Rationalising
the Structural Material Choice Process
for High Rise Buildings in the Netherlands

Master Thesis

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for High Rise Buildings in the Netherlands

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Abstract

De Randstad is popular place to work and live. The amount of residents will continue to grow and because of that, the housing demand increases the coming years. To accommodate the city growth in a small country as the Netherlands is, the municipalities of de cities in De Randstad turn to high rise buildings.
The floor plan of a high rise building gets repeated on every floor and because of that, the design decisions that are part of this repetition are important. The structural material choice is one of these repeated design decisions and thus important. The structural material choice is also important, because it is linked to all the disciplines on the design team and factors like cost and sustainability.

Currently 64% of the high rise buildings in the world have *only* reinforced concrete as structural material. Of the buildings in the Netherlands above 120 m, 86% have *only* reinforced concrete as structural material. This raises the question if the preference in the Netherlands for concrete comes from a clear decision-making process or if it originates elsewhere?
In theory this decision-making process follows an organized cycle called the Basic design cycle. In practice preferences based on experience gained from former projects play a role, which results in deviation from the theoretical decision-making process. By gaining insight in the differences between theory and practice in the decision-making process, this thesis tries to identify the main differences arising in the structural material choice process. Then these differences are further researched using interviews.
Finally, there is concluded if the established differences between theory and practice result in a non-optimal design. The differences that result in a non-optimal design and this thesis then tries to offer a solution for these differences.

The goal of this thesis is to create a decision-making framework for the structural material choice for high rise buildings (between 70 m and 250 m) in the Netherlands. The main research question is: *How is the structural material for a high rise building in the Netherlands chosen and how can this process become structured?*

In this thesis the design process for high rise in general is theoretically explored, following the five steps from the basic design cycle: analysis, synthesis, simulation, evaluation and decision. A high rise project always starts with certain project starting points: requirements which the design of a high rise building must meet. The project starting points can be categorised in *ten* types. *Two* of those types are chosen to be further used in this thesis: cost and sustainability. Cost is chosen, because it is often mentioned by structural engineers and contractors as the most important project starting point. Sustainability is chosen, because it will become more important in the future.
Rotterdam changed the theoretical maximum height from 200 m to 250 m high, which is a maximum height that will be adopted by this thesis. The current situation of high rise in the Netherlands is researched by looking at the buildings in the Netherlands currently (being December 2019) above 120 m. An important fact is that out of the buildings in the Netherlands above 120 m, *nineteen* are concrete structure only and *three* are mixed buildings (steel and concrete mixed). This raises the question why none of the stability systems are made of *steel* only?

Four differences between theory and practice – regarding the structural material choice process of high rise buildings in the Netherlands – are identified. By conducting interviews, these differences between theory and practice are further researched and confirmed.
(1) Steel is often briefly considered as structural material, but then rejected. After introducing the option of steel during the interviews, the first response was often that in practice *'steel just doesn't work'* or *'isn't a common option to consider'*.
(2) In practice the theoretical Basic design cycle is often not completely followed when comparing design options. Instead, arguments based on preference and experience are used. The problem is that the reasoning behind these arguments is often not made clear, as it would have been when the Basic design cycle would have been followed.
(3) Contractors often have a preference for a certain building method, because their whole company is focussed on that certain building method. The building method of a contractor is linked to the chosen structural material, which means that a contractor will influence the structural material choice to fit a their building method. The exact influence of the contractor depends on the type and size of the

project.
(4) This thesis noticed that certain arguments and expectations don't match the results in reality. Figures based on the construction time of the buildings in the Netherlands above 120 m show that prefab concrete buildings don't always have a shorter construction time than cast in-situ concrete. This refutes the commonly used argument that prefab concrete builds faster than cast in-situ concrete.

In this thesis Difference 2 and 3 are combined and addressed together, because they both find their origin in the fact that preferences based on experience are leading in the decision-making process, instead of the organized theoretical process of the Basic design cycle. Both differences are addressed by creating an advisory excel-tool that can be used to quickly respond to the dynamics of the design process, by getting early in the design process insight in the decision-making process.

The goal of this excel-tool is to give the structural engineer – early in the design process of a high rise project – insight in the influence of the structural typology on the earlier mentioned two chosen project starting points: cost (direct and indirect costs) and sustainability (environmental cost).
Early in the design process very little details are available about the design of the high rise building and a lot of things can still change. Because of that, the input of the tool is kept simple: the height of the high rise building.
As output a top ten of structural *combinations* is given. The structural combinations are a combinations of (1) stability system (core, shear walls, core + rigid frame, outrigger, tube: frame, tube: braced, tube: diagrid); (2) structural material (cast in-situ concrete, prefab concrete, steel) and (3) floor type (flat slab floor, hollow core slab, composite floor). This top ten is determined by calculating the (direct and indirect) costs *and* the environmental cost (sustainability) of *twenty-six* different structural *combinations* at all heights within the height range of that stability system. Eventually the top ten shows which out of the twenty-six structural *combinations* have the lowest (direct and indirect) costs and the lowest environmental cost (sustainability). This way a structural engineer can explore early in the design process what the influence of his or her design choices are on the final result and take the top ten structural *combinations* into consideration.

Acknowledgements

This thesis was the final part in my Msc Building Engineering at the Delft University of Technology to complete my master's degree in Civil Engineering.

For this I would like to thank my graduation committee from the TU Delft: Roy Crielaard, Peter de Jong and Jan Rots. I would like to thank Roy Crielaard for his guidance during the whole process, answering all my content and process related questions, and his support. I would like to thank Peter de Jong for his knowledge about building management, and his guidance during the last half of my thesis. I would like to thank Jan Rots for his guidance during the committee meetings, and as chairman of the graduation committee.

I also would like to thank the Structural Engineering & Design department of the Arcadis office in Rotterdam for allowing me to join their pleasant working environment. I would especially like to thank Tom Borst who took it upon himself to be my supervisor during my thesis and helped me with his knowledge about high rise projects.

I would also like to thank the people who responded to my request for a face-to-face interview or who filled-in my online survey. I especially would like to thank Harmen Bunk (Arcadis, Arnhem) for his help with costs for high rise buildings and Steven Kraker (Heijmans, Rosmalen) for his help with construction time for high rise buildings.

Finally, I would like to thank my friends and family for always being there for me.

Esmee Koopman

Delft, July 2020

Personal goals

The design process of a high rise building is complex, because it involves a lot of different people from different disciplines. The challenge is to integrate all the complex elements – coming from these disciplines – into *one design*. To be able to do this, the design team should know about each other struggles and limits from the start of the project, so together they can prevent problems occurring.

While working on this thesis I wanted to learn as a structural engineer about the different disciplines and what moves them. Next, I wanted to convey what I've learned to my fellow structural engineers to let them profit from the knowledge I have gained.
As focus I chose the structural material choice process, because the material choice is a process that touches all disciplines and is complex because of that. Because the structural engineer often initiates structural material choice process, he or she can create a fluent process by organizing the process and considering all other disciplines.

Dear reader, I hope you enjoy reading my work. I certainly enjoyed writing this thesis, because it combined all my interests, on why I chose to study Civil Engineering in the first place.

Introduction

The last few years the demand for high rise in the Netherlands increased. De Randstad, where Rotterdam, Den Haag and Amsterdam are located, is a popular place to live. The municipalities of these cities aim at increasing the city density using high rise. This way the growing housing demand can be satisfied while using as little ground as possible (Buck Consultants International, 2009).

Because the city centre of Rotterdam was bombed during World War II, the city centre is relatively new. The municipality of Rotterdam has been working on city development since then. With their *High Rise Vision*, the municipality tries to increase capacity of the city in a controlled way. In October 2019 Rotterdam updated their High Rise Vision from 2011. First, the guideline for the maximum height was 200 m in the city centre. That has now been increased to 250 m (Gemeente Rotterdam, 2019). De Zalmhaventoren of 215 m will become the highest building in Rotterdam in 2022.
Other cities in the Randstad are following Rotterdam in their ambition to build high rise. Right now the highest building in Den Haag is 140 m high, but around the time the Zalmhaventoren is finished, Den Haag plans to cross the 140 m and finish a residential tower of 180 m high (Gemeente Den Haag, 2017). Just like in Rotterdam, Den Haag has appointed zones where high rise can develop.

This thesis wants to respond to the high rise development by researching what the possibilities are for developing high rise in the Netherlands. The higher a building becomes, the more repetition is found in the design and thus the more important every design decision is (Vambersky, 2001). Choosing the material for the main load-bearing structure is such a design decision. Because the structural material choice influences the design of each floor in a high rise building, it is important to choose the structural material that meets the project starting points (the goals and requirements set at the start of a project) the most.
This is however difficult, because after the initiative for the project, the choice for the structural material is made early in the design phase (Bouwend Nederland, 2017). This is because the material choice influences not only the design of the structural engineer, but also the design of the other disciplines. Because the structural material is chosen early in the design stage, the influence of the material choice on project starting points – like cost and sustainability – is unclear (Figure 1).

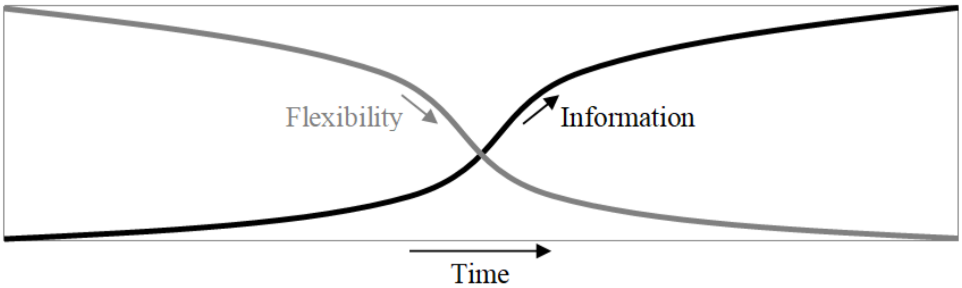

Figure 1: Flexibility to change the design versus the amount of information that is available to estimate what the outcome of certain design choices will be, over time.

The goal of this thesis is to get insight in the structural material choice process for the main load-bearing structure of high rise buildings in the Netherlands and what the influence of the structural material is on the project starting points. The main load-bearing structure includes: the frame (columns and beams), the core and the stability system (sometimes the same) and the floor type. This thesis considers high rise buildings in the Netherlands between the 70 m and the current height guideline in Rotterdam of 250 m. The materials that will be researched are cast in-situ concrete, prefab concrete and steel.
The theoretical design process and the structural material choice process in practice will be compared to each other. The differences between theory and practice will be testing by using interviews. In the end an advisory tool will help solve the main issue in the material choice process by getting insight early in the influence of the structural material choice on the project starting points.

Nomenclature

Term	Description
Basic design cycle	The design process which each design goes through, consisting of five phases: analysis, synthesis, simulation, evaluation, decision. In Dutch: elementaire ontwerpcyclus (Hertogh, et al., 2019).
Building time	Preparation time + Construction time.
Composite building	A building in which the elements itself are made of different materials (for example a composite floor).
Cradle-to-cradle assessment	An analysis the includes all the stages through which a product can go: Product stage A, Construction process stage B, Use stage C and Beyond D (reuse, recover, recycle).
Cradle-to-gate assessment	An analysis that includes only the Product stage A.
DO	Final design (Dutch: Definitef ontwerp).
Elements	The structural parts of which a building is made. For example: columns, beams, floors and walls.
Frame	The grid of columns and beams. The system that takes on the vertical loads (live load, own weight, etc). The frame can become a part of the stability system; then it also takes on a part of the horizontal loads (wind load, earthquake load).
JIT delivery	Just-In-Time delivery. The Just-In-Time (JIT) delivery model aims to reduce these problems by optimizing the delivery time and reducing the stock. Small deliveries are made at the right time, just enough to finish a certain task.
LCA	Life Cycle Assessment. It assesses the environmental impact of products or services.
Mixed building	A building in which the different elements are made of different materials (for example a concrete core with a steel outrigger).
Objective	Based on facts and not on opinions and the opposite of subjective.
Project starting points	The goals and requirements set at the start of a project. This thesis identifies ten project starting points in Chapter 4 of which cost and sustainability will be used to create the tool in Chapter 8.
Shadow price	The amount of environmental impact expressed in €/kg.
SO	Design as a sketch (Dutch: Schetsontwerp).
Structural typology	The combination of stability system and floor type; often also linked to the structural material.
TO	Technical design (Dutch: Technisch ontwerp).
VO	Preliminary design (Dutch: Voorlopig ontwerp).

Table of Contents

1. Thesis outline

This chapter states the problem that will be discussed in this thesis: the difference between theory and practice, regarding the structural material choice process of high rise buildings in the Netherlands. By gaining insight in differences between theory and practice, this thesis tries to identify the main issues arising in the structural material choice process and tries to offer a solution for these issues. This is done using seven research questions. Each chapter – from Chapter 2 to 9 – answers one of these research questions.

1.1. Problem statement

The design of a high rise building is made in design stages: going from a general design to the details. In the early design stages the material in which the main load-bearing structure will be built, is chosen. The most common materials used for the structure of a high rise building are concrete or steel or a combination of both. The last few years sustainability became more important, so timber also became a potential material.
The material choice is an important design decision, made early in the design process. In theory this decision-making process follows an organized cycle called the basic design cycle, but how is this decision made in practice?

Preferences

It can be that the initiating party already prefers a certain material, based on experience from previous projects. For example, in the case of the Breitner Center the developer preferred a steel frame and composite floors (Table 1). The Rembrandt Tower – located next to it – was also built by them and was executed with a steel frame and composite floors. This building had been a success, so based on this experience they preferred steel again for the frame and composite floors as floor type (Groot, 2000).
The contractor may also play an important role. The building contracts nowadays are more integrated. This means *one* party – the contractor in most cases – is responsible for execution, maintenance and usage (Paul, 2013). Choosing a certain building material influences the building method and thus the execution, maintenance and usage (Cederhout & Sterken, 2002). As a result, contractors have a large influence on the choice for a structural material, because in the end they are responsible for the execution *and* maintenance of the building.
The preference of using a certain building method for a certain project comes from the knowledge the contractor has, the means that a contractor has available and the automatism to choose a certain building method (Veeken, 2005). Sometimes the contractor is already involved during the design process and thus directs the design towards a building material and building method that the contractor can execute. For example, in the Hoftoren in Den Haag originally wide-slab floors with post-tension would be used, but the contractor preferred cast in-situ concrete flat slabs, so in the end these were applied (Eerden, 2001).

Arguments

When comparing both concrete and steel, arguments that are often used for steel are: the short construction time, the large spans that results a flexible floor plan and the low own weight working on the foundation. For concrete the arguments are often: the good fire resistance and sound insulation, experience with this material in the Netherlands and low cost (Groot, 2000).
Sometimes these arguments are also used for the other material or appear random. For example: in the Breitner Center a steel frame is used, because of the "fast construction time and the *quick* finishing". For the Mondriaan Tower concrete was chosen as material, because concrete is cheaper and contractors in the Netherlands have experience with this material. A reason not to choose steel was that "the construction time of steel is faster, but the finishing with a steel frame is *slower*" (Groot, 2000). Both buildings were designed and executed in the same year by the same structural engineer and for both buildings the same argument was used to execute the high rise building with a different structural material (Table 1). This contradiction of arguments confirms that an objective comparison of materials is difficult, and it suggests that *first* the structural material is chosen and the arguments are picked afterwards.

Table 1: The three towers built in De Omval, Amsterdam.

Building	Height	Design team	Structure	Construction time
Rembrandt Tower	135 m	*Developer*: Sedijko *Architect*: SOM *Structural engineer*: Van Rossum	Cast in-situ concrete core with a steel frame with composite floors.	43 months
Mondriaan Toren	115 m	*Developer*: Delta Llyod *Architect*: ZZ+P *Structural engineer*: Van Rossum and Corsmit	Cast in-situ concrete tube with sliding formwork and cast floors.	36 months
Breitner Center	93 m	*Developer*: Sedijko *Architect*: SOM *Structural engineer*: Van Rossum	Cast in-situ concrete core with a steel frame with composite floors.	32 months

Another example is Het Strijkijzer in Den Haag. Het Strijkijzer had a small building site and was surrounded by roads. The structural engineer preferred cast in-situ concrete, because tunnelling is cheap and fast. One of the surrounding roads could have been closed off and then the tunnel could have been pulled out above this closed-of road, so it's still safe for passers-by. The contractor however preferred prefab concrete for the same reason: safety on and around the small building site. So, both used the same argument for a different structural material. According to the contractor, tunnelling could have been dangerous, while prefab elements can be used without closing off roads for safety. However, they did build a roof to protect passers-by against small components. Eventually the contactor convinced everyone to choose prefab concrete, because the shorter construction time (compared to cast in-situ concrete) resulted in extra profit for the developer. They convinced the other parties by comparing both options, partially based on preference from experience and partially based on numbers: the cost and the construction time.

Theory and practice

The material choice is thus sometimes based on experience or preference. When arguments are used to compare several options to each other, these arguments can be used inconsistently or they are not clearly written down.
The inconsistent design process makes it difficult to see the influence of design choices – like the material choice – on the result, early in the design process. Insight needs to be gained in the difference between theory and practice regarding the structural material choice process, to be able to structure the design process.

1.2. Relevance

In 2012 worldwide sixty-six buildings above 200 m high where built (Cement, 2013). The main load-bearing structure of 64% of these sixty-six buildings was made of concrete and only 2% was made of steel (Figure 2). The remaining percentage (34% total) was made of composite elements or steel and concrete elements mixed. Composite buildings use elements (for example a composite floor or steel reinforced concrete columns) where multiple material types are combined in one element, using their characteristics optimally. Mixed buildings mix elements made of different materials; for example, concrete columns and steel beams.

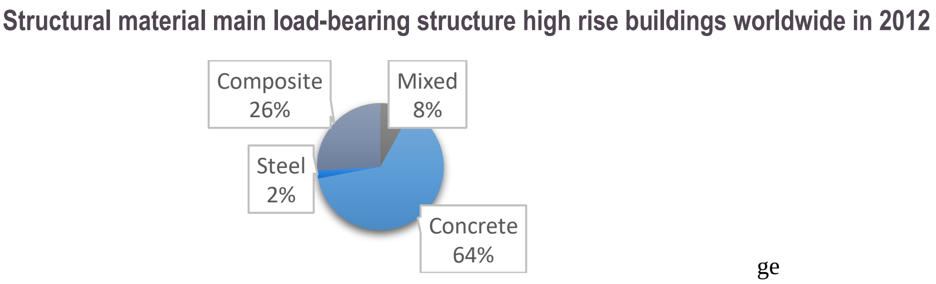

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Figure 2: Main load-bearing structure building materials used in high rise buildings higher than 200 m worldwide in 2012 (Cement, 2013).

The worldwide habit to build high rise buildings with concrete is also the custom in the Netherlands and this has not changed over the years. In 2019 the construction of seven high rise buildings above the 100 m has started in the Netherlands. Of these seven projects, none uses steel in the structural design (Table 2). As can be seen from this numbers we are used to building a high rise building in concrete, while steel or composite elements or a mix of concrete and steel might be a very good alternative (Sterken & Timmermans, 1988). Does the preference for concrete come from a clear decision-making process? How is the structural material chosen?

Table 2: The high rise projects in the Netherlands of which the construction has started in 2019.

Nr.	High rise project	Height [m]	Location	Function	Structural material
1	Bunkertoren	103	Eindhoven	Housing & Office	Concrete
2	CasaNova	110	Rotterdam	Housing	Concrete
3	Cooltoren	150	Rotterdam	Housing	Concrete
4	Grotius	120, 100	Den Haag	Housing	Concrete
5	The Terraced Tower	107	Rotterdam	Housing	Concrete
6	Valley	100, 80	Amsterdam	Housing & Office	Concrete
7	Zalmhaventoren	212, 70, 70	Rotterdam	Housing	Concrete

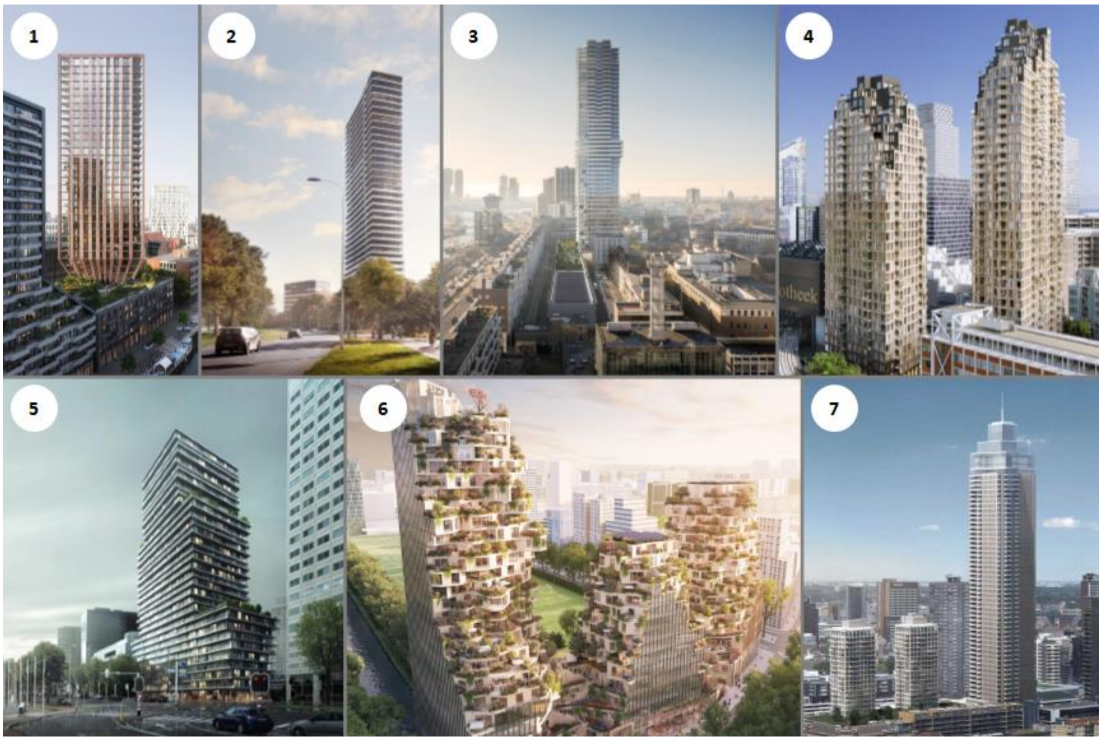


Figure 3: The designs of the towers mentioned in Table 2.

1.3. Research aim

This thesis in divided in Part A, B and C. Each part contains chapters and each chapter answers one research question.

The goal of this thesis:
Create a decision-making framework for the structural material choice for high rise buildings in the Netherlands.

Research questions

The main research question is:

How is the structural material for a high rise building in the Netherlands chosen and how can this process become structured?

Part A: Theory and practice.

1. How can the general design process of a high rise building be theoretically described?
2. What is the current situation regarding the design process and structural material choice of high rise buildings in the Netherlands?
3. Which project starting points influence the structural material choice for high rise buildings?
4. Where lie the expected differences between the structural material choice process in theory and in practice?

Part B: Exploring key differences.

5. What research method can be used to research the differences between the structural material choice process in theory and in practice?
6. Which differences can be addressed, using a tool?

Part C: Working towards a solution.

7. How can a tool give insight in the relation between structural material, structural typology and the project starting points?
8. How can the content and the design of the tool be tested?

Limitations

The structural material choice process of a high rise building includes many parameters. The get an overview of all the parameters that may play a role in this thesis, research after these parameters has been performed and written down in Appendix A. Appendix A starts with a mind map – including all the parameters – and then continues with zooming in on the structural material and the structural typology (stability systems and floor types).

The following factors *will* be included in this research:

- High rise buildings (above 70 m high and below the current height guideline in Rotterdam of 250 m).
- In the Netherlands.
- The main load-bearing structure: the frame (columns and beams), the core and the stability system (sometimes the same).
- Structural materials: concrete and steel.
- Function: housing and office.
- Two chosen project starting points: cost and sustainability (see Chapter 2 for explanation).
- Seen from the perspective of the structural engineer.

The following factors *won't* be included in this research.

- Other disciplines, o.a. building physics and architecture.
- Dynamics of the wind. The wind conditions from the Eurocode will be used.
- Earthquakes.

- High strength concrete and steel.
- Structural material: timber
- Settlements soil due to the foundation.
- Sustainability: re-use, modularity and recycling, circularity.
- Maintenance.
- Comfort: acoustics and fire safety.
- Building risks.

1.4. Methodology

The methodology describes how the research questions will be answered and what the planning, to answer these questions, will look like.

Research approach

Part A: Theory and practice.

First, the design process of high rise buildings is researched by analysing the basic design cycle. Second, the current situation regarding high rise in the Netherlands is defined. This includes what the height limits for high rise are. Also, the high rise buildings above 120 m in the Netherlands will be researched, with a focus on the design of the high rise building and the structural material choice process. Eventually this will result in a list of differences between theory and practice.
Also, the project starting points (the goals and requirements set at the start of a project) will be listed and the two most important and interesting will be used in Part C of this thesis.

Part B: Exploring key differences.

To be able to test the differences found in the literature in Part A, interviews will be used. First, the interview set-up will be described. Next, the interviews will be used to see which difference between theory and practice is the main issue in the structural material choice process.

Part C: Working towards a solution.

To address some of the differences found in Part B of this thesis, a tool will be created. This tool will give insight in the influence of the structural material choice on the two most important project starting points identified in Part A.
The tool will be tested on four subjects: uncertainty, verification, validation and comparison.

Planning overview

Table 3 gives an overview of the three parts of the thesis, the belonging research questions and how these research question will be answered.

Table 3: The planning.

Month	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020
Thesis month	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Part A: *Theory and practice.*	Literature study								
1.									
2.									
3.									
4.									
Part B: *Exploring key differences.*			Interviews and survey						
5.									
6.									

Part C: *Working towards a solution.*					Tool					
7.										
8.										
Finishing										

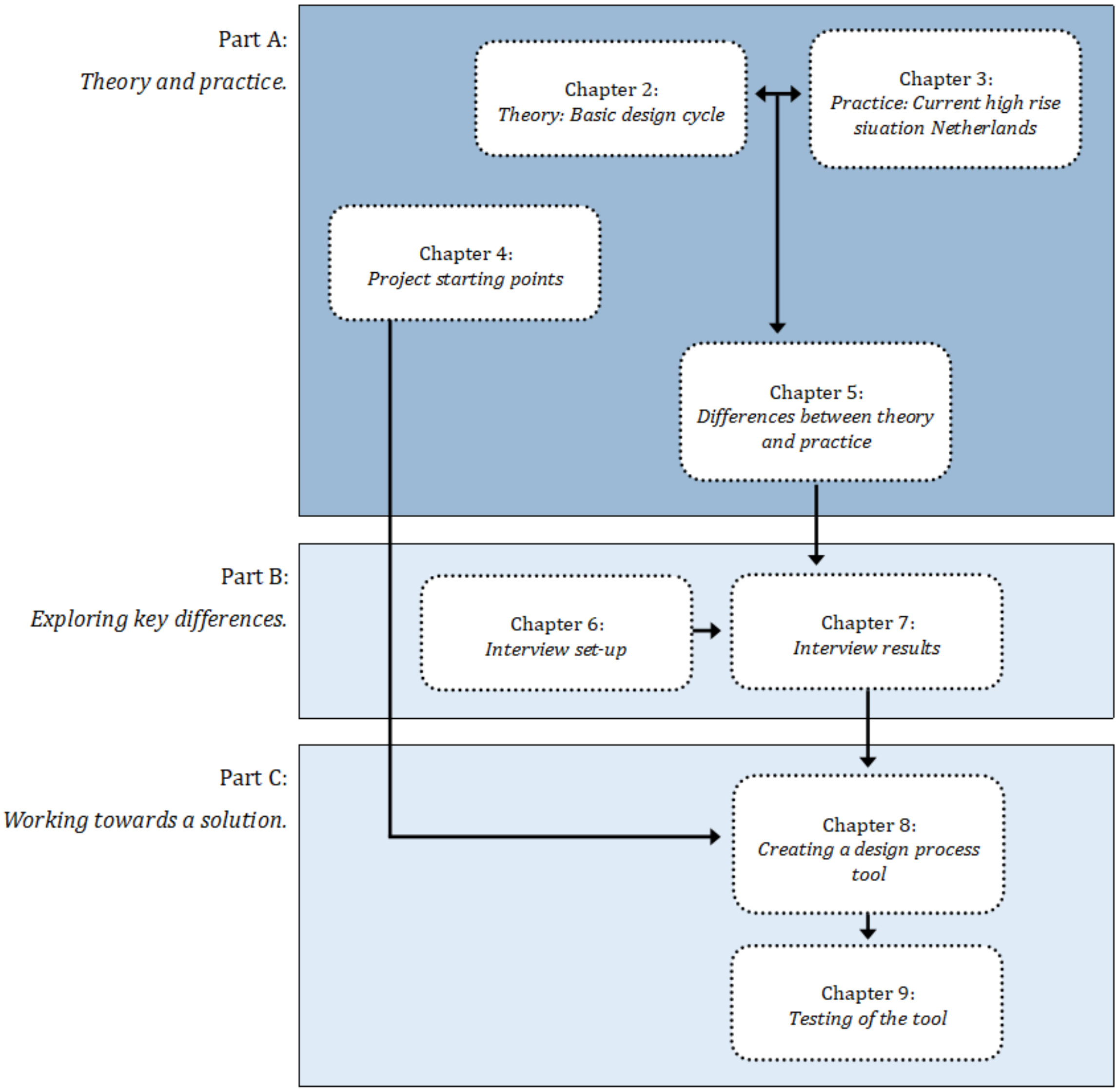
1.5. Conclusion

There are differences between theory and practice, regarding the structural material process of a high rise building in the Netherlands. Some examples about remarkable design decisions were given in the paragraph Problem statement.

The goal for this thesis is to create a decision-making framework for the structural material choice for high rise buildings in the Netherlands. First, the differences between theory and practice will be researched, using literature and interviews. Eventually a tool will give insight in the influence of the structural material choice on certain project starting points.

PART A:

THEORY AND PRACTICE



2. Theory: General design process

This chapter aims to theoretically explore the design process of a high rise building by using the Basic design cycle. The general design process, including the choice for a structural material choice and structural typology, should theoretically follow the Basic design cycle. This chapter will explain the theory, but it will also explore where the theory might deviate from practice and where the design team of a high rise building needs to pay attention to.

2.1. Basic design cycle

The basic design cycle (Dutch: elementaire ontwerpcyclus) describes from a theoretical point of view the design process, that a design team of a high rise building goes through (Figure 4) (Hertogh, et al., 2019). Every discipline goes through this basic design cycle and sometimes their cycles are intertwined. First, this happens at macro level and is slowly becomes more detailed (Figure 5).

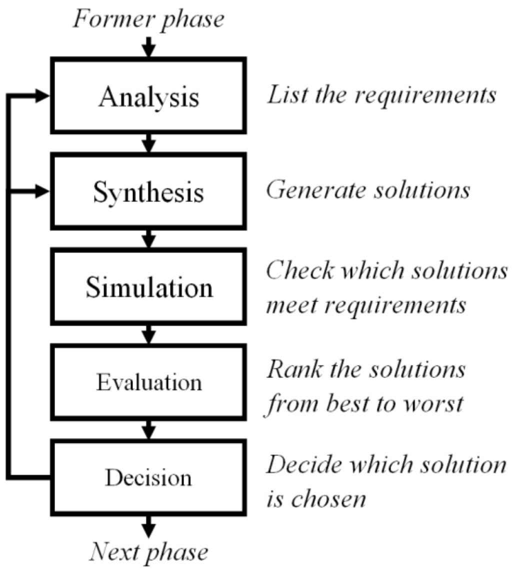


Figure 4: The basic design cycle (Dutch: elementaire ontwerpcyclus) (Hertogh, et al., 2019).

Analysis

During the Analysis phase the problem is formulated, the goal is established and the project starting points (the goals and requirements set at the start of a project) are formulated.

Before design options can be compared to each other, the aspects on which they will be compared, need to be established. In practice these aspects are often stated in the assignment given to the design team or the contractor. These aspects influence the structural material choice and the structural typology, for example a short construction time. The design team can also have goals. Someone can have a preference, for example an architect who wants a sustainable looking building, so demands wood as a structural material. All these requirements, goals and preferences need to be communicated with the other parties and officially listed as *criteria*. When the scope goes from macro to micro, the list of project starting points will become longer and more detailed. In practice the

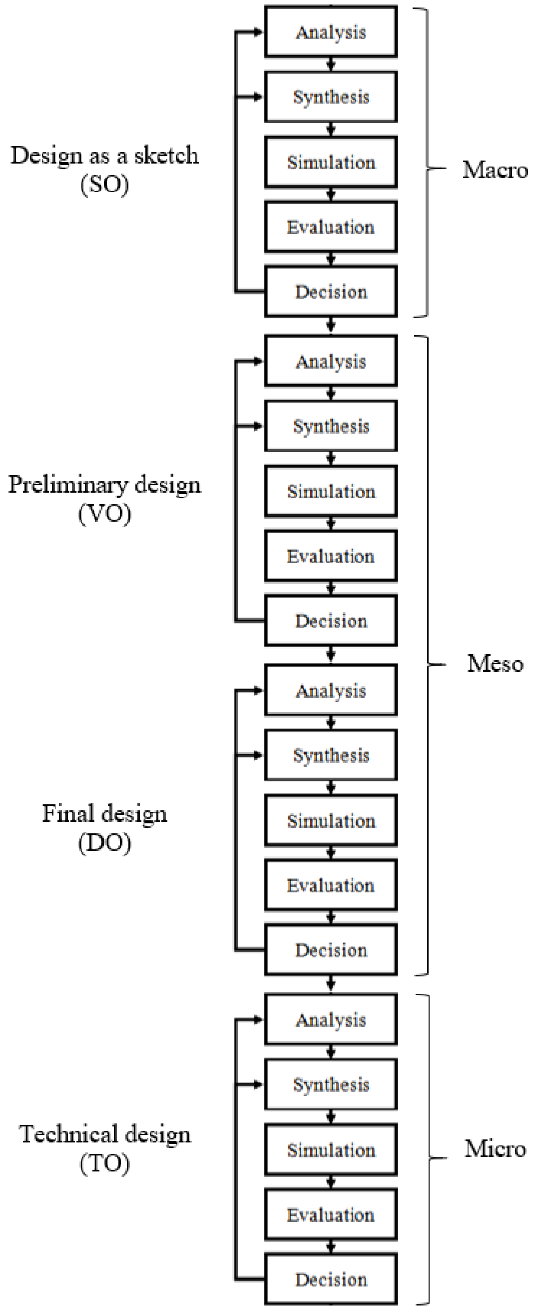


Figure 5: The basic design cycle in every design stage (Hertogh, et al., 2019).

developer's goals and motivation are clear at the beginning of the project, but over time – when also the design team can have preferences and goals – the criteria are not written down anymore and are thus not clear to everyone anymore. This can lead to tunnel vision or miscommunication.

Synthesis

In the Synthesis phase, possible solutions to the problem are created.

When solutions for the structural typology (stability system, frame and floor type) are generated, the structural material plays a role in the different solutions. In this stage all possible options need to be listed, so also options that include steel, even though steel is less common in the Netherlands as show in Chapter 3.

Simulation

In the Simulation phase there is checked if the solutions meet the requirements. The solutions that don't meet the requirements are put aside.

If a solution from the synthesis stage doesn't meet the starting points from the analysis stage, it won't be considered anymore. If any of the members of the design team wants to scratch a solution, the reason needs to be added to the list of starting points. For example, if a contractor wants to execute in prefab concrete, because that is what his building method is aimed at, this needs to be added as a starting point. The other members of the design team can then decide to accept it, or they can deny it if they have reason to believe it will negatively affect the project and they can find another contractor *can* execute the proposed solution.

Evaluation

The remaining solutions are ranked in the Evaluation phase.

Ranking the solutions is based on how well they score on the project starting points and how well they score on certain wishes members of the design team have. These wishes are not *musts*, but when one solution is chosen over another also here the reason needs to be written down.

Decision

Eventually the best solution is chosen in the Decision phase.

The final solution is chosen, based on the outcome of the evaluation phase. If it turns out that this solution can't be executed in practice or doesn't work in a more detailed design stage later on, the reason can be found in the analysis stage or the synthesis stage. Because all reasonings are written down, going back in the basic design cycle is easy. This loop (shown in Figure 5 with two black arrows) makes sure that all options are considered and the design team doesn't get stuck in tunnel vision.

2.2. **Conclusion**

This chapter provided an answer to the research question: *How can the general design process of a high rise building be theoretically described?*

The general design process of a high rise building tries to follow the Basic design cycle. The Basic design cycle consists of five steps: analysis, synthesis, simulation, evaluation and decision. This Basic design cycle is repeated while going from macro level to micro level.

3. Practice: Current high rise situation Netherlands

The goal of this chapter is to describe how the high rise situation currently is in the Netherlands. This will be done by reviewing the context of high rise is researched by reviewing the visions on high rise of the municipalities of Rotterdam, Den Haag and Amsterdam. Next, the size, construction time, function and structural material of the buildings above 120 m in the Netherlands will be shown in a table. From this table some statistics will be taken that show certain patterns in the design process of high rise.

