject can help reduce global warming. The study provides insight in the concept of reuse, standardization, modularity and provides an overview of materials and techniques involving CO2 capture and storage as well as different types of concrete.

1.4 Research questions

With the problem and its main objectives explained, the main research question can be formulated:

Main research question

How can a sustainable concrete façade system be designed for the Dutch housing market in order to make it reusable?

The aspects that follow up on this question are finding out what the technical and design criteria are needed for a concrete façade system in order to succeed, researching the sustainability of concrete and asses the best concrete for this project, finding the best suitable dimensions for a reusable façade system in the Dutch housing market and research how a concrete façade system can guarantee structural safety. These aspects are formulated in 5 different sub-questions:

SQ1: What are the technical and design criteria for a sustainable and reusable concrete façade system in the housing market?

SQ2: What are the characteristics of all the different of types concrete; its strengths and weaknesses?

SQ3: Which factors are playing a role in reducing, capturing and storing CO2 in concrete?

SQ4: What dimensions are best suitable for a reusable façade system for the housing market?

SQ5: How to design a reusable facade system that guarantees structural safety?

Each of these will be further addressed and answered in the upcoming chapters.

Design question: How can a concrete façade system be designed in order to make it reusable?

1.5 Approach and methodology

As seen in the research framework (*Figure 2*), the method per aspect/chapter is described that helps finding the right information and answers that is needed to complete this research. A few methods are going to be used to conduct this research: literature research, case studies and research by design. Each aspect and research question can be divided into these approaches. Below is specified per approach which questions belong to this.

Literature research: This is used to get the basic knowledge about some of the keywords in the research questions (reusable (extra: design for disassembly, circularity), sustainable (CO2), concrete, Dutch housing market).
How? In the next chapter of this graduation plan (literature and general practical preference), per chapter and its keywords, the literature found is explained. This research method is mostly used for SQ1, SQ2 and SQ3.

Case studies: To find out what dimensions are best for the concrete façade system (SQ4) and how current architectural drawings in the apartment building sector are looking like to understand which criteria the façade system needs to meet, case studies (at least 2 to 4 facades of two different buildings) are needed to compare and find out what the best dimensions are to make the façade system reusable/standardized in these Dutch apartment buildings. Criteria for the case study can be found in the thesis/report ("Analysis of the building details"). The design will be applied to these case studies.
How? Need to find suitable case studies that perhaps the faculty of Architecture or a municipality can provide. Architectural drawings and details can also be found on SBR details to give a general look into these types of apartments.

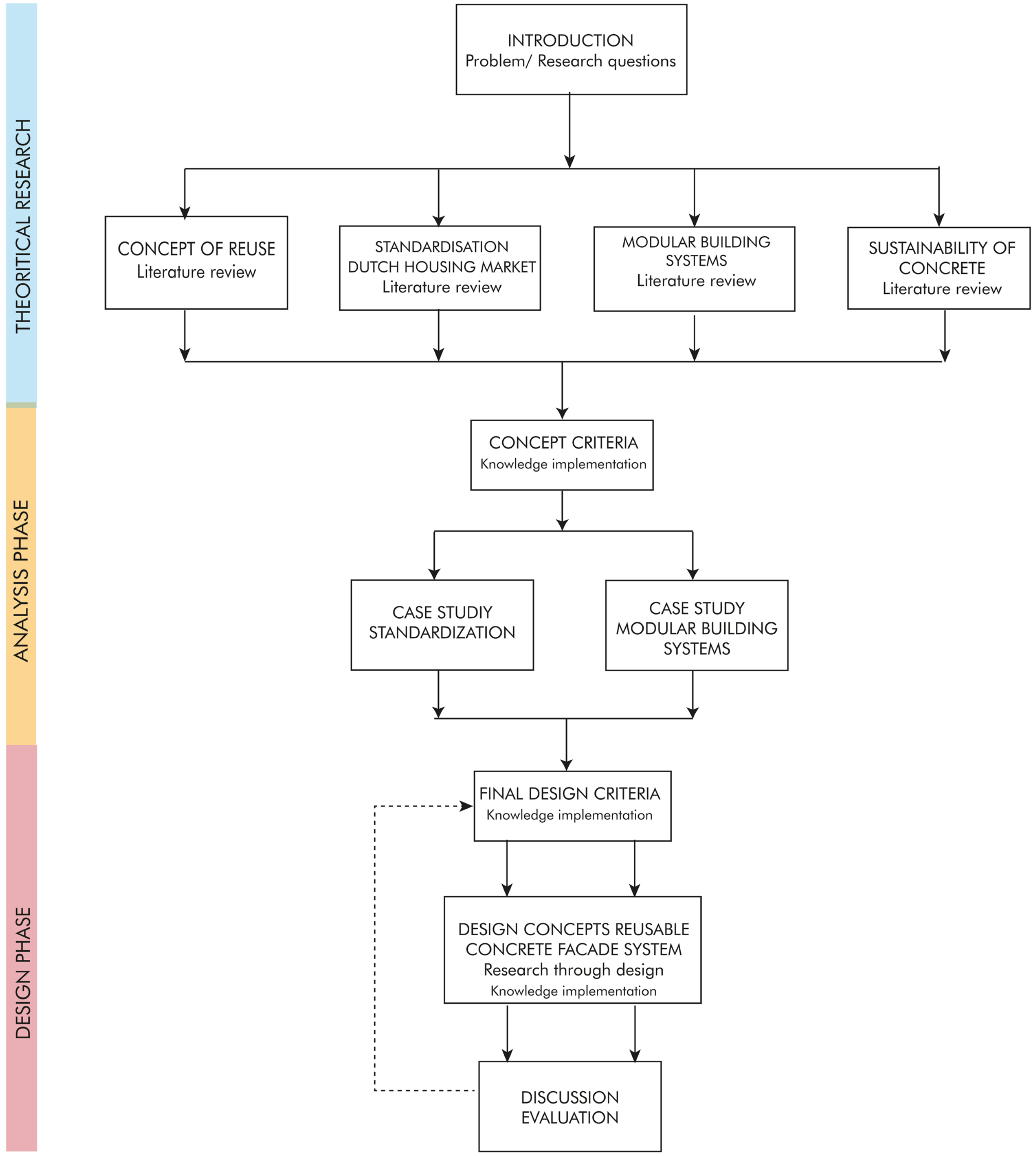


Figure 2: Research methodoloy scheme Source: (own ill.)

Research through design: When the previous methods in the research are done, the questions SQ1, SQ2, SQ3 (and SQ4 partly) can be answered. A few design concepts can be made with all this information, whereas these will be more explored by research through design.
How? By sketching, using computer programs and looking back and forth between all the research questions. For example, dimensions and structural strength or stiffness are related to each other.

Figure 2 describes the steps of this research divided into the theoretical research, analysis and design phase.

EXPECTED IN- AND OUTPUT PER CHAPTER
These approaches can also be translated to the expected in- and output of each chapter.

RESEARCH PHASE – Literature research

Chapter: *Concept of reuse*

Output: Importance of reuse, the barriers of reuse, advise on reusing concrete elements (by literature study)
Input for: Information is input for the design phase: the design criteria and design concepts

Chapter: *Standardisation in the Dutch* housing market
Output: Knowledge about existing standardisation in the Dutch housing market, maximum and minimum dimensions for the concrete facade panels
Input for: Information is input for the analysis phase where further the best suitable dimensions for a concrete panel for in the Dutch housing market will be analysed and the design criteria.

Chapter: *Modular building systems*
Output: How to implement parts of the concept of design disassembly, knowledge from existing modular systems and an overview of demountable connection systems.
Input for: Information is input for the design criteria and its importance to assess the case study that analyses existing modular building systems in depth.

Chapter: *Sustainability of concrete*
Output: Knowledge of different types of concrete, sustainable concrete techniques, improvements that can be done in the material/production process
Input for: Information (what kind of concrete and technique to use) is input for the design phase: the design criteria and design concepts

Chapter: *Concept technical and design criteria*
Output: A first draft of the technical and design criteria for a sustainable and reusable concrete façade system
Input for: to assess the modular case studies and for the final design criteria.

ANALYSIS PHASE – Case studies

Chapter: *Standardisation in the Dutch housing market*
Output: Best suitable dimensions for the Dutch housing market.
Input for: the final technical and design criteria and the final design concept.

Chapter: *Modular building systems*
Output: Knowledge gained from the modular case studies: Assessment made according to the concept design criteria and contains knowledge about the strengths and weaknesses of modular building systems.
Input for: the final technical and design criteria and the final design concept.

DESIGN PHASE – Knowledge implementation and research through design

Chapter: *Final technical and design criteria*
Output: Final requirements/criteria for the design concepts: standardization, modularity, sustainability and adaptability (knowledge implementation)
Input for: The final criteria are the base/starting point for the design.

Chapter: *Design concepts*
Output: Design concepts based on all the information gathered that are further researched through design and calculated
Input for: Final design strategy

Chapter: *Final design strategy*
Output: A final design strategy is presented that has implemented all
Input for: Final design strategy

Chapter: *Discussion and evaluation*
Output: discussing and evaluating the design concepts made and look if these need to be optimized or not (see if the design and its criteria are correct)
Input for: Design criteria, standardisation of the Dutch housing market (the latter because the final dimensions of the façade system can change due to, for example, structural safety that is calculated and not sufficient)
Input for: Design criteria, standardisation of the Dutch housing market (the latter because the final dimensions of the façade system can change due to, for example, structural safety that is calculated and not sufficient)

1.7 Relevance

Societal relevance
We all want to work towards a better environment, so that the generations after us can also live their lives carefree. It is therefore important that people start to convert their mindset and realize how important it is to work towards a future that is more circular. Making elements reusable and making materials more sustainable helps us in making a better world. It can also create more jobs and improve its quality as reusability and sustainability requires different kind of knowledge. Hopefully this research can take us a little step closer to our fight against global warming.

Scientific relevance
This research can contribute to a more sustainable construction sector. Since concrete is still the most used building product in the Netherlands for the time being, it is important that we design and use it more responsibly. This research can be a reason for others to continue with and improve, or use the information to start a new research or design.

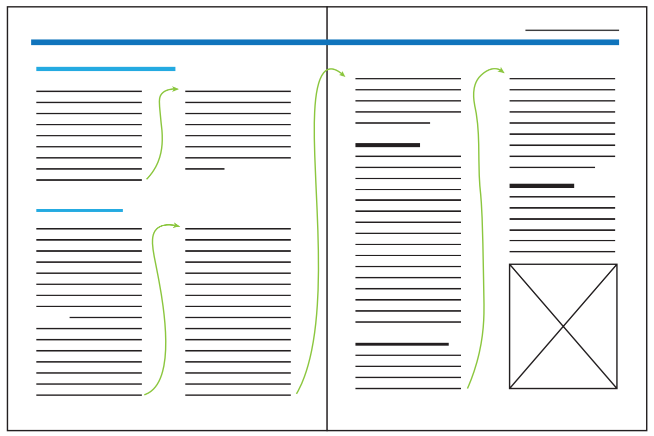
1.8 List of definitions and abbreviations

RQ	Research question
SQ	Sub question
DQ	Design question
CO2	Carbon dioxide (chemical formula CO 2)
w/c ratio	Water to cement ratio
Clinker:	Portland cement clinker
DfD	Design for Disassembly
Beukmaat	The width of a house
Bouwbesluit	It is a Dutch platform in which regulations for safety, energy efficiency, usability, health and the environment are described with which every building in the Netherlands must comply to.

1.9 Guideline of the paper

On the right, a quick guide is seen that shows how to read the text in this thesis. Also, colour areas will be used in the paper that indicate:

- *This is extra information:* not necessary to read to understand the rest of the paper, but it may possibly be referenced
- *Additional information on a term*



2 THEORITICAL RESEARCH

In the first phase, the literature study that has been carried out is presented, which starts with explaining a number of leading strategies. Then the principle of reuse will be discussed that will result in studies on standardization and modular building systems, followed by a chapter on the sustainability of concrete. Finally these chapters will result in a concept with technical and design criteria.

Strategies

To reduce the impact of the production of concrete there are a few strategies that can help tackle this problem and will be discussed further in this research. One of those strategies lies in maximizing the life cycle of concrete by reusing the concrete elements, which is a complex subject to implement in the current society. It is important to design a product for reuse in its early stages and focus on *(Schilperoort, 2016)*:

FUNCTIONAL FLEXIBILITY
The building isn't just made for one function (apartment, offices, etc.), but is flexible enough that it can change to another function without needing too much investment. Flexibility can lie in open floor plans, but also which type of façade to use. Standardization is a factor that can help in making the flexibility of a building easier. Functional flexibility is also an important factor for consumer's appreciation. Consumers need to have flexibility in their choices if it comes to their own space to be able to enjoy the place.

TECHNICAL ADAPTABILITY
This focuses on the separation of elements and components of a building as every part has its function and life cycle. They should be changed or removed easily when needed, without costing too much time and money. It is closely related to functional flexibility and you can get an improved design when applying both. This is important in the world of reuse and is a big part of the concept of *Modular construction* and *Design for Disassembly (DfD)*.

Another important strategy lies in the reduction of CO2 emissions, waste and material use:

MAKING CONCRETE MORE SUSTAINABLE
Finding ways to lower the impact of concrete on material and production level, and therefore tackling the problem.

BUILDING LIGHTWEIGHT
By designing lightweight, less material will be needed to produce which has a positive effect on all the embodied energy.
All these themes will be discussed in this thesis as they will contribute to designing a reusable concrete façade system to help improve some of the problems concrete is responsible for.

2.1 Concept of reuse

First of all, it is important to understand what is meant by reuse, why reuse is so important to implement in our economy and what we need to change to make reuse successful. First, the definition of reuse will be explained, second why we want to reuse and its impact, thirdly what the barriers are to reuse high-value concrete, fourthly existing examples of reused concrete elements and at last conclusions are drawn that are used for the final design criteria as well input for the final design.

2.1.1 What is meant by reuse?

By reuse, we mean the reuse of material in its original form. This can be the entire material as a whole or separate component that can serve as the (or comparable) function for which they were conceived originally with minimal processing as possible. Recycling is a form of reuse that occurs more often in the Netherlands, but most of the time requires more processing and therefore costs more energy. Well-known examples of reuse are secondary clothes that can be bought in second-hand clothing shops or online platforms like the Vinted app, or the digital platform Marktplaats where you can sell for example a couch to others as second-hand furniture.

Reuse is an important part of closing down the waste streams that play a big role in construction, making it responsible for an average of 23.8 Megatons of construction and demolition waste in the years 2001-2014 *(Rijkswaterstaat, 2013, p. 30; CBS, 2019)*.

Although reuse in the form of recycling is already common, around 38 percent of the materials used in construction in 2016 *(CBS, 2019)*, the share of reuse of materials in its original form is growing less rapidly.

The Netherlands and the European Commissions (EC) have to collaborate on a new policy program 'maak de cirkel rond', to work towards a circular economy and encourage countries to preserve the value of products and materials until the end of its life and minimize the waste production. As *Ellen MacArthur Foundation* (*2012, p. 7*) said, a circular economy is an industrial system that has the ambition to eliminate all waste through different aspects like the design of materials (*Figure 3*) and business models and wants the 'end of life' concept replaced by restoration. In this, waste and its materials are seen as closed-loop and it assumes that systems and products will be designed for reuse and disassembly.

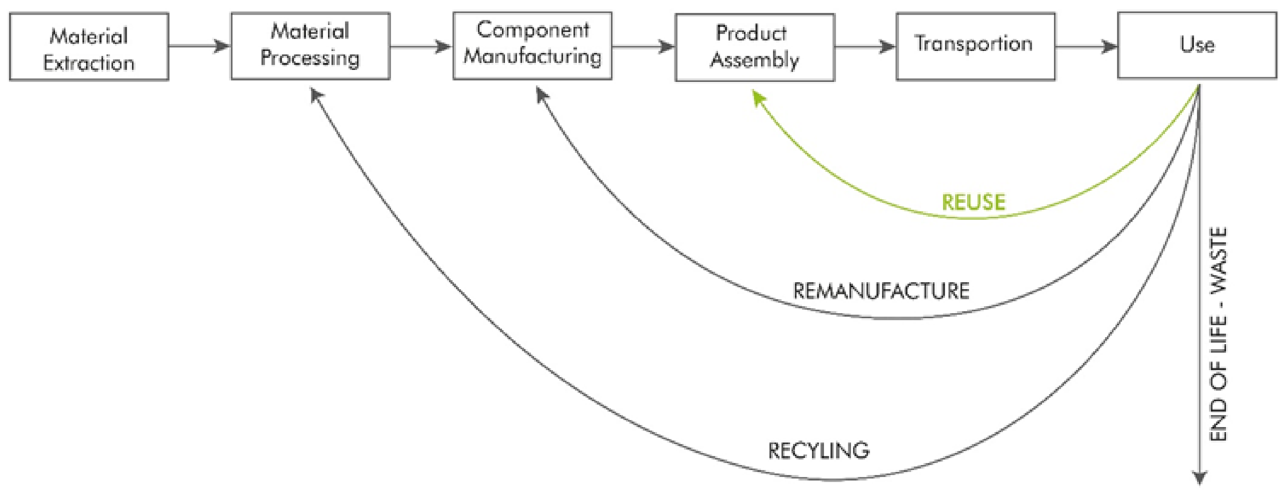


Figure 3: Reuse principle. Based on: (Ellen MacArthur Foundation, 2012)

DEFINITION: CIRCULARITY

There are so many definitions for 'circularity in the built environment' and a 'circular economy' that it changes from person to person. Currently, the Netherlands is trying to find the right definition for circularity, so that it can always be measured in the same way and everyone in the built environment is aligned.

In this thesis the definition according to *Ellen MacArthur Foundation* will be further used: The goal of a circular economy is to close the loop of raw materials with the lowest possible loss of value, to use renewable energy sources; diverse systems that focus on modularity, versatility, and adaptivity diverse, and finally to think in systems whereas it is important to know how parts or components influence each other and how their relationship is mutual.

2.1.2 Why do we want to reuse?

The reuse of materials and a circular economy entails many positive factors, both socially, economically, technologically and a positive impact on the environment. These will each be discussed to give a better picture of what reuse ultimately contributes to society.

SOCIAL IMPACT

We all want to work towards a better environment so the next generations are not stuck with major climate problems that we've created over the years. It is therefore important that people transform their mindset and realize how important it is to work towards a future that uses recycled materials.

In addition to this, reuse requires a different way of working. Materials and products will be carefully removed in the construction industry and selected, which requires new types of companies that specialize in this. Research by Acceleratio *(Van Eijk, 2015)* shows that it is estimated that at least 54,000 new jobs will be created in a circular economy in the Netherlands. Instead of jobs disappearing, more are being created, which has a positive impact on society. Also, high-quality reuse requires more high-skilled jobs, since better knowledge of the product is required and therefore the quality of the jobs will be improved *(Nederland Circulair !, 2015)*.

ECONOMIC IMPACT

A circular economy can generate a profit of around 7.3 billion euros per year, about 1.4% of the GFD (Gross fiscal deficit) *(Van Eijk, 2015)*. The Netherlands is a leader when it comes to achieving circularity (and reusing materials) which offers us many economic opportunities *(Rakhorst, 2018)*. We can assume a better market position and circularity has the chance to become one of our largest export products *(Voor de Wereld van Morgen, 2017)*.

TECHNOLOGICAL IMPACT

Various developments are needed within the process of a material, element, etc. to make it reusable. It becomes a different way of thinking, which means that there is a newer perspective on, for example, the design process. More knowledge and new insights will emerge that can also help work more efficiently. Reuse can if properly designed, be ready for a new location faster than a whole new production process.

ENVIRONMENTAL MPACT

The CO_2 emissions that are released during the production process of materials are harmful to the environment. Although the Netherlands already does a great job at recycling, reusing materials is better for the environment. As a comparison: for example with steel beams, the life cycle costs are 10%, and the total energy requirement 50% less compared to the costs of not recycling at all and bring it to a landfill. Reusing materials will be even better with up to 40% fewer costs and 80% less energy use (*Nederland Circulair !, 2015*). Depleting less raw materials and using less energy, the better it is for the environment.

2.1.3 The barriers of high-value reuse of concrete

Although the Netherlands is well on its way from a linear economy to a circular economy and the reuse of all waste products, there are still many problems of the current linear economy that cause reuse not yet being fully utilized. The many regulations in the Netherlands, consumer behavior, financing, lack of knowledge and technology that strives for high-quality reuse cause a lot of obstacles. Also, circular construction is currently even more expensive than traditional building. There is still insufficient experience with circular construction and it is more labour-intensive because more is involved in the assembly and dismantling of parts. The supply and demand of its used materials are also insufficiently aligned, temporary storage of materials is required (costs money) and the valuation/ measurability of circularity remains unclear. We will discuss the most important barriers that take place in the Netherlands:

GOVERNEMENT

Although the Dutch government is improving its policies, it's still has a lot of conflicting regulations and a lack of subsidies in comparison to the ambition to be CO_2 neutral by 2050. These barriers withhold the opportunity to use the knowledge and techniques of reusing concrete that we've already made available. Without the government putting pressure on using circular concrete or provide funding, the new technologies will not be commercialized. If CO_2 emissions will be taxed it can help create new businesses. By reacting and moving the fastest with new technologies that reduce CO_2 emissions per MPa companies can profit the most rapidly from it (*Aïtcin & Mindess, 2011*).

The reuse of high-value concrete is also being hindered by the strict requirements for the building industry that is being regulated by the government. More requirements are being added to the categories of safety, utility, fire resistance and low energy use.

Another thing is that there is a lack of clarity in the classification of waste which hinders the reuse of concrete. If something is labelled as waste, it cannot easily be reused as it will require much time, effort and money to be able to change this classification to a normal product. Instead of labelling parts of concrete, such as a structural component, as 'waste', it should be labelled as a 'by-product' to make harvesting and reusing of these components possible. *(Nederland Circulair !, 2015)*

TECHNOLOGY

Because reuse is still a relatively new topic, technology is behind and still not available or in development. As said before, it is a new way of thinking, and reusing materials or elements directly from a building is becoming more and more complex to recover effective and efficient *(Nederland Circulair !, 2015)*. Products are often designed to perform unique functions and make it hard to dis- and reassemble elsewhere. The technology still has to grow a lot and collaboration and sharing information between companies is necessary to make the concept of reuse work.

CONSUMER BEHAVIOUR

In the mindset of the consumer, a reused product is still seen as a product of less value than a new one and it is a very hard perception to change *(Nederland Circulair !, 2015)*. This is mostly because it is unsure (and the negative perception of reuse) for consumers if the quality, safety and health is good enough, but rather not take the risk and go for new product. People need to be taught by several outlets that a reused product of high value can be of more value in for example an environmental way. It is important that the government is closely involved and tries to encourage the reuse of products and educate consumers about the quality and impact of using them. Subsidies for using reused products or higher-taxed on new products can also be a way to change the mindset of consumers.

An example that has changed a part of the reuse mindset of consumers can be second-hand clothing. In recent years it has been becoming more popular and it becomes more of a fashion statement that it is reused. Sometimes you get a good quality or brand clothing for a much lower price, but with the same value as it was before. Sometimes even of more value when it is a special/vintage piece. It is especially the digital platform that brought this subject to a bigger audition, through apps like "United Wardrobe" and "Vinted" where you can sell your old clothing on their website.

RISK
Because there is no contractor in the early stage of designing, the client has to spend money upfront on buying reused components, which most don't want to do, because of the risk. Therefore it is best to have a management contractor in the beginning already, who is going to be responsible for getting reused building products.

MISMATCH SUPPLY & DEMAND
Another reason is that the reuse of concrete isn't fully working yet, is that there is no current demand for used structural concrete products (reuse of building products). There is a lack of a coordinated supply chain that ensures a consistent supply *(Hobbs & Adams, 2017)*.

MARKET
One of the biggest market barriers is the companies that are not yet confident in the concept of reuse. There is still too little knowledge and applications in the construction sector to gain this confidence from companies so that investments are less likely to come loose. There is often still too much risk. Besides, many companies believe that innovation is countered by reuse, while it requires innovative and creative thinking. Other aspects that make it difficult for companies to adopt high-value reuse are insufficient access and infrastructure for reuse. *(Netherlands circular!, 2015)*.

One of the biggest obstacles to reuse is that people do not have confidence in the product without certification, especially when it comes to structural capacity. Problems such as not knowing how long it has been in a particular application and no clarity as to where the product comes from. Reused product testing often involves high costs and these costs are added to the final cost of the product. This makes a reused product more expensive than the initial thought of saving *(Hobbs & Adams, 2017)*.

QUALITY CONTROL
There is uncertainty about the quantity and quality to reuse concrete elements *(Salama, 2017)*. It creates a reluctance to use products without a certification that proves that its tested performance is approved. This is especially very important for structural concrete components. To make this work, not only is a certification needed, but also a database that tracks these components so it is always clear where the product comes from, how long it has been used somewhere and in what capacity. Currently, there are no internationally used tools to check the quality and therefore people are not certain if it is good enough or not. As long as people don't trust it, they will not comply. *(Hobbs&Adams, 2017; Nederland Circulair !, 2015; Mark Gorgolewski, 2008)*

COSTS
To implement these technologies to reuse concrete is expensive. For example, the development of creating demountable connections in a concrete façade system will require time and money. But also the quality control can be expensive as testing the performance of concrete components to get a certificate can be expensive *(Hobbs&Adams, 2017)*. In short term, it will cost money, but people only have to see that these technologies of reusing concrete will eventually save money and especially reduce CO2 emissions, waste and the use of raw materials in the long run.

2.1.4 Reusability of concrete elements

Unfortunately, the current mindset for concrete elements is not to preserve and reuse it, but to demolish. It is often crushed, recycled and used for roadbeds, but unfortunately, this results in interrupting its potential full life cycle. This is often the case because concrete is a composite material and therefore it is difficult to dismantle its material levels *(Salama, 2017)*. The 10 R's of Jaqueline Cramer describes very well how to achieve a circular economy in the building sector (*Figure 4*).

All of the R's can be seen as strategies that can be applied to the early stages of design. With the design process of a reusable and sustainable concrete façade system in mind, this process will start with rethinking the design and make more of its functionality by designing it for multiple uses, improves adaptability, or its durability. The second will be to reduce the material and emissions flow in the design by using recycled materials or use fewer materials. The stage where the façade system is meant for, reuse, requires thinking about modular design and designed for deconstruction among other things.

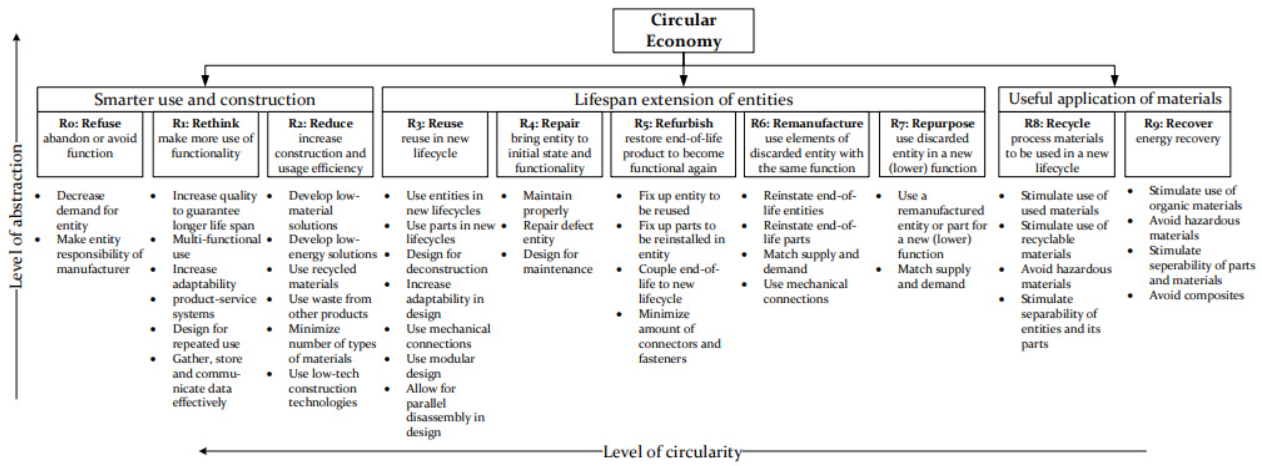


Figure 4: Circular economy: the 10 R's. Source: (Coenen, 2019)

Rethink, Reduce and Reuse can be used as strategies and are useful in creating a circular design and can help in judging and finalizing the design. Important focus points within these that concentrate on the design are *(Coenen, 2019)*:

RETHINK *'making more use of its functionality'*
Design the product for multi-functional use, increase its adaptability and design for repeated use

REDUCE *'increasing the construction and usage efficiency'*
Develop low material solutions, recycled material, develop low energy solutions and minimize the number of types of materials

REUSE *'reusing it for a new lifecycle'*
Use a modular design, mechanical connections, increase adaptability of design and allow for parallel disassembly in design.

Opportunities and options of reusing concrete elements

The reuse of concrete elements also has a lot of opportunities and options that support it. Two of these opportunities and options will be further assessed in this thesis as a strategy to improve the reuse of concrete elements and are based on the previous paragraphs and literature of *Salama (2017)*:

USE LESS MATERIAL, WASTE & CO2 EMISSIONS
By reusing concrete elements, the production of concrete will be less which results in less use of materials like, cement, aggregate, sand, limestone, etc.. Also less waste and CO2 emissions, which will be further explained in *Section 2.4 "Sustainability of concrete"*.

FEWER COSTS IN THE LONG RUN
It will be an investment in the short run because designing concrete elements for reuse is a more expensive option. These costs can be higher because of, for example, more expensive and complex (dry) connections. But because the elements are being less produced, it will cost less in the long run. There will only be expenses on maintenance and assembly.

CREATING LARGE ELEMENTS ANT MATERIAL YARDS
As explained in the previous chapter, there is a mismatch of demand and supply. The supply chain needs to become bigger to give customers more freedom to choose out different concrete elements that suit their project. By creating a large element and material yards, there will be a more stable supply chain.

In the Netherlands, there is already a company, New Horizon, that specializes itself in urban mining. Meaning they harvest elements and components (like concrete) before the building gets demolished. They have created an online platform that sells these elements and components, like prefab concrete and service products, to be reused.

NEW TECHNOLOGIES: the use of llighweight or ultra-strength concrete
An issue of concrete elements is the size and weight of it, whereas light-weight (less weight) or ultra-strength concrete (reduced size so less weight) can be an option to use. It will result in less material, waste, and also CO2 Emissions which will be further explained in *Chapter 2.4 "Sustainability of concrete"*.

REFERENCE PROJECTS: REUSE OF ELEMENTS FOR THE SAME FUNCTION

The reuse of elements for the same function is the best way that ensures a cyclic loop, but only if after inspection it can still be classified as reusable (Salama, 2017). Some projects have tried to reclaim and dismantle concrete elements, but it has always been a risky move. Others have already tried to design concrete elements for reuse, but this is more recent. Here are a few projects that involve reusing concrete elements for the same purpose.

MIDDELBURG, Netherlands - (Coenen, Lentz, & Prak, 1990; Naber, 2012)
This is a project that was happening in 1986 where they deconstructed 7 out of 11 concrete floors from a residential building in Middelburg and placed it in another apartment building. This was new at the time, as it was the first project to reuse concrete elements in the Netherland and was considered a big risk.

After the WOII there was a high demand for apartment buildings and standard systems for the construction of residential buildings where developed, like BMB by the construction company 'de Delta'. In the Middelburg project, they were successful in carefully dismantling the concrete elements because of the use of dry connections (Figure 5). Although the preparation took a long time and the costs were higher because of this and the use of special equipment, the project was considered successful and was the first step in the direction of the reuse of concrete elements.

MAASSLUIS, Netherlands - (Naber, 2012)
This was unfortunately a less successful attempt to reuse concrete elements compared to the project in Middelburg. They had a choice to renovate or newly built the flat, so they chose to demount concrete elements to reuse them in the building again. The principle was the same with the previous reference project: the building being built after the WOII with a standard system and where the new designers and engineers demounted concrete elements of a residential building down to the second floor to reuse them in the same building but with some adjustments.

Eventually, the project failed in reusing the concrete elements which had several reasons. First of all, because it was about the same building, it was a difficult task to logistically synchronize the demounting of the concrete elements of the existing building to the new building that was going to be constructed. They didn't have enough space on the ground floor to store these elements and create a logic system to be able to speed up assembly time. The second reason it failed was that getting the elements down was more complicated than they expected. The last reason being that the Dutch government didn't grant a subsidy to the company for creating a residential building with used elements.

CIRCULAR VIADUCT - (Van Hattum en Blankevoort, n.d.)
A more recent project (2019) that has been successful in disassembling a structure and reassembling it at another site is the Circular Viaduct (Figure 6). The project involves the contractor Van Hattum & Blankevoort and the prefab-concrete construction company Consolis Spanbeton to construct a concrete aqueduct. It is built out of forty concrete blocks of the same size (module) which can reach a span of 20 meters and can be dismantled and relocated elsewhere. Normally aqueducts are being dismantled after a few decades where these can stand for over 200 years. It is considered a success and a project that has created innovative connections (a cable system) that complements its structural ability and can be seen as an example of standardized modules. Since it has a one sized module, it ensures repetition in the production process, which eventually will result in a quicker and safer production process.

In a further chapter, the project will be discussed and judged later in this thesis on its modular system.

Figure 5: Project Middelburg: a concrete element has been dismantled and is being levelled down. Source: Naber (2012)

Figure 6: Circular Viaduct in Source: Van Hattum en Blankevoort (n.d.)

2.1.5 Conclusion on the concept of reuse

To maximize the life cycle of concrete, reusing concrete elements should be implemented in our current society. By focusing on aspects like functional flexibility and technical adaptability early on in the design phase, it becomes easier for a product to be adaptable in the future. Another strategy to maximize the life cycle of concrete lies in the reduction of CO2 emissions, waste and material use. Making concrete more sustainable by finding ways to lower the concrete production and by designing lightweight so less material needs to be produced. Reusing concrete will not only have a positive impact on the environment and technology but also has a social and economic impact. By improving the circular economy, a better environment is created for future generations, resulting in a better market position, more jobs and a sustainable environment.

Although there is progress in rethinking, reducing and reusing concrete elements, these strategies aren´t enough to be implemented fully in the current society. Barriers that complicate the high/value reuse of concrete in the Netherlands are the confliction regulations (and subsidies) of the government about energy-waste/recycling, the use of new technology and its high costs, the negative perception of the reuse, the risk for a client to apply a reuse strategy, mismatch of supply& demand due to lack of coordination, uncertainty about the quantity and quality of reusing concrete elements and the lack of confidence of the market. Not only barriers but also opportunities arise that support concrete elements, such as reducing the use of material, waste and CO2 emissions, the use of new technologies, long-term economic benefits and the creating of material yards that will improve the supply chain.

In the Netherlands, a few examples of rethinking, reducing and reusing already exist. Thirty years ago a company tried to reusing concrete elements and was considered a success and a first step in the direction of reuse of concrete elements. Another successful project is the Circular viaduct that uses a standardized module to form a reusable bridge. In the case of the three projects discussed, improvements can still be made in the even faster assembly and disassembly, but also in the simplification of complex connections, a more standardized construction sector to improve the building efficiency and the logistics aspect. The latter ensures that the disassembly and assembly are done most efficiently when this all has to been done at the same location. This requires a complete logistics system.

Also remarkable is that most projects involve horizontal structures (floors and roofs) and less vertical structures (walls). This can be because of greater knowledge in this section, less complex connections, fewer exterior influences, existing standardization, and fewer materials and functions (separation of life-cycles) that are involved in horizontal structures. Further research will bring more clarity to this.

2.2 Standardization

As seen in the previous chapter, the improvement of the building efficiency can lie in standardization. The Circular Viaduct was mainly successful by having repetition in its production process: producing, assembling and disassembling a module of a certain size very quickly. All modules were the same size and produced in multiple moulds which quickens the design, production and construction process. The project can be seen as an example of reducing waste, material use and CO2 emissions as this are where the construction (especially the concrete) industry has been blamed for years. Standardization is a concept that can help to reduce these problems, although it encounters problems that make it difficult to make it work in society. In the upcoming paragraphs it is explained why the Dutch housing market is chosen for this thesis, as well as the advantages and disadvantages of standardization, how to achieve it and at last a look at existing standardization in the built environment. This helps to understand the concept of standardization as well as coming closer to finding the best suitable dimensions for the reusable concrete façade elements for the Dutch housing sector.

2.2.1 Trend in the Dutch housing market

The Netherlands expects a population of 18,8 million by 2035. To meet this growing housing demand, the Netherlands Is expected to have built around 845 000 houses by 2030, contributing to the ambition to have built 1 million houses by then. Currently, the housing shortage is already about 331.000 (4,2 percent) of the Dutch housing stock. The ambition is to decrease this shortage to 2 percent by 2035 *(Rijksoverheid, 2020)*. This all allows the introducing the reuse of concrete in the Dutch housing sector on a bigger scale.

Another important aspect is that more and more people want to live in the city, but that space is lacking. Instead of only expanding the cities in width, which takes up more space per square meters, the focus should lie more on building up in the air, this in the form of apartment buildings that will increase the density per square meters.

2.2.2 Advantages of standardization

Standardization stands for the formation of certain rules or standards that are used for the use or testing of a product or process. It means that there is regularity, repetition and also a record of successful practice *(Gibb, 2001)*. In this thesis, it is meant that dimensions must be defined for the concrete elements to make reusability easier. Standards are set to bring all the interested parties, like the manufacturers, consumers, and regulators of a material, service product, etc. together (*Aapaoja & Haapasalo, 2014*). It will lead to some important advantages *(Yasin & Rjoub, 2017; Ulrich, 1993; Aapaoja & Haapasalo, 2014):*

1. High quality and better quality control
By producing the product constantly the same, the quality will be better than creating a single product just one time. Fewer mistakes will be made because those have been solved in the earlier stages of producing the product.

2. Lower construction costs
Construction workers and end-user know what kind of product they are getting and how it should be used.

3. Less CO2 emissions
By standardizing the product, it is made possible to be reused. By reusing it, fewer products have to be made which will lead to lower CO2 emissions. Especially with concrete, where cement produces a lot of CO2 during production, it can save a lot of CO2. This will be made clearer in *Section 2.4.3 "Cement"*.

4. Less use of raw materials and less waste
Standardization will eventually lead to less use of raw materials, because of the possibility of reuse. Also, through familiarization with the production process, it will lead to less waste.

5. Faster production time
By making the product over and over again, a smart and faster logistics setup can be made which makes the production process a lot faster.

6. Fewer production costs
Because of the standardized product being produced in high volume, it will lower the cost economically.

7. A better understanding of what is required of a project's party, from whom and by when
This leads to fewer claims, conflicts and change of orders, and therefore also less unplanned costs.

8. Increased safety and knowledge of product customers and the environment
The higher volume will lead to greater economies of scale and more learning.

9. Easier to obtain replacement parts

10. Easier to track
When setting up a database to track the components to reuse, standardized components are easier to be tracked than unique panels.

It is best to work on the process and product development simultaneously, so the best results can be found. An example of this can be prefabrication and modularity (standardized product), and takt[1] time (standardized process).

By producing the product constantly the same, the quality will be better than creating a single product just one time. Fewer mistakes will be made because those have been solved in the earlier stages of producing the product.

Without standardization in the construction sector, it is difficult to make an element reusable, because the aim is that the building elements can be used in different ways and locations. Unfortunately, standardization is difficult to implement in the current construction market and it is often at the expense of flexibility and adaptability (similarity vs. customization), which is very important in the construction world. The regulations and the demands of people require flexibility and cause the design to be constantly adjusted over the years. This will be discussed in more detail in the next paragraph.

2.2.3 Problems of standardization

Standardization is not an easy concept to achieve and has some barriers with some that have similarities with the concept of reuse (Milan, Ana, & Bojan, 2015; Pasquire & Gibb, 2002; Aapaoja & Haapasalo, 2014):

Flexibility
It is the biggest problem as it tends to average the needs of the user/owner.

The value of modularity/standard products/ components is not yet understood.
Not enough projects in the building industry to learn from

Lack of collaboration
Not enough trust and commitment in the building industry

Traditional management methods
Traditional contracting and construction management methods are preventing standardization from being realized.

High investment costs
Investment in product development and performance for a manufacturing firm has high costs in short term and low in the long term. The high costs at the start can demotivate the manufacturer to standardize.

It has multiple barriers that need to be solved simultaneously to be able to successfully implement in the building industry.

[1] *Takt time is time a product needs to be completed in order to meet your clients demand. It can be seen as the average time between the production of one product and the start of the next one to meet the clients demand (Kanbanize, n.d.).*

2.2.4 How are you going to achieve standardization?

Next to solving these barriers, there are also other ways to achieve standardization, some of them being *(Yasin & Rjoub, 2017)*:

- Finding out what the most popular sizes and models that are being used in the production process of the element that you are designing;
- Unification of specifications to optimize the quality, production process and method;
- For these specifications, a list of requirements should set be set up to summarize it for a product so it becomes clear that a product or element does meet the requirements
- A summary of the requirements for an element or product should be defined for these specifications to have a clear overview that it can suffice these requirements.

The first mentioned aspect is mainly the one that will be further researched in both the literature study *Section 2.2.5* and the case study *(Chapter 3.1)*. A design strategy for this can be to design the elements to be modular.

Modularization increases the chances to make standardisation possible, as will be further discussed in *Chapter 2.3.4 Modular building systems*. Standardization comes into play when elements in a building are divided into modules, pieces of a building, or elements that together will form a whole. With having compatible standardized interfaces, elements or component, they can be connected like puzzle pieces without any problems *(Figure 7)*.

Modularization is meant to be a flexible design that allows variations without changing the whole design. So if a new owner of a building wants to change the cladding, this is possible without removing the whole insulation and exterior wall. A few objectives for a modular facade can be *(Hövels, 2007)*:

- Making the design so that it can be updated to the latest wishes of the users
- Making the design so that it can be updated with the latest regulations
- Flexible enough so architects have freedom in designing with it

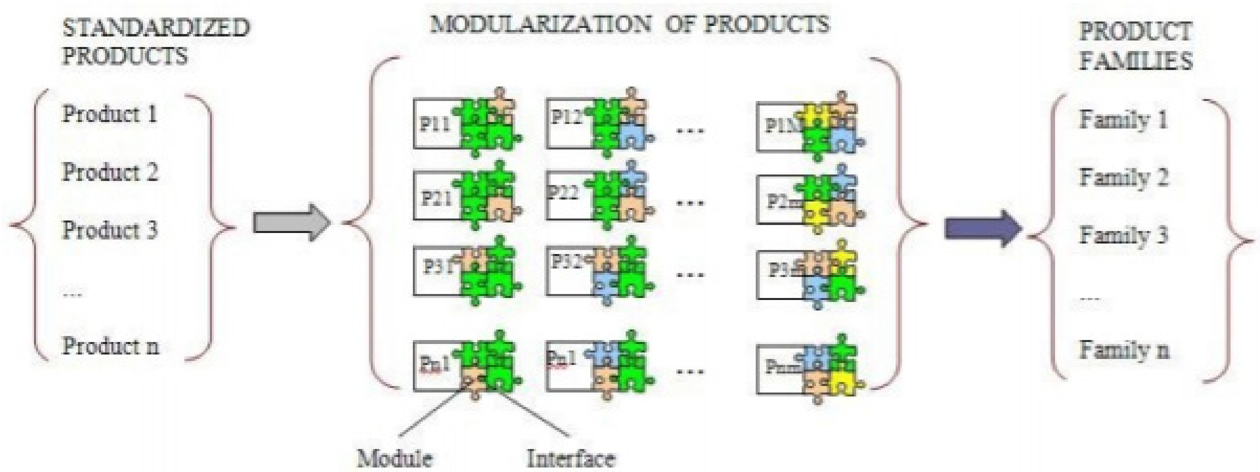


Figure 7: Basis concept of product modularization – Source: (Milan, Ana, & Bojan, 2015)

Like design for disassembly, it is important to start thinking about modularization at the beginning of the design process. A few questions could be asked when designing the façade system regarding standardization and modularity:

- Which functional elements are likely to change over time? (Hövels, 2007)

This will be discussed in Section 2.3.3 Building layers where is described which functional elements should be separated in the design.

- Which variants of the façade components are preferable to best match the user preferences? *(Hövels, 2007)*

The question can be answered after researching by design with the information gathered from the research and analysis part of the thesis. This question will be considered as: improving the production process of a standardized

- Where can the standardized component reduce development time or complexity and in favour of project management? *(Ulrich, 1993)*

product. The question will be dealt with more often in the thesis, but with a final advice on the production process in section 4.2.4 "Design process and strategies".

Finding the best dimensions for the standardized panels in residential construction will be discussed and will also consider whether the complexity, production and development time can be reduced. This will be discussed during the next chapters.

2.2.5 Existing standardization in the built environment

Before finding the best suitable dimensions for the concrete façade elements in the case study, it is important to look at, for example, existing standardization in the built environment which can help narrow the dimensions down to a minimum and maximum. These dimensions have then used an input for the case study and the final concrete facade system. A few questions where set up that can help to find these dimensions:

- What are the requirements in Bouwbesluit regarding dimensions in a residential building?
- What are current examples of standardization in the building industry?
- What are the convenient dimensions for transport?
- Are there common dimensions for residential buildings?
- Case study: what similarities does the apartment building have regarding dimensions? *This will be answered in the analysis phase, Chapter 3.1 "Standardization"*

Requirements Bouwbesluit

The Bouwbesluit (2012) has set up some rules and requirements for the construction sector to follow (*Figure 8*). These include heights and widths regarding the safety or for example comfort. All rules apply to newly built projects or renovation, not already existing buildings that were built before 2012.

- The minimal height of living space needs to be at least 2,6 meters.
- For doors that function as an escape route or are leading to a common area in the house, Bouwbesluit (2012) sets the free passage requirements for a width of 85 cm and a height of 230 cm.
- The partition between floor and window needs to be at least 0,85 meters.

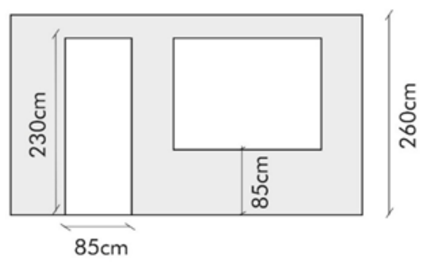


Figure 8: Bouwbesluit rules and requirements for a façade element. Source: own ill.

OTTHER REQUIREMENTS

For the construction of the load-bearing walls and floors, there are certain guidelines. For a prefab concrete load-bearing wall, a commonly used height is 3 meters (Richel Lubbers architecten, n.d.). In this thesis, the load-bearing wall of the façade system will not be higher than 3 meters, so these rules and guidelines will be followed (see Figure 9). If a façade system higher than 3 meters is preferred, a full calculation should be done to guarantee structural safety.

KOLOMMEN / WANDEN (h.o.h. afstand 5 à 6 meter) — **TABEL 1.2** — **BETON**

Element	Horizontale en verticale doorsnede	Gebruikelijke hoogte	ℓ/d tussen zijdelingse steunpunten	Kritische factoren voor dimensionering	opmerkingen
Prefab dragend wandelement		tot 3 m'	20 à 25	- knik - verbindingen - spanning t.g.v. transport en montage	

Figure 9: Rules of thumb for construction, Source: (Richel Lubbers architecten, n.d.)

Examples of standardization

Concrete hollow-core slab

This type of floor is widely used in residential, institutional, commercial and industrial buildings. They are a good barrier for airborne and impact sounds, fire-resistant and have low heat transmission characteristics *(Simovic, 1984)*. The holes in the floor make the floor lighter than a solid slab which will result in lower ma-terial use of about 50% and transportation costs *(Consolis VBI, 2019)*. The holes are also useful for mechan-ical services. It is also known for being a more sustainable floor system with a lower CO2 footprint than for example CLT slabs.

The hollow-core slabs are known for their standardization that consists of standard width of 1200 mm and fitted slabs of 300, 600 and 900 mm *(Table 1)*. The thickness depends on the span, but the floor has a minimum of 110 mm and has a range until 400 mm. In the Netherlands it is more common to have a floor of a minimum thickness of 150 mm. *(Consolis VBI, n.d.; Betonson Prefab B.V., n.d.)*

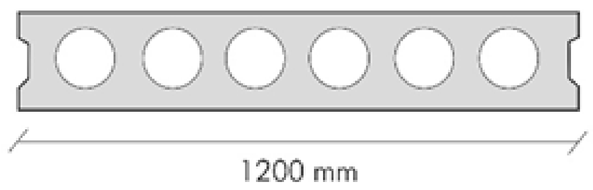


Figure 10: Concrete hollow-core slab. Source: own ill.

Sizes concrete hollow-core slab (NL)	**Sizes in mm**
Standard width	1200
Fitted pieces	300 – 600 - 900
Thickness	150 – 200 – 255/260 – 320 - 400
Length	5000 – 17 500

Table 1: Sizes of concrete hollow-core slab in the Netherlands. Based on: Consolis VBI (n.d.); Betonson Prefab B.V. (n.d.)

Beukmaten/Standard width sizes of a house

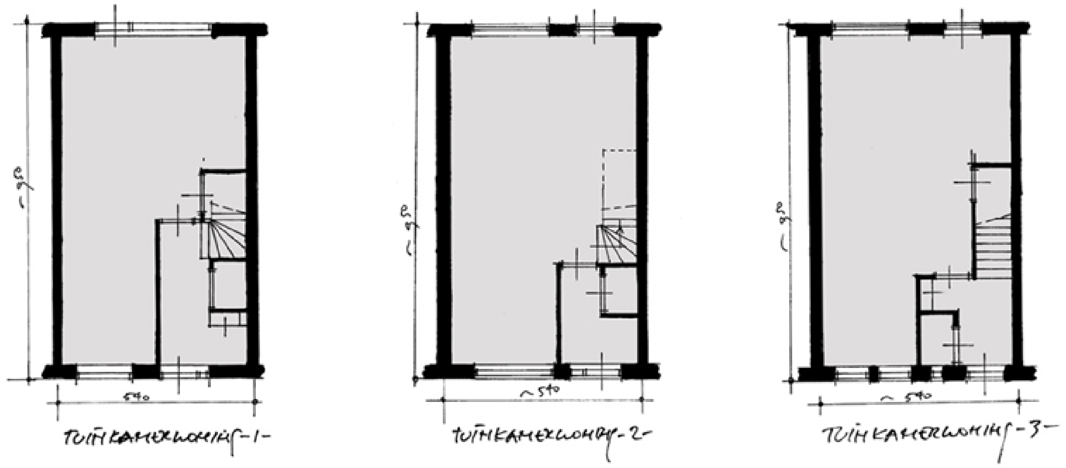


Figure 11: Standard width sizes of a single family house in the Netherlands. Source: (Liebregts, 2012)

These are the widths of a house that are commonly used in the Netherlands. After WOII a lot of houses needed to be built and fast. It was then that standardization and terms like customization and short construction time were becoming popular. A beukmaat of 5,4 and a depth of 9,00 meters were dominant for single-family houses that are in the category of 'tuinkamerwoningen'. These single-family houses are the most
built-in in the Netherlands between 1975 till now *(Liebregts, 2012)*.