3.1. Height limits

The definition of what high rise and what super high rise is, differs per country and even per city. It depends on the history of the city development and the structural and financial limits. Buildings higher than 70 m are a separate category in Bouwbesluit in the Netherlands. This category has a special set of rules regarding fire safety, because the higher a building the longer the evacuation time is (Buck Consultants International, 2009).
In general the high rise in Den Haag is lower than in Rotterdam. This is caused by the difference in history of both cities. The centre of Rotterdam was bombed in World War II and the city has favoured modern high rise since then (Gemeente Rotterdam, 2011). Rotterdam calls buildings higher than 70 m *high rise* and higher than 150 m *super high rise*. However, Den Haag traditionally calls buildings higher than the Binnenhof - with a height of 50 m - *high rise* and for a long time it was forbidden to pass this height. This resulted in many relatively low buildings. After World War II this changed and buildings of 70 m to 150 m were built (Gemeente Den Haag, 2017).
Amsterdam has a more difficult situation regarding high rise. The city centre of Amsterdam is UNESCO area and thus it is not allowed to see high rise from inside the city centre. Amsterdam uses a limit of 30 m high, except for some areas around the A10: the limit there is 60 m (Gemeente Amsterdam, 2011).

The municipalities of Rotterdam, Den Haag and Amsterdam all have written a vision on high rise in their cities. Rotterdam upheld a theoretical maximum height of 200 m for high rise, but changed that in October 2019 to 250 m high (Gemeente Rotterdam, 2019).
The vision of the municipality of Den Haag resembles the one of Rotterdam – regarding the quality of the plinth and the maximum width of high rise – except Den Haag doesn't use a maximum height (Gemeente Den Haag, 2017).

3.2. Buildings above 120 m in the Netherlands

Table 4 contains a list of high rise buildings above 120 m in the Netherlands of which the construction has started in 2019 at the latest. This thesis considers buildings of 70 m and higher *high rise*, but there was a lack of information about buildings below 120 m, so Table 4 only contains high rise buildings higher than 120 m. Even though high rise buildings between 70 m and 120 m are not in the table, they have been researched and are included in the four differences between theory and practice in Chapter 5.

Table 4 shows the height of the tower, all the parts of which the new building consists (cellar, plinth, low rise and tower), the construction time (measured from the start of the foundation to the delivery by the contractor), the gross area and the function. The last columns show the stability system, the core (when it is not part of the stability system) and the frame (also, when it is not part of the stability system). Also, the building methods that are used to build the tower are shown. The colours in the table show the structural material of which the main load-bearing structure is made:

- Grey: cast in-situ concrete.
- Blue: prefab concrete.
- Red: steel.
- A diagonal line: not applicable.
- Unknown: the information could not be found.

Table 4: The high rise buildings in the Netherlands higher than 120 m and of which the construction started in 2019 at the latest, are shown in the table below. The Grotius of 120 m has been excluded, because no detailed information was found on this building. Grey: cast in-situ concrete. Blue: prefab concrete. Red: steel. A diagonal line: not applicable. Unknown: the information could not be found. (Zandbelt, et al., 2008; Bouwregister, n.d.; *Carlton:* Eerden, 2011; Tissink, 2009; Eerden, 2008. *Cooltoren:* Odijk, 2017; Ballast Nedam, 2018. *De Kroon:* Hendriks & Middelkoop, 2012. *De Rotterdam:* Freide & Fitoury, 2013; Anon., 2011. *Delftse Poort:* Boo & Mans, 1990. *Erasmus MC:* Vermeulen, 2013. *First Rotterdam:* Arts & Luttmer, 2014. *Het Strijkijzer:* Boel & van Eesteren, n.d.; Velden, 2010; Betonhuis Constructief Prefab, n.d.; Freide, et al., 2006. *Hoftoren:* Eerden, 2001; *JuBi-torens:* Linde, 2011; Anon., 2009. *Maastoren:* Windt, 2009. *Millennium:* Anon., 2013. *Montevideo:* F.P. Bos, 2006; Rozemeijer, 2006; Anon., 2005; ABT, n.d.; Eerden & Rozemeijer, 2004. *New Babylon*: Woudenberg & Roos, 2008; Luttmer & Woudenberg, 2009. *New Orleans:* Gruter & Kuijer, 2009; Bovenkamp & Kuijer, 2010; Bovenkamp & Odenhoven, 2009. *Red Apple:* Middelkoop & Arts, 2009; Stuart, 2012. *Rembrandt Tower:* Mens, 2004; Holla, 1995. *World Port Centre:* BrandInformatieSysteem, n.d.; Lagendijk & Henkens, 2001. *Mondriaantoren:* Groot, 2000. *Zalmhaventoren*: Hesselink & Schaap, 2019.)

Name	Heig ht m]	City	All building parts	Construc-tion time	Gross area [m^2]	Function	Stability system		Core	Building methods	Frame	Floor type
Zalmhaven toren	215	Rotterdam	Cellar (2 floors) and tower	*Predicted:* Around 39 months	109 575	Housing	Shear walls		< Shear walls	Lifting shed	< Shear walls	Wide-slab floor.
Maastoren	165	Rotterdam	Cellar (2 floors) and tower	37 months	52 000	Office	Outer tube (frame)	Inner tube (core)		*Core:* Climbing formwork		Hollow core slab
New Orleans	158	Rotterdam	Cellar (2 floors) and tower	42 months	42 750	Housing	Shear walls		< Shear walls	*Shear walls:* Climbing formwork	< Shear walls	*(Unknown)*
Montevide o	152	Rotterdam	Cellar (2 floors), low rise and tower	34 months	57 530	Housing	Core			*Core:* Climbing formwork	Walls	Traditional formwork concrete floor.
Delftse Poort	151	Rotterdam	Cellar (1 floor) above the metro, plinth and two towers	43 months	106 000	Office	Tube (frame)			Lifting shed & *Core:* Sliding formwork	Colum ns	Prefab waffle slab.
Cooltoren	150	Rotterdam	Plinth and tower	*Predicted:* Around 25 months	37 000	Housing	Core	Outrig ger		*Core:* Self-climbing formwork	Colum ns	Traditional formwork concrete floor.
De Rotterdam	149	Rotterdam	Cellar (2 floors) and three towers	47 months	160 000	Housing & Office	Core			*(Unknown)*	Colum ns	Traditional formwork concrete floor.

Jubi-torens	146, 146	Den Haag	Cellar (2 floors), plinth and two towers	48 months	131 600	Office	Outer tube (frame)	Inner tube (core)		*Core:* Climbing formwork		Bubble-deck floor.
Hoftoren ('De Vulpen')	142	Den Haag	Cellar (2 floors), plinth and tower	55 months	48 000	Office	Core (and one stability wall)			*Core:* Self-climbing formwork	Columns	Traditional formwork concrete floor.
Westpoint	142	Tilburg	Cellar (1 floor) and tower	31 months	33 020	Housing	Shear walls			*(Unknown)*	*(Unknown)*	*(Unknown)*
New Babylon	140, 100	Den Haag	Low rise above existing building and two towers	63 months	80 000	Housing	Shear walls		< Shear walls	*Shear walls:* Tunnelling	< Shear walls	Traditional formwork concrete floor.
Rembrandt Tower	135	Amsterdam	Cellar (4 floors) and tower	43 months	29 870	Office	Core	Frame		*(Unknown)*	< Frame	Composite floor.
Het Strijkijzer	132	Den Haag	Cellar (2 floors) and tower	26 months	30 450	Housing	Tube (frame)			Cranes	Walls	Prefab massive floor
Millennium	131	Rotterdam	Cellar (2 floors) and tower	34 months	24 550	Office	Core			*Core:* Self-climbing formwork	Façade	Bubble deck floor.
De Kroon	125	Den Haag	Cellar (2 floors), plinth, low rise and tower	38 months	49 500	Housing	Shear walls	Façade *(other direct.)*	< Shear walls	*Shear walls:* Tunnelling	< Shear walls	Hollow core slab.
First Rotterdam	125	Rotterdam	Cellar (2 floors), plinth and tower	34 months	54 000	Office	Core	Outrigger		*(Unknown)*		Hollow core slab.
The Red Apple	124	Rotterdam	Low rise and tower	39 months	35 000	Housing	Shear walls	Shear walls	< Shear walls	*Shear walls:* Climbing formwork		Traditional formwork concrete floor.
World Port Centre	123	Rotterdam	Cellar (1 floor) and tower	30 months	40 000	Office	Core	Frame		Cranes	< Frame	Composite floor.

Mondriaan toren	123	Amsterdam	Low rise and tower	36 months	30 000	Office	Tube (frame)		Walls	*Tube & Core:* Sliding-formwork		Traditional formwork concrete floor.
Carlton *(part of l'Hermitage)*	120, *(75, 85)*	Almere	Cellar (4 floors) and three towers	40 months	90 000	Office	Core	Outrigger		*(Unknown)*	Columns	*(Unknown)*
Erasmus MC tower	120	Rotterdam	Large low rise part and tower	40 months	185 000	Office	Tube (frame)			*Tube:* Lifting shed		Prefab massive floor

3.3. Numbers and statistics

Table 4 shows the high rise buildings of 120 m and higher in the Netherlands. The following statistics can be taken from the table:

- 4 out of 22 buildings use *only* a core for stability (Figure 6). All these cores are executed with cast in-situ concrete.
- 6 out of 22 buildings use shear walls for stability (Figure 6). All shear walls are completely made of cast in-situ concrete, except for two. All 6 buildings with shear walls have *housing* as a function.
- 6 out of 22 of the buildings use a tube or a tube in tube stability system (Figure 6). All tubes or outer tubes are made of prefab concrete, except for one. All buildings with tubes, except for one, have *office* as function. All Tubes and Tube in Tubes use a frame structure and not a diagrid or mega structure.

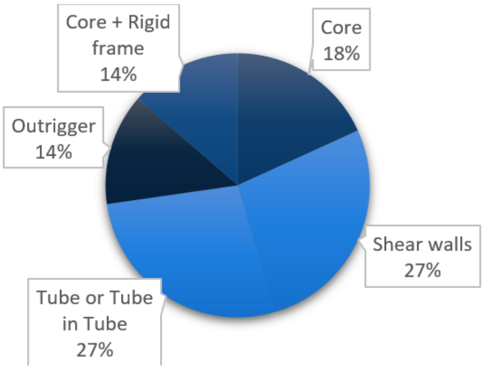


Figure 6: The stability systems used in the high rise buildings in the Netherlands that are higher than 120 m.

- The highest 7 buildings are located in Rotterdam.
- 11 out of 22 buildings have *housing* as function (one has a housing *and* an office function). 5 out of 11 use shear walls as stability system.
- 11 out of 22 buildings have *office* as function (one has a housing *and* an office function). 5 out of 11 use a tube as stability system.
- 10 out of 22 buildings use a form of sliding or (self-)climbing formwork; 8 of them used a form of sliding or (self) climbing formwork for the *core* and 2 for *shear walls*, forming a core.
- The structural material (cast in-situ, prefab, steel) or the stability system do not appear to be linked to the height of the high rise buildings in Table 4. The chosen structural material thus seems to be independent of the building height.
  The highest building in the world (the Burj Khalifa in Dubai) and the second highest building in the world (the Taipei 101) seem to confirm this. The Burj Khalifa is made of concrete, while the Taipei 101 is made of steel.
- There are no high rise buildings in the Netherlands made of only steel. There *are* three mixed buildings.

3.4. Conclusion

This chapter provided an answer to the research question: *What is the current situation regarding the design process and structural material choice of high rise buildings in the Netherlands?*

The Randstad in the Netherlands (containing the cities Rotterdam, Den Haag, Amsterdam) is aiming to build higher buildings, to solve the growing housing demand. Each city has its own historical view and laws on high rise. This thesis defines *high rise* as buildings higher than 70 m, because these buildings are a separate category with in Bouwbesluit due to fire safety requirements. Rotterdam changed the theoretical maximum height from 200 m to 250 m high, which is a maximum height that will be adopted by this thesis.

From the table with the twenty-two buildings in the Netherlands above 120 m, some facts were stated:

- 45% of the *office* buildings uses a tube as stability system.
- 45% of the *housing* buildings uses shear walls as stability system.

- Also, there can be concluded that steel is almost not used in these high rise buildings above 120 m. It is striking that only 14% (three out of twenty-two) of the high rise buildings are mixed (mixed concrete elements with steel elements) and two of those have been designed by foreign architects.

There was a lack of information about buildings below 120 m, so the detailed table with the twenty-two high rise buildings in the Netherlands only contains high rise buildings higher than 120 m. Even though high rise buildings between 70 m and 120 m are not in the table, they have been researched and are included in the four differences between theory and practice in Chapter 5.

4. Project starting points

Project starting points are defined as the goals and requirements set at the start of a project. When the scope goes from macro to micro, the list of project starting points will become longer and more detailed. This chapter explores the project starting points that the developer and the design team have at the start of a project. All the design choices – including the material choice – are trying to meet those project starting points. All optional project starting points will be identified in this chapter and eventually two will be chosen, to be used for the tool in Part C of this thesis.

4.1. Ten project starting points

When a high rise building is designed, all the design, engineering and execution choices that are made – including the material choice – contribute to the success of the project. The success of a project can be measured in how far their initial goals have been achieved. At the start of a project the design team wants, for example, to design a cheap building or a sustainable building. The following project starting points are often used in high rise projects (Crielaard & Terwel, 2019; Cederhout & Sterken, 2002; Lankhorst, 2018; Sterken, 2006):

- Cost — *The cost for the building site, the design and the execution.*
- Constructability — *How easy can a contractor execute a project? Things like difficult connections, nuisance limits and availability of materials all influence how easy project can be executed.*
- Construction time — *The time it takes to execute a high rise project (excluding the preparation time in the design phase; together the building time).*
- Risks — *The risks that can result in extra cost or delay.*
- Maintenance — *The frequency and the easy access of the maintenance procedures.*
- Net floor area — *The sellable or rentable floor area (so excluding elevators and hallways).*
- Safety — *The location and size of the building site or the height of the building can create dangerous circumstances. Certain building methods can increase safety for the workers and the surrounding.*
- Foundation and settlements — *The weight of the building and the division of loads determines the size of the foundation and the resulting settlements.*
- Comfort and fire safety — *Acoustics, heating and fire safety are important issues to determine the comfort of the user of the building.*
- Sustainability — *The environmental impact of the building on the earth during:*
  - *Production phase*
  - *Construction phase*
  - *Usage phase*
  - *Demolition phase: recyclability, modularity, reusage*

Any goals, requirements or preferences the design team or the developer has, can be linked to these project starting points. The most suitable structural material is chosen, by estimating the influence of the material choice and the related parameters on the project starting points mentioned in the summation above. In this thesis the following two starting points will be chosen to check the influence of the structural material choice on the result: cost and sustainability.

Why cost?

Cost is often a means in which every other project goal is expressed or on which every design decision is based. At the beginning of a project a loan needs to be taken, to be able to pay all the designers, workers, materials and machines. When the building is finished, this all needs to be earned back within the life time of the building.
The construction of a building is an important parameter within this cost, because the construction time determines how high the interest over the initial investment becomes (Vambersky, 2006). At the beginning of a project the developer often gets a loan to be able to finance the high investment cost of the execution.

The longer it takes before the project is finished, the longer it takes before the loan can be paid off and the total amount of interest becomes lower.
Once a high rise building is finished, it needs to be put on the market in *one* time. This means the whole building needs to be finished, before people can start to use the building and thus before the first profit can be earned to start paying off the investment loan (Dunnebacke & Sterken, 2002). A short construction time will reduce the building cost (Hubar, 2009). Especially in high rise with the function *housing*, the houses won't be sold years before the building is finished. A short construction time will thus give more certainty that a project will be sold. Both construction time and cost thus influence each other and this influence is complex and fluctuates over time.
The building cost and construction time influence the choices made regarding building method, building materials and the size of the building site (Sterken, 1999). Execution thus measures its achievements in cost and time. The type of material and how much of that material needs to be used, influences the total cost of the project. On the other hand, the material influences the choice for a building method and thus the construction time. The longer the construction time, the longer the developer needs to loan money to finance the project and the higher the total amount of interest (cost again) becomes for the developer. A longer construction time also means that the developer might lose attention of buyers or the market becomes unfavourable. The construction time is thus an important parameter in the total building cost.

Why sustainability?

Sustainability is a project starting point that will become more important in the future. In accordance with the Paris Agreement from June 2019, the Netherlands wants to reduce its greenhouse gas emissions with 49% by 2030 and with 95% by 2050 (compared to 1990). In Europe, buildings are responsible for 40% to 45% of the energy consumption and thus greenhouse gas emissions (United Nations Environment Programme, 2007). This means the building sector needs to invest in the reduction of energy consumption. To reduce the energy consumption, insight first needs to be gained in how to build in a sustainable way. Sustainability can be expressed in environmental cost. When calculating the environmental impact of a building by using an LCA analysis, this includes the energy consumption, but also things like water use and waste in the life cycles of that building. All these effects are can be combined environmental cost: how much the damage done to the environment would cost to repair. Calculating how much impact a high rise building has on the environment, can help making sustainable design decisions.

Other starting points

This paragrapgh explains why the other starting points weren't chosen to use in this thesis.

- Risks can be identified, but are difficult to compare objectively to the reality. To be able to objectively analyse the material choice process, an objective *goal* needs to be used. The same applies to comfort and fire safety: both concrete and steel can be fire safe, but the choice is often related to cost. Constructabilty and net floor area are also directly related to cost, or profit.
- Maintenance is more applicable to the façade, than the load-bearing structure and the net area is influenced more by architectural design.
- The importance of safety depends on the building and the location. The material choice influences the building method and this influences the safety measures that need to be taken. Safety is thus not directly influences by the chosen structural material and is for that reason not suitable to focus on in this thesis.
- The foundation and settlements might be a good goal to use, but this goal doesn't meet the scope of the thesis: the material choice *inside* a high rise building. It also doesn't meet the personal knowledge goal of this thesis.

4.2. **Cost**

There are a lot of different types of cost (Oss, 2007). To be able to built a high rise building, a piece of land needs to be purchased (land costs). Then a design team needs to be assembled and needs to create a design (design costs). Eventually the contractor starts working at the building site. The construction time determines how long this building site, the machines and the executor need to be present (indirect costs). The materials and workers needed depend on the type and amount of activities needed to built the design (direct costs). All these costs together are called the investment costs and this is amount of money the investor needs to cover with a loan. The investment needs the be payed off during the lifespan of the building. According to Oss (2007) the direct and indirect costs are 52,6% of the total investment costs.

Cost of the main load-bearing structure

Oss (2007) has researched the influence of the height of a high rise building on the investment cost. Table 5 shows that the load-bearing structure and floors thus have a share of 16% in the total direct and indirect costs. The cost for the load-bearing structure and floors grows with 10% to 15% each time ten floors are added to the structure. The load-bearing structure is thus an large cost factor, but how much does the cost change when another structural typology is used?

Table 5: The influence of different parts in a high rise building on the total direct and indirect cost (Oss, 2007).

Element	Share of total costs (direct and indirect)	Increase of direct and indirect cost per ten floors for that specific element per 10 floors
Foundation	2.1%	2%
Façade	17.8%	3% to 4%
Load-bearing structure and floors	16,3%	10% to 15%
Installation	25,2%	10% to 15%
Elevators	3,0%	15 to 20%
Other	35,6%	0

In the eighties in the Netherlands the cost for steel was 20% higher than for concrete. The cost for steel is only 35% of the total cost for the load bearing structure. Connections play a big role too and take up the other 65% cost for the load bearing structure. Estimated is that the load bearing structure is responsible for 15% to 20% of the total cost. This means that when steel was chosen over concrete as material for the load bearing structure, this heightens the total building cost for only 20% * 35% * 15% to 20% = 1.1% to 1.4% (Sterken & Timmermans, 1988; Hubar, 2009). The cost difference between concrete and steel is thus very little.

Changing the structural typology probably thus doesn't influence the cost a lot. Everything is however measured using cost. The cost of a building is connected to a lot of other factors, for example for the loan an investor has to take. This means a small difference in initial cost will decrease the amount of interest an investor has to pay. Even though the total cost might not differ a lot when another structural typology is chosen, it is still an important factor.

Direct costs

In this thesis the direct and indirect costs will be included, because these are directly influenced by the design. This thesis has taken a standard design and tries to compare these designs with each other. This means the land costs and the design costs don't play a role.

Direct costs are directly linked to the high rise structure and depend mainly on the type and amount of material that is used during construction. Table 6 shows the direct costs per floor type and Table 7 shows the direct costs per material.

Table 6: The floor cost per m^2 for the three floor types that will be used in this thesis.

Floor type	Floor thickness	Price [€/m^2]
Flat slab floor	315 mm	160
Hollow core slab	260 mm	152
Composite floor	160 mm	132

Table 7: The direct cost per material (including material, workforce and formwork).

Material	Element	Price [€/m³]
Cast in-situ concrete	Core	1 050
	Beams	875
	Columns	1400
Prefab concrete	Beams	900
	Columns	2 000
Steel	All steel elements	40 000
	Gypsum sheet	5 000

Indirect costs

Indirect costs are the cost for the building site (organisation and equipment). They can thus vary, depending on the location of a high rise building. The indirect costs are time-bound costs and thus depend on the construction time.
The indirect costs increase when a building becomes higher, because it takes more time to lift materials and people to the correct height. This so called increase in cost is called the *high rise factor.*

A cost expert from Arcadis has helped estimating these the indirect costs per month, including the belonging high rise factor (Bunk, 2020). Figure 7 shows four lines: two thick lines and two dotted lines, both in two colours. The thick lines (and the belonging shown formulas) are the indirect costs given by Arcadis for both cast in-situ concrete and steel (blue); and prefab (orange).
The dotted lines represent the thesis of Oss (2007). Oss stated that the indirect costs increase with 1.5% per floor. Using an assumed floor height of 3.8 m, the indirect costs estimated by Arcadis have been compared to this 1.5% increase per floor. At a height of 250 m the percental difference of the *blue line* by Arcadis divided by the *dotted blue line* by Oss is 105%. At a height of 250 m the percental difference of the *orange line* by Arcadis divided by the *dotted orange line* by Oss is 116%. This is a small difference that can depend on many factors that play a role in reality. There can thus be concluded that the indirect costs as estimated by Arcadis are correct and can be used later in this thesis.
To get the total indirect costs for a high rise building, the time-bound cost at the correct height from Figure 7 need to be multiplied with the construction time in months of that high rise building.
Table 8 shows which costs of the building site are included in the calculation of the indirect costs by Arcadis. As an example, the black dot in Figure 7 at 150 m height matches the total indirect costs shown in Table 8.

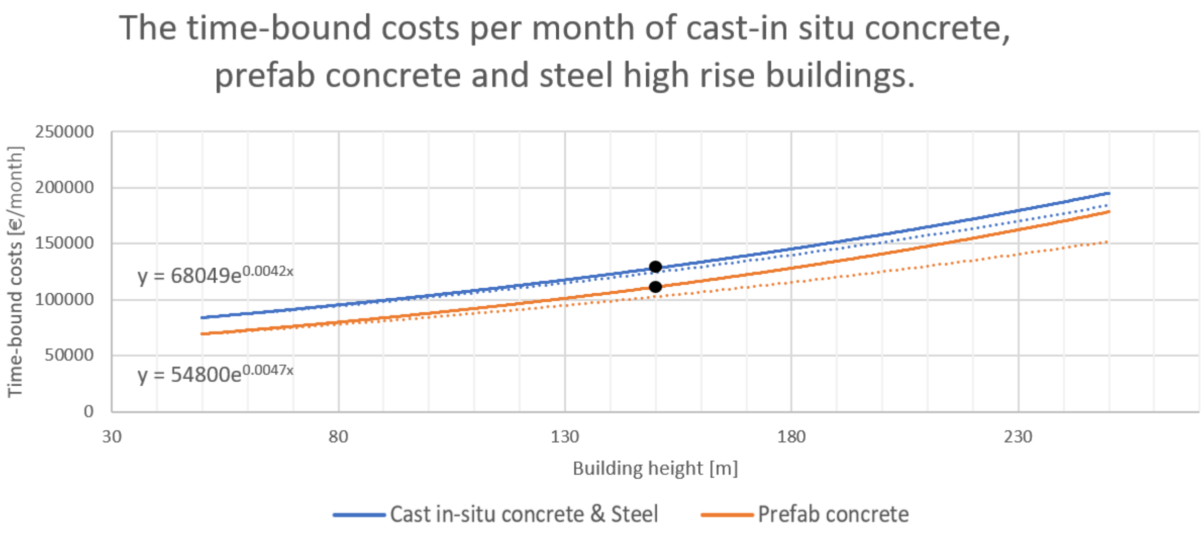


Figure 7: The time-bound costs per month for each building height and structural material. The thick lines (and the belonging formulas) are the indirect costs per month given by Arcadis (Bunk, 2020). The dotted lines are the indirect costs per month as stated by Oss (2007).

Table 8: The time-bound costs of a 150 m high building per month with a size of 30 m x 30 m and a floor height of 3.8 m; split in five subcategories. Assumed is that 4,2 weeks are *one* month (Bunk, 2020).

	Cast in-situ concrete & Steel	Prefab concrete
Construction site employees	€ 84 000	€ 63 000
Construction site services	€ 8 400	€ 8 400
Construction site arrangements and management	€ 14 700	€ 14 700
Transport and logistics	€ 14 700	€ 18 900
Temporary connections	€ 6 300	€ 6 300
Total	**€ 128 100**	**€ 111 300**

4.3. Sustainability

Lankhorst (2018) has already researched the impact of the structural design in high rise on the environment during his master thesis. In his LCA calculation he only included the production phase (green in Figure 8), not the construction, user and demolition phase (red in Figure 8). This means a cradle-to-gate assessment. The choice to include only the production phase was made to reduce the complexity of the calculations and compare more structural variations and also because there was only about the production phase accurate and reliable information available (information from the National Environmental Database).

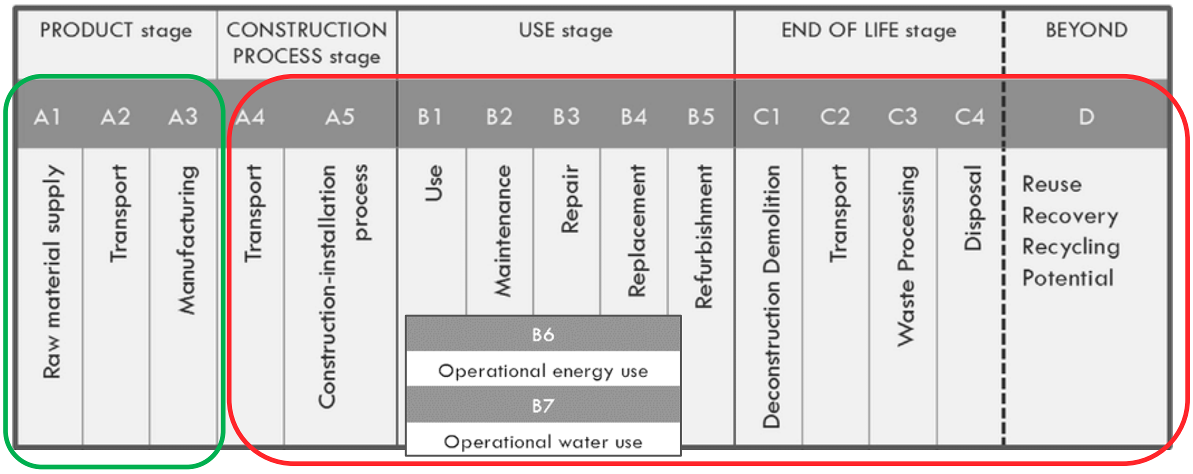


Figure 8: All the building phases in an LCA calculation (Wolf, et al., 2017).

The type of material and the amount of material used, determines how sustainable a building is. The sustainability can be expressed by taking the amount of material and multiplying it with the environmental cost of that material. The environment cost is the impact of a design on the environment, expressed in money.

Lankhorst (2018) has researched this by taking three building heights (150 m, 200 m, 250 m), five different types of stability systems – executed in cast in-situ concrete, prefab concrete or steel – and three different floor types. The core and the outriggers were always executed in cast in-situ concrete C35/45, while the other elements of the load-bearing structure could be executed in cast in-situ concrete, prefab concrete or steel. An overview of his researched models can be found in Figure 9. Eventually he calculated the environmental cost of each model.

Input

First, the basic measures of a high rise building were needed, to create a realistic total environmental cost. The measures of the used buildings of 150 m, 200 m and 250 m can be found in Table 9. These measures were based on existing hog rise buildings and were used to determine the amount of material that is needed to have a structurally working building.

Table 10 shows the structural materials Lankhorst has used and the belonging shadow price. In general, one

can state that the shadow price goes up, when the material becomes stronger.
Lankhorst has compared the stability systems from Table 11 with each other. He has compared several geometries of the stability systems to each other and eventually continued with the most sustainable one of each stability system. The most sustainable geometries are shown in the second column of Table 11 and the restrictions of each stability system in the third column.

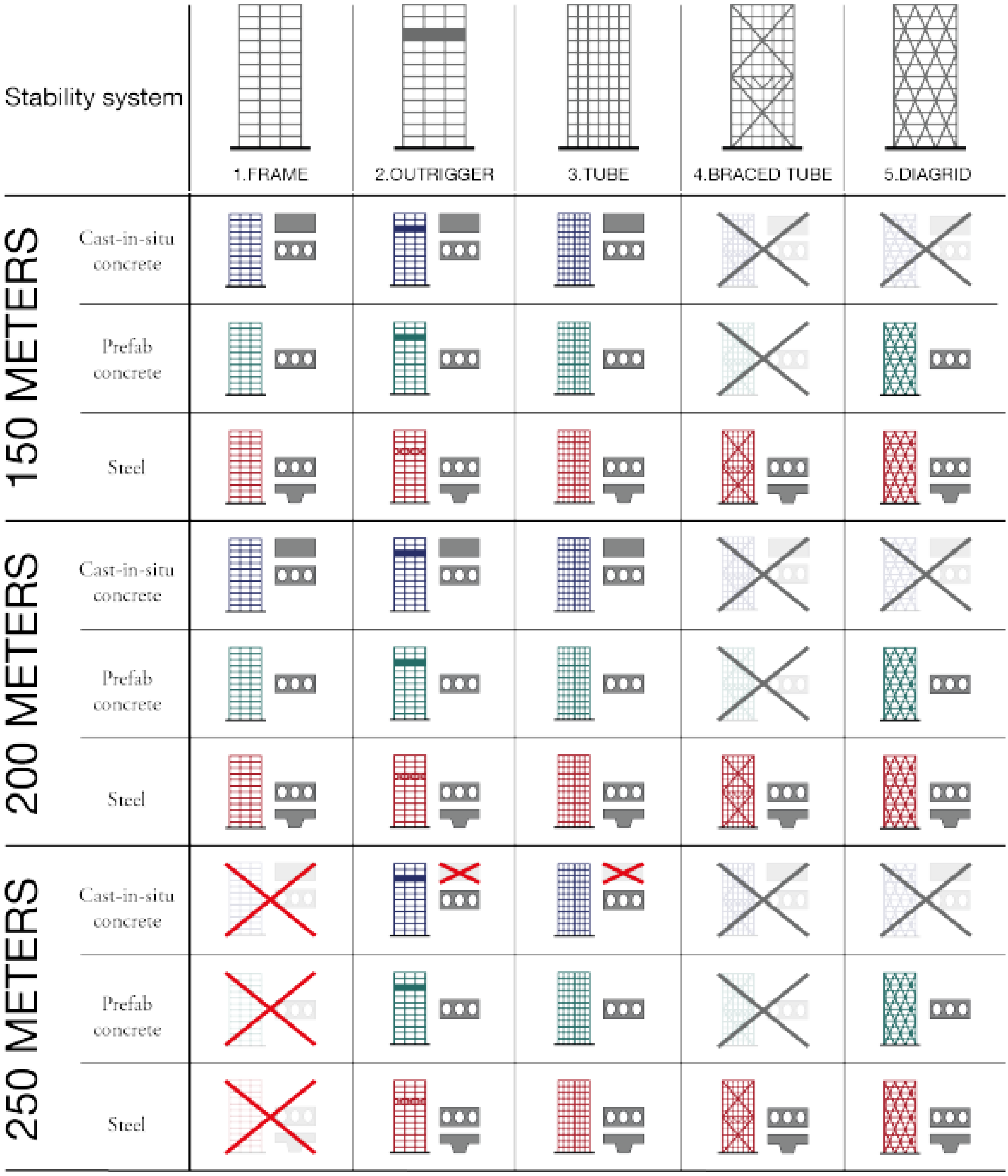


Figure 9: The variations Lankhorst (2018) used in his thesis (in the thesis on page 58). Grey crosses represent models that were excluded beforehand. Red crosses represent models that were excluded during calculations.

Table 9: The basic dimensions of the buildings of 150 m, 200 m and 250 m, used to calculate the measures of all the structural elements.

	Height	Width and depth	Slenderness	Core size	*If applied:* Outriggers

Building A	152.0 m	30.0 m * 30.0 m	5,1	12.0 m * 12.0 m	1
Building B	197.6 m	31.5 m * 31.5 m	6,3	13.5 m * 13.5 m	2
Building C	243.2 m	33.0 m * 33.0 m	7,4	15.0 m * 15.0 m	3

Table 10: The structural material types that are used for cast in-situ concrete and the reinforcement, prefab concrete and steel. The shadow price, used to calculate the environmental cost, is shown in the last column.

Structural material	Type	Density	Shadow price
Cast in-situ concrete	C35/45	2400 kg/m^3	0.00750 €/kg
Prefab concrete	C55/67	2400 kg/m^3	0,00898 €/kg
Steel	S355	7800 kg/m^3	0,06750 €/kg
Reinforcement	FeB500	7800 kg/m^3	0,24711 €/kg
Fire safety insulation	Gypsum sheet	870 kg/m^3	0.069241 €/kg

Table 11: The most sustainable geometries of each stability system are shown below, together with the limits of each stability system.

Stability system	Most sustainable geometry	Restrictions
Core + Rigid frame	8 columns per façade	Not above 200 m, because the profiles would become too large.
Outrigger	8 columns per façade 2 storey high outrigger in both directions Belt truss	Not above 200 m with flat slab. Flat slabs are heavy, so with cast in-situ concrete the profiles would become too large.
Tube: frame	11 columns per façade	Not above 200 m with flat slab. Flat slabs are heavy, so with cast in-situ concrete the profiles would become too large.
Tube: braced	11 columns per façade	Not in cast in-situ concrete or prefab concrete, because of constructability.
Tube: diagrid	71° angle for the trusses	Not in cast in-situ concrete, because of constructability.

Output

Lankhorst has calculated the total environmental cost of each buildings displayed in Figure 9. This information will later be used to create a tool (Chapter 8). In general, the following points can be taken from his research:

- Steel stability systems have 6% to 35% *higher* environmental cost than concrete stability systems.
- There is no difference in environmental impact between cast in-situ and prefab concrete.

The order of the five stability system based on the *lowest* environmental impact of concrete is as follows:

- Tube: diagrid — 17% to 41% lower than the Core + Rigid frame
- Outrigger — 5% to 26% lower than the Core + Rigid frame
- Tube: braced — 7% to 12% lower than the Core + Rigid frame
- Tube: frame — 5% to 11% lower than the Core + Rigid frame
- Core + Rigid frame

- Floors: are responsible for the main part (32% to 73%) of the environmental impact of the main load-bearings structure.

The order of the three floor types based on the *lowest* environmental impact is as follows:

- Hollow core slab () 17% to 26% lower than the Flat slab
- Composite floor () 14% to 18% lower than the Flat slab

- Flat slab ( )

- Between the heights of 150 m, 200 m and 250 m there are no large differences in environmental cost per m^2 gross floor area.

To conclude: a *concrete* building with as stability system '*Tube: diagrid*' and *hollow core slabs*, would be the most sustainable. Only *prefab concrete* is an option in case of a '*Tube: diagrid*', because cast in-situ is not possible from a constructible point of view (see *Restrictions* in Table 11).

4.4. Conclusion

This chapter provided an answer to the research question: *Which project starting points influence the structural material choice?*

Out of the ten potential project starting points, two project starting points will be further used in this thesis: cost and sustainability.
Cost was chosen, because all other goals and requirements are often expressed in cost. Only direct and indirect costs will be taken into account, because these are directly influenced by the design. Direct costs are directly linked to the high rise structure and depend mainly on the type and amount of material that is used during construction. Construction time influences the indirect cost.
Sustainability was chosen, because this starting point will become more and more important in the future. Environmental cost will be used to express the sustainability of a high rise building. The thesis of Lankhorst (2018) will be used to calculate the total environmental cost of different structural typologies and structural materials. The assumptions and limitations Lankhorst used, are also used by this thesis, so that extra calculations can be added to his existing work. An important limitation is that only the production phase is included in the calculations of sustainability.

5. Differences between theory and practice

From the literature several differences between the theory of the basic design cycle and the design process of several high rise projects in the Netherlands were found. These differences will be discussed below and tested in Part B of this thesis by using interviews.

5.1. Difference 1: *Disproportionately less steel.*

Table 4 lists only three high rise buildings above the 120 m that have steel in the stability system (Rembrandt Tower, World Port Centre, Carlton). Most other buildings with steel in the main load-bearing structure are lower than 70 m. The following remaining buildings in the Netherlands containing steel, with a height of 70 m to 120 m, were found:

- *EPO, Rijswijk, height: 107 m*
  EPO (Europees Octrooibureau) is an office building, that consists of a steel structure combined with Slimline-floors. It is an oblong shaped building with two concrete cores and six steel trusses in the short direction (four near the cores and two near the end). They chose steel (high strength) because it’s light, has high construction speed and results in a flexible floor plan (Robbemont, 2019). The construction time was 48 months with a gross area of 85 800 m^2 (Knudsen, 2018).
- *Blaak 555, Rotterdam, height: 107 m*
  Two steel outriggers are connected to the concrete core (Kraus & Wiltjer, 1996; Anon., 2013).
- *Castalia, Den Haag, height: 104 m*
  The steel frame with the concrete floor turned out to be strong enough to be reused (Bouwen met staal, n.d.).
- *Viñoly Mahler 4, Amsterdam, height: 95 m*
  Two concrete cores and a steel frame (Architectuur centrum Amsterdam, 2004).
- *Stadskantoor, Utrecht, height: 94 m*
  This building has two towers and one of these towers (the South tower) is built above a train station. The North tower contains concrete cores, while the South tower is completely made of steel. The steel structure in the South tower transfers all the loads to the concrete cores in the North tower, which are responsible for the stability of the whole building (Hoorn, n.d.).
- *Oval toren Amsterdam, Amsterdam, height: 94 m*
  The office tower is mainly made with prefab concrete, but the outriggers are steel (Zonneveld ingenieurs, 2001).
- *Blaak 8, Rotterdam, height: 70 m*
  This building is made of concrete, but it has a cantilever that is strengthened by five steel frames. These frames are designed in a way that they support the stability of the building (Ingenieurs, n.d.).

Concluding: out of the total of 154 high rise buildings (higher than 70 m) in the Netherlands, only 10 (that’s 6.5%) use steel for a large part of the main load-bearing structure (Zandbelt, et al., 2008).

The remaining question: *is the little use of steel a consequence of objective comparison of structural materials; or is it preference for concrete?*

5.2. Difference 2: *Reasoning behind design decisions.*

The literature of high rise projects in the Netherlands mentions the chosen structural material and the main load-bearing structure, but often there is no mention of the decision-making process. Arguments for a certain decision are named, but it is not clear how the comparison exactly happened or if a comparison was performed at all. This gives the impression that not all options are compared or that the comparison isn’t written down.
Of the high rise buildings mentioned in Table 4 only the Jubi-torens and the Rembrandt Tower showed a comparison of different materials in the found articles (Linde, 2011; Holla, 1995). De Rotterdam did compare options, but eventually the building method of the contractor was the deciding factor, according to the articles.

Preferences might also play a role in the decision-making process. Preference for a certain material or knowledge about a certain material, influences the design choices. The developer, architect, structural engineer and contractor can all influence this choice. When a preference and the reason for it are not clearly stated or written down, it can also make the decision-making process less objective. Examples of preferences from the literature:

- With the design of the Rembrandt Tower and the Breitner Center, the developer already had a preference to use steel, because it's light-weighted and has a fast construction speed. Naturally this resulted in a steel structure (Groot, 2000).
- Both architects of De Kroon and First Rotterdam didn't want a tube as stability system. In the end De Kroon used shear walls and the First Rotterdam used an outrigger in one direction and shear walls in the other direction to maintain the stability of the high rise (Hendriks & Middelkoop, 2012; Arts & Luttmer, 2014).
- The Strijkijzer was originally designed in cast in-situ concrete, but together with the contractor this was turned into prefab concrete to increase the construction speed (Freide, et al., 2006). The Zalmhaventoren is being built by the same contractor and was also originally designed in cast in-situ concrete, but is now executed in prefab concrete (Freide, 2019). This contractor thus seems to prefer prefab concrete, while they also have the means to build with cast in-situ concrete.
- There are two mixed buildings with a concrete core and a steel frame (Rembrandt Tower and World Port Centre). Both are office buildings and designed by foreign architects. The Millennium is also designed by a foreign architect, but made of cast in-situ concrete. The Carlton is the only other mixed
- building, consisting of a core with steel outriggers.

The high rise buildings that were researched using literature, all emphasized the main argument for which a certain material was chosen. The reasoning behind this argument was not emphasized.

In the theory of the Basic design cycle the comparison takes place in the second and third step: Synthesis and Simulation. In the Synthesis step it is important that *all possible solutions are generated*. In practice it can happen that not all options are written down, but a selection is made beforehand (conscious or unconsciously).
In the Simulation step the design team checks which possible solutions meet the requirements. These requirements were stated in the first step (Analysis). When comparing solutions to these requirements the reasoning for accepting of declining a solution needs to be clear (weather with an objective comparison or based on experience). Important in this whole process is that everything is written down, so that everyone in the design team can understand the reasoning and later in the process the design team can come back to earlier made decisions.

The remaining question: *is deviating from the comparison method described in the Basic design cycle a problem?*

5.3. Difference 3: *Building methods of contractors*.

Contractors are not only involved in the execution phase of a project, but also in the design process of a project. Especially the building method and the belonging structural material are important to them – because in the end they need to be able to work with the chosen building method – and these are established in the design phase.

The following examples of contractor involvement and the difficulties were found in the literature:

- In the case of Het Strijkijzer, the final contractor got involved in the TO. The contractor was only confident to execute in prefab concrete, so the design had to be revised to go from cast in-situ concrete to prefab concrete, very late in the design stage.
- In the case of the Cooltoren, multiple contractors tried to meet the budget of the developer. When they couldn't, the next contractor tried it. When they could, they had a preference to build in a certain way (because this is what their production is aimed at). Asking them to change this would result in unnecessary higher cost.
- De Rotterdam also had multiple contractors tried to meet the budget of the developer. The structural material in the design was, together with the contractor, adapted to the building method of the

contractor. Once a contractor was found that met the budget requirements of the contractor, the structural material of their preference became the finally chosen structural material.

Contractors are thus involved in the design process, because it influences their building method. How well the contractor can execute the chosen building method, determines the cost that contractor makes and the risk that contractor takes. A contractor will influence the structural material choice to fit a their building method. So *why* contractors are involved is clear, but the only remaining question is: *how are contractors involved in the design process of a high rise building*?

5.4. Difference 4: *Arguments and expectations don't match reality.*

An argument to choose prefab, based on common knowledge and experience, is that prefab has a shorter construction time than cast in-situ concrete. However, when Table 4 is sorted on construction time (Figure 10), it shows that the structural material does *not* seem to be linked to the construction time.
Figure 11 shows the construction time per m height, which also shows the structural material in random order. Taking into account the building height thus changes nothing in the complete order of high rise buildings from Figure 10.
Figure 12 shows the buildings sorted from shortest construction time per m^2 gross area, to the longest. This changes the complete order of the buildings drastically, compared to Figure 10 and Figure 11, because some buildings contained low rise next to the tower (see column 'all building parts' in Table 4). There is however still no link between the structural material and the construction time per m^2.

We can conclude that not the structural material, but something else is normative for the construction time. The building method is often mentioned as an important factor linked to the structural material. The remaining question: *is the building method more important than the structural material for the construction time of a high rise building?*

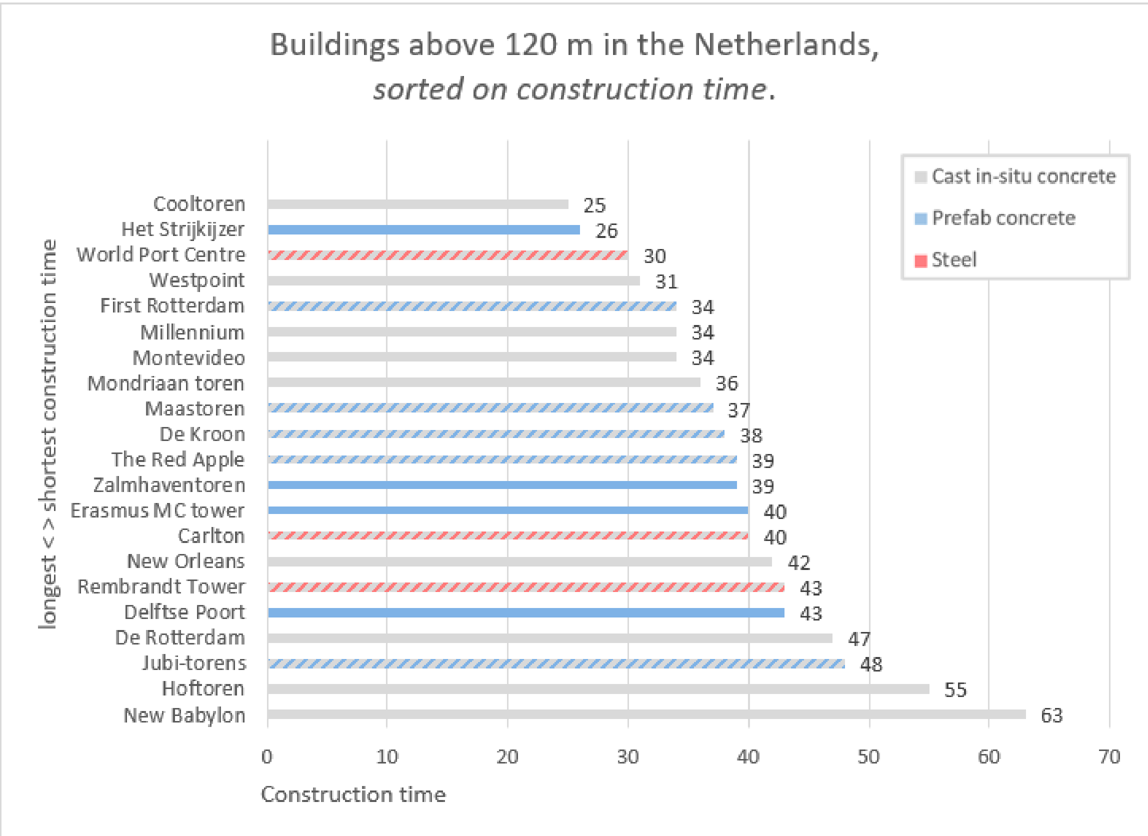


Figure 10: The construction time (in months) of the buildings in the Netherlands above 120 m.

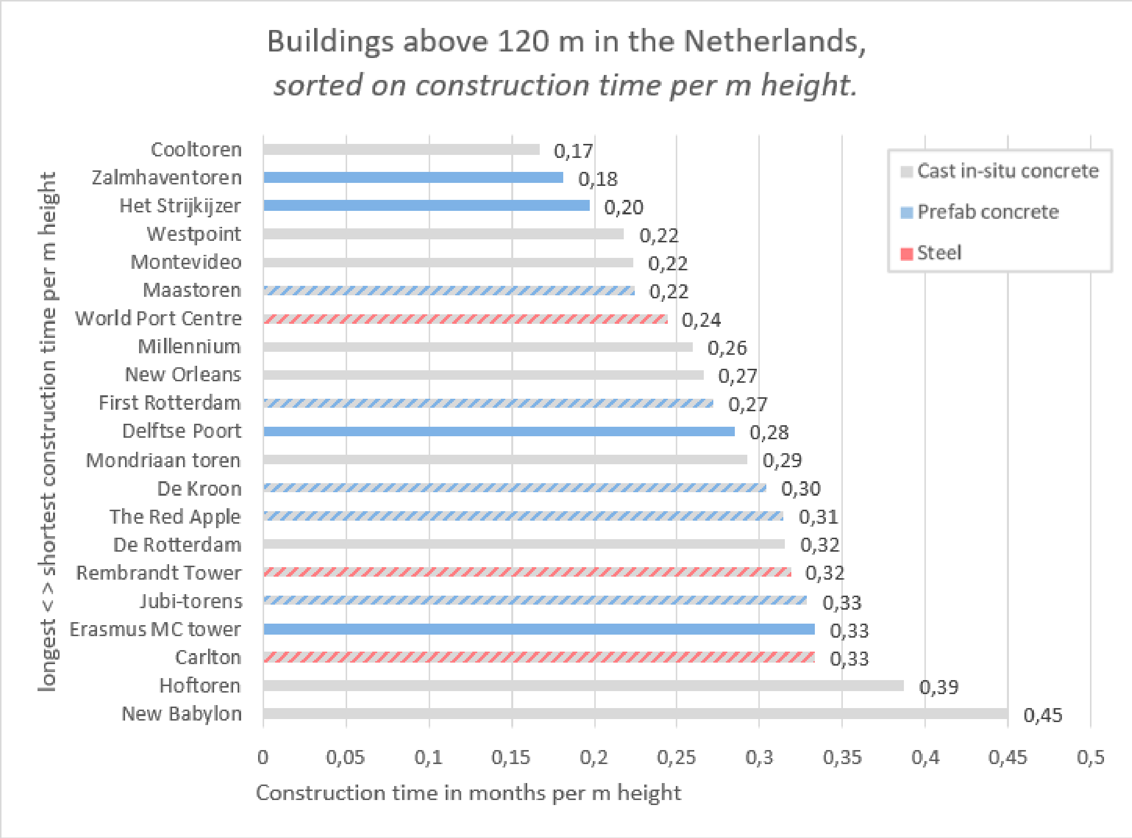


Figure 11: The construction time (in months) of the buildings in the Netherlands above 120 m. The buildings are sorted from shortest construction time per m height to longest.

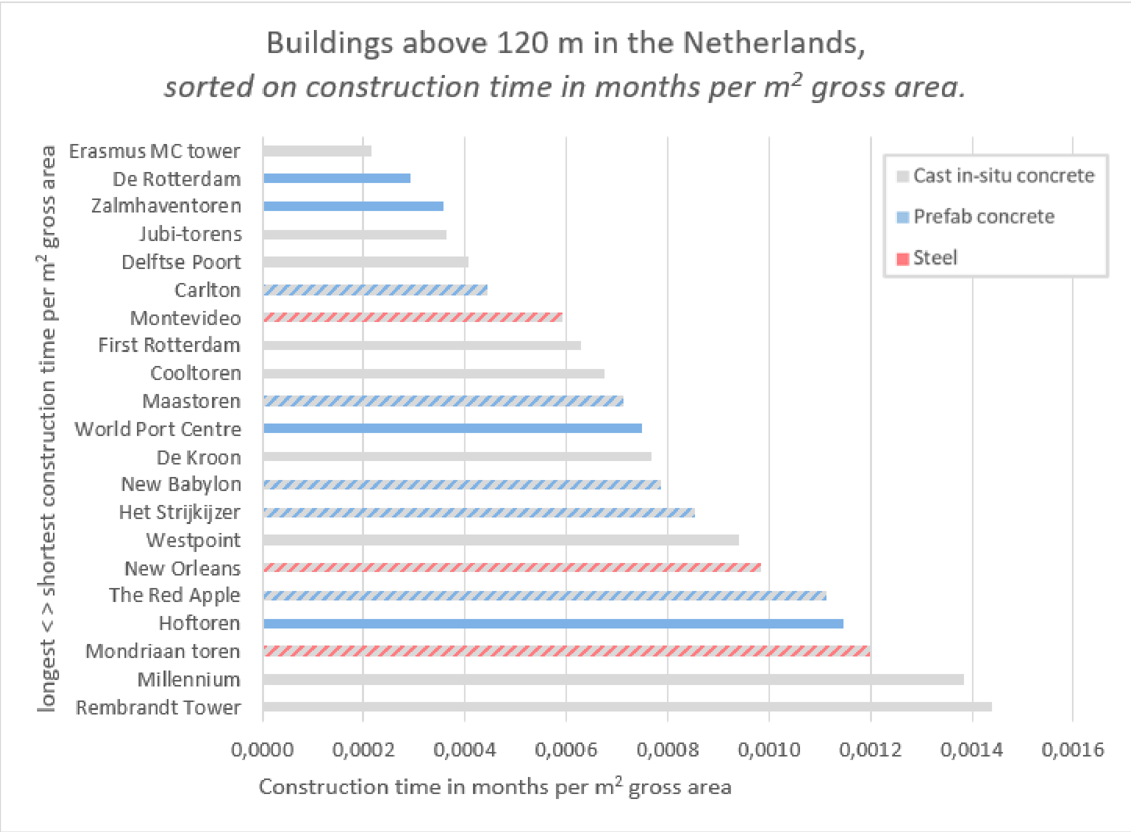


Figure 12: The construction time (in months) of the buildings in the Netherlands above 120 m. The buildings are sorted from shortest construction time per m^2 gross area to longest.

5.5. Conclusion

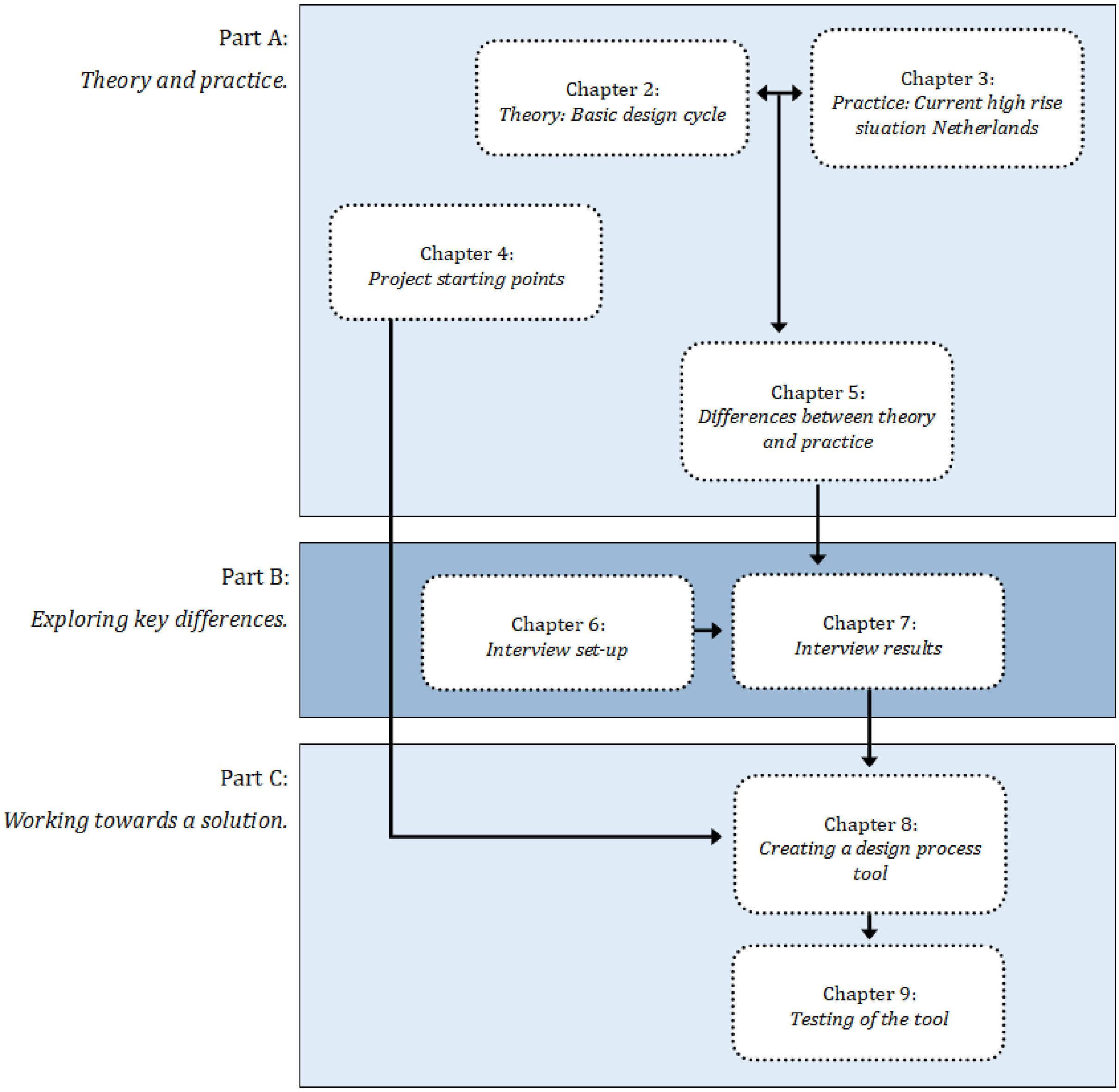
This chapter provided an answer to the research question: *Where lie the expected differences between the structural material choice process in theory and in practice?*

Four differences between theory and practice were found:

- Almost no steel is used for high rise buildings in the Netherlands. Is the little use of steel however a consequence of objective comparison of structural materials; or is it preference for concrete?
- The decision-making process in practice appears to deviate from the theoretical Basic design cycle. Not always all possible options are considered; and preference and experience play a large role in the decision-making process. The problem is that the reasoning behind the used arguments is not always made clear. Is deviating from the comparison method described in the Basic design however cycle a problem?
- The contractor is not only involved in the execution phase, but also in the design phase of a project. Their involvement is caused by the fact that the structural material choice influence their building method. Why contractors are involved is clear, but *how* are contractor involved in the design process of a high rise building?
- The argument that prefab concrete always has a short construction time doesn't seem to match reality. In reality the structural material appears not to be linked to the construction time. Might the building method then be more important than the structural material for the construction time of a high rise building?

PART B:

EXPLORING KEY DIFFERENCES



6. Interview set-up

To see why and how the differences between theory and practice – described in Chapter 5 – are caused, interviews were held with structural engineers and a few contractors. These members of the design team were chosen, because the structural engineer initiates the structural material choice process and the contractor often has a final say in the structural material choice, because it influences the building method. Interviews were chosen as research method, because the decision-making process is a human process and interviews can shed a light on why and how things are done a certain way.

6.1. Research method

The goal of the interviews was to get insight in the structural material choice process and to see where the theory of the Basic design cycle deviates from practice. To understand the structural material process, the follow questions needed to be answered:

- How is the structural material currently chosen?
  Why?
- Is it a problem that the structural material is currently chosen like this?
  Why?
- Which other ways to choose the structural material are there?
  Are these better?

Figure 13 shows the interview set-up. First, four orientation interviews with open questions were held about some of the high rise buildings in the Netherlands (Cooltoren, Het Strijkijzer, Millennium, De Rotterdam). The questions mentioned above – together with the differences between theory and practice from Chapter 5 – were guiding the orientation interview questions. The goal will be to understand the structural material choice process and get more insight in the differences between theory and practice from Chapter 5. The second goal was to check and shape the questions into a multiple-choice format.
Next, this multiple-choice format was sent twenty experts to see if the presumed material choice process was right and supported by multiple people in the building sector. Follow-ups on the survey were conducted to ask more about the reasoning behind some of the results.

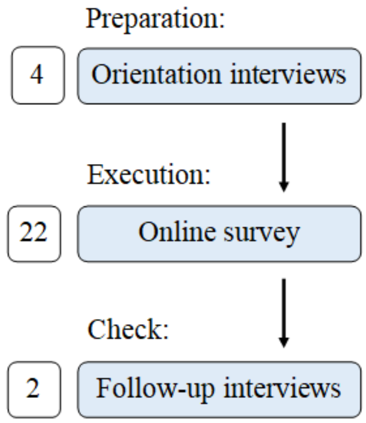


Figure 13: The interview set-up consist of three stages

6.2. Types of interviews

The details of the three stages in the interview set-up will be further elaborated below.

Orientation interviews

Appendix B shows the questions asked during the orientation interviews. Two structural engineers and two contractors were interviewed, to see the difference in perspective and to see if other questions needed to be asked to these two different parties in the design process. Because all parties were Dutch, these interviews were conducted in Dutch. After that, the conversations were summarized in reports, that were typed in English. These can be found in Appendix C.

Online survey

The Appendix D shows the questions asked in the survey. Eighteen structural engineers and four contractors answered the survey. All these twenty-two people worked on at least one high rise building, which – following the paper of Meuser & Nagel (2009) – makes them experts on high rise. They all specifically filled in the online survey with one of their high rise projects in the back of their mind.
Ten of these experts were involved in high rise buildings above 120 m in the Netherlands, which gives a response rate of 45% for high rise buildings above 120 m in the Netherlands. When these twenty-two

experts are compared to the total of 154 high rise buildings in the Netherlands, this gives a response rate of 14%. The results of the complete survey can be found in the Appendix E.

The online survey was used to get a quick opinion of a lot of experts about the differences between theory and practice found in the structural material process. Also, some points stated earlier in this thesis, were confirmed during the orientation interviews and in the online survey:

- It is confirmed by the orientation interviews and the online survey that at the beginning of a project, *project starting points* are established. The developer is leading in setting these goals and requirements. Cost is most often named as a project starting point, as already expected and explained in Chapter 4. Sustainability is mentioned as a project starting point, when future developments are addressed.
- Prumpeler (2019) confirmed that the stuctural material is always chosen early in the design process, because it is a fundamental choice. The online survey confirmed that in 65% of the projects, the structural material was chosen in the Design as a sketch (SO) or the Preliminary design (VO) stage.
- Prumpeler (2019) also confirmed that the function housing results in a concrete building. Building with housing as a function have a lot of walls and when these walls are made of concrete, they meet the sound insulation requirements without extra measures needed.

Follow-up interviews

To check results of the online survey two follow-up interviews with two employees of Arcadis were held. No outstanding results came out of these interviews.

6.3. Reflection on research method

Interviews are used as research method to explore the differences between theory and practice of the design process of high rise buildings in the Netherlands. The chosen research method has certain limitations which can be reflected upon. The Reflection cycle of Korthagen (1985) will be used to structure the reflection. First the chosen research method (Interviews) will be discussed (Step 1); next the execution of that method (Step 2); then the results and aspects of the chosen method (Step 3); and finally attention points for the rest of this thesis and future research will be discussed (Step 4).

Step 1: Action

Interviewing was chosen as research method, because the decision-making process of high rise buildings is a human process and interviews can shed a light on why and how things are done a certain way. A semi-structured and structured interview approach have been combined (McLeod, 2014).
The Orientation interviews used a semi-structured interview approach, where the follow-up questions are adapted to the answers of the interviewee on the first couple of questions. The advantage is that the questions are flexible, can be adapted to the given answers and this can result in unexpected new insights (Barriball & While, 1994).
The Online survey used a structured approach, where a set list of questions is used. The advantage is that there is control over the answers, which results in an easy analysis of the results and a clear conclusion. When a structured approach is used, large numbers of participants result in a clear and substantiated conclusion.
By combining both interview approaches, the advantages of both methods have been utilised.

Step 2: Looking back on the action

The interviews were used to gain insight in the actions of the design team and the reasoning behind the actions. The focus was on the structural material choice, because this is a difficult design decision that occurs early in the design process. The structural material however is connected to many conditions and other decisions, which made it difficult to disconnect the questions about the structural material choice from the rest of the design process.

As anticipated, the questions changed while performing the Orientation interviews. At the end of the Orientation interviews a clear format for the Online survey was created. When the Online survey was held however the results came back with still a lot of remarks. This meant an analysis of the results was difficult and the given remarks needed to be interpreted and processed.

Another problem was that it was difficult to find structural engineers and contractors that build high rise buildings above (70 m). During the whole interview process twenty-six experts – all of which have helped design at least one high rise building – have been questioned. When these twenty-two experts are compared to the total of 154 high rise buildings in the Netherlands, this gives however a response rate of only 14%.

Step 3: Awareness of essential aspects

From the former two steps, the following aspects can be taken:

- The structural material choice is *one* of many design decisions that is important for high rise buildings. The interviews focus mainly on the structural material choice under the assumption that this design decision is an important one. It is however important to stay focused on the *complete* design process, because deviation from the Basic design cycle can occur everywhere in the design process.
- A difficult aspect of interviews is that the course of the questions changes during the process, because of newly gained knowledge. The uncertainty that comes with this aspect of interviews can be eliminated by having a bulk amount of people participate. In practice this proved to be difficult, because (1) there are not many structural engineers and contractors that have built a high rise building and (2) these structural engineers and contractors need to be willing to participate.
- Interviewing is a research method that is based on opinions. The answers of the participants are influenced by their opinion, experience and knowledge. This means the results can't be seen as an objective truth. This is a disadvantage of the research method, that needs to be kept in mind when analysing the results. The advantage still remains that insight in the reasoning behind certain decisions is gathered.

Step 4: Creating alternative methods of action

This thesis has chosen the structural material choice as focus, but while performing research after this design decision is it important to keep the complete design process in mind.
After this research is finished, the results need to be reviewed while bearing in mind that a limited amount of structural engineers and contractors participated in the interviews. Also, the results are opinions from experts in the field, but these opinions do not represent an absolute truth. The conclusions that come out of these interviews can however still indicate interesting points for future research.

6.4. Conclusion

This chapter provided an answer to the research question: *What research method can be used to research the differences between the structural material choice process in theory and in practice?*

Interviews were chosen as research method, because the structural material choice process is a human process and the people in the design team can elaborate on why or how certain things were chosen. The interview set-up contains three stages: orientation interviews, online survey and follow-up interviews.

After reflecting on choosing *Interviews* as research method, the following aspects that need attention regarding the chosen methodology were summed up:

- The focus of this thesis on the structural material choice process needs to be placed in the context of the *whole* design process of a high rise building.
- The conclusions from the interviews and the rest of this thesis can be used as triggers for future research, but one needs to keep in mind that a limited amount of structural engineers and contractors participated in the interviews; and that *Interviewing* is a research method that is based on opinions and thus doesn't represent an absolute truth.

7. Interview results

Chapter 5 stated four differences between theory and practice arising in the design process of high rise buildings in the Netherlands. Interviews have been used to research these differences in depth. The resulting detailed analysis can be found below. In the end the difference(s) that can be addressed with a tool will be chosen, to be further used in Part C of this thesis.

7.1. Difference 1: *Disproportionately less steel.*

None of the buildings discussed during the orientation interviews uses steel. Steel is often briefly considered, but then rejected. After introducing the option of steel during the interviews, the first response was often that steel just doesn't work or isn't a common option to consider.
After that first response, several reasons why came up. The first reason is that the fireproof coating of steel is expensive and time consuming. Also, the cost of steel itself is more unpredictable. Another reason is that we just don't have the experience in the Netherlands to build withs steel. It is not the tradition here; steel is American. Often only several options in concrete are considered (cast in-situ and prefab concrete).

The online survey confirmed this issues of almost no use of steel. Steel is considered in 55% of the comparisons, but steel is often not chosen, because: applying fireproof coating takes too much time and money; doesn't fit the design; or in the Netherlands we don't have the experience to build with steel.

During the follow-up interviews there was specifically asked if it is a problem that steel is underrepresented. The answer was no, but it will become more of an issue in the future, because sustainability will become more important (Borst, 2019; Kuypers, 2019). The thesis of Lankhorst (2018) shows however that steel is not more sustainable than concrete, as often is assumed. This thus coincides with Difference 3: *Arguments and expectations don't match reality*.

So the remaining question: *is the little use of steel a consequence of objective comparison of structural materials; or is it preference for concrete?*
The first argument that is often mentioned is that *steel isn't a common option to consider* and *in the Netherlands we don't have the experience to build with steel*. Secondly some reasons for not using steel are mentioned, but these reasons are not included in an objective comparison.

7.2. Difference 2: *Reasoning behind design decisions.*

The orientation interviews were used to try and find out how the structural material was chosen. Concluded can be that the structural material can be chosen in many ways, depending many project related factors (for example the type of project or the assembly of the design team). When asking the interviewees if they found the current decision-making process a problem, they replied: it is a partially objective, partially subjective process, but this is not a problem.
For example, the experience and preference of contractor and their building method were leading in the final choice for the structural material of the Cooltoren. Prumpeler (2019) doesn't think this is a problem, because going against the contractor, would result in an inefficient design.

The method that is used to compare several design options to each other is thus not the problem. However, reason behind the partially objective, partially subjective process is further researched in the online survey. The online survey also asked how the structural material was chosen during the high rise projects of the interviewees. In the online survey 58% answered that the structural material was chosen based on a comparison of options. By using two statements, the reasoning behind this answer was checked. It turned out that the comparison isn't as structured as one might think. Things like preference of the developer or the building method of the contractor also play a role. The other 42% already indicated that experience plays a large role and that experience is partially objective, partially subjective, depending on how the process exactly goes.

During the follow-up interviews there was specifically asked if the subjective process and the lack of comparison based on numbers is a problem. As the online survey already stated: it is not a problem.

However, during the follow-up interviews, structuring the design process came up as a thing that might help to improve the process.

The remaining question: *is deviating from the comparison method described in the Basic design cycle a problem?*
The fact is that during the design process the Basic design cycle is often not completely followed. Preferences and experience often intervene and the arguments based on preference and experience are not written down. From the interviews however can be concluded that '*this is not a problem, because it is the way reality works'*.

7.3. Difference 3: *Building methods of contractors.*

Sometimes there is one contractor, sometimes there are multiple contractors involved. The contractor is always involved in the design stage, because the contractor needs to confirm that it is a design they can built. This means the design and the chosen structural material only become final after the contractor has been involved.
Contractors are in the end responsible for the construction of the building and this entails risks. Contractors have invested in a certain building method for years and it's too costly to deviate from that building method. Contractors are stuck with their building method and the belonging structural material: often concrete in the Netherlands.

From the four orientation interviews, the following two statements were created:

- The structural engineer starts with a comparison of all/some options and comes up with a preferred structural material based on factual arguments. Based on this, the search for a contractor is started.
- Potential contactors try to meet the requirements of the developer with their offer. If they succeed, the contractor is hired. It might be that the contactor doesn't match the structural material conceived in advance. The structural material is in that case adapted to the building method of the contractor.

The first statement was confirmed by 60% of the people that answered the online survey. The people that didn't agree, gave as reason that the comparison is sometimes influenced by preferences or based on experience.
The second bullet point was confirmed by 52% of the people that answered the online survey. The people that didn't agree, gave as reason that the contractor can't make a lot of demands, because he must meet the requirements and the money that the developer made available. Because high rise buildings are difficult, it will become harder for contractors to meet the stated requirements and the requirements need to be drafted in mutual consultation. Also, if multiple contractors are available to build the project, the power of the contractor over the design reduces. High rise projects are difficult and not a lot of contractors dare take the risk. Both arguments result in the fact that projects – like high rise building – that are hard to execute for a contractor give the contractors influence on the design, the structural material and the building method.

Follow-up interviews confirmed that the contractor play a big role in the design decision-making process, because they are in the end responsible to execute the building and need to accept the cost and risks that come with it. When multiple contractors can execute the design, this contractor involvement reduces.

The remaining question: *how are contractors involved in the design process of a high rise building*?
Contractors often have a preference for a certain building method, because their workers are used to building that way and investments in machines and materials are focussed on that building method. The building method is linked to the structural material, which means the contractor will try to influence the structural material choice. The influence of the contractor depends on the type and size of the project.

7.4. Difference 4: *Arguments and expectations don't match reality.*

The question that was asked to the interviewees during the orientation interviews and online survey: do the expectations match the reality? This is a difficult question, because after a project is finished, the results are not analysed and compared to the original idea. Also, when this issue was addressed, it turned out to be a difficult and easily biased topic. Everybody thought they did the best they could. It is not a completely objective process, because it involves more people and *subjectivity just plays a role in collaboration and communication*. Both Prumpeler and Meijer stressed that they tried to do what they can to choose the right structural material, but it is a team effort in the end. They take responsibility for their part in the design, but they can't change what others want or do.

In the literature the argument that prefab concrete has a shorter construction time than cast in-situ concrete, was refuted by Figure 10, Figure 11 and Figure 12. In an interview Freide (2019) said that prefab doesn't always have to be faster. It depends on the selected contractor and his building method. This confirms the conclusion drawn from the literature.

> *"If Het Strijkijzer was executed in cast in-situ concrete, by using tunnelling, it might have been built equally fast (as with prefab now)."*
> *– Interview J. Font Freide, 2019*

The remaining question: *is the building method more important than the structural material for the construction time of a high rise building?*
It is a difficult topic to confirm while using interviews and thus extra research using data needs to be done.

7.5. Summary of the differences

First a summary of the found differences is given in Table 12.

Table 12: A summary of the differences arising in the structural material choice process.

	Difference	Description
1	Disproportionately less steel *Is the little use of steel a consequence of objective comparison of structural materials; or is it preference for concrete?*	Steel is often not considered as structural material, because *'it is not a common option to consider'* and *'there is a lack of experience in the Netherlands to build with steel'*. After this first response some reasons for not using steel are mentioned, but steel is already discarded before these reasons are have been tested in an objective comparison.
2	Reasoning behind design decisions *Is deviating from the comparison method described in the Basic design cycle a problem?*	In practice the theoretical Basic design cycle is often not completely followed when comparing design options. Instead, arguments based on preference and experience are used, but the reasoning behind these arguments is not made clear. According to the interviewees this is however not a problem, because it is the way reality works.
3	Building methods of contractors *How are contractors involved in the design process of a high rise building*?	Contractors often have a preference for a certain building method, because their whole company is focussed on that certain building method. The building method is linked to the structural material, which means the contractor will try to influence the structural material choice during the design process of a high rise building.
4	Arguments and expectations don't match reality *Is the building method more important than the structural material for the construction time of a high rise building?*	Data about the construction time of the buildings in the Netherlands above 120 m shows that prefab concrete doesn't always have a shorter construction time than cast in-situ concrete. This refutes the commonly used argument that prefab concrete builds faster than cast in-situ concrete. It suggests that arguments that are commonly known and are used to choose certain structural materials, might not always be correct.

7.6. Optional solutions

Optional solutions to the four differences will be discussed below.

- In case of Difference 1 there are a reasons for not using steel, but a change in culture of the building sector can give design team more options for the structural material choice. Once steel becomes an option, objective comparison of structural materials can indicate which structural material is the most suitable for each high rise project.

- Difference 4 can be further researched by comparing the design to the reality, using case studies. A factual comparison of design and result might give clear answers as to why the construction time doesn't seem connected to the used structural material.

- Differences 2 and 3 can be addresses together, because they both find their origin in the fact that preferences based on experience are leading in the decision-making process.
  In case of Difference 2 the reasoning behind certain design decisions is not made clear and according to the interviews this is however not a problem, because it is the way reality works. This thesis however states that this reality can be accepted, but a tool might help to the structural engineer to quickly get more insight in the influence of the structural material choice on the project starting points. This way the structural engineer can quickly respond to the dynamics of the design process.
  In case of Difference 3, insight early in the design process in the wishes of contractors can make sure that a contractor that fits the design is more easily found and the design doesn't need to be adapted later on in the design process.

So, Difference 2 and 3 both emphasize that insight in early in the design process on the final result of a high rise project can help to improve the workability of the Basic design cycle. As a solution to these issues a tool can be created to give the structural engineer insight in the influence of the structural material choice on project starting points like cost and sustainability. Issues 2 and 3 will thus both be used in Part C of this thesis.