Although a width of 5,4 meters is mostly used, a width of 5,7 becomes more popular over the years. As seen in *Figure 11,* the width gives the owner enough flexibility to adjust the interior of the house to their likings. As you can see, both sizes (5,4 and 9,0 meters) are based on a grid of 300 mm. Even chances in these sizes conclude to a grid of 300 mm.

During the literature study for this thesis, a lot of Dutch construction companies were encountered that hold on to this size. A few of these examples are also being discussed in *Section 3.2.2 "Modular systems in the construction sector".*

Residential buildings in the Netherlands

Apartments have a part of 33% in the housing market in the Netherlands in 2012 whereas 1/3 is rental and 2/3 of owner-occupied housing *(Agentschap NL, NEN, & DGMR, 2012)*. The average surface of an owner-occupied house is 105 m2 which includes luxurious penthouses as well as simple gallery apartments. So what are other characteristics of a residential building?

- Apartments can be situated on one level or have multiple levels and private stairs.
- It has a central space with elevators and staircases to ensure so all levels in the building can be reached.
- Most of the time an elongated apartment building has large window openings on the front and back of the façade, but the side façades are fully closed or a minimum of windows due to their load-bearing function.
- Balconies are common for residential buildings to have.
- The dimensions of an apartment in many cases differ from those of ordinary terraced houses. They are often single-story houses with a wider beukmaat. Some going from 5.4 up to 8.3 (those are often on a single level) and in length 9.6 to 14.4 meters of which 10m is the most common.

Maximum size transport (truck - trailer)

Preferred is transporting the panels by the smallest truck size with the lowest weight to avoid producing extra CO2. Although it is also necessary to look at how often the truck will have to drive in comparison with a larger truck and trailer.

Maximum permissible dimensions and total weights for road transport (depends on particular approving authority): *(Bachmann & Steinle, 2011, p. 21)*

	Without special permit	**With annual permit**
Width	2.55 m	3.00 m
Height	4.00 m	4.00 m
Length	15.50 m	24.00 m
Total weight	40 ton	48 ton

Table 2: Standard door dimensions in the Netherlands . Based on: Bachmann & Steinle (2012)

2.2.6 Conclusion on standardization in the building sector

The Netherlands is dealing with a major housing shortage and to meet its growing demand, it is expected to build 1 million houses by 2030. That means that cities are going to expand as more and more people want to live in the city. As there is a lack of space in the Netherlands and it wants to keeps its green environment, cities should be expanding in height and increase the density per square meters by building more high apartment buildings than just single-family houses. It allows applying standardization of a concrete element in this sector.

Standardization for a concrete element means repetition and regularity, making reuse easier to use in the future. It concentrates on the strategy of rethink: design for repeated use. It has many important advantages like:

- A better understanding of a project's party
- Increased safety and knowledge of a product
- Easier to obtain replacement parts
- Easier to track
- Higher quality and better quality control
- Lower construction costs
- Less CO2 emissions
- Less use of raw materials and less waste
- Faster production time
- Lower production costs (repetition)

Unfortunately, standardization is not the easiest concept to apply. It has some restrictions regarding designing a standardized product with flexibility being its main problems. Standard projects obstruct the architectural and form freedom when a building is designed. Other problems that exist are trust issues and lack of collaboration, lack of successful standardization projects, obstructing management methods, high cost in short term, and the failed involvement of manufacturers and suppliers early on.

To be able to achieve standardization, methods have been discussed that can further add to a design strategy and contribute to answer SQ4 *"What dimensions are best suitable for a reusable façade system for the housing market"*.

First of all, modularity is a good design strategy to use in designing a reusable concrete façade system. By using standardized interfaces and modules in this system, these will become compatible compo-nents that fit like puzzle pieces. Secondly finding existing popular sizes and models in the current Dutch housing market, as well as summarizing the requirements of the product can optimize quality, the pro-duction process and method. To answer the research question, thorough research will have to be done regarding the suiting dimensions for the Dutch housing market by analysing existing apartment build-ings and houses and their sizes, based upon the conclusions of existing popular dimensions.

The conclusions of existing popular dimensions in the building industry have resulted in a mini-mum and maximum size for the concrete façade panels used for the building system *(Figure 12)*. These sizes are based on the requirements of Bouwbesluit, the standardization of hollow-core slabs, the maximum transport sizes without needing a special permit, grid sizes and other encountered require-ments. This overview of dimensions can be seen in *Table 2*, where the minimum and maximum dimen-sions for a concrete panel are indicated on the right and the recommended dimensions on the left that focus more on existing standardized dimensions in the building sector.

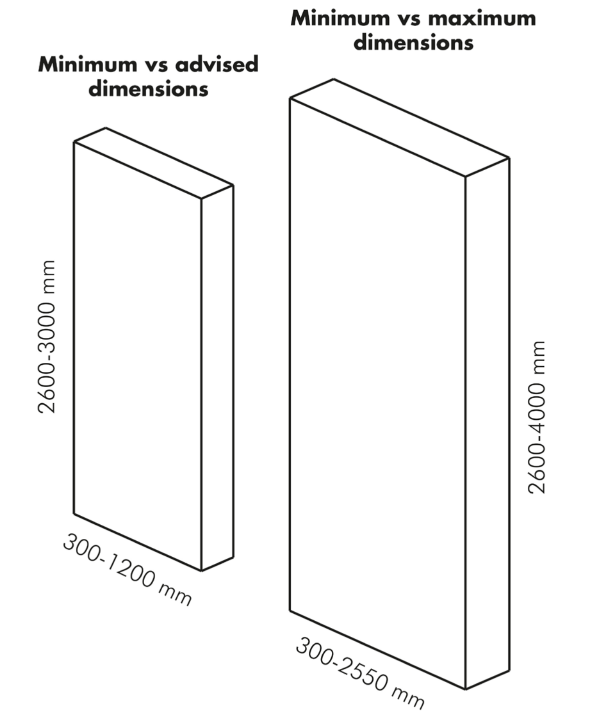


Figure 12: Minimum, maximum and advised dimensions for the concrete façade panels. Source: own ill.

	Bouwbesluit	Hollow-core slabs	Transport	Grid	Other requirements
Min. width		300 mm		300 mm	
Max. width		1200 mm	2550 mm		
Min. length	2600 mm			300 mm	3000 mm
Max. length			4000 mm		

Table 3: Overview of minimum and maximum sizes for a concrete facade panel

2.3 Modular building systems

One of the ways to achieve standardization is to design the product as a modular building system. To connect standardized products as puzzle pieces, modularity helps to make this as flexible as possible. Multiple variations can be made possible without having to change the entire design. In the following paragraphs, this will be explained in more detail about what modularity exactly entails, a comparison between a traditional and modular building system, the concept design for disassembly and time-related building layer, examples of a few connections and modular building systems.

2.3.1 What is building modular?

Modularity in construction often emerges as prefabricated and standardized components or modules designed to manufacture, assemble and disassemble as quickly as possible. It is often adapted for projects that have a temporary and lightweight character. These components or modules are demountable by dry connections and standardized, so expanding or stacking them has been made easier and construction time more efficient. The building time needed for these modules is often lower than traditional building systems as they are designed and fabricated in a way to spend as little time on it as possible. When a module needs to be replaced because of change in user comfort or maintenance, these can be demounted very easily, be updated or maintained and reassembled again.

The question rises if a modular building system is better than a traditional building system, which is used often in the Dutch housing market. To know and choose whether a modular construction is considerably better than a traditional system, both systems their advantages and disadvantages will be discussed and compared.

Advantages & disadvantages of a traditional building system

A traditional building system in the Netherlands is built fully on-site although in recent years it is more common to combine it with the advantages of prefab. A traditional building system consists of an inner cavity wall in building blocks with a certain cladding. This often consists of a cavity wall with a 100 to 125 mm sand-lime brick on the inner side of the house, mineral wool (130 - 180 mm), an air cavity of 40 mm and on the outside a masonry wall of 100 mm thick *(Figure 13)*. These are all placed or bricked on-site and use a wide slab floor or hollow core slab floor. In this construction system, concrete floor systems and hand-made masonry facades are used. In Table 5, an overview of the advantages and disadvantages of a traditional building system can be seen based on *Karthik, Sharareh, & Behzad (2020) and Kingspan Tek (2015).*

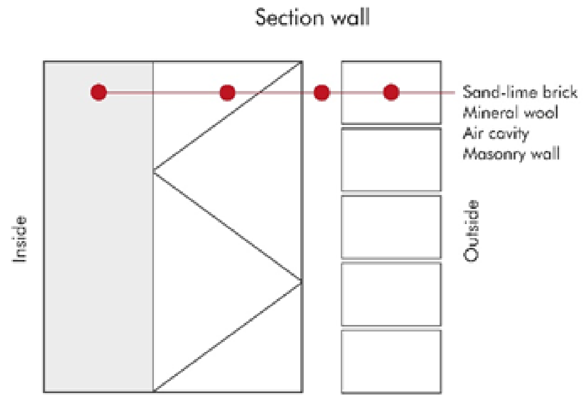


Figure 13: Section of a traditional building system. Source: (own ill.)

ADVANTAGES

- Great flexibility in design: freedom in cladding and variations in brick bonds
- Good thermal and acoustic insulation
- Relatively low costs of materials

DISADVANTAGES

- Longer construction time: not prefabricated but built on site
- Labour intensive (more costs)
- Smaller floor space, due to thick insulation
- High weight
- Dependent on weather conditions

Flexibility: Constructing a housing project traditional often means more design flexibility for the designer. The designer does not have to stick to certain module sizes and can make crazier shapes with them.

Low material cost: the production of lime and masonry bricks are sold locally and relatively cheaply in the Netherlands, as well as the relatively cheap and often, used mineral wool
.

Longer construction time, labor-intensive and dependent on weather conditions: in traditional construction, everything is built piece by piece on the construction site. This takes up a lot of time and manpower than other construction methods. Also, it is much more dependent on weather conditions, which can be delayed and entails more risks such as the risk of more accidents because the work is labor-intensive and requires heavy work, among other things.

Smaller floor space: The system uses thick insulation and ensures that less living space is created. Also, Bouwbesluit is constantly tightening up its requirements, which means that the insulation of a traditional construction system is getting thicker.

Overall, the traditional construction system has its focus *not on the speed of construction and labor intensity,* but more on the *flexibility and the lower material costs* it offers. The question is whether a modular construction system is better suited for a reusable system than a traditional one.

Advantages & disadvantages of a modular building system

Modular construction has many advantages, but also some disadvantages that need to be discussed to consider modular above traditional construction. Both will be discussed whereas the advantages of a modular building system lie in the building speed/efficiency, cost-effectiveness, improved safety, production speed/efficiency and reduced environmental impact based on information gathered from *Karthik, Sharareh, & Behzad (2020) and De La Torre (1994):*

ADVANTAGES	DISADVANTAGES
The building speed/efficiency	Extra planning and construction effort required
Cost-effectiveness in construction	Complex coordination
Improved safety	Transportation difficulties
Production speed/efficiency	Negative perception
Improved environmental impact	Reduced flexibility/adaptability to design changes
	Increased costs due to its complexity

The building speed/efficiency
What makes a modular construction so efficient and fast, is that several activities can take place at the same time and by prefabricating it, weather conditions have less impact on the schedule and there is less risk of delay. As a result, the construction time in a modular constructive project is often 40% less than a traditional construction system. This is very suitable for projects that need to be built up quickly due to, for example, a shortage of housing or a building reconstruction after destruction.

Cost-effectiveness in construction
When building modular, it is expected that construction costs are 10% to 25% lower than building traditionally. This is because prefabrication in a factory ensures the efficient construction of building components, less need to transport materials to the construction site, less labour-intensive work on the construction site and less impact from weather conditions, which causes delays which costs money. Also, standardization is an important cost aspect of modular construction. Failure costs are relatively low and often little to no repair work is required to resolve errors in planning, design, or implementation. This means that projects are delivered considerably earlier, which benefits the efficiency of the customer. Also, the repetition in the production process significantly improves production speed and reduces costs.

Improved safety
By working a lot on the construction site, the safety of the workers is compromised. Due to the increasing accidents on the construction site, scientists have been looking for safer construction methods to limit these dangerous situations as much as possible. Modular construction reduces construction site accidents by 80%, but it must be remembered that special safety requirements must be considered for this type of construction. Not to be forgotten is also the repetition in the production process through standardization, which ensures greater safety. Mistakes are less likely to happen at the factory by repeating the same process.

Production speed/efficiency
The production is greatly improved by standardizing, controlling and automating the process of a modular product. As said before, repetition causes the process to be more safe and fast as labourers are performing the same procedure over and over again. In the end, such a production process has great potential in making a product that is quickly produced, of higher quality, less expensive, and can be produced on a larger scale in a short period than products produced at a construction site.
Improved environmental impact
By prefabrication, the waste generated in modular construction is way lower than that of a traditional system. The biggest aspect is that the product or components within the product can be replaced, reused and if needed, easily recycled due to the separation of building layers. Another factor is that these modular constructions are often built lightweight and contribute to less material use and therefore less CO_2 emissions.

Unfortunately, modular construction also has some disadvantages which include a need of extra attention for the planning and construction, difficulties with transportation, the negative perception of a modular building system/reuse, the flexibility or adaptability to design changes (due to standardization) and the increased costs of the often complex logistics within a factory *(Karthik, Sharareh, & Behzad (2020); De La Torre (1994)):*

Extra planning and construction effort required
The planning is especially challenging when building modular as a modular building system is often more complex than a traditional project. The production process requires extensive planning to have such a complex product produced and assembled fully in a factory. It also means putting more effort into designing and engineering such a product and requires excellent logistics to be produced automatically and quickly.

Complex coordination
To be able to build a modular system as efficient, safe and as fast as possible on site, a well thought out coordination is required.

Construction planning is often complex and requires good coordination to be able to finish a project on time and make it cost-effectively.

Transportation difficulties
The prefabricated modular products or components are often bigger than the loose materials that need to be transported for a traditional building system to the construction size. Transportation difficulties can happen when a product is oversized which can result in extra costs for special permits, need more planning and can cause delays. These problems can be avoided when considering this in the early stages of the design.

Negative perception
Disassembling a product and reusing it again has still a negative perception in the current society. As said before in *Section 2.1.3 'The barriers of high-value reuse of concrete'*, questions about, for example, the structural ability after usage arises. It can take a while before such perception will disappear.

Reduced flexibility/adaptability to design changes
Standardization is an important aspect of modularity and causes less freedom in flexibility/adaptability in designing as well as adding changes to a project at a later stage.

Increased costs due to its complexity
Although the construction cost is greatly reduced by prefabricating the product rather than producing and manufacturing it on-site, the costs will increase off-site. Manufacturing everything in a factory, requires space, expensive machinery and complex logistics. It is also a relatively new concept that requires parties involved to know about modular and prefabricated construction and building systems. Modular designs have often innovative ideas that are new and complex and can result in increased costs when being produced and manufactured. Besides, reusing modular structures means that certifications are needed that proves they still meet the structural requirements after repeated and thus gain the confidence of consumers but leading to higher costs.

Advantages & disadvantages of a modular building system

So what makes a modular building system better compared to a traditional system?

The biggest advantages of a modular system are economic and sustainable aspects. It offers the possibility to be assembled and disassembled quickly by using innovative connections that are demountable. By building modular you ensure less material use and waste by both prefabricating the whole system in the factory and being able to build the system lightweight. Besides, standardization in a modular construction system ensures repetition in the production process, which has many advantages such as better product quality and a faster and safer production process. By prefabricating everything in the factory, you ensure fewer risks on the construction site itself, which means less dependence on weather conditions and less risk of delay (which costs money), but it also has less labour-intensive work compared to a traditional system. Everything has to be put brick by brick on the construction site by masons with a traditional system instead of building this more efficient. Finally, a modular system is special because it offers the possibility to disassemble it due to its dry and detachable connections.

Overall, a modular building system is a better method to use as a tool to design a sustainable and reusable concrete facade system. Speed in production and construction, being standardized and demountable are one of the most important factors. They are needed to achieve the ambition to build 1 million houses before 2030 in the Netherlands and is necessary to make the built environment more sustainable.

2.3.1 Concept of design for disassembly

To make a design reusable and therefore modular, it is a must to design with the concept of design for disassembly. Design for disassembly is an approach to carefully and methodically disassemble the product to reuse it again and give it a new life. Unfortunately, it has not been used very often in the past in the Netherlands, but it is getting more attention in recent years.

As seen in *Appendix A*, a big part of our housing stock is built after the Second World War (from 1945), when the Netherlands needed to build fast and efficient to be able to supplement the housing shortage after the loss of a lot of houses during this difficult period in history. The problem with these houses and residential buildings is that they can't be reused in elements or components as it is not designed to do so. Still, architects and engineers think of a conventional way of constructing these (concrete) buildings and focus on the aesthetics and the function, instead of giving thought to the end-of-life phase of the building *(Salama, 2017)*. Most are recycled when demolished and the rest dumped at a landfill. It is regrettable because when designing the product with a DfD mindset from the beginning, it can encourage the concept of reuse, spare a lot of materials, extends its service life and therefore reducing CO_2 emissions.

To make the concept of Design for Disassembly work, there are a few key principles for Design for Disassembly set up by *Durmisevic (2010) and Rios, Chong, & Grau (2015)*:

Key principles Design for Disassembly (DfD)

Proper documentation of the materials used and the methods for deconstruction
Design the accessible connections and jointing methods to ease dismantling o Use the right connections (dry) o Use prefabricated and/or modular structure
Separate non-recyclable, non-reusable and non-disposable items if it contains mechanical, electrical and plumbing systems
Design a simple structure and forms that will allow standardisation of components and dimensions
A design that compliments labor practices, productivity and safety.

Figure 14: Key principles of Design for Diassembly. Based on Durmisevic (2010) and Rios, Chong, & Grau

For the design of a reusable concrete façade system, the focus will lie mainly on the use of accessible connections and jointing methods that ease dismantling, designing a simple structure and forms that allow for standardization of components and dimensions, and a design that compliments labour practices, productivity and safety.

It is important that elements or components of value that are being reused stay in a good shape after being disassembled, otherwise it cannot be guaranteed to be safe or of enough value to be reused. These principles will be further explained through a few themes that will apply according to *Crowther (2005), Durmisevic (2006) and Salama (2017)*:

- **The functional,** technical and physical **composition of a building**
- **Time-related building layers**
- Recycling hierarchy

Hereby, the focus will lie upon understanding the functional composition of a building and the time-related building layers, because of the importance of:

- **Independence:** elements and components being separated from each other to be maintained or replaced individually to increase the lifespan of the product.
- **Exchangeability:** designing a simple and easy to be produced, assembled and disassembled product

Functional composition of a buildingon of a building

As described by Durmisevic's model in *Figure 15*, the key indicators of reuse are the independence and ex-changeability of building products. Independence drives on the separation of functions on building, system and component levels as well as focusing on independent function modular elements. Exchangeability stands for making the design as easy as possible: minimize the complexity, reduce the number of relations of elements that are intertwined with each other and try to use correct connections that are supporting design for disassembly and reuse *(Durmisevic, Beurskens, Adrosevic, & Westerdijk, 2017)*.

The figure shows different design domains, performance criteria and disassembly aspects which are associated with eight design criteria (*Figure 16*). The first two design criteria of functional decomposition involve an explanation of the separation of functions and lifecycles and will be explained further to understand the independence of elements. The importance of a type of connection (criteria 7) will be explained in the next *Section "Connections"*.

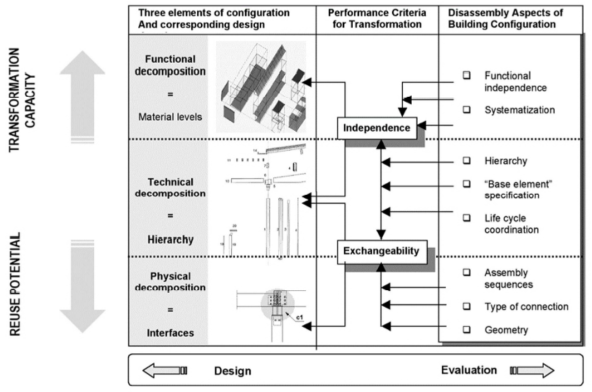


Figure 15: Guidelines of Durmisevic's model to see how much a building structure can be reused and disassembled safely. Source: Durmisevic, Beurskens, Adrosevic, & Westerdijk (2017)

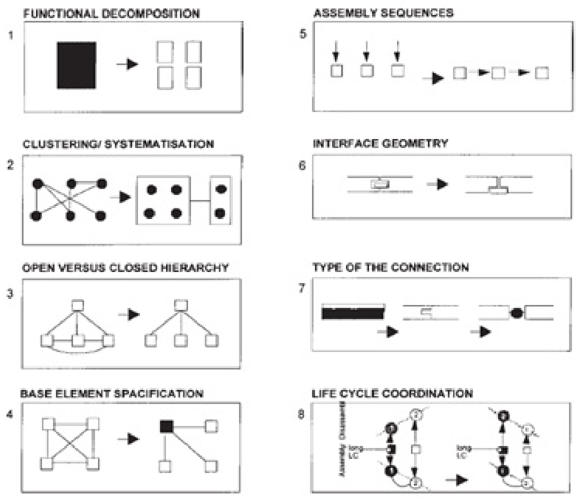


Figure 16: Eight design for disassembly aspects of building configuration Source: Durmisevic (2006)

Functional decomposition

Most of the time this is the first domain architects and engineers are confronted with when they design a modular structure that involves two aspects of *Figure 18* (Durmisevic, 2006):

1. Functional decomposition (independence)

In design, it is necessary to separate all relations between functions and components to make it as less complex as it can be and easier to be dismantled. So make each function that has a different life cycle and performance independent form each other.

In this thesis, it will be focusing on an exterior wall system with functions such as finishing, insulat-ing and bearing. The goal is to separate these to be able to disassemble independently because of their different life cycles (*Figure 17*). This will be exampled further in the next *Subsection "Time-related building layers"*.

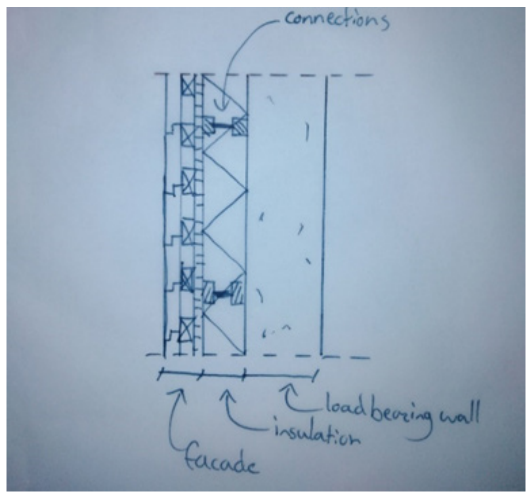


Figure 17: Functional independence external wall. Based on: Durmisevic (2006)

2. Clustering/systematisation:

This aspect is to categorize/cluster elements or components so they can perform a certain function. The complexity of the design's technical composition depends on which functions are integrated or which aren't. This is mostly influenced by the life cycles of all the layers/functions and how to separate these, and what their functions are. It is important to have as few disassembly options as possible because this can lead to the decision to choose demolition over reusing a product as it can become a too complex and time-consuming process. The clustering of the correct functions and life cycles can lead to a few disassembly options.

Time-related building layers

The concept has been founded by Frank Duffy and later on further elaborated by Stewart Brand as they see that a building consists of different layers that are changing over time. The following *Table 4 and Figure 18* describes how Brand sees the layers of the building and its life span *(Crowther, 2005)*:

Layer of a building	Life span (years)
Site	Eternal
Structure	30-300
Skin	20
Services	7-15
Space plan	3-30
Stuff	Daily

Table 4: Building layers and their life span according to Brand, Based on: Crowther (2005)

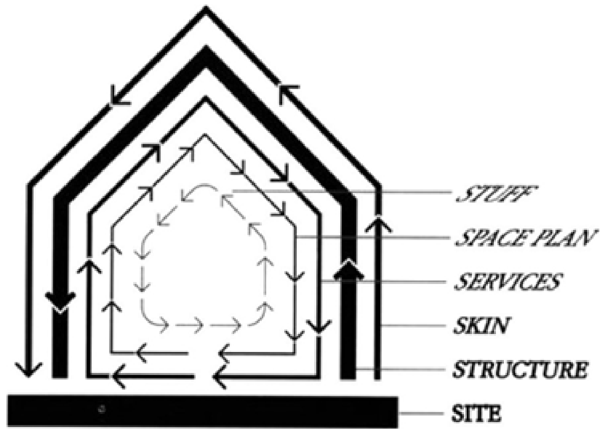


Figure 89: Building layers and their life span according to Brand, Source: Salama (2017)

- **Site:** the location of the building.
- **Structure:** load-bearing elements & foundation
- **Skin:** external surfaces
- **Services:** things like plumbing and electrical wiring, ventilation, etc.
- **Space plan:** the inner layout of a building like partition walls, ceilings, windows, etc.
- **Stuff:** the interior, like couches, tables, kitchen, etc.

When designing a reusable concrete facade system, you must take into account all these different layers and their life spans as these need to be separated to ensure that all the layers can be replaced or changed without having to damage or remove one and another. The product has to deal with different kind of scenarios where these layers must be able to change separate from each other. To know what to separate in the reusable concrete facade system, *Figure 19* shows information about the layers and their life span.

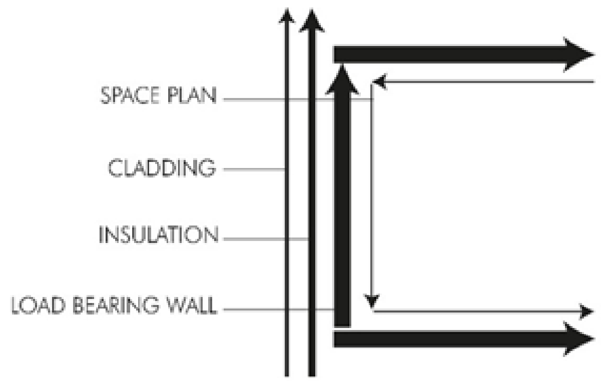


Figure 19: Facade layers and estimated life span. Source: own ill.

2.3.3 Connection

Designing joints and a connection for a precast concrete structure is one of the most important things to keep it standing. They have to transmit forces between structural members so it will provide robustness and stability. Not only have joints resist loads, but also abnormal loads due to fire, impact and explosion. Alt-hough this is an important factor, in this research these loads will be excluded. There is a different kind of connections that can achieve these criteria which will be discussed in the next chapter. One connection can be a smarter move than the other, depending on different kinds of aspects of the design and construction of a building.

It can be that there are several load-transmitting joints within a single connection. It is therefore important to explain the difference between joint and connection:

A **joint** is the action of forces (shear, tension, compression, etc.) that happens at the interface between two (or more) structural elements. Between these structural elements, there is often in between, such as rubber, steel, felt, cementitious mortar, etc..

Connection types

There are three types of connections: direct (integral), indirect (accessory), and filled *(Durmisevic, 2018):*

Integral connections: a connection where the geometry of the edges of the components forms a complete connection.

- *Overlapped connections (Figure 20)*
  Most of the time used on vertical external façade components, components in the vertical or horizontal direction. Disassembly depends on the assembly sequence, the hierarchical position of components and their relationship, but also the material of the connection. It often needs an external connection to ensure structural safety.

- *Interlocked connections (Figure 20)*
  Disassembly is more difficult because the shape of the edges causes a sequential assembly. Like overlapped connections, it often needs an external connection to ensure structural safety.

A **connection** is the action of forces (shear, tension, compression, etc) and/or moments (bending, torsion) that happens with an assembly of one (or more) interfaces.

Before choosing certain connections, some things must be considered and asked that can be set the base of the technical requirements *(C.H. Raths, 1974):*

- Which forces are there on the structure and how can the connection transfer forces?
- Is the connection easy and reliable?
- If the details are practical, do they lend themselves to standardization?
- Is it demountable?

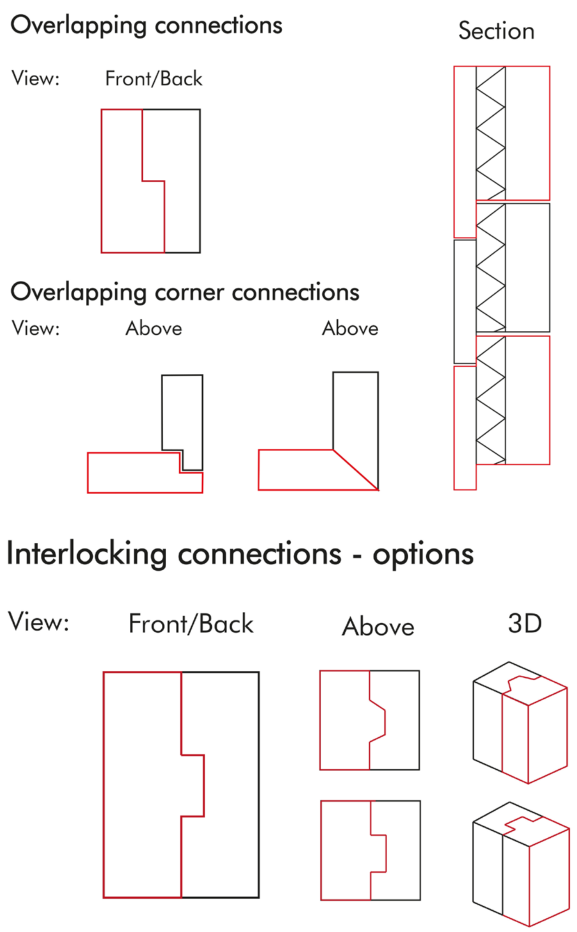


Figure 20: Examples of overlapping and interlocking connections. Source: own ill.

STRUCTURAL SUPPORT SYSTEMS

To understand what kind of connections are necessary to use for your design, we begin looking at what kind of supports exist (Figure 21) and what they do. A structural connection can be (Luebkman, & Peting, 1998):

1. Roller support: This support is free to rotate and transfers its force along the surface upon which the roller is resting. It can only transfer a single force that is perpendicular to the support surface. It doesn't matter in which angle the surface is laying. For example, if the support surface is the floor it can only take vertical forces.

It is often used for bridges, so the structure can expand and contract when there are temperature changes. Fixing it in its place can heavily damage the structure when expanding, so roller support is necessary.

2. Hinge/pinned support: A hinge can transfer tension, compression and shear forces, so both vertical and horizontal forces but not a moment. It can rotate but not to transfer in any direction. Take a door, for example, when opening the door it will allow rotation only around a distinct axis and blocks it from going towards the other axis. The hinge blocks vertical and horizontal translation.

3. Fixed support: It can resist a moment, vertical and horizontal forces. It is also called rigid support as the supports block rotation and translating. An easy example can be a lamppost set into a concrete base.

4. Simple support: It is frictionless surface support if the reaction in a single force that is perpendicular to the surface. To have sufficient resistance to side loads, the gravity force and the friction it has to endure must be considered. It looks a lot like roller support, but the difference is that simple support cannot handle lateral loads. An example can be a plank that is being laid across the ditch to serve as a bridge. It will stay in place unless you move it because it is a simple connection that doesn't have any resistance to the lateral load it is receiving.

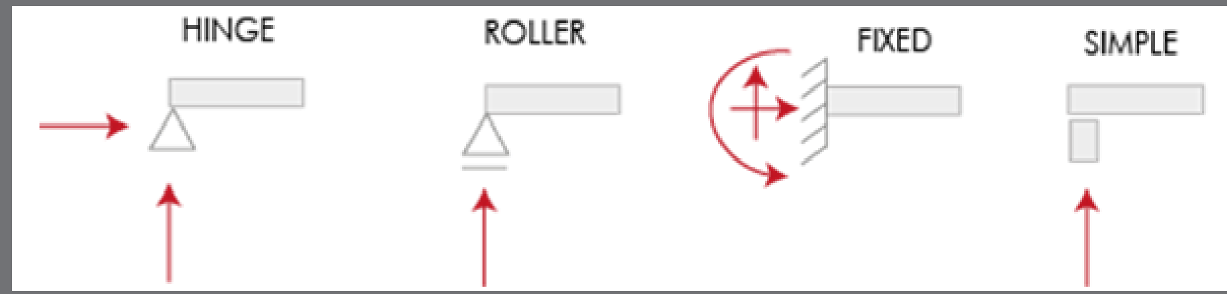


Figure 21: Types of supports and their reactions. Source: own ill.

- *Accessory connections:* extra components are used to form parts of a connection
  - Internal connection: a loose accessory that links components. Dismantling these connec-tions is difficult.
  - External connection: dismantling is easier with for example the use of a frame and cover strips attached to it.

- *Filled connections*: the connection between two components that are filled on-site with chemical materials. The chemical materials often cause an element to be unable to be dismantled and the method is also labour-intensive. An example is a welded connection.

Out of these connections, the *overlapping, interlocking, or external accessory connections* should be considered as possible connections for the design of the concrete facade system. When designing, different factors that influence the disassembly of a connection should be taken into account:

- *The number of connected devices:* minimize the number of different materials, connections and components
- *Type of material used in a connection*
- *The form of a components edge*
- *A fixed (wet) or flexible (dry) connection:* a wet connection can greatly damage an element when disassembling. An indirect dry connection is the best way to make a demountable element without damaging the rest of the building.

Connections of a precast concrete wall element

In this chapter different types of connections regarding precast concrete wall elements and what kind of loads there are designed for will be discussed. We can separate the term 'walls' as load-bearing and non-load bearing walls. They are support elements between the floors, roofs, or beams. Non-load bearing walls only involves carrying their dead weight and the wind load. The loads on top of a wall element are being resisted by horizontal joints. Next to that horizontal and vertical joints have to resist the shearing forces that are occurring on the wall by wind. To transfer the forces of the wind and deadweight onto the wall, it can be fixed to the load-bearing system, so it's supported by it. The connections that fix this are forming a bridge between the elements and provide structural chains that are connected to the stability elements, like shears walls or the core. The connections have to guarantee structural continuity of the structure as a whole and transfer all the forces between the structural elements when loaded.

The connections of a precast wall are exposed to different forces and can be different in each of them. As explained before, the joint is the element that is transmitting these forces in the connection. The goals of a connection and joint are:

- To transmit forces between structural components
- Provide overall stability
- Provide strength to the structure
- Prevent external leakages

Forces and loads on a building

Vertical loads are transferred by bridging elements and supporting elements. Bridging elements in a building can be the floor, beams, the roof and stairs. Supporting elements are load-bearing walls or columns. Horizontal forces, like the wind (or forced forces like shrinkage, creep, etc.), are transferred to the foundation by stabilizing structural elements.

Connections transfer forces between elements due to 'normal' vertical and horizontal loads, but also forces due to shrinkage, thermal deformation, fire, etc. It also has to provide a reliable and robust structure that also accounts for accidental loads.

Existing connection systems

When designing a reusable concrete facade system, it is useful to gain an overview of existing connection systems that are innovative and focus on efficient and demountable construction. *Appendix B* explains these different connection systems in which it is discussed how it works and what the advantages and disadvantages are.

Each of these systems belongs to a connection type *(Figure 22)* of which an overview will be created in the following subset that clearly shows which systems can be applied to which connection type.

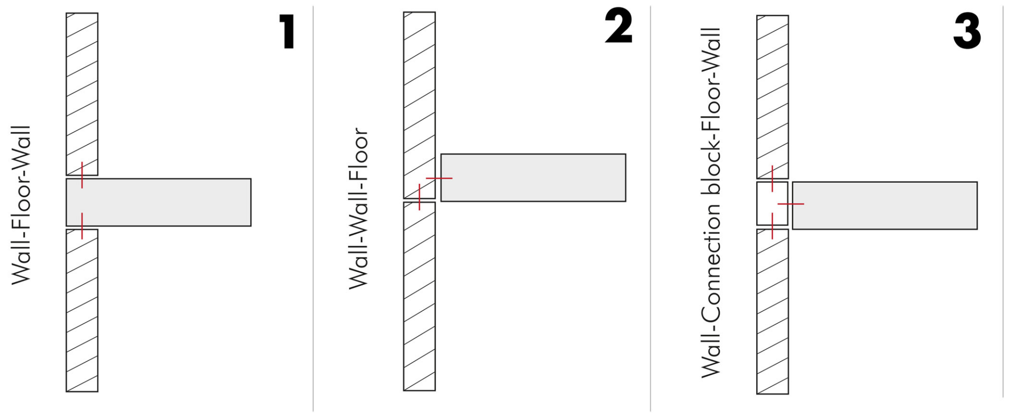


Figure 22: Three different connection types. Source: own ill.

2.3.4 Modular systems and building projects

There are many companies nowadays engaged in the principle of modular construction. This is especially with projects that need to be finished very fast or are temporary buildings like, for example, schools, houses, or office buildings. It is important to see what current projects are aiming for and what they are doing well when it comes to modular construction so that this can be applied in the final design. Therefore, a few modular projects on different scales and from the Netherlands or abroad will be discussed.

Keramus Utrecht – Jan Snel

A residential building is designed for students in Utrecht which needed to meet the strict requirements of Bouwbesluit and aimed for low energy use. The housing modules were prefabricated and therefore could be mounted together on-site very fast. On some days they could even assembly 16 modules a day which resulted in being finished after altogether (design, production and assembling) in 10 months.

The housing modules consisted of an outer size of 3,2m by 7,7m with a net floor space of 21 m2 which consisted of living space, a small kitchen and a bathroom. Each module is built up by a steel cage construction with concrete flooring and timber frame walls and ceilings. Between the modules are air cavi-ties that ensures very good sound insulation. The prefab modules are stacked dismountable and can be reused when this is necessary.

The modules are not adaptable to change as the modules come in one form only but from the per-spective of the architect that makes sense. The architect has chosen for a specific target audience, stu-dents, where such one sized model and temporary character fits this. It is also remarkable that they used steel cage construction and timber walls for the modules, probably because of its lightweight characteris-tics.

Figure 23: Construction of Keramus Source: Jan Snel (2019)

20 NoM-housing Belle-Vue Delftlanden, Emmen – Ursem 2019

Belle-Vue is a project of forty prefabricated house units that have been produced in 2 months, in 20 days on-site. Each unit consists of concrete floors and timber supporting construction to be the base for the single-family house of 105 m2. They are very easy to stack, mount and eventually to demount. The maximum modules sizes are 4000 mm by 14400 mm.

Ursem also has Modular building systems that consist of a concrete support system. These have a maximum of 4000 mm by 9000 mm for the module because of the weight of concrete. Here the concrete floor, the concrete columns and the stability braces (in the walls) support the housing unit. In this way, the modules can easily be stacked.

Remarkable is that Ursem presents to different construction types, one that consists of timber and the other of concrete. With timber being lighter, but concrete having a better acoustic performance and is probably better when stacked next to each other.

U-build system – Studio Bark, 2019

The system is a modular construction system that is made for people to build their homes by themselves (*Figure 24*). It consists of a flat-pack kit that is made from wood which can be connected to make a building frame. After it is time for something new, it can easily be demounted and reused again (*Crook, 2019*). The package comes in various sizes which makes it possible to make all kinds of different frames and openings. The idea is that it can be made with simple tools, such as a hammer and a screw drill machine, and that it doesn't require a lot of skill and experience.

It is a good example of a project that focuses on exchangeability, the easiness of how it can be built. It is standardized but available in different sizes and useable in different directions which makes the design more flexible. It is also adaptable to change, although changing or replacing an element will result in partly disassembling the structure. This project also has a clear target audience, the do-it-yourself audience.

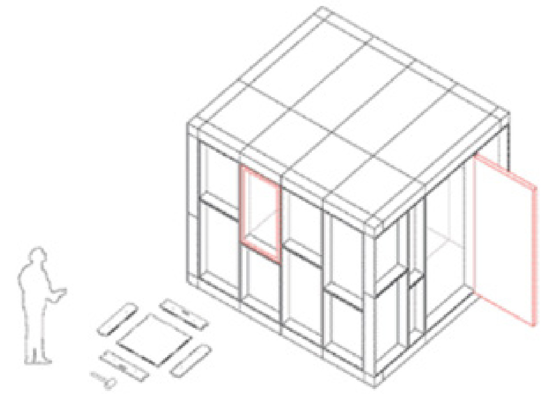


Figure 24: Flat pack kit that can be assembled into variety of different building frames. Source: Crook (2019)

Building system MUWI, the Netherlands - Muijs en De Winter's Bouw- en Aannemingsbedrijf

This MUWI system is used for apartment floors (before 1965) and gallery flats (after 1965), where during this time around 30 000 houses were built, making it the most successful post-war building system (*Andeweg, 2013*). Different types of housing could be built together as long as it holds onto the standard dimensions. Often in multi-family housing flats, several housing types were built, ranging from two to five-room houses (*BouwhulpGroep, 2013*).

It is a stacking building system that has a lot of developing phases during its existence to enhance the construction, thermal and acoustic performances. It consists of (hollow) lightweight concrete block (*Figure 25*) of around 50 cm long, 19,4 cm high and 21 cm wide that are stacked in a 'halfsteensverband' to form walls and are used as filling elements for the floors between concrete beams. After the bearing walls are stacked, the holes are filled with concrete on-site so it becomes a stiff and massive wall. The load-bearing walls didn't need any reinforcement if it had four building levels or lower. The walls are part of a cavity wall which has some insulation advantages that were developed during 1954-1959 (*BouwhulpGroep, 2013*). Because of the larger 'beuk' sizes, it is flexible in changing the layout within the existing dividing walls. These sizes were often based on the minimal sizes of the living room, entry and kitchen in a house (*Bouwhulpgroep, 2016*). The living room has often a width between 2.4 till 4.8 meters.

The most remarkable aspect of the MUWI building system is its use of lightweight concrete blocks that are hollow and contribute to the strategy of building lightweight.

It has been proven that it is a successful system as only under 5 percent of the building built with MUWI has been demolished in the past thirty years, although the houses require renovation because of higher requirements of Bouwbesluit (*Liebregts, 2013*).

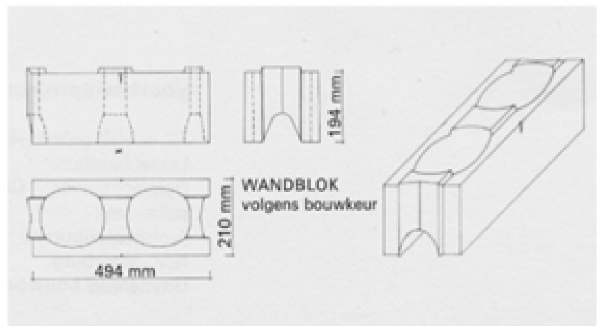


Figure 25: MUWI building block. Source: Andeweg (2013)

Remarks

They all have a clear target group in mind and designed, produced and built extremely quickly. Further, it is striking that the first two modular projects (Keramus and Ursem) consist of a 'box' module. You are therefore bound to a certain layout and it is no longer possible to adjust it in size. This was a conscious choice by the architects, who have chosen a specific target group and have less likely to different preferences in the future. It is also striking that many works with wooden frames as supporting structures. That choice will probably be based on its light character and one of the important strategies of reuse strategies is building lightweight. Although this is also possible with concrete and the MUWI building system is proof of that. By creating a lightweight form in the structurally safe concrete block, it also contributes to the strategy of building lightweight. At last, the principle of exchangeability was also very clear with most projects, making the assemble and disassemble method as easy as possible.

2.3.5 Conclusion on modular building systems

In the building industry modularity characterizes itself in being temporary, prefabricated and consisting of standardized modules or components that are designed to be manufactured assembled and disassembled as efficiently as possible. A modular building system offers advantages that compete with those of a traditional system, but it has some disadvantages as well:

ADVANTAGES

- The building speed/efficiency
- Cost-effectiveness in construction
- Improved safety
- Production speed/efficiency
- Improved environmental impact

DISADVANTAGES

- Extra planning and construction effort required
- Complex coordination
- Transportation difficulties
- Negative perception
- Reduced flexibility/adaptability to design changes
- Increased costs due to its complexity

Although it seems to have many disadvantages, most of them can be overcome in the short and long term. If thinking about coordination and transportation in the early stages of the design process, these difficulties can be avoided. Increased costs due to complexity and a negative perception of the public eye and in the building industry, are barriers that can take a longer time to overcome but can speed up if more modular projects are being realized.

The advantages of a modular building system outweigh those of a traditional system regards designing a reusable concrete building system. Especially in its building speed/efficiency and improved environmental impact, but loses when it comes to flexibility in design, an aspect that requires creative and innovative solutions when designing a modular building system.

When designing a reusable and modular system, the concept of design for disassembly should be used as an approach to carefully and methodically disassemble the system to be able to reuse it multiple times contributing to the strategy of **Reuse**. Principles that help create such an approach are understanding the function composition for building and time-related building layers. Their focus is on the independence of the product and separation of functions or layers of different levels, like systems or components, and in making the design as easy as possible, its exchangeability. The type of connection is part of realizing functional decomposition and needs special attention to be able to independently change components within a system. More importantly, the type of connection is important for the structural safety of a system and will help with the answering of:

SQ5: *How to design a reusable facade system that guarantees structural safety?*

Overlapped, interlocking or external accessory connections are good examples of demountable connections for a building system. With these connections, attention should be given to minimizing the number of devices, the type of material in a connection and the form of the edge of the component to be able to disassemble a connection. A few existing demountable and innovative connections systems have been looked up, analyzed and will be used in the design for a reusable concrete façade system as possible connections for load-bearing parts.

To understand modular building projects better, a few projects were shortly looked into. They all designed, produced and built very quickly, but striking was that some consisted of 'box' modules which makes it difficult to adapt to change in the future, but the architects have thought this through as their target audience is less dependent to change. In the design, it is important to look at different target audiences and their preferences to better understand their needs. Another remark was that some projects worked with steel and timber frame instead of concrete for lightweight purposes, but by making a (hollow) lightweight form in the concrete panel or block, like the MUWI-system or a hollow-core slab, the strategy of building lightweight can also be achieved with a concrete system.

All these conclusions can be translated into two main focus points and sub-points for the design criteria and process that partly answers SQ1:

Building efficiency: how fast and efficient the design can be produced and built

- *Prefabrication:* Minimum construction time, waste and construction site costs
- *Standardization in production*: repetition in the production process
- *Faster construction time:* Less interest and labour costs etc.
- *Designed for disassembly:* the system can be reused
- *Weight and material savings:* Thinner and lightweight walls, less construction waste

Adaptability: how easy the design is to adapt to user preferences

- *The independence of functions and life cycles*

2.4 Sustainability of concrete

2.4.1 Introduction

Sustainable development: *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" – Brundtland, 1987*

It is hard to imagine a world and built environment without concrete as it is the second most used material in the world. The demand will continue to exist in the future and so it is important that we continue to strive for a concrete industry that is more sustainable, durable and economical (Aïtcin & Mindess, 2011; Şanal, 2018). This acquires major changes in the industry to achieve these goals that involves all levels of the lifecycle of concrete: material, production, manufacture, design etc.. Especially the carbon emissions gasses that concrete produces throughout its life are a problem that is getting more attention now that global warming is a bigger issue than ever before.

To answer the SQ3 *"Which factors of capturing and storing CO2 play a role in the lifecycle of concrete?"*, we first need to begin researching SQ2 *"What are the characteristics of all the different of types concrete; its strengths and weaknesses?"*. There are a number of ways to make concrete more sustainable and there already are some techniques that contribute to this. To make it more sustainable there are a few approaches that can be reviewed *(Aïtcin & Mindess, 2011)* and cseen in the summary to the right.

The focus in this research will be mainly on the highlighted approaches. Both the material as the production process of concrete will be discussed, evaluated and how these approaches are already improving the sustainability of concrete or can be further improved.

The focus of this research will be mainly on the **highlighted** approaches. Both the material as the production process of concrete will be discussed, evaluated and how these approaches are already improving the sustainability of concrete or can be further improved.

SUSTAINABLE APPROACHES

- **Finding ways to capture and store CO2 emissions**
- Using concrete of higher strength
- **Reduce the portion of Portland cement by at least 50% with other cementing materials**
- **Manufacturing Portland cement more efficiently** (focus is on compressive strength instead of durability)
- Using fillers (materials that do not react chemically with Portland cement)
- **Making concrete more durable**
- **Using recycled concrete or other wastes materials as aggregate sources** (Slimbreken has this technique)
- Using less water during production of concrete
- Using waste materials as fuels
- The use of cement kiln dust instead of Portland cement
- Improved structural design and building codes

2.4.2 Characteristics of modern concrete

Nowadays concrete is all over the world. In the Netherlands alone we already produce a total of 13 million m3 concrete per year which results in about 0,75 m3 concrete per resident (on the whole earth this is even 1,4 m3 per person); about 4,5 million m3 is used for the concrete product industry, mostly in the housing sector, and 7,5 million m3 by the concrete mortar industry, for street tiles and elements for the housing and utility market. The CO2 emissions causes around 3,5Mt per year and 80% of this is due to the production of cement. To put this in perspective, this 3,5 Mt is 1,7% of our yearly CO2-emmision *(Betonhuis, n.d.)* and one ton of cement produces an average of 750 kg CO2 *(Cement&Beton centrum, n.d.)*.

If it produces so much CO2, why do we use it so often? Well, it is an excellent construction material *(Aïtcin & Mindess, 2011; Mindess, Young, & Darwin, 2003; Mindess & Young, 1981)*:

ADVANTAGES	DISADVANTAGES
Durable	Low fracture toughness
Strength	Low tensile strength
Economical	Low specific strength
Safe	Low ductility
Versatility	Shrinkage
Energy efficient	Mold or framewrok needed
Excellent sound & vibration insulation	High weight~strenght ratio
Fire resistant	Strict quality control needed
100% recyclable	Requires curing
Often produced locally	Undergoes creep
On-site fabrication	

Figure 26: Advantages and disadvantages of concrete

ADVANTAGES OF CONRETE

Durable
It is built to last and has an average service life of 50-100 years. Concrete structures are resistant to weather conditions and need therefor few repairs and maintenance. It is also ideal to underwater structures because concrete can handle water without serious deterioration.

Strength
It is strong enough to provide protection against earthquakes and severe weather conditions. The strength is gained when the concrete hardens and this process can be done in all ambient weather conditions. Concrete even gets stronger over time.

Economical
The production process of concrete is pretty low. The ingredients of concrete are available over the whole world and of low cost at local markets. It is more accessible compared to materials like steel and polymers.

Safe
Safety can be translated to secure and healthy as the concrete is fire resistant and isn't vulnerable to mold. It also holds back outsides pollutions which can provide an indoor air quality that is healthy. The indoor air quality can also be perfectly controlled by the user or owner of the building.

Versatility
Flexible in form, texture and colour.

During its lifecycle it has a low carbon footprint
The question could arise why we want to change concrete when it already has a low carbon footprint. This is true, but because concrete is produced in such huge amounts, it causes a lot of CO2 emissions and therefor still need to be more sustainable.

Energy efficient through its thermal mass
It leads to thermal stability. This will eventually save energy and costs because the indoor climate is controllable for our own needs.

Often produced locally
Because it is a highly available product, it is produced locally and therefor the transportation to at site is minimized.

On-site fabrication
It is a flexible product that can be poured on site. Local materials can be used and will keep the costs down.