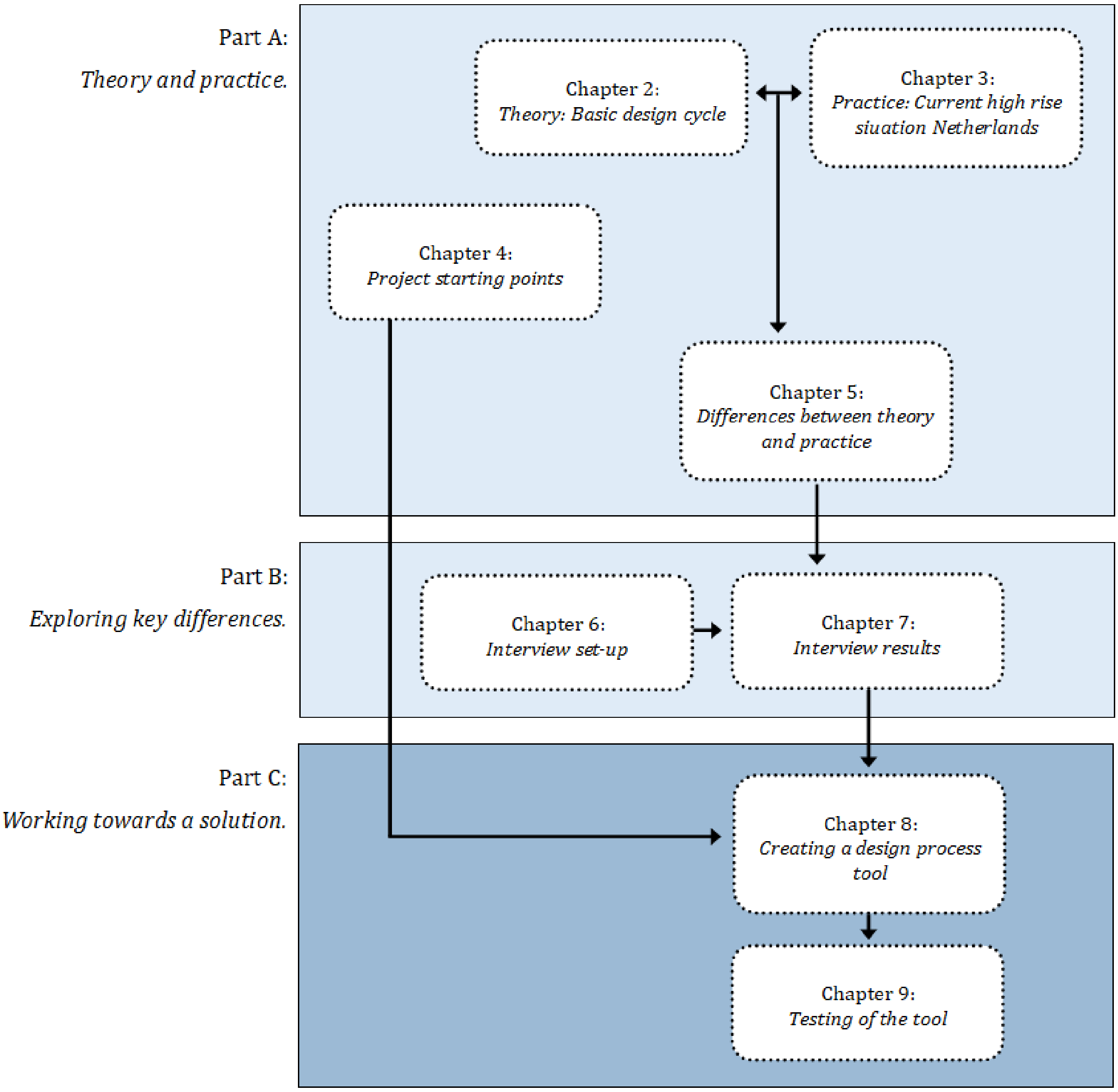
7.7. Conclusion

This chapter provided an answer to the research question: *Which differences can be addressed, using a tool?*

In Chapter 5 four differences between theory and practice, regarding the structural material choice were stated. These differences have been further research in depth using interviews and the results have been captured in *issues* and further discussed in this chapter.
Eventually Differences 2 and 3 were chosen to be used in Part C of this thesis. They are combined, because they both emphasize that insight in early in the design process can give the structural engineer a way to create a structured design process that follows the Basic design cycle.

PART C:

WORKING TOWARDS A SOLUTION



8. Creating a design process tool

Early in the design process it is difficult to see what the influence of certain design decisions on the result will be. The structural material choice is such a design decision, made early in the design process. To give the structural engineer insight in the influence of structural material on cost and sustainability, an excel tool has been created. This tool can be used by the structural engineer to see which stability system, structural material and floor type fits his or her high rise project best.

This thesis partially builds on the thesis of Lankhorst (2018) were he calculates how sustainable different structural typologies for high rise are. The goal of this thesis was to broaden the perspective by adding cost. Also the stability systems *Core* and *Shear walls* are added to make the research more applicable for the situation in the Netherlands.

8.1. Included parameters

The following output parameters will be included in the tool (these parameters and their limits were already explored in Chapter 4):

- Cost:
  Direct (material, workforce, formwork) and indirect (construction time and building site).
- Sustainability:
  Environmental cost (A1-A3 product stage).

Depending on the weight of the output parameters – given by the structural engineer – the most suitable structural typology and structural material will be shown. This includes a *combination* of:

- Stability system:
  Core, Shear walls, Core + Rigid frame, Outrigger, Tube: frame, Tube: braced, Tube: diagrid
- Structural material:
  Cast in-situ concrete, Prefab concrete, Steel
- Floor type:
  Flat slab floor, Hollow core slab, Composite floor

The twenty-six structural *combinations* of structural typology and structural material that will be shown as a result in the tool, are shown in Table 13. Some combinations were not included for the following reasons:

- *Core.*
  A steel core is very rare and never used in the Netherlands before. A steel core is thus not included in the tool, because the tool is aimed at the Netherlands.
- *Shear walls.*
  The steel alternative of shear walls would be steel trusses. These are however very rarely used in the Netherlands as stability system, especially combined with a concrete core. Steel is thus not included in the tool, because the tool is aimed at the Netherlands. Also, steel trusses connected to the core on every floor would make a building difficult to adapt.
- *Tube: braced.*
  Cast in-situ concrete has been excluded, because this would require complex formwork. Prefab concrete is possible, but excluded because it would require difficult reinforcement (Lankhorst, 2018).
- *Tube: diagrid.*
  Cast in-situ concrete has been excluded, because this would require complex formwork (Lankhorst, 2018).

Table 13: The structural typologies included in the excel tool.

Stability system:	Structural material:	Floor type:
Core		
1	Cast in-situ concrete	Flat slab floor
2	Cast in-situ concrete	Hollow core slab
3	Prefab concrete	Hollow core slab
Shear walls		
4	Cast in-situ concrete	Flat slab floor
5	Cast in-situ concrete	Hollow core slab
6	Prefab concrete	Hollow core slab
Core + Rigid frame		
7	Cast in-situ concrete	Flat slab floor
8	Cast in-situ concrete	Hollow core slab
9	Prefab concrete	Hollow core slab
10	Steel	Composite floor
11	Steel	Hollow core slab
Outrigger		
12	Cast in-situ concrete	Flat slab floor
13	Cast in-situ concrete	Hollow core slab
14	Prefab concrete	Hollow core slab
15	Steel	Composite floor
16	Steel	Hollow core slab
Tube: frame		
17	Cast in-situ concrete	Flat slab floor
18	Cast in-situ concrete	Hollow core slab
19	Prefab concrete	Hollow core slab
20	Steel	Composite floor
21	Steel	Hollow core slab
Tube: braced		
22	Steel	Composite floor
23	Steel	Hollow core slab
Tube: diagrid		
24	Prefab concrete	Hollow core slab
25	Steel	Composite floor
26	Steel	Hollow core slab

For each of the twenty-six *combinations* the cost and sustainability is calculated. The excel-tool will eventually show the top ten *combinations* with the lowest cost and sustainability. A top ten is chosen to give the structural engineer the option to explore what the influence of his or her design choices are on the final result and take the top ten structural *combinations* into consideration. Figure 14 contains a flowchart that shows all the calculations that are part of the excel-tool. All these calculations will be explained in the rest of this chapter.

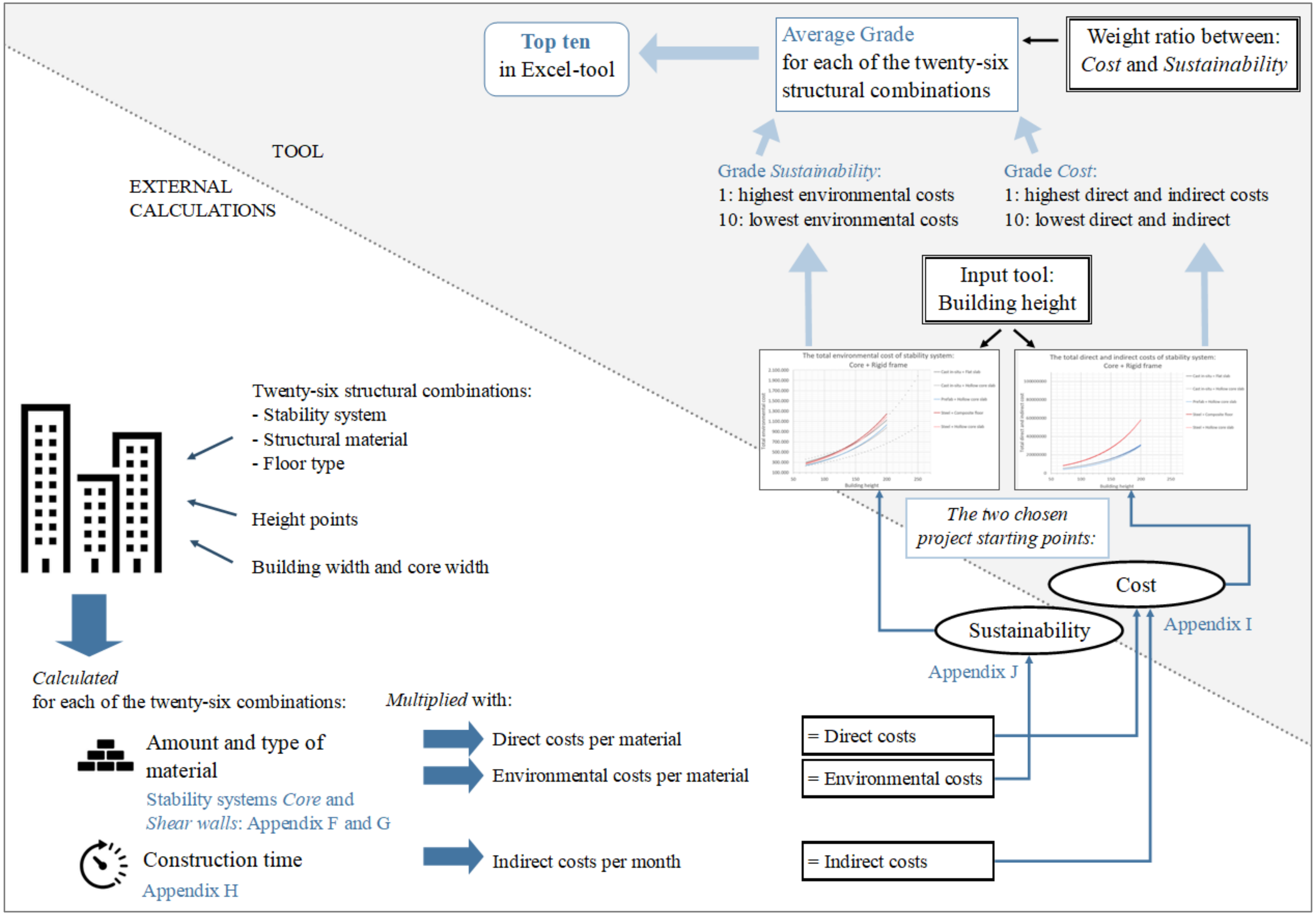


Figure 14: This flowchart shows all the external calculations that served at input for the excel tool (white area) and the calculation that are part of the excel-tool (grey area).

8.2. Measures and assumptions

The stability systems are limited to a certain height range (shown in third column of Table 14). Within this height range, several *height points* are appointed (the second column of Table 14). For each of the twenty-six *combinations* mentioned in Table 13 the costs (direct and indirect) and sustainability (environmental cost) is calculated for these building height points. The height points are the points that are used per *combination* to draw an exponential cost and sustainability line through, covering the height range.
Both the direct costs and environmental costs were calculated by using the total amount and type of material used. The indirect costs are calculated by using the construction time. The construction time is calculated, by using the book *Bouwplanning* (Flapper, 1995).

Table 14: The height limits for the calculations for each stability system.

Stability system	Height points	Height range	Reasoning
Core	50 m, 100 m, 150 m	50 m to 120 m	The *Core* is a stability system that is used for the lower high rise buildings, so that's why 50 m is chosen (instead of 70 m). During the calculations 120 m appeared to be the practical maximum height for a *Core* (Appendix F).
Shear walls	50 m, 100 m, 150 m, 200 m	50 m to 200 m	Shear walls is a stability system that is used for the lower high rise buildings, so that's why 50 m is chosen (instead of 70 m). During the calculations 200 m appeared to be the practical maximum height for a *Shear walls* (Appendix G).
Core + Rigid frame	150 m, 200 m	70 m to 200 m	From 70 m buildings are called *high rise*. Above 200 m the profiles of the building elements became too big.
Outrigger	150 m, 200 m, 250 m	70 m to 250 m	From 70 m buildings are called *high rise*. The upper limit of this thesis is 250 m.
Tube: frame	150 m, 200 m, 250 m	70 m to 250 m	From 70 m buildings are called *high rise*. The upper limit of this thesis is 250 m.
Tube: braced	150 m, 200 m, 250 m	70 m to 250 m	From 70 m buildings are called *high rise*. The upper limit of this thesis is 250 m.
Tube: diagrid	150 m, 200 m, 250 m	70 m to 250 m	From 70 m buildings are called *high rise*. The upper limit of this thesis is 250 m.

Both the direct costs and environmental costs will be calculated by using the total amount and type of material used. Lankhorst has already determined for *combination* 7 to *combination* 26 from Table 13 how much and what type of material is needed by performing a series of structural calculations to calculate the cross sections. This thesis has also performed a series of calculations for the *Core* and *Shear walls* (*combination* 1 to 6), to calculate how much and what type of material is needed. See Appendix F and G for these calculations.
Eventually the amount of material will be multiplied with the direct costs per material and the environmental costs per material. The indirect costs are calculated by multiplying the construction time with the indirect costs per month construction time. The construction time is calculated, by using the book *Bouwplanning* (Flapper, 1995) (Appendix H).

To get the total amount and type of material that is needed for each of the twenty-six *combinations*, the basic measures of a high rise building at each height point were needed. The measures of the used buildings of 50 m, 100 m, 150 m, 200 m and 250 m can be found in Table 9.
The assumed building width and core width are determined by Lankhorst (2018) and this thesis has adopted these values. Lankhorst based the core measurements on the existing buildings: First, Maastoren and De Rotterdam. The distance from the core to the façade is kept at 9 m for each building to meet the Dutch regulations for daylight entry. This results in the netto floor area percentages above 75% for each assumed building width, which ensures that the buildings are economically profitable (Sarkisian, 2016).

The measures in Table 9 were used to determine the amount of material that is needed to have a structurally working building.

Table 16 shows the structural materials that have been used. The core and the outriggers were always executed in cast in-situ concrete C35/45, while the other elements of the load-bearing structure could be executed in cast in-situ concrete, prefab concrete or steel (Lankhorst, 2018).

Table 15: The basic dimensions of the buildings of 50 m, 100 m, 150 m, 200 m and 250 m, used to calculate the measures of all the structural elements.

Height	Width and depth	Building slenderness	Amount of floors	Core size	Netto floor area
49.4 m	27 m x 27 m	1.8	13	9 m x 9 m	89%
98.8 m	28.5 m x 28.5 m	3.5	26	10.5 m x 10.5 m	86%
152.0 m	30.0 m x 30.0 m	5.1	40	12.0 m x 12.0 m	84%
197.6 m	31.5 m x 31.5 m	6.3	52	13.5 m x 13.5 m	82%
243.2 m	33.0 m x 33.0 m	7.4	66	15.0 m x 15.0 m	79%

Table 16: The structural material types that are used for cast in-situ concrete and the reinforcement, prefab concrete and steel.

Structural material	Type	Density
Cast in-situ concrete	C35/45	2400 kg/m^3
Prefab concrete	C55/67	2400 kg/m^3
Steel	S355	7800 kg/m^3
Reinforcement	FeB500	7800 kg/m^3
Fire safety insulation	Gypsum sheet	870 kg/m^3

8.3. Cost

This thesis considers direct costs and indirect costs (as discussed in Chapter 4). The direct costs are calculated by multiplying the cost per m^3 with the amount of that material. The cost per m^3 material has already been shown Table 7 in Chapter 4.
Lankhorst (2018) has calculated the type and amount of material needed in the twenty-six *combinations* from Table 13 (excluding the *Core* and *Shear walls*) in high rise buildings of 150 m, 200 m and 250 m high. This thesis has also calculated the type and amount of materials needed when only a *Core* or *Shear walls* is applied, because these are very common stability system in the Netherlands. The calculations and tables with the total amount of needed materials for a *Core* and *Shear walls* can be found in the appendix (Appendix F and G).
The resulting total direct costs of each of the twenty-six *combinations* can be found in Appendix I.

The indirect costs are influenced by the construction time, so the construction time is used as input for this type of cost. The calculation of the construction time for each of the twenty-six *combinations* from Table 13 – using the book *Bouwplanning* by H.A.J. Flapper – can be found in Appendix H.
The time-bound costs for each of twenty-six *combinations* are taken from Figure 7 in Chapter 4 and multiplied with the construction time (in months) calculated in Appendix H. The indirect costs can be found in Appendix I.

For each of the twenty-six *combinations* the direct and indirect costs have been calculated within the height ranges shown in Table 14, using the mentioned height points. The total amount of cost has been plotted in figures – using an exponential function through the height points – to be able to estimate the total cost of each *combination* on each height. Figure 15 is one of these plotted figures. In Appendix I all the figures are shown. These figures and their belonging formulas have been implemented in excel and can calculate which *combination* is the cheapest on each building height.

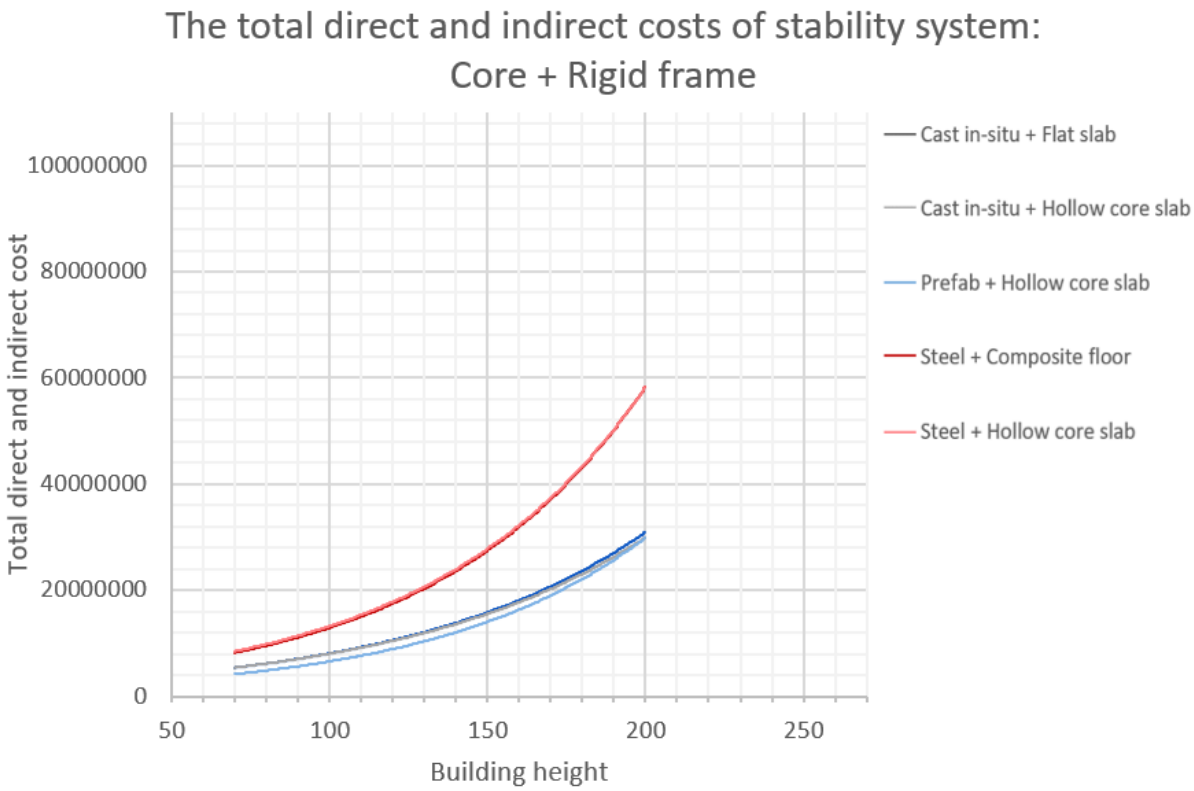


Figure 15: The total direct and indirect costs plotted against the building height for a Core + Rigid frame stability system.

8.4. Sustainability

Lankhorst (2018) has calculated the environmental costs of the twenty-six *combinations* from Table 13 (excluding the *Core* and *Shear walls*) in high rise buildings of 150 m, 200 m and 250 m high. This thesis also has calculated total environmental costs when only a *Core* or *Shear walls* are applied by multiplying the amount of material (Appendix F and G) with the environmental costs of that material. The results can be found in Appendix J

This thesis has taken all those results, plotted them in figures and has drawn an exponential function through them, to be able to estimate the total environmental costs of each *combination* on each height. Figure 16 is one of these plotted figures. In the Appendix I all the figures are shown. These figures and their belonging formulas have been implemented in excel and can calculate which *combination* is the most sustainable per building height.

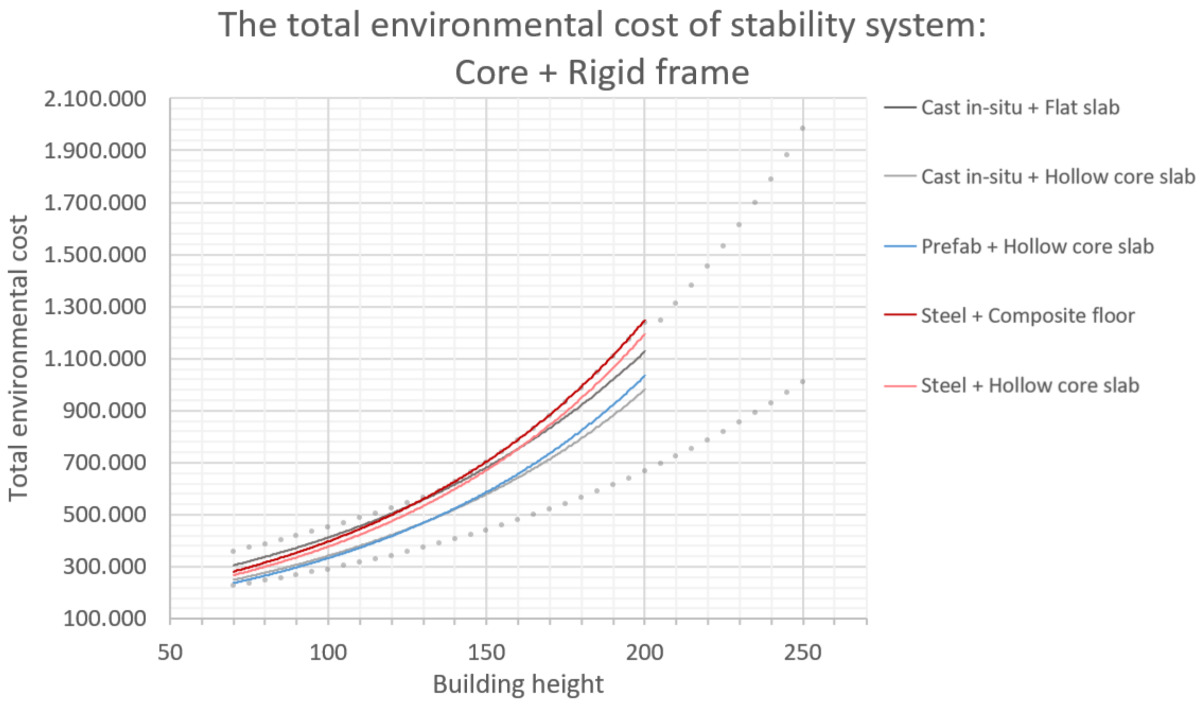


Figure 16: The total environment costs plotted against the building height for a Core + Rigid frame stability system.

8.5. Resulting interface

A tool has been created to give the structural engineer early in the design process of a high rise building to opportunity to compare different structural typologies to each other based on cost (direct and indirect) and sustainability (environmental cost). Excel is chosen as program for the tool, because it is an easy program to work with and most computer packages have excel, so no special licenses are needed.

As input only the height of the high rise project is needed (Figure 17, cell E20). The tool then shows the belonging assumed building width and core width on the right (cells J20 and J21). The assumed building width and core width are determined by Lankhorst (2018) and this tool has adopted these values. Lankhorst based the core measurements on the existing buildings: First, Maastoren and De Rotterdam. The distance from the core to the façade is kept at 9 m for each building to meet the Dutch regulations for daylight entry. This results in the netto floor area percentages above 75% for each assumed building width, which ensures that the buildings are economically profitable (Sarkisian, 2016).

Optionally, some of the stability systems, structural materials or floor types can be excluded (cells D28 to D30; cells D32 to D35; and cells F28 to F35). For example, when the function of you building is an office, you can exclude *Shear walls*.
If for example you find cost much more important than sustainability, you can include that in the tool in cells F41 and F42. The structural engineer can determine the importance – using a weight factor on a scale from 1 to 5 – of the two output parameters: cost and sustainability. Also, a zero can be chosen as a weight factor, if the structural engineer wants to exclude one of the two output parameters.

After the button "*(re)Calculate*" is pushed, a top ten combinations of stability system, structural material and floor type is shown (Figure 18). This top ten is determined as follows:
The cost and sustainability of each of the twenty-six *combinations* are calculated at the building height given as input by the structural engineer. Each of the twenty-six *combinations* then gets two grades (one for cost and the other for sustainability). This grade goes from 1 – the highest direct and indirect costs *or* environmental costs of the twenty-six combinations – to 10 – lowest direct and indirect costs *or* environmental costs of the twenty-six combinations. The average grade of each *combination* is calculated by taking the grade for cost and the grade for sustainability and taking the weight factor given as input by

the structural engineer into account. The best structural *combination* for that building height has the highest average grade.

The best combination is shown in dark orange in row 58. The grade in cell E58 can be compared to the other grades to see the relative difference with the other *combinations*. The *Combination number* in cell D58 can be found again in the sub-results below the output to see the exact direct and indirect costs and environmental costs that this tool calculated.
The sub-results of *Cost* are shown in Figure 18 and sub-results of *Sustainability* are shown in Figure 19. Each of these tables shows the complete ranking of the twenty-six *combinations* based on Cost and Sustainability.

When looking at the results, one thing stands out. The floor type influences the environmental costs for the biggest part. Hollow core slabs are the most sustainable, so when looking at the most sustainable solutions, solutions including hollow core slabs will always end up on top.

8.6. Conclusion

This chapter provided an answer to the research question: *How can a tool give insight in the relation between structural material, structural typology and the project starting points?*

The excel-tool aims to give the structural engineer early in the design process of a high rise building insight in the influence of the combination of stability system, structural material and floor type on cost (direct and indirect) and sustainability (environmental cost). Table 13 showed the twenty-six combinations of stability system, structural material and floor type included in the excel-tool. Each of these combinations has a certain height range and height points. The Cost and Sustainability of the twenty-six *combinations* is calculated on each of these height points. Next, an exponential function is drawn through the calculated Cost and Sustainability on these height points, covering the height range of the belonging c*ombination*.

The direct costs are calculated by multiplying the amount of material for each *combination* with the direct costs per material. The indirect costs calculated by multiplying the construction time for each *combination* with the indirect costs per month construction time.
The environmental costs have already been calculated by Lankhorst (2018) for all stability systems, except for a *Core* and *Shear walls*. This thesis has calculated total environmental costs of these two stability systems by calculating the amount of material needed and multiplying that with the environmental costs per material.

Eventually the results for all twenty-six *combinations* are plotted in figures by drawing an exponential function through both the calculated Cost and Sustainability at the given height points. These figures can then be used in estimating the total direct and indirect costs and environmental costs of each *combination* on each height. Finally, the figures and their belonging formulas have been implemented in excel and can calculate which *combination* is the cheapest and the most sustainable.

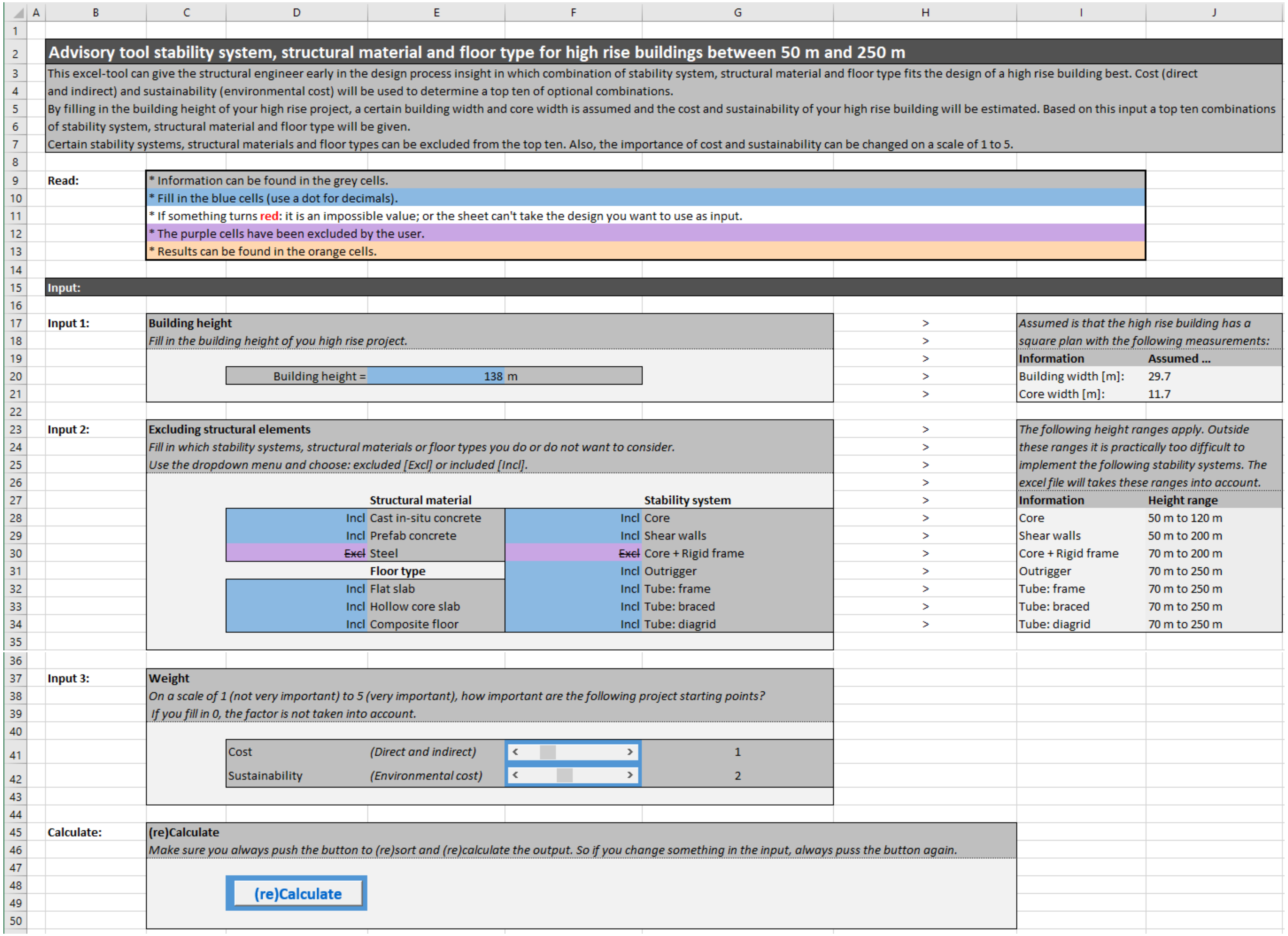


Figure 17: The input of the tool.

Output:

Result:

The ten best combinations of stability system, structural material and floor type are shown below, based on the input given above. The combination number is shown on the left and matches with the sub-results table below this one.
If [No more combinations] appears, less than ten combinations are possible due to the Excluded elements or Height limitations.

Ranking	Combination number	Grade	Stability system	Structural material *Core is cast in-situ*	Floor type
1	6	10.0	Shear walls	Prefab concrete (core is prefab!)	Hollow core slab
2	5	8.8	Shear walls	Cast in-situ concrete	Hollow core slab
3	26	8.2	Tube: diagrid	Prefab concrete	Hollow core slab
4	14	6.3	Outrigger	Prefab concrete	Hollow core slab
5	13	6.1	Outrigger	Cast in-situ concrete	Hollow core slab
6	19	6.1	Tube: frame	Prefab concrete	Hollow core slab
7	18	5.6	Tube: frame	Cast in-situ concrete	Hollow core slab
8	4	4.3	Shear walls	Cast in-situ concrete	Flat slab
9	12	1.9	Outrigger	Cast in-situ concrete	Flat slab
10	17	1.0	Tube: frame	Cast in-situ concrete	Flat slab

Sub-results:

Sub-result: COST

All twenty-six optional combinations, sorted from lowest direct and indirect costs to highest. The combination at the top in dark orange has the lowest direct and indirect costs and thus the highest grade on a scale of 1 to 10. The three columns on the right show the stability system, structural material and floor type belonging to each combination.

Combination number	A grade on a scale of 1 (worst solution) to 10 (best solution)	Direct and indirect costs [€]	Excluded?	Stability system	Structural material *Core is cast in-situ*	Floor type
26	10.0	6.50E+06		Tube: diagrid	Prefab concrete	Hollow core slab
6	9.9	6.69E+06		Shear walls	Prefab concrete (*core is prefab!*)	Hollow core slab
19	9.1	8.16E+06		Tube: frame	Prefab concrete	Hollow core slab
14	8.2	9.64E+06		Outrigger	Prefab concrete	Hollow core slab
5	8.1	9.87E+06		Shear walls	Cast in-situ concrete	Hollow core slab
4	7.4	1.10E+07		Shear walls	Cast in-situ concrete	Flat slab
13	7.3	1.13E+07		Outrigger	Cast in-situ concrete	Hollow core slab
18	7.1	1.17E+07		Tube: frame	Cast in-situ concrete	Hollow core slab
9	7.0	1.17E+07	EXCLUDED	Core + Rigid frame	Prefab concrete	Hollow core slab
24	6.4	1.29E+07	EXCLUDED	Tube: diagrid	Steel	Hollow core slab
25	6.4	1.29E+07	EXCLUDED	Tube: diagrid	Steel	Composite floor
8	6.2	1.32E+07	EXCLUDED	Core + Rigid frame	Cast in-situ concrete	Hollow core slab
7	6.0	1.35E+07	EXCLUDED	Core + Rigid frame	Cast in-situ concrete	Flat slab
12	5.8	1.39E+07		Outrigger	Cast in-situ concrete	Flat slab
16	5.0	1.53E+07	EXCLUDED	Outrigger	Steel	Composite floor
23	5.0	1.53E+07	EXCLUDED	Tube: braced	Steel	Composite floor
22	4.9	1.55E+07	EXCLUDED	Tube: braced	Steel	Hollow core slab
15	4.7	1.59E+07	EXCLUDED	Outrigger	Steel	Hollow core slab
17	2.7	1.93E+07		Tube: frame	Cast in-situ concrete	Flat slab
11	0.6	2.31E+07	EXCLUDED	Core + Rigid frame	Steel	Composite floor
21	0.5	2.32E+07	EXCLUDED	Tube: frame	Steel	Composite floor
10	0.5	2.32E+07	EXCLUDED	Core + Rigid frame	Steel	Hollow core slab
20	0.0	2.41E+07	EXCLUDED	Tube: frame	Steel	Hollow core slab
1	NaN	NaN	Not within height range	Core	Cast in-situ concrete	Flat slab
2	NaN	NaN	Not within height range	Core	Cast in-situ concrete	Hollow core slab
3	NaN	NaN	Not within height range	Core	Prefab concrete	Hollow core slab

Figure 18: The output of the tool. Also, the sub-result of COST is shown.

	A	B	C	D	E	F	G	H	I	J
104		**Sub-result:**	*All twenty-six optional combinations, sorted from lowest environmental cost to highest. The combination at the top in dark orange has the lowest*							
105		**SUSTAINABILITY**	*environmental cost and thus the highest grade on a scale of 1 to 10. The three columns on the right show the stability system, structural material and floor type*							
106			*belonging to each combination.*							
107			**Combination number**	**A grade on a scale of 1 (worst solution) to 10 (best solution)**	**Environmental cost [€env]**	**Excluded?**	**Stability system**	**Structural material** *Core is cast in-situ*	**Floor type**	
108										
109			6	10.0	3.20E+05		Shear walls	Prefab concrete (*core is prefab!*)	Hollow core slab	
110			5	9.2	3.43E+05		Shear walls	Cast in-situ concrete	Hollow core slab	
111			26	7.2	3.99E+05		Tube: diagrid	Prefab concrete	Hollow core slab	
112			13	5.5	4.46E+05		Outrigger	Cast in-situ concrete	Hollow core slab	
113			14	5.4	4.51E+05		Outrigger	Prefab concrete	Hollow core slab	
114			18	4.9	4.63E+05		Tube: frame	Cast in-situ concrete	Hollow core slab	
115			19	4.6	4.72E+05		Tube: frame	Prefab concrete	Hollow core slab	
116			4	2.8	5.24E+05		Shear walls	Cast in-situ concrete	Flat slab	
117			17	0.1	6.01E+05		Tube: frame	Cast in-situ concrete	Flat slab	
118			12	0.0	6.03E+05		Outrigger	Cast in-situ concrete	Flat slab	
119			22	NaN	NaN	EXCLUDED	Tube: braced	Steel	Hollow core slab	
120			8	NaN	NaN	EXCLUDED	Core + Rigid frame	Cast in-situ concrete	Hollow core slab	
121			23	NaN	NaN	EXCLUDED	Tube: braced	Steel	Composite floor	
122			16	NaN	NaN	EXCLUDED	Outrigger	Steel	Composite floor	
123			15	NaN	NaN	EXCLUDED	Outrigger	Steel	Hollow core slab	
124			9	NaN	NaN	EXCLUDED	Core + Rigid frame	Prefab concrete	Hollow core slab	
125			24	NaN	NaN	EXCLUDED	Tube: diagrid	Steel	Hollow core slab	
126			7	NaN	NaN	EXCLUDED	Core + Rigid frame	Cast in-situ concrete	Flat slab	
127			25	NaN	NaN	EXCLUDED	Tube: diagrid	Steel	Composite floor	
128			10	NaN	NaN	EXCLUDED	Core + Rigid frame	Steel	Hollow core slab	
129			21	NaN	NaN	EXCLUDED	Tube: frame	Steel	Composite floor	
130			11	NaN	NaN	EXCLUDED	Core + Rigid frame	Steel	Composite floor	
131			20	NaN	NaN	EXCLUDED	Tube: frame	Steel	Hollow core slab	
132			2	NaN	NaN	Not within height range	Core	Cast in-situ concrete	Hollow core slab	
133			3	NaN	NaN	Not within height range	Core	Prefab concrete	Hollow core slab	
134			1	NaN	NaN	Not within height range	Core	Cast in-situ concrete	Flat slab	

Figure 19: The sub-result of SUSTAINABILITY is shown.

9. Testing of the tool

The design tool is tested by looking at: uncertainty, verification, validation, comparison and patterns. First, the uncertainty between the used height points and the plotted exponential function is discussed. Next, the verification tests how well the tool matches reality. The validation tests the usability of the tool and how well the tool meets the needs of the structural engineer. The comparison explores how well the current high rise designs in the Netherlands match the structural advise given by the tool. At the end certain patterns in the tool are highlighted.

9.1. Uncertainty

For the calculations *height points* are used per *combination* shown in Table 13. For each *combination* the cost, construction time and environmental cost is calculated on these height points. Afterwards, an exponential function – with a height range that is different for each *combination* and shown in Table 14 – is drawn through these three points (extrapolation). An exponential function was chosen, because this function follows the three calculated points best.
This means however, that there might be a difference between the calculations performed at the height points and the exponential function. This uncertainty can be limited by performing extra calculations and check if these results match the exponential functions in the graphs. Since a lot of height points that were used in this thesis were above 150 m, especially calculations for the lower high rise buildings (lower than 150 m) can reduce the sensitivity.

When the structural material or the size of the building is very different from the assumptions made by Lankhorst (explained in Chapter 4) and this thesis, the actual environmental impact can differ from the figures. However, assumed is that the environment costs of *each* structural scenario will increase proportional to the increase of the assumptions used in this thesis.

The goal of the excel-tool is give insight in the structural design of a high rise building, very early in the design process. Early in the design process very little details are available about the design of the high rise building and a lot of things can still change. Because of that, the input of the tool is kept simple: the height of the high rise building. This means that even when a lot more calculations and extra building shapes and sizes are added, the simple input stays. This simple input creates a certain uncertainty, because not all details of the design can be taken into account. The simple input however also creates the opportunity for the structural engineer to get a feeling about the result of his or her design from the start of the design process. The tool is created to be used in an early design stage with less detailed information available, so the tool will give an impression of the different options and their sustainability.

9.2. Verification

During the verification the content of the tool will be compared to reality. Figure 20 shows the calculation process for the tool and the green squares show the two points that will be validated. The tool can be compared to reality at two points: construction time and cost. These two points were chosen, because information from real projects was available about these two points.

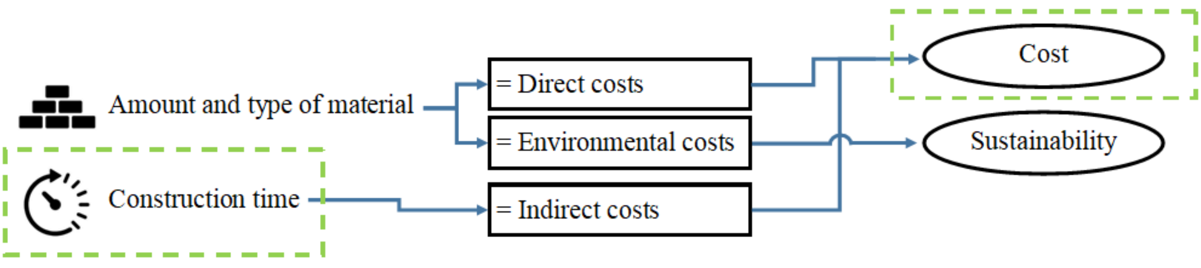


Figure 20: The two points in the calculation process of the tool that will be validated: construction time and cost.

Construction time verification

Table 17 shows the verification of the *construction time*. The last column Table 17 shows how well the calculated construction time that is used in the tool matches the real construction time of the twenty-two high rise buildings above 120 m in the Netherlands. The closer the percentage is to 100%, the better it matches. The buildings that were *out of range* in the tool or have not been finished yet in reality, have not been included in the validation (for example the Zalmhaventoren).

The closer the percentage is to 100%, the better it matches. The table shows that some percentages are above 100% and some below. Most percentages lie between 70% and 130%. This deviation is caused by small factors that influence the construction time in reality.
The percentage of the Erasmus MC tower is only 65%, because this building is a hospital (coloured blue in the table). While calculating the construction time, this thesis assumed an easy finishing, while actual hospital finishing would take 5.4 times longer than assumed (Flapper, 1995).
The percentage of the Jubi-torens and the New Babylon are 60% and 63%, but this is caused by the fact that these projects contain multiple towers which results in a longer construction time.
There can be concluded that the calculated construction time matches with the construction time in reality.

Table 17: The verification of the tool by comparing the calculated construction time that used to calculate the indirect costs of the tool with the real construction time of the twenty-two high rise buildings above 120 m in the Netherlands (already discussed in Table 4, Chapter 3). The blue percentage indicate that the tool doesn't match reality there.

Name	Height [m]	Construction time in *Reality* [in months]	Construction time in *Tool* [in months]	Ratio [%]: Construction time in *Tool* / Construction time in *Reality*
Zalmhaventoren	215	*Predicted:* Around 39 months	-	-
Maastoren	165	37 months	31 months	84%
New Orleans	158	42 months	47 months	112%
Montevideo	152	34 months	*Out of range*	-
Delftse Poort	151	43 months	30 months	70%
Cooltoren	150	*Predicted:* Around 25 months	-	-
De Rotterdam	149	47 months	*Out of range*	-
Jubi-torens	146, 146	48 months	29 months	**60%**
Hoftoren ('De Vulpen')	142	55 months	*Out of range*	-
Westpoint	142	31 months	41 months	132%
New Babylon	140, 100	63 months	40 months	**63%**
Rembrandt Tower	135	43 months	37 months	86%
Het Strijkijzer	132	26 months	27 months	104%
Millennium	131	34 months	*Out of range*	-
De Kroon	125	38 months	36 months	95%
First Rotterdam	125	34 months	26 months	76%

The Red Apple	124	39 months	38 months	97%
World Port Centre	123	30 months	34 months	113%
Mondriaan toren	123	36 months	41 months	114%
Carlton *(part of l'Hermitage)*	120, *(75, 85)*	40 months	35 months	85%
Erasmus MC tower	120	40 months	26 months	**65%**

Cost verification

For the verification of the cost, the construction costs of the main load-bearing structures of eight buildings will be used. The tool will also calculated the construction costs of the main load-bearing structures that were applied in these eight buildings. The construction costs of the main-load bearing structure in *reality* will be compared to the cost calculated by the *tool*.

- The cost in the tool is calculated with the following input: The stability system, structural material and floor type in the tool matches the structure that was used in reality.

Construction costs of the main-load bearing structure *in Reality* are calculated by taking a percentage of the investment costs or the construction cost. According to Oss (2007) the direct and indirect costs are 52,6% of the total investment costs and the load-bearing structure and floors thus have a share of 16% in the total direct and indirect costs. So for example: the total investment cost of the Cooltoren is found and to get the construction cost of the main-load bearing structure, the total investment cost is multiplied with 52.6% and 16%. It is important to keep in mind that these percentages might result in extra uncertainty.

To be able to compare them objectively, the costs in *reality* will be corrected for inflation. The correction factor depends on the year the building was finished and the inflation per year (see Table 18).
Also, the costs in the *tool* will be corrected for the gross area. The tool assumes a certain building width and assumes the building has a square plan, while in reality this is often not the case. The ration between the gross area in *reality* and in the *tool* are used to correct this. It is important to keep in mind that these corrections might result in extra uncertainty.

Table 18: The inflation percentage over the years (Inflation.eu, 2020).

Year	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Inflation [%]	3.19	2.58	2.80	1.93	2.11	2.11	1.96	2.16	2.36	4.16	3.29
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Inflation [%]	2.09	1.26	1.69	1.10	1.61	2.49	1.19	1.28	2.34	2.46	2.51
Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**					
Inflation [%]	0.98	0.60	0.32	1.38	1.70	2.63					

The last column in Table 19 shows how well the calculated cost by the tool (after the two corrections) match the reality. The closer the percentage is to 100%, the better it matches.
The cost calculated by the tool for the Erasmus MC tower only meets for 45% (coloured blue in the table). This low percentage is caused by the expensive devices and finishing that is needed for a hospital. While calculating the cost, this thesis assumed an finishing suitable for *housing* or *office* and not an expensive hospital finishing. The high percentage of the Cooltoren can be caused by the fact that this building isn't finished yet. It will finish in 2001.
The cost calculated by the *tool* for the remaining six buildings meet the cost in *reality* for 81% to 130%. For now there can thus be concluded that calculated construction costs in the *tool* match with the construction costs in *reality*. The verification of cost was however performed with *only* eight buildings and with a lot of percentages. To be able to draw a substantiated conclusion, more buildings need to be used in the verification.

Table 19: The verification of the tool by comparing the calculated costs of the *tool* with the *real* construction costs of the main load-bearing structure of eight high rise buildings. These costs are corrected for Gross area (using columns 2, 4, 5, 6, 7, 8, 10) and Inflation (using columns 7, 8, 11) (De Architect, 1987; B. Priem, sd; Hanff, 2018; De Architect, 2009; Architectenweb, 2012; Benjamin, 2003; Stedenbouw, 2016; Cobouw, 2017).

Name	Year	Height [m]	Gross area *in Reality* [m^2]	Gross area *in Tool* [m^2]	Ratio Gross area	Construction cost main-load bearing structure *in Reality* [€]	Construction cost main-load bearing structure *in Reality* corrected for Inflation [€]	Construction cost main-load bearing structure *in Tool* [€]	Ratio [%]: Cost in Tool / Cost in Reality *corrected* for Inflation and Gross area
Maastoren	2010	165	52 000	40 392	1 : 0.78	*65 000 000 * 0.16 =* 10 400 000	12 209 320	11 600 000	122% *= 11 600 000 / (12 209 320 * 0.78)*
Delftse Poort	1992	151	106 000	36 002	1 : 0.34	*108 900 000 * 0.16 =* 17 424 000	30 390952	9 660 000	93%
Cooltoren	2021	150	37 000	35 764	1 : 0.97	Predicted: *140 000 000 * 0.526 * 0.16 =* 11 780 000	11 780 000	15 500 000	**136%**
Jubi-torens	2012	146, 146	131 600	34 349	1 : 0.26	*330 000 000 * 0.526 * 0.16 =* 27 773 000	31 456 603	9 050 000	111%
Westpoint	2004	142	33 020	33 185	1 : 1.00	*70 000 000 * 0.16 =* 11 200 000	14 424 442	11 700 000	81%
First Rotterdam	2015	125	54 000	28 240	1 : 0.52	*80 000 000 * 0.16 =* 12 800 000	13 803 156	8 090 000	113%
The Red Apple	2009	124	35 000	28 014	1 : 0.80	*45 000 000 * 0.16 =* 7 200 000	8 553 192	8 920 000	130%
Erasmus MC tower	2017	120	185 000	26741	1 : 0.14	*600 000 000 * 0.16 =* 96 000 000	101 582 478	6 460 000	**45%**

9.3. Validation

Validation of the excel-tool is used to test if the tool meets the needs of the structural engineer early in a design process of a high rise building. The Structural Engineering & Design department of the Arcadis office in Rotterdam has been asked to give different parts of the tool a grade on a scale of 1 to 5. Eleven people graded the tool.

For each part of the tool they gave a grade. The average grade for each part of the tool can be found in Appendix K. The lowest average grade given by the Structural Engineering & Design department was 3.3 for the part about the goal of the tool. The average grade taken over all the average grades for different parts of the tool was 3.8.
Also, they gave several practical suggestions on how to improve the lay-out and functionality of the tool. All of these practical suggestions have been implemented, so the average grade will now probably be higher than 3.8. The conclusion is that the tool is sufficient.
They also gave a few suggestions on how the content of the tool could be improved or expanded. These suggestions have all been included in Chapter 11 (Discussion and recommendations).

9.4. Comparison

A comparison is made between some *real* high rise projects and the advice that the *tool* would have given their design team. This comparison is between:

- the twenty-two high rise buildings above 120 m in the Netherlands and their finally chosen structural combination of stability system *and* structural material (already discussed in Chapter 3);
- and the advice that the tool would have given them early in their design process.

The hollow core slab almost always ends up as the best floor type, so the floor type was excluded from the comparison.

As input the following is used:

- All stability systems, structural materials and floor types have been included.
- The ratio between Cost and Sustainability is 1:1.

The last column in Table 20 shows what place the *actually used* stability system and structural material would have gotten in the advisory tool.

Table 20: A comparison between the stability system and structural material of the high rise buildings above 120 m in the Netherlands and the position this stability system and structural material would have gotten as advise in the tool.

Name	Height m]	Function	The in reality-used structural combination: Stability system – Structural material	Place in the tool of this structural combination
Zalmhaven toren	215	Housing	Shear walls – Prefab concrete	Not shown in top 10
Maastoren	165	Office	Tube: frame – Prefab concrete (cast in-situ core)	5th place *(Tube: diagrid came in 2nd place)*
New Orleans	158	Housing	Shear walls – Cast in-situ concrete	3nd place
Montevideo	152	Housing	Core – Cast in-situ concrete	Not shown in top 10
Delftse Poort	151	Office	Tube: frame – Prefab concrete	4th place *(Tube: diagrid came in 2nd place)*
Cooltoren	150	Housing	Outrigger – Cast in-situ concrete	6th place

De Rotterdam	149	Housing & Office	Core – Cast in-situ concrete	Not shown in top 10
Jubi-torens	146, 146	Office	Tube: frame – Prefab concrete (cast in-situ core)	4th place *(Tube: diagrid came in 2nd place)*
Hoftoren ('De Vulpen')	142	Office	Core – Cast in-situ concrete	Not shown in top 10
Westpoint	142	Housing	Shear walls – Cast in-situ concrete	3nd place
New Babylon	140, 100	Housing	Shear walls – Cast in-situ concrete	3nd place
Rembrandt Tower	135	Office	Core + Rigid frame – Steel (cast in-situ core)	Not shown in top 10 *(cast in-situ concrete in 6th and 7th place)*
Het Strijkijzer	132	Housing	Tube: frame – Prefab concrete	4th place *(Tube: diagrid came in 2nd place)*
Millennium	131	Office	Core – Cast in-situ concrete	Not shown in top 10
De Kroon	125	Housing	Shear walls – Cast in-situ + Prefab concrete	1st place
First Rotterdam	125	Office	Outrigger – Prefab concrete (cast in-situ core)	5th place
The Red Apple	124	Housing	Shear walls – Cast in-situ + Prefab concrete – Traditional formwork concrete floor	1st place
World Port Centre	123	Office	Core + Rigid frame – Steel (cast in-situ core)	Not shown in top 10 *(cast in-situ concrete and prefab in 8th and 10th place)*
Mondriaan toren	123	Office	Tube: frame – Cast in-situ concrete	7th place *(Tube: diagrid came in 2nd place)*
Carlton *(part of l'Hermitage)*	120, *(75, 85)*	Office	Outrigger – Steel (cast in-situ core)	Not shown in top 10 *(cast in-situ concrete and prefab in 5th and 6th place)*
Erasmus MC tower	120	Office	Tube: frame – Prefab concrete	4th place *(Tube: diagrid came in 2nd place)*

The stability system and structural material of the Kroon and the Red Apple show up in the first place of the top ten of the excel-tool. Out of the remaining twenty buildings, eleven (50%) were shown in the top ten of the tool and eight (36%) not. A lot of structural combinations that didn't shown in the top ten of the tool had a very good alternative that was shown in the top ten. For example, the *Outrigger* of the Carlton was made of steel and didn't shown up in the top ten of the tool, but the *Outriggers* made of cast in-situ concrete and prefab concrete both showed up in the 5th and 6th place of the top ten.
Changing the input, might change the top ten and thus the similarity between the tool and the reality. For example: shear walls are now included in the tool, even though some buildings in Table 20 are *office* buildings and thus *Shear walls* probably wouldn't be considered an option.

So 36% of the chosen structural combinations didn't show in the top ten of the tool. This can be caused by the fact that, next to *Cost* and *Sustainability*, other design choices played a role. For example:

- The contractor can't build with a certain structural material.

- Shear walls don’t work in an office building.
- The structural engineer minimized the core and thus has to choose another stability system or use high strength materials (which are not included in the tool).
- The size or shape of the building differed from the assumptions made in the tool.
- The design team required certain design freedom in the plan.
- The structurally optimal design didn’t match the wished of the other disciplines in the design team.

9.5. Patterns

The following patterns in the tool have been discovered:

- The top ten in the excel-tool contains always six to ten structural *combinations* with a hollow core slab as floor type, independent of the building height that serves as input and the weight ratio between *Cost* and *Sustainability*. The hollow core slab is thus the most sustainable and cheapest floor type.
- When the weight ratio between *Cost* and *Sustainability* is kept at 1:1, the top three stays the same between 90 m and 200 m:
  1st place: *Shear walls, Prefab concrete (core also made of prefab concrete), Hollow core slab*
  2nd place: *Tube: diagrid, Prefab concrete, Hollow core slab*.
  3rd place: *Shear walls, Cast in-situ, Hollow core slab*
  At 200 m the stability system *Shear walls* reaches the maximum height of its height range and thus this stability system disappears from the top ten. Outside the range of 90 m to 200 m and outside the top three, the structural combinations change places and no pattern can be found.

9.6. Conclusion

This chapter provided an answer to the research question: *How can the content and the design of the tool be tested?*

The tool has been tested by looking at: uncertainty, verification, validation, comparison and patterns. The following conclusions have been draw by performing these four tests.

- Uncertainty:
  There might be a difference between the calculations performed at the height points and the exponential function that has been drawn through these height points. This uncertainty can be limited by performing extra calculations at different height points. Also, adding more types of structural materials or different sizes and shapes of high rise buildings can help the tool to fit the high rise projects in reality better.
  The input of the tool is kept simple and this simple input creates a certain uncertainty for when the input and the assumptions of the tool don’t match the high rise building design exactly. It however also creates the opportunity *early* in the design process for the structural engineer to get insight in the influence of the structural design on cost and sustainability.
- Verification:
  The tool was compared to reality at two points: construction time and cost.
  - The construction time that was calculated by this thesis to determine the indirect costs has been compared to the construction time of fourteen high rise buildings in the Netherlands. The closer the percentage was to 100%, the better it matches. Almost all percentages lay between 70% and 130%. There was concluded that the calculated construction time matches with the construction time in reality.
  - The construction costs of the main-load bearing structure of eight buildings in *reality* were compared to the costs calculated by the *tool.* The cost in *reality* has been corrected for inflation and gross area, to match the assumptions made in the *tool.* The closer the percentage was to 100%, the better it matches. The cost calculated by the *tool* meets the cost in *reality* for 81% to 130%.
    For now there can thus be concluded that calculated construction costs in the *tool* match with the construction costs in *reality*. The verification of cost was however performed with *only* eight buildings. Also, the percentages used to correct the cost in *reality* for inflation and gross area; and to correct the cost in the *tool* for direct and indirect costs of the main loading-bearing

structure, create uncertainty. To be able to draw a substantiated conclusion, more buildings need to be used in the verification.

- Validation:

- Validation:
  Eleven members of the Structural Engineering & Design department of the Arcadis office in Rotterdam have graded different parts of the tool on a scale of 1 to 5. The average grade given by them was 3.8. All the practical suggestions they gave on how to improve the lay-out and functionality of the tool have been implemented, so the average grade will now probably be higher than 3.8. The conclusion is that the tool is sufficient.
- Comparison:
  The finally chosen structural combination of stability system *and* structural material of the twenty-two high rise buildings above 120 m in the Netherlands have been compared to the advice that the tool would have given them early in their design process. The results:
  - 14% of the structural typologies that were applied in reality, showed up in the first place of the top ten of the excel-tool.
  - 50% of the structural typologies that were applied in reality, showed up in the top ten of the excel-tool.
- Patterns:
  - The top ten in the excel-tool contains always six to ten structural *combinations* with a hollow core slab as floor type, independent from the input by the user. The hollow core slab is thus the most sustainable and cheapest floor type.
  - The top three in the excel tool stays the same with a building height between 90 m and 200 m.
    1st place: *Shear walls, Prefab concrete (core also made of prefab concrete), Hollow core slab*
    2nd place: *Tube: diagrid, Prefab concrete, Hollow core slab*.
    3rd place: *Shear walls, Cast in-situ, Hollow core slab*

WRAPPING UP

10. Conclusion

The goal of this thesis was to create a decision-making framework for the structural material choice for high rise buildings in the Netherlands. This was done by researching the design process – in theory and in practice – for high rise buildings in the Netherlands.

This chapter will describe the results. Each research question and the represents one chapter. The results are summed up in bullet points. Sometimes the text refers back to a table of figure that can be found in the report. In that case the page number of that table or figure is always mentioned.

10.1. Part A: Theory and practice

➢ Research question 1:
How can the general design process of a high rise building be theoretically described?

In theory the design process of a high rise building follows the Basic design cycle.

- The Basic design cycle consists of five steps: analysis, synthesis, simulation, evaluation and decision. During the design process these five steps are repeated while going from a macro level (general) to a micro level (detailed).

➢ Research question 2:
What is the current situation regarding the design process and structural material choice of high rise buildings in the Netherlands?

A lot of Dutch cities have created high rise visions and plans to solve the growing housing demand the coming years, by using high rise buildings. A detailed analysis of the twenty-two high rise buildings in the Netherlands above 120 m, resulted in a table showing among others the building height, the used structural materials and the used stability systems (Table 4 at page 22).

- From this table there was concluded that 45% of the *office* buildings uses a tube as stability system and 45% of the *housing* buildings uses shear walls as stability system.
- This table also shows that only 14% (three out of twenty-two) buildings are mixed (mixed concrete elements with steel elements) and two of those three have been designed by foreign architects. Steel is thus almost not used in these high rise buildings above 120 m.

➢ Research question 3:
Which project starting points influence the structural material choice for high rise buildings?

Each design process starts with listing the project starting points required for that project.

- The following ten project starting points were identified: cost, constructability, construction time, risks, maintenance, net floor area, safety, foundation and settlements, comfort and fire safety, sustainability.

Two out of ten identified project starting points have been used in part C of this thesis: *Cost* and *Sustainability*. *Cost* was chosen, because all other project starting points are often expressed in cost. *Sustainability* was chosen, because this project starting point will become more important in the future. With *Cost* this thesis focussed on: direct costs (material, workforce and formwork) and indirect costs (construction time and building site). This thesis expressed *Sustainability* in environmental cost.

- The direct costs are calculated by multiplying the direct costs per material with the total amount of material. The indirect costs are calculated by multiplying the indirect costs per month with the construction time. The direct costs per material and per floor type have been shown in Table 6 and Table 7 (page 30). The indirect costs per month increase when a building becomes higher, because it takes more time to lift materials and people to the correct height (called *high rise factor)*. The indirect costs per month have been shown in Figure 7 (page 30).

- The environmental cost of a building is calculated by multiplying the environmental costs per material with the total amount of material. The environmental costs per material have been shown in Table 10 (page 33).

➢ Research question 4:
Where lie the expected differences between the structural material choice process in theory and in practice?

Eventually four differences between theory and practice were found:

1. Disproportionately less steel:
   Only 10 buildings in the Netherlands (6.5%) use steel for a large part of the main load-bearing structure.
   - The remaining question: *is the little use of steel a consequence of objective comparison of structural materials; or is it preference for concrete?*
2. Reasoning behind design decisions:
   When the design process deviates from the Basic design cycle, arguments based on preferences and experience start playing a role. The problem is that the reasoning behind the used arguments and the taken design decisions is often not made clear.
   - The remaining question: *is deviating from the comparison method described in the Basic design cycle a problem?*
3. Building methods of contractors:
   A contractor will influence the structural material choice to fit a their building method.
   - So *why* contractors are involved is clear, but the only remaining question is: *how are contractors involved in the design process of a high rise building*?
4. Arguments and expectations don't match reality:
   A commonly used argument is that prefab concrete has a shorter construction time than cast in-situ concrete. However, figures showing the construction time and the structural material of the buildings in the Netherlands above 120 m, show that is not always true (Figure 10, Figure 11 and Figure 12 at page 37).
   - The remaining question: *is the building method more important than the structural material for the construction time of a high rise building?*

10.2. Part B: Exploring key differences

➢ Research question 5:
What research method can be used to research the differences between the structural material choice process in theory and in practice?

Interviews were chosen as research method to research the differences in more depth. The structural material choice process is a human process and with interviews the people in the design team can elaborate on why or how certain things in the design process occurred.

- The interview set-up consisted of three stages: orientation interviews, online survey and follow-up interviews.

A reflection on the interview method gave the following results:

- The focus of the interviews lay on the structural material choice. The results taken from these interviews need to be placed in the context of the complete design process and all the other design decisions.
- What needs to be kept in mind is that a limited amount of structural engineers and contractors participated in the interviews; and that *Interviewing* is a research method that is based on opinions

and thus doesn't represent an absolute truth.

- Research question 6:
  Which differences can be addressed, using a tool?

Four differences between theory and practice have already been stated, based on literature. These four differences have been researched in depth, using interviews. Also, potential solutions or next research steps have been proposed.

1. Disproportionately less steel:
   When the option of steel was introduced during the interview the first responses where: *'it is not a common option to consider'* and *'there is a lack of experience in the Netherlands to build with steel'*. After this first response, some arguments against steel were mentioned. These arguments have however not been tested in an actual comparison, because steel was discarded beforehand.
   - An optional solution might be: *a change in culture of the building sector to include steel in the comparison as an option. Once steel becomes an option, objective comparison of structural materials can indicate which structural material is the most suitable for each high rise project.*
2. Reasoning behind design decisions:
   In practice arguments based on preference and experience are used, but the reasoning behind these arguments is not made clear. This deviation from the theoretical Basic design cycle is however not a problem according to the interviewees, because it is the way reality works.
   - This reality can be accepted, but an optional solution might be: *a tool to give the structural engineer insight in the influence of the structural material choice on the project starting points. This way the structural engineer can quickly respond to the dynamics of the design process.*
3. Building methods of contractors:
   The building method is linked to the structural material choice, which means the contractor will try to influence the structural material choice during the design process of a high rise building.
   - An optional solution might be: *insight early in the design process in the wishes of contractors to make sure that the contractor and the design can fit each other more easily.*
4. Arguments and expectations don't match reality:
   A commonly used argument is that prefab concrete builds faster than cast in-situ concrete. However, data about the construction time of the buildings in the Netherlands above 120 m show that prefab concrete doesn't always have a shorter construction time when compared to cast in-situ concrete.
   - An optional solution might be: *to do more research, using case studies, by performing a factual comparison between the design of the building and the real building once it is finished.*

Differences 2 and 3 both find their origin in the fact that preferences based on experience are leading in the decision-making process. Differences 2 and 3 will both be used in Part C of this thesis, because both differences can be addressed by creating an advisory excel-tool.

10.3. **Part C: Working towards a solution**

- Research question 7:
  How can a tool give insight in the relation between structural material, structural typology and the project starting points?

The goal of the created excel-tool is to give the structural engineer – early in the design process of a high rise building in the Netherlands – insight in the influence of structural material on Cost and Sustainability. From research question 3 there was concluded that Cost would include direct and indirect cost and Sustainability would be expresses in environmental cost.

The tool includes twenty-six structural *combinations*. These *combinations* are a combination of:

- *Stability system*: core, shear walls, core + rigid frame, outrigger, tube: frame, tube: braced, tube: diagrid.
- *Structural material*: cast in-situ concrete, prefab concrete, steel.
- *Floor type*: flat slab floor, hollow core slab, composite floor.

For each of twenty-six structural *combinations* the Cost and Sustainability of have been calculated at certain building heights. These so called *height points* lie within the height range of the stability system belonging to that combination. The used height points are shown in Figure 21 with blue triangles and the height ranges with black lines.

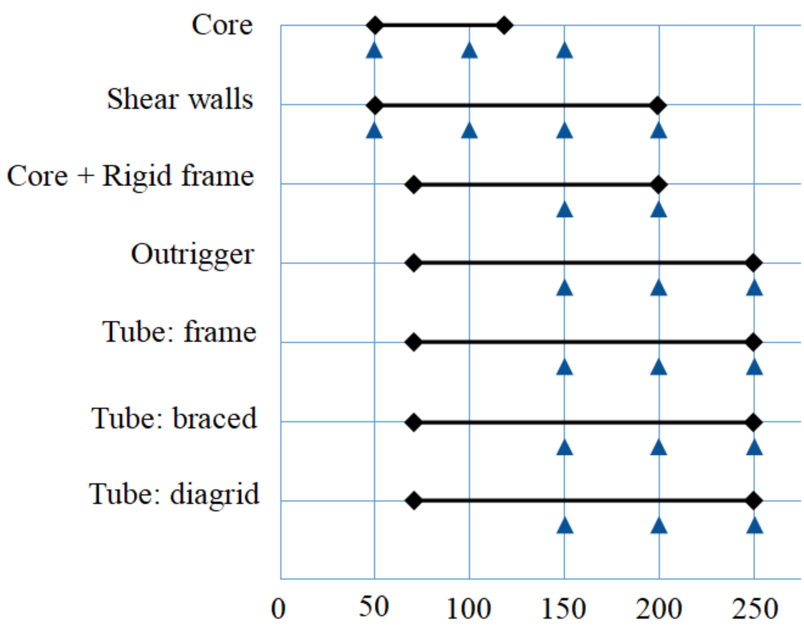


Figure 21: The height range of the stability systems used in this thesis are shown in black. The blue triangles indicate at which height cost and sustainability calculations are performed.

To be able to calculate the Cost and Sustainability for each combinations certain measures of the building are assumed (Table 15 at page 53). The assumed building width lies around 30 m and the distance between the façade and the core is kept at 9 m to meet the Dutch regulations for daylight entry. This results in the netto floor area percentages above 75%, which ensures that the buildings are economically profitable.

Adding more types of structural materials or different sizes and shapes of high rise buildings can help the tool to fit better to reality, were not all high rise projects have a square plan of 30 m building width. Also, this thesis assumed only cast-in-situ concrete cores for the calculations. However, also prefab concrete cores and maybe even steel cores are interesting the use in the calculations for further research. Also, a mix of structural materials is interesting to research (for example: a concrete core with a steel frame).

The following calculations have been performed (see Figure 22 for a flow chart of the performed calculations):

- The direct costs are calculated by multiplying the direct costs per material with the amount of type of structural material needed for each of twenty-six combinations at each height point. The amount and type of structural material needed for each *combinations* is calculated by performing structural calculations to determine the cross section size for each of the structural elements (see Appendix F for the calculations of the combinations that include the stability system *Core*; see Appendix G for the calculations of the combinations that include the stability system *Shear walls*; and see Lankhorst (2018) for the remaining stability systems).
- The indirect costs are calculated by multiplying the indirect costs per material with the construction time of each of twenty-six combinations at each height point. The construction time is calculated for each of the combinations by calculating how long the construction time is per building phase (see Appendix H for the calculation).
- The environmental costs are calculated by multiplying the environmental costs per material with the amount of type of structural material needed for each of twenty-six combinations at each height

point. The amount of type of structural material that is used in this calculation is the same as used for the direct costs.

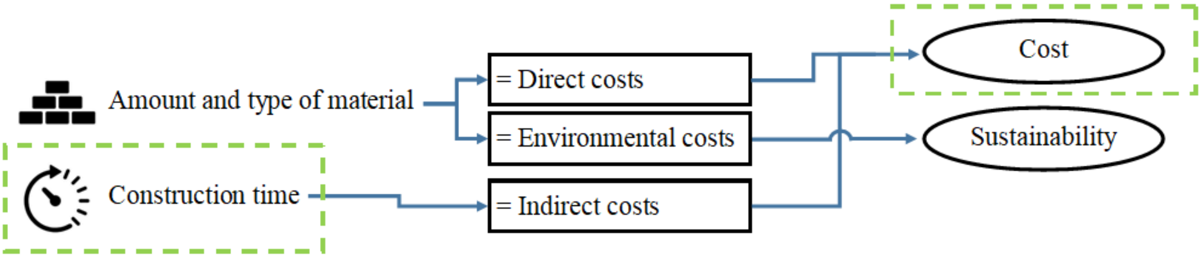
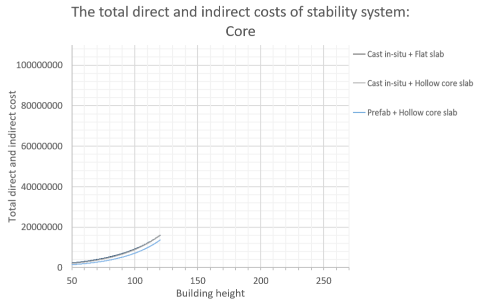
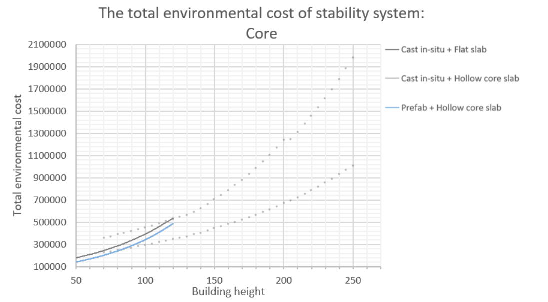
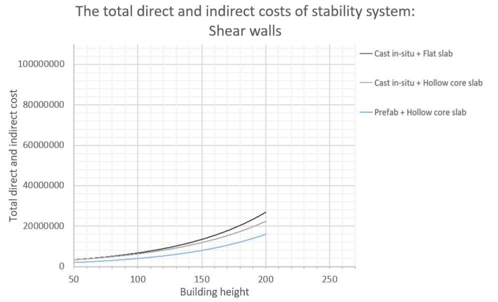
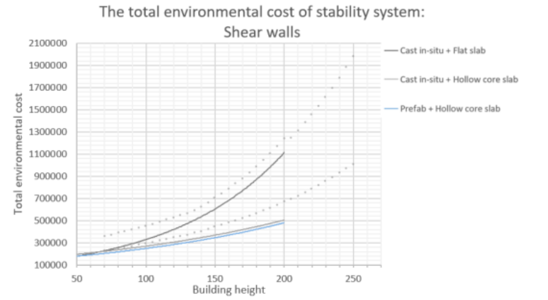
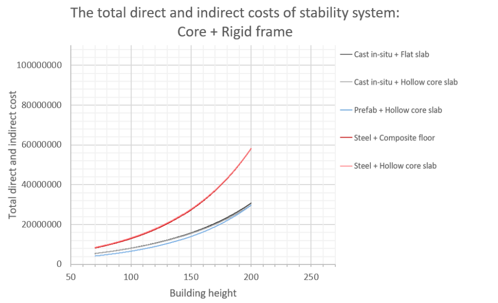
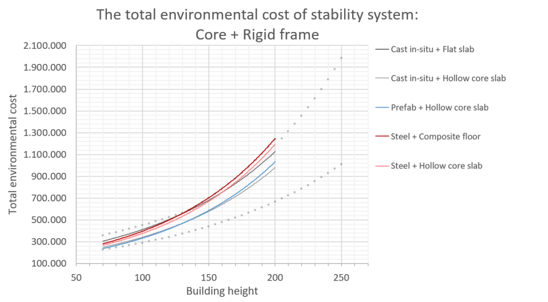
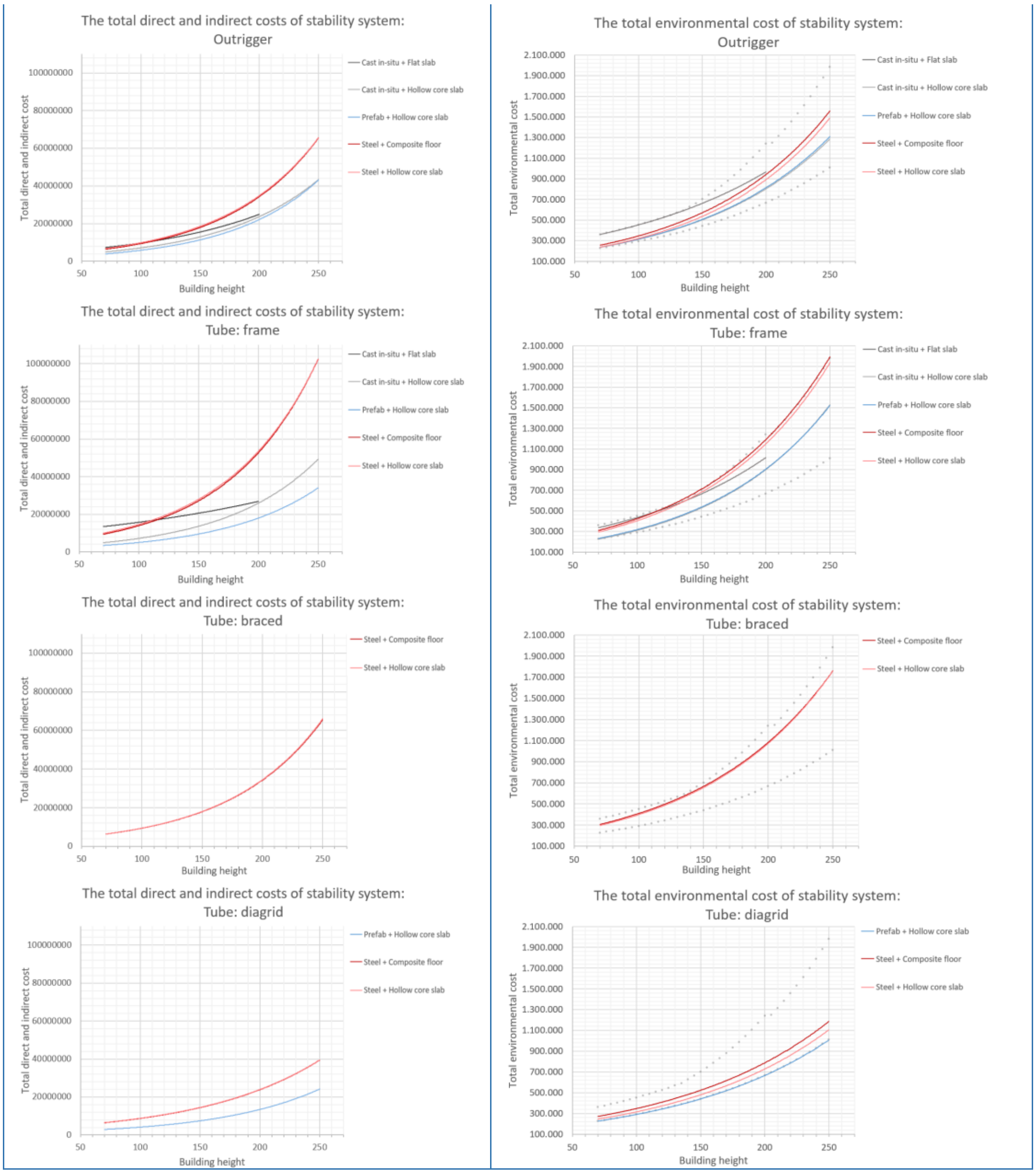


Figure 22: The calculation flow chart, showing how the direct costs, indirect costs and environmental costs of each of the twenty-six structural *combinations* have been calculated. The two points in the calculation process of the tool that were validated are circled with a green square: construction time and cost.