Excellent sound and vibration insulation

Fire resistant

100% recyclable

HISTORY: ROMAN CONCRETE

Concrete has been used for years and years for multiple causes. It started early with the Romans who, as far as we know, were the first to discover the material and use it for all their mega structures and imposing buildings. Unfortunately, this knowledge has been partially lost because little has been documented about their concrete formula.

A few years ago, the molecular composition of concrete from the Roman era was left behind, hoping to discover how the concrete could be so durable and strong. The rare material "aluminium tobermorite", which is volcanic ash, in Roman concrete provides structural strength. Unfortunately, it has not yet been possible to produce tobermorite at 20 degrees Celsius and the crystals are found in rocks that have formed after volcanic eruptions. It is therefore a fairly rare material and difficult to make in the lab. The volcanic area was close by for the Romans, but for a country such as the Netherlands, which is not located in such an area, not favourable when it comes to transport and the CO2 it entails. Moreover, the greenhouse effect on Roman concrete is very different from that of modern concrete. With modern concrete, one third of the emissions are caused by the production of cement and the heat required for the furnaces. Half of the emissions come from the same process but then from sand-lime bricks. The Roman concrete consists of lime, volcanic ash and seawater and CO2 reacts here with lime in seawater. This means that the CO2 is stored in the concrete instead of being emitted (Bouw Wereld, 2017; Jackson et al., 2017).

It is special to see that the Roman constructions, which are completely in seawater from the coast, have remained intact all those 2000 years. The mortar of Roman sea concrete is seen as the prototype of the concrete that partially replaces Portland cement with natural pozzolan to reduce CO2 emissions and produce resilient C-A-S-H binder (calcium-aluminium-silicate hydrate). The material was mentioned by Vitruvius around the second half of the first century B.C.:
If the natural pozzolan wasn't available anymore, Vitruvius knew that finely crushed burnt brick could give a similar effect. A very impressive and one of the best-preserved building from the Roman period is the Pantheon (Figure 27). It consists of a dome with a diameter of 43 meters that is constructed by pouring concrete into ribbed sections and let it harden until it was done to be put together.

Figure 27: Interior of the Pantheon, Rome by Giovanni Paolo Panini c. 1734 – National Gallery of Art, Washington

The C-A-S-H binder that was used by the Romans was made by the reaction with seawater, lime calcined form limestone and zeolitized volcanic ash that mostly came from the Campi Flegrei volcano near Naples. It is a poor variant of aluminium tobermorite that is rarer than the C-A-S-H binder (Jackson et al., 2017). If modern concrete would be exposed to seawater, it would degrade the structure and causes weathering instead of making the concrete more durable and add additional reinforcement by splashing seawater like the Romans had. The seawater that goes through the concrete, dissolve the components of the volcanic ash, whereby new minerals, one of them being aluminium-tobermorite can arise from the highly alkaline leaked liquids (University of Utah, 2017).

Overall, it is a surprising discovery that has led to a few questions: how did the Romans produce the aluminium tobermorite at ambient temperatures? And how do the Roman concrete structures remain in good condition with the alkali silicia (AS) that is released form rock aggregate? In Portland cement AS is known as the "concrete cancer" which is a swelling reaction that occurs over time and therefore degrades the structure. We have still got a lot to learn from the Romans and it may can help by improving our own modern concrete.

"There is also a kind of powder which, by nature, produces wonderful results. It is found in the neighbourhood of Baiae and in the lands of the municipalities round Mount Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also, when piers are built in the sea, they set under water." (Mindess & Young, 1981)

But it also has its limitations (*Engineering Civil, 2016; Mindess, Young, & Darwin, 2003)(Figure 31)*:

DISADVANTAGES OF CONRETE

Low fracture toughness
Although this can be helped by adding steel reinforcement within the concrete so it can handle tension. Also known as reinforced concrete

Low toughness
Not able to consume a lot of impact energy. It is 1/100th to 2/100th of the ability of steel. Fibre reinforced concrete can provide better toughness.

Low tensile strength
It represents 1/10th of the compressive strength. The tensile capacity can be strengthened by adding fibres and polymers.

High weight compared to strength
Can influence in making a tall building.

Low specific strength
It means the ratio strength to density. Lightweight concrete and high strength concrete are examples that improve the specific strength.

Low ductility
Not able to have concrete undergo a big transformation without breaking (like being stretched)

Shrinkage
It can cause cracks in concrete and loses strength. Volume change can affect the long-term strength and durability.

A mould or framework is needed
Concrete starts of as liquid. When placed in-situ (cast on site) this can lead to more costs and can be labour intensive. Creating precast elements can help this limitation.

Strict quality control is needed
To be sure concrete is of excellent quality, skilled labour is needed during the production of concrete
Requires curing

Compressive strength	= 35 Mpa
Flexural strength	= 6 Mpa
Tensile strength	= 3 Mpa
Modulus of elasticity	= 28 Mpa
Poisson's ratio	= 0.18
Tensile strain at failure	= 0.001
Coeficient of thermal expansion	= 10 x 10^(-6)/°C
Ultimate shrinkage strain	= 0.05-0.1%
Density	
Normal weight	= 2300 kg/m^3
Lightweight	= 1800 kg/m^3

Figure 28: Typical engineering properties of structural concrete - Source: Mindess & Young (1981)

The curing lasts 28-days to give concrete its full strength, it therefor needs extra care. If not done properly it will result in poor quality concrete.

Undergoes creep
The structure can deformed under long term pressure or stress

The big culprit for causing CO2 emissions, is the binder of concrete: cement. Our modern concrete contains mostly Portland cement that involves 100% clinker which causes a lot of CO2. Modern concrete is a mix of water, aggregate (rock, but often sand and gravel) and (the binder) cement *(Aïtcin & Mindess, 2011; Mindess, Young, & Darwin, 2003)*.

Although our modern concrete hasn't got the sustainable quality of that of the Roman concrete, we need to work and are working to more sustainable, durable and economical concrete structures that contains as less Portland cement clinker as possible *(Aïtcin & Mindess, 2011)*. But there can be looked further then only cement: the extraction of sand and gravel will come under pressure due to the damage to the landscape in the Netherlands. People are increasingly looking for alternatives to these materials in order to become more sustainable and to reduce the environmental footprint. Alternative aggregate materials can be looked at, such as natural aggregate materials, demolition waste, etc. *(Betonvereniging, 2018)*.

The Netherlands leads the way when it comes to the lowest vowel (clinker) content in the world. We use an average of 50% clinker in our cement (Cement & Beton center, etc.).Unfortunately, products, such as blast furnace slag and powdered coal fly ash, that we use for this cement are scarcer for other countries. Besides, quality requirements have been set by the cement industry for these raw materials, which means that not all suppliers can meet their CO2 footprint.

2.4.3 Cement

As said before, to make concrete more sustainable we need to work towards cement with less Portland cement and manufacture it more efficiently. The problem of Portland cement is the way it is made. Making the clinker that comes from heating cement provides the largest amounts of CO2. The process itself is simple (*Figure 29):* the cement is made from limestone and clay that are quarried, crushed and blended with iron ore or ash (other raw material). It is put in a large cylinder, the kiln, which is then heated to 1400-1600°C, which is the temperature where both materials will chemically interact to form calcium silicates *(Mindess & Young 1981)*. The material will be split into calcium oxide and CO2 by the process of "calcination". The new material will come out as marble sized gray balls that are called clinker. After this process, the clinker will be cooled off and mixed with gypsum (and sometimes) limestone. Finally the cement is transported to companies that are making concrete of it (*Aïccin & Mindess, 2011; Mindess & Young, 1981; Betonvereniging, 2018)*. Portland cement is known to be very alliable for fast curing.

However Portland cement is still not used properly and is something that companies still need to improve. Unfortunately because of this, large amounts of concrete (and cements) are still wasted *(Aïtcin & Mindess, 2011)*. This is because a number of reasons:

- When designing a concrete structure the focus is too much on strength and less on the environmental impact of it

- The placing and curing specifications are poorly written

- Contractors are not paid to place and cure concrete and is therefore not done properly

It is unfortunate that the durability of the concrete structures are being decreased by these mistakes and can cause high costs on repair. Having often repairs means high labour and social (traffic jams, accidents etc.) costs.
For the cement there are a few things that can make it more sustainable, which means more durable kN's with less CO2 emissions (Aïtcin & Mindess, 2011, p.32):

SUSTAINABLE APPROACHES

- Less cement in concrete
- Less clinker in cement
- Clinker made with less limestone and less fuel
- More kN's with less cement and less aggregate
- More durable structures with a longer life cycle

DIFFENT CEMENT TYPES
There are different types of cement that are categorized in CEM I till CEM V and each involve different portions of clinker (GMB, 2019, p. 7):
CEM I: Portland cement with a maximal of 5% of other materials

CEM II: all kind of hybrids of Portland cement with for example slate, fly
ash, with a minimum 65% of Portland cement.

CEM III: blast furnace/Portland cement mixture in 3 classes: A, B and C; whereby CEM III/A contains the least (36-65%) and CEM III/C contains the most (81-95%) slag

CEM IV: Pozzolana cement varieties

CEM V: composite cements, with mixtures of Portland cement, slag and Pozzolana.

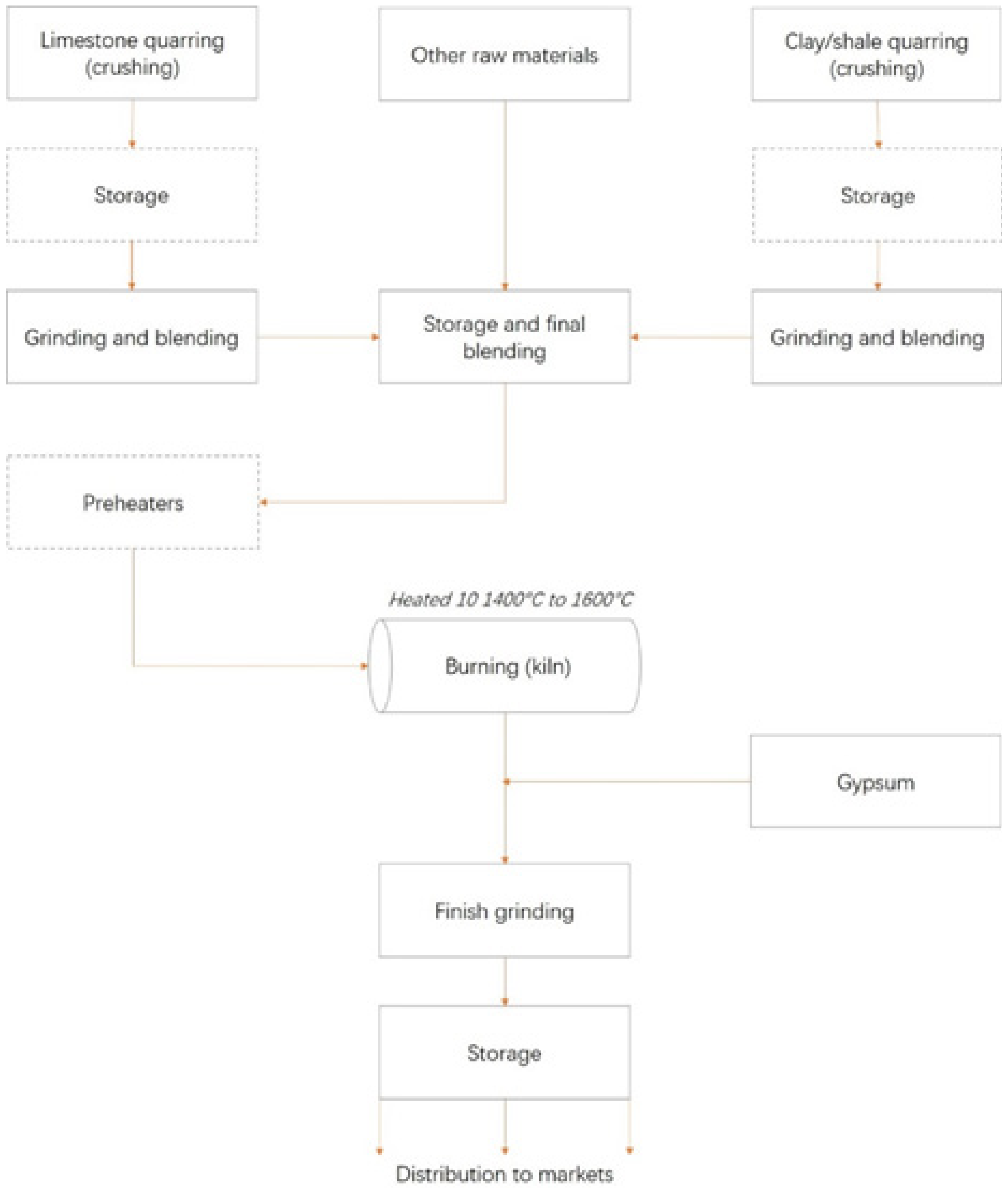


Figure 29: Schematic outline of cement production -Based on: Mindess & Young (1981)

Portland cement (CEM I) is considered the worst and consists of 100% of clinker whereas blast furnace (CEM III) cement contains around 30% clinker, which is used often in the Netherlands and especially in a sea environment *(Beton Lexicon, 2019)*.

The Netherlands uses the lowest clinker content in the world, but this can be lower if we are prepared to invest more and change our concrete industry. Unfortunately the blast furnace slag will also become scarcer in the Netherlands, because the coal-fired power centrals (its source) are being closed because of its unsustainable character. Therefor the Netherlands should be investing in finding a alternative clinker- and cement type, so the reduced CO_2 factor of blast furnace slag doesn't get lost.

2.4.4 Different types of concrete

Having discussed the production process of cement and concrete, and how to make it more sustainable, a few different types of concrete will be discussed that focus on the strategy of building efficient and lightweight. There are an awful lot of concrete types that cannot all be discussed, therefore four types of concrete have been chosen to be shortly evaluated that involves lightweight and high strength concrete. They are both interesting because they contribute to the strategies of building lightweight and reducing CO_2 emissions, waste and the use of less materials. The way the concrete will have a great effect on building efficiency: its speed, and safety among other things. Using less materials has a positive effect on the embodied energy and therefore the choice for a certain type of concrete is important. Therefore, these two aspects will be discussed, assessed and finally a conclusion will be drawn in which type of concrete will be advised for the sustainable and reusable concrete façade system.

Advantages & disadvantages of a traditional building system

Precast/prefab concrete

Precast or prefab concrete is made off-site by using a mould. This is also its greatest advantage because by prefabrication an element it reduces the time it needs to be on-site and all its risk it brings with it (like delay due to weather conditions). The speed at which it can be assembled is remarkable and will save time and cost (*Ermolli, 2007; Nitterhouse, 2016)*.

The concrete can be made stronger by adding wire or rebar (reinforced concrete) which provides tension in concrete when it is cured. The release of the wire or rebar tension transfers strength to the concrete, creating a stronger material. Prefab concrete is often used in apartment buildings for its fire resistance and sound barrier.

The process of prefab concrete is done in a factory: the concrete is poured into a mould that is made of steel or wood, cured in a controlled environment and when finished, it is transported to a construction site and put into place. The advantages and disadvantages focus on the aspects discussed in previous chapters, such as building efficiency, reuse and sustainability.

ADVANTAGES

- **Building efficiency:** a controlled manufacturing environment that creates a speedy construction process
- **Sustainable process:** water used is recycled, reduce waste on bracing and formwork, excessive concrete, packaging and debris on-site
- **High quality and shorter building time**
- **Easier reused when removed**
- **Fire-resistant and sound-attenuating**
- **Versatility:** flexible in (smaller) form, texture and colour
- **Employee environment safer and healthier:** safety hazards, noise and air quality is controlled
- **Economies of scale:** precast concrete uses standard forms and can be mass-produced which improves the economies of scale

DISADVANTAGES

- The use of joints between panels can be complicated and therefore also **expensive.**

In-situ/site cast/poured concrete
Opposite from precast concrete, this is poured or moulded and cured on-site (*Nitterhouse, 2019*). As seen in the summary to the right, It is a very adaptable construction method for concrete that doesn't need large machines, but by pouring on-site the hardening process can take longer because it is vulnerable to weather conditions that can result in great delays.

Conclusion
It is best to design a precast/prefab concrete element when listing all the pros and cons of both methods (*Table 5*) and with the design for a sustainable and reusable concrete facade system in mind. Site cast concrete has its main advantage to cast larger forms, but as the design focuses on designing smaller wall panels, this advantage is not applicable here. As building efficiency and as less labour-intensive work as possible is going to be one of the main criteria, precast concrete is a better option than site cast. Prefabricating the concrete beforehand in the factory reduces building time and improves safety, among other things. Site cast can cause delays because of the weather conditions and the hardening process. Also, the concrete facade system is going to be standardized and produced on a larger scale and only possible with precast concrete. It needs to have the ability to be reused, but this is not the case with in-situ concrete as its poured in and not designed for repeated use. Overall, precast concrete scores best on almost every aspect when using the method for a sustainable and reusable concrete façade system.

The points are as follow: Low=4, Medium=3, good=2, high=1, the lower the total points, the better the material. An exception for the points is for weight/density, creep & shrinkage, thermal conductivity and costs. These criteria are judged the other way around: Low=1, Medium=2, (good is skipped), high=4.

ADVANTAGES

- **Adaptable to almost every building shape.** Very large forms are better poured, moulded and cured on site. These moulds are often too big to fit on a truck.

DISADVANTAGES

- **Low building efficiency:** the hardening process takes place on-site and can cause delays in the construction process. In non-preferable weather conditions like rain or humidity, concrete can take longer to harden than in a controlled production environment like with prefab concrete.
- The logistics of site casting: you are **dependent on the weather conditions** if you are casting.
- **More changes on mistakes:** often have to work using far less precise tools
- Some elements, like insulation, cannot be incorporated within the concrete. **This will cost more time to integrate on-site and architectural space.**

Type of concrete	Precast concrete	In-situ concrete
Reusability	High	Low
Sustainability	High	Medium
Building efficiency	High	Low
Standardization	High	Low, not possible
Adaptability/ versatility	Medium	High
Weather conditions	Independent	Dependent
Construction costs	Low	High
Safety	High	Medium
Total points	9	19

Table 5: Precast vs. in-situ concrete. Source: own ill.

Types of concrete

Different types of concrete will be discussed to be able to use the information in the final design. As sustainability is a big factor in choosing the concrete type, there will be looked at concrete that can contribute to lower CO2 emissions, such factors like the weight of the material versus strength ratio, but also criteria like durability, thermal conductivity and costs. Besides this, the different types of concrete will be discussed in terms of building efficiency and strength.

Reinforced concrete
Concrete on its own is vulnerable to tension forces and can only process compressive forces. By adding steel bars or fibres the concrete will be reinforced and better resistance to these tension forces (Salama, 2017). Furthermore, it is a flexible material that can be used in any sort of shape. But unfortunately, the use of steel reinforcement in concrete (to ensure it can resist tensile stress) exposes it to deterioration because of its corrosion. The steel will rust and will take up a greater volume in the concrete than normal, this will cause cracking in the concrete because of the tensile stresses that will occur (Salama, 2017). Though, this can be remedied by adding waterproof, epoxy, or an organic coating on steel reinforcement to avoid corrosion.

Another problem is the mixture of materials. If the facade needs to be recycled, it is best to mix as few materials as possible and keep them separate. With reinforcement in the concrete, this separation is inevitable. Reinforcement by an organic or a lighter material might be a good sustainable alternative, like engineered bamboo or continuous basalt fibre, but this is something that is still under research.

Lightweight concrete
(Mishra, 2011; Ismail, Fathi, & Manaf, 2003)
It is a type of concrete that is known to be a lightweight version than normal concrete. Instead of using gravel in the concrete mixture, a lighter grain is used such as lava, expanded clay granules or expanded fly ash granules. It is about 87 to 23% lighter than normal concrete if comparing the density with each other (*Ismail, Fathi, & Manaf, 2003*). If there is an insufficient water-cement ratio in the mixture, it can cause the loss in strength of concrete, because there is less cohesion between the water and cement.

An old example of a lightweight concrete structure is The Pantheon (*Figure 31* that is discussed on page 51. There they used volcanic ash instead of gravel which causes it to be lighter than modern concrete. Nowadays it is often used as precast elements for the construction of building blocks and low-cost housing, and partition and panel walls in a frame structure (*Figure 30*). It can function as general insulation of walls, but also as covering for architectural purposes.

As the aim is to design a reusable concrete façade system for a residential building, the type of concrete has to be strong enough to be able to build multiple levels. Hereby the specified compressive strength for reinforced concrete walls has to have a minimum of 17 MPa (*Gerald B. Neville, 2012*).

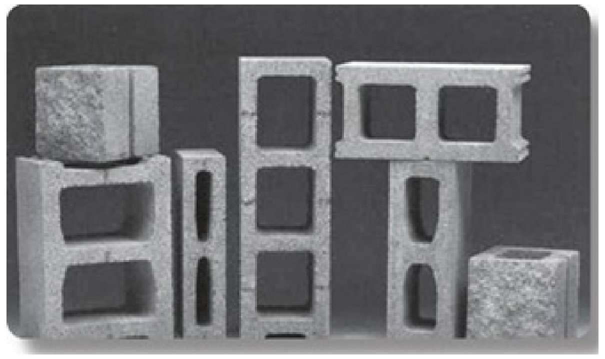


Figure 30: Lightweight concrete blocks. Source: (Mishra, 2011)

ADVANTAGES

- **Low density, low weight:** more design freedom
- **More sustainable and low costs:** the structural system can be thinner due to less load on the construction. This will lead to less material use and fewer costs.
- **Faster building rates in construction** as a result of dead load reduction

- **A lower haulage load:** there is a maximum load possible on a truck which will be easier achieved by lightweight concrete
- **Lower handling costs**
- **Improved fire resistance**
- **Low thermal conductivity:** it means a better

Lightweight concrete can be produced through two methods: injecting air in its composition or by leaving out finer sizes of the aggregate. It can also be replaced by hollow, cellular or porous aggregate. In the next sections, three different types of lightweight concrete are discussed: no-fines concrete, (structural) lightweight aggregate concrete and Aerated concrete.

DISADVANTAGES

- The mixing process can **cost more time** to be sure that the concrete is properly mixed
- **More water to cement ratio** (than normal concrete) causes it to have a longer time to harden.
- Lightweight concrete is **brittle** and damages more easily than normal concrete

No-fines concrete

(Concrete Civil, 2017; Ismail, Fathi, & Manaf, 2003)

Also known as pervious or porous concrete, that has almost no fines. It consists of cement, water and coarse aggregate, whereas the cement is used as a thin paste coating. A characteristic of the coarse aggregate particles is that it allows water to pass through. It is therefore often used as material for pavement areas to let the water go to the ground.

Figure 31: No-fines concrete. Source: Concrete Civil (2017)

ADVANTAGES

- **Density is low:** It has a lot of voids which makes it lightweight. About 25-30% lighter than normal concrete
- **Lower cement content means less CO2 emissions:** only a small layer of cement is put over the aggregate
- **Production cost is comparatively lower** because lower cement content is used. As it has no fine aggregates, the surface area required for cement coating is reduced.
- **(Drying) Shrinkage is lower than normal** concrete because it has not had sand or fine aggregates in its composition.

DISADVANTAGES

- **The compressive strength is very low.** This is due to the aggregate, the water-cement ratio and the cement mix.
- **The concrete can't be reinforced**, because water can get through the concrete that will have steel will
- It needs an **extra layer of masonry plaster** to make the concrete impermeable which will increase costs
- **The value of workability and its test methods are relatively unknown**

(Structural) Lightweight aggregate concrete (SLWAC)

(Mishra, 2011; Ismail, Fathi, & Manaf, 2003)

The coarse-aggregate is what makes the material different from normal concrete. SLWAC can consist of pumice, scoria and all of those of volcanic origin whereas normal concrete uses natural crushed stone. The aggregate that is made nowadays such as expanded blast-furnace slag and clinker aggregate, is making the concrete more sustainable. This type of concrete is what looks the most like the concrete the Romans used for their buildings. Nowadays it is mainly used for precast concrete blocks or panels and cast-in-situ roofs and walls. This type of concrete must have enough strength and low density to avoid cracking by having a low drying shrinkage.

Figure 32: (Structural) Lightweight aggregate concrete. Source: Mishra (2011)

ADVANTAGES

- **Compressive strength sufficient** for a lower residential building
- **Can be used in reinforced concrete**
- **Resistant to effects of the environment:** chemical, frost and fire resistant, etc.
- **Low thermal conductivity**
- **Scores well on sustainability and durability**
- **Lightweight**

DISADVANTAGES

- **Big water absorption**
- **Higher shrinkage than normal concrete**
- **Brittle:** handle with care, it may crumble with repeated use

Aerated concrete

(Mishra, 2011; Ismail, Fathi, & Manaf, 2003)

Aerated concrete is a lightweight, cellular material consisting of cement and/or lime and sand or other siliceous material. It has no aggregate, consists ¾ out of the air and the pores are evenly distributed. It can be made by two different processes: mechanical or physical. It is high-pressure steam-cured when produced as a structural material. It is made into precast elements, like blocks, for floors, walls or roofs.

Figure 33: Aerated concrete. Source: Mishra (2011)

ADVANTAGES	DISADVANTAGES
Has the lowest density: low water absorption	**Lowest compressive strength**
Lowest thermal conductivity	**Inconsistency in the quality**
Sustainable: it produces less waste and CO_2 emissions	**Brittle:** they need to be handled carefully during installation
Quick installation: easy to be screwed, sawn or nailed	**Must apply a finish to make it durable:** a finish that is not permeable so that the wall is protected
Can be used in reinforced concrete	
Good sound insulation	
Ventilation advantages: absorbs moisture and also releases humidity	

Ultra-High performance concrete (UHPC)

(Azmee & Shafiq, 2018)

Expect for the three different lightweight concrete, it is also a good idea to look beyond those and discuss a concrete that has better structural properties than lightweight concrete and see where the difference lies. Ultra-high performance concrete is an upcoming and very strong concrete with excellent durability. It has the potential to make the building environment more sustainable, but it still has some problems with being fully implemented in the building sector. It is often used for infrastructures, such as bridges and tunnels, and is increasingly used as a construction material in high-rise buildings. But the knowledge on the material and production is still limited. There is a lack of design codes and it is still an expensive material to produce. But it is an interesting type of concrete to use because the characteristics allow for a slender, durable, lightweight and aesthetic structure. Because of its excellent durability, it needs very little maintenance during its life cycle, enhancing its sustainability and making it a good material to be reused.

Unfortunately the concrete uses more Portland cement and sand than normal or high strength concrete, but it has silica fume in its substance and it does not use coarse aggregate. But the high material cost and energy consumption (due to Portland cement) during production make it less compatible with normal concrete. *Azmee & Shafiq (2018)* argue that these two problems need to be researched and improved to be able to compete better in the concrete industry.

ADVANTAGES
High compressive strength
Excellent durability: low maintenance costs
High ductility
High strength: means thinner and lighter construction that is more sustainable
Low creep & shrinkage

DISADVANTAGES
High costs
Low sustainable production process

In the summary above, when assessing the materials, the cost and sustainability criteria are based as follows: because of the high durability (long lifecycle) and the possibility to create light and slender structures (less material needed for strength and lower transportation emissions), it is judged as a sustainability factor of 'medium' compared to normal concrete. The costs will be judged as 'medium' as it requires less maintenance and its high durability.

Assessment of the types of concrete

The different types of concrete are assessed based on a comparison with normal concrete *(Table 6)*. From here it is further reasoned whether the concrete has better qualities than normal concrete. Several aspects are further explained to explain why these scores are given:

Compressive strength

When this falls below the minimum of 17MPa, the material cannot be used for load-bearing panels. No-fines and aerated concrete are therefore discarded, although these could be used for non-load-bearing panels if they had further good properties. UHPC has an extremely high value, but this will not be necessary for a low-rise residential building. The material is mainly intended for high buildings where a minimum specified strength of 70 to 100 MPa is required *(Gerald B. Neville, 2012)*. It would mean that thinner panels can be produced because the required strength of at least 17 MPa can be achieved. SLWAC also achieves the minimum compressive strength and can be used for the load-bearing facade system.

Because only normal concrete, UHPC and SLWAC can be chosen for a load-bearing facade system, the focus will mainly be on the comparison of these three.

Weight / density

The lighter the better. Normal concrete and UHPC are the heaviest, but UHPC is also much stronger and therefore a thinner and lighter construction is possible than normal concrete. The lightweight concrete types are generally quite light compared to normal concrete. Where aerated concrete is the lightest of the three and structural lightweight aggregate concrete the heaviest, but still relatively lighter than normal concrete.

Sustainability

This concerns both the production of concrete and building lightweight, both of which complement sustainability. In the assessment, normal concrete scores lower than UHPC assuming that the normal concrete is produced with Portland cement type CEM III (see page 53). With UHPC, Portland cement is also used, which does not make the material more durable, but because it is stronger than normal concrete, a thinner structure can be built with UPHC, which contributes to the principle of building lightweight and the production of less concrete. That is why normal concrete scores lower here than ultra-high performance concrete. In both cases, the production process of the concrete is not sustainable, but with the methods described in *Sections 2.4.1 to 2.4.3*, this may be improved in the future.

Furthermore, lightweight concrete is more durable than normal concrete because it is extremely light, produces less waste and has a more sustainable production process because it uses, among other things, a lower content of cement. SLWAC scores slightly lower than the other two lightweight materials, because it contains a slightly less sustainable production process (quite the same as the production of Portland cement, but with different materials).

Durability

The score depends on the durability of the materials as well as how brittle it is. SLWAC is relatively brittle and has to be handled carefully to stay in good shape after repeated use. Aerated concrete is extremely brittle and needs an extra layer for protection of the concrete, making it inadvisable to use for the concrete facade system. Furthermore, SLWAC is resistant to the effects of the environment, making it also a more durable material in contrast to the other lightweight concrete types. Both normal concrete as UHPC has good durability, although normal concrete needs to be reinforced to be durable, otherwise, cracks will show after being under tension for a longer period. UHPC has the best durability because of its strength, resistance and low maintenance.

Type of concrete	Normal concrete *(chapter 2.4.2, figure 30&31)*	No-fines concrete *(Concrete Civil, 2017; Ismail, Fathi, & Manaf, 2003)*	(structural) Lightweight aggregate concrete *Mishra, 2011; Ismail, Fathi, & Manaf, 2003*	Aerated concrete *Mishra, 2011; Ismail, Fathi, & Manaf, 2003*	Ultra- high-performance concrete *Azmee & Shafiq, 2018*
Appliances	Structural and non-structural applications	Pavement, parking areas, greenhouses	precast concrete blocks or walls & panels in frame structures	Precast blocks, walls, floors and roofs	Structural and non-structural precast components: bridges, tunnels, high-rise buildings
Compressive strength (MPa)[1]	35-70 (good)	1.4 – 14 (low)	20-48 (Medium)	0.5-7.5 (low)	120 – 500 (High)
Weight/density (kg/m³)	2240-2400 (high)	*360- 1900 (low-medium)	1440-1840 (medium)	300-800 (Low)	2200–2800 kg/m3 (high)
Thermal conductivity W/(m•K)	Medium	Low	Low	Low	High
Creep & shrinkage	Medium	Low	High	-	Low
Precast or in-situ	Both	Both	Both	Precast	Precast
Sustainability	Low	High	Good	High	Medium
Durability	Good**	Medium	Good	Low	High
Fire resistance	Good	Good	High	High	Medium/Good
Frost resistance	High	Low	High	Medium	High
Reinforcement possible	Yes	No	Yes	Yes	Yes
Total points	22	24	18	20	18

Table 6: Overview normal concrete vs lightweight concrete. Source: (Mishra, 2011)
**360 kg/m3: made from lightweight aggregate. 1600-1900 kg/3: made from normal concrete aggregate*
*** Only if the concrete is reinforced, otherwise cracks will show after being under tension for too long.*

The points are as follows: Low=4, Medium=3, good=2, high=1, the lower the total points, the better the material. An exception for the points is for weight/density, creep & shrinkage and thermal conductivity. These criteria are judged the other way around: Low=1, Medium=2, (good is skipped), high=4. For "Reinforcement possible" yes=1 point and no=3 points, also "precast or in-situ" is not counted as all of them can be prefabricated which is the chosen method in "Concrete production method".

Conclusion

SQ2: *What are the characteristics of all the different of types concrete; its strengths and weaknesses?*

Concrete is one of the most used materials in the built environment because it has many good qualities such as its compressive strength, good sound & vibration insulation, durability, 100% recyclable and is economical. Unfortunately, the material does have disadvantages when it comes to its structural values. For example, it cannot withstand tensile forces, although reinforcing it will solve this, and it is relatively heavy compared to its strength. Also, curing takes 28 days to give the concrete its full strength and it always requires a mould or framework to produce, which increases the costs and the use of materials. The disadvantages do not outweigh the advantages and it remains an easy building material to use around the world. Unfortunately, the material is not very sustainable because it is produced on a large scale with Portland cement. That is why it is important to look at other concrete options that are, among other things, more durable and strong enough.

Having discussed and evaluated all the different types of concrete on the lightweight aggregate concrete and UHPC come out as the best choice for the concrete façade system. The decision is mainly based on the importance of being strong enough, durable and contributing to the sustainable strategies of building lightweight and reducing CO2, waste and the use of concrete. It is only questionable that it may not be necessary to use such a high strength concrete as UHPC in the concrete façade system. It can be used as the material for the building structure that supports the façade system, which will result in a much slimmer, lighter, durable and low maintenance structure. It is an option that can be evaluated in the next research. Lightweight aggregate concrete is a more suitable option to use for the facade system as it would fit the requirements for a residential building of a few levels. It scores well on most things, with the very importance that it is lightweight, sustainable, durable and strong enough. Unfortunately, the aggregates used in the concrete can form a problem, because of its high chance of creep and shrinkage. But it is possible to reduce this by multiple things such as: choosing an aggregate with low voids content, an aggregate that is dense and hard, the type and amount of cement and a different curing process, one that that is quicker and uses less moist during curing. Another drawback is that it is brittle, which makes it more likely to be damaged by repeated use. A solution should be devised for this so that it crumbling is less likely and can be reused more often.

To design a reusable façade system, durability is a very important aspect and complements the strategy of Rethink, by increasing its life span. The longer it lasts, the better and more often the element can be reused, thereby temporarily stopping the flow of material. Although the sustainability of the material can be improved by researching different kinds of elements and ratio's in the material itself. For example, a way to reduce the Portland cement, a higher dose of silica fume, or a different water/cement ratio. As UHPC is still a relatively new type of concrete in comparison with the rest, it is still plausible that improvement in the aspect of sustainability. But taking in all of the above, the best option from all the discussed materials is using structural lightweight aggregate concrete for the reusable concrete façade system. There are many other types of concrete that

2.4.5 CO2 reducing and capturing techniques

One of the approaches to make concrete more sustainable is to find ways to capture and store CO2 emissions and to use recycled concrete or other wastes materials as aggregate sources. For both approaches, an innovative technique will be discussed that contributes to the goal of sustainable concrete.

Smartcrusher *Slimbreker (n.d.)*
In traditional construction, concrete is often produced by concrete crushers in concrete granulate, which consists of pieces of rubble. The concrete is ground into small grains, of which 98% is further used for foundation material for infrastructure, especially for roads. Only 2% of this crushed concrete rubble is used for new concrete, but to achieve good strength and concrete quality, more cement is always needed. Not only is the bulk moved as a low-grade material to another construction sector, but the machines that grind the concrete debris also cost a lot of energy and still cause a lot of CO2 emissions. Something we want to avoid in a circular built environment.

The method 'smart crusher' is used by multiple innovative companies, like Slimbreker. The new technique that has been devised, takes into account the structure of concrete consisting of sand, cement, cement stone and gravel. The different materials are separated and only the cement stone is milled. The rest remains in the status as it is with the demolition. The cement in the old concrete is not fully cured and can be used as cement for new concrete, resulting in a CO2 reduction of 100%, whereas the cement stone is hardened by supplied with water, resulting in a CO2 reduction of 50%.

Thereby the technique contributes to the reuse of cement that is regained by old grounded concrete.

CO2 capture and storage

"You can get better concrete and a lower carbon footprint, all at the same price. Why wouldn't you do that?"
CarbonCure Technologies CEO Robert Niven.

There is a new technique that focuses on reducing the carbon footprint by injecting CO2 in concrete during manufacture. The CO2 can be captured from emitters such as ethanol, fertilizer and cement plants *(CarbonCure & Pangaea Ventures Ltd., n.d.)*. A company called CarbonCure Technologies is already applying this technique and it has a lot of potentials. It recently had an investment from Breakthrough Energy Ventures that is being chaired by Microsoft co-founder Bill Gates and co-funded by promising names like Jeff Bezos, Michael Bloom and Sir Richard Branson *(Bleasby, 2019; Noe, 2019)*. Its technology removes CO2 from the atmosphere forever and independent tests have shown that during the process the strength of the concrete improves and that it costs a minimal amount more for manufactures *(Appendix C-1)*.

So how does it carbon curing work?
In the wet concrete mix, CO2 is injected and will react with calcium form cement that will create nano-sized calcium carbonate mineral (CaCo3) that becomes captured in the concrete forever *(Figure 34)*. The company does not capture or distribute CO2 but gather it from local industrial gas supply companies *(CarbonCure Technologies, 2019)*.

The new method for CO2 capture and storage becomes a more popular subject for researchers and a lot of research teams are busy perfecting this technique. It is different in its materials, curing method and hardening reaction in comparison to modern concrete *(see Appendix C-2)*. As described by Yoshioka et al. (2013) and *Section 2.4.3*, using a by-product such as fly ash or granulated blast-furnace slag, instead of cement, already reduces CO2 emissions and can be seen as the main method. It can reduce CO2 emissions by respectively 15% and 40% according to the Japan Society of Civil Engineers. With this in mind, a set of three Japanese companies have developed an ecological concrete named "CO2-SUICOM" (CO2 Storage under Infrastructure by Concrete Materials) that achieves a CO2 emission level below zero by capturing CO2 emitted form thermal power stations *(Yoshioka et al., 2013)*. They use a special admixture, instead of cement, which already has a low level of CO2 and hardens the concrete by reacting with CO2. It produces about 1/5th of that of ordinary Portland cement.

Companies will further research this new technology and will focus more on the evaluation of the concrete's long-term durability, strength, how to produce on large scale and to expand the product range so it will apply to more types of products, especially larger ones.

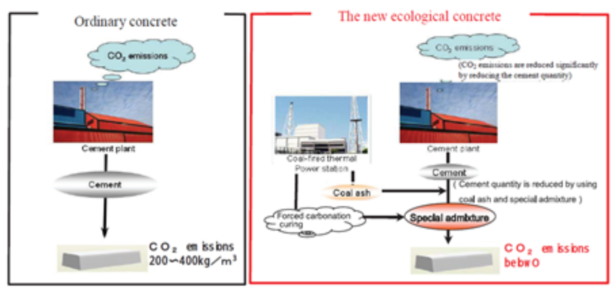


Figure 34: Concept CO2 curing, source: (Yoshioka et al., 2013)

Other CO2 reducing techniques
As discussed before in *Section 2.4.3 Cement*, CO2 can already be reduced significantly by adjusting the cement used in concrete:

- Less cement in concrete
- Less clinker in cement
- Clinker made with less limestone and l less fuel
- More kN's with less cement and less aggregate
- More durable structures with a longer life cycle

These adjustments are the more usual and common techniques in the Netherlands to applicate than the two previously discussed techniques, as those are still quite new. Another CO2 reducing technique is the improvement of the production process used to make the cement and concrete, such as improving the furnaces.

Conclusion

SQ3: Which factors are playing a role in reducing, capturing and storing CO2 in concrete?

To improve the product according to the **Reduce** strategy, different ways and techniques can reduce, capture or store CO2 in concrete. The factors that play role in this area within the material itself (the aggregate, cement and clinker), the curing method, and the recycling and reuse factor. The more common method is adjusting the concrete by using less cement, aggregate and less or an alternative type of clinker, which focuses on reducing the CO2 emissions significantly. On the other hand, a technique that focuses on reducing CO2 by recycling used concrete and reuse the cement to make new concrete, such as the SmartCrusher. But best would be to capture and store CO2 produced during manufacturing to reduce the CO2 even below zero. It takes a lot of time for some techniques to fully integrate into the concrete industry as some aspects can only be evaluated after years of usage, such as durability and strength over time. These techniques can go in combination with (structural) lightweight aggregate concrete that was chosen in the previous chapter to use for the façade system. Especially replacing the aggregate with a more sustainable one or that comes from recycled concrete is a sustainable solution.

Overall it is still cheaper to use modern concrete with Portland cement. Certain policies should be pushed forward by the government to help increase the use of these technologies more, such as put a higher tax on carbon, which is thankfully happening in the Netherlands from 2021. The government will introduce a 'tax-free rate; where companies don't have to pay up to a certain maximum. Is this maximum exceeded, then they will have to pay tax on every extra ton of CO2. In 2021 this will start at 30 euros per extra ton CO2 and by 2030 this increase to 150 euros. This can be a big stimulation for the concrete sector to make concrete more sustainable by introducing CO2 reducing techniques. Still, the question arises if such a policy will be enough to transform the concrete construction sector into a more sustainable one.

There are enough techniques to explore and evaluate more, but it requires patience. Although the Netherlands is on its way to making the concrete industry more sustainable, the ambition to become CO2 neutral by 2030 is going to be a tough one if they don't apply more strict regulations and stimulate more innovation.

2.5 Concept technical and design criteria

The literature study forms the basis for the design of a sustainable and reusable concrete facade system for the Dutch housing market and complements its strategies Rethink, Reduce and Reuse. The main focus is on functional flexibility, technical adaptability, and ways to reduce CO2 emissions, waste and use of materials by making concrete more sustainable and building lightweight. The most important aspects of the technical and design criteria that have been found and discussed are:

- **Standardization:** reusability of elements and repetition of the production process
- **Sustainability:** creating less waste, CO2 and the use of less materials by building lightweight.
- **The building efficiency:** the fast, efficient and safe way of production and assembling of the product
- **Adaptability:** the easiness of adapting to the client's user preferences

The technical and design criteria found are subdivided into these three strategies, as seen in *Figure 35*, and it will be explained per aspect of what is understood by them.

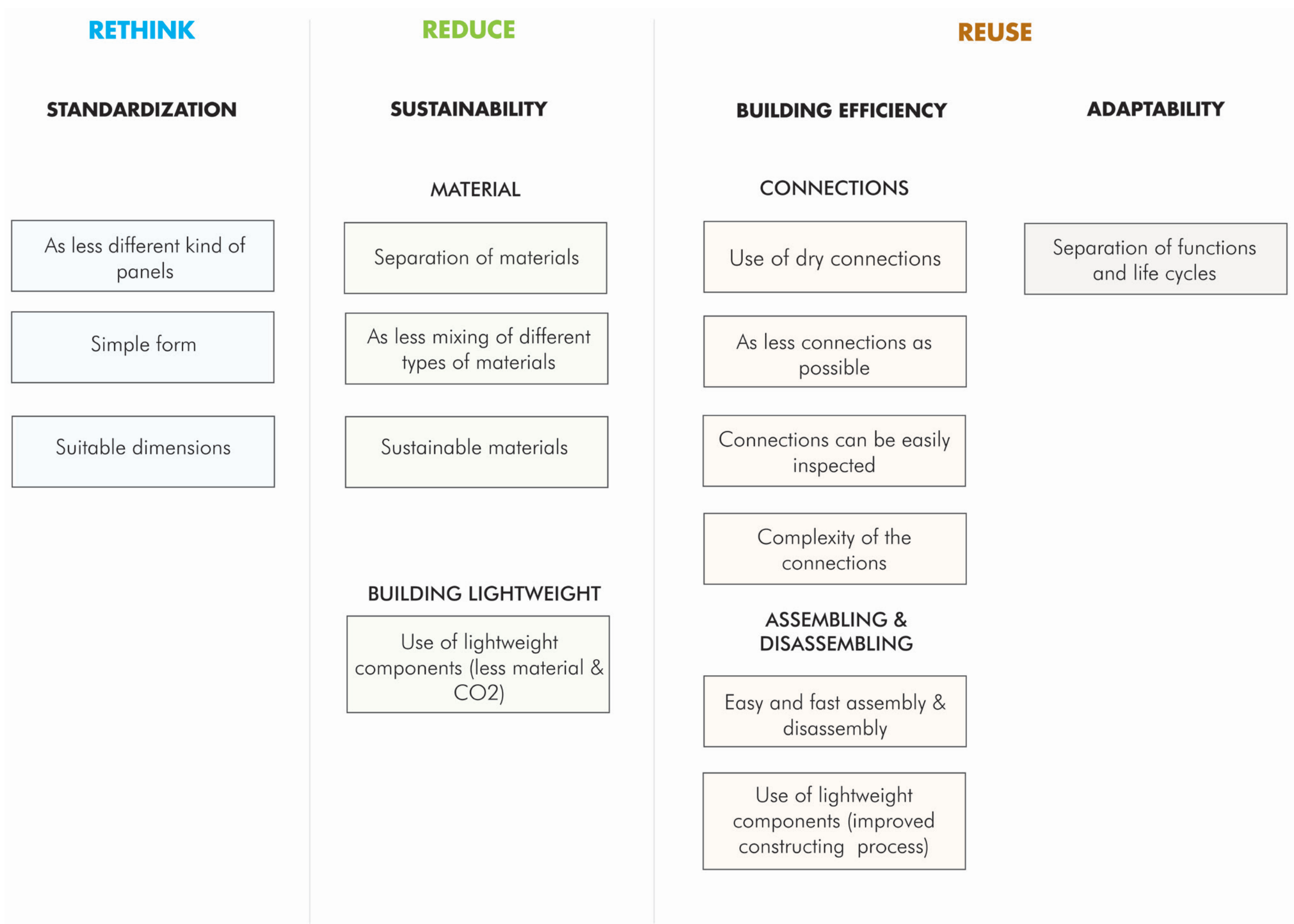


Figure 35: criteria divided into the strategies Rethink, Reduce, Reuse. Source: (own ill.)

2.5.1 Rethink

STANDARDIZATION

- As less different kind of panels (and panel sizes)
- Simple form
- (Suitable) Dimensions

To design a product for repeated use, standardization is an important aspect of the reusability of elements and repetition of the production process. Hereby it is preferable to have as less different kinds of panels (and panel sizes) to speed up the production process, but enough flexibility to be adaptable to different preferences in the future. Another aspect that compliments the speed of the production process as well as the assembling and disassembling speed, is the use of a simple form. By designing a simple shape, mistakes will be made less quickly.

The dimensions of the panels (or modules) count that it cannot exceed that of the maximum sizes of the transport given. It also has a minimum of 300 mm x 300 mm that is based on the general structural grid sizes that are being used for houses (beukbreedte van 5,1 m, 5,4 m, etc.) and other discussed elements like the dimensions of the concrete hollow core slab that has been used often in the build of residential buildings and is standardized with a width of 1200 mm and sometimes even 300 mm. *Table 7* shows an overview of the maximum and minimum dimensions for the concrete panel, gathered from the literature study.

	Bouwbesluit	**Other requirements**	**Hollow-core slabs**	**Transport**	**Grid**
Min. width			300 mm*		300 mm
Max width			1200 mm*	2550 mm	
Min. length/ height	2600 mm	3000 mm			300 mm
Max. length/ height				4000 mm	
Max length				16500 mm	
Max. weight truck				50 000 kg	

Table 7: Maximum and minimum dimensions for the concrete panels. Source: (own ill.)

** Recommended dimensions for the panel, as this is the smallest width of a standardized concrete hollow slab core. This floor type will be taken into account in the design because of its standardization and strength. This will be discussed later in the design process.*

2.5.2 Reduce

Chapter 2.4 "Sustainability of concrete" researched the possibilities to make concrete more sustainable and a few different concrete types have been analysed to conclude that of these types the lightweight aggregate concrete is the best choice for a sustainable and reusable concrete façade system. Another aspect of this strategy lies in lowering the material used in the design by building lightweight. Hereby the use of lightweight aggregate concrete plays a big factor as well as using a lightweight form of the concrete facade system that is structurally strong enough. Both aspects resulting in approaches to lower the CO2 emissions in the design.

Another factor is to minimize the number of types of material to increase its recyclability when it eventually needs to be deconstructed. Not to forget that separating materials is an important factor for this as well. Finally, by building lightweight, the production process will also be sped up and will improve labour intensity, resulting in less costs, risks and improved safety.

SUSTAINABILITY

MATERIAL

- Separation of materials
- As less mixing of materials: no compromised material quality
- Sustainable materials: lightweight aggregate concrete

BUILDING LIGHTWEIGHT

- Use of lightweight components (sustainable): Less material use and less CO2 emissions
- Use of lightweight components (building efficiency): increased construction speed and improves labour intensity

2.5.3 Reuse

The reuse strategy is mainly about how to design a reusable concrete facade system. This results in criteria that focus upon modularity and design for disassembly that can be translated to the building efficient and adaptability.

ADAPTABILITY

- Adaptable to change

BUILDING EFFICIENCY

CONNECTIONS

- Use of demountable (dry) connections: Bolts, screws, nails, etc.
- As less connections as possible: low costs, faster installation
- Exchangeability of the connection: complexity
- Connections can be easily inspected

ASSEMBLING & DISASSEMBLING

- Easy and fast assembly & disassembly:
  - Hierarchy of disassembly
  - Easy dismantling to replace insulation and cladding
  - Design that increases productivity, practices and safety
- Seperation of functions and lifecycles: insulation, cladding, connections, etc.

For the building efficiency and reusability, the first criteria are to design with demountable connections to ensure that the facade system can be reused. To have a fast, efficient, and safe way of assembling and disassembling, the design has to minimize the number of connections, increase its exchangeability or easiness and have it to be easily inspected. Subsequently, the design must consist of a good hierarchy that ensures an efficient assembly and disassembly, and one that improves productivity, practices and safety. The last criterion is the separation of functions and lifecycles to both improve the building efficiency as well as the adaptability to make changes in the future more easily.

2.5.4 Other criteria

The aesthetics criterion is less important than the criteria discussed but still notable. Having hidden connections have a positive effect on the aesthetics in a building, but it can also have fewer consequences for the joint widths in a system since elements can then be put together more seamlessly. This but also, for example, the form of the façade system can affect the

AESTHETIC

- Finishing
- Hidden connections

finishing. It is good to keep in mind that the choices you make affect the aesthetics of a building.

In *Appendix D*, the last criteria can be seen that includes the technical requirements of the Bouwbesluit, which are based on the requirements for a residential building. It is important to work with these requirements if a facade system is to be designed in reality and are included in the criteria list against which it can be tested, but the final design will not be going into further detail here.

2.5.5 Criteria list, rating system and priority elements

All these criteria together form a list, as seen in *Figure 36,* that will be used to rate the upcoming case stud-ies of modular systems and buildings as well for the design process and form the basis of answering SQ1: *"What are the technical and design criteria for a sustainable and reusable concrete façade system in the housing market?"*. Within these criteria, the focus will lie mainly upon:

- **Reusability**
  - **Standardization**
  - **The building efficiency**
    - Demountable connections
    - Assembling & disassembling speed
- **Sustainability:** material use
- **Adaptability:** customizable to the owner's preferences

As the challenges lie in finding the right dimensions for a concrete panel in the Dutch housing market and its importance that it can be reused over hundreds of years initially, flexibility will focus more on the separa-tion of functions & life cycles in the façade system itself and not on the full flexibility of the whole façade in a building. If total flexibility would be the main priority, standardized panels will not work as they become an obstruction for this concept. Therefore standardization has a higher priority than flexibility.