The amount of Cost and Sustainability for each of the twenty-six combinations at each height point has been plotted in graphs. By drawing an exponential line through these points (extrapolation), the Cost and Sustainability of each *combinations* can be determined on each height (within the height range of the belonging stability system) (Table 21, the graphs can be seen in full size in Appendix I and J).
To check the accuracy of the performed extrapolation, extra calculations can be performed at more height points (especially for the high rise buildings lower than 150 m as can be seen in Figure 21).

Table 21: The plotted graphs containing the Cost and Sustainability of each of the twenty-six structural *combinations*. The graphs can be seen in full size in Appendix I and J.

Cost	Sustainability
	
	
	



The formulas belonging to the exponential lines in the graphs are used in the excel-tool to calculate the Cost and Sustainability of a high rise building. Only the building height is needed as input. This simple input creates a certain uncertainty, because not all details of the design can be taken into account. The simple input however also creates the opportunity for the structural engineer to get a feeling about the result of his or her design from the start of the design process. The tool is created to be used in an early design stage with less detailed information available, so the tool will give an impression of the different options and their sustainability.

When the user of the excel-tool fills is the building height of his or her high rise project, the Cost and Sustainability for each of the twenty-six structural combinations is calculated at that height. All the combinations are ranked from best to worst based on Cost and Sustainability and given a grade from 10 (best) to 1 (worst). The average grade of each *combination* is calculated by taking the grade for cost and the grade for sustainability and taking the weight factor given as input by the structural engineer into account. The ten combinations with the best average grade then end up in the top ten of the excel-tool. This way a structural engineer can explore early in the design process what the influence of his or her design choices are on the final result and take the top ten structural *combinations* into consideration.

- Research question 8:
  How can the content and the design of the tool be tested?

The tool has been tested by looking at: uncertainty, verification, validation, comparison and patterns.

1. Uncertainty:
   - The direct and indirect cost and the environmental cost are calculated on certain height points and then extrapolated. This results in a uncertainty between the calculated points and the exponential line that goes through these points. More calculations performed at more height points can solve this.
   - This thesis used a square plan with a core in the middle. Adding more types of structural materials or different sizes and shapes of high rise buildings can help the tool to fit better to reality of high rise projects. It can help reach the ultimate goal of this excel-tool: *to create an excel-database and tool with Cost and Sustainability for all building types.*
2. Verification:
   During the verification the content of the tool will be compared to reality. The tool was compared to reality at two points: construction time and cost (the green squares in Figure 22). These two points were chosen, because information from real projects was available about these two points. As can be seen in Figure 22, the flow of Cost is validated at two points, while the Sustainability isn't validated due to lack of information. Extra research needs to be performed, to *also* validate the Sustainability.
   - The construction time that was calculated by this thesis to determine the indirect costs has been compared to the construction time of fourteen high rise buildings in the Netherlands. The closer the percentage was to 100%, the better it matches. Almost all percentages lay between 70% and 130%. This deviation can be caused by small factors that influence the construction time in reality. There was concluded that the calculated construction time matches with the construction time in reality.
   - The construction costs of the main-load bearing structure of eight buildings in *reality* were compared to the costs calculated by the *tool.* The cost in *reality* has been corrected for inflation and gross area, to match the assumptions made in the *tool.*
     The closer the percentage was to 100%, the better it matches. Almost all percentages lay between 81% and 130%. For now there can thus be concluded that calculated construction costs in the *tool* match with the construction costs in *reality*. The verification of cost was however performed with *only* eight buildings. Also, the percentages used to correct the cost in *reality* for inflation and gross area; and to correct the cost in the *tool* for direct and indirect costs of the main loading-bearing structure, create uncertainty. To be able to draw a substantiated conclusion, more buildings need to be used in the verification.
3. Validation:
   Eleven members of the Structural Engineering & Design department of the Arcadis office in Rotterdam have graded different parts of the tool on a scale of 1 to 5. The average grade given by them was 3.8. There was concluded that the tool is sufficient.
4. Comparison:
   A comparison was made between twenty-two *real* high rise projects and the advice that the *tool* would have given their design team. The results:
   - 14% of the structural typologies that were applied in reality, showed up in the first place of the top ten of the excel-tool.
   - 50% of the structural typologies that were applied in reality, showed up in the top ten of the excel-tool.
   - 36% of the structural typologies that were applied in reality, didn't showed up in the top ten of the excel-tool.
     This can be caused by the fact that, next to *Cost* and *Sustainability*, other design choices played a role. For example: the structural engineer minimized the core and thus has to choose another stability system or use high strength materials (which are not included in

the tool); the size or shape of the building differed from the assumptions made in the tool; or the design team required certain design freedom in the plan.

5. Patterns:
    - The top ten in the excel-tool contains always six to ten structural *combinations* with a hollow core slab as floor type, independent from the input by the user. The hollow core slab is thus the most sustainable and cheapest floor type.
    - The top three in the excel tool stays the same with a building height between 90 m and 200 m.
      1st place: *Shear walls, Prefab concrete (core also made of prefab concrete), Hollow core slab.*
      2nd place: *Tube: diagrid, Prefab concrete, Hollow core slab*.
      3rd place: *Shear walls, Cast in-situ, Hollow core slab.*

Ultimate goal for the tool

The ultimate goal for this tool can be to create an excel-database that includes the *Cost* and *Sustainability* (and maybe even more project starting points) for all building types that can be found in practice. This way the structural engineer can gain insight in the dynamics of the decision-making process of high rise buildings in the Netherlands and the differences that were found between theory and practice can become less of an issue.

11. Discussion and recommendations

The results that have been acquired and have been described in this thesis are partly based on assumptions and therefore have also limitations. Below, these assumptions and limitations will be mentioned and there will be explained how future research can respond to this.

Remarks regarding the two chosen project starting points:

- The focus of this thesis lies on direct and indirect building costs. This is however a *part* of the total investment.
- The environmental cost calculated in this thesis takes only the production phase (A1-3) into account. This is a cradle-to-gate assessment, while the most accurate assessment would be a cradle-to-cradle assessment. The lack of structured and reliable information means it would take too much time within the limits of this thesis to acquire all the needed information for a cradle-to-cradle assessment. Further research would give a more complete picture of the *combination* that would be the most sustainable.

Remarks regarding the found differences in the structural material choice process:

- This thesis only focused on Differences 2 and 3, because these differences could be addresses by creating an excel-tool. Differences 1 (not steel) and 4 (arguments and expectations don't match reality) however can also be further researched.

Design options to expand the excel-tool with are:

- The foundation is now not included in the calculations. The foundation only accounts for 2% of the cost (see Table 5), but accounts for 13% of embodied carbon (Wolf, 2014). Also, a lot of delays in construction time are caused by unexpected soil conditions on which the foundation needs to be build. Foundation thus has a large influence on the project starting point of sustainability.
- This thesis used only cast-in-situ concrete cores for the calculations. However, also prefab concrete cores and maybe even steel cores are interesting the use in the calculations.
  Also, a mix of structural materials is interesting to research. For example: a concrete core with a steel frame or a concrete tube with a steel frame. These systems combine the light weight of the steel with the stiffness of the concrete at places where it is needed.
- Create different plans. This thesis and Lankhorst both use a square plan with a core in the middle. A rectangular plan with more cores is, especially for housing lower than 150 m, a building type that is widely used in the Netherlands a lot. The stability system of *Shear walls*, often used at high rise with housing as a function, is then also very interesting to apply.

Extra testing of the tool can be done by:

- Performing calculations to check if the graphs in this thesis, for each stability system, about *Sustainability* and *Cost* are right; especially for the lower high rise buildings (lower than 150 m). Figure 23 shows the height range of each stability system and the blue triangles show at which height calculations are performed. With the outrigger and the tube stability systems there's a lack of blue

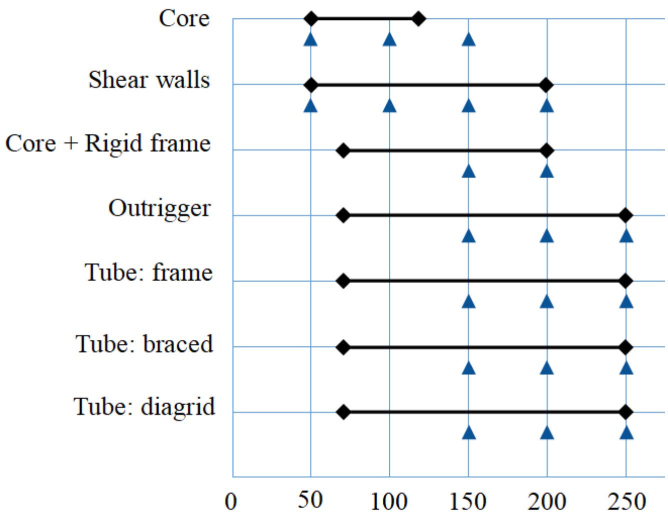


Figure 23: The height range of the stability systems used in this thesis are shown in black. The blue triangles indicate at which height cost and sustainability calculations are performed.

triangles in the lower heights. To check the accuracy of the performed extrapolation, extra calculations are needed here.

- During the verification the content of the tool was compared to reality at two points: construction time and cost. As can be seen in Figure 24, the flow of *Cost* is validated at two points, while the Sustainability isn't validated due to lack of information. Extra research needs to be performed, to *also* validate the *Sustainability*.
- The verification of cost was performed with *only* eight buildings. To be able to draw a substantiated conclusion, more buildings need to be used in the verification.

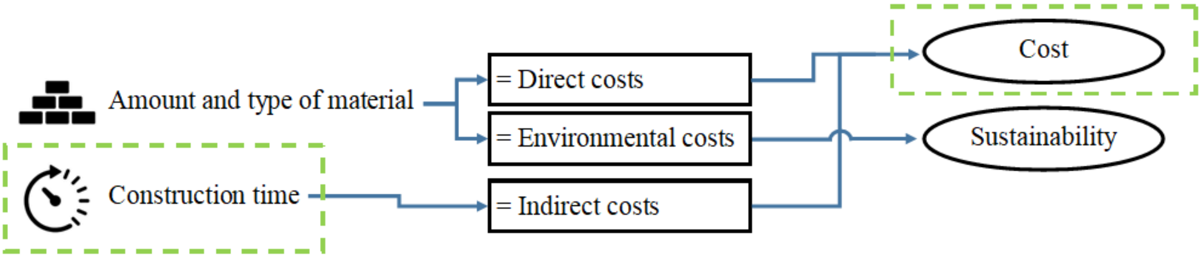


Figure 24: The calculation flow chart, showing how the direct costs, indirect costs and environmental costs of each of the twenty-six structural *combinations* have been calculated. The two points in the calculation process of the tool that were validated are circled with a green square: construction time and cost.

When other designs and height, as described above, are added to the database and also their cost, construction time and sustainability are calculated, the database becomes more complete. When more design options have been added to the database, this gives the structural engineer a better idea about how the structural typology and the structural material influence the cost, construction time and sustainability.

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APPENDICES

A. Parameters influencing the structural material choice

While performing a literature study after the high rise buildings in the Netherlands, all sorts of parameters came up regarding the structural material choice process. These parameters will be used to explore the scope of this thesis by visualising them in a mind map. After that the structural material choice and the structural typology are further discussed, because these two factors influence each other and will be used during this thesis.

A.1. Mind map

Figure 25 shows all the factors that are part of the design process of high rise buildings and need to be kept in mind when the structural material process is researched during this thesis. Some of these factors will come back in other parts of this thesis. Other factors are outside the scope of this thesis, but needed to be kept in the back of the mind.

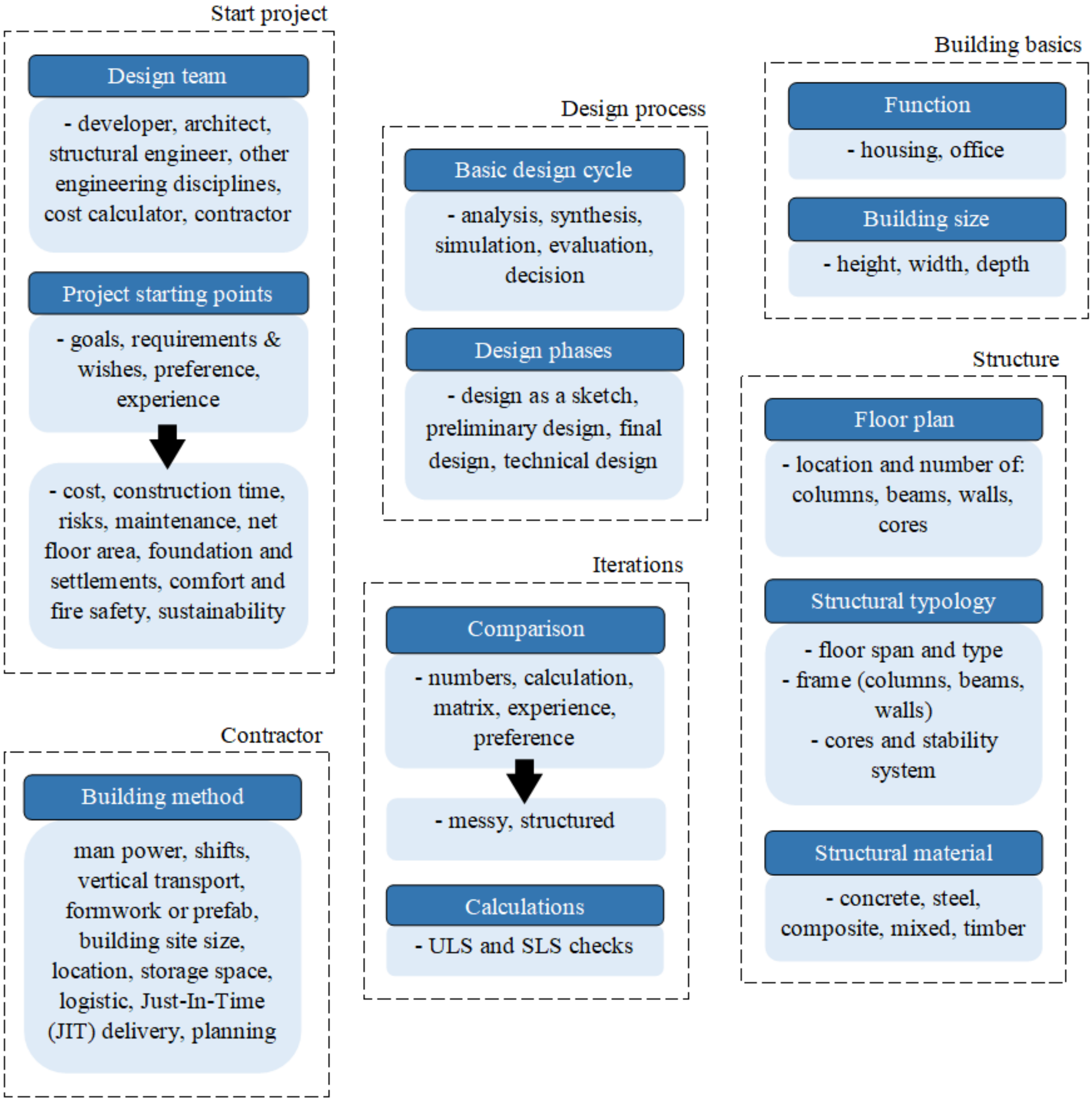


Figure 25: A mind map that includes all the factors that play a role in this thesis.

A.2. Material choice: concrete or steel?

In Table 22 the material properties, structural properties and advantages and disadvantages of concrete and steel are shown. The starred aspects (*1 to *6) have an extra explanation below the table.

Table 22: The properties of concrete and steel as material and the differences when they are applied in a structure.

	Concrete: Cast in-situ	Concrete: Prefab	Steel
Material properties			
Weight*1	2400 kg/m^3		7800 kg/m^3
Compressive strength	C12/15 = 12 N/mm^2 to C55/67 = 55 N/mm^2		S235 = 235 N/mm^2 S275 = 275 N/mm^2 S355 = 355 N/mm^2
Tensile strength	C12/15 = 1.57 N/mm^2 to C55/67 = 4.21 N/mm^2		S235 = 235 N/mm^2 S275 = 275 N/mm^2 S355 = 355 N/mm^2
Modulus of elasticity	30 000 N/mm^2 *(10 000 N/mm^2 when cracked)*		210 000 N/mm^2
Failure	Brittle failure (creep and cracking) *> Reinforced concrete as a solution*		Deformation (lateral and flexural buckling)
Structural properties			
Economic floor span	6 – 9 m	9 – 12 m	> 12 m (limited by transport)
Profile size	Large	Medium *(because more optimized)*	Small
Connections	Cast (easy)	Injections or welding (difficult)	Bolted or screwed (easier)
Building site size	Space needed to cast concrete.	Can be assembled immediately or needs to be stored.	Can be assembled immediately or needs to be stored.
Vertical movement	Liquid concrete with crane or pump and formwork and falsework with construction or jump elevators.	Elements are heavy, so more crane movement needed.	Elements are light, so less crane movement needed.
Strength	50% after 1 day; 100% after 28 days.	100% gained in factory.	100% immediately in factory.
Advantages and disadvantages *(++ = very good; -- = very bad)*			
Net floor height*2	-	+	++
Fire resistant	++	++	-- *> Fireproof insulation as a solution*
Water resistant	++	++	-- *> Waterproof sealant as a solution*
Sound insulation	++	++	-- *> Sound insulation as a solution*
Free form of elements	++	+	--
Adaptability during construction	++	--	--
Material price*3	++ (consistent)	++ (consistent)	(fluctuates)

Assembly difficulty[*4]	++	+	--
Recyclability & re-use[*5]	--	-	++
Shadow price[*1]	++	++	--
Preparation time[*6]	++	--	--
Construction time[*4]	--	+	++
Experience in the Netherlands	++	+	--

*1: Concrete as a material is lighter and has lower shadow price sustainable than steel. However, steel profiles often need to use less material than concrete profiles, because steel is stronger than concrete. This results in the fact that concrete structures are heavier and less sustainable than steel structures.

*2: Steel uses smaller profiles and thus results in a smaller the beam and floor height. Also, installations can be integrated in a steel structure. Both reasons result in thar fact that steel has a smaller net floor height than concrete.

*3: Steel and cement prices and the amount in which they are produced, are determined by global market (Paul, 2013). In general, the prices for concrete are lower and more consistent than the ones for steel.

*4: The construction time for steel is shorter than for concrete. Steel goes three floors per week and concrete two floors (based on 60 hours work per week in the USA) (Sterken & Timmermans, 1988). However, for the assembly of steel the workers need to have higher skills.

*5: Concrete can be reused as a replacement for aggregate. However, in practice only 20% of the aggregates are replaced by reused concrete. 50% Of the steel profiles are reused and the other 50% are recycled into scrap (Faber & Vákár, 2013).

*6: Prefab concrete and steel have a longer preparation time, but a shorter construction time when compared to cast in-situ concrete. This is caused by the fact that the prefab concrete and steel already have their full strength when arriving on the building site. When arriving on the building site the elements can be assembled quickly. However, to make sure everything can be assembled fast, a long preparation time is needed to design all required details. After the design of a prefab steel building has been given to the company delivering the steel elements, it takes about three months before its ready in the Netherlands (Paul, 2013).

Material type of structural elements

Table 23: Which structural element can be executed in which material (Faber & Vákár, 2013)?

	Material
Foundation	Concrete (Steel only temporary structures)
Columns	Concrete, Steel, Composite, Mixed
Beams	Concrete, Steel, Composite, Mixed
Floors	Concrete, Composite
Shear walls	Concrete, Steel, Composite, Mixed (In practice core is often concrete)

Table 23 shows which structural element in a building can be designed in which material (Faber & Vákár, 2013):

- Foundations and water retaining structures are made of concrete. Only temporary situations like building pits use steel.
- Columns can be made of steel or concrete. Steel columns are slimmer, but need a fire safety coating so eventually will approach the size of concrete column. When high-strength concrete is used, the difference between concrete columns and steel columns also becomes less.
- Beams can be made of steel and concrete. Concrete beams need reinforcement to take the bending of the beam. The concrete needs to crack for the reinforcement to work. This reduces the stiffness of the concrete and thus the size of the concrete beam needs to be larger to achieve the same amount of strength as a steel beam. Thus, concrete beams are larger than steel beams. Steel beams can also be better integrated with the floor.
- Floors are always made of concrete or at least include concrete.

- Shear walls can be made of concrete or steel. The core is often made of concrete, but can also be made of steel.

Steel and concrete can also be mixed in a building and work perfectly together, combining features of both materials (Paul, 2013). This means that structural elements executed in different materials can work together. For example: a concrete tube taking the wind loads and working together with a steel frame to take the vertical loads. This reduces the own weight of the building on the foundation, while the wind load is still easily taken by a concrete structure (Sterken & Timmermans, 1988). Also, steel and concrete can work together inside the structural elements; for example, in a steel deck floor.

A.3. Structural typology: stability systems and floor types

A high rise building needs to be able to take vertical and horizontal loads. Vertical loads are the own weight of the building and permanent and variable loads. The wind load is the most important horizontal load in the Netherlands. Because the wind load increases with height, high rise buildings require a special structural system to take this load: the stability system.

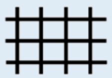
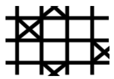
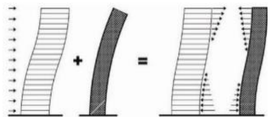
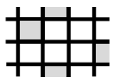
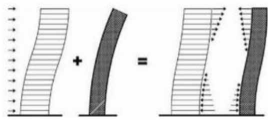
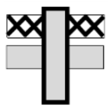
Stability systems

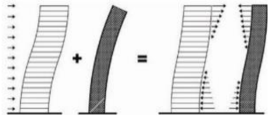
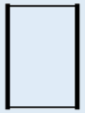
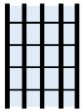
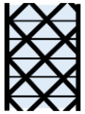
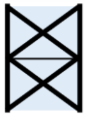
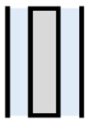
There are roughly five basic types of stability systems (see the blue rows in Table 24). The two most basic ones are the *braces* in steel or the *wall* in concrete. These two systems are often used in flats or industrial halls. The *rigid frame* is a combination of columns and beams and is more suitable for low rise buildings. The most common stability system is *the core,* using the area for the elevators – and the vertical transport of gas, water and light – for structural stability. These four stability systems can all be combined. If these combinations still can't take the load, using the whole building as a 'core' can work. A *tube* structure is a stability system that is located on the outside of the building, together with the façade. Depending on the chosen material, each one of these stability systems can get a different outlook.

In Table 24 the five basic stability systems (blue rows) and their combinations (white rows) are shown (Ali & Moon, 2007; Sterken & Timmermans, 1988). The table then shows which stability system can be executed in which material: concrete or steel. Table 24 shows that all five basic stability systems can be executed in concrete and in steel, except for the two most basic ones: a brace and a shear wall. A brace can only be executed in steel, because concrete can't take tension and concrete cross section profiles become very large. Also, a brace requires a lot of connections and these are easier to execute in steel. A shear wall is often made of concrete, because concrete has a high shear stiffness. A steel shear wall would be very thin and would need extra measures to prevent buckling under the shear load.
Cores are often executed in concrete – because extra fire safety measures need to be taken when executed in steel – but *can* also be executed in steel. The *tube diagrid* is a lot of braces connected to each other and is not executable in concrete for the same reason as the *brace*: too many connections and concrete cross section profiles would be too large. With a *tube braced* the columns form a pattern with windows in between. The bracing can be done with a steel cross or when some of these windows are filled up in a large cross shape, a concrete brace is created.

The combination *concrete* core with a *steel* rigid frame or *concrete* tube with *steel* rigid frame tries to combine the best of concrete and steel. The stiff concrete can take the dynamic load of wind, while the steel carries the vertical loads. This results in flexible floor plan, low own weight of the building and a high building speed. Only in the execution the steel and concrete building process planned around each other. Often the inner core in built first, after that the frame follows a few floors later and the façade or the tube comes after that (Sterken & Timmermans, 1988).

Table 24: The different types of basic stability systems are coloured blue. The white rows contain combinations of these systems (Ali & Moon, 2017; Sterken & Timmermans, 1988). Every row shows if the stability system can be executed in concrete (grey) or steel (red.)

Stability systems *Height (concrete or steel)*	**Symbol**	**Description**	**Concrete**	**Steel**
Braces *To 10 floors.*		Braces can be placed in a K or X shape. A brace is a triangular system with only axial deformation when loaded.		X
Shear walls *To 30 floors.* *(If the core and some walls are made of shear walls, the building can go to 70 floors.)*		A thick wall that takes horizontal lateral forces perpendicular to the plane of the wall.	X	
Rigid frame *To 20 or 30 floors.*		Columns and beams form a frame. The connections are (semi-)rigidly connected and let the beams and columns work together to takt the wind load.	X	X
Rigid frame + Braces *To 40 floors.*		The frame takes the shear load and the braces take the bending (Sterken & Timmermans, 1988). 		X
Rigid frame + Shear walls *To 70 or 60 floors.*		The frame takes the shear load and the shear walls take the bending (Sterken & Timmermans, 1988). 	X	
Core *To 50 floors.*		The elevator shaft serves as a spine in the building, taking the horizontal wind load.	X	X
Core + Braces and/or Shear walls as Outrigger *To 150 floors.*		The core can be combined with an outrigger. The outrigger creates a stiff floor that connects the core to the façade. When the core bends because of the wind load, the columns in the façade pull the core back.	X	X

Core + Rigid frame *To 50 floors.*		The frame takes the shear load and the core takes the bending (Sterken & Timmermans, 1988). 		
Tube		The whole building is treated as if it’s a core. This means the stability elements are located on the outside of the building; in or behind the façade.		
Tube: Frame *To 60 or 80 floors.*		A frame with rigidly connected columns and beams in the façade. The façade then becomes a tube with small holes for windows. Shear lag can reduce the effectivity.		
Tube: Diagrid *To 100 floors.*		The tube contains only x-shaped braces. This creates a very stiff tube with only axial deformations. Disadvantage is the large amount of connections. Also, vertical loads are taking a detour, so this makes the cross sections profiles larger.		
Tube: Braced *To 100 floors.*		Columns at a normal distance, made stiff by large diagonals (braces). These diagonals take the wind load and pass in on to the vertical columns.		
Partial tube *To 100 floors.*		Only *parts* of the building are enclosed with a tube structure (viewed from above often in a U-shape, to maintain the symmetry).		
Tube in Tube *To 80 floors.*		The façade and the core are used as two tubes working together. The number of holes in the façade determines how much of the wind load, the outer tube takes. The outer tube is connected to the core with the floors. The inner tube takes the shear load and the inner tube (core) takes the bending.		

Floor types

Table 25 shows a list of all possible floors types that can be used in high rise buildings. Each floor type includes concrete, but some are prefabricated and some cast in-situ.

Table 25: The floor types that are used in high rise buildings. The table states if the floor is prefabricated or cast in-situ and what the maximum span is (TU Delft, 2000).

Floor type	Cast in-situ or Prefab	Span
Traditional floor (Flat slab)	Cast in-situ & Prefab	8 m (10 m with pre-tension)
Strip floor & Waffle floor	Cast in-situ	8 m (10 m with pre-tension)
Composite slab	Cast in-situ	9 m
Wide-slab floor	Cast in-situ & Prefab	8 m (10 m with pre-tension)
Hollow core slab	Prefab	6 m to 17 m
Bubble deck floor	Prefab	8 m to 12 m
Double-T floor	Prefab	2 m to 22 m
Wing floor plate	Prefab	8 m
Massive floor	Prefab	m

B. Orientation interview questions

The interviews were conducted in Dutch. The English translation can be found below the Dutch questions. The numbered sentences are the questions that were asked. The *italic* sentences are things I say, must remember or can suggest.

B.1. The orientation interview questions (Dutch version)

Introductie

Introductie van mijzelf en het afstudeeronderzoek. Mijn naam, opleidingen, leeftijd, stage en afstudeerperiode. Introductie van de ander.
Het onderwerp: hoogbouw en materiaalkeuze. Het is lastig om een constructief materiaal al zo vroeg in het ontwerpstadium te kiezen. Dit is een onderzoek naar het keuzeproces en de knelpunten.

Alle extra input is welkom: opmerkingen, toevoegingen, tips, meningen, ervaringen, projecten. Omdat u een van de eerste geinterviewden bent, vraag ik u aan het einde ook of u vragen mist.

Over de bronvermelding. Ik kan de geinterviewden anoniem, met alleen bedrijfsnaam of met hun eigen naam benoemen. Na het interview, zal ik vragen wat uw voorkeur heeft.
Daarnaast wil ik dit interview graag opnemen. Ik alleen zal toegang tot deze bestanden hebben en ik zal ze alleen voor mijn afstudeeronderzoek gebruiken.

Opname aan.

Eerste een introductie van het gebouw waar we het over gaan hebben. Hiermee check ik of mijn informatie overeenkomt met uw informatie en kunnen we een beetje inkomen.

- Naam, hoogte, functie, stad gebouw.
- Stabiliteitssysteem.
- Constructief materiaal: stabiliteitssysteem en frame.

1. Zijn er aan het begin van uw hoogbouwproject meerder ontwerpdoelen/eisen naar voren gekomen voor het gebouw?
   (kijk naar Table 26)

De constructieve materiaalkeuze binnen uw hoogbouwproject

Nu gaan we het hebben over het ontwerpproces van het gebouw, met de focus op de constructieve materiaalkeuze.

2. Wie werd er wanneer bij het ontwerp betrokken?
   (Ontwikkelaar, architect, constructeur, installaties, aannemer (al in de ontwerpfase?))
3. Wie initieerde het constructieve materiaalkeuzeproces?
   (constructeur en/of aannemer, vanuit bouwmethode)
4. Wanneer werd het constructieve materiaal gekozen?
   (concept en / of definitief)

Table 26: Overzicht met alle ontwerpdoelen/-eisen (deze lijst is terug te vinden in Hoofdstuk 2).

Doelen / Eisen:	Argumenten:
Kosten	Goedkoop of duur; Stijfheid; Ervaring met het materiaal; Duurzaamheidscertificaat
Bouwtijd	Verticaal transport; Aanpasbaar; Ervaring met het materiaal; Vroege start; Bouwsnelheid; Verbindingen; Weersomstandigheden (vrieskou, wind)
Risico’s	Verticaal transport; Ervaring met het materiaal
Onderhoud	?

Netto vloeroppervlak	Profielgrootte
Fundering en zettingen	Eigen gewicht
Comfort (geluid- en wateroverlast) en brandveiligheid	Brandveiligheid, waterbestendig, geluidswerend;
Duurzaamheid	Flexibele plattegrond; Duurzaamheidscertificaat

5. Hoe werd het constructieve materiaal gekozen?
(denk aan ervaring, voorkeur of eisen/doelen/argumenten uit Table 26, of gewoon aangenomen?)

6a. Dus er was een **voorkeur** voor bepaald een materiaal?

6aa. Ja: waarop was die voorkeur gebaseerd? *(Ervaring of persoonlijke argumenten uit* Table 26

6ab. *Ja:* Waarom is het constructieve materiaalkeuzeproces zo gelopen?
(geen tijd of geld voor vergelijking, materiaal gwn aangenomen)

6b. Dus er zijn verschillende constructieve materialen met elkaar **vergeleken**?

6ba. Ja: hoe zijn deze met elkaar vergeleken? (met een matrix of berekening)
*Bepaald doel (*Table 26*) voor ogen?*

6bb. Ja: Zijn volgens u alle opties bekeken?

6bc. Ja: Zijn volgens u alle opties objectief vergeleken?

6bd. Ja: Kwamen de verwachtingen (*de argumenten*) overeen met de werkelijkheid?

Even samenvatten van het constructieve materiaalkeuzeproces tot nu toe: "Dus het materiaal is in uw hoogbouwproject zo gekozen: ... (ervaring, vergelijken, voorkeur, niet bewust gekozen)"

7. Verliep het constructieve materiaalkeuzeproces objectief?
Nee: Welke processstappen of personen creeren deze subjectiviteit?
Ja: Dus zal het constructieve materiaalkeuzeproces nu verloopt, is het geen probleem? *STOP*
8. Is het een probleem dat het materiaalkeuzeproces, zoals u het beschreven heeft, zo verloopt?
Ja: Waarom? *(projecten gaan niet door, overschrijden kosten of tijd)*
Nee: *STOP*
9. Hoe kan het constructieve materiaalkeuzeproces verbeterd worden?
(*hulpmiddelen, bouwcultuur, benoemen van subjectiviteit*)
10. Zullen deze oplossingen het materiaalkeuzeproces verbeteren?

Afsluiting

Dit waren mijn vragen. Hartelijk bedankt.

- Mist u nog vragen?
- Heeft u nog opmerkingen, toevoegingen, tips of ervaringen?
- Hoe wilt u dat er naar u verwezen wordt: anoniem, medewerker van uw bedrijf, of uw naam?

B.2. The orientation interview questions (English version)

Introduction

Introduce myself and the thesis research. My name, education, age, internship and graduating time span. The other person introduces himself/herself.
The subject: high rise and material choice. It is difficult to choose the structural material early on in the design process. This is a research after the process and the difficulties.

All extra input is welcome: comments, additions, tips, opinions, experiences, projects. You are one of ther first interviewees; that's why at the end I will ask if you miss any questions.

About source reference: I can mention interviewees anonymously, as employee of their company or with their own name. After the interview I will ask you what your preference is.
Also, I would like to record the interview. Only I will have access to these files and I will only use them for my thesis.

Recording on.

First, let's introduce the building we are going to talk about. I will check if the information I have and you have, are the same and this way we can start up the conversation easily.

- Name, height, function, city.
- Stability system.
- Structural material: stability system and frame.

1. At the start of your high rise project, are project goals/requirements stated for the building? *(see Table 27)*

The structural material choice for your high rise project

Now we're going to talk about the design process of the building, with a focus on the structural material choice.

2. Who was involved when during the design? *(Developer, architect, structural engineer, installations, contractor (already in the design phase?))*
3. Who initiated the structural material choice process? *(structural engineer and/or contractor; from his building method)*
4. When was the structural material chosen? *(concept and / or final)*

Table 27: Overview with all project goals/requirements (this list is taken from Chapter 2).

Doelen / Eisen:	**Arguments:**
Cost	Cheap or expensive; Stiffness; Experience with material; Sustainability certificate
Construction time	Vertical transport; Adaptability; Experience with material; Early start; Construction speed; Connections; Weather (frost and wind)
Risks	Vertical transport; Experience with material
Maintenance	?
Net surface area	Profile size
Foundations and settlements	Own weight
Comfort (sound insulation and water resistance) and fire safety	Fire safety; Sound insulation; Water resistance
Sustainability	Flexibele plan; Sustainability certificate

5. How is the structural material chosen? *(think about experience, preference of goals/requirements from Table 27, or just assumed?)*

6a. So, there was a **preference** for a certain material?

6aa. Ja: waarop was die voorkeur gebaseerd? *(experience or personal arguments from Table 27)*

6ab. Yes*:* Why did the material choice process go like this?

6b. So, several structural materials were **compared** to each other?

6ba. Yes: How are they compared? (matrix or calculation) *(certain goal Table 27?)*

6bb. Yes: Have all options been compared?

(no time/money for comparison, material just assumed)

6bc. Yes: Are all options objectively compared?

6bd. Yes: Did the expectations (*arguments*) meet reality?

A summary of the structural material choice process till now: "So the structural material for your high rise building is chosen as follows: ... (experience, comparison, preference, etc)"

7. Was the material choice process objective?
   No: Which steps in the process created this subjectivity?
   Yes: So, the way the material process now is, is not a problem? *STOP*
8. Is it a problem that the structural material choice process goes the way you described it?
   Yes: Why? *(projects are cancelled or exceed cost or time)*
   No: STOP
9. How can the structural material choice process be improved?
   (tools, change in culture, naming subjectivity)
10. Will these solutions improve the structural material choice process?

Wrapping up

These were my questions. Thank you very much.

- Do you miss any questions?
- Do you have comments, additions, tips or experiences?
- How do you want me to refer to you: anonymously, as employee of your company or with your own name?

C. Orientation interview reports

This appendix contains the interviews of:

- M. Prumpeler (2019) about the Cooltoren.
- P. Alblas (2019) about Het Strijkijzer.
- F. Meijer (2019) about Millennium.
- J. Font Freide (2019) about Het Strijkijzer and De Rotterdam.

The questions and the belonging answers per interviewee are listed below. Sometimes questions were answered in a different order. While creating the reports shown below, the answers were structured again per question. The blue coloured sentences are remarks made by the author of this thesis.

C.1. Interview report M. Prumpeler

Structural engineer: Van Rossum
Interviewed person: Maurice Prumpeler
High rise building: Cooltoren
28-11-2019 9:00 - 9:30

Interview questions

Question 1: At the start of your high rise project, are project goals/requirements stated for the building?

Project goal(s) come(s) from the developer. In this case it was cost. The developer had a budget and wanted a design that fit that budget. This determined if the tower was going to be built or not. The developer determines the goal and that directs the design and the material choice.

Question 2: Who was involved when during the design?

SO: developer and architect.
Start VO: technical advisors.
During VO: contractors. Several contractors were involved during the VO to get their input on the design, optimize the design and make a project feasible. Normally it is not common that several contractors are being tried out.

Question 3: Who initiated the structural material choice process?

Structural engineer. Partially in consult with the contractor.

Question 4: When was the structural material chosen?

VO. The material choice is important to state early in the design process, because it is fundamental: the structure is very important in high rise. Quickly contractors were tried out and if the design didn't meet the budget, the next contractor was invited.

Question 5 and 6: How is the structural material chosen? Preference or comparison?

The function of the Cooltoren is housing. Early in the VO phase the structural engineer decided to use concrete for the floors and the walls, to meet the sound insulation requirements. When 25 cm concrete is used for the floor, the sounds requirement is met (for example, a hollow core slab needs extra measures). Because the function is housing, the walls and the floors are there anyway, so you can better use them for sound insulation.

Together with the contractor the material and the building method were chosen. The contractor always had a preference to build in a certain way, because this is what their production is aimed at. Asking them to change this would result in higher cost.
Tunneling is the cheapest and fastest, but all contractors in this project preferred the traditional way: first casting the walls and then the floors.

The core was early on already designed in concrete with climbing formwork. This results in independency from the cycle time. In general, the contractor tries to create one floor per week.

There were different contractors involved in this project. First, a contractor was tried. If the design exceeded the cost, the developer or the contractor would choose to move on.
After the second last contractor couldn't meet the budget (with a steel outrigger and steel columns), the design team checked again if the tower could be optimized. 1: Extra floors were added above the walkway. 2: the tower was allowed to be a little bit higher than originally. By reducing the floor height from 3 m to 2.95 m, an extra floor could be added. 3: material optimization.
The second last contractor wanted to do the outrigger and the columns in steel. The current contractor uses prefab concrete columns and cast in-situ outriggers, because that is his preference and works the best in their system.

- Summary of the process, by the interviewer:
  Started with a comparison matrix. Then, during the contractor conversations, the contractor's method and the achieving of the goal (cost) become more important.
  So first: Comparison.
  Then in practice: Experience.

Early in the exploring process a matrix was used to see which concrete type works best: prefab, tunneling or cast walls with wide slab floors. That was during the former design (with the dense columns in the façade).
In the end, while having contact with the contractors the design changed. The final design contained a core designed in concrete, because you can't do that in steel.

Question 7: Was the material choice process objective?

No. Partially objective, partially subjective. When a contractor is involved, with their experience and knowledge it becomes based on experience and preference. Going against the building method of the contractor would result in a much more expensive design and that would create a conflict with the project goal: fixed budget.

Question 8: Is it a problem that the structural material choice process goes the way you described it?

It is no problem that the structural material choice process is partially subjective. We as structural engineers can calculated every structure and every material, so the subjectivity doesn't depend on us. We are used to building with concrete in the Netherlands, but I think that the structural engineer tries to choose a material in the most objective way.

Question 9: How can the structural material choice process be improved?

Not applicable.

Question 10: Will these solutions improve the structural material choice process?

Not applicable.

C.2. Interview report P. Alblas

Contractor: Boele & Van Eesteren
Interviewed person: Paco Alblas
High rise building: Het Strijkijzer
28-11-2019 15:00 – 16:00

Developer: Vestia
Structural engineer: Aveco Bondt
First contractor (before Boele & Van Eesteren): Heijmans

Interview questions

Question 1: At the start of your high rise project, are project goals/requirements stated for the building?

- The building site was only 800 m2 and located in the middle of the city center with transport all around. Safety was thus very important.
- Short construction time, the developer always wants this. If the market now wants houses or offices, this can change quickly, so a building needs to be ready quickly. No investor can predict the market.
- Flexible building, from the developer this time.

Prefab or cast in-situ concrete depends on the market. A thriving economy results in full factories and high prices.
Steel? No that's American. Halls are made of steel, but the building culture in the Netherlands is not directed at steel. We don't think about it. There's also no experience with it. It's not the tradition. Steel is combined with traditional floors, so prefab concrete is then more modern. Also, cost of steel is high and depended on the world market.

Question 2: Who was involved when during the design?

First, there was another contractor involved (Heijmans). The DO was already finished then. We got involved in the TO and the design had to be revised to go from cast in-situ concrete to prefab.

Question 3: Who initiated the structural material choice process?

VO by Heijmans.
TO by Boele & Van Eesteren.

Question 4: When was the structural material chosen?

Heijmans and the structural engineer have decided to tunnel. Then this collaboration didn't work out. Prefab was advised in TO by us as contractor and the structural engineer was convinced to do design it in prefab.

Question 5 and 6: How is the structural material chosen? Preference or comparison?

Prefab was chosen based on the fact that logistics are easier; the construction space was small and prefab created safety for the workers and passers-by.
There was not a huge difference in cost between cast in-situ concrete and prefab this project.

Tunneling is still the most common way, because it's still the cheapest and fastest. The first contractor Ballast Nedam wanted to do tunneling, but Boele & Van Eesteren wanted to do prefab from the beginning. Prefab doesn't need all the roads closed off for safety.
Prefab however can be more expensive, because of the crane type needed (depending on the size of the elements).

Between getting the assignment and starting construction, the contractors in the Netherlands only have three months to start. This means mostly the lower floors are cast in-situ concrete (and because the commercial lower floors don't have repetition in it), so that this leaves time to draw (8 months in this case) and send the other floors to the prefab factory. After that, the delivery of prefab can take up to 10 months in the current overheated market.

The expectations met the reality.

Question 7: Was the material choice process objective?

Yes.

Question 8: Is it a problem that the structural material choice process goes the way you described it?

No.

Question 9: How can the structural material choice process be improved?

Not applicable.

Question 10: Will these solutions improve the structural material choice process?

Not applicable.

C.3. Interview report F. Meijer

Contractor: Ballast Nedam
Interviewed person: Fred Meijer
High rise building: Millennium
29-11-2019 9:00 – 10:00

Interview questions

Question 1: At the start of your high rise project, are project goals/requirements stated for the building?

Ballast Nedam was involved too late in the process too know this, because they often come up in the design process.

Question 2: Who was involved when during the design?

We as contractor were involved after the design. The contract included partial responsibility for the design, but we were not really involved.

Question 3: Who initiated the structural material choice process?

Structural engineer.

Question 4: When was the structural material chosen?

Ballast Nedam was involved too late in the process too know this, because they often come up in the design process.

Question 5 and 6: How is the structural material chosen? Preference or comparison?

Stability and money, I think. In the USA steel is more normal, but why? I didn't really think about that. Cast in-situ concrete makes a building site messier, so prefab could solve this problem.

Question 7: Was the material choice process objective?

What is objective?

"Objective", as stated by this thesis: based on facts and not on opinions and the opposite of subjective.

No, but as contractor it is less important that the structural material is chosen objectively. We must worry about being able to execute it.

Question 8: Is it a problem that the structural material choice process goes the way you described it?

No.

Question 9: How can the structural material choice process be improved?

Not applicable.

Question 10: Will these solutions improve the structural material choice process?

Not applicable.

C.4. Interview report J. Font Freide

Structural engineer: Royal Haskoning
Interviewed person: Jan Font Freide
High rise buildings: Het Strijkijzer and De Rotterdam
02-12-2019 9:00 - 9:45

First contractor: IBC
Second contractor: Boele & Van Eesteren

Interview questions: Het Strijkijzer

Question 1: At the start of your high rise project, are project goals/requirements stated for the building?

At the beginning: the small building site and safety were important (and created a preference for prefab concrete with the second contractor).
The second contractor compared cast in-situ concrete and prefab, based on cost and construction time. Eventually prefab was chosen.

Question 2: Who was involved when during the design?

The architect initiated the process and had taken in structural engineers for advice. Then a developer was involved. Eventually a contractor was added to the design team.

Question 3: Who initiated the structural material choice process?

The first contractor wanted a prefab structure. When that didn't work, the structural engineer made a design in cast in-situ concrete. Eventually the second and final contractor preferred prefab concrete, so this became the final material.

Question 4: When was the structural material chosen?

After the tender, so after the TO.

Question 5 and 6: How is the structural material chosen? Preference or comparison?

It is never very clear why. It doesn't really depend on rules. It is biased.

After the design was made and the developer was involved, the developer had a design team with a structural engineer and a contractor. The first contractor preferred prefab concrete, because they had a factory for this and thought it was easier in prefab. So, the first design was prefab. This turned out to be too expensive, so a tender was started to select another contractor.
The structural engineer thought it was easier to use cast in-situ concrete, so they changed the design. Then a second contractor became involved and they again preferred a prefab structure.
The contractor gave for both cast in-situ and prefab a price and a construction time. The prefab design was more expensive, but had a shorter construction time. The developer then calculated if a shorter construction time would overcome the extra cost. Eventually this turned out to be the case and the prefab structure was chosen.

It is a very small building site with traffic all around. That is the reason the structural engineer wanted a cast in-situ structure. With a prefab structure, large elements need to be transported to the building site and lifted above passers-by. With tunneling there was just enough space to pull out the tunnel, above a piece of ground that had no traffic on it.

Eventually the building was still executed in prefab concrete. The second contractor constructed a roof to protect the passers-by against small things that fall. When large elements needed to be transported above the roads, the trams were stopped.
(From the interview with the contractor Boele & Van Eesteren (see chapter 0) we hear that they got no complaints from the trams).

Concluded: the structural material choice was based on the preference of the contractor and the construction time.

However, according to the structural engineer, it is not always true that prefab is always constructed faster. If you have a contractor that can has experience with cast in-situ, it can be equally fast.
Steel is always checked in the design phase, but it never seems to be the optimal solution, because of fireproof coating (the cost and time to execute it).

Interview questions: De Rotterdam

Question 1: At the start of your high rise project, are project goals/requirements stated for the building?

Cost and construction time.

Question 2: Who was involved when during the design?

The structural engineering was involved from the beginning. However, it took ten years before the building could be executed. In the end a German contractor was chosen.

Question 3: Who initiated the structural material choice process?

The structural engineer.

A lot of contractors tried to meet the design requirements, but they all turned out to be too expensive (all sorts of materials were tried out by them, including steel). In the end a German contractor was chosen. The contractor was thus very important the realize the project.
Funnily enough, the original design and material choice (cast in-situ concrete) of the structural engineer were executed in the end, after all these contractors.

Question 4: When was the structural material chosen?

The structural engineer made the design in the VO.

Question 5 and 6: How is the structural material chosen? Preference or comparison?

The structural engineer wanted to execute in cast in-situ concrete.
After that, a lot of contractors were trying to match the required cost and construction time of the developer (by using all sorts of materials). A lot of them were too expensive. Also, sometimes the developer didn't have buyers.
This process took ten years. Eventually cast in-situ concrete was applied.

Steel was checked too, by the structural engineer who went to England to gain knowledge. The structural engineer started a collaboration with Hollandia. Together they also made a design. However, in the end this also turned out to be too expensive and take too long, because the fireproof coating.
Steel often doesn't work. Also, with offices. The cost of steel often fluctuates, so that it might be too expensive is not per se the problem. Compared to foreign buildings, our buildings are not more expensive, but we are just very good at making concrete buildings.

Interview questions: General

Question 7: Was the material choice process objective?

What is objective?

"Objective", as stated by this thesis: based on facts and not on opinions and the opposite of subjective.

It is a combination of objective and subjective; maybe more experience and preference (subjective). The structural engineer compares option. Then the contractor bases things on experience and preference.

Question 8: Is it a problem that the structural material choice process goes the way you described it?

No problem.

Question 9: How can the structural material choice process be improved?

Not applicable.

Question 10: Will these solutions improve the structural material choice process?

Not applicable.

D. Online survey questions

The online survey was conducted in Dutch. The English translation of the questions can be found below the Dutch questions.

D.1. Online survey questions (Dutch version)

Mijn naam is Esmee Koopman en ik ben op dit moment bezig met mijn afstudeeronderzoek voor de master Building Engineering aan de TU Delft. Daarnaast loop ik ook stage voor mijn afstuderen bij Arcadis in Rotterdam. Voor mijn master heb ik mijn bachelor Civiele Techniek aan de Universiteit Twente afgerond.

Hoogbouw heeft al heel lang mijn interesse en tijdens mijn afstudeeronderzoek richt ik me op de constructieve materiaalkeuze voor hoogbouw in Nederland. Het is lastig om een constructief materiaal vroeg in het ontwerpstadium te kiezen en daarom wil ik onderzoeken hoe het keuzeproces verloopt en waar de knelpunten in dit proces zitten. Deze enquête is een hulpmiddel om hier achter te komen en ik ben dan ook erg blij wanneer u input zou willen geven voor mijn onderzoek.

Wat is uw email adres?

____

Over de bronvermelding in het uiteindelijke rapport: Ik kan u anoniem, als medewerker van uw bedrijf of met uw eigen naam benoemen. Aan het einde van de enquete, zal ik vragen wat uw voorkeur heeft.

Wat is uw (voor- en achter)naam?

____

Voor welk hoogbouwproject bent u gevraagd deze enquête in te vullen?

____

Voor welk bedrijf werkt(e) u aan dit hoogbouwproject?

____

Introductievragen over uw hoogbouwproject

1. Wanneer werd de constructeur voor het eerst bij het ontwerp betrokken?
O Schetsontwerp
O Vroeg in het voorontwerp
O Later in het voorontwerp
O Vroeg in het defintief ontwerp
O Later in het defintief ontwerp
O Technisch ontwerp
O Anders: ____

2. Hebben meerdere aannemers een ontwerppoging gedaan om uw hoogbouwproject uit te mogen voeren? Of maar eentje?
O Meerdere > Ga naar vraag 4 en 5
O Eentje

3. Wanneer werd de aannemer bij het project betrokken?
> Ga hierna naar vraag 6
O Schetsontwerp
O Vroeg in het voorontwerp
O Later in het voorontwerp
O Vroeg in het defintief ontwerp
O Later in het defintief ontwerp
O Technisch ontwerp
O Uitvoering (na alle ontwerpfases)
O Anders: ____

4. Wanneer werd de eerste aannemer bij het ontwerp betrokken?
O Schetsontwerp
O Vroeg in het voorontwerp
O Later in het voorontwerp
O Vroeg in het defintief ontwerp
O Later in het defintief ontwerp
O Technisch ontwerp
O Uitvoering (na alle ontwerpfases)
O Anders: ____

5. Wanneer werd de uiteindelijk aangenomen aannemer bij het project betrokken?
O Schetsontwerp
O Vroeg in het voorontwerp
O Later in het voorontwerp
O Vroeg in het defintief ontwerp
O Later in het defintief ontwerp
O Technisch ontwerp
O Uitvoering (na alle ontwerpfases)
O Anders: ____

6. Zijn er aan het begin van uw hoogbouwproject doelen of eisen vastgesteld voor het gebouw?
Denk bijvoorbeeld aan: zo laag mogelijke kosten, een zo kort mogelijke bouwtijd, zo min mogelijk risico, zo min mogelijk onderhoud hoeven te plegen, een zo groot mogelijk netto vloeroppervlak halen, een kleine fundering of weinig zettingen, efficiënt gebruik van materiaal met als resultaat geluidswering en brandveiligheid, een bepaald duurzaamheidscertificaat halen.
O Ja
O Nee > Ga naar vraag 8

7. Waar hadden deze doelen betrekking op?
O Kosten
O Bouwtijd
O Risico's
O Onderhoud
O Netto vloeroppervlak
O Veiligheid
O Fundering en zettingen
O Comfort (geluid- en wateroverlast) en brandveiligheid
O Duurzaamheid
O Anders: ____

8. Wie waren er betrokken bij de start van het constructieve materiaalkeuzeproces betrokken?
O Ontwikkelaar
O Architect
O Constructeur
O Een van de andere technische disciplines (bijvoorbeeld installaties)
O Kostendeskundige
O Aannemer
O Anders: ____

9. Hoe werd er met het constructieve materiaalkeuzeproces gestart?
O Met een vergelijking van verschillende opties (constructies en materialen). > Ga naar vraag 13
O Er was een voorkeur voor een bepaald materiaal (gebaseerd op ervaring uit eerdere projecten).
> Ga naar vraag 13
O Er is niet bewust gekozen; vanaf een bepaald punt werd er uitgegaan van een bepaald materiaal.
> Ga naar vraag 13
O Anders: ____ > Ga naar vraag 13

10. Welke materialen voor de hoofddraagconstructie (exclusief vloeren) zijn als optie meegenomen in die vergelijking?
O Gestort beton
O Prefab beton
O Staal
O Hout
O Anders: ____

11. Op welke vlakken zijn materialen met elkaar vergeleken?
O Kosten
O Bouwtijd
O Risico's
O Onderhoud
O Netto vloeroppervlak
O Veiligheid
O Fundering en zettingen
O Comfort (geluid- en wateroverlast) en brandveiligheid
O Duurzaamheid
O Anders: ____

12. Zijn alle opties objectief met elkaar vergeleken?
"Objectief", zoals gedefinieerd door dit onderzoek: Gebaseerd op feiten en niet op meningen en het tegenovergestelde van subjectief.
O Ja
O Nee, niet alle opties zijn met elkaar vergeleken.
O Nee, niet alle opties zijn met elkaar vergeleken, maar de meest logische opties zijn met elkaar vergeleken.
O Nee, het vergelijkingsproces gebeurde niet objectief.

13. Wie waren er betrokken bij de definitieve constructieve materiaalkeuze?
O Ontwikkelaar
O Architect
O Constructeur
O Een van de andere technische disciplines (bijvoorbeeld installaties)
O Kostendeskundige
O Aannemer
O Anders: ____

14. Op basis waarvan werd het definitieve constructieve materiaal vastgesteld?
O Op basis van een vergelijking van verschillende opties (materialen en bijbehorende constructies).
> Ga naar vraag 16
O Op basis van een voorkeur voor een bepaald materiaal (gebaseerde op ervaring uit eerdere projecten).
O Er is niet bewust gekozen; vanaf een bepaald punt werd er uitgegaan van een bepaald materiaal.
> Ga naar vraag 16
O Anders: ____ > Ga naar vraag 16

15. Waarom is de materiaalkeuze gemaakt op basis van voorkeur (en ervaring)?
Deze antwoorden zijn gebaseerd op eerdere interviews met personen die betrokken waren bij hoogbouwprojecten. Aanvullingen zijn van harte welkom.
O De aannemer had een bepaalde bouwmethodiek die aansloot bij een bepaald constructief materiaal. De materiaalkeuze werd aangepast op deze bouwmethodiek.
O Er was geen of te weinig tijd of geld voor een objectieve vergelijking (met een matrix of een berekening).
O De voorkeur voor een materiaal kwam voort uit eisen of wensen van een ontwikkelaar of architect.
O Andere manieren (niet gebaseerd op voorkeur of ervaring) om het constructieve materiaal te kiezen, zijn niet ter sprake gekomen.
O Anders: ____

16. Welk constructief materiaal is uiteindelijk voor de hoofddraagconstructie gekozen (exclusief vloeren)?
O Gestort beton
O Prefab beton
O Combinatie van prefab beton en gestort beton
O Staal > Ga eerst naar vraag 17 en 18 en dan naar vraag 20
O Combinatie van beton (prefab en/of gestort) en staal > Ga eerst naar vraag 17 en 18 en dan naar vraag 20
O Anders: ____

17. Wanneer is het constructieve materiaal definitief gekozen?
O Schetsontwerp
O Vroeg in het voorontwerp
O Later in het voorontwerp
O Vroeg in het defintief ontwerp
O Later in het defintief ontwerp
O Technisch ontwerp
O Anders: ____

18. Kwamen de argumenten en verwachtingen waarop de constructieve materiaalkeuze gebaseerd waren, overeen met de werkelijkheid?
O Ja
O Nee
O Weet ik (nog) niet

Herinnering: > Ga naar vraag 20, als je dat bij vraag 16 moest.

19. Waarom is staal als optie afgevallen?
Deze antwoorden zijn gebaseerd op eerdere interviews met personen die betrokken waren bij hoogbouwprojecten. Aanvullingen zijn van harte welkom.
O Te duur en/of het duurt te lang om het brandwerend te bekleden.
O Staal als materiaal is duur en de prijs schommelt te veel.
O Te weinig aannemers kunnen in staal bouwen.
O Wij zijn niet gewend om te bouwen met staal in Nederland. Wij zijn beter met beton.
O Anders: ____

20. In hoeverre bent u het eens met de volgende stelling: "De constructeur begint met het vergelijken van een aantal/alle opties en komt met een voorkeur voor een constructief materiaal gebaseerd op feitelijke argumenten. Op basis hiervan wordt de zoektocht naar een aannemer gestart."
Deze stelling is gebaseerd op eerdere interviews met personen die betrokken waren bij hoogbouwprojecten. Aanvullingen zijn van harte welkom.
O Zeer mee eens
O Mee eens
O Neutraal
O Mee oneens
O Zeer meer oneens

Mocht u willen toelichten: Waarom?

____

21. In hoeverre bent u het eens met de volgende stelling: "De potentiële aannemer probeert met zijn aanbieding (van het gemaakte ontwerp) aan de eisen van de ontwikkelaar te voldoen. Als dit lukt, worden deze aannemer aangenomen. Het kan zijn dat de bouwmethode van de aannemer niet bij het vooraf bedachte constructieve materiaal past. Het constructieve materiaal wordt in dat geval aangepast aan de bouwmethode van de aannemer."
Deze stelling is gebaseerd op eerdere interviews met personen die betrokken waren bij hoogbouwprojecten. Aanvullingen zijn van harte welkom.
O Zeer mee eens
O Mee eens

O Neutraal
O Mee oneens
O Zeer meer oneens

Mocht u willen toelichten: Waarom?

____

Algemene vragen over de constructieve materiaalkeuze in hoogbouwprojecten

22. In het algemeen, verloopt het constructieve materiaalkeuzeproces gestructureerd/objectief?
O Nee, het verloopt subjectief
O Het verloopt deels objectief en deels subjectief
O Ja, het verloopt objectief > Ga naar vraag sectie “Afrondingsvragen”
O Het is (deels) gebaseerd op ervaring, maar dit vind ik niet subjectief. > Ga naar vraag 26

23. Welke personen of processtappen creëren de rommeligheid/subjectiviteit?
O Ontwikkelaar
O Architect
O Constructeur
O Een van de andere technische disciplines (bijvoorbeeld installaties)
O Kostendeskundige
O Aannemer
O Tijdens het schetsontwerp
O Tijdens het voorontwerp
O Tijdens het definitief ontwerp
O Tijdens het technische ontwerp
O Tijdens de uitvoering

24. Is het een probleem dat het materiaalkeuzeproces, zoals u het beschreven heeft, zo verloopt?
O Ja
O Nee > Ga naar vraag sectie “Afrondingsvragen”

25. Waarom is het een probleem dat het materiaalkeuzeproces zo verloopt?
O Projecten gaan niet door.
O De begrote kosten of tijd worden overschreden.
O Omdat de uiteindelijke keuze niet gebaseerd is op een overzichtelijke en logische vergelijking van opties.
O Omdat de kwaliteit of het gebruiksgemak van hoogbouw hierdoor niet zo hoog is als het had kunnen zijn.

26. Hoe kan het materiaalkeuze proces objectiever worden?
O Hulpmiddelen om de invloed van de materiaalkeuze op doelen als kosten, bouwtijd, duurzaamheid, etc te bekijken.
O Het benoemen van de subjectiviteit in het project.
O Verandering in de bouwcultuur. Het materiaalkeuzeproces moet anders uitgevoerd gaan worden.

27. Zullen deze oplossingen het materiaalkeuzeproces verbeteren?
O Ja
O Misschien
O Nee

Mocht u een toelichting willen geven: Ja of nee, want?

____

Afrondingsvragen

Heeft u nog toevoegingen, opmerkingen of vragen? Alle extra input is welkom: tips, meningen, ervaringen, projecten, etc.

____

Mag ik naar aanleiding van uw antwoorden contact met u opnemen, mocht ik verdere vragen hebben of mocht er iets niet duidelijk zijn?
O Ja
O Nee

Hoe wilt u dat er naar u verwezen wordt als bron?
O Bron: 'uw eigen naam'
O Bron: medewerker van 'uw bedrijf'
O Bron: 'anoniem'
O Anders: ____

Dit waren mijn vragen. Hartelijk bedankt.

D.2. Online survey questions (English version)

My name is Esmee Koopman and right now I'm working on my thesis for the master Building Engineering at the Technical University of Delft. I'm doing this, while being an intern at Arcadis in Rotterdam. Before that, I finished my bachelor Civil Engineering at the University of Twente.

For a long time, I've been interested in high rise buildings and for my thesis I will focus on the structural material process for high rise in the Netherlands. It is difficult to choose a structural material early in the design process and that's why I want to research what the material choice process looks like and were the bottlenecks in the process are. This survey is a tool to find this out and I'm very happy with your input for my research.

What is your email address?

____

About source references in the report: I can write you down as anonymous, as an employee of your company or with your own name. At the end of the survey, I will ask what your preference is.

What is your (first and last) name?

____

For which high rise project have you been asked to fill in this survey?

____

For which company did you work/ are you working on this high rise project?

____

Introduction questions about your high rise project

1. When became the structural engineer involved in the design for the first time?
O Design as a sketch
O Early in the Preliminary design
O Late in the Preliminary design
O Early in the Final design
O Late in the Final design
O Technical design
O Other: ____

2. Have multiple contractors attempted to execute your high rise project? Or just one?
O Multiple > Go to question 4 and 5
O One

3. When became the contractor involved in the project for the first time?
> After this, go to question 6
O Design as a sketch
O Early in the Preliminary design
O Late in the Preliminary design

O Early in the Final design
O Late in the Final design
O Technical design
O Execution (after all design phases)
O Other: ____

4. When became the first contractor involved in the project?
O Design as a sketch
O Early in the Preliminary design
O Late in the Preliminary design
O Early in the Final design
O Late in the Final design
O Technical design
O Execution (after all design phases)
O Other: ____

5. When became the final contractor involved in the project?
O Design as a sketch
O Early in the Preliminary design
O Late in the Preliminary design
O Early in the Final design
O Late in the Final design
O Technical design
O Execution (after all design phases)
O Other: ____

6. Are there project goals or requirements established for the high rise project?
For example: lowest cost, shortest construction time, least possible risk, least possible maintenance, largest possible net floor area, a small foundation or least possible settlements, efficient use of material with as a results sound insulation and fire safety, getting a certain sustainability certificate.
O Yes
O No > Go to question 8

7. To which of the following categories, were these project goals and requirements related?
O Cost
O Construction time
O Risk
O Maintenance
O Net floor area
O Safety
O Foundation and settlements
O Comfort (sound insulation and water resistance) and fire safety
O Sustainability
O Other: ____

8. Who were involved at the start of the structural material process?
O Developer
O Architect
O Structural engineer
O One of the other technical disciplines (for example installations)
O Cost expert
O Contractor
O Other: ____

9. How did the structural material process start?
O With a comparison of several options (structures and materials). > Go to question 13
O There was a preference for a certain material (based on experience from former projects).

> Go to question 13
O The choice was not deliberately made; from a certain point a certain material was assumed.
> Go to question 13
O Other: ____ > Go to question 13

10. Which materials for the main load-bearing structure (excluding floors) were taken into account during the comparison?
O Cast in-situ concrete
O Prefab concrete
O Steel
O Timber
O Other: ____

11. Based on which aspects are the materials compared to each other?
O Cost
O Construction time
O Risk
O Maintenance
O Net floor area
O Safety
O Foundation and settlements
O Comfort (sound insulation and water resistance) and fire safety
O Sustainability
O Other: ____

12. Are these options objectively compared to each other?
"Objective", as stated by this thesis: based on facts and not on opinions and the opposite of subjective.
O Yes
O No, not all options have been compared to each other.
O No, not all options have been compared to each other, but the most logical options have been compared to each other.
O No, the comparison wasn't objective.

13. Who were involved in the final material choice?
O Developer
O Architect
O Structural engineer
O One of the other technical disciplines (for example installations)
O Cost expert
O Contractor
O Other: ____

14. Based on what has the final structural material process been chosen?
O Based on a comparison of several options (structures and materials). > Go to question 16
O Based on a preference for a certain material (based on experience from former projects).
> Go to question 16
O The choice was not deliberately made; from a certain point a certain material was assumed.
> Go to question 16
O Other: ____ > Go to question 16

15. Why is the structural material choice chosen based on preference (based on experience?
These answers have been based on answers from previous interviews with people that were involved in high-rise projects. Additions are welcome.
O The contractor had a certain building method that was linked to a certain structural material. The material choice was adapted to the building method.
O There was no or little time or money to perform an objective comparison (with a matrix or a calculation).
O The preference for a certain material came from the requirements or wishes of a developer or architect.

O Other methods (not based on preference or experience) to choose the structural material have not been discussed.
O Other: ____

16. Which structural material has eventually been chosen for the main load-bearing structure (excluding floors)?
O Cast in-situ concrete
O Prefab concrete
O Combination of prefab concrete and cast in-situ concrete
O Steel > First, go to question 17 and 18; next to question 20
O Combination of concrete (prefab and/or cast in-situ) and steel > First, go to question 17 and 18; next to question 20
O Other: ____

17. When has the structural material definitively been chosen?
O Design as a sketch
O Early in the Preliminary design
O Late in the Preliminary design
O Early in the Final design
O Late in the Final design
O Technical design
O Other: ____

18. Became the arguments and expectations on which the structural material choice was based, reality after the project was finished?
O Yes
O No
O I don't know (yet)

Reminder: > Go to question 20, if that was the instruction at questions 16.

19. Why is steel not chosen?
These answers have been based on answers from previous interviews with people that were involved in high-rise projects. Additions are welcome.
O It is too expensive / it takes too long to apply fireproof coating on the steel.
O Too few contractors can build with steel.
O We are not used to build with steel in the Netherlands. We are better with concrete.
O Other: ____

20. To what extent do you agree with the following statement: "The structural engineer starts with a comparison of all/some options and comes up with a preferred structural material based on factual arguments. Based on this, the search for a contractor is started."
This statement has been based on answers from previous interviews with people that were involved in high-rise projects. Additions are welcome.
O Strongly agree
O Agree
O Neutral
O Disagree
O Strongly disagree

If you would like to explain: Why?

____

21. To what extent do you agree with the following statement: "Potential contactors try to meet the requirements of the developer with their offer. If they succeed, the contractor is hired. It might be that the contactor doesn't match the structural material conceived in advance. The structural material is in that case adapted to the building method of the contractor."

This statement has been based on answers from previous interviews with people that were involved in high-rise projects. Additions are welcome.
O Strongly agree
O Agree
O Neutral
O Disagree
O Strongly disagree

If you would like to explain: Why?

____

General questions about the structural material choice in high rise projects

22. In general, is the structural material choice process structured/objective?
O No, it is subjective
O It is partially objective, partially subjective
O Yes, it is objective > Go to question section "Completion"
O It is (partially) based on experience, but I don't think this is subjective > Go to question 26

23. Which people or process steps create this messiness/subjectivity?
O Developer
O Architect
O Structural engineer
O One of the other technical disciplines (for example installations)
O Cost expert
O Contractor
O During the Design as a sketch
O During the Preliminary design
O During the Final design
O During the Technical design

24. Is it a problem that the structural material choice process goes, as you described it?
O Yes
O No > Go to question section "Completion"

25. Why is it a problem that the structural material choice process goes this way?
O Projects are cancelled.
O The expected cost or time is exceeded.
O Because the final choice wasn't based on a well-arranged and logical comparison of options.
O Because the quality or the ease of use are lower than they could have been.

26. How can the structural material choice process become more objective?
O Tools to see the influence of the material choice on project goals and requirements like cost, construction time, sustainability, etc.
O Naming the subjectivity in the project.
O Changing the culture in the building sector. The material choice process needs to be executed differently.

27. Shall these solutions improve the material choice process?
O Yes
O Maybe
O N

If you want to give an explanation: Yes or no, because?

____

Completion

Do you have any additions, comments or questions? All extra input is welcome: tips, opinions, experiences, projects, etc.

____

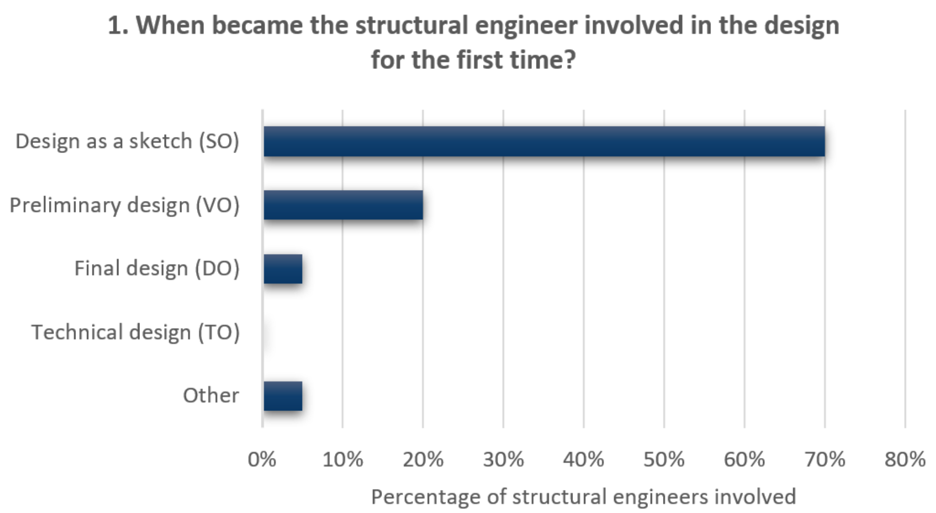
May I contact you, should I have further questions, or should something not be clear about your answers?
O Yes
O No

How do you want to be shown as a source reference?
O Source: ‘your own name’
O Source: employee of ‘your company’
O Source: ‘anonymously’
O Other: ____

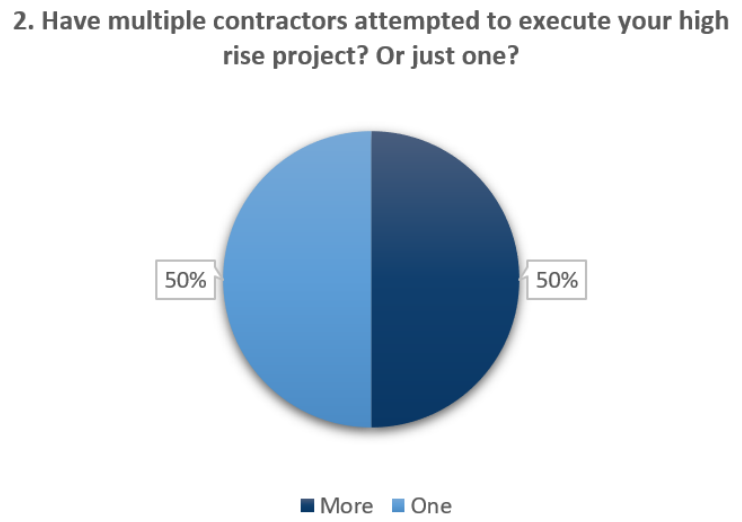
These were my questions. Thank you.