The technical and aesthetic requirements are getting less attention than the main criteria described as these are of less importance for designing a sustainable and reusable concrete façade system. These criteria will still be used for the case studies though, as possible solutions or ideas in these areas can be learned from. This can be taken into account in the final design.

This criteria list will be used to rate the case studies that will be evaluated in chapter 3.2 "Modular case studies". How the assessment works is further described in *Appendix E*. Based on these criteria, it will be clear which elements in the modular case studies work well, and which don't and can be improved. After this evaluation, the criteria list will be adjusted and refined to be able to answer SQ1 and to translate these criteria into a design for a sustainable and reusable concrete facade system.

Design/Case study criteria	1
General requirements	
Prefab	
Stackable	
Load bearing capacity	
Technical requirements	
Thermal insulation	
Fire safety	
Sound insulation	
Standardization	
Number of different panels	
Simple form	
Dimensions	
Building efficiency	
Connections	
Use of dry connections (demountable)	
Number of connections per panel	
Connections can easily be inspected	
Complexity	
Assembling & disassembling	
Separation of functions and lifecycles (replacement)	
Easy and fast assembly & disassembly	
Adaptability	
Adaptable to change	
Sustainability	
Material	
Separation of materials	
Sustainable materials	
Amount of materials used	
Building lightweight	
Use of lightweight components	
(Lightweight) form	
Aesthetics	
Hidden connections	
Overall points	
Total	

Figure 36: Design/case study criteria list. Source: (own ill.)

3 ANALYSIS PHASE

In the previous chapters, we have discussed the main focus points for the design of a reusable and sustainable concrete façade system and how these resulted in the main concept criteria. Those main criteria are standardization, building efficiency, adaptability and sustainability. The first two being the main priority for the design and require more evaluation to see what fits a design for a reusable and sustainable concrete façade system. Therefore the analysis phase will conclude two different studies: one being the research to find the best suitable dimensions for the standardized concrete prefab panels and the other one is about studying existing modular systems and buildings. These analyses will help further in the design process and conclude in concept ideas for the final design.

3.1 Standardization

Standardization is one of the most important factors in making a product reusable on a larger scale. We have already seen in Chapter 2.2 that standardization already exists in the Netherlands in, for example, the hollow-core slab industry. To make a reusable concrete facade system work in the Dutch housing market, it needs such a standardization strategy as well.

In this case study, the facades of a few residential buildings and houses will be analyzed by looking at the dimensions of the concrete parts in these facades. So evaluating if there already are existing standardized dimensions for concrete prefab panels. The focus of this study will lie in fitting the pieces horizontally in the façade and focuses less on the height of the panel. The goal is to see if *at least 75%* of the (closed part of the) facade can be clad with standardized panels based on the dimensions concluded from *Chapter 2.2.6*. This percentage should be enough to make the standardization lucrative enough to put on the market.

3.1.1 Defining case study

To analyze if there is already standardization in the facades in the Dutch housing sector, the cases have to be chosen according to certain criteria that will best evaluate this. The cases consist of five different cases that are divided into two different types of housing and construction periods. The first being three post-war residential buildings (1960-1985) that are part of the largest housing stock (of residential buildings) in the Netherlands (*Rijksoverheid, 2016; Appendix A)* and consist of traditional precast concrete building systems with basic facade layouts, like for example the discussed MUWI-system. The other two are recently built houses with a more unique façade layout and are not built according to the traditional way of construction. The choice to analyze different types of housing and construction periods is to see how facades can change per type and over the years. Post-war houses were built fast and had less architectural freedom than the buildings built nowadays.

Panel dimensions used in the case study

As concluded in *Chapter 2.2.6,* maximum and minimum dimensions were given for the standardized concrete façade panels (see *Table 8*). So these dimensions are the basis for the panels that are going to be used in the analysis. In width not smaller than 30 cm and not larger than 255 cm, although a maximum of 120 cm is advised.

Since the grid is 30 cm, from the standard minimum panel of 30 cm, 30 cm will always be added up to the maximum panel of 120 cm. So the standard panels that will be used for the case studies will be: 30, 60, 90 and 120 cm *(Figure 37)*. For panels smaller than 30 cm, another solution will have to be devised, such as filling with a different material.

	Minimum	Advised	Maximum	Grid
Min. width	30 cm	30 cm	-	30cm
Max. width	-	120 cm	255 cm	30 cm
Min. length vertically	260 cm	260 cm	-	-
Max. length vertically	-	300 cm	400 cm	-

Table 8 : The minimum, maximum and advised dimensions for the use in the case study. Source: own ill.

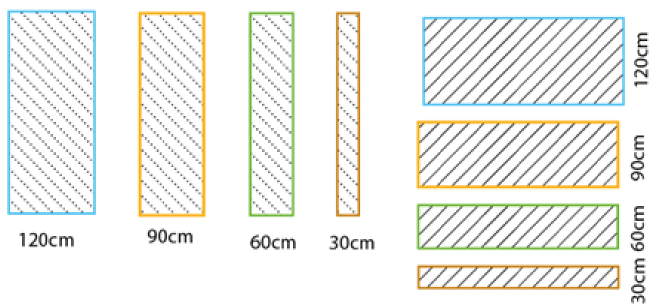


Figure 37: Standard panels for analysis case studies. Source: own ill.

3.1.2 Method

By fitting the standard panels in *Figure 38* into the facades as puzzle pieces, it will become clear which panels fit best in the facades of the case studies. The drawings that have been collected show how long, wide and high all five buildings are. The standard panels are fitted in the drawing and then the lengths of the panels are added together again to check if it matches the beukmaten given *(Figure 36)*. Also, several other things should be taken into account when measuring:

- An attempt will always be made to fit the largest (standard) panel possible into the facade.
- Each panel stops (in a vertical direction) at the floor height because it is not yet known what kind of connection method will be used in this project (Figure X connection overview)
- Very small pieces of less than 15 cm between, for example, windows are not included, because it may be better to use different padding for this.
- No panels smaller than 15 cm wide are used, as a panel can then become too fragile. As a result, for numbers below 45cm (30 + 15cm max) like 42cm, no panels of 30cm and 12cm are used
- In some cases, numbers higher than 45 cm are used as one panel, because this is a better option in terms of their connection to the adjacent panels.
- For the residential buildings, two houses wide are measured, because there is often a piece of facade between the houses and it is best not to split that up
- A constant is used in the Excel file that indicates how many houses in total are in a row and thereby calculates the entire facade surface of the houses
- Above and below a window prefer horizontal panels, to maintain the possibility that these can be connected at the sides with the adjacent panels
- The thickness of the supporting walls has been taken into account and taken into account on either the side of the front / rear façade
- The last two case studies (CB008 and CB010) consist of a single house and therefore will be multiplied by the average constant of the first three case studies (the residential buildings), which is 7. The houses in the residential building have all one level, therefore the houses (that have three levels each) shall be counted as three houses.

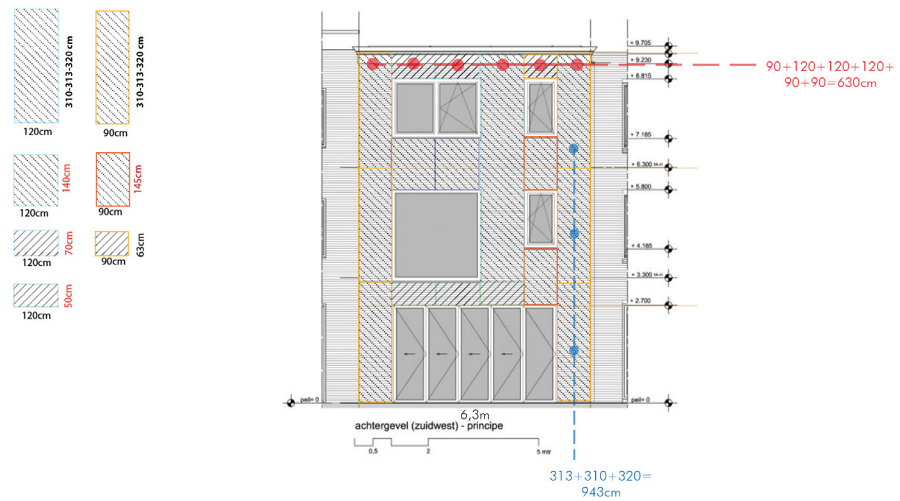


Figure 38: Checking the beukmaat dimensions. Source: own ill.

The drawings are scaled up to 1:100 so that the computer file does not become too large and makes it easier to work with. By digitally analyzing the drawings, the work can be done more precisely. Finally, less attention has been paid to the length of the standard panels, this could be an entirely new study that is just as relevant.

Limitations

Some limitations come with this chosen this type of analysis. The precise measurement of the facades entails inaccuracies, especially with the old construction drawings. These inaccuracies are caused either by scaling up drawings yourself, or, with drawings that are already the correct scale, the thickness of lines or other minimal inaccuracies that can occur, so that the measurement is sometimes just off. That is why in this case study the widths and lengths of the panels were often counted together *(as seen in Figure 38)* to check whether it matched the beukmaten that were given on the drawings. For example, it has happened more often than numbers measured as 9.78 mm are rounded to 10mm and checked if this is consistent with the addition.

Another deviation can be the difference of dimensions between the concrete panels (behind the cladding and not visible) and the cladding itself (which we do see on the drawing). Although the grid lines have often been taken into account assuming this is the boundary of the concrete. All of this and because calculation errors can be made, the decision is made to work with a margin of error of 5% on the standard panels, which will be deducted from the findings.

All panels together				
Percentage				
	Total % facade surface	**Total % of closed surface**		
Standard panel				
Panel 120cm	24%	42%		
Panel 90cm	6%	10%		
Panel 60cm	16%	28%		
Panel 30cm	4%	7%		***margin of error minus***
Deviating panels in 3cm grid			**88%**	***83%***
Panel 42cm	2%	3%		
Panel 24 cm	0%	0%		
Panel 18 cm	0%	0%		
Panel 15cm	0%	1%		
Deviating panels not in 3cm grid				
Alle afwijkende panelen	5%	8%		***margin of error plus***
	57%	100%	**12%**	***17%***
			deviating panels	
Without side walls building				
Percentage				
	Percentage totaal			
Standard panel	**Total % facade surface**	**Total % of closed surface**		
Paneel 120cm	15%	30%		
Paneel 90cm	6%	12%		
Paneel 60cm	18%	35%		
Paneel 30cm	5%	9%		***margin of error minus***
Deviating panels in 3cm grid			**87%**	***82%***
Panel 42cm	2%	3%		
Panel 24 cm	0%	1%		
Panel 18 cm	0%	0%		
Panel 15cm	0%	0%		
Deviating panels not in 3cm grid		0%		
Alle afwijkende panelen	4%	9%		***margin of error plus***
	50%	100%	**13%**	***18%***
			deviating panels	

Figure 39: All panels counted together (top). All panels counted together without the side walls of the building (bottom) Source: own ill.

3.1.3 Findings

After analyzing the different facades, the findings and numbers were put into an excel to calculate the percentages of how much the standardized panels could fill up the total façade as well as the % of the closed surface of a façade. All of the findings of the analysis can be found in Appendix F. Here still the margin of error of 5% has to be deducted from

Of all facades (of the case studies) added together, an average of 40% of these are open and 60% closed *(Table 10)*. Without counting the side walls/ the façades in the length of the building, this average is both 46% and 54% respectively.

Panels 120 cm and 60 cm are the most common as seen in Figure 37 and Appendix X, with panels 90, 30 and 42 cm somewhat less common but still important to fill up smaller parts of the building. The 42 cm panel is mainly because of the rule that panels less than 45cm have to be in one piece instead of divided into a standard panel and deviating panel. Because 42 cm panels are just a really small percentage of the total façade, these will not be taken into account in the final choice of which dimensions are best for standardized panels for a reusable concrete facade system.

There are two different calculations (full calcutation in *Apeendix F-1*): one with the sidewalls of the buildings included (*Figure 39 top*) and one without side walls (*Figure 39 bottom*). This is because the front and rear facades often have a completely different facade composition with different window surfaces and door openings. The sidewall has in most cases been a completely closed off wall. With the sidewalls added, 42% could be done with panels of 120 cm, around a quarter with 60 cm, and 1/10 with 90 panels. Without the sidewalls, the percentage is slightly lower, but the 120 and 60 cm panels were still able to fill the walls with 65% (see most right column of the bottom table). In total, the standard panels from 30 to 120 cm could fill up 88% of all closed surfaces and 87% without the sidewalls of the buildings, but because it has already been told about possible inaccuracies in the analysis, an error margin of 5% is calculated for both numbers, which then results in standard panels from 30 to 120 cm can fill up 83% of all closed surfaces and 82% without the sidewalls of the buildings. This is the result when all façade surfaces are added together, but this is somewhat not entirely presentable as a result because one building/case study is larger than the other. That is why there will also be looked at the average that can be filled with standard panels of each case study. The average of all these together will form the final result.

Findings per case study

Case studies	The total % of standardized panels that fill the closed surface: all panels together (front, back, sides)	The total % of standardized panels that fill the closed surface: all panels together without side walls
CB008	90%	78%
CB010	83%	78%
Willemskerkestraat	85%	78%
Saaftingsestraat	90%	89%
Botteskerksingel	84%	83%
Total (average)	**86%**	**81%**

Table 9: Total % of standardised panels that fill the closed surface in each case study. Source: own ill.

All findings and the drawings where the panels are fitted in can be found in *Appendix F*, divided into sections that refer to each of the five case studies. The notable aspects per case study will shortly be discussed:

CB008 and CB010
In Table 15 the findings per case study can be found and it stands out that CB008 has a big difference between the total % of standardized panels that fill the closed surface: all panels together and all panels together without the side walls. This is because house CB008 has a more unique façade on the front and backside with more separate small windows. Another striking thing is that CB010 has a more unique façade on the front side that needs more deviating panels, but on the backside, it could be filled with standard panels. This may say that standardization also prevails in the current construction period in a 300mm grid, even though more unique facades have been introduced.

Botteskerkesingel
It has the largest share of deviating panels from the residential buildings built in the 1960s and that is mainly due to the front facade. Due to the different heights of the windows, a more distinct facade composition, there are often deviating panels below or above these windows. The back has a more simple composition and consists of a lot of straight lines where 96% of the closed facade can consist of standard panels.

Saaftingsestraat
The back has a simple composition, with all the same type of windows, but has considerably more different panels (15% or closed surface) than the front (7% or closed surface), which has a slightly more different composition.

Willemskerkestraat
It has a somewhat more unusual composition in terms of windows, which causes the height/length of a panel to often differ. The difference under the windows is 78cm, where it can already be seen that it is not according to the current Bouwbesluit rules, which ensures that a unique/deviating piece must always be added. But then above the windows, it is precisely 60 cm and perfect for a standard panel. The back has a simpler composition but does not differ much from the front in terms of the total percentage of deviating / unique panels (9%).

Having analysed how much percentage of all the closed surface can be filled on average with standard panels, it is also smart to look at how much surface is open and closed on average. This is because if having a really low percentage of the closed surface then one has to wonder whether it makes sense to use standardized panels. As seen in Table 16, on average 40% of all the surfaces are open, so that means that the 86% and 81% that can be filled standard panels of a closed surface *(Table 9)* is based upon the fact that of the case studies on average 60% is closed. This means it useful to have a standardized façade system.

Case studies	The total % of open surface: all panels together (front, back, sides)	The total % of open surface: all panels together (without side walls
CB008	33%	41%
CB010	34%	40%
Willemskerkestraat	44%	52%
Saaftingsestraat	40%	43%
Botteskerksingel	49%	51%
Total (average)	**40%**	**46%**

Table 10: Total % open surface in each case study. Source: own ill.

3.1.4 Conclusions & discussion

At the beginning of this chapter, the goal was stated that at least 75% of the closed facade should be able to be filled with standard panels of 120, 90, 60 or 30 cm (in the 300mm grid). With these case studies, this goal is achieved with the standard panels of 30, 60, 90 and 120 cm with panels 120 cm and 60 cm almost filling up ¾ the facades and 90 and 30 cm together almost 1/5.

As seen in *Table 9*, an average of 86% of all panels (of the closed surface of a building) can be filled with standardized panels. To give flexibility in the layout of the faced and design freedom for the client or architect that is going to use this reusable concrete facade system, a range should be communicated that sets a requirement for the minimum percentage that the closed surface should be filled with standardized panels. With the margin of errors of 5% deducted from the percentage, it results in at least 81% of the total closed surface facade and 76% of the closed surface of the front and back facade could be filled with standardized panels in these case studies. The other 19% and 24% is to have that flexibility in the layout of the façade and design freedom for the client and architect. So because this research has limitations and gives companies more flexibility, a *range of 75% to 85%* will be communicated to companies that want to use the building system as on average 81% can be filled with standard panels. The higher the percentages, the better and this is something that should be encouraged by, for example, subsidy by the government.

During the analysis, the percentage of the closed facade in the case studies together was 60% (conducted from 100%-40% of *Table 10)*. This can be translated into the proportion that can be filled in total with standard panels in the entire building (including the proportion of open surface). This percentage then comes to 59%, see *Table 11* for the calculation. So this means that all facades in the entire building will have to consist of *55% to 65%* standard panels.

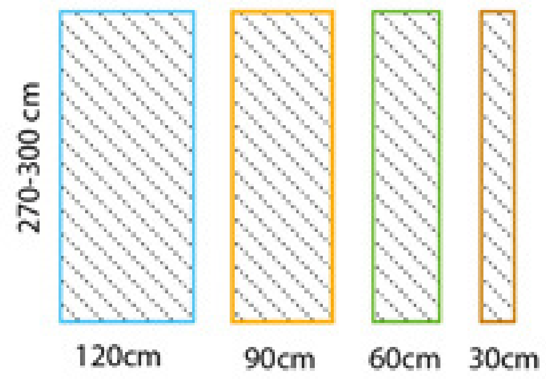


Figure 40: Final chosen standard panels for reusable concrete façade system. Source: own ill.

Surface:	100 m2
60% is closed surface	60 m2
81% of closed surface filled with standard panels:	59m2
Average filling of standard panels of the total façade surfaces of a building	**59%**

Table 11: Total percentage filled with standard panels. Source: own ill.

SQ4: "What dimensions are best suitable for a reusable façade system for the housing market?"

With these findings, SQ4 can be answered, the answer being that panels of 120 cm and 60 cm are the most common and best suitable for a reusable concrete façade system, followed by panels of 90 and 30 cm. Besides, deviating panels are needed for the flexibility and design freedom of the architect or client. That is why a range of *75% -85% of the entire closed surface* of a building and *45% -55% of the total surface* of a building *(Figure 41)* will have to be achieved, which must be filled with standardized panels to successfully implement a standardized concrete façade system.

Figure 41: Range for closed surface and total surface filled with standard panels. Source: own ill.

Discussion

Eventually, this percentage could have been higher if the load-bearing walls inside the case study that consists of residential buildings would have been taken into account. If this was done, the percentage that could be filled with standard panels will likely be higher as these walls all have closed surfaces with maybe only a door opening. This would otherwise result in an overall higher percentage that could be filled with standard panels, but if keeping the *range of 75-85%* this would overall give the client more freedom to have a unique façade. Also, the connection type is not taken into account in the residential buildings. In most of these types of 1960's buildings, the load-bearing concrete wall stands on the floor and the facade cladding is continuous. This has not been taken into account and therefore the results are not entirely correct, especially in terms of height (and therefore the number of surface areas). The dimensions are larger than they should have been.

Another thing is the final results of *Figure 39*, which differs from the results of *Table 9* because counting all façade surfaces together means that bigger buildings have more influence on the results than smaller ones. Therefore *Table 9* was used as an average, although there wasn't enough time to do this for all the separate standard panels as well and see what their average is.

New research should be done to find the right dimensions for the height of the panels. A common thing in analyzing the case studies with the standard panels is that they did fit in the width, but often had deviating dimensions in the height, for example, different level heights, and below and above a window or door. A solution should be found for these kinds of panels. For the full height of a level in a building, an often encountered height was 2,8 m. Other more often heights were 2,7m and 3,0m. For now, these are also the heights that are going to be advised for further use for the concrete façade system, but further research focusing on this part is needed to achieve real results.

3.2 Modular case studies

In many cases, it is best to learn from existing projects before beginning on your own. As modular systems and buildings are relatively new and upcoming, analyzing existing projects can help to answer which design criteria are needed for a sustainable and reusable concrete façade system. A total of four case studies will be discussed, each with their advantages and disadvantages in connections, modules, among other things. By analyzing these modular projects, the advantages and the points of improvement will become visible. Both of these will be discussed and reviewed, so the final technical and design criteria can be formed and used in the design process.

3.2.1 Approach to rate the case study

The case studies will be assessed based on the discussed concept criteria of *Section 2.5.5*, with the focus on the following aspects:

- **Standardization**
- **Sustainability**
- **The building efficiency**
- **Adaptability**

For each case study, these criteria will be discussed in more detail and it will ultimately have to become clear where the strengths and weaknesses lie in each case study and how these could be improved. With this information, the technical and design criteria can then be refined and the points for improvement made applicable in the design during the design phase.

3.2.2 Modular systems in the construction sector

The Cloud – Student housing Utrecht by Onix Architect 2015

The Cloud, situated in Utrecht, is designed to house students on the Campus of Utrecht University. The concept of The Cloud comes from the typical Dutch weather: a cloudy sky. This is visible by its form but mostly through its materialization.

Facade composition & standardized panels

The building has a modular construction that consists of concrete prefabricated panels and façade elements. In the design of the concrete panels you can see that the dimensions of the tiles have been taken into account: 290 x 90 x15 mm. As seen in *Appendix G*, the ceramic tiles can be fitted in the dimensions of the windows and the rest of the panel.

Each panel (with an exception of a few) consist of two modules of 3,4 m wide and 3,3 m high each, but from the exterior, the two modules are shown as two individual objects. In total there were six moulds used to create 8 different modules.

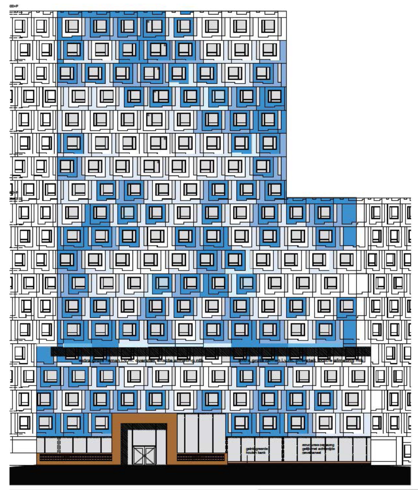


Figure 42: Facade composition of The Cloud. Source: Lincheng, Montemayor, & Cunqueiro (2019)

Panel form

The façade looks like a random composition which they have smartly done by having creep between the panels and tiles that move one tile to the left or right every level. The creep is meant for structural reasons and water tightness but helps with the architectural design of the façade composition. This is also seen if you look at the interlocking panels, both in the vertical and horizontal direction as sketched in *Figure 43*. It results in a smooth transition of the cladding and makes it harder for water to seep into the panel and functions as a tolerance.

Fixing systems
Another thing to look into is how the fixing systems of the panels work. They have two different systems: one for non-load bearing (see *Appendix G*) and one for a load-bearing panel. They are both connected to a concrete building structure, with the facades on the west and east side (at the end of the building) being load-bearing.

The load-bearing panels are part of the structural composition of the building which is placed along with the construction of slabs and connected by metallic strips. They used an anchor system that is placed into holes in the inner concrete layers in the top and bottom of the panel. After stacking the panels on top of each other and after installation of the anchors, concrete is poured in to give the connection its final strength. Unfortunately, this last step makes the connection and panel not reusable for in the future. So a point of improvement is to use a dry connection that has the same structural advantages both can be easily demounted.

The non-load bearing panels are horizontally fixed with each other through T-shaped beams that are embedded in the concrete wall (primary structure). These beams are connected with the concrete slabs and fixed by pins. Both (side) panels are placed into the beams and fixed by (initially) pins. Another fixing system in this panel is meant for transportation. The transportation anchors are fixed on top of the inner concrete layers so when pulled up it can be easily put in the correct position and this without damaging the cladding. T-profiles are used to connect the panels to sideways.

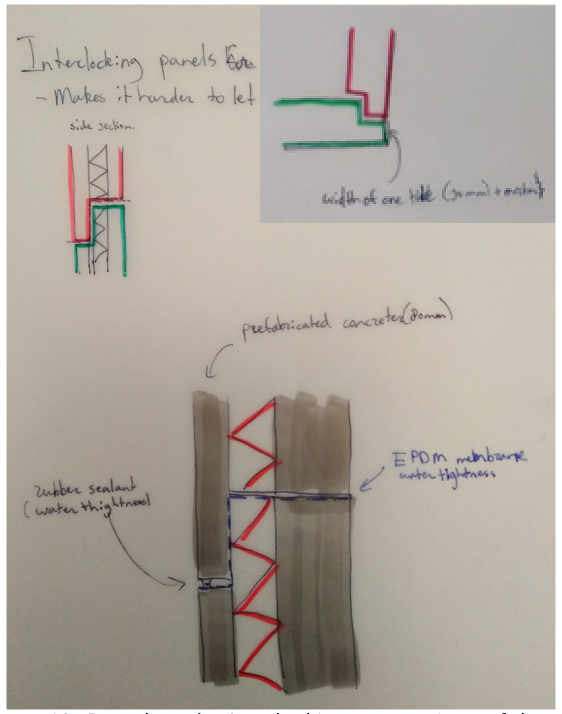


Figure 43: Based on the Interlocking connections of the concrete panels. Source: own ill.

Reviewing the case study

Standardization

- Six different moulds were needed to make eight different panels which speed up the process a bit. This is because they inversed two types of modules.
- The sizes of the modules are based on the facade finish (the tile sizes) so that the facade seems to blend smoothly. This in combination with the interlocking panels.

Sustainability

- The outer layer concrete has multiple smart functions: it protects the interior of the facade (insulation and inner concrete layer) and it functions as the attachment for the tiles. The protection means a longer life cycle for the interior layers.

Building efficiency

- The dimensions and the prefab panels cause a faster assembly process (although this comes with complex connections, structure, façade composition, etc).
- Attach two modules of the same size to speed up the assembling process instead of loose modules (*Figure 44*)
- Transportation fixing system on the top of the modules so transporting goes faster and safer, without damaging the exterior.
- Using a steel beam to connect panels. Steel structures may even be overextended to connect these modules or embed an extra beam in the concrete primary structure.

Other advantages

- By smartly interlocking the panels, the cladding in the corners looks uninterrupted from the exterior. The vertical interlocking panels also function as tolerance and water tightness
- The sandwich panel is difficult to recycle, which decreases sustainability. The rest of the design isn't focused on sustainability.

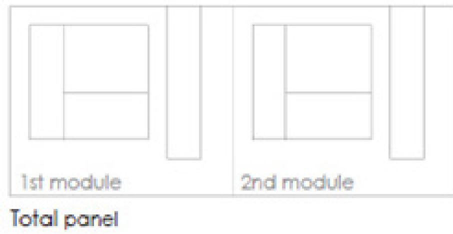


Figure 44: Two modules assembled together off-site. Source: Lincheng, Montemayor, & Cunqueiro, 2019

Points of improvement
Flexibility/Adaptability is a factor that can be improved. The façade consists of a sandwich panel of the inner layer of concrete, insulation, outer layer of concrete and tile cladding. When insulation or the concrete layers need to be replaced, the whole panel needs to be disassembled. Although this is less likely because the outer layer protects the internal part of the facade. When the tiles need to be replaced, they break it off the concrete, including the concrete itself, and refill it. Cladding is not adaptable to change for user preference and refilling the concrete is not sustainable.

Another thing is the double layer of concrete on the interior as well as the exterior. It makes the façade heavy and uses extra material which is less sustainable. The heavy façade meant that extra connections were needed to be used, which can cost more time and money. Although extra connections between the interior concrete and cladding can cause more thermal bridges. Also, the whole design isn't focused on sustainability. The sandwich panel is difficult to recycle, which decreases sustainability.

The load-bearing walls have often wet connections, which will damage the panel when disassembled. A dry connection system like Peikko's wall shoe can replace the fixing system. Another solution can be by making the connection to the floor primary.

The last point of improvement is the loss of fire resistance at the aluminium window frames. It can be solved by adding strips of steel.

Circular viaduct Kampen & Circular concrete pavilion

Both designs work with prestressed cables where the Circular concrete pavilion in the Green Village of the TU Delft is inspired by the Circulair Viaduct. The prefab concrete elements are placed together, cables are put through the holes and at last, they are put under stress to form a girder. When demounted, stress is taken off the cables so the elements can be transported and reused at another location.

Both projects involve a reinforced cable system in the longitude and transfers connection. The difference between the projects is that the Circulair Viaduct's prefab elements are five loose girders that are each made in the factory, then all five of them put together on-site and transverse reinforcement cables are added to form a complete bridge (*Figure 45 left*). The Circular concrete pavilion is formed on-site and has cables in two directions *(Figure 45 right)* which clamps all the square concrete pieces together to form a whole.

Adaptability is a strong aspect of these designs. As for the circular viaduct, it has the option to be extended or strengthened by improving the longitudinal reinforcement cables. The whole concrete cascade can be reused if wanting to change the structural ability of the project.

This fixing system is an option that can be considered for the reusable concrete façade system. Though the challenge is that all these examples show horizontal structures, a roof and floor, and the loads are different than a vertical structure. For this thesis, it is important to know how high a vertical structure like this can exist. An example could be curtain walls, as these have the same principle, but is made from different material like the glass curtain wall of the Markthal by Octatube. A big glass wall that is put together by prestressed cables. Unlike the Markthal, the façade panels can be fixed to the floor at multiple points which makes it easier to have a stiff facade construction.

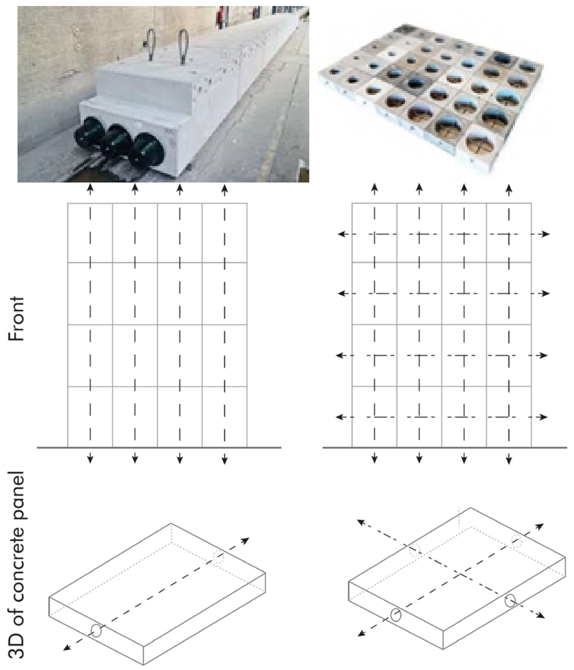


Figure 45: Schema of prestressed concrete façade panel options. Source: own ill.

Reviewing the case study

Standardization

- Both projects have standardized prefab elements: Circular viaduct has an element that comes in only one size, but it doesn't obstruct the adaptability, as it still can become wider or longer because of its structural design (explained at adaptability). The pavilion has the same principle which is inspired by the viaduct. A concrete element that is squared and all the same size. In this sense, less is more.
- Both panels have a simple form and only one or two moulds are needed for production (the circular viaducts segment consists of two concrete elements). Only the circular pavilion has different panels, but of the same size. Holes of different diameters are drilled into the newly produced square panels. This way they can create a completely different roof appearance by mixing up the different panels.

Sustainability

- The circular viaduct can be fully deconstructed without having waste and is easy to transport.
- The concrete circular pavilion uses reused and recycled materials, like recycled concrete granulate, green concrete and geopolymer (a sustainable replacement for cement)
- Both are built lightweight because they consist of hollow shaped forms. Contributing to the aspect of using less materials

Building efficiency

- Both use elements of the same size, making the structure less complex and more easy and fast to assemble and disassemble.
- They use very few (and dry) connections, which improves the construction time.
- The ends of the cable system can be easily inspected. Furthermore, sensors in the circular viaduct girder segment keep an eye on the structural ability of the bridge.

Adaptibility

- Both designs can be extended or reduced and are over-dimensioned in that way. The holes are big enough to have thicker reinforced cables in it.

Other advantages

- The standardized panels and the simple design results in a safer environment and less specialized skills are needed to assemble and disassemble the elements.
- The connections are covered by an extra element, which covers it up but it is also made easy to inspect the cable connections if needed.

Points of improvements

It would have even been a better circular project if they used reused or recycled concrete as the material input. The question is though if it would have the desired structural abilities compared to new concrete. According to the literature studies, this is possible through a technique by, for example, Slimbreken.

Often bridges have an integral construction containing every function, without thinking about shearing layers (Brand and Duffy). This also happened partly with the Circular viaduct. Although they did a perfect job of separating most functions, the service layer is cast into the elements. Things like the electronics (sensors) are embedded in the segments, making it irreplaceable unless demolition. Also, the replacement of an element can form a bigger problem with both case studies. If a replacement is needed, the whole structure needs to be deconstructed. It can be argued though that the designs are intended to be temporary and can also be disassembled in a few days which makes a replacement a quick task. It is less of a problem for the pavilion than for the circular viaduct as a bridge still needs to be closed off for transport which costs a lot of money and time on the logistics side of it.

Furthermore, it is unclear if they used specialized concrete that results in a more slender and lighter concrete element. If not, this can be a point of improvement.

CD20: building construction system recommendation

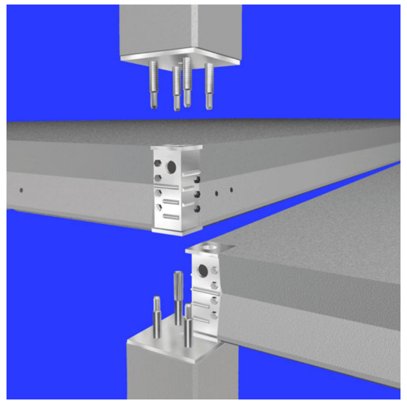


Figure 46: CD20 building system. Source: CD20 Building Systems, n.d.

The CD20 is the first modular concrete building system that has a beamless structure *(Figure 46)*. It even has been awarded the Bouwwereld prize in 1982 and has since then been used for all kinds of types of buildings such as offices, schools, parking garages and later on residential buildings *(CD20 Building Systems, n.d.)*.

The most important thing is that the system can be reused. It uses a simple and innovative connection that guarantees structural strength and one that can be easily and quickly assembled and disassembled. It has also a lot of freedom in expanding the building in width.

The system will lead to reduced construction time and cost, because of the simple connections and building structure as well as having a lightweight structure. It doesn't need an extra concrete layer on top of the floor to ensure structural safety and is therefore very slim and lightweight. It is also beamless what adds to the adaptability of the design. Being beamless creates a slimmer structure and is less an obstacle for climate systems.

On their website, they have a few examples of CD20-systems, see *Figure 47*, with load-bearing walls which consist of module dimensions of 5.4 and 9.0 meters (in a grid of 300mm) based on the floorplates. The buildings consist of 11 levels that consist of their CD20 column and floor system, load-bearing walls and stability walls. It can be assembled in 43 days which is very quick for such a high building. On average they build one story per 4 or 5 days that are around the size of *Figure 47*.

The connection system is what it makes special. At each end of the column are four pins that connect four-floor slabs who in turn have four connections points on their corners to connect four columns. The floor is a rib-cassette floor which consists of prestressed concrete beams with a thick layer of concrete on top of it. The capacity of the floors can be further expanded by adding layers of concrete on top of it. The walls are connected through the pins of the column and its bottom is placed on a layer of mortar.

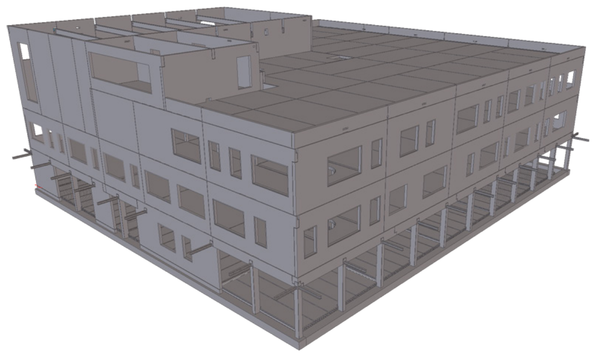


Figure 47:CD20 system example with load-bearing wall. Source: CD20 Building Systems, n.d.

Reviewing the case study

Standardization

- The module dimensions in a grid of 300 mm and the load-bearing walls of modules 5.4 and 9.0 meters which corresponds to the standardized dimensions in the Netherlands found in the literature study.
- There is a wide range of floor slab sizes. The most commonly used size is 3.6 meters wide and 7.2 meters long. The lengths are all in a grid of 300 mm

Building efficiency

- The systems use a tube inside the connection to align the pins of the two columns perfectly together *(Figure 48)*
- A crane does all the hard work of lifting all the elements to their positions, which makes up for a safer environment and less complex skills are needed.
- On many occasions, a crew of 7 men and one crane can finish the job, saving labour costs
- A very simple connection that connects 4 in one, which makes the construction time fast
- When finishing the structure of a level, a new level can be built on top of while installing services on the finished level. Therefore making the construction time even shorter.
- On the corners of the building, the supporting facades have a form that gives an extra structural advantage. It also closes off the corners neater.
- Very fast construction time: 11 stories built in 43 days.

Sustainability

- Certain elements led to very lightweight construction, reducing the material use and emissions for transport. The columns, floors and walls can be made slimmer than a traditional building structure.

Adaptability

- The company has different systems for different functions and preferences where one can have more freedom than the other one.

Points of improvements

The first disadvantage is that after connecting the floor slabs and columns, concrete has to be poured in the connection to make in watertight. There are holes on the side of the slabs that are connected through tunnels to the connection. It is not meant for the connection to be stronger but only for water reasons. The structure is still reusable, but a better solution can probably found for this. The second problem is that when a construction element has to be replaced, the entire construction system will have to be disassembled, because of the interlocking connection system that consists of pins into the floor. Thirdly, the connection system for the floor and concrete colums have an innovative connection system, but there can be a better way to join the walls, floors and columns together than the system they use now. Maybe also a system that can connect more elements together. At last, It is not clear if they have used a sustainable (or lightweight)or sustainable method to produce concrete.

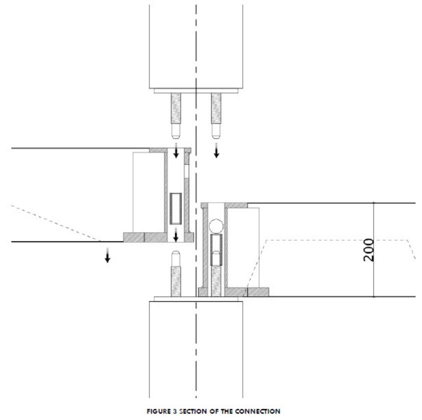


Figure 48: Section of CD 20 system – Connection and assembling method. Source: CD20 Building Systems, n.d.

3.2.2 Review modular systems according to criteria

After analyzing the case studies, all the pros and cons were incorporated into the criteria lists. The list consists of the technical and design criteria from *Chapter 2.5* and each case study is awarded a point on all these criteria:

Criteria: 5| 4 | 3 | 2 | 1

With 5 insufficient/very bad and 1 excellent. With exceptions for criteria that ask for a number or require a yes (1) or no (5). The lower the points, the better the design. This order of numbers (with 5 being the lowest) is chosen because the lower the number of the questions '*Number of connections per panel*' and '*Number of different panels*', the better the design is.

In *Appendix H* you will find the full criteria list of all four case studies. It could be concluded that the Cloud overall doesn't fit the criteria that are listed for this thesis's design of a concrete facade system. Although the project is smart about the use of modules which made their construction time on-site much faster. The most important point for improvement for the Cloud is the use of demountable connections to enable reuse. Unfortunately, the materials, functions and lifecycles are also not separated in the facade system, which makes replacement difficult. Besides, the facade system is not sustainable as it cannot be reused, it is difficult to recycle, is heavy due to the extra layer of concrete and therefore more material is used.

The circular viaduct and circular concrete pavilion have an overall good score, especially is standardization and building efficiency. It has one connection system, which saved time, was easy for transport and created a safer work environment. The only real improvement for the circular viaduct is to use more sustainable materials.

The CD-20 system is overall the best scoring case study, excelling in its standardization, reusing ability and its lightweight form. An extended building system of CD-20 is the CD20 load-bearing facade system where the facade is part of the load-bearing structure. It has most of the same qualities as the CD-20 system, but there was still something missing in the criteria list in which this system was better at the layout flexibility in a building. This system gives more freedom to change and gives the building a more durable character. The client can change functions more easily and this is a strong point in this system.

They all provided insight into elements that are good for the design of a sustainable and reusable concrete facade system, but also shows points for improvement that must be included in the design process and the technical and design criteria. Aspects that were still missing and that emerged from this section are described in the next Chapter 4.1 "Final design criteria" and added to the criteria list.

4

DESIGN PHASE

The next phase describes the design process, starting with the final design criteria that guide the process. From this follows a design workframe that will be the structure for this portion of the paper. Then every aspect and what choices have been made is explained. Finally, a final design strategy will result from this that forms the conclusion of the design question.

4.1 Final design criteria

Analyzing the case studies has brought in some new criteria that are important for the design. These criteria are:

Building efficiency

- *Safety* (work environment): this is related to both the production process in the factory as well as the safety on site when assembling and disassembling the façade system.
- *Man power needed*: another word for it is labour intensive. How many men are required to install the façade system? Big or small machines needed or by man?

Adaptability

- *Lay-out flexibility*: lay-out flexibility gives a lot of freedom to change functions within the building which makes a building more durable and important to this project. This is very dependent on the building structure.

Sustainability

- *Amount of material used:* The less material used, the more sustainable.

In the case studies, a few elements were encountered that is very important for the overall design but are getting less attention in this design process as the priority lies with building efficiency, standardization, sustainability and adaptability. For example, elements/requirements such as:

- *Thermal insulation*
- *Acoustic insulation*
- *Fire safety*
- *Reinforced concrete*
- *Tolerances and movement*
- *Electrical wiring*
- *Water tightness*

It can be advised to do further research in these elements in the future.

Final design criteria	Minimum	Maximum
General requirements		
Prefab (thickness)	100/120 mm	-
Stackable	-	-
Load bearing capacity	-	-
Technical requirements		
Thermal insulation	4.5 m2K/W	-
Fire safety	120 minutes	-
Sound insulation	>52 DB	
Water tightness		
Standardization		
Number of different panels	1	4
Simple form		
Dimensions	300 mm	1200 mm
Building efficiency		
Connections		
Use of dry connections (demountable)	-	-
Number of connections per panel	1	4
Connections can easily be inspected	-	-
Complexity	-	-
Assembling & disassembling		
Easy and fast assembly & disassembly	-	-
Separation of functions and lifecycles (replacement)	-	-
Safety	-	-
Man power needed		
Adaptability		
Lay-out flexibility	-	-
Adaptable to change	-	-
Sustainability		
Material		
Separation of materials	-	-
Sustainable materials	-	-
Amount of materials used		
Building lightweight		
Use of lightweight components	-	-
(Lightweight) form	-	-
Aesthetics		
Finishing	-	-
Hidden connections	-	-
Overall points		
Total		

Figure 49: Final design criteria. Source: own ill.

Approach rating the design concepts

To rate the design concepts in the upcoming chapter and make a selection out of it, the same rating system as for the modular case studies in *Section 3.2.2* is going to be used. With the rating being:

Criteria: 5(low)l 4 l 3 l 2 l 1 (high)

OTHER ELEMENTS/REQUIREMENTS

Reinforced concrete

By adding wire or rebar to concrete, tension is created in concrete when cured. This is needed to strengthen the concrete to be able to endure all the tensile forces when its function is load-bearing. As said in Section 2.4.4 "Different types of concrete", a problem is the mixture of materials where the steel will erode when in contact with moisture or water and causes strengthen problems for the reinforced concrete. Also, when the facade needs to be recycled, it is best to mix as few materials as possible and keep them separate. With reinforcement in the concrete, this separation is inevitable. Reinforcement by an organic or a lighter material might be a good sustainable alternative, like engineered bamboo or continuous basalt fiber, but this is something still under research.

Tolerances and movement

Tolerance means that there is a difference between the position that came out of the design calculations and the position in the reality of a given element or component. Those differences can cause too large, but also too small gaps that won't allow enough movement that is needed for structural reasons. It is important to know the right tolerance for concrete to avoid both occurrences.

When connecting the concrete panels, some tolerance between them is necessary. These tolerances can be partly hidden away in the design by, for example, giving the panel a special form. An example could be the tolerance gaps and panel forms of The Cloud (Section 3.2.2). In prefab concrete tolerances structure can take place of up to 3 cm.

Electrical wiring

Something that should not be forgotten is how the electrical wires run through the facade system. As these materials mustn't be mixed with the concrete by embedding the wiring during the production process, a solution must be found for this. There are already existing ideas were during designing the concrete wall, holes are being drawn for electrical wire to come through (Figure 50). Some do embed plastic onto the reinforcement within the concrete, so the electrical wiring can run through freely. Another idea could be to make use out of the form of the concrete panels, if shaped like a hollow-core slab to make it more lightweight, then those holes could be used to run through the electrical wiring whereas at some points holes should be made in the wall to let the electrical wiring go out of it (Figure 50).

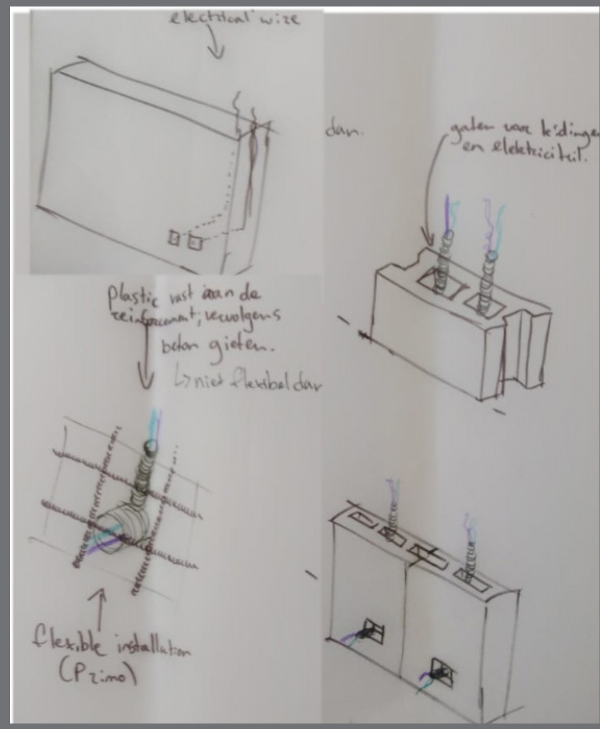


Figure 50: Electrical wiring in a concrete panel (left). Electerica wiring through the light weight formed panels (right).

4.2 Design concepts

Now that the final design criteria have been formed, aspects such as building efficiency can be further investigated by designing. We have seen how the criteria have formed through the literature study and analysis. The design aims to create a reusable and durable concrete facade system that is prefabricated and modular. A design that complements:

- **Standardization**
- **Building efficiency**
- **Adaptability**
- **Sustainability**

By examining the various aspects, which will be explained in more detail in the next *Section "Design work frame"*, it will be possible to answer the design question.

DQ: *"How can a concrete facade system be designed in order to make it reusable?"*

The aspects to be discussed will become strategies that can be used as tools to design a reusable concrete facade system.

4.2.1 Design workframe

WORKFRAME FOR A SUSTAINABLE AND REUSABLE CONCRETE FACADE SYSTEM

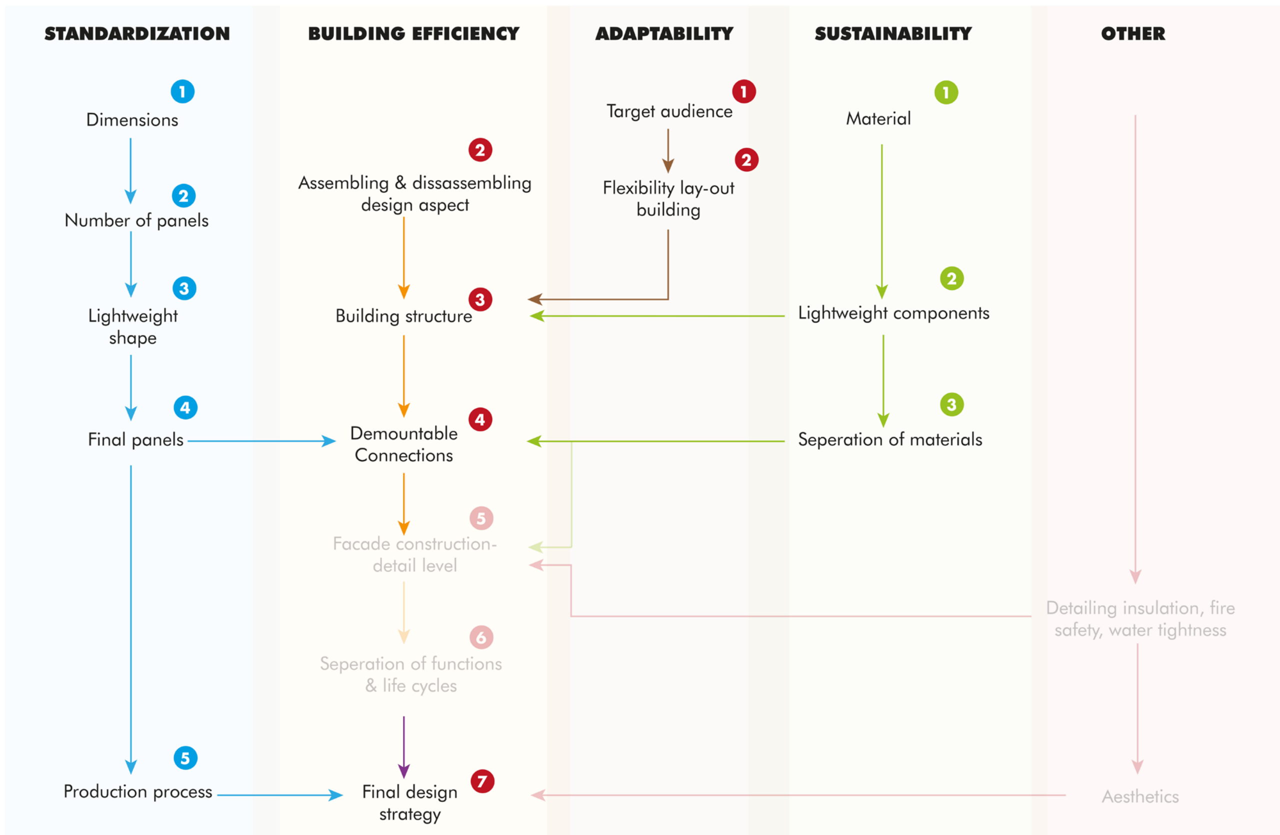


Figure 51: Workframe for the design process. Source: own ill.

The design process will be based upon this work frame in *Figure 51*, with the building efficiency as the leading aspect where all other aspects will come together. First, the residential building parties and their preference will be discussed (target audience), followed by scenarios. Secondly, as the structure of this design phase will start from left to right, the section will start with standardization: the number of panels and dimensions, which is already concluded in *Section 3.1.5,* the panel form and the production process. After this, the assembling & disassembling aspect of the building efficiency will be further assessed and designed. Thereafter building structures will be assessed and evaluated, followed by an overview of possible connection systems. Finally, all these aspects will come together to form a final design strategy in *Chapter 4.3 "Final design strategy"*.

4.2.2 Residential building parties and scenario's

As stated in *Section 2.3.5*, the choice of the target group has a great effect on the choices made in the design. That's why it's important to discuss some residential building parties and their characteristics. In the Dutch housing market, three different housing parties/ corporations must be taken into account.

These parties will want to rent or sell homes in a building. Each party builds for a specific target group and type of home. In *Figure 52* the target groups are divided into owner-occupied, housing corporations and private rental homes.

	OWNER OCCUPIED HOMES	HOUSING CORPORATION	PRIVATE RENTAL
RESIDNETIL BUILDING PARTIES			
CHARACTERISTICS	- Good acoustic performance - Outdoor space: balcony / garden / roof terrace - Flexibility to change facade - Flexibility to have an open or unique facade	- Flexibility in adapting, enlarging or reducing a home - Social housing - affordable --> as cheap as possible - Smaller or no outdoor spaces - Every home has the same facade	- Flexibility to change lay out home - Have often same facades in one building - Outdoor space: balcony / garden / roof terrace - Acoutsic performance

Figure 52: Residential building parties and their chracateristics. Source: own ill.

1) Owner-occupied homes
Ownership of the building is split between multiple people. When a building is being built for this target group, there must be enough freedom to be able to have their exterior facades adapted to their preferences. This can range from wanting more window surfaces to other types of window frames or cladding. Other things that characterize owner-occupied homes are the availability of outdoor space and a good acoustic performance from your neighbour as the surrounding environment.

2) Housing corporation
This corporation is part of the social housing in the Netherlands and has ownership of the whole building that they rent out. The housing corporation is subsidized by the Dutch government to build and rent out (on a non-profit basis) working-class houses that are meant for people that can't afford to buy or rent a home independently. As these homes have to be affordable and housing corporations have less money to spend on construction, the homes are often the same in a building, sometimes variation in for example size. The buildings often have simple façade layouts and cheaper materials that are the same on the whole façade.

It can be important for a housing corporation that they can adapt, enlarge or reduce home homes within their building to be able to better meet the requirements that then currently exist. This type of building will change faster internally than a building filled with owner-occupied houses. Another characteristic is that they often have smaller or no outdoor spaces.

3) Private rental homes
Ownership is the same as a housing corporation, but private rental homes are relatively more expensive and because they are not based on a non-profit basis. The price of the rent is based on a points system, where aspects such as location, energy efficiency, surface indoor and outdoor space are the basics that form the price of the rent. Private rental homes (like owner-occupied homes) often have different target groups such as starters, students and ex-pats that all have their own needs. But for all of them, they have a preference to be able to change the layout of the house, have and outdoor space in the form of a balcony, garden or roof terrace, good acoustic performance and these homes often have the same layout of the façade, although the last aspect can be different if multiple owners rent out homes in the same building.

Most likely, the majority of this project will be used to build owner-occupied homes, as it makes up 2/3 of the Dutch housing market, as stated in *Section 2.2.5 "Residential buildings in the Netherlands"*. The logical choice would be to mainly focused on making a strategy for this target group. More strategies for this kind of housing should be presented at the end.

Limitations
However, it must be taken into account that if you individually (owner-occupied or owner-occupied private residence) want to change the exterior facade to your own preferences, this is due to the regulations drawn up by the architect, the municipality and/or national government. These requirements often depend on whether this fits within the built environment. The individual adaptation of the facades can create a different street scene. It can create a nice image and offer more freedom. A regulation could be that facades can be different, but with certain requirements.

In addition, there is a requirement for a building made with the reusable concrete façade system that 40 to 50 percent of the entire façade system (open and closed) must consist of standardized panels, which makes the layout of the facade less flexible, but still offers enough room to create a building with unique characteristics in the façade.

Scenarios
Here, three scenarios have been outlined which must be taken into account in the design. All scenarios are connected to the different residential building parties and target groups:

Scenario 1 (within 20 years)
Different facades finish due to change in taste or a different owner. Only the facade finish changes. (Groups 1 and 3)

Scenario 2 (after 20 years)
Building gets a different layout due to newer requirements for building, taste or function change. Panels are reused within the building. This may be a preference for more window area or large apartments, which changes the facade. (Groups 2 and 3)

Scenario 3 (50-100 years)
Building is partially or completely disassembled to create a new design. Panels are reused in the design if it falls within the structural boundary of the panels, with possible adjustments to the insulation if requirements of Bouwbesluit have changed. Otherwise, panels are free to be used on another location within the structural boundaries. (Groups 1,2,3)

4.2.3 Design process and strategies

The aspects will be handled and discussed according to the workframe and together form the final design strategy.

Number of panels and dimensions

The number of panels and its dimensions will consist out of the results that are discussed in *Section 3.1.3 Findings*. In *Figure 53*, the panels and their dimensions can be seen and will be used in the final design as the standardized panels for the reusable concrete facade system. The standardized panels consist of four different widths in a grid of 300mm and three different heights. Although for the preferable heights, further research is needed to conclude the best suitable height dimensions. For now, there will be continued with the three different height sizes that were encountered the most in the case studies.

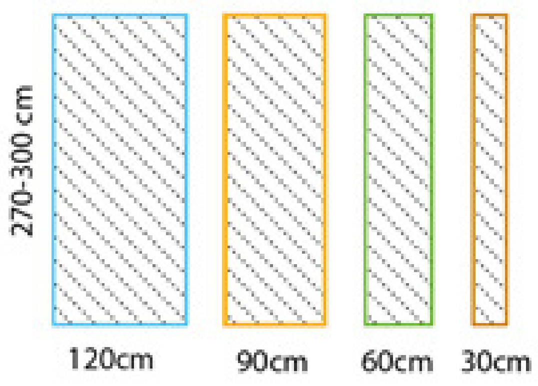


Figure 53: Final chosen standard panels for reusable concrete façade system. Source: own ill.

On one hand, as less different sizes are preferable for a standardized production process that is on a larger scale, so this process is sped up. On the other hand, it can take away the freedom of an architect. Users of the concrete façade system have to be encouraged by, for example, the government, to use the standardized panels and as less deviating panels. The rule for using this system will be the same as the resulting average of the % closed façade of all case studies together. As discussed in *Section 3.1.4 "Conclusions and discussions"*, between *75 and 85%* has to be filled with standardized panels of all the facades in the building. The other *25 to 15%* is to ensure enough design freedom for the architect or client. If a customer decides to go below the 30 cm, panels that do not fall within the 30 cm grid (like 42 cm) or with special shapes, these will be considered as deviating or unique panels *(Figure 54)*. For these panels, a solution should be found.

A possible solution could be by filling the unique pieces up with lightweight concrete or other materials, for example, wood. Wood is a good material to get in various shapes.

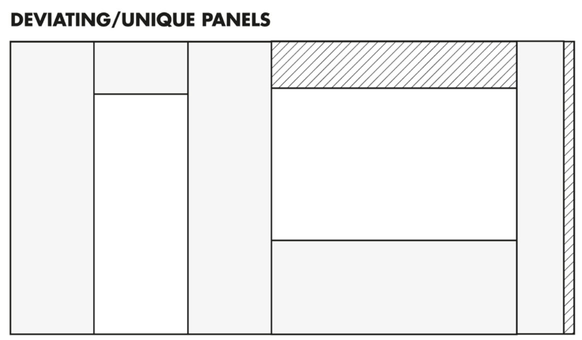


Figure 54: 'Unique pieces' in a facade. Source: own ill.

Although using another material like wood can complicate connecting the panels. It would also help the production process if it stays with the lightweight concrete. As all of these panels could then be made in one mould with fitting pieces and don't need a special mould to be made, which will be explained in the *Paragraph "production process"*.

Building lightweight - Panel form

The hollow-core slabs are a good example of elements with a hollow core that makes an element lightweight and structurally strong. The hollow core can be placed horizontally or vertically, the question rises if both axes are strong enough if there are put under pressure when standing in a building (*Figure 55*).

With the verticals holes, the element functions as columns, which can withstand pressure, and can be considered as a plausible option for the lightweight panel. There are existing examples of vertical hollow core concrete blocks, like the MUWI system *(Section 2.2.5)*.

The axis of the horizontal hollow slab core will not be strong enough to endure the compression of the weight from above and will cave in. There are no known successful examples of horizontal holes. So therefore the panel used for the concrete facade system will have vertical holes that are made of lightweight aggregate concrete.

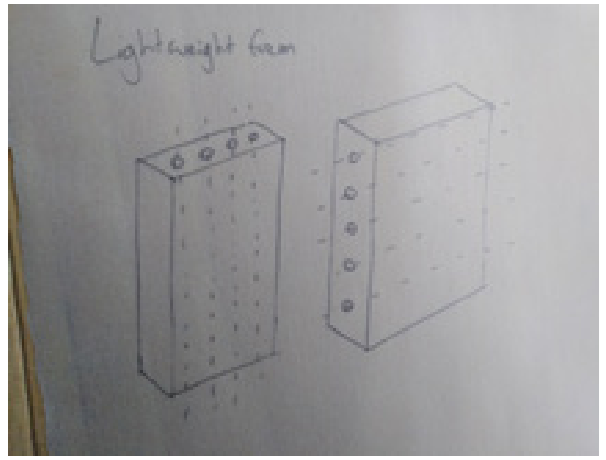


Figure 55: Panel form with horizontal or vertical holes. Source: (own ill

Repetition in the production process

The repetition in the production process in this project is seen as more important than the size diversity for the architect because the aspects of speed, reducing costs and sustainability are more important than form freedom (flexibility in sizes) and the diversity for the architect. Because the Netherlands also wants to build quickly to reach 1 million houses by 2030, production and assembly speed is an important aspect. How unique buildings are will be of less importance in this project, although diversity in buildings is always desirable. This can only be achieved through the diverse use of facade cladding and not only through size diversity. For this project, it is more important that the building can adapt to new requirements and preferences over the years (the scenario's) so that both the layout of the building and the appearance can change and a 'new' building can be created without the entire construction being the same. Should this nevertheless be the case, because the shape of the building changes or a different facade layout, the same panels in the building can be reused to achieve this. Unfortunately, the architect's freedom of design is somewhat diminished by standardization, but in return, a standardized concrete façade system will increase the building efficiency that helps reach 1 million houses by 2030 and contributes to a more sustainable built environment.

Manufacturing

The concrete will be prefabricated and the manufacturing of the concrete facade system will take place completely in one factory. Suppliers for the insolation, cladding and other things have to deliver their supplies to the factory where all these elements are being assembled.

The manufacturer who assembles the system has its concrete plant on location for the prefab concrete. In this way, the factory also has control over the preservation of the concrete during production. Besides, this manufacturer knows exactly how everything works and is specialized in handling concrete, which is what this system is all about. It is therefore best to merge the concrete production and the construction system manufacturer to minimize logistics emissions.

For the production of the different standard panels, it is common to use moulds that can be adjusted to the correct dimensions. After this, the reinforcement and connections must be placed in the correct position. Ideally, everything would be automated, to have the fastest and automated production process.

A robotic production process like this already exists. An example is Voorbij, who uses robots, that are instructed by BIM, to adjust sizes with steel profiles onto the steel formwork slab (mould) which are secured with magnets (*Figure 56*). Then the reinforcement and the connections are placed in the correct position. The electrical installation is attached to the reinforcement and has to be strong enough so leakage isn't possible. The moulds go through a kind of drive-through where they drive from station to station. At each station, certain handling takes place based on a computer controlled system.

Choosing for an automated and robotized production process is a logical choice for in the future. Known industries that have been successful with robotizing their industry are the car and recycling industry, the timber building sector, and the agriculture industry. By robotizing the production of the concrete panels, it will become more controlled, faster, flexible and a constant product of quality can be ensured. The labour in these industries can be intensive and as labour becomes too expensive, robots can be seen as a solution to take these things over. Although jobs will be lost because of this, new jobs will be created in controlling and automizing the logistic process.

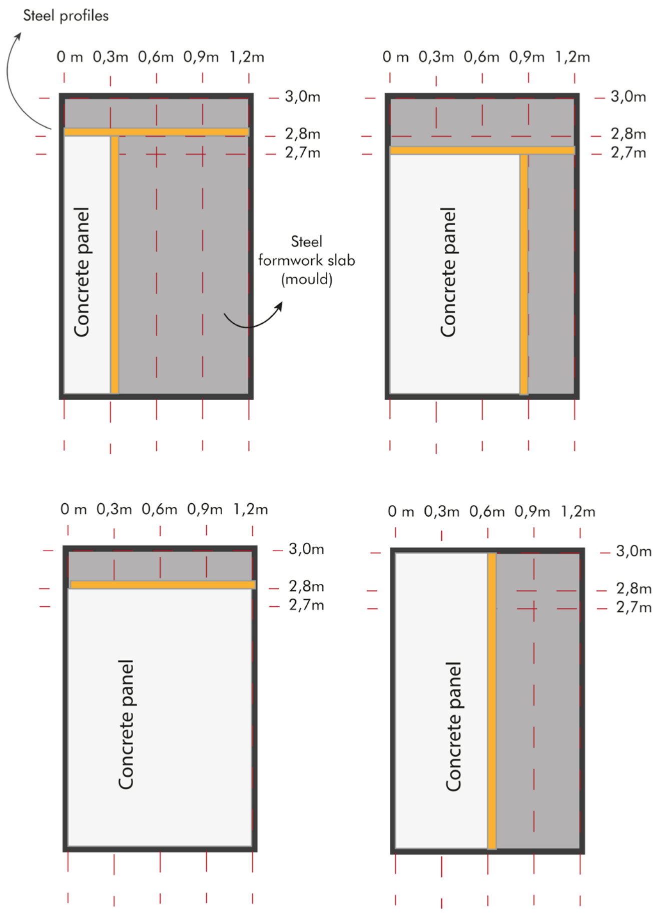


Figure 56: Production of concrete panel: moulds with fitting pieces. Source: own ill.

Assembling & disassembling aspect

After analyzing the case studies, what stood out was that a few had a really fast construction time. This because of assembling the precast elements before transporting it to its location. This can be translated to certain options shown in *Figure 57*. Three options can be seen:

- **Assembled one by one on location:** Slows down the construction time, requires more man-power, makes the work more complex, increased chance of errors and creates an unsafer work environment
- **Assembled as one module (panels put in a frame):** quick assemble & disassemble on site, less chance of errors on site as well as at assembling location, requires heavier machines but less manpower (safer)
- **Assembles as multiple modules:** building time slower than one module, a more complex system with a higher chance of mistakes, more freedom in connections and or building structure.

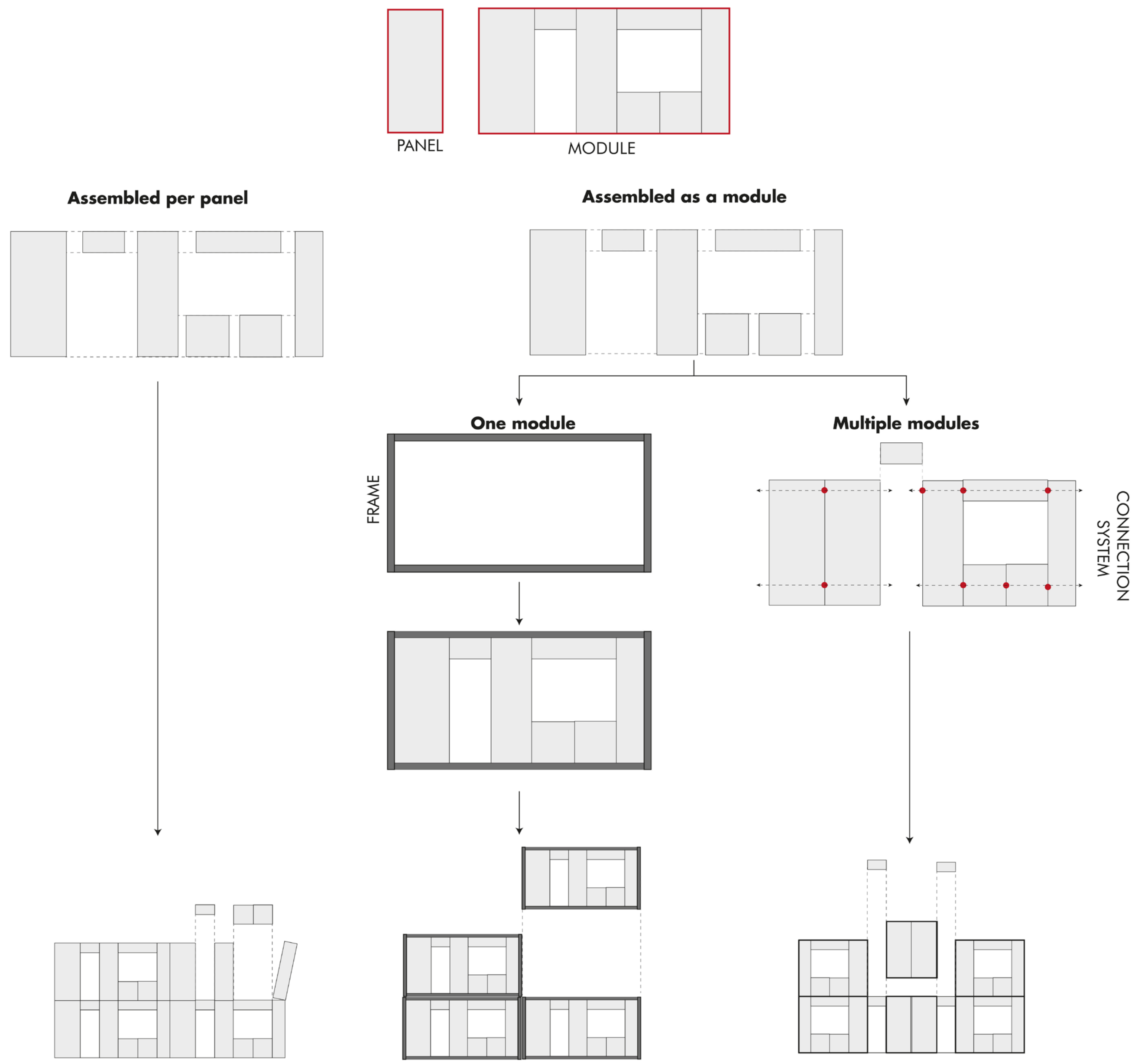


Figure 57: Panel assembling options. Source: own ill.

If subjecting the different types of assembling in the criteria to building efficiency (*Appendix I*), the option of the panels in one module has the fastest and safest characteristics, although the connection between the frame, the panels and the building structure should be analyzed in the upcoming chapters.

Another option evaluated than the module in a frame is a system that consisted of one big module by making a connection with a cable system, like the project Circular viaduct (*Appendix J-1*). But when putting it through the criteria list (*Appendix J-2*), it could be concluded that a module in a frame would be better as a cable system is relatively unknown for facades and scores low on the separation of components, among other things.

Dimensions of the frame

The dimensions for the frame also have to be decided, to ensure that there is a right standardized rhythm between the panels, frame and building structure. There are many possibilities for the panels to form a facade of different dimensions, but the frame can't be endlessly long as this would not be preferable for transportation. The goal is to transport the modules without needing a special permit. As mentioned in Section 2.2.5, the sizes are limited to a maximum of 2,55 m in width; 15,5 m in length and 4,0m in height, which means that the frame has to be within the boundaries of a maximum of 15,5m in width and 4,0m in height.

Then the question rises which dimensions are preferable now and for in the future. Are these sizes going to be the same preferable sizes for in the future? As seen in Section 2.2.5 "Residential buildings" and 3.1.5 "Findings", standardization is already visible in the form of beukmaten. Most of the single-family homes go from sizes 5.4 to 5.7 meters in width and 9,0 to 10,0 meters in length. With 5.7 meters becoming more popular over the years.

For apartment homes, this can range from 5.4 m to 7,5 meters. With the most encountered ones in the case studies being 5,4m; 6,0m and 7,5m in width and 10-10,2m meters in length.

Based on these numbers, the best option is to go for dimensions that fit both the factor of the front of an apartment as well as the sides of the apartments or go for different frames that fit both of these different aspects. But first, we go back to the question:

"What sizes are going to be preferable for in the future?"

The source *Kalloe (2018)* has recalled that the Dutch population is going to live smaller because the household composition is changing. This is because, people divorce more often, families are smaller than in the past (fewer kids), there are more singles or single households and the elderly stay at home longer. Due to these developments, there is more demand for a smaller living space. More people want to live smaller, so that there is more left for fun things, such as making long trips which were less possible back in the day. In addition to this, space in the city is becoming increasingly scarce and construction of a smaller building will also become more common.

With these factors in mind, should there be one size for the frame or multiple sizes? Because the heights of the standardized panels are 2,7 m; 2,8 m and 3,0 m, there are 3 different sizes for the frame. This can change when thorough research is done on the dimensions for the height. The decision for the dimensions of the width should lie with the two different beukmaten, the one in the width and the other one being in the length. For the one in the width, a beukmaat of 5,4 m would be the most obvious choice, because the chance is high that more people are going to live smaller in the future. Smaller sizes will also be available but will be disregarded for now.

Module in a frame - material

As it is chosen that a frame is going to be used to attach the concrete panels so the building efficiency will be increased, it still raises the question of which material is best to use in this project. The choice lies in between a metal or concrete frame (*Figure 58*), as materials like wood or aluminum would be too weak to carry the concrete panels.

Metal/steel

Metal or steel is known for being a very strong and durable material used often as a building material for high buildings. Because of its strong specifications, a thin building structure is possible with steel in comparison to concrete. In this project, it is important to look at the different profiles such as a HEA-, IPH- or a U-profile that is the best fit for the concrete panels that go in the frame.

The HEA and IPH are very strong steel profiles, but they are causing a big joint width for the facade system, which can change the standard dimensions of the project and a solution should be found for this. Also, if the concrete panels are load-bearing a very strong steel profile isn't necessary, as the loads will be shared with the concrete panels. U-profile is the best option when choosing steel. Best would be if the thickness of the concrete panels fits in the width of the U-profile so a joint width can be avoided. Although there still has to be room for a connection between the frame and the panels and this (and the frame itself) can cause thermal bridges. This can be solved by covering the facade with insulation continuously.

Concrete

The frame can also consist of concrete, so the whole structure consists of one material (except for the connections). The disadvantage of a concrete frame is that it takes in extra space as the concrete frame will be a solid square or rectangular. The connection between the two elements will be easier and can happen in the element itself instead of it happening outside the frame and panels. But the extra space causes larger joint widths to exist. There will also be a thicker construction with a concrete frame if it has to be load-bearing as it does not have the same strength as a steel profile. At last, there is a good chance that the concrete will crumble after multiple uses as it is a brittle material.

Material Choice

In the end, choosing a steel or metal frame is the best option as it is structurally strong, allowing for a thinner structure, doesn't have consequences for the joint width and is more resistant to more frequent use.

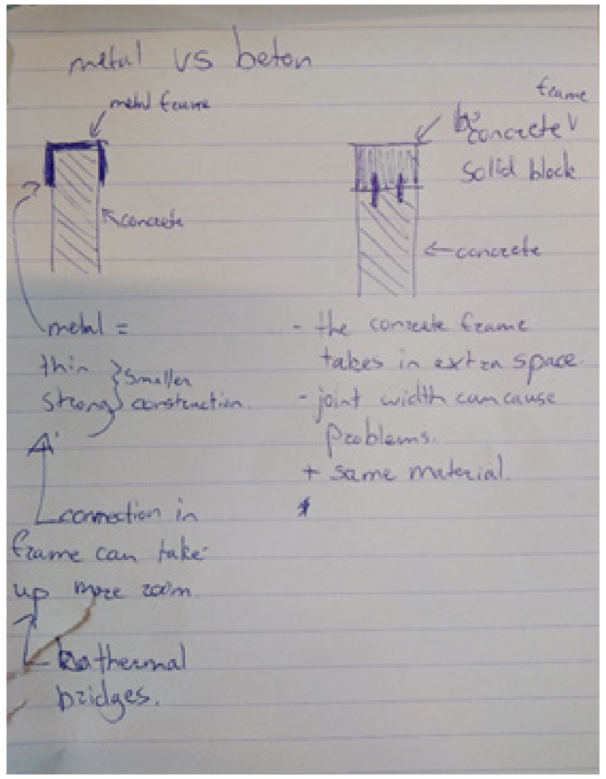


Figure 58: Material options for frame - Metal vs. concrete. Source: own ill.

Building structure - material choice

If the premise is that the concrete is produced with sustainable materials and a sustainable production process then this is more sustainable than the use of steel. On the other hand, the combination of steel makes for a thinner construction, but since a metal frame was chosen in the previous section, this is already being done on a smaller scale. It may be somewhat superfluous to make the entire construction of steel. Steel construction is often more convenient in this sense when creating very large spans, although in the project it can provide a lot of flexibility. The spans in this thesis will not be so large that a steel construction will be required, it is more a preference of choice.

The spans will be approximately the dimensions of the beech dimensions of a normal house in the Netherlands (eg 5.4m wide and 9.0m long).

Besides, concrete, especially reinforced concrete, is ultimately safer when it comes to fire resistance and its weather resistance (and therefore also its durability). The only real drawback of concrete compared to steel is that it can withstand little pulling forces, but that can be overcome by arming it. One requirement is that this covering must be 100% recyclable. Also, the steel frame will partly take on these forces.

Considering all of the above, the choice would go to a *concrete building structure*. Especially when it comes to its sustainability factor. The following paragraph will discuss the different supporting structures that are suitable for concrete residential buildings.

Building structure

After it has been determined to use a module in a steel frame as a tool to fix the panels, according to the criteria list, the next step is to choose the main supporting structure based on this decision. The aim is to make it as easy as possible for the client to choose a building structure according to his requirements. Each building structure is applicable but has its advantages and disadvantages that better suit certain requirements or target group.

As said in the previous paragraph, the building structure will consist of concrete. Three different building structures *(Figure 59)* are analyzed and assessed through the criteria list (*Appendix K-1*) which will focus on building efficiency (assembling&disassembling aspect), adaptability (layout flexibility) and sustainability (material use). Other criteria are left out or changed for this decision as not all are of importance for this decision like, for example, the standardization aspects, as in this stage it is independent of choosing a building structure. Also, the 'separation of functions and life cycles (maintenance)' will be seen as how easy it is to replace the module/façade without damaging or having to take the whole structure apart, therefore naming the criteria 'separation of supporting structure and module/facade'. besides, aspects such as fire safety, thermal and sound insulation are included, as it indicates, for example, in the case of thick concrete walls that less insulation needs to be added due to the good properties of concrete, as described in *Section 2.4.2*. The last thing to mention is that this only concerns the building structure consisting of load-bearing modules and not non-load-bearing modules this section. We will discuss the most important details of each building structure:

1 – Span: wall~wall

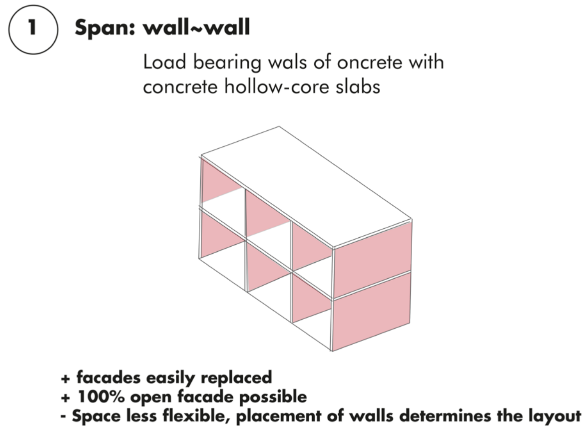


Figure 59: Concrete building structure 1. Source: own ill.

The building structure scores lower in the aspect of the flexibility of the layout of the building and how much concrete it needs to use in comparison to the other two structures. It does have advantages in its fire-resistant, and thermal and acoustic properties which result in needing fewer additions in the load-bearing partition walls that will save costs. The thick concrete walls do mean that more concrete is needed, but assuming that the concrete is sustainable and sustainably produced, this is a less serious factor. The owner of the building is free to change the front and back facade system as it isn't part of the main structure, enhancing the flexibility to replace a module without having to take apart the whole building.

This all can be an interesting choice for owner-occupied homes, where change within a function is a less likely factor. Then the rating for lay-out flexibility will be taken less into account. Also, the flexibility of changing the module, without having to disassemble the rest of the building, can be great for owner-occupied homes as all separate owners can choose on their own time to change the cladding, insulation or the layout of the facade if it is within the architectural and technical policies of the building.

In this building structure, the modules on the front and back will function as non-load bearing walls. The modules on the side, the partition and shear walls are load-bearing.

2 – Span: portal~wall or portal~portal

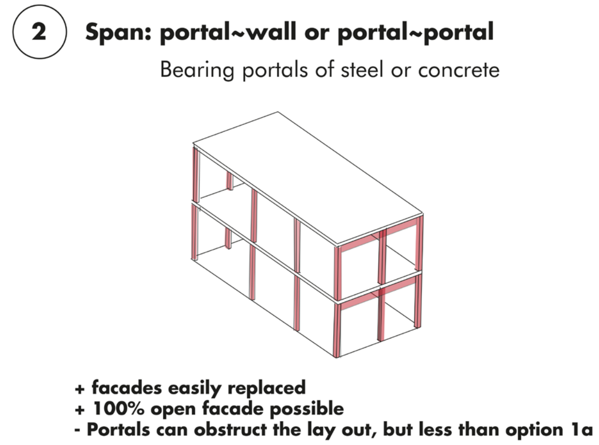


Figure 60: Concrete building structure 2. Source: own ill.

It scores well on the separation of supporting structure and module/facade, as the modules can easily be replaced without interfering with the building structure. It scores average on the flexibility of the layout, as it requires columns to be in the layout of the building for the building structure (although the amount depends on the size of the building) This type of flexibility fits more the character of a house corporation or, especially, a private tenant as an owner, where a change in flexibility happens more often. The private tenant comes under a landlord and it is possible that several landlords, instead of one, can rent out their homes in a residential building. It is therefore important that they can apply changes on their own if necessary. The modules can change in layout to the preferences of the owner.

The modules in the front and back can be made non-loadbearing if there are enough concrete columns to support this. If choosing to not use columns, then the modules have to function as load-bearing walls for the building structure. The sides need portals like the module to support the building structure, so here they will function as load-bearing walls.

The last thing to mention is that it does need a lot of additions to improve its fire safety, and acoustic and thermal insulation.

3 – Span: facade~facade:

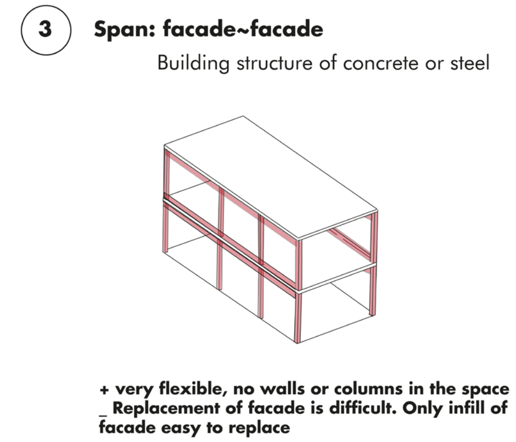


Figure 61: Concrete building structure 2. Source: own ill.

Building structure 3 is the most flexible one of them all. It doesn't require extra columns in the layout, because the facade carries all the load. It does mean that it is difficult to replace the facade/module on the front and back side when damaged, as it does interfere with the supporting structure. Therefore it scores lower on this aspect, but high on flexibility. This fits mostly with the profile of a housing corporation. Within for example a housing corporation, it is more likely that change happens in the whole building, making flexibility in the layout of the building important and change of individual modules (because a tenant hasn't ownership of their home) less likely to happen. Another notable thing is that, as it doesn't have a supporting structure in the centre, it saves the use of concrete. Although the modules on the front and backside will likely be thicker than building structure 1 due to it being fully supporting the building structure.

The last mentionable aspect is the same as building structure 2, it will need more addition to make the fire safety, and acoustic and thermal insulation sufficient.

Criteria list - Building structures
Seen also in *Appendix K-1*, building structure one has the best outcome considering building efficiency, but they all have their qualities that fit better with certain ownership. Looking at the housing market, it is more likely that the building will be designed for owner-occupied houses since 2/3 of the current apartments consists of this type of housing *(Section 2.2.5 Residential buildings). In Appendix K-2* the housing types and building structures are connected, each with their preferences and qualities and which housing type best suits which building structure.

When it comes to flexibility to be able to adapt the layout of a home or building, it is best not to choose building structure 1 but to consider one of the others, because the load-bearing modules determine the layout of the building. Also, it applies that if it is expected that after, for example, 20 years the entire facade or some modules will have to be adapted, it is best to use building structures 1 or 2, since the front and the rear facade is independent of the supporting structure, but this is due to the type of connection system that is chosen. Number 3 could also be possible, but that would mean that the entire building would have to be disassembled and reassembled which will end up taking more time and money. Structures 2 and 3 do have much more freedom to organize their building and possibly use other preferred material for the partition wall, but on the other hand, building structure 1 already has a head start on insulation with its concrete supporting modules.

In the end, all options are open and the goal is to provide enough choice for the customer. With the help of the criteria, it is easier to determine what his package of requirements is and what fits best with it.

Type of floor

It advised using a hollow core slab floor for the supporting structure because of its lightweight character which fits the concept of the concrete facade system. It has advantages in its large span range, due to its shape, resulting in the use of fewer materials (therefore lightweight), fast assembly and lower costs. Despite the advice, the type of floor depends on the choice of the connection system. For example, when choosing the CD20 system from *Section 3.2.2*, a solid floor will be used.

Connection systems – panels, frame, building structure

Because the concrete panels are mounted in a frame and it has been decided to make this from steel, it is necessary to consider how they are connected. Firstly, it must be decided what is the best steel profile for this. Secondly, how the profile and the concrete panels are connected to make a completely rigid facade.

For the steel profiles there has been looked at four different options: the HEA profile vertical (left) and horizontal (right), U profile and L profile *(Figure 62)*. For a load-bearing facade/module, the Figure shows that the L-profile (with a second steel plate clamped against it) has been chosen as the best choice. This is tailored to the criteria joint width and accessibility of the connection *(Appendix L)*. The explanation for this is:

- The **(vertical) HEA profiles** ensures a lot of joint width between the modules in the length. However, it is easy to access connections.
- Although the panels would fit into the profile conveniently, the **(horizontal) HEA profiles** mutually ensure joint width in the length. It also makes it difficult to tighten any connections like a wall shoe when it is going to be mounted.
- The **U profile** ensures that the panels can fit neatly in, but makes access to the connections more difficult.
- The **L-profile** has the same principle as the U-profile but the connections are accessible because it is open on one side. As a result, an extra steel plate has to be attached after tightening the connections to make the module completely rigid.

METAL FRAME - PROFILE CHOICE

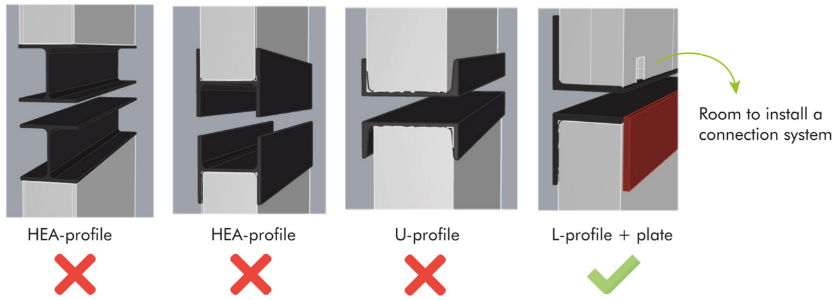


Figure 62: Choosing the profile Source: Source: own ill.

Connection systems – panels, frame, building structure

In *Figure 63* is drawn how a connection system for the frame and panels would work: off-site the panels are put into the L-profile with already welded nuts to it and rubber strips to protect the concrete (1), then when the module is assembled on the supporting structure by, for example, a walls shoe, a steel plate is fixed onto the L-profile with rubber strips and concrete panels by securing screw thread (2) that ensures that the panels are clamped in the frame (3). In the following Figure X3, the step by step construction is drawn which shows how the panels are attached to the frame when the modules are mutually connected.

Unfortunately, the structural lightweight aggregate concrete is a brittle material that is more easily damaged. As explained in Section 2.4.4, it must be handled carefully if wanting to keep it in good shape. The metal frame can protect the outer edges of the structural lightweight aggregate concrete panels from damage. But as said in paragraph *"Module in a frame material"*, it does also need protection from the metal frame itself. The clinging and direct contact between the frame and the concrete can damage the material more quickly. Direct contact must be avoided and this can be done by, for example, placing rubber strips between the concrete and the frame as seen in *Figure 63*.

METAL FRAME - STEP BY STEP CONNECTION MANUAL

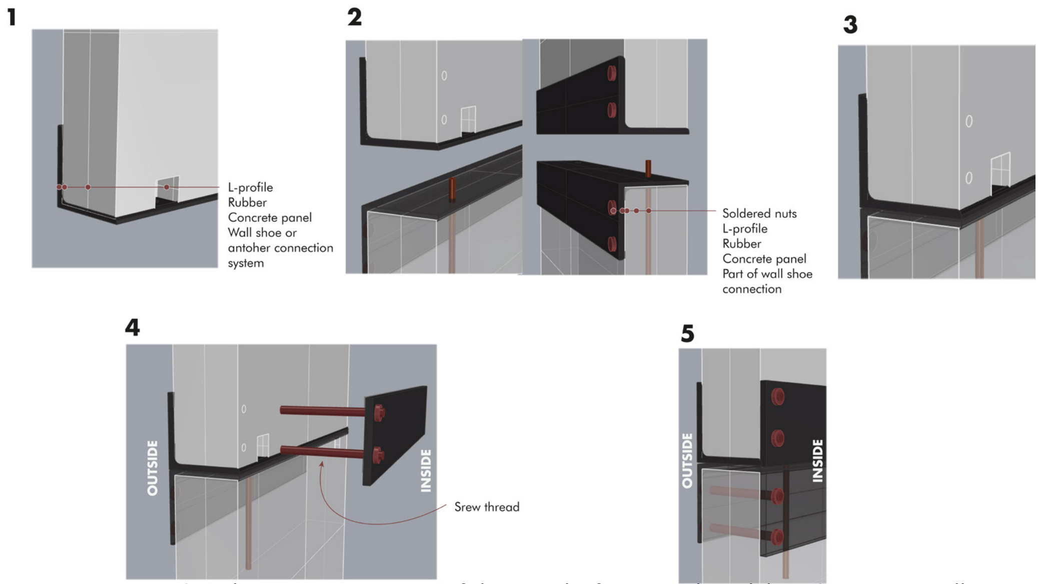


Figure 63: Step by step construction of the panels, frame and modules. Source: own ill.

Connection systems – load-bearing panels and non-load-bearing panels

Load-bearing panels
To ensure structural safety for modules that are going to be used, an external connection will be used for the load-bearing facades. A possible external connection can be a Halfen Hek *(Figure 64)* or a horizontal Wall shoe of Peikko, the examples of *Appendix B* and overview of *Section 2.2.4*.

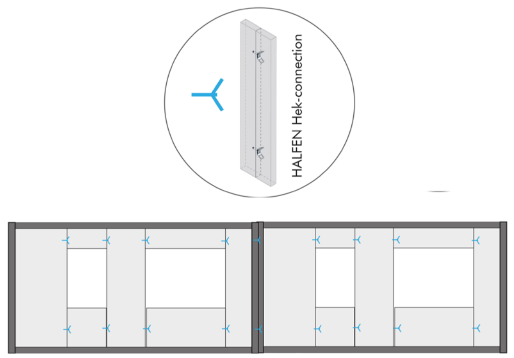


Figure 64: Halfen Hek connection between panels and modules. Source: own ill.

Non-load-bearing panels
As mentioned in *Section 2.2.4 "Connections"*, the connections for a non-load-bearing module don't need an external connection to be structurally able to cope with the loads it has to endure. The shape of the panel itself can be used as a connection, by overlapping or interlocking *(Figure 20)*. Further research can be done in finding the best connection that suits the whole design of this facade system. For now, the connection will consist of interlocking connections, because an over-lapping connection influences the height that the top pieces need to be fixed on, reducing the design free-dom for the architect of the panels and causes of deviating panels, although the advantages are that it can serve as a lintel *(Figure 65)*. An overlapping connection is used most of the time on vertical external facades components and holds a better structural safety (also seen in the CD20 building example in *Section 3.2.2*), but this is not necessary when the concrete panels are already clamped in the metal frame.

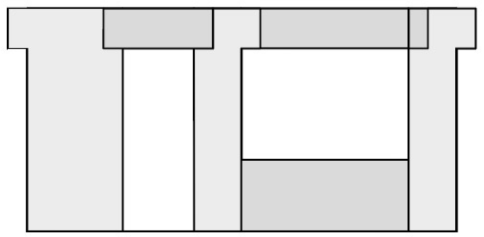


Figure 65: Overlapping panels. Source: own ill.

Lintel/Top concrete pieces
Although an overlapping connection could be a solution for using its shape to function as a lintel and install the top pieces, it affects the design freedom. Therefore, these pieces will not be connected in this way but by utilizing a pin connection, as shown in *Figure 66*. Then the next panel is slid into the holes.

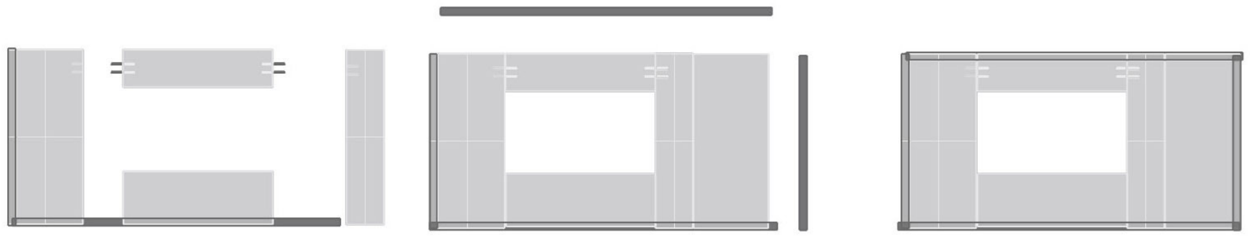


Figure 66: Merge of frame and non-load bearing panels. Source: own ill.

Approach to find the right connection system

As discussed in *Section 2.3.4 "Connections" and 3.2.2 "Modular systems in the construction sector"*, there are several connection systems to choose from. The choice eventually depends on the building structure and other requirements the client has for a project, like having a preference for a particular connection system or company. For this thesis it is preferable when a building structure and connection type is chosen, say for example building structure 1 and connection type 2, it stays with just one connection type and its systems.

In *Figure 67* an updated version of the load-bearing connection systems, with connection systems added that comes from the analysis of "Modular systems in the construction sector". For each connection type, multiple connection systems are giving as options. These all have its advantages or disadvantages and have been put in a criteria list to compare them with each other and see where their strength and weaknesses lie in *(Appendix M)*.

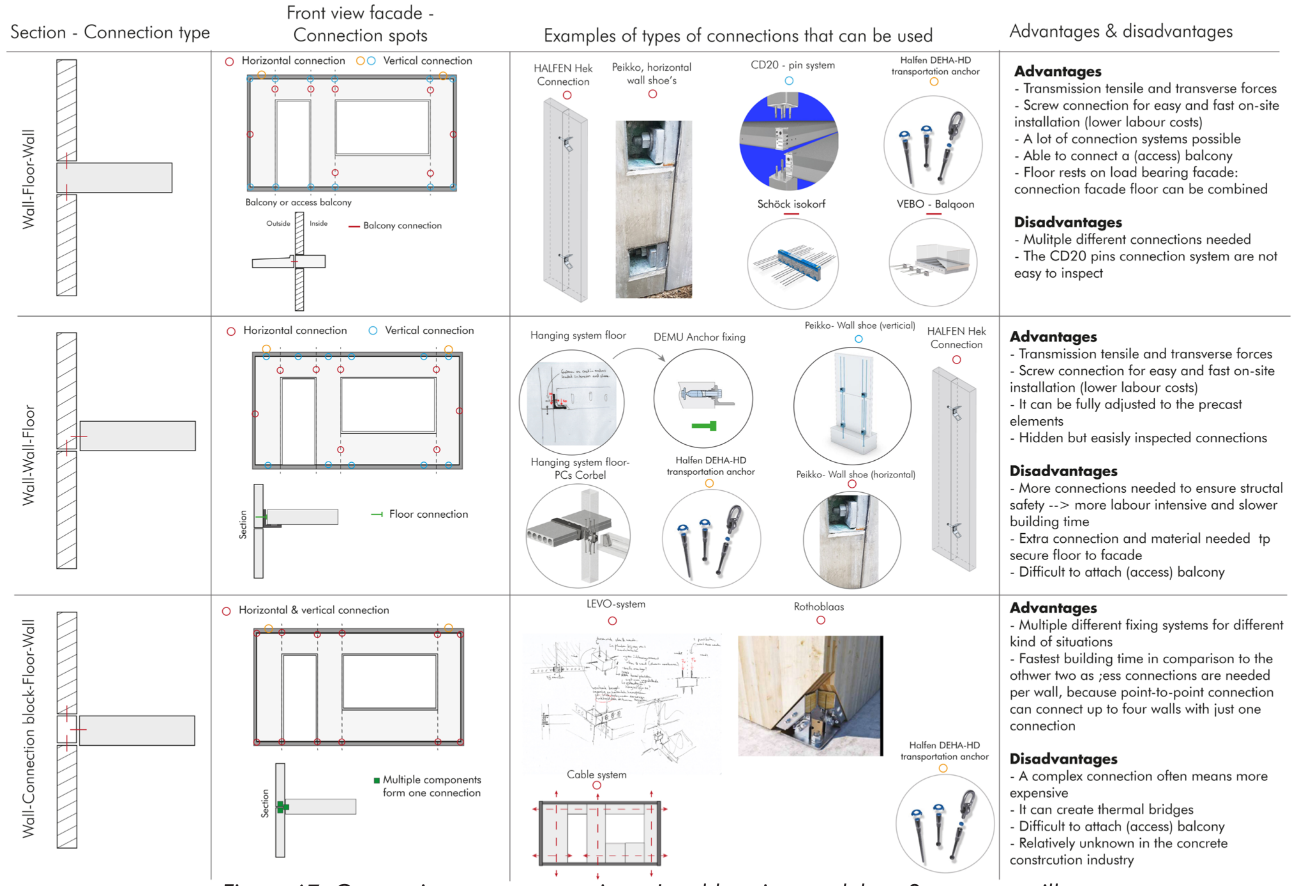


Figure 67: Connection systems overview - Load-bearing modules. Source: own ill.

Connection system 1 *(Figure 68)*
The connection system has its strengths in the fact that it is the only system that can attach an access balcony. Furthermore, its horizontal connections can be easily inspected, as connections like Halfen HEK or Peikko SUMO are designed to do so. Another thing is that the type of connection (wall-floor-wall) is simple and a common way of building residential buildings. It scores relatively well on the speed of assembling and disassembling, safety, the amount of manpower needed and that the connections are hidden that causes it not to have any joint widths and smoothly disappearing in the concrete panel.

Its weaknesses show in the inspection of the vertical connections that are embedded in the floor because of the use of pins as connections, but also that this type of connection takes up space in the building. Another disadvantage is the floor between the panels, where a joint width fill occurs, causing joint widths.

Connection system 2 *(Figure 69 and 70)*
Unfortunately, this connection type can't attach a balcony to it but has the advantage that there is a seamless flow between the panels and with the finishing so that no joint widths arise that otherwise could cause problems. These connections are also perfectly hidden and they can be easily inspected, although it is horizontally slightly more difficult because of the connection system to the floor which can hinder the accessibility of the connections. It is also the best option a shear wall needs to be installed.

The biggest disadvantages of this system are the number of connections it uses per module, needing an extra connection system for the floor. Therefore also increasing its complexity in comparison to connection type 1. For the rest of the criteria, it seems a lot like connection type 1, like the speed of assembling and disassembling, safety, etc..

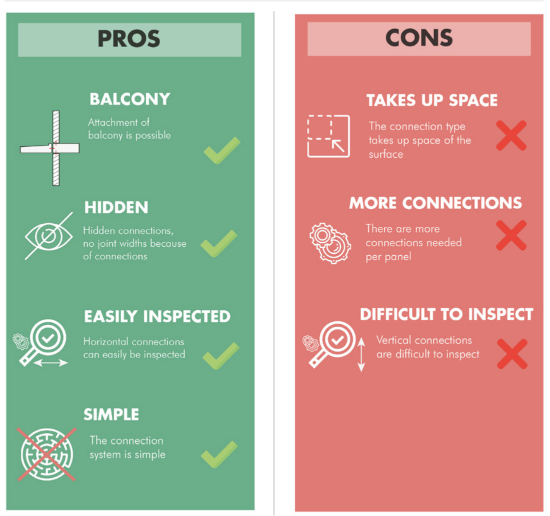


Figure 68: Connection system 1 - Pro's and con's. Source: own ill.

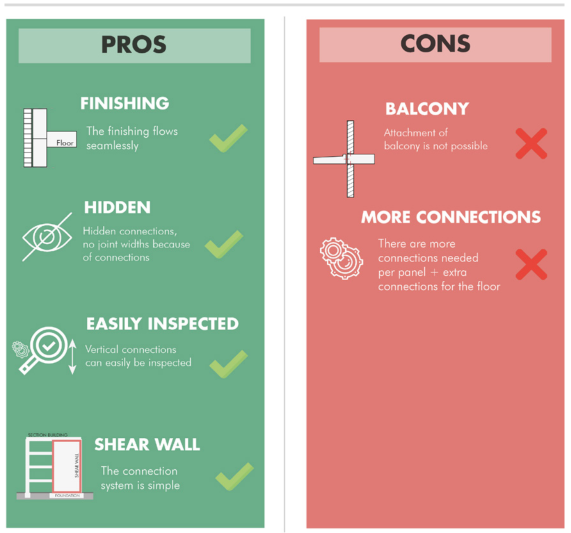


Figure 69: Connection system 2 - Pro's and con's. Source: own ill.

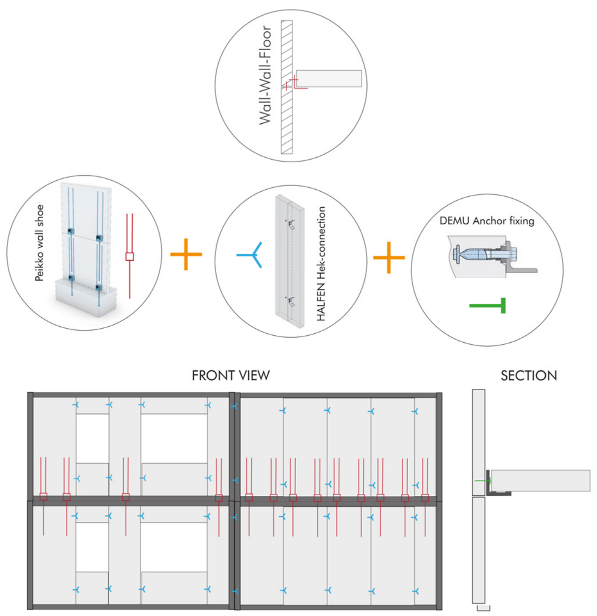


Figure 70: Connection options - Connection system 2. Source: own ill.

Connection system 3 *(Figure 71)*
Connection system 3 is best to choose if time is the most important aspect and it needs to be built in a very short time. Because the connections can connect more than 1 element, it will speed up the building process. But this makes the system much more complex than the other two systems and requires more specialized workers that will increase the costs of the project. The system can also cause thermal bridges, but this can be fixed. A positive thing is that the connections can be easily and quickly inspected on one side, both vertically and horizontally, because this is often in the same connection. If its is easily inspected from the outside, the insulation and can get in the way, but that is not assumed now.

Like connection system 2 it can't attach a balcony as this has not been explored and assumed as not possible. Another disadvantage is that the connections are not hidden, which causes joint width in the building. This must be taken into account during the design, otherwise, problems with dimensions and problems arise with the facade finish

(Access) Balconies
"(Access) Balcony" is added to the criteria list because it is very plausible that this will become a requirement of the client. Although it may be possible for connection type 2 and 3 to have balconies, they have not been taken into account because these possibilities have not been explored and the overview is based on discussed connections. There may be better suiting connection systems for these types, but there are too many in the building industry to be able to discuss them all. So in this thesis, connection type 1 and its systems will be chosen if a balcony needs to be attached to the building.

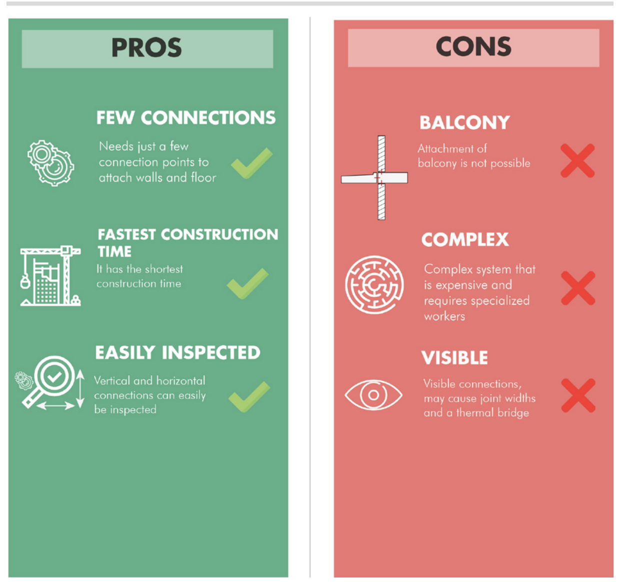


Figure 71: Connection system 2 - Pro's and con's. Source: own ill.

4.2.5 Summary

WORKFRAME FOR A SUSTAINABLE AND REUSABLE CONCRETE FACADE SYSTEM

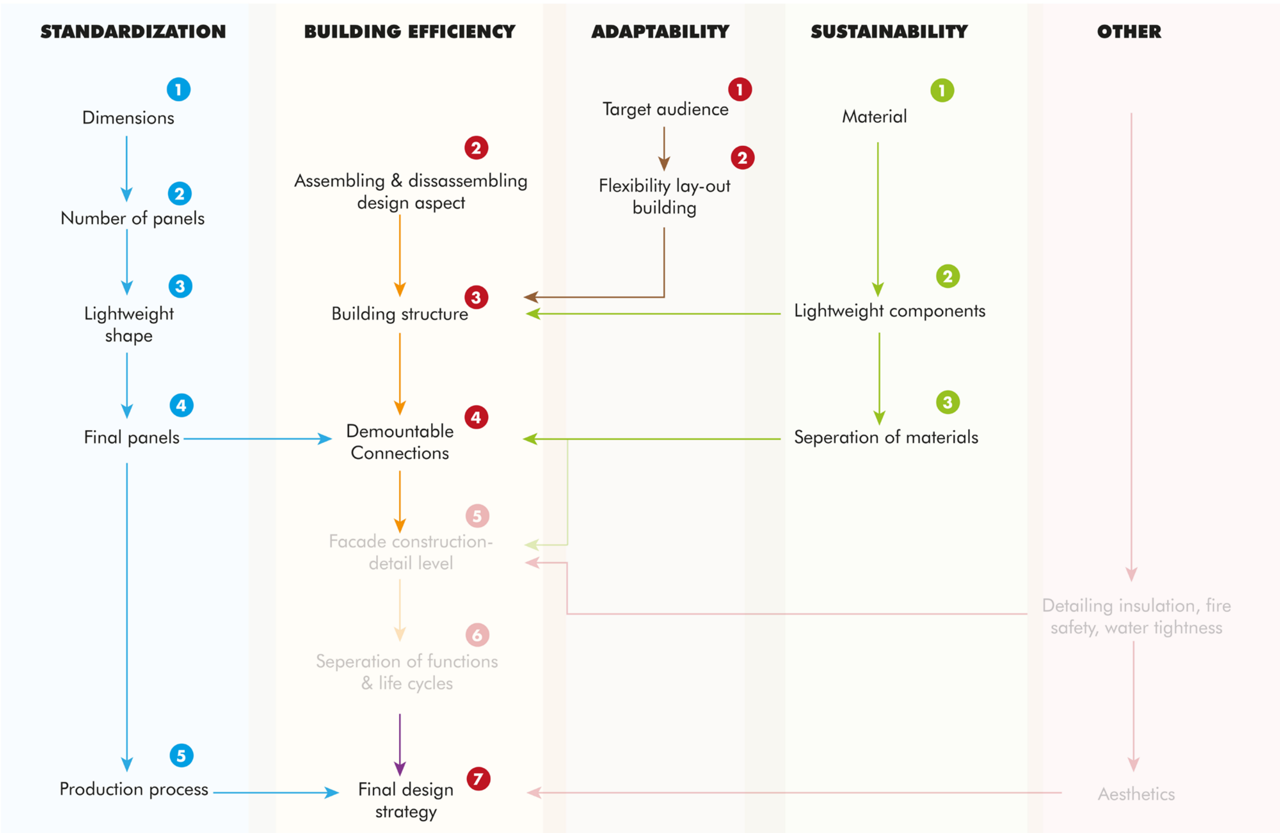


Figure 72: Workframe for the design of a sustainable and reusable concrete facade system. Source: own ill.

Standardization 1,2 and 3 - Sustainability 1 and 2

It starts with determining the dimensions of the panels. In this paper, this is determined using the findings of the literature review as well as the results of *Section 3.1.3 Findings*. It was concluded that the standardized panels consist of *four different widths* and *3 different heights*. It is preferable to have a few sizes as possible to increase the production process on a large scale, but fewer sizes also take away the freedom of the architect. That is why a percentage of 75-85% has been agreed for a building that must be filled with standardized panels so that 15-25% flexibility remains for the architect's design freedom.

After this, the number of panels will have to be calculated over the surface of the building. Finally, the shape of the panel is determined, which should contribute to strategy of building lightweight. But first, the choice must be made as to what type of concrete is going to be used in the design This choice has already been made in *Section 2.4.4* and results in a panel made of lightweight aggregate concrete with a hollow-core shape.

Adaptability 1 and 2

To determine the final building system, the target group and their preferences will have to be considered, because they have a lot of influence on the choices that have to be made in the design. Three parties were discussed here: owner-occupied housing, housing corporation and private rental housing. The choice of this will influence, among other things, the flexibility of the layout of the building and how important it is to be able to adapt the layout and the facade in the future. Subsequently, this choice will influence the choice of the building structure.

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Building efficiency 2

Simultaneously with the decision for which target group the building will be used, a decision must be made on how the panels can best be attached. Three options were considered, including assembling one by one on location, assembling as one module (panels put in a frame), or assembling as multiple modules. All three options were assessed by the criteria and a metal frame was chosen as a tool to attach the panels and the building.

Subsequently, it has been determined that the maximum dimensions of the frame may not exceed the maximum dimensions of a transport vehicle: the sizes are limited to a maximum of 2.55 m in width; 15.5 m in length and 4.0 m in height. Also, it was decided that the frame will be made of steel because it is strong and does not provide joint widths, as concrete otherwise would.

Finally, it must be decided what kind of steel profile will be used and how the profile and the panels are connected to become a rigid whole. After a quick analysis, a steel L profile was chosen because it does not interfere with the main connection system and ensures a seamless transition between modules. The steel frame also provides impact protection as lightweight aggregate concrete is quite brittle.

Building efficiency 3, 4, (5, 6) and 7 - Sustainability 3

After the assembling & disassembling aspect and the target group have been chosen, the building structure can be determined. The paragraph describes the advantages and disadvantages of all three building structures that have been encountered from the criteria list in *Appendix K-1*. The paragraph also indicates which target groups would best suit each building structure.

After determining the building structure, suitable connection systems can be examined and are shown in an overview. These have been drawn up from both the findings of *Sections 2.3.3 and 3.2.3*. These also have been assessed by the criteria and show the advantages and disadvantages of each system. Besides, the paragraph makes a distinction is between load-bearing and non-load-bearing modules, both of which must be examined separately for each building structure to determine if they are suitable or not. Which systems best suit a building structure will be further explained in *Sections 4.4.1 and 4.4.2*.

Standardization 4

The repetition in the production process in this project is seen as more important than the size diversity for the architect because the aspects of speed, reducing costs and sustainability are more important than form freedom (flexibility in sizes) and the diversity for the architect. To realize the ambition of the Netherlands to build 1 million houses by 2030, the production process must be optimized and a robotised production process can make a lot of difference in this. The entire system will be prefabricated in large moulds with fitting pieces for the panels that are controlled by robots. The choice of connection systems influences how the production process should proceed and how these should be placed in the moulds.

4.3 Final design strategy

The final design strategy aims to combine all the discussed strategies and its aspects to create different options that resemble a reusable and sustainable concrete facade system. A sustainable and reusable design strategy that summarizes:

- **RETHINK:** Standardization
- **REDUCE:** Sustainability
- **REUSE**: Building efficiency & Adaptability

These strategies and aspects have led to a design strategy that presents the best way to design a reusable and sustainable concrete facade system (*Figure 73*). The strategy functions as a tool to design a sustainable and reusable system and guides consumers through the options and choices. It must provide insight into what choices have to be made to design such a system. All the criteria set up are means to determine what the facade system is going to look like.

The strategy consists of one main strategy, namely the building system strategy. This contains the most important parts of setting up a reusable facade system, including the choices in the assembling & disassembling method, housing type, building structure, and connection systems for load-bearing and non-load-bearing modules that ultimately form the complete building system. This system will be further explained in the next section and a description is given of how decisions are made.

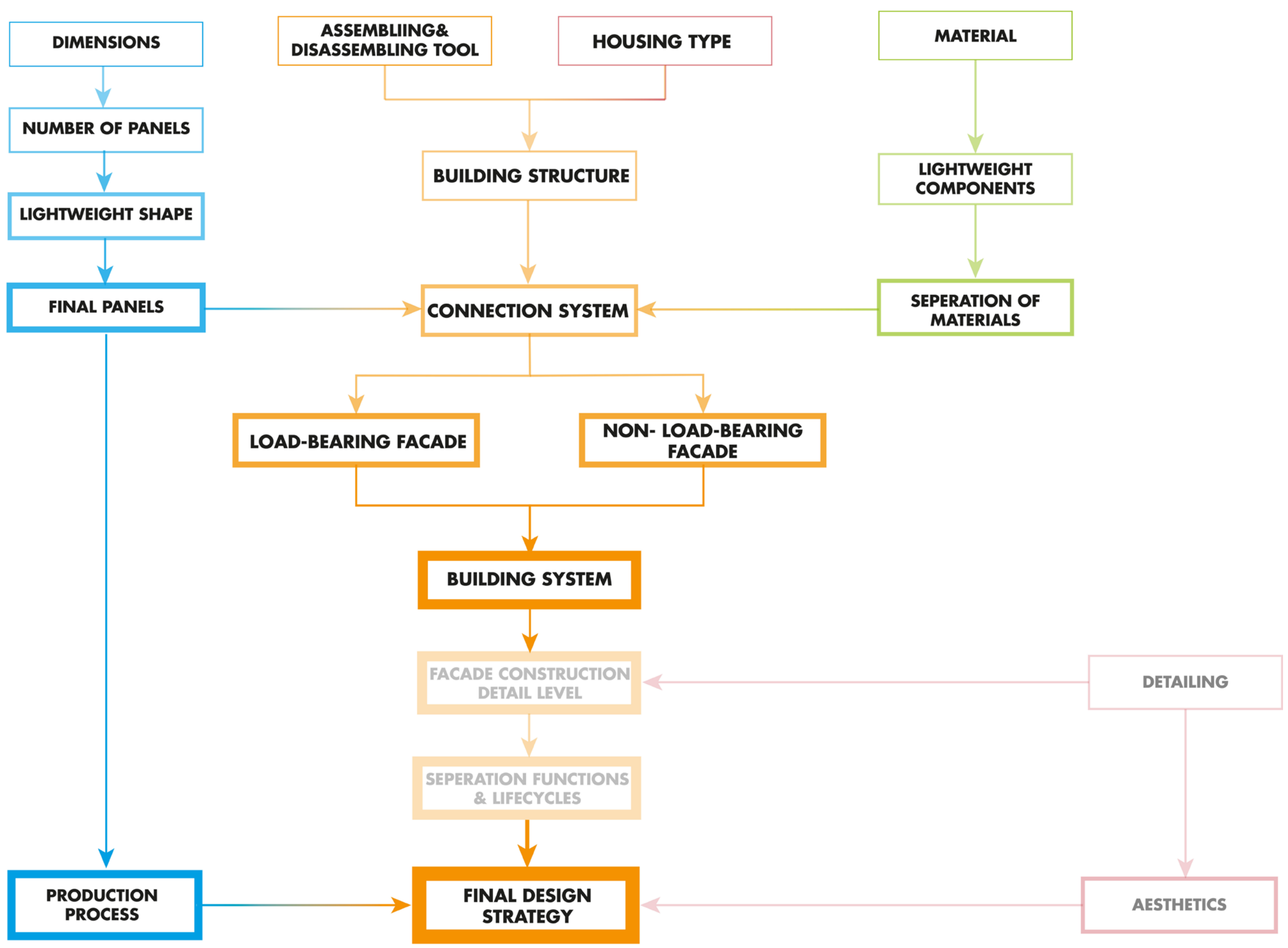

Figure 73: Final design strategy. Source: own ill.

4.3.1 Building system strategy

As part of the final design strategy, building system strategy *(Figure 74)* presents the main system and the modules, with possibilities for multiple sub-systems. This creates flexibility in being able to create different buildings with specific needs. The design possibilities are given shape in a decision chart to guide the designer through all possible options and thus be able to compile his package based on his criteria *(Figure 77)*.

The design of a reusable and sustainable concrete facade system starts with selecting the target group for who the building is initially meant. These target groups are important for their individual prefer-ences and have a great effect on the choice of the building structure, layout and building system of the modules (*Figure 75*). This also indicates to what extent a building will change over the years. This will be different for owner-occupied homes than for social housing.

After the client has made his choice, a suitable building structure can be chosen according to the preferences and requirements that have been set up. Because standardization already is conflicting with the flexibility of a building, it is compensated by the fact that there will be more design freedom for the architect and engineer by having multiple options for building structures and connection systems. This choice can depend on aspects like a preference for a specific connection method, that is for example cheaper and less complex or trust that has been built up with a company through long-term good coopera-tion. The connection systems for a selected building structure are chosen based on whether they are load-bearing or non-load-bearing. This affects the thickness of the building system and the type of connections.

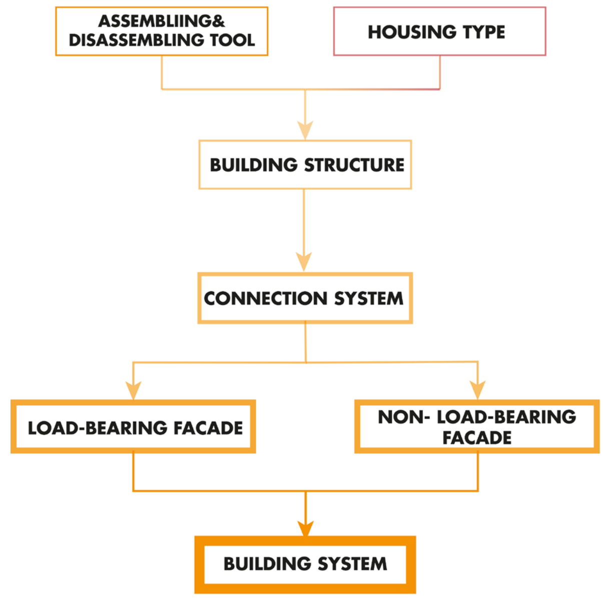

Figure 74: Building system strategy. Source: own ill.

The modules with their standardized and sustainable concrete panels form the basis of designing the final facade system of the whole building. The dimensions, connection systems and layout of the build-ing are being shaped by the modules that are prefabricated in a metal frame of standardized sizes due to the standard panels based on the analysis in *Chapter 3.1 "Standardization"*.

All of the decisions made are strategies and advises for the client. If a client wants to build owner-occupied homes and rather wants to go for building structure 3 instead of 1 or 2 because his main criterion is to be built as fast as possible, this is still possible, but not recommended due to the outcome of the assessments.

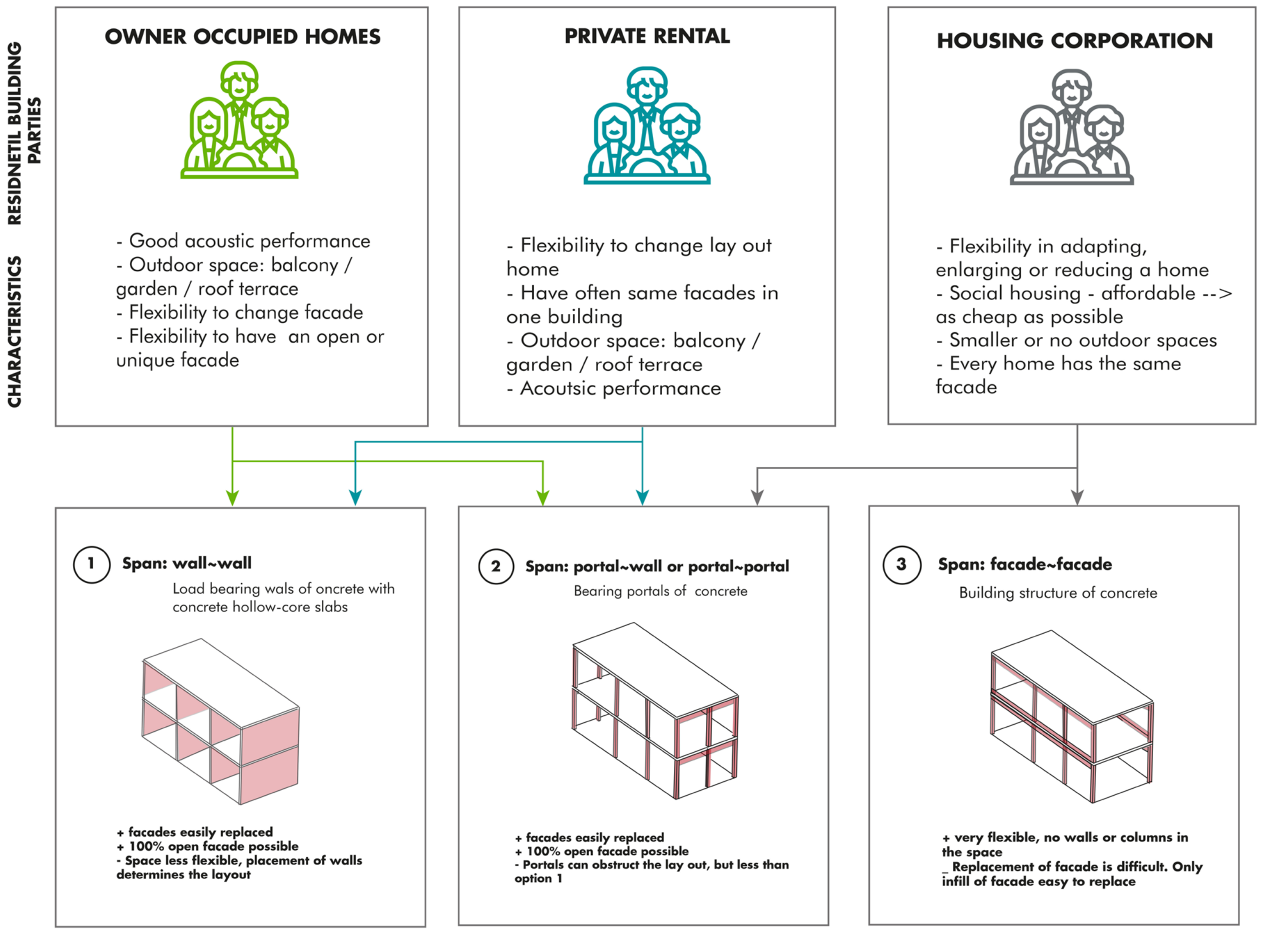

Figure 75: Characteristics of target groups with matching building structures. Source: own ill.

The decision chart

The decision chart for the building systems shows how every decision leads to different possibilities for building structures and connection systems *(Figure 77)*. The chart mainly revolves around the load-bearing connection system, but to get a complete system it is important to also coordinate this with the non-load-bearing modules and connection systems. Each building structure can choose from four different connection systems, although connection system 4 only applies when it comes to connecting balconies. For each connection system it has been checked whether it fits well with the building structure, this is indicated by means of a cross, checkmark or dash.

Explanation of the chart:

- A *checkmark* means that the connection method is suitable for the building structure
- Elements with a *cross* are not a suitable connection method for a particular building structure. This choice is based on the researched connection systems and criteria.
- Elements with a *grey dash* are inapplicable
- Elements with *two icons* means that it is suitable, not suitable or inapplicable for a part of the building structure. This is further explained in the building system examples
- Elements with an *orange cross* means that multiple connection systems need to be used. When choosing a load-bearing connection system with an orange cross, a different connection system must be used for the non-load-bearing modules.

Load-bearing and non-load bearing modules
All red-coloured walls and portals in the building structures will act as load-bearing modules. Load-bearing modules won't be used together with load-bearing columns because this is superfluous. In such a situation, non-load-bearing modules will be placed between or in front of the columns instead.

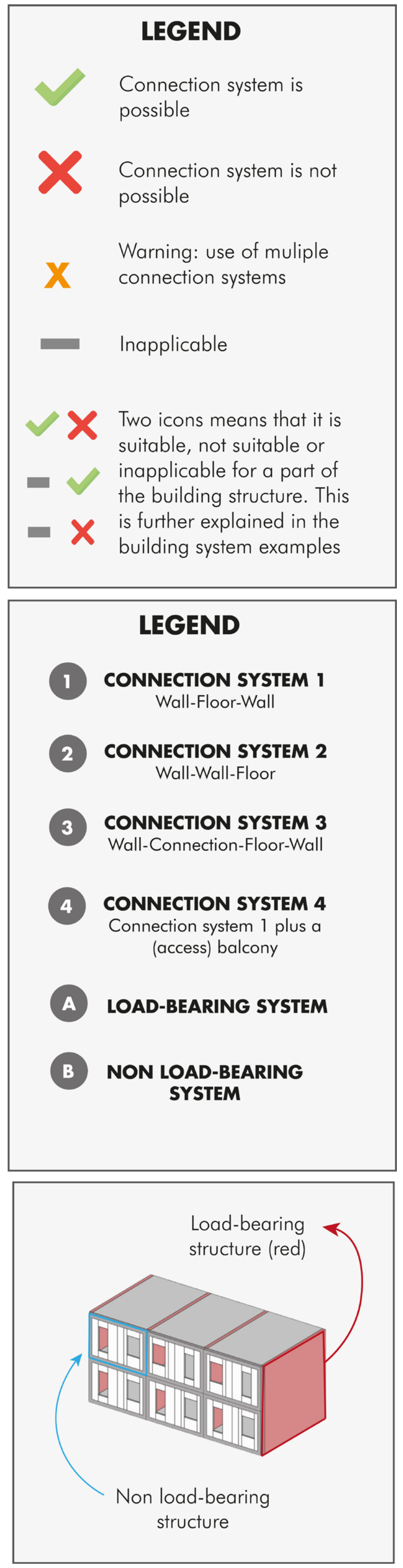

Figure 76: Legend of deicion chart - Building system strategy. Source: own ill.

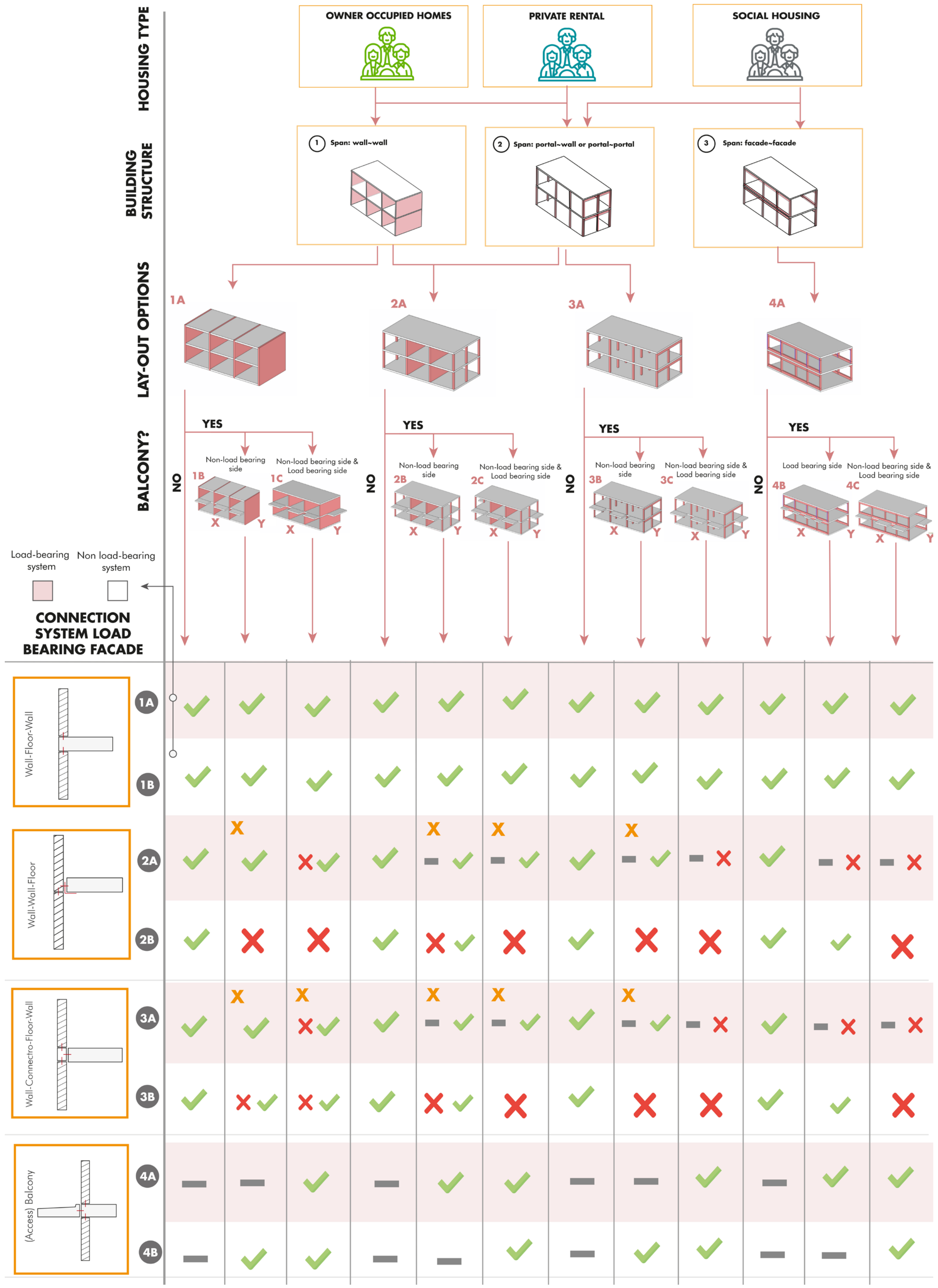

Figure 77: Decision chart for the building systems. Source: own ill.

(Access) Balcony connection system

When a balcony connection is to be used, connection system 1 (&4) will be assumed and the other two connection systems will be discarded as an option. This is because this connection type is the only encountered and discussed connection in the literature study that can connect balconies. It is assumed that the balconies take up all the space of the edge of the floor (on the facade side) and no room for another connection system like number 2 or 3 (*Figure 78*). In reality, this doesn't have to be the case, but this idea is rejected in this thesis and it is assumed that only connection system 1 can be used when using balconies.

Multiple systems are often possible, so there are still many options open. This offers the possibility of more flexibility when choosing a system. Subsequently, the final system can be determined by comparing the package of requirements with the advantages and disadvantages of the remaining connection systems

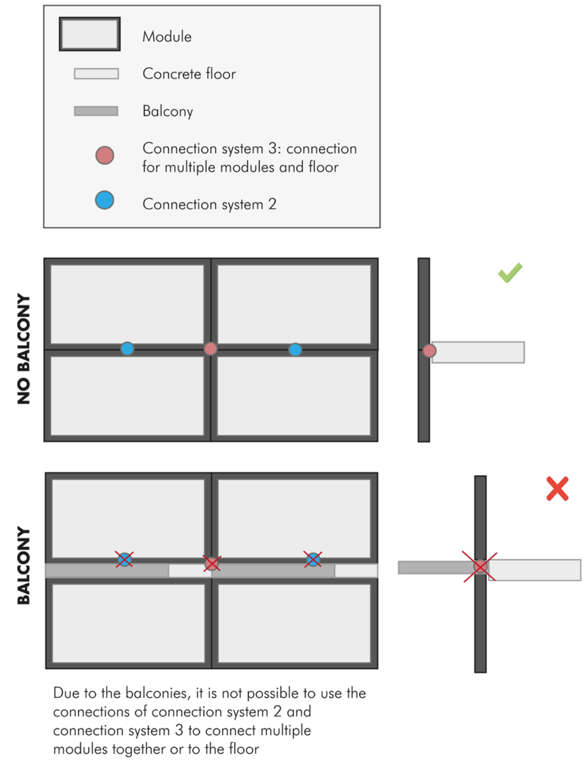

Figure 78: Explanation of the connection system for a (access) balcony. Source: own ill.

4.3.2 Building system strategy – Examples

The final choice depends on the advantages and disadvantages of each connection system. Each building structure has several options, each of which has been briefly evaluated and describes whether the connection system is suitable or not. Each of these building structures are described in *Appendix N*, one of which will be discussed here to have a sense of how the decision chart works. *Figure 74* shows an example will be given on how to choose a specific building system.

A client has commissioned the architect and engineers to design a building for *owner-occupied homes*. He indicates that it is important that the *acoustics perform well* in the building, have a *large outdoor terrace* at the back of the house, that *a lot of light* can enter the rooms and that there are different type of houses.

- Owner-occupied
- Well acoustics
- The large outdoor terrace at the BACK, which means on the non-load bearing side (a massive floor plate needs to be used)
- A lot of light: 75% to 85% of the closed surface of the building needs to consists of standard panels and 40 to 50% of the whole building. This can be for now translated to the surface of one house, stating that the rest of the building consists of the same type of houses (minus maybe an entrance hall, but this is disregarded for now).

If you look at *Figure 71*, building structure 1 will fit this description for owner-occupied homes the best. This is translated to building structure 1 in the decision chart on the next page (*Figure 79*). Because an outdoor terrace is asked, balconies have to be attached to the building and that will lead to building structure 1B.

Figure 80 and 81 show which connection systems are most suitable. Connection system 4B must be used to attach the balconies to the non-load-bearing side of the building. Connection system 4A is inapplicable as there are no balconies on the load-bearing side. Since balconies need to be attached,

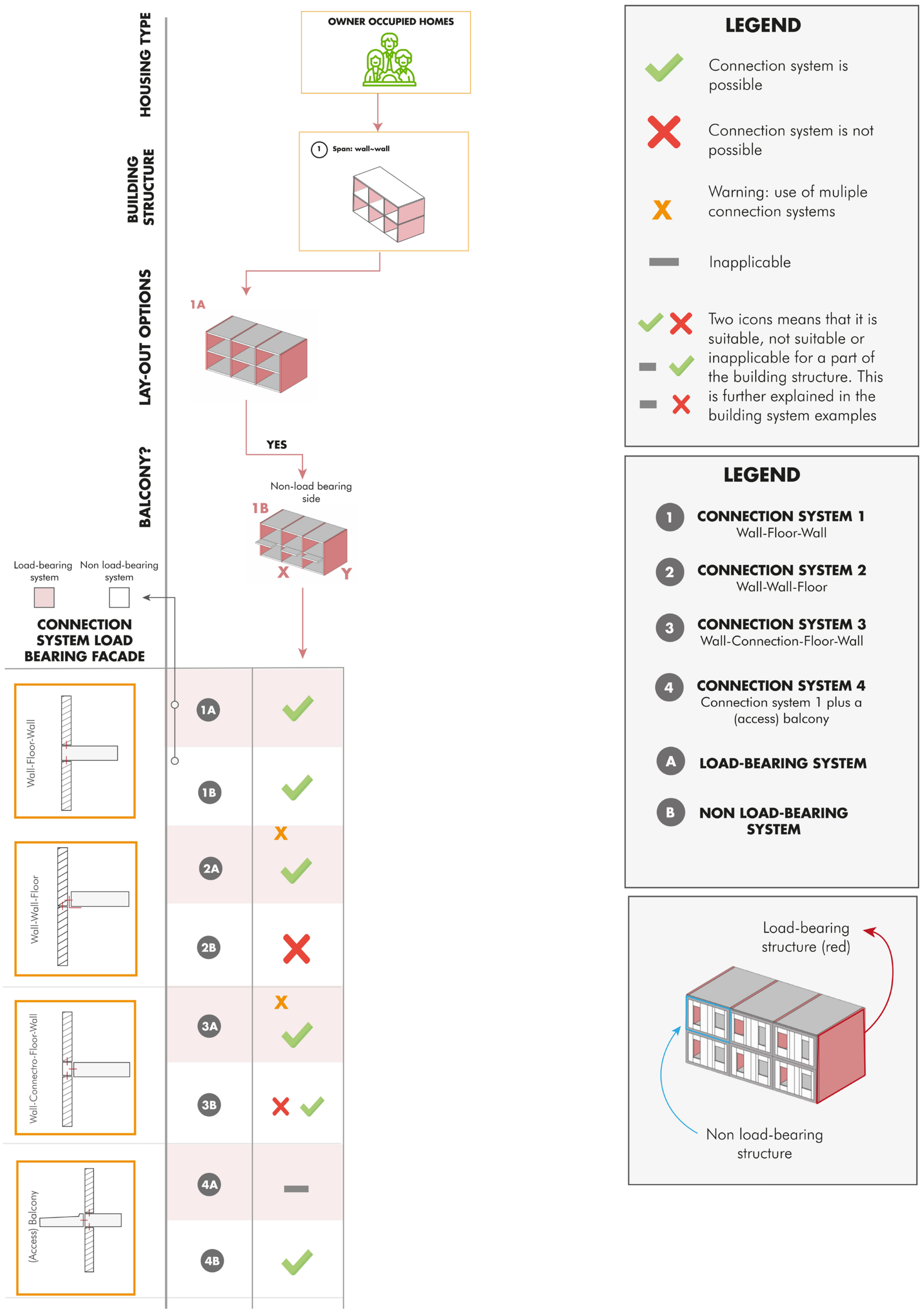

Figure 79: Choosing a building system - Example. Source: own ill.

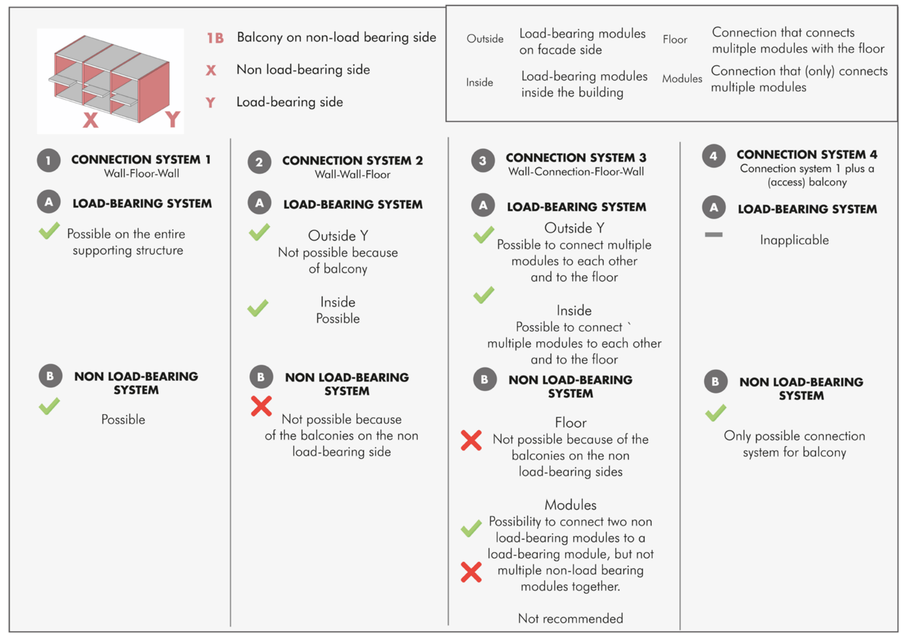

Figure 80: Brief overview and explanation of possible connection systems for building structure 1B. Source: own ill.

connection system 1 is the most suitable from the first point of view, because both modules (load-bearing and non-load-bearing) can be connected this way. Connection systems 2A and 3A can also be applied to the load-bearing modules, but are not suitable for the non-load-bearing one. This is because with connection system 2 the balconies get in the way and the modules therefore cannot be connected *(Figure 78)*. With connection system 3, the non-load-bearing modules can optionally be connected to the load-bearing modules located inside the building, but the non-load-bearing modules themselves cannot be connected, just like the modules to the floor, because of the balcony connections.

The architect or engineer is free to choose what kind of load-bearing connection system they use but is limited in options for the non-load-bearing connection systems. If wanting one connection system for the whole building, the only option is connection system 1. The use of this connection method (wall-floor-wall) has consequences on the joint width, which has to be considered in the designing process. The insulation and cladding must be able to flow through by extending the insulation and cladding that covers the joint width and prevents a thermal bridge.

In *Appendix O*, building structure 1B has been elaborated according to connection system 1 for the load-bearing and non-load-bearing modules. It is designed how the building can look like with the modules and which connections can be applied that are discussed. 2.3.4 *"Connections"* and subsection *"Approach to find the right connection system"* in the previous chapter.

Since there are many possible options, not all of them can be discussed. An overview has been made of each building structure option in *Appendix N*, which indicates which connection systems are possible and which are not, explaining where the crosses, checkmarks and dashes come from. These overviews have been drawn up as shown in *Figure 80*.

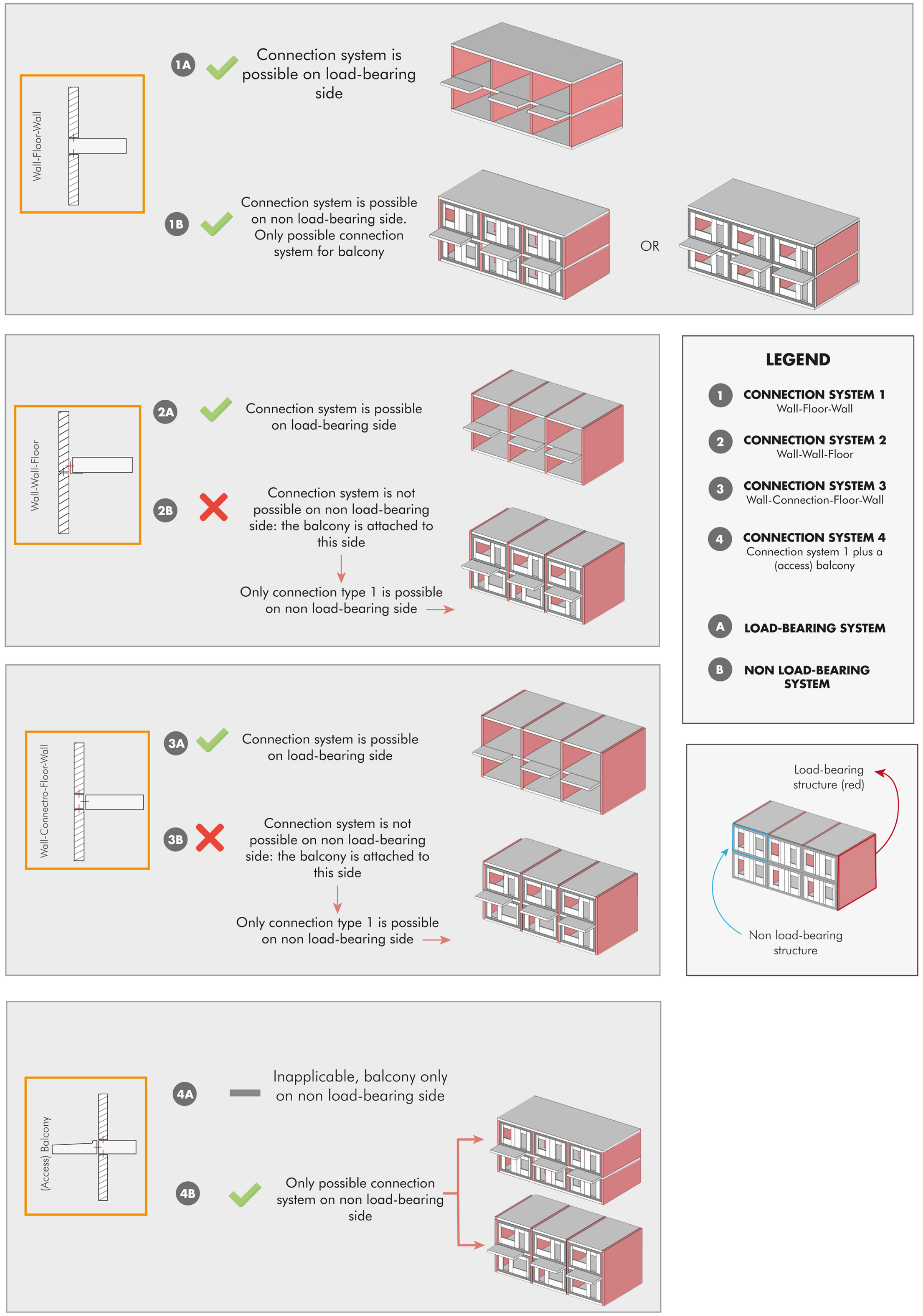

Figure 81: Overview and visuals of possible connection systems for building structure 1B. Source: own ill.

4.3.3 Conclusion of the final design strategy

The final design strategy and the decision chart arise from the literature study, analyses and research by design. The aim is to present a strategy that provides insight into how a reusable concrete facade system can best be designed through the concepts of standardization, building efficiency, sustainability and adaptability. The decision chart shows different choices of building systems that should help the user or designer to make choices. This is influenced by various aspects, such as the target group, how it is assembled and disassembled, the building structure and matching connection systems. Each choice is a tool that can be used to design the facade system.

It mainly focuses on the strategies of functional flexibility and technical adaptability, which enables reuse and thereby contributing to one of the main strategies **Reuse**. The other main strategies, **Rethink** and **Reduce**, are reflected in the form of lightweight construction and the reduction of CO2, waste and use of concrete and relate to the standardization and sustainability of concrete that are part of the design workframe, shown in *Figure 51 and 72.*

There are many more options than what is shown here, but it forms the basis for discovering and assessing the available options through established technical and design criteria It is important to show many options so that the architect or client has more freedom in the design process. The decision chart should make this choice easier.

DQ: "How can a concrete facade system be designed in order to make it reusable?"

Consisting of a design work-frame and a building system strategy, that consist of a decision chart, the final design strategy functions as a tool to design a sustainable concrete façade system that is reusable. This has been achieved by implementing the final design criteria and research through design.

5 CONCLUSION & DISCUSSION

In this chapter, the conclusions that are based on the literature study, the case studies and research by design will be presented and discussed. It will be followed by a discussion and evaluation, reviewing the findings and discussing the limitations and relevance of this research. After this, recommendations will be discussed and finally, the process of the research, the methodology and the position of the research, in relation to the faculty and graduation studio, will be reflected on.

5.1 Conclusion

The reusable and sustainable concrete façade system represents working towards a better environment. The concrete construction sector requires a change to ensure a more sustainable industry. First of all, the product will contribute to the ambition of reducing CO2 emissions, waste and use of raw materials in the building industry and therefore being an example of how new designs and techniques focusing on this subject can help reduce global warming. Secondly, the project enables the ambition of building 1 million houses in 2030 in the Netherlands to be realised by creating a façade system for the Dutch housing market that can be quickly produced and assembled.

MAIN RQ: "How can a sustainable concrete façade system be designed for the Dutch housing market in order to make it reusable?"

To make a sustainable concrete facade system for the Dutch housing market reusable, strategies must be used that focus on *building efficiency, standardization, sustainability and adaptability*. The process starts with **rethinking** the design for repeated use and improve its functionality by designing the building system for multiple uses and target audiences, increase its adaptability and durability. The second target is to **reduce** the waste, material and CO2 emissions in the design by using sustainable produced concrete and by building lightweight through the use of lightweight concrete and the hollow shaped panel. Lastly, during the stage of **reuse**, the modularity of the components shapes the design by focusing on the concept of design for disassembly.

SQ1: "What are the technical and design criteria for a sustainable and reusable concrete façade system in the housing market?"

Research has shown that *building efficiency, standardization, sustainability and adaptability* are the most important factors to design a sustainable and reusable concrete facade system for the housing market. Therefore, the envisioned product has to be a *prefab modular facade system* that incorporates a fast, efficient and safe way of production, assembling and disassembling. Through the use of *standardized panels* made in moulds and fitting pieces, that are available in four different widths, the production process will be greatly improved. The use of repetition provides *improved quality and better quality control, faster production time, lower costs, and a safer work environment*. Adaptability will increase by having a *flexible layout in a building* and by *separation of functions and life cycles*, whereas sustainability has its focus on reducing materials, by *building lightweight, waste and reducing, capturing or storing CO2 emissions of concrete.*

SQ2: "What are the characteristics of all the different of types concrete; its strengths and weaknesses?"

It is hard to imagine a world and built environment without concrete as it is the second most used material in the world. And that has its reasons; concrete has many advantages in terms of its durability, strength, recyclability, versatility and is economically efficient. But it also has disadvantages, such as low tensile strength, high weight compared to strength, required curing and especially a high CO2 emission during the production of modern concrete. For the design of a reusable and sustainable concrete facade system, durability is a very important aspect in the method of how it is produced. The longer it lasts, the better and more often the element can be reused, thereby temporarily stopping the flow of material. The research and assessment showed that prefabricated lightweight aggregate concrete suits these criteria best as it is lightweight, sustainable, durable and strong enough. The use of the light material and the use of a hollow shaped concrete panel complements the goal to build lightweight.

SQ3: "Which factors are playing a role in reducing, capturing and storing CO2 in concrete?"

However, more important is reducing, capturing and storing CO2 in concrete that will help change improving global warming. The factors that play a part in reducing CO2 in concrete are the materials it consists of, the curing method, and the recycling and reuse factor. Through the use of recycled concrete or by using less cement, aggregate and less, or an alternative type of clinker, CO2 emissions in concrete can be reduced greatly. But even better is to get the emissions below zero through capturing or storing CO2 in concrete during production by injecting CO2 into the concrete. Now, it is among others in the hands of the government who must stimulate these kinds of methods using stricter rules and other incentives.

SQ4: "What dimensions are best suitable for a reusable facade system for the housing market? "

Research has shown that panels of 30, 60, 90 and 120 cm wide are best to use as standard panels for the concrete façade system. Future prediction states that these sizes will stay within a 300mm grid. With these standard panels, the aim of filling up to 75% of the closed facade in the case studies has been achieved and results in presenting potential clients with the requirements of filling up the closed surfaces in their projects with at least 75-85% standard panels to make full use of the reusable building system and contribute to a better environment. The other percentages, 25-15%, are necessary to give the architect and engineer more design freedom and more flexibility in the layout of the façade to be adaptable in the future.

SQ5: "How to design a reusable facade system that guarantees structural safety? "

The product consists of prefabricated modules consisting of a metal frame filled with standardized concrete panels that function as the main system for this project to enable a really fast construction time, reducing costs and risks of delay. In contrast to a traditional system, the facade system as well as its *adaptable layers* (the cladding, insulation and concrete panel) are designed to be reused and are easily and quickly assembled and disassembled by using *demountable and simplistic connections*. A quick replacement of a module is made possible by the separation of building systems. The different options of building structures that come with the design strategy for a reusable concrete facade system provide flexibility for the layout of a building depending on the preferences of the target audience and expanding its lifespan as it can change with different kind of trends and preferences.

DQ: "How can a concrete facade system be designed in order to make it reusable?"

The final design strategy gives insight into how a concrete facade system can be designed in order to make reusable by setting up strategies that are based on the technical and design criteria, and by providing a decision chart that creates a set of options for building systems for different functions and preferences. The strategy aims to give the architect the freedom to choose a building system according to their preferences that are guided by the decision chart.

The research and final design strategy provide insight into the design of a sustainable and reusable concrete facade system that encourage more companies in the building industry to dive into the concept of reuse and making the concrete industry more sustainable. If we don't work together towards a better environment, we will saddle the next generations up with bigger problems than we will ever have.

5.2 Discussion and evaluation

The discussion will look more deeply into the effect of the methods and terminologies used in this thesis. This involves looking at the interpretations, why the results are relevant and, lastly, what the limitations are of the research and the methods used.

Interpretations

The results ultimately provide a good insight into which aspects are important for the design of a sustainable and reusable concrete facade system in the Dutch housing market. Initially, the idea was to develop a product, but due to the still relatively unknown and complicated concept of reusability of a concrete facade system, this has shifted halfway through the research to presenting strategies that can be used as a design tool to create such a facade system.This was the right choice, as the design needs a good concept before a good product can come out.

The biggest question that remains is what the chances of success are of introducing a reused concrete facade system in the housing market. It still has to contend with many barriers that are described in the literature study and that have been discovered through research by design. Reuse still needs acceptance from the construction sector and the people, and hinders innovation in the direction of reuse and thereby modular construction and standardization. Other barriers are the need of flexibility in a building and not knowing what the future will look like in terms change in building types and facade aesthetics. A project will have a better chance to succeed if a circular business case is developed that deals with the content of solving these problems and describes the best way to introduce this specific reusable and sustainable concrete facade system in our current society.

It can be said that the research offers strategies that provide insight into how a reusable concrete facade system can best be tackled and designed. In addition, also how to deal with standardization and what dimensions suit this best. Finally, it shows ways how concrete can be made more sustainable.

Relevance of the research

Climate change is getting worse and is prompting us to think how this can be improved. At the beginning of the study, it was said that it is important to think about ways to close the loop of materials so that we can reduce CO2 emissions, waste and the use of these natural materials. The topic of the reuse of concrete in the building environment was formed as literature study showed that concrete is a notable contributor to global warming. Added to this is the ambition of the Netherlands to build 1 million houses by 2030, which requires an efficient and fast way of construction. The subject has been given more attention in recent years in the Dutch built environment, but reusing concrete elements is still relatively unknow. Nowadays, it often concerns the reuse of individual floors or other structural elements. Unfortunately, knowledge is still lacking about the use of a concrete facade system.

This research has gathered information relating to the design of a sustainable and reusable concrete facade system and gives insight on the barriers, principles behind it and on how to approach such a design. The project contributes to thinking about a sustainable construction sector and aims to encourage others to continue to explore a sustainable and reusable concrete facade system.

Limitations

The research methods have also brought limitations and have consequences for the results. The scope and literature are reviewed, followed by a discussion of the limitations of the research methods.

Scope

In the early stages of the literature research, a better scope should have been done to get more depth on a different subject. This could have been better when assessing the concrete types. The search was too broad, which made it difficult to sort everything out and compare different types of concrete. It would have been better if the focus had been more on certain aspects of concrete, for example, research into the carbon footprint of concrete or durability that is based on the discussed strategies. Besides, so many types of concrete are known that it could be a research on its own and it is difficult to say whether lightweight aggregate concrete is the best solution, although this can be assumed in this thesis based on what has been researched.

Literature review

Because the research was mainly broad and needed a lot of information, a lot of different literature was used and scientific literature was sometimes difficult to find. The disadvantage of this is that not everyone uses the same terminologies and data, so when using this information you must pay close attention to whether they all use the same criteria to build your case and what consequences this could have on the results. This problem mainly arose when it came to finding certain values to be able to compare them, for example when searching for values of and assessing the different types of concrete. These were not always found in the same literature and it was sometimes unclear whether the sources used the same criteria, especially when it came to concepts such as sustainability, durability, modularity and circularity. As a result, these findings are not entirely aligned and should be viewed critically.

In addition to scientific, non-scientific sources were also looked into. This was especially the case when looking for modular systems and existing standardization in the construction environment. Sometimes there was no scientific literature to be found and it was necessary to divert to information that was more commercially oriented. Care had to be taken to ensure that certain aspects were not made overly beautiful or worse, because it is in their best interest to convince you in favour of them. This was sometimes forgotten and later on, these types of sources were often briefly compared with or replaced by scientific sources to see if they matched and to get verification whether the content is correct. The consequence of these types of sources for the results is that they can be biased and exaggerated compared to reality. Also, it was sometimes difficult to estimate whether something was a relevant and scientific source or not.

The methodology of the standardization case studies

Limitations exist in the research of the standardization in the case studies. First of all, more case studies are needed to be analysed to get a more accurate result. The case study should consist of more complex facades which include thinking about how to deal with difficult sizes and shapes have to be dealt with. Secondly, more case studies should be used that have been built in recent years as they would best represent how the Dutch housing market will evolve in the future. Thirdly, as discussed in *Section 3.1.2*, the precise measurement of the facades does entail inaccuracies and can be caused by, for example, the thickness of lines. Therefore, it was chosen to add a margin of error to the results to somewhat compensate for these inaccuracies The last limitation is that also the load-bearing walls inside the building should have been included in the analysis. It emerged that these walls are often completely closed due to their load-bearing function and will help increase the total percentage of used standardized panels in the building. Not including these walls results in a lower percentage of closed the facades that can be filled with standard panels than it would be in reality. If it were to be investigated further, a distinction should be made between load-bearing and non-load-bearing facade elements. This to ensure a higher percentage of standard panels that can probably be filled into the load-bearing modules which will leave more design freedom for the architect to design the outer facade.

Methodology – criteria assessment

The criteria lists are constructed according to the literature research and the analyses. By properly applying this method to assess the case studies and design ideas, and to make choices, proper use must be made of sources, terminologies, data and also by properly interpreting this information. Sometimes it was difficult to assess certain aspects because they were not the same, this was especially the case when assessing the modular case studies. This was often difficult because the case studies were difficult to compare because they were designed on different scales levels. For example, the Cloud and CD20 load-bearing facade system are buildings whereas the CD20 structural system, the circular viaduct and circular pavilion are building systems. The difference in scale level is that the building systems are part of a building. As a result, not all criteria points could be answered in the best and the same way. Because of this problem, the "overall points" were often no longer considered and the focus was more on the individual aspects and where their strengths and weaknesses lie.

The choice to link the building systems to the requirements of different housing types was a smart move and made the choices for different building systems a more logical choice. But it can be argued how the rest of the choices are being assessed. It was difficult to assess the different connection systems and to say which option is better than the other. It often came down to the same thing, for example, the construction time. An estimate was made, but the difference is unlikely to be very big. It could have been a choice to focus more on this and zoom in deeper into the area of a fast construction time in the literature research and analysis.

5.3 Recommendations

Multiple directions within the research of this paper can be continued or researched to be able to make a reusable concrete façade system more successful.

Firstly, it would be interesting to look beyond the full use of concrete panels in the building system. The project only looked at the use of concrete panels in the building system, this is especially good for modules with a load-bearing function, but the question is whether this is also ideal for a non-load-bearing facade system. The use of wooden panels could be considered, which will ensure a lighter facade system than concrete, contributing to a more sustainable façade system. Of course, it also has its drawbacks, such as workability, inferior insulation values and needed protection to ensure a longer lifespan, but this should become clear from a new study. Besides, it can also be examined whether it is better to use wooden panels as filling in the load-bearing modules, above and below the windows and doors, and what demountable connections can be used to secure it to the concrete panels.

Secondly, the study looked at the most common dimensions in the Dutch housing market with a focus on width. Another new study can be done into the most common heights for the Dutch housing market and how these will evolve in the future. In addition to the full length of a concrete panel, this also concerns the panels above and below a window or door. In the case studies examined, the measurements often differed and it will be examined whether standardization is possible or useful at all for the total flexibility of the construction system.

Thirdly, in addition to the housing market, there is also the office market, where it can be investigated whether a reusable facade system could work in this sector. Also, whether the function of these building systems for the housing market could change to an office function, or whether these markets and their requirements for the building systems and structures are so different that they cannot be easily combined.

Fourthly and as mentioned earlier, this project needs to present a good business case that focuses on the barriers of reuse and how these can best be resolved. Aspects that can research more thorough are: what the government can best do to encourage companies to use reuse building systems more often and how to change the negative perception of the reuse and how to resolve the lack of confidence in the reused concrete product, because the structural ability of a reused product isn't tested and unknown. The last one can be a research on how to assess and test a reused concrete module of this project on its structural ability and providing a certificate indicating that the product is safe to use for further reuse so that the customer's trust is gained.

6 REFLECTION

In the final chapter, the process of the research, the methodology and the position of the research, in relation to the faculty and graduation studio, will be reflected on.

6 Reflection

Relation of the graduation studio and chosen subject – Position of the research
This research is part of the Sustainable Design Graduation Studio of de masters Building technology. The graduation studio asks its students to carry out both a technical related research as well as a design process. The results of the research are implemented in this design. The entire studio is largely based on sustainability aspects within the number of disciplines of Building Technology, such as Facade, Climate or Structural design. As mentioned earlier, the theme of this graduation research is related to the field of Facade design, including the themes of circularity, modularity and design for deconstruction. Besides, not only the technical aspect is important, but also the management side of the subject. It needs to be considered how such a design could function in today's society.

Relevance
The concrete industry is responsible for 7% of the world CO2 emissions and with more and more concrete buildings being demolished and built again, it is time to change the building sector to a more sustainable one. The project has contributed to this by designing a sustainable and reusable concrete facade system that helps to close the material loop of concrete. The design meant to use sustainably produced concrete and is supposed to be reused within the Dutch housing market. But unfortunately, we need more than just a design; a whole business model is needed to implement a reused facade system in the current society. The current traditional design processes need to shift to a circular one, but changing the way of thinking of everyone takes time and remain a big challenge. Overall, improving the concrete building sector is making a step at a time.
The methodological line of approach
The research method that Building Technology uses, is to start with a literature study, which can also include an extensive analysis if applicable, followed by research through design and finally the conclusion and discussion. This method has also been applied in this graduation project, in the form of a literature study, analysis of case studies and research through design
.

Literature study
The goal of the literature study was to get a better understanding of the concept of reuse, why standardisation is important for reuse to succeed, the need of modularity in a reusable design and how concrete can be made more sustainable. It required to search in a very broad spectrum and it was easy to lose sight of the main concepts. I found myself often, researching extra information instead and got distracted quickly from the main theme. That is why ultimately much broader research has emerged than I had expected. In the beginning, it would have been better to define the topics even more and go deeper into certain aspects, but I found this quite difficult. I was sometimes "scared" to make choices because I was not quite sure how this would affect the rest of my research. Also, the broader search often made it difficult to find literature that used the same terms and had the same criteria in mind. I later noticed that this can cause some problems with the results.

Analysis of the case studies
The analysis was fun to do, but I had problems with beginning them. I had to find my way in how best to start this. I noticed when analysing the case studies that in the beginning, I did not know where to look and how to get the case studies. As I started looking outside for buildings, they often looked the same and it was difficult to find buildings with more unique facades. In retrospect, I could have put more time in finding better case studies. I have mixed feelings about the findings, on the one hand, I am happy with the outcome, but on the other hand, it still contains many limitations and it is a pity that a good result cannot be achieved. This is since many more different case studies are needed to conclude a realistic outcome.

The analysis of the modular case studies against this was easier to investigate and it was a great way to make a more extensive analysis of existing modular systems. The method that was used for this, the assessment via the criteria list set up in the literature study, worked well and made it easier to get a good overview of where each modular system has its weaknesses and strengths. This could well be taken into account in further design.

Research through design
The chapters above gave a good picture of what the reusable concrete facade system must meet. It also helped to form a design work frame that is part of the final design strategy. By working out all these aspects, it helped me to get a better idea of what is needed to design the facade system. Sometimes I could no longer "see the wood for the trees". It wasn't until much later that I got the idea to make a decision chart that shows all elements in a scheme. Only then did I think I had everything sorted out and I knew how I wanted to approach and present the final design strategy.

Research and design process
The direction of the graduation project started with the chosen theme of reuse of waste products. I chose the subject because of my interest in reuse and therefore thinking about a more sustainable built environment. It is a broad subject that could go in any direction, but it is the concrete industry that has been causing a lot of climate problems for years and desperately needs improvement. I have had the opportunity to learn more about this and to express this in a circular facade design. This involves designing a sustainable and reusable concrete façade system in my mentors in the area of circularity, design for deconstruction and prefab concrete where important to have and supervise the graduation project.

The research process was instructive, but far too much time was spent in the literature research in particular. This was because it was still too little defined and I was still looking for a good and clear direction. Nevertheless, the results were good for starting my design process, especially setting up all the design criteria helped to define the main purpose of the thesis. The two case study analyses (Standardization and Modular building systems) also gave a lot of insight by learning from the mistakes made in previous projects and therefore helping my own design choices.

It can be concluded that the research part was very important for the graduation project and had a lot of influence on the design criteria and design process. Only this could have happened in a shorter time if I had previously set up a clear approach and direction for myself and further defined it.

I often encountered myself in the fact that I looked up too much information, lost the overview and subsequently found it difficult to incorporate all information into the conclusions and the design. Also, sometimes in-depth was missing in certain chapters, which sometimes made it more superficial research. It has taught me to zoom in even more next time to make it easy for yourself and to get more depth in a research paper.

Despite all the circumstances of this year I am very proud of my process and the outcome, it took some time and guidance from my mentors to get on the right track, but I think a nice concept has been put in place. Besides, I have become much more interested in circular designs and the sustainability of concrete. I think this thesis will have a lot of influence on my choice to work at a company that pays a lot of attention to this and I am thankful for this!

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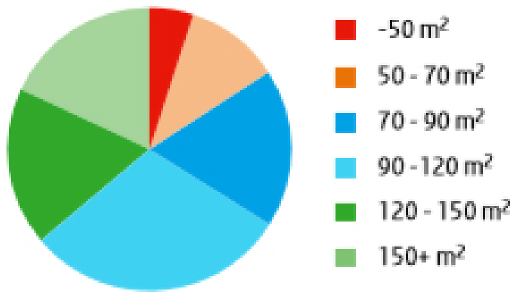
8 APPENDICES

Appendix A – Housing stock in the Netherlands

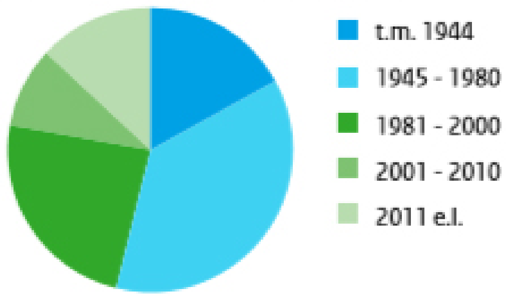
1.3 Woningvoorraad naar gebruiksoppervlakte en bouwjaar, 2012-2018

	2012	2013	2014	2015	2016	2017	2018
Voorraad totaal	**7.369.400**	**7.439.600**	**7.530.500**	**7.585.200**	**7.640.300**	**7.686.200**	**7.741.000**
Gebruiksoppervlakte*							
-50 m²	328.300	340.500	381.300	394.300	409.700	407.400	409.200
50-70 m²	794.100	795.200	815.900	820.600	824.800	834.400	839.200
70-90 m²	1.325.600	1.333.700	1.339.400	1.346.800	1.354.900	1.360.000	1.369.500
90-120 m²	2.259.400	2.281.400	2.288.400	2.297.000	2.306.900	2.310.800	2.315.100
120-150 m²	1.306.500	1.325.400	1.330.800	1.340.900	1.347.500	1.363.400	1.378.400
150+ m²	1.332.800	1.356.300	1.368.300	1.379.900	1.391.800	1.407.000	1.426.700
Bouwjaar							
voor 1906	356.700	359.300	362.200	363.300	367.800	367.900	369.300
1906-1944	1.089.500	1.091.900	1.094.300	1.095.200	1.092.700	1.093.600	1.094.200
1945-1959	731.600	727.800	726.300	724.200	720.700	717.900	713.800
1960-1970	1.202.400	1.197.600	1.201.800	1.201.800	1.198.900	1.190.600	1.183.900
1971-1980	1.223.500	1.225.500	1.231.100	1.233.100	1.236.400	1.234.000	1.233.300
1981-1990	1.103.800	1.104.600	1.113.100	1.117.400	1.120.500	1.122.200	1.124.100
1991-2000	897.600	899.700	905.300	905.700	908.700	909.500	909.100
2001-2010	721.900	731.700	738.900	738.700	739.800	740.400	738.200
2011 e.l.	42.300	101.300	157.300	205.700	254.700	310.100	375.000

Woningvoorraad naar gebruiksoppervlakte, 2018



Woningvoorraad naar bouwjaar, 2018



** De gepresenteerde oppervlakte is de GBO (gebruiksoppervlakte). Dit is inclusief gebruiksruimten (hal, e.d.). Door afronding en/of onbekend zal de som van uitsplitsingen afwijken van het totaal.*

Bron: BAG en DG BRW/Systeem Woningvoorraad SYSWOV. Peildatum: 1 januari.

Housing stock by users surface and year of construction, 2012-2018. Source: Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019, p. 12

Appendix B - Existing connection systems

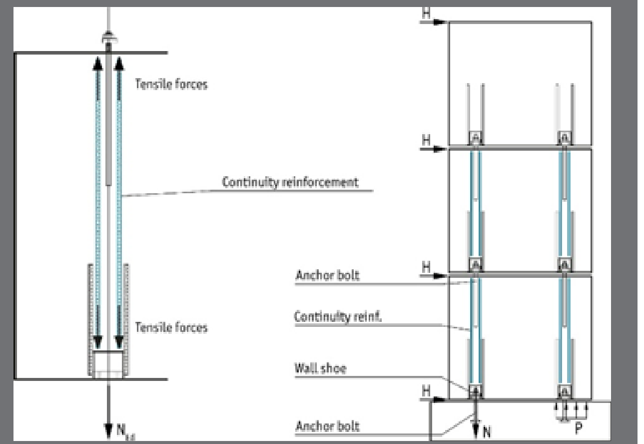
EXISTING CONNECTION SYSTEMS

Peikko - SUMO

The connection consists of two pieces: the anchor bolts and the wall glove that are connected and together manage to transfer the tensile forces to the foundation. The forces are transferred from the bottom of the wall element (wall shoe) to the top of the next wall element (anchor bolt) by also having vertical reinforcement attached on both the wall shoe and anchor bolt (Figure 24). One of its main advantages is that it can transfer tensile forces directly after the wall elements are placed in their position.

Peikko has a connection like this called the SUMO® wall shoe. They are an effective application to interconnect precast concrete walls or to connect them to the foundation. The wall shoes are attached to mould by bolts or clamps into the reinforcement where concrete is poured to form into a precast concrete wall, while the anchor bolts are poured into the foundation or the other wall.

This connection is excellent for reuse. It is easy and fast to assemble and disassemble because the wall shoe is a dry connection and fewer connection points are needed in a wall element which can save money and time. Another advantage is the placement of the wall shoe and that it is a bit hidden. It won't interfere with the interior layer of a building as the wall shoe is placed in a 'carved' square in the wall element.



Section of the wall shoe connection. Source: (Peikko, n.d.)

SO WHAT DOES IT DO?

- Tensile forces in the precast concrete walls are directly transmitted after assembling
- Provide stability in the buildings (more often for rigid discs)
- The loads are transferred from the wall to other load-bearing structures

ADVANTAGES

- Dismountable: dry connection
- Tensile forces can be transferred via the joints immediately after placing elements
- The connection can easily be inspected
- A hidden connection that does not protrude. Results in a smooth surface

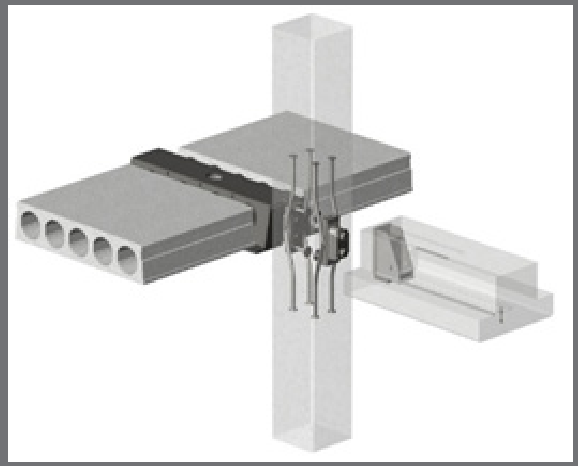
DISADVANTAGES

- It needs a minimum distance from the wall edges so the correct reinforcement can be placed*

* A minimum thickness ranges from 90 to 250 mm and edge distances (from the center of the wall shoe) 160 to 250 mm.

EXISTING CONNECTION SYSTEMS

PCs Corbel
Peikko's Pcs corbel system is an invisible connection for supporting beams. It is used as vertical support between, for example, reinforced concrete beams and reinforces concrete columns or walls ellent for reuse. It is easy and fast to assemble and disassemble because the wall shoe is a dry connection and fewer connection points are needed in a wall element which can save money.



PCs Corbel system for supporting beams. Source: (Peikko, n.d.)

SO WHAT DOES IT DO?

- Serves as a vertical connection for a wall and floor

ADVANTAGES

- More free space because of using the hidden corbels
- Corbel location is adjustable after casting the column
- Easy installation of beams
- Vertical and torsion resistance

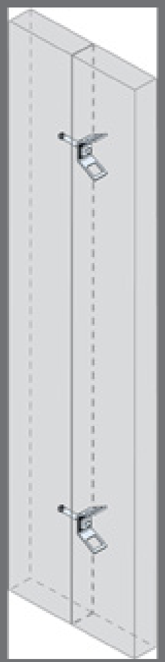
HALFEN HEK connection
It is a dry prefab connection that can be used horizontally as well as vertically. Cast-in DEMU Fixing anchors, bolt, or bar anchors transfer the tension and shear force into the precast element (Figure 26). The connection can be subjected to the load right away after it is installed (HALFEN, n.d.).

SO WHAT DOES IT DO?

- Transfer tension and shear force into the precast element

ADVANTAGES

- Transmission tensile and transverse forces
- Screw connection for easy and fast on-site installation (lower labor costs)
- It can be fully adjusted to the precast elements
- Erection independent from weather
- Can be applied to elements of thickness > 100 mm
- A hidden connection: the connection does not protrude

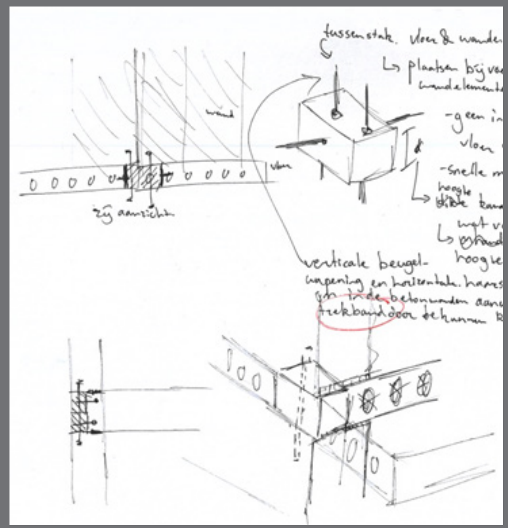


3D view of HEK connection in walls. Source: (HALFEN, n.d.)

Appendix B - Existing connection systems

EXISTING CONNECTION SYSTEMS

LEVO-system
In the LEVO-system, also known as LECON-system, concrete blocks are placed between the walls at the location of the joint (Crommentuyn, 2005). The LEVO block transfers vertical forces through its steel wires and connects the wall to the concrete hollow core slab. The drawbar reinforcement for the disk/shear action of the floors becomes integrated into the wall and in the LEVO block, so without a landfill or pressure layer.



Levo-system. Based on: Crommentuyn (2005)

SO WHAT DOES IT DO?

- It is a hinged connection between the floor and walls
- A cavity in the concrete slabs is necessary to connect walls and slabs

ADVANTAGES

- No fixed moment between floor and wall (thinner construction possible)
- No pressure layer on the slabs
- No upper rebar necessary
- No consoles and ridges
- Easy and quick installation

DISADVANTAGES

- Not demountable because of cement pouring in the connection afterward
- Not fully realized yet

Transportation connection:
Halfen DEHA-HD transportation anchor
Not only is it important to think about connections for the stability of a building, but also how to transport the concrete facade system. There are existing transportation connections that can be implemented in the final design. It has a screw-in fuse that protects the connection from dirt and makes it easy to attach and detach the hook.

Halfen DEHA-HD transportation anchor. Source: (Halfen, n.d.)

SO WHAT DOES IT DO?

- It is used for transportation of prefab elements during prefab production as well as on the building site

ADVANTAGES

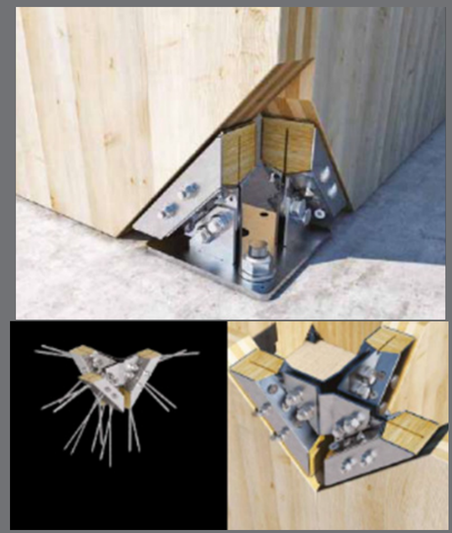
- It has nine different load classes ranging from 1.3 to 25.0
- A light but robust lifting hook
- A screw-in fuse for protection and easiness

EXISTING CONNECTION SYSTEMS

ROTHOBLAAS – X-Rad connection
Rothoblaas has designed connections that can connect up to four walls and has everything for every corner. In Figure 29 you can see the X-Base connection that connects two walls in the corner. A very smart system that is put together in a few moments. But the complex connections will come with a price.

The connections can be translated and working for concrete walls, but because of corners cut, it may lose its thermal conductivity as a whole system. Though this is something where a solution can be found for.

Although this connection is meant for wooden walls, beams and plates, it can be a option to use a connection like this that can connect more than two concrete elements.



X-Rad connection.
Source: Rothoblaas (n.d.)

SO WHAT DOES IT DO?

- Fixing system between walls in different levels, floors and roofs
- Designed to transfers tensile and shear forces

ADVANTAGES

- Multiple different fixing system for different kind of situations
- Point-to-point connection that can connect up to four walls with just one connection, which means less connections needed per wall
- Easy and quick installation

DISADVANTAGES

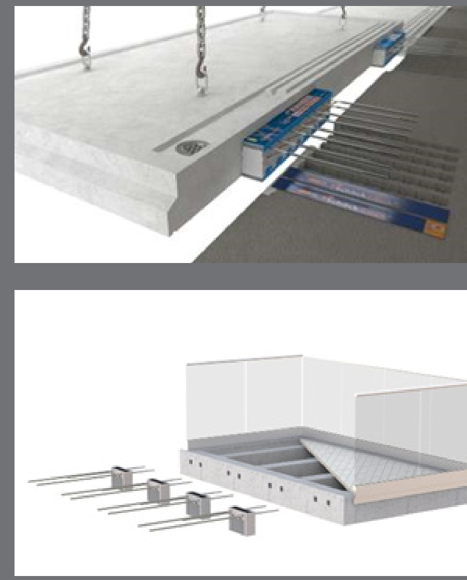
- A complex connection often means more expensive
- It can create thermal bridges

Appendix B - Existing connection systems

EXISTING CONNECTION SYSTEMS

Schöck isokorf and Vebo Balqoon
Both Schöck as Vebo is producing an innovative prefab balcony and galley system, whose goal is to build as fast and efficient as possible. The system allows for assembling or disassembling of the balcony or gallery at any time. Thereby is Vebo Balqoon lighter than a traditional balcony, because the elements are produced 'hollow'.

During production, the balcony connection system is laid in a mold where then concrete is poured into so it will form a floor for a balcony or gallery and, on the other hand, a (extra) solid floor plate is made where the connections will be attached to that is being laid at the edge of the building. Thereafter, the element can be connected to the building at any moment. Balcony connections do not yet exist for a hollow core slab.



Schöck IDock (top) and Vebo Balqoon (bottom).
Source: Schöck (n.d.) & Vebo (2017)

SO WHAT DOES IT DO?

- Connecting balcony systems to a building

ADVANTAGES

- Attachment of the element to the building possible at any moment.
- A fast and efficient way to add an outdoor element
- Vebo: lightweight, using 40-50% less materials than traditional balcony systems
- Demountable connections

Transportation connection:
Halfen DEHA-HD transportation anchor
Not only is it important to think about connections for the stability of a building, but also how to transport the concrete facade system. There are existing transportation connections that can be implemented in the final design. It has a screw-in fuse that protects the connection from dirt and makes it easy to attach and detach the hook.

SO WHAT DOES IT DO?

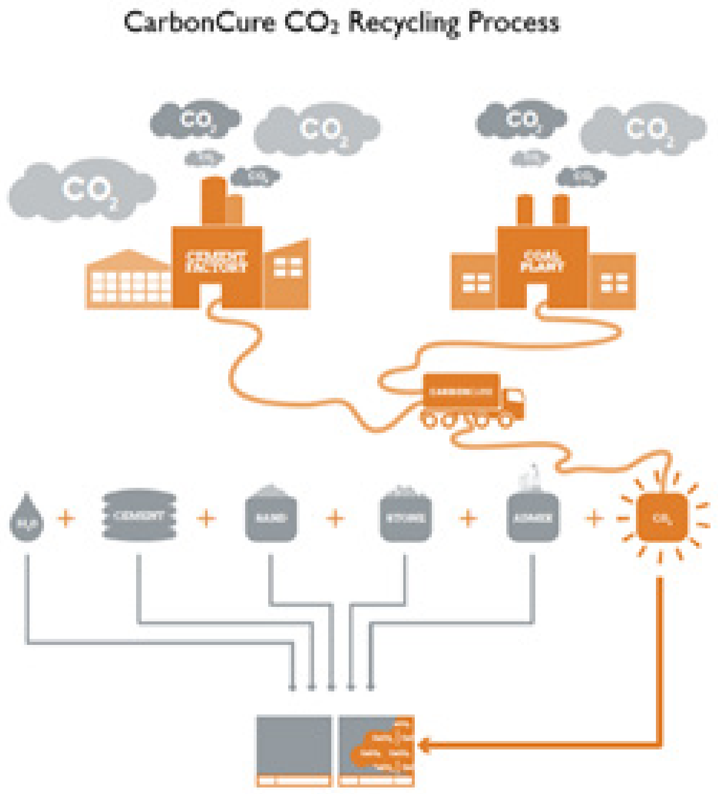
- It is used for transportation of prefab elements during prefab production as well as on the building site

ADVANTAGES

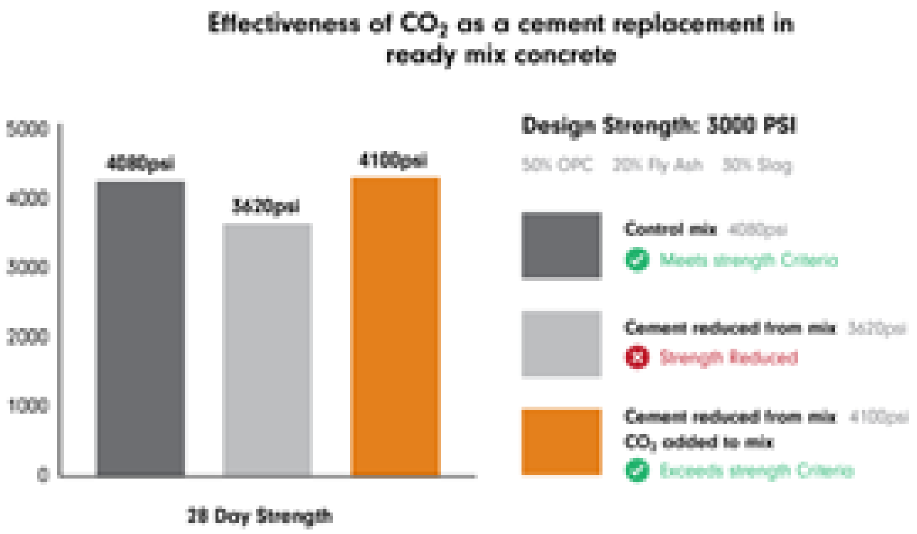
- It has nine different load classes ranging from 1.3 to 25.0
- A light but robust lifting hook
- A screw-in fuse for protection and easiness

Halfen DEHA-HD transportation anchor. Source: (Halfen, n.d.)

Appendix C–1 - CO2 capturing technique from CarbonCure



CarbonCure process. Source: CarbonCure & Pangaea Ventures Ltd., n.d.



Design strength compare. Source: CarbonCure Technologies, n.d.

Appendix C–2 - CO2 capturing technique process

Table 1. Differences between ordinary concrete and the new ecological concrete CO_2-SUICOM

	Ordinary concrete	The new ecological concrete CO_2-SUICOM
Concrete materials	Water + cement + aggregate	Water + cement + aggregate + special admixture + coal-ash
Curing method	Water curing or air curing	Curing by CO_2 contained in gas emitted from thermal power station
Hardening reaction	Hydration reaction between water and cement	Carbonation reaction of CO_2 and special admixture in addition to hydration reaction between water and cement

Differences between ordinary concrete and the new ecological concrete. Source: Yoshioka et al., 2013, p. 6021

Appendix D – Technical requirements

Requirements for a residential building:

Subject	Limit value	Unit
Thermal insulation (RC)	4,5	M^2K/W
Fire safety	120	minutes
Minimal thickness prefabricated concrete	100/120	mm
Sound insulation	>52	dB

Requirements for a residential building according to Bouwbesluit (2012)

Thermal insulation
For the insulation of buildings where people are staying for a long time, the insulation value of the facades for new construction must have a minimum RC-value of 4.5 m2K / W (Isolatieshop, 2020). As the rules in the Netherlands are constantly being tightened, it is important to take into account the design's extra space for possible thicker insulation (insulation with a higher RC-value).

Fire safety
For the fire behavior requirements of a façade construction, it must comply with fire class B. It will ultimately depend on the other insulation material on what type of fire safety it must comply (DGMR Bouw, 2019).
With a ventilated cavity, there must be a cavity interruption in the façade system to prevent fire propagation (DGMR Bouw, 2019, p. 9). Also, errors in connections must be prevented to make the facade and the entire building fire-resistant.

Because the façade will also function as a load-bearing wall in a residential building, the fire requirements are more strict. For a building higher than 13 meters, a fire-resistance time of 120 minutes is required (DGMR Bouw, 2019).

For prefabricated concrete walls, a minimal thickness of 100 or 120 mm is sufficient enough for fire resistance of 120 minutes.

Sound insulation
We assume a higher noise level so that the facade system can be used in most places in the Netherlands. The road, rail, industrial and aircraft noise near a civilian airport have the highest noise level of 33 dB, which means that the sound insulation of the outer shell must be at least 20dB (Rockwool, n.d.).

Airtightness
With airtight construction, the intention is to have as few openings as possible in the facade/shell of the building. ER will therefore have to be built airtight that ensures that air, moisture, or heat cannot penetrate or leave the building. It ensures good soundproofing, living comfort and ultimately also energy saving.

Appendix E - Concept technical and design criteria

Criteria: 5| 4 | 3 | 2 | 1

With 5 insufficient/very bad and 1 excellent. With exceptions for criteria that ask for a number or require a yes (1) or no (5). The lower the points, the better the design. This order of numbers (with 5 being the lowest) is chosen because the lower the number of the questions 'Number of connections per panel' and 'Number of different panels', the better the design is.

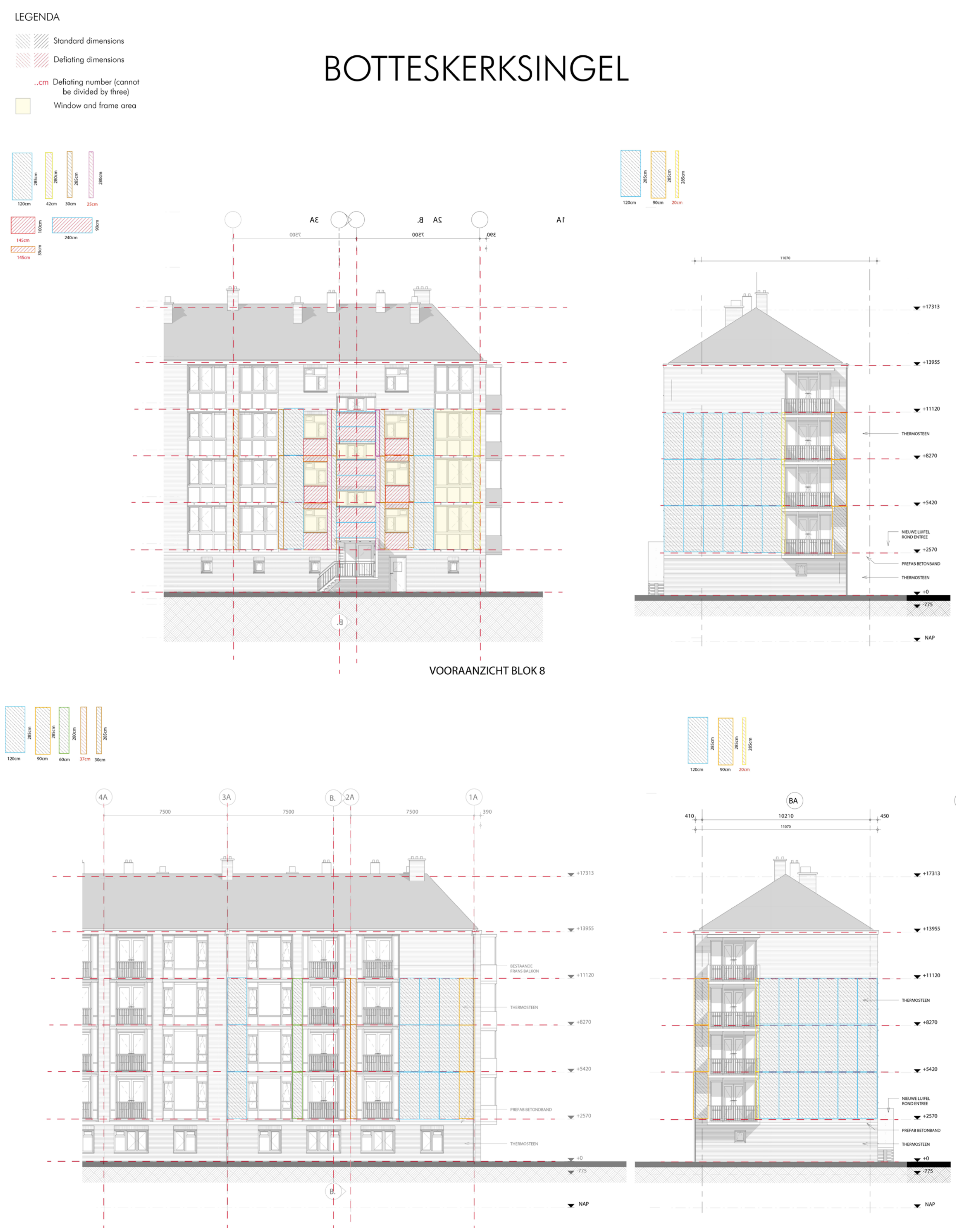
Design/Case study criteria	1
General requirements	
Prefab	
Stackable	
Load bearing capacity	
Technical requirements	
Thermal insulation	
Fire safety	
Sound insulation	
Standardization	
Number of different panels	
Simple form	
Dimensions	
Building efficiency	
Connections	
Use of dry connections (demountable)	
Number of connections per panel	
Connections can easily be inspected	
Complexity	
Assembling & disassembling	
Separation of functions and lifecycles (replacement)	
Easy and fast assembly & disassembly	
Adaptability	
Adaptable to change	
Sustainability	
Material	
Separation of materials	
Sustainable materials	
Amount of materials used	
Building lightweight	
Use of lightweight components	
(Lightweight) form	
Aesthetics	
Hidden connections	
Overall points	
Total	

Appendix F-1 - Total findings of all case studies

All panels together	Facade surface	Open surface	Closed surface			
	7680,6	3265	4415,2			
Percentage	100%	43%	57%			
	Surface panel	Number of panels	Total surface	Total % facade surface	Total % of closed surface	
Standard panel						
Panel 120cm		808	1872,1	24%	42%	
Panel 90cm		310	461,8	6%	10%	
Panel 60cm		682	1218,1	16%	28%	
Panel 30cm		312	325,0	4%	7%	
Deviating panels in 3cm grid						**88%**
Panel 42cm		141	116,2	2%	3%	
Panel 24 cm			21,2	0%	0%	
Panel 18 cm		42	18,9	0%	0%	
Panel 15cm			25,1	0%	1%	
Deviating panels not in 3cm grid						
Alle afwijkende panelen			356,8	5%	8%	
			4415,2	57%	100%	**12%**
						deviating panels

Without side walls building	Facade surface	Open surface	Closed surface			
	6753,2	3357	3396,3			
Percentage	100%	50%	50%			
	Oppervlakte paneel	Aantal	Totale oppervlakte	Percentage totaal		
Standard panel	Surface panel	Number of panels	Total surface	Total % facade surface	Total % of closed surface	
Paneel 120cm			1029,6	15%	30%	
Paneel 90cm			419,9	6%	12%	
Paneel 60cm			1188,7	18%	35%	
Paneel 30cm			308,4	5%	9%	
Deviating panels in 3cm grid						**87%**
Panel 42cm			108,1	2%	3%	
Panel 24 cm			21,2	0%	1%	
Panel 18 cm			15,9	0%	0%	
Panel 15cm			12,2	0%	0%	
Deviating panels not in 3cm grid					0%	
Alle afwijkende panelen			292,5	4%	9%	
			3396,3	50%	100%	**13%**
						deviating panels

Appendix F-2 - Findings & drawings of Botteskerksingel



Appendix F-3 - Findings & drawings of Saaftingsestraat

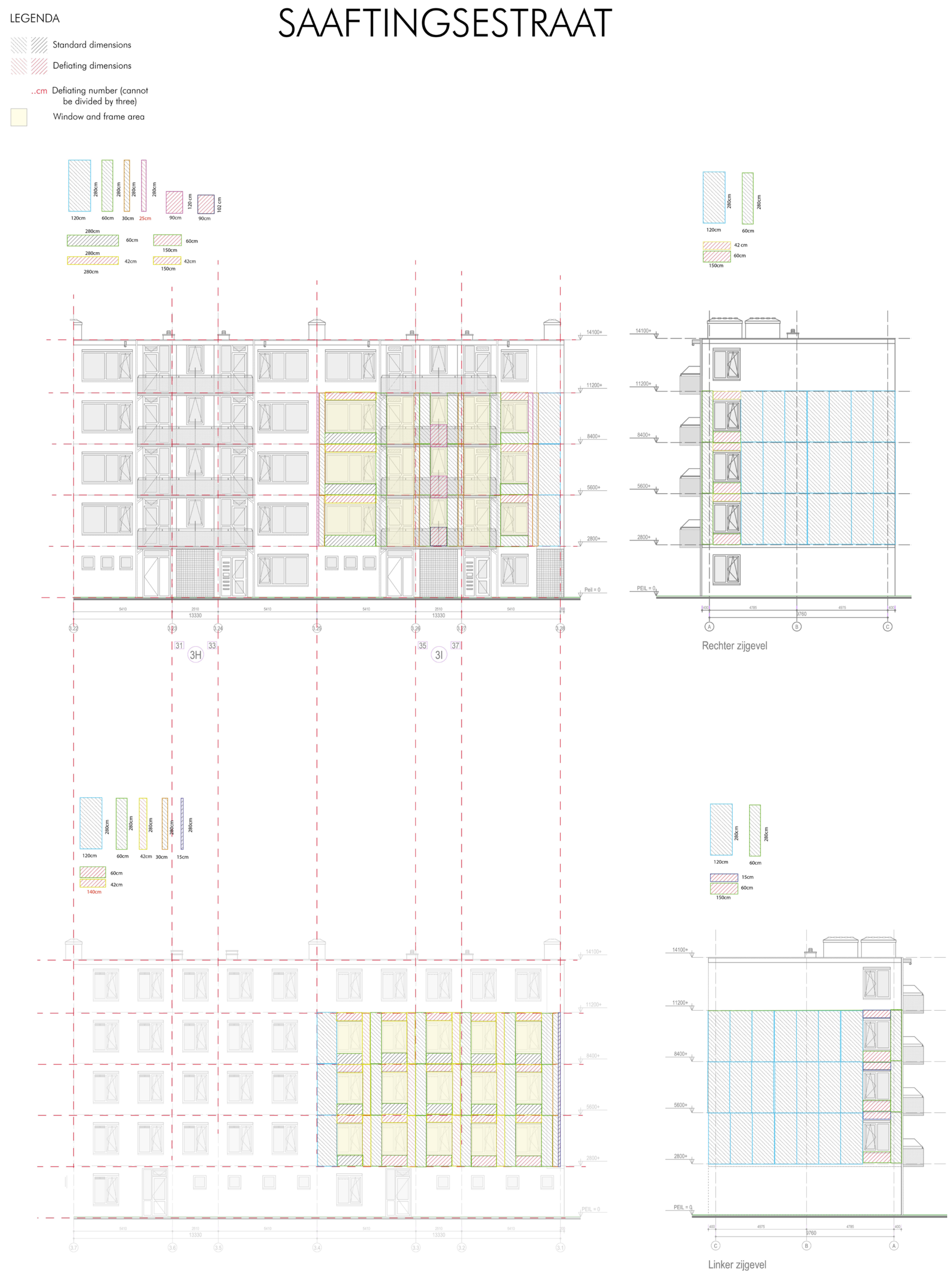
Botteskerksingel	1 woonblok =8*2 woningen naast elkaar					
Voorgevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**		**Constante**	
	1026,0	507	519,2		8	
Percentage	100%	49%	51%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	48				
120x285	3,4	48	164,2	16%	32%	
Paneel 90x240cm	2,2	48	103,7	10%	20%	
Paneel 60cm	0,0	0				
Paneel 30cm	0,9	120	102,6	10%	20%	
Afwijkende panelen deelbaar door 3						
Paneel 42cm	1,2	24	28,7	3%	6%	
Afwijkende panelen ondeelbaar door 3						**77%**
Paneel 145cm	1,9	48				
145x100	1,5	48	69,6	7%	13%	
145x35	0,5	32	16,2	2%	3%	
Paneel 25cm	0,7	48	34,2	3%	7%	
			519,2	51%		**23%**

Achtergevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	1026,0	549	476,7			
Percentage	100%	54%	46%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	Percentage totaal	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	96	328,3	32%	69%	
Paneel 90cm	2,6	24	61,6	6%	13%	
Paneel 60cm	1,7	24	41,0	4%	9%	
Paneel 30cm	0,9	24	20,5	2%	4%	
Afwijkende panelen deelbaar door 3						**95%**
Afwijkende panelen ondeelbaar door 3						
Paneel 37cm	1,1	24	25,3	2%	5%	
			476,7	46%		**5%**

Zijgevels (2x)	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**	
	189,3	47	141,9	
Percentage	100%	25%	75%	
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**
Standaardpaneel				
Paneel 120cm	3,4	36	123,1	65%
Paneel 90cm	2,6	6	15,4	8%
Paneel 60cm	0,0	0		
Paneel 30cm	0,9	0		
Afwijkende panelen deelbaar door 3				
Afwijkende panelen ondeelbaar door 3				
Paneel 20cm	0,6	6	3,4	2%
				75%

Alle gevels bij elkaar	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	2241,3	1103	1137,9			
Percentage	100%	49%	51%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	180	615,6	27%	54%	
Paneel 90cm	2,6	78	180,6	8%	16%	
Paneel 60cm	0,0	24	41,0	2%	4%	
Paneel 30cm	0,9	144	123,1	5%	11%	
Afwijkende panelen deelbaar door 3						**84%**
Paneel 42cm	1,2	24	28,7	1%	3%	
Afwijkende panelen ondeelbaar door 3						
Paneel 145cm	1,9	80	85,8	4%	8%	
Paneel 37cm	1,1	24	25,3	1%	2%	
Paneel 25cm	0,7	48	34,2	2%	3%	
Paneel 20cm	0,6	6	3,4	0%	0%	
			1137,9	51%	100%	**16%**

Zonder zijgevels	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	2052,0	1056	996,0			
Percentage	100%	51%	49%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	144	492,5	24%	49%	
Paneel 90cm	2,6	72	165,2	8%	17%	
Paneel 60cm	0,0	24	41,0	2%	4%	
Paneel 30cm	0,9	144	123,1	6%	12%	
Afwijkende panelen deelbaar door 3						**83%**
Paneel 42cm	1,2	24	28,7	1%	3%	
Afwijkende panelen ondeelbaar door 3						
Paneel 145cm	0,0	80	85,8	4%	9%	
Paneel 37cm	1,0	24	25,3	1%	3%	
Paneel 25cm	189,3	48	34,2	2%	3%	
			996,0	49%	100%	**17%**



Appendix F-3 - Findings & drawings of Willemskerkestraat

Saaftingsestraat	1 woonblok= 9*2 woningen naast elkaar					
Voorgevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**		**Constante**	
	1009,3	401	608,5		9	
Percentage	100%	40%	60%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	54				
120x280	3,4	27	181,4	18%	30%	
120x90	1,1	18	19,4	2%	3%	
Paneel 90 cm (90x102)	0,9	9	8,3	1%	1%	
Paneel 60cm		162				
60x280	1,7	135	226,8	22%	37%	
60x150	0,9	27	24,3	2%	4%	
Paneel 30cm		135				
30x280	0,8	108	90,7	9%	15%	
30x150	0,5	27	12,2	1%	2%	93%
Afwijkende panelen deelbaar door 3						
Afwijkende panelen ondeelbaar door 3						
Paneel 10cm	0,3	27	7,6	1%	1%	
Paneel 25cm	0,7	54	37,8	4%	6%	7%
			608,5	60%		

Achtergevel	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	1007,7	461	546,8			
Percentage	100%	46%	54%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	Percentage totaa	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	27	92,3	9%	15%	
Paneel 90cm	2,6	0				
Paneel 60cm	1,7	270				
60x280	1,7	135	226,8	23%	37%	
60x 140	0,8	135	113,4	11%	19%	
Paneel 30cm	0,8	27	22,7	2%	4%	75%
Afwijkende panelen deelbaar door 3						
Paneel 42cm		243				
42x 140	0,6	135	79,4	8%	13%	
Paneel 15 cm	0,5	27	12,2	1%	2%	15%
Afwijkende panelen ondeelbaar door 3						

Zijgevels (2x)	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht		
	177,4	15	162,9		
Percentage	100%	8%	92%		
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	
Standaardpaneel					
Paneel 120cm	3,4	42	143,6	81%	88%
Paneel 90cm	2,6				
Paneel 60cm	0,0	12			
60x280	1,7	6	10,1	6%	
60x150	0,9	6	5,4	3%	
Paneel 30cm	0,9				
Afwijkende panelen deelbaar door 3					
Paneel 42x150cm	0,6	6	3,8	2%	
Afwijkende panelen ondeelbaar door 3					
				92%	

Alle gevels bij elkaar	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	2194,4	876	1318,2			
Percentage	100%	40%	60%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	123	436,9	20%	34%	
Paneel 90cm	2,6	9	8,3	0%	1%	
Paneel 60cm	0,0	444	606,8	28%	46%	
Paneel 30cm	0,9	162	125,6	6%	10%	
Afwijkende panelen deelbaar door 3						**90%**
Paneel 42cm	2,1	141	83,2	4%	6%	
Paneel 15 cm	0,0	27	12,2	1%	1%	
Afwijkende panelen ondeelbaar door 3						
Paneel 25cm	0,7	54	45,4	2%	3%	
			1318,2	60%	101%	**11%**

Zonder zijgevels	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	2017,0	862	1155,3			
Percentage	100%	43%	57%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	486	293,2	15%	26%	
Paneel 90cm	2,6	0	8,3	0%	1%	
Paneel 60cm	0,0	39	591,3	29%	51%	
Paneel 30cm	0,9	135	125,6	6%	11%	
Afwijkende panelen deelbaar door 3						**89%**
Paneel 42cm	2,1	54	79,4	4%	7%	
Paneel 15 cm	0,0	27	12,2	1%	1%	
Afwijkende panelen ondeelbaar door 3						
Paneel 25cm	0,7	27	45,4	2%	4%	
			1155,3	57%	101%	**12%**

LEGENDA

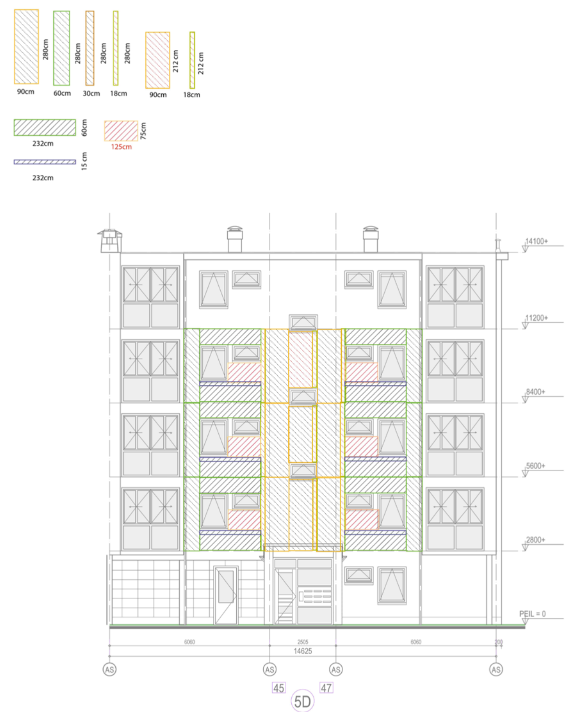
Standard dimensions

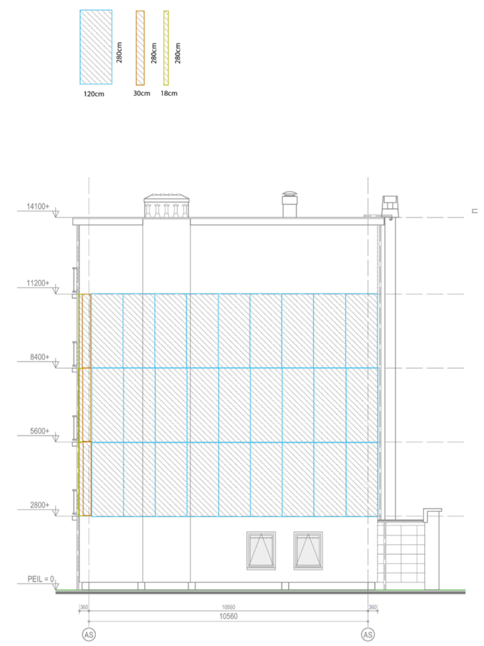
Deflating dimensions

...cm Deflating number (cannot be divided by three)

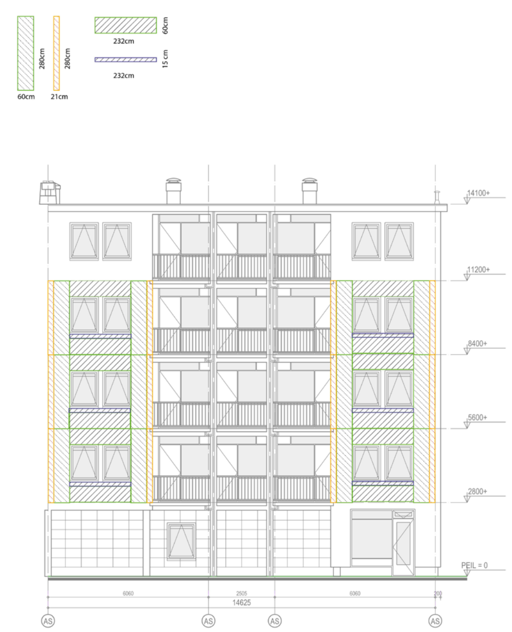
Window and frame area

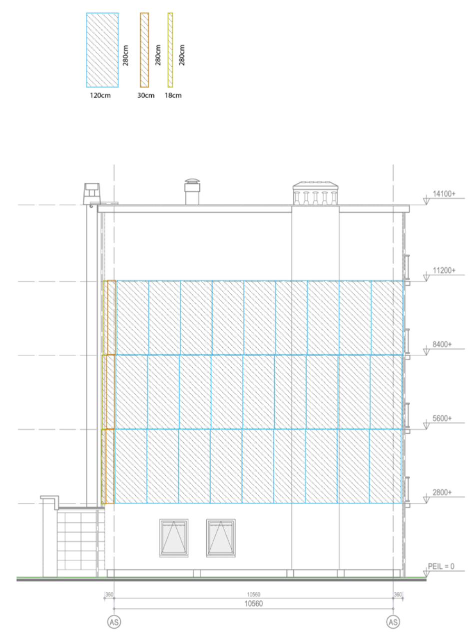
WILLEMSKERKESTRAAT





Linker zijgevel





Rechter zijgevel

Willemskerkestraat - 1 blok	4x alles					
Voorgevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**		**constante**	
	491,4	275	216,1		4	
Percentage	100%	56%	44%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,36					
Paneel 90cm	2,5	28				
90x280	2,5	28	70,6	14%	33%	
90x212	1,9	8	15,3	3%	7%	
Paneel 60cm	1,7	60				
60x280	1,7	24	40,3	8%	19%	
60x232	0,9	48	43,2	9%	20%	
Paneel 30cm	0,8					
Afwijkende panelen deelbaar door 3						**78%**
Paneel 75cm						
75x125	0,9	24	22,5	5%	10%	
Paneel 18cm		48				
18x280	0,5	28	14,1	3%	7%	
18x212	0,2	8	1,7	0%	1%	
Paneel 15cm	0,3	24	8,4	2%	4%	
Afwijkende panelen ondeelbaar door 3						**22%**
			216,1	44%		
Achtergevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	491,4	299	192,4			
Percentage	100%	61%	39%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	0				
Paneel 90cm	2,5	0				
Paneel 60cm	1,7	72				
60x280	1,7	48	80,6	16%	42%	
60 x 232	1,4	48	66,8	14%	35%	
Paneel 30cm	0,8	0	0,0			
Afwijkende panelen deelbaar door 3						**77%**
Paneel 21cm	0,6	48	28,2	6%	15%	
Paneel 15 cm	0,3	48	16,7	3%	9%	
Afwijkende panelen ondeelbaar door 3						
				39%		**23%**
Zijgevels (2x)	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	189,5	0	189,5			
Percentage	100%	0%	100%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**		
Standaardpaneel						
Paneel 120cm	3,4	54	181,4	96%		
Paneel 90cm	2,5		0,0	0%		
Paneel 60cm	1,7		0,0			
Paneel 30cm	0,8		0,0			
Afwijkende panelen deelbaar door 3						
Paneel 48cm	1,3	6	8,1	4%		
Afwijkende panelen ondeelbaar door 3						
				100%		
Alle gevels bij elkaar	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	1172,3	574,4	597,9			
Percentage	100%	49%	51%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	54	181,4	15%	30%	
Paneel 90cm	2,6	36	85,8	7%	14%	
Paneel 60cm	0,0	168	231,0	20%	39%	
Paneel 30cm	0,9	6	5,0	0%	1%	
Afwijkende panelen deelbaar door 3						**84%**
Paneel 75cm		24	22,5	2%	4%	
Paneel 21cm	0,6	48	28,2	2%	5%	
Paneel 18cm		42	18,9	2%	3%	
Paneel 15cm		48	25,1	2%	4%	
			597,9	51%		**16%**
Zonder zijgevels	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	982,8	574,4	408,4			
Percentage	100%	58%	42%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm	3,4	0	0,0			
Paneel 90cm	2,6	36	85,8	9%	21%	
Paneel 60cm	0,0	168	231,0	24%	57%	
Paneel 30cm	0,9	0				
Afwijkende panelen deelbaar door 3						**78%**
Paneel 75cm		24	22,5	2%	6%	
Paneel 21cm	0,6	48	28,2	3%	7%	
Paneel 18cm		36	15,9	2%	4%	
Paneel 15cm		48	25,1	3%	6%	
			408,4	42%		**22%**

Appendix F-4 - Findings & drawings of CB008

Coendersbuurt Delft - CB008						
					Average Const:	(9+8+4)/3
Voorgevel	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht		Constante	7
	458,6	181	278,0			
Percentage	100%	39%	61%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm	0	0	0,0			
120x105	1,26	1	8,8	2%	3%	
Paneel 90cm			0,0			
Paneel 60cm			0,0			
60x270	1,6	7	79,4	17%	29%	
60x300	1,8	3	37,8	8%	14%	
60x305	1,8	6	76,9	17%	28%	
Paneel 30cm	0,3		0,0		0%	
30x270	0,81	2	11,3	2%	4%	
30x105	0,315	1	2,2	0%	1%	
Afwijkende panelen deelbaar door 3			0,0			78%
Afwijkende panelen ondeelbaar door 3			0,0			
Paneel 100cm	1,3	1	8,8	2%	3%	
Paneel 50cm	1,3	2	17,9	4%	6%	
Paneel 40cm			0,0			
40x255	1,0	2	14,3	3%	5%	
40x105	0,4	4	11,8	3%	4%	
Paneel 25cm	0,6	2	8,9	2%	3%	
25x 300	0,8	1	5,3	1%	2%	
25x305	0,8	2	10,7	2%	4%	
			2057,3	61%		28%

Achtergevel 1	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	248,6	94	154,2			
Percentage	100%	38%	62%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm						
120x355	4,26	1	29,8	12%	19%	
120x310	3,72	1	26,0	10%	17%	
Paneel 90cm			0,0	0%		
90x160	1,44	1	10,1	4%	7%	
90x110	0,99	3	20,8	8%	13%	
Paneel 60cm			0,0	0%		
60x355	2,1	2	29,8	12%	19%	
60x310	1,9	2	26,0	10%	17%	
Paneel 30cm				0%		
Afwijkende panelen deelbaar door 3						92%
Afwijkende panelen ondeelbaar door 3						
Paneel 25cm						
25x355	0,9	1	6,2	2%	4%	
25x310	0,8	1	5,4	2%	4%	
			154,2	62%		8%

Achtergevel 2	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	162,5	81	81,7			
Percentage	100%	50%	50%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm						
120x155	1,86	4	52,1	21%	64%	
Paneel 90cm						
Paneel 60cm						
60x275	1,7	2	23,1	9%	28%	
60x155	0,9	1	6,5	3%	8%	
Paneel 30cm				0%		
Afwijkende panelen deelbaar door 3						100%
Afwijkende panelen ondeelbaar door 3						
			81,7	33%		

Appendix F-4 - Findings & drawings of CB008

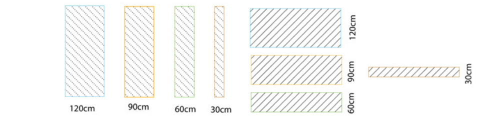
Zijgevels (2x)	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht	
	201,3	0	201,3	
Percentage	100%	0%	100%	
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal
Standaardpaneel				
Paneel 120cm				
120x300	3,6	18	64,8	32%
120x290	3,48	6	20,9	10%
120x270	3,24	32	103,7	51%
Paneel 90cm				
Paneel 60cm				
60x300	1,8	2	3,6	2%
Paneel 30cm				
Afwijkende panelen deelbaar door 3				
Paneel 42cm	1,1	4	4,3	2%
Afwijkende panelen ondeelbaar door 3				
Paneel 70cm	2,0	2	4,1	2%
			201,3	100%

Alle gevels bij elkaar	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht		Average Constante:	(9+8+4)/3
	2279,1	355,8	1889,0		**Constante**	**7**
Percentage	100%	16%	83%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm		63	1442,3	63%	76%	
Paneel 90cm		4	30,9	1%	2%	
Paneel 60cm		25	304,7	13%	16%	
Paneel 30cm		3	13,5	1%	1%	
Afwijkende panelen deelbaar door 3						95%
Paneel 42cm	1,1	4	4,3	0%	0%	
Afwijkende panelen ondeelbaar door 3						
Paneel 100cm		1	8,8	0%	0%	
Paneel 70cm		2	28,4	1%	2%	
Paneel 50cm	1,3	2	2,6	0%	0%	
Paneel 40cm		10	26,0	1%	1%	
Paneel 25cm		2	27,6	1%	1%	
			1889,0	83%		5%
	gehele gevel	van alle panelen				
Afwijkende panelen	4%	5%				
Standaard panelen	79%	95%				
120 naar 60	77%	92%				

Voor en achter gevels	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	869,7	355,8	513,9			
Percentage	100%	41%	59%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm		63	116,8	13%	23%	
Paneel 90cm		4	4,4	1%	1%	
Paneel 60cm		25	279,5	32%	54%	
Paneel 30cm		3	1,9	0%	0%	
Afwijkende panelen deelbaar door 3						78%
Paneel 42cm		0	0,0	0%	0%	
Afwijkende panelen ondeelbaar door 3						
Paneel 100cm		1	1,3	0%	0%	
Paneel 70cm		0		0%	0%	
Paneel 50cm	1,3	2	2,6	0%	0%	
Paneel 40cm		10	3,7	0%	1%	
Paneel 25cm		2	3,9	0%	1%	
			276,3	48%		2%
	gehele gevel	van alle panelen				
Afwijkende panelen	1%	2%				
Standaard panelen	46%	78%				
120 naar 60	46%	77%				

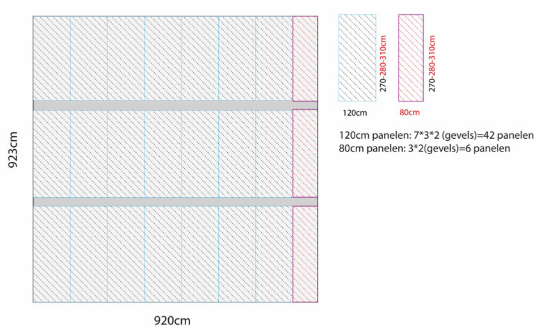
Appendix F-5 - Findings & drawings of CB010

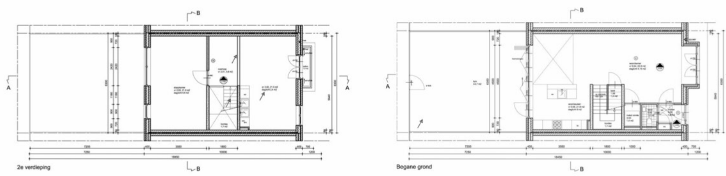
1:100 STANDAARD PANELEN



17 (met openvoeg)*54=918cm, dus 923-918=5 cm over

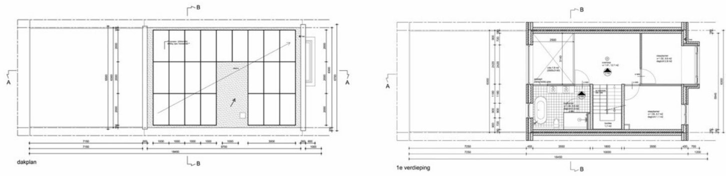
170mm is de maximale breedte voor alle soort houtengevelbekleding





Lengte woning=10 m
Breedte zijgevels:10000-400*2=9200mm
Draagmuur aan de zijgevels
Hoogte=9230 (min de vloer)
Dikte vloer ongeveer: 30cm

Hoogte draagmuur 1e verdieping: 310cm
Hoogte draagmuur 2e verdieping: 280cm
Hoogte draagmuur 3e verdieping: 270cm



Appendix F-5 - Findings & drawings of CB010

Coendersbuurt Delft - CB010						
					Average Constante:	(9+8+4)/3
Voorgevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**		**Constante**	**7**
	415,9	160	256,3			
Percentage	100%	38%	62%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm						
120x110	1,32	1	9,2	2%	4%	
120x90	1,08	1	7,6	2%	3%	
120x60	0,72	1	5,0	1%	2%	
120x 50	0,6	1	4,2	1%	2%	
Paneel 90cm						
90 x240	2,2	1	15,1	4%	6%	
Paneel 60cm						
60 x320	1,9	1	13,4	3%	5%	
60x313	1,9	1	13,1	3%	5%	
60 x310	1,9	1	13,0	3%	5%	
60x150	0,9	1	6,3	2%	2%	
Paneel 30cm						
30 x320	1,0	2	13,4	3%	5%	
30 x313	0,9	4	26,3	6%	10%	
30 x310	0,9	2	13,0	3%	5%	
30x240	0,7	1	5,0	1%	2%	
Afwijkende panelen deelbaar door 3						**57%**
Paneel 24cm						
24 x320	0,8	2	10,8	3%	4%	
24x 310	0,7	2	10,4	3%	4%	
Afwijkende panelen ondeelbaar door 3						
Paneel 40cm		*8*				
40x320	1,3	2	17,9	4%	7%	
40x313	1,3	4	35,1	8%	14%	
40x310	1,2	2	17,4	4%	7%	
Paneel 20cm						
20x320	0,6	1	4,5	1%	2%	
20x313	0,6	1	4,4	1%	2%	
20x310	0,6	1	4,3	1%	2%	
20x240	0,5	2	6,7	2%	3%	
			256,3	40%		**43%**

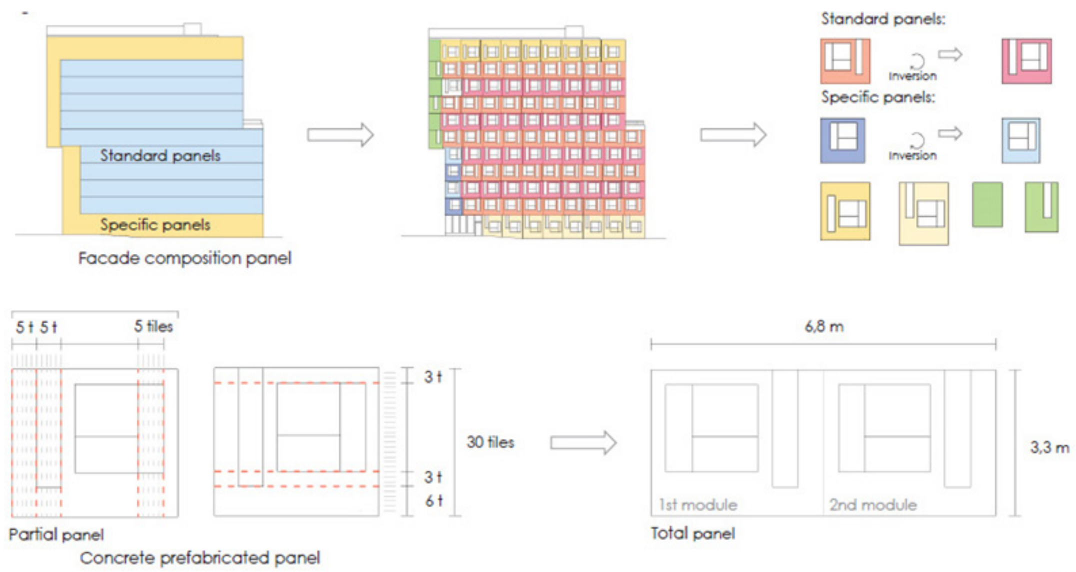
Achtergevel	**Oppervlakte gevel**	**Oppervlakte open**	**Oppevlakte dicht**			
	415,9	174	242,1			
Percentage	100%	42%	58%			
	Oppervlakte paneel	**Aantal**	**Totale oppervlakte panelen**	**Percentage totaal**	**% van dichte oppervlakte**	
Standaardpaneel						
Paneel 120cm						
120 x320	3,84	1	26,9	6%	11%	
120 x313	3,756	1	26,3	6%	11%	
120 x140	1,68	2	23,5	6%	10%	
120 x70	0,84	2	11,8	3%	5%	
120 x50	0,6	3	12,6	3%	5%	
Paneel 90cm						
90 x320	2,9	2	40,3	10%	17%	
90 x313	2,8	2	39,4	9%	16%	
90 x310	2,8	2	39,1	9%	16%	
90 x145	1,3	2	18,3	4%	8%	
90x63	0,6	1	4,0	1%	2%	
Paneel 60cm						
Paneel 30cm						
Afwijkende panelen deelbaar door 3						**100%**
Afwijkende panelen ondeelbaar door 3						
			242,1	58%		

Zijgevels (2x)	Oppervlakte gevel	Oppervlakte vloer	Oppevlakte dicht			
	169,8	12	158,2			
Percentage	100%	7%	93%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm						
120x310	3,6	14	50,4	30%	32%	
120x280	3,48	14	48,7	29%	31%	
120x270	3,24	14	45,4	27%	29%	
Paneel 90cm						
Paneel 60cm						
60x310	1,9	2	3,7	2%	2%	
60x280	1,7	2	3,4	2%	2%	
60x270	1,6	2	3,2	2%	2%	
Paneel 30cm						
Afwijkende panelen deelbaar door 3						98%
Afwijkende panelen ondeelbaar door 3						
Paneel 20cm						
20x310	0,62	2	1,2	1%	1%	
20x280	0,56	2	1,1	1%	1%	
20x270	0,54	2	1,1	1%	1%	
			158,2	93%		2%

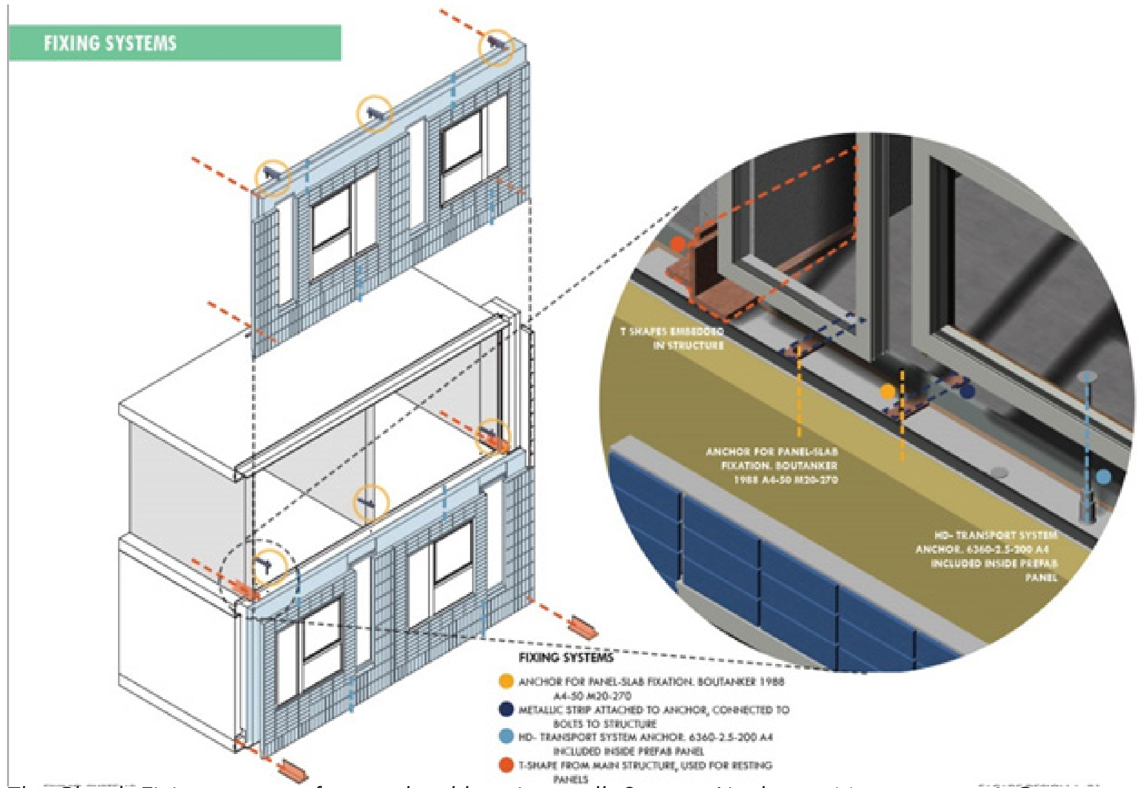
Alle gevels bij elkaar	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht		Average Constante:	(9+8+4)/3
	1001,6	344,9	656,6		Constante	7
Percentage	100%	34%	66%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm			271,6	27%	41%	
Paneel 90cm			156,2	16%	24%	
Paneel 60cm			56,2	6%	9%	
Paneel 30cm			57,8	6%	9%	83%
Afwijkende panelen deelbaar door 3						standard panels
Paneel 24cm			21,2	2%	3%	
Afwijkende panelen ondeelbaar door 3						
Paneel 40cm			70,3	7%	11%	
Paneel 20cm			23,4	2%	4%	
			656,6	66%	100%	14%
	gehele gevel	van alle panelen				deviating panels
Afwijkende panelen	11%	17%				
Standaard panelen	54%	41%				
120 naar 60	33%	50%				

Voor en achter gevels	Oppervlakte gevel	Oppervlakte open	Oppevlakte dicht			
	831,7	333,3	498,4			
Percentage	100%	40%	60%			
	Oppervlakte paneel	Aantal	Totale oppervlakte panelen	Percentage totaal	% van dichte oppervlakte	
Standaardpaneel						
Paneel 120cm			127,1	13%	26%	
Paneel 90cm			156,2	16%	31%	
Paneel 60cm			45,9	5%	9%	
Paneel 30cm			57,8	7%	12%	
Afwijkende panelen deelbaar door 3						78%
Paneel 24cm			21,2	2%	4%	standard panels
Afwijkende panelen ondeelbaar door 3						
Paneel 40cm			70,3	7%	14%	
Paneel 20cm			19,9	2%	4%	
			498,4	51%		22%
						deviating panels
	gehele gevel	van alle panelen				
Afwijkende panelen	11%	22%				
Standaard panelen	47%	78%				
120 naar 60	17%	35%				

Appendix G - Drawings of the Cloud



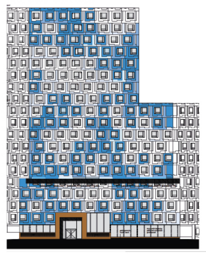
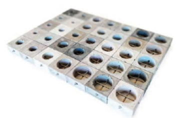
Facade composition and concrete prefabricated modules of the Cloud. Source: Lincheng, Montemayor, & Cunqueiro, 2019



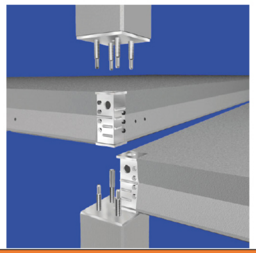
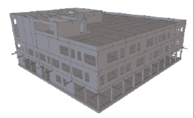
The Cloud: Fixing system of a non-load bearing wall. Source: Lincheng, Montemayor, & Cunqueiro, 2019

Appendix H - Criteria list of the modular case studies

The Cloud , Circular Viaduct & Circular pavilion

Design/Case study criteria	1. The Cloud 	2. Circulair viaduct (left)  Circular concrete pavilion  (right)
General requirements		
Prefab	1	1
Stackable	1	1
Load bearing capacity	1	1
Technical requirements		
Thermal insulation	-	-
Fire safety	-	-
Sound insulation	-	-
Standardization		
Number of different panels	3	1
Simple form	4	1
Dimensions (flexibility/based on 300 mm grid)	5	1
Building efficiency		
Connections		
Use of dry connections (demountable)	4	1
Number of connections per panel	4>	2
Connections can easily be inspected	3	2
Complexity	4	1
Assembling & disassembling		
Separation of functions and lifecycles (replacement)	5	5
Easy and fast assembly & disassembly	3	1
Adaptability		
Adaptable to change	4	1
Sustainability		
Material		
Separation of materials	3	3
Sustainable materials	5	5 (viaduct) – 1 (paviljon)
Building lightweight		
Use of lightweight components	5	4 (viaduct)- 2 (pavilion)
(Lightweight) form	5	1
Aesthetics		
Finishing	2	3
Hidden connections	4	1
Overall points		
Total	66	36-30

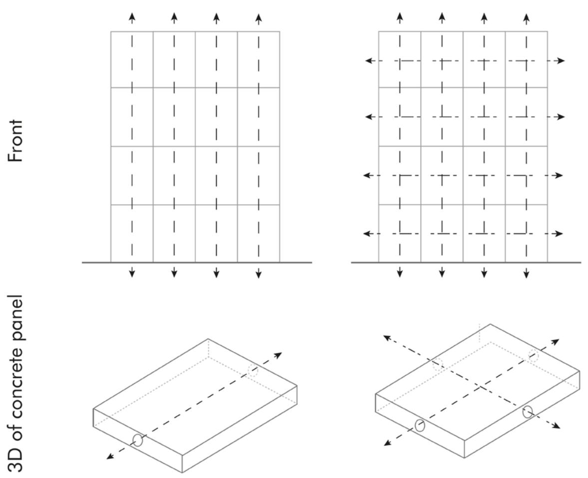
CD20 Structural and CD20 load bearing facade system

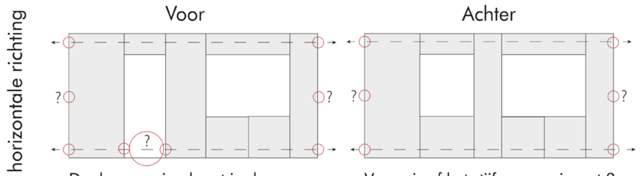
Design/Case study criteria	3. CD20 structural system 	4. CD20 load bearing façade system 
General requirements		
Prefab	1	1
Stackable	1	1
Load bearing capacity	1	1
Technical requirements		
Thermal insulation	-	-
Fire safety	-	-
Sound insulation	-	-
Standardization		
Number of different panels	1 Both columns as floor slabs come in different sizes. Facades depended on these sizes.	4>
Simple form	1	3
Dimensions (flexibility/based on 300 mm grid)	1	1
Building efficiency		
Connections		
Use of dry connections (demountable)	1	2
Number of connections per panel	Per column: 1 on each end, so 2 (one column can connect 4 floors)	3
Connections can easily be inspected	5	5
Complexity	1	2
Assembling & disassembling		
Separation of functions and lifecycles (replacement)	5	5
Easy and fast assembly & disassembly	1	1
Adaptability		
Adaptable to change	1	1
Sustainability		
Material		
Separation of materials	3	3
Sustainable materials	5	5
Building lightweight		
Use of lightweight components	1	1
(Lightweight) form	1	5
Aesthetics		
Finishing	2	2
Hidden connections	1	3
Overall points		

Appendix I – Criteria list for assembling & dissembling aspect

Criteria	**1 Assembled per panel**	**2 One module**	**3 Multiple modules**
Building efficiency			
Connections			
Use of dry connections (demountable)	1	1	1
Number of connections per panel	>4	<4	>4
Connections can easily be inspected	-	-	-
Complexity	4	1	3
Assembling & disassembling			
Easy and fast assembly & disassembly	5	1	2/3
Separation of functions and lifecycles (maintenance)	-	-	-
Safety	5	1	3
Overall points			
Total	16	4	9/10

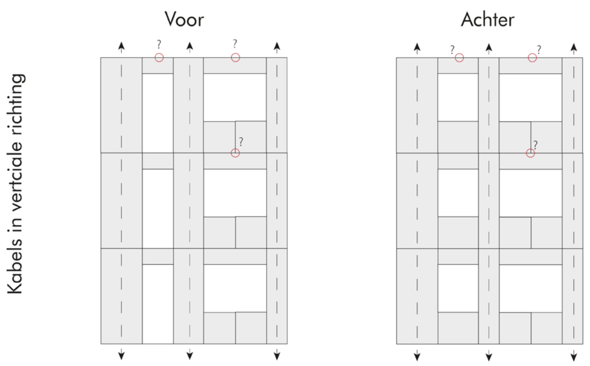
Appendix J – 1 Connection ideas for modules – cable system



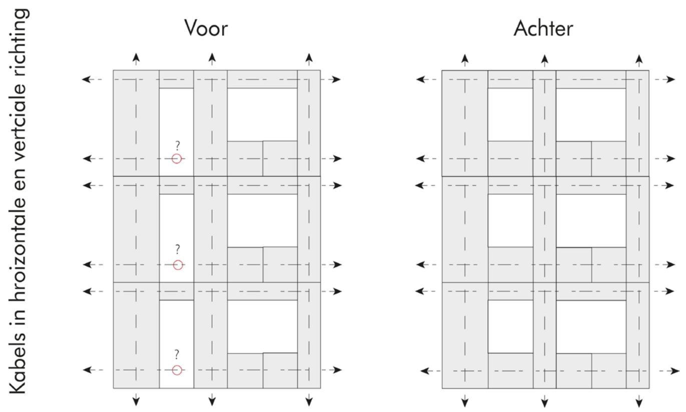


De deuropening loopt in de weg van de kabels.

Vraag is of het stijf genoeg is met 2 (uiterste) kabel punten.
De voorbeeld projecten hebben altijd deze punten in het midden liggen.



Panelen worden verticaal gekoppeld. De tussenpanelen kunnen niet met kabels geconnected worden door de openingen. Het is een inefficiente manier om het zo te bouwen en geeft minder (makkelijke) vrijheid in gevelverandering. De hele rij aan verticale deelpanelen zullen ontkoppeld moeten worden bij vervanging of verandering van de gevel.

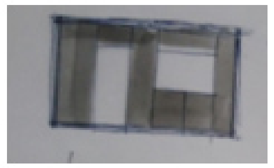
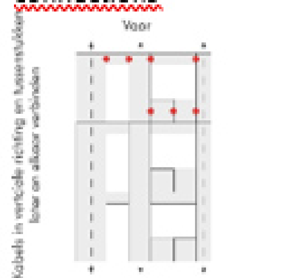


De deuropening blijft een probleem. Hierdoor kan er kabel door geheel horizontaal doorlopen. Dit lukt wel aan een gevel zonder een opening wat volledig door loopt.

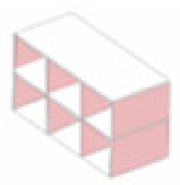
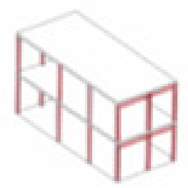
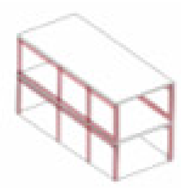
Conclusie: heeft het wel zin om dit per paneel te gaan doen?
Nee, dan raakt het zijn hele functie kwijt

Heeft het wel zin om dit per gevel deel te doen? Bv horizontaal of verticaal?
In horizontale richting kan het problemen opleveren, dus zou eventueel alleen de verticale richting oke kunnen zijn.

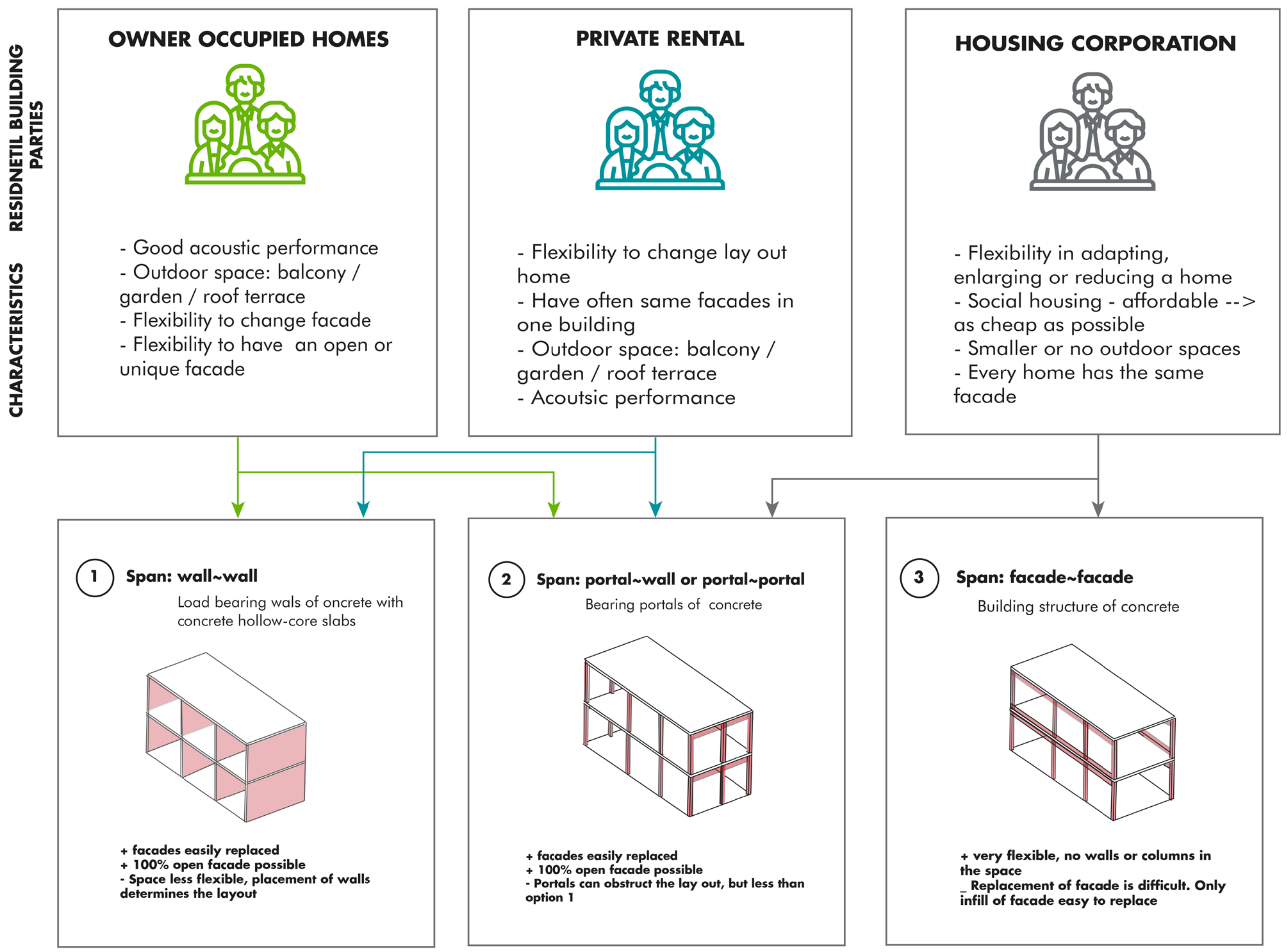
Appendix J – 2 Criteria list for assembling & dissembling aspect – Frame or cable system?

Final design criteria	1 Module in a frame 	Cable system & other connections 
Building efficiency		
Connections		
Use of dry connections (demountable)	1	1
Number of connections per panel	2-4 panel 4> for module	2-4 panel 4> for module
Connections can easily be inspected	2	4
Complexity	1	4
Assembling & disassembling		
Easy and fast assembly & disassembly	1	3
Separation of functions and lifecycles (replacement)	2	4 (concrete layer)
Safety	1	3
Man power needed	1	3
Overall points		
Total	12	25

Appendix K-1 – Criteria list building structures

Final design criteria	1 Span: wall~wall 	2 Span: portal~wall or portal~portal 	3 Span: facade~facade 
Technical requirements			
Thermal insulation	1	3	3
Fire safety	1	3	3
Sound insulation	1	3	3
Building efficiency			
Assembling & disassembling			
Easy and fast assembly & disassembly	2	2	1
Separation of supporting structure and module/façade (replacement)	3	1	5
Man power needed	4	2	2
Adaptability			
Lay-out flexibility	5	3	1
Sustainability			
Material			
Amount of material used	3	1	2
Overall points			
Total	20	18	20

Appendix K-2 – Matching housing types and building structures

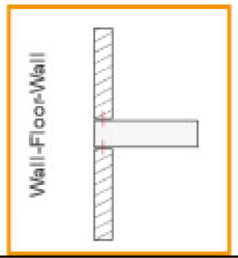
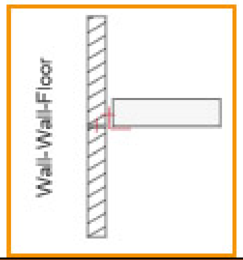
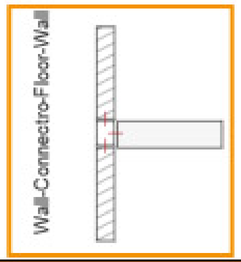


Appendix L - Choosing the profile for the metal frame

Final design criteria	1 HEA-profile (vertcial)	2 HEA-profile (horizontal)	3 U profile	4 L-profile (+plate)
Building efficiency				
Connections				
Connections can easily be inspected (accessibility)	5	1	5	1
Assembling & disassembling				
Joint width	5	5	1	1
Overall points				
Total				

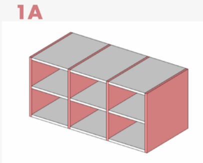
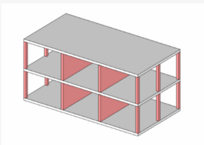
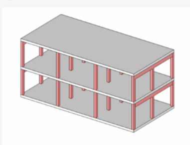
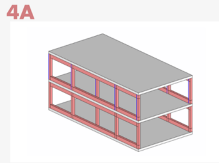
In this case, the answers are giving as: accessibility Yes (1) and No (5) and joint width Yes (5) and No 1)

Appendix M - Criteria list connection systems – Strengths & weaknesses

Final design criteria	1 	2 	3 
General			
Stackable	Yes	Yes	Yes
Load bearing capacity	1	1	1
(Access) Balcony *Not counted in total*	Yes	No	No
Technical requirements			
Thermal bridge	1	1	3
Building efficiency			
Connections			
Use of dry connections (demountable)	1	1	1
Number of connections per panel	4	4 +1 floor = 4>	2
Connections can easily be inspected	5 vertical 1 horizontal = 3 average	1 vertical 3 horizontal (wall+floor) = 2 average	1 vertical 1 horizontal = 1 average
Complexity	1	2	5
Assembling & disassembling			
Easy and fast assembly & disassembly	2	2	1
Safety	2	2	1
Man power needed	2	3	1
Adaptability			
Lay-out flexibility	2	1	1
Aesthetics			
Finishing	3	1	3
Hidden connections	1	1	5
Overall points			
Total	23	22	25

Appendix N - Connection assessment for every building structure

Building structure 1A, 2A, 3A and 4A

1A

2A

3A

4A


1 CONNECTION SYSTEM 1
Wall-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible

B NON LOAD-BEARING SYSTEM
✓ Possible

2 CONNECTION SYSTEM 2
Wall-Wall-Floor

A LOAD-BEARING SYSTEM
✓ Possible

B NON LOAD-BEARING SYSTEM
✓ Possible

3 CONNECTION SYSTEM 3
Wall-Connection-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible

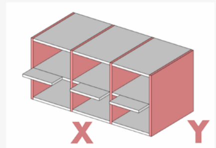
B NON LOAD-BEARING SYSTEM
✓ Possible

4 CONNECTION SYSTEM 4
Connection system 1 plus a (access) balcony

A LOAD-BEARING SYSTEM
— Inapplicable

B NON LOAD-BEARING SYSTEM
— Inapplicable

Building structure 1B and 1C



1B Balcony on non-load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1
Wall-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible on the entire supporting structure

B NON LOAD-BEARING SYSTEM
✓ Possible

2 CONNECTION SYSTEM 2
Wall-Wall-Floor

A LOAD-BEARING SYSTEM
✓ Outside Y
Not possible because of balcony

✓ Inside
Possible

B NON LOAD-BEARING SYSTEM
✗ Not possible because of the balconies on the non load-bearing side

3 CONNECTION SYSTEM 3
Wall-Connection-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Outside Y
Possible to connect multiple modules to each other and to the floor

✓ Inside
Possible to connect ` multiple modules to each other and to the floor

B NON LOAD-BEARING SYSTEM
✗ Floor
Not possible because of the balconies on the non load-bearing sides

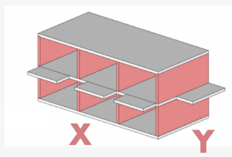
✓ ✗ Modules
Possibility to connect two non load-bearing modules to a load-bearing module, but not multiple non-load bearing modules together.

Not recommended

4 CONNECTION SYSTEM 4
Connection system 1 plus a (access) balcony

A LOAD-BEARING SYSTEM
— Inapplicable

B NON LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony



1C Balcony on non-load bearing side and load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects multiple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1
Wall-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible on the entire supporting structure

B NON LOAD-BEARING SYSTEM
✓ Possible

2 CONNECTION SYSTEM 2
Wall-Wall-Floor

A LOAD-BEARING SYSTEM
✗ Outside Y
Not possible because of balcony

✓ Inside
Possible

B NON LOAD-BEARING SYSTEM
✗ Not possible because of the balconies on the non load-bearing side

3 CONNECTION SYSTEM 3
Wall-Connection-Floor-Wall

A LOAD-BEARING SYSTEM
✗ Floor
Not possible on outside because of the balconies on the non load-bearing sides. Possible on inside.

✓ Modules
Possible

B NON LOAD-BEARING SYSTEM
Floor
Not possible because of the balconies on the non load-bearing sides

✓ Modules
Possibility to connect two non load-bearing modules to a load-bearing module, but not multiple non-load bearing modules together.

Not recommended

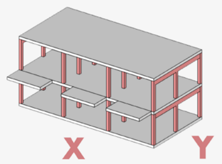
4 CONNECTION SYSTEM 4
Connection system 1 plus a (access) balcony

A LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony

B NON LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony

Appendix N - Connection assessment for every building structure

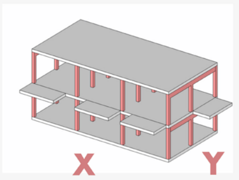
Building structure 2B and 2C



3B Balcony on non-load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1 Wall-Floor-Wall	2 CONNECTION SYSTEM 2 Wall-Wall-Floor	3 CONNECTION SYSTEM 3 Wall-Connection-Floor-Wall	4 CONNECTION SYSTEM 4 Connection system 1 plus a (access) balcony
A LOAD-BEARING SYSTEM	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**
✓ Possible on the entire supporting structure	✓ Outside Y Possible — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	✓ Outside Y Possible to connect multiple modules to each other and to the floor — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	— Inapplicable
B NON LOAD-BEARING SYSTEM	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**
✓ Possible	✗ Not possible on X side because of balcony.	✗ Floor Not possible because of the balconies X side. ✗ Modules Not possible to connect multiple modules on X side because of balconies	✓ Only possible connection system for balcony

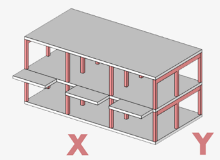


3C Balcony on non-load bearing side and load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1 Wall-Floor-Wall	2 CONNECTION SYSTEM 2 Wall-Wall-Floor	3 CONNECTION SYSTEM 3 Wall-Connection-Floor-Wall	4 CONNECTION SYSTEM 4 Connection system 1 plus a (access) balcony
A LOAD-BEARING SYSTEM	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**
✓ Possible on the entire supporting structure	✗ Outside Y Not possible due to balcones — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls.	✗ Outside Y Not possible due to balcones — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	✓ Only possible connection system for balcony
B NON LOAD-BEARING SYSTEM	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**
✓ Possible	✗ Not possible on X side because of balcony.	✗ Floor Not possible because of the balconies X side. ✗ Modules Not possible to connect multiple modules on X side because of balconies	✓ Only possible connection system for balcony

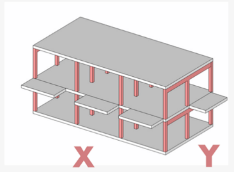
Building structure 3B and 3C



3B Balcony on non-load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1 Wall-Floor-Wall	2 CONNECTION SYSTEM 2 Wall-Wall-Floor	3 CONNECTION SYSTEM 3 Wall-Connection-Floor-Wall	4 CONNECTION SYSTEM 4 Connection system 1 plus a (access) balcony
A LOAD-BEARING SYSTEM	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**
✓ Possible on the entire supporting structure	✓ Outside Y Possible — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	✓ Outside Y Possible to connect multiple modules to each other and to the floor — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	— Inapplicable
B NON LOAD-BEARING SYSTEM	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**
✓ Possible	✗ Not possible on X side because of balcony.	✗ Floor Not possible because of the balconies X side. ✗ Modules Not possible to connect multiple modules on X side because of balconies	✓ Only possible connection system for balcony



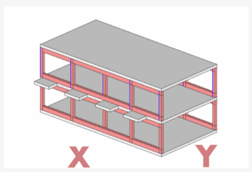
3C Balcony on non-load bearing side and load bearing side
X Non load-bearing side
Y Load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1 Wall-Floor-Wall	2 CONNECTION SYSTEM 2 Wall-Wall-Floor	3 CONNECTION SYSTEM 3 Wall-Connection-Floor-Wall	4 CONNECTION SYSTEM 4 Connection system 1 plus a (access) balcony
A LOAD-BEARING SYSTEM	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**	**A LOAD-BEARING SYSTEM**
✓ Possible on the entire supporting structure	✗ Outside Y Not possible due to balcones — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls.	✗ Outside Y Not possible due to balcones — Inside Inappicable, use of columns. Choice of architect to use modules or other partition walls	✓ Only possible connection system for balcony
B NON LOAD-BEARING SYSTEM	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**	**B NON LOAD-BEARING SYSTEM**
✓ Possible	✗ Not possible on X side because of balcony.	✗ Floor Not possible because of the balconies X side. ✗ Modules Not possible to connect multiple modules on X side because of balconies	✓ Only possible connection system for balcony

Appendix N - Connection assessment for every building structure

Building structure 4B and 4C



4B Balcony on non-load bearing side

X Load-bearing side

Y Non load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1
Wall-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible on the entire supporting structure

B NON LOAD-BEARING SYSTEM
✓ Possible

2 CONNECTION SYSTEM 2
Wall-Wall-Floor

A LOAD-BEARING SYSTEM
✗ Outside X
Not possible because of balconies on X side

– Inside
Inappicable. Choice of architect to use modules or other partition walls

B NON LOAD-BEARING SYSTEM
✓ Possible

3 CONNECTION SYSTEM 3
Wall-Connection-Floor-Wall

A LOAD-BEARING SYSTEM
✗ Outside X
Not possible because of balconies on X side

– Inside
Inappicable. Choice of architect to use modules or other partition walls

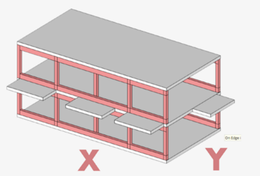
B NON LOAD-BEARING SYSTEM
✓ Floor
Possible to connect multiple modules and floor on Y side

✓ Modules
Possible to connect multiple modules on Y side

4 CONNECTION SYSTEM 4
Connection system 1 plus a (access) balcony

A LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony

B NON LOAD-BEARING SYSTEM
– Inapplicable



4C Balcony on non-load bearing side and load bearing side

X Load-bearing side

Y Non load-bearing side

Outside	Load-bearing modules on facade side	Floor	Connection that connects mulitple modules with the floor
Inside	Load-bearing modules inside the building	Modules	Connection that (only) connects multiple modules

1 CONNECTION SYSTEM 1
Wall-Floor-Wall

A LOAD-BEARING SYSTEM
✓ Possible on the entire supporting structure

B NON LOAD-BEARING SYSTEM
✓ Possible

2 CONNECTION SYSTEM 2
Wall-Wall-Floor

A LOAD-BEARING SYSTEM
✗ Outside X
Not possible due to balconies

– Inside
Inappicable, use of columns. Choice of architect to use modules or other partition walls.

B NON LOAD-BEARING SYSTEM
✗ Not possible because of balcony on Y side

3 CONNECTION SYSTEM 3
Wall-Connection-Floor-Wall

A LOAD-BEARING SYSTEM
✗ Outside X
Not possible due to balconies

– Inside
Inappicable, use of columns. Choice of architect to use modules or other partition walls

B NON LOAD-BEARING SYSTEM
✗ Floor
Not possible because of the balconies Y side.

✗ Modules
Not possible to connect multiple modules on Y side because of balconies

4 CONNECTION SYSTEM 4
Connection system 1 plus a (access) balcony

A LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony

B NON LOAD-BEARING SYSTEM
✓ Only possible connection system for balcony

Appendix O - Choices for a building system