E. Online survey results

Company	Number of people
ABT	2
Anoniem	2
Arcadis	4
Aronsohn	1
BAM	2
Byldis	1
Royal HaskoningDHV	3
Van Rossum	2
Zonneveld	3
Totaal	20

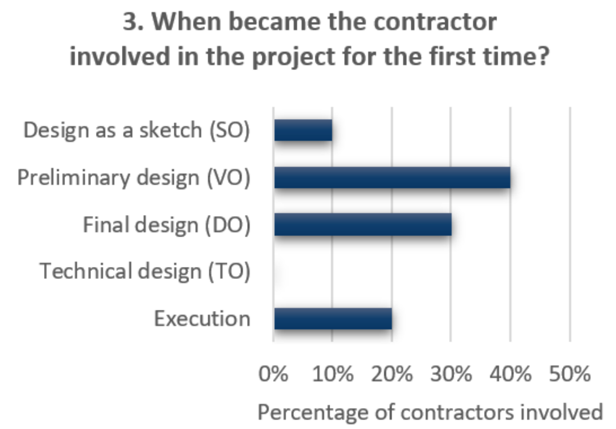


All 20 people answered this question.

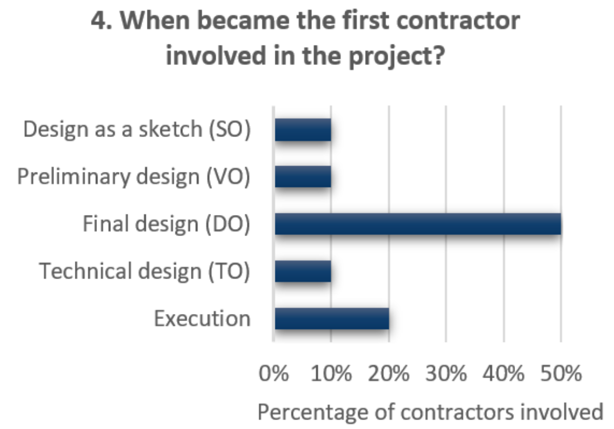


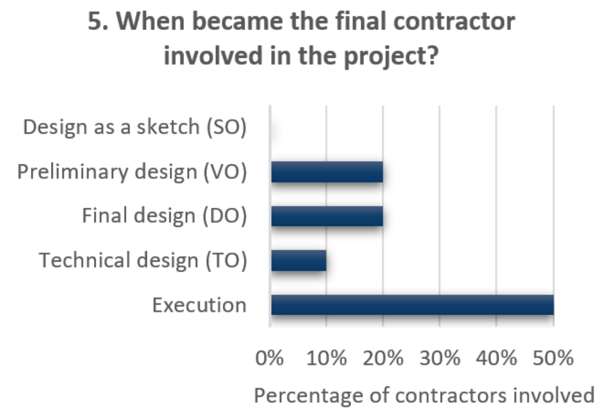
All 20 people answered this question.

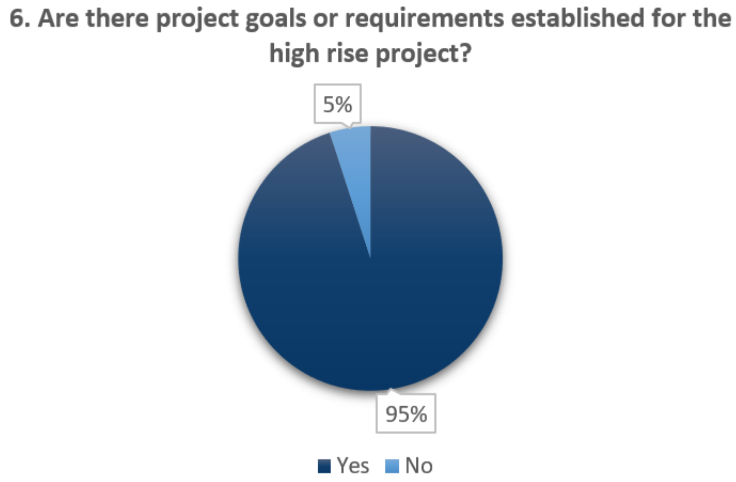
Answer to question 2: “One”
10 out of 20 people answered this question:



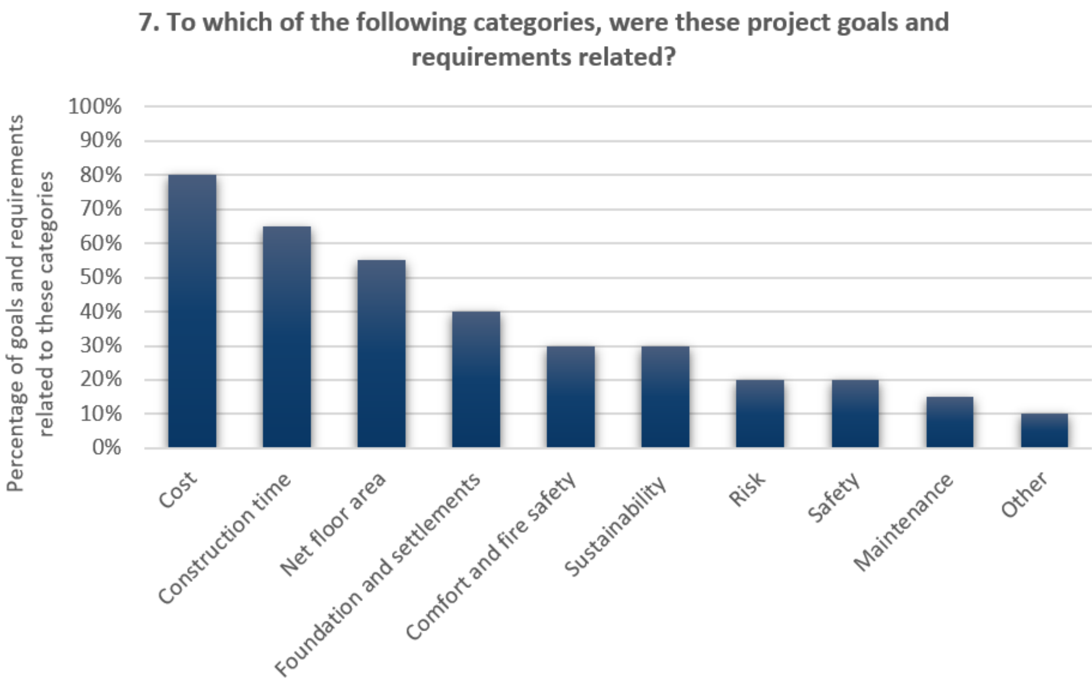
Answer to question 2: “More”
10 out of 20 people answered these questions.



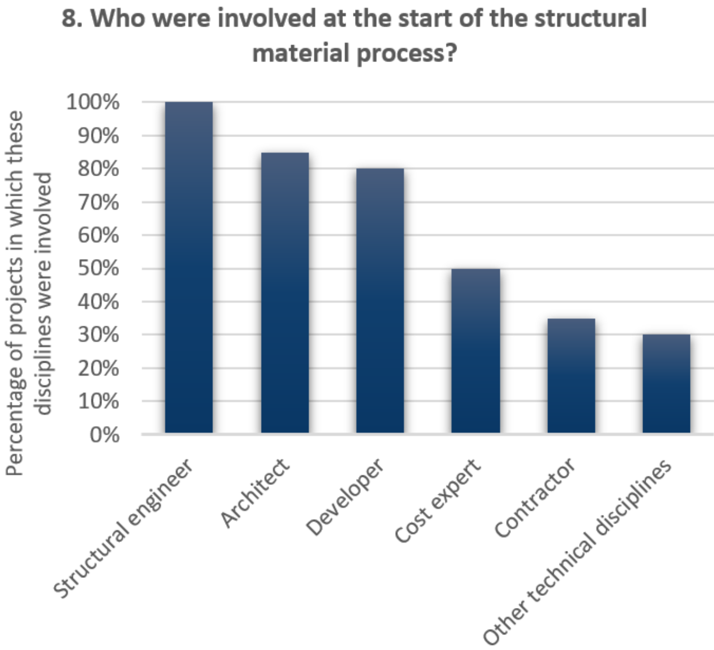




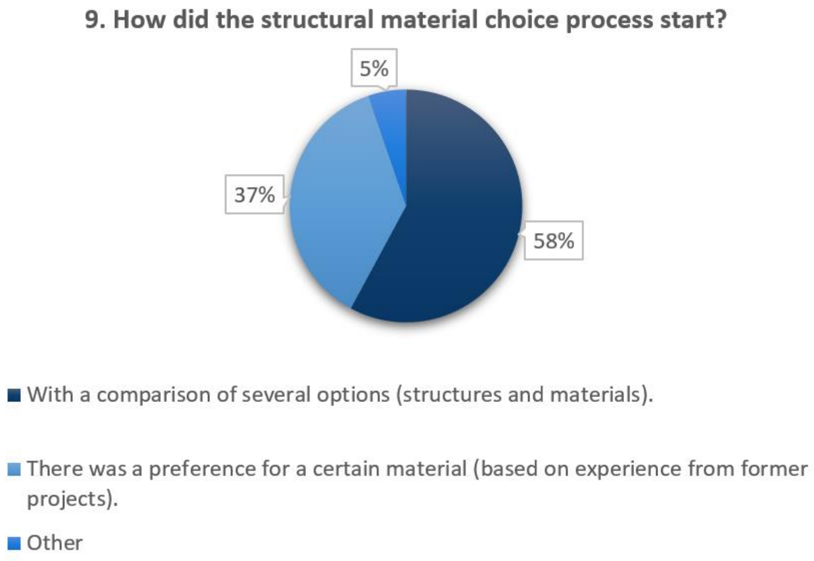
All 20 people answered this question.



All 20 people answered this question.



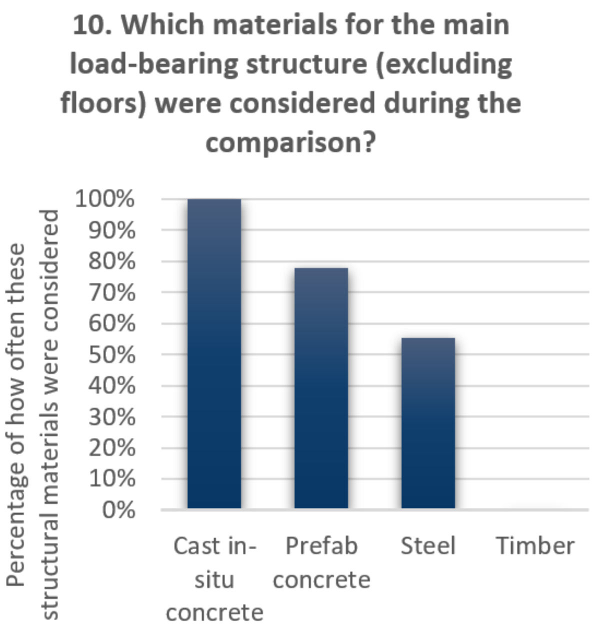
All 20 people answered this question.



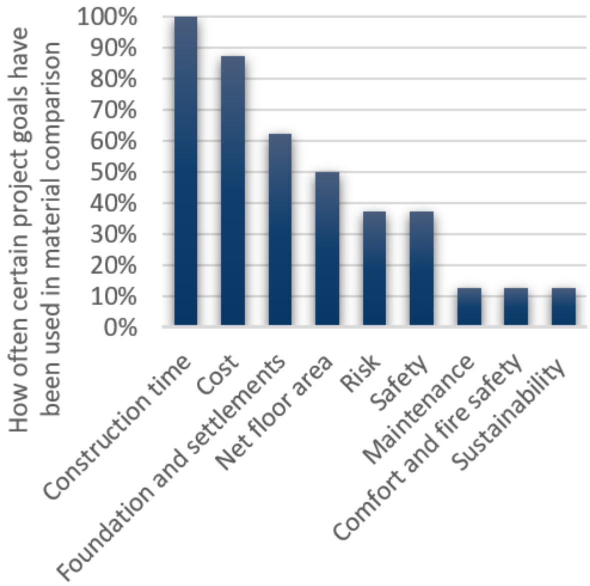
All 20 people answered this question.

Answer to question 9: "With a comparison of several options (structures and materials)."

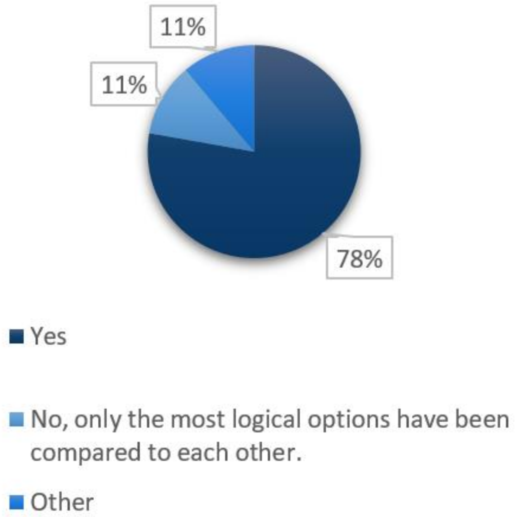
9 out of 20 people answered these questions:

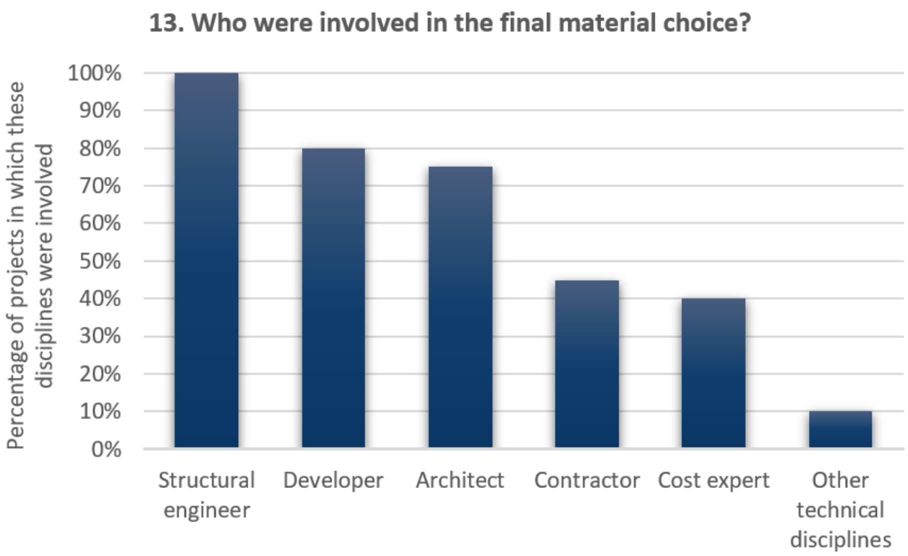


11. Based on which aspects were the materials compared to each other?

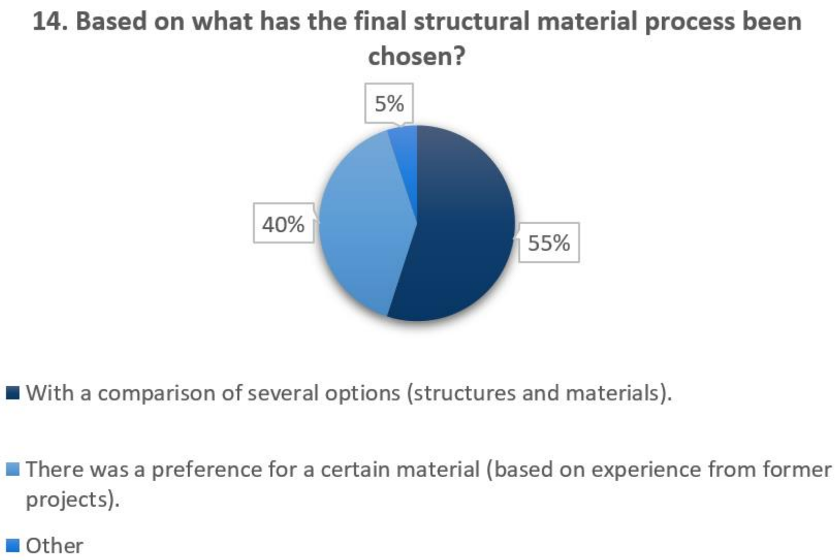


12. Were these options objectively compared to each other?





All 20 people answered this question.



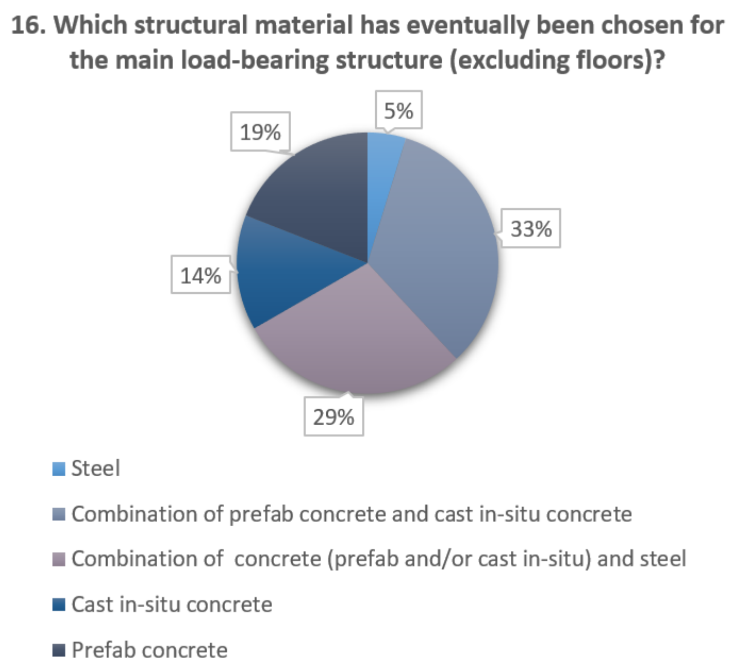
All 20 people answered this question.

Answer to question 14: "There was preference for a certain material (based on experience from former projects)."

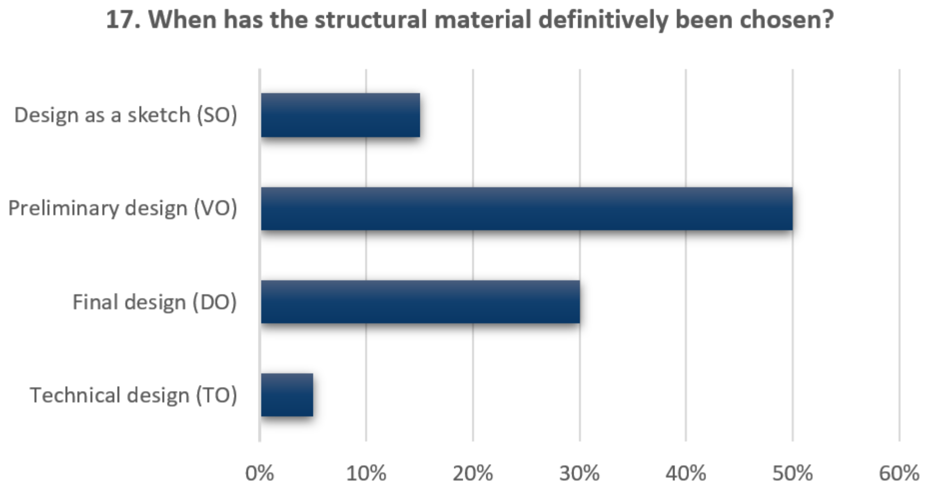
8 out of 20 people answered this question:

15. Why is the structural material choice chosen, based on preference or experience?

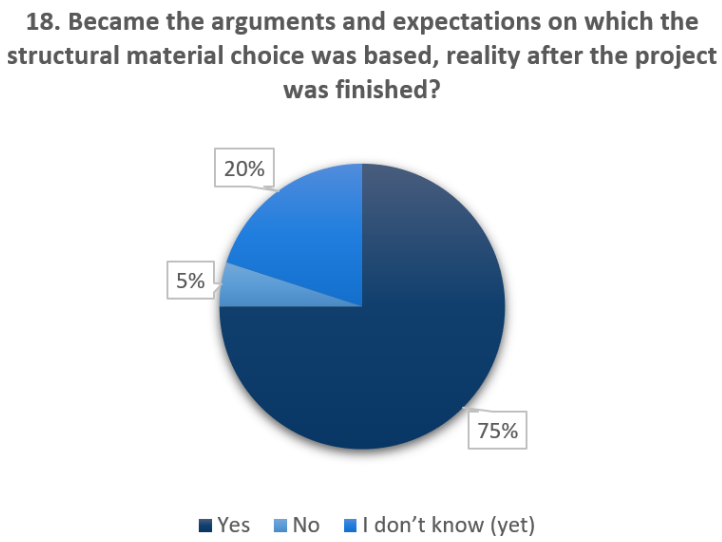
- The contractor had a certain building method that was linked to a certain structural material. The material choice was adapted to the building method.
- The structural engineer preferred a certain building method. Cost and building physics also played a role.
- Concrete was chosen, because of the sound insulation.
- Experience with this material.



All 20 people answered this question.



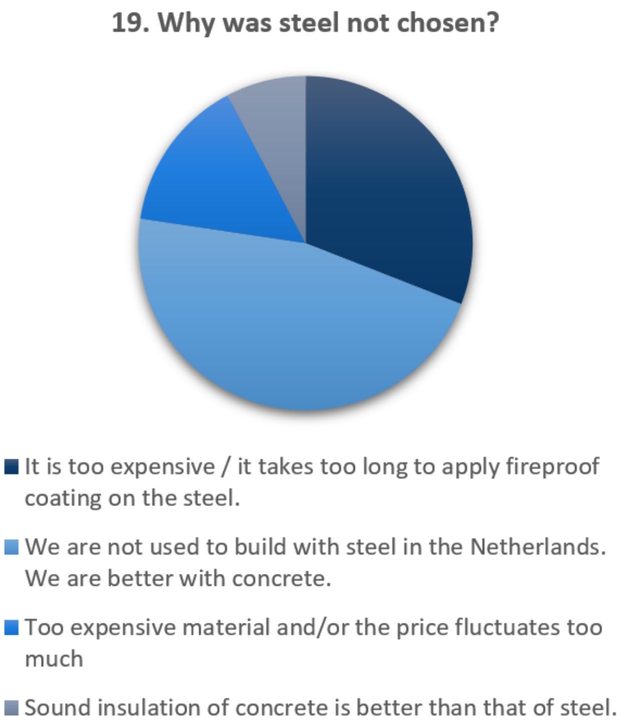
All 20 people answered this question.

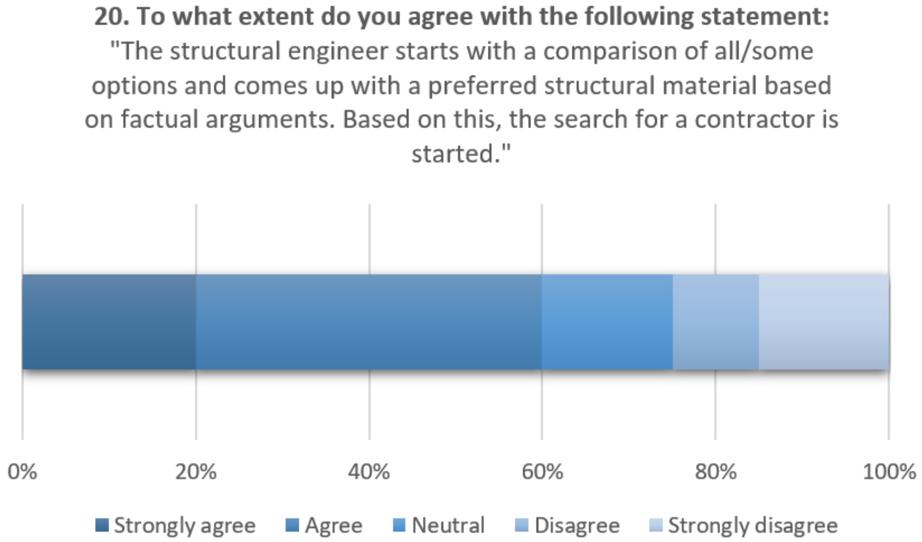


All 20 people answered this question.

Answer to question 16: "Combination of prefab concrete and cast in-situ concrete", "Cast in-situ concrete"; or "Prefab concrete"

14 out of 20 people answered this question:

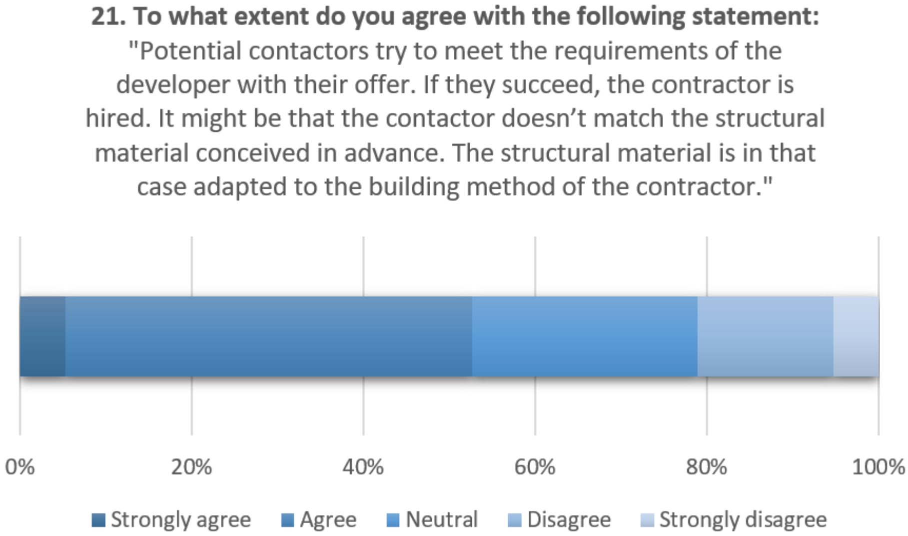




Explanations:

- Some people in the design team can have a preference. If so, this will then be taken into in the comparison.
- Sometimes experience determines which material will be chosen, without considering other options.
- Based on experience, but these are facts.

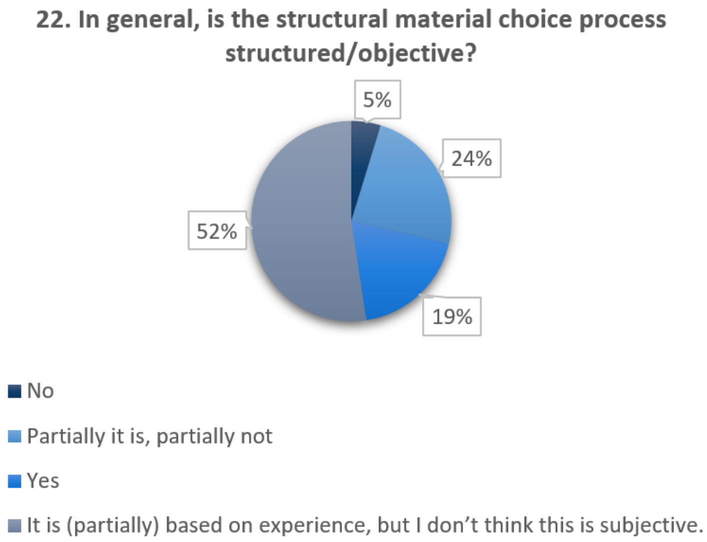
All 20 people answered this question.



Explanations:

- Often there are multiple contractors available and then the most suitable one can be chosen.
- Contractors are not always involved in the design process.
- Initially the contractor needs to try to execute the designed building in its proposal. If this is not possible alternative solutions need to be found.
- Contractor often manages to sell its execution proposal anyway.

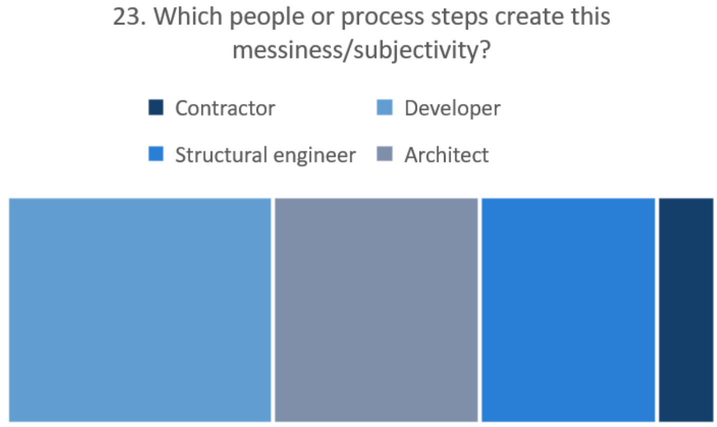
All 20 people answered this question.

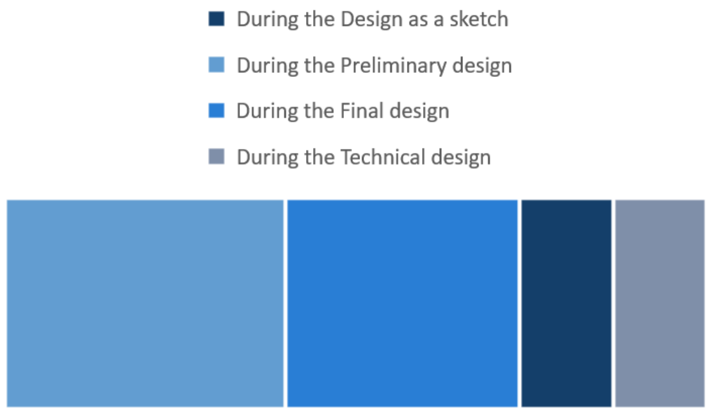


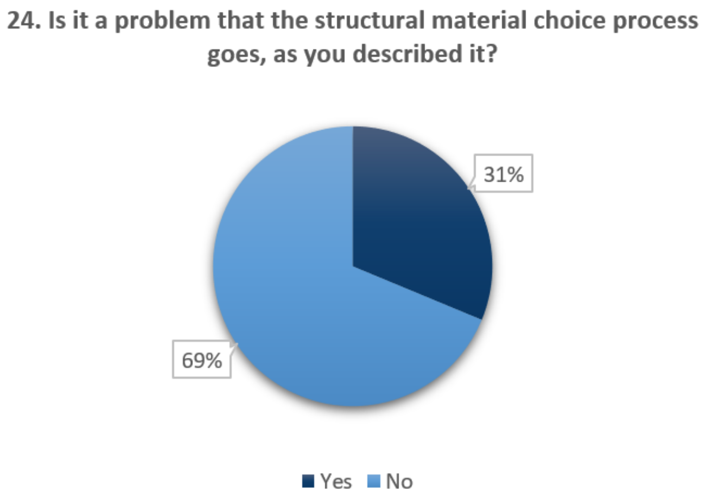
All 20 people answered this question.

➔ **Survey ends when the answer to question 22 was: "Yes"**

Answer to question 22: "No"; "Partially it is, partially not."
11 out of 20 people answered this question:







The remaining 16 out of 20 people answered this question.

Question 25, 26 and 27 are asking for an explanation and possible solutions.
The five people who said yes to question 24, said: It is a problem that the final choice is not based on a clear and logical comparison. Projects are sometimes cancelled, because the project process stagnates. Maybe tools to see the influence of the structural material choice on goals like cost, construction time and sustainability can help. Also, a change in culture is needed.
The remaining 5 out of 13 people answered this question.

F. Calculation of high rise with *Core* as stability system

The measurements of the structural elements nine variations of high rise buildings are calculated. The nine variations are three heights (50 m, 100 m, 150 m), mixed with three different material and floor combinations (Cast in-situ C35/45 & Flat slab, Cast in-situ C35/45 & Hollow core slab, Prefab C55/67 & Hollow core slab).

Problems are expected with 100 m and especially with 150 m, because when the slenderness is larger than 8, the core probably can't handle the wind load.

F.1. Measurements

The width and depth of the buildings are the same (square plan). The depth is based on a few existing buildings by Lankhorst (2018). The core size is chosen, such that the netto floor area doesn't drop below the 75%, because the buildings requires a netto floor area of 75% or higher to be economically profitable (Sarkisian, 2016).

Table 28: The heights used to calculate a *core* and the belonging measurements.

Height building	Width building	Size core	Amount of floors	Slenderness	Netto floor area
49.4 m	27 m	9 m x 9 m	13	5.6	89%
98.8 m	28.5 m	10.5 m x 10.5 m	26	9.5	86%
152 m	30 m	12 m x 12 m	40	12.5	84%

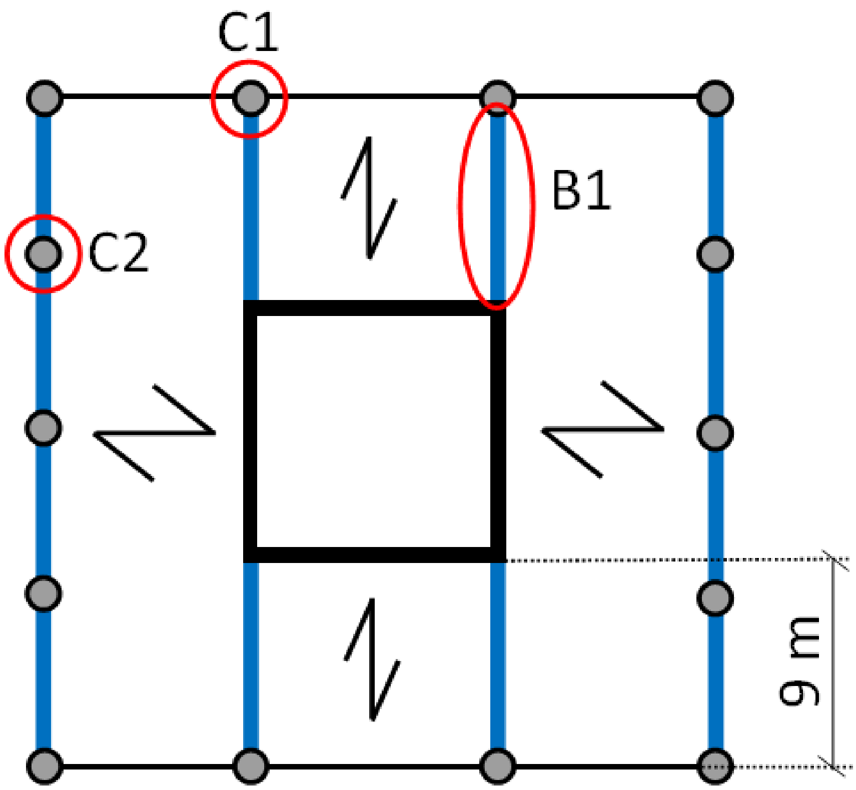


Figure 26: The measurements of the plan used for a high rise building with a *Core* as stability system.

This is the lay-out of all the high rise variations. The grey circles are the columns: four corner columns, two columns at the upper and lower facades (supporting the beams coming from the core) and three columns on the other two façades. The blue lines are the beams and the black square in the middle is the core. The distance between the core and the façade is always kept at 9 m, to maintain a netto floor area of 75% or higher. The size of the building plan and core is different for all three heights. The normative columns and beam are circled with a red line (C1, C2, B1) and their cross section sizes will be calculated.

F.2. Loads

For the high rise buildings of 100 m and 150 m, safety class CC3 is valid. For the high rise buildings of 50 m, safety class CC2 is valid.
Qo is the office live load; Qw the wind load. Ψo = 0.5 and Ψw = 0.0

The load combinations belonging to CC3:

ULS
LC1: 1.32 * G + Ψo * 1.65 Qo + 1.5 * Qw
LC2: 1.49 * G + Ψo * 1.65 Qo
LC3: 0.9 * G + 1.65 * Qw
SLS
LC4: G + Ψo * Qo + Qw
LC5: G + Qw

The load combinations belonging to CC2:

ULS
LC1: 1.2 * G + Ψo * 1.5 Qo + 1.5 * Qw
LC2: 1.35 * G + Ψo * 1.5 Qo
LC3: 0.9 * G + 1.5 * Qw
SLS
LC4: G + Ψo * Qo + Qw
LC5: G + Qw

Table 29: The loads used in the calculations.

Load	Value [kN/m2]
Wind load: *(50 m, 100 m, 150 m)*	1.8, 2.2, 2.5
Live load:	2.5[*1]
Own weight:	Total = 4.5
Partition walls	*1.0*
Mechanical installations and ceiling	*0.3*
Finishing top floor	*1.3*
Facade	*2.0*
Floor type:	
Flat slab (315 mm)	8.8
Hollow core slab (260 mm)	3.8

*1: The live load of office buildings is larger than the live load of housing, so the live load of office is used.

F.3. Cross section and reinforcement

The resulting cross section profiles and amount of reinforcement of beams, columns and the core are shown below.

Beams
The beam cross section size is calculated using LC4 (because this load combination is normative) and a maximum deflection of L/250. Beam 1 (B1 in Figure 26) is normative.

Deflection formula:

$$\frac{5 * q_{own\,weight+live\,load} * l_{beam}^{4}}{384 * EI_{beam}} \leq \frac{l_{beam}}{250} * 0.9$$

The beams connected to the core are normative and thus decided the beam profile for the whole building.

Table 30: The beam cross sections.

Structural material & Floor type:	50 m high	100 m high	150 m high
Cast in-situ C35/45 & Flat slab	630 mm x 630 mm	650 mm x 650 mm	660 mm x 660 mm
Cast in-situ C35/45 & Hollow core slab	580 mm x 580 mm	590 mm x 590 mm	600 mm x 600 mm
Prefab C55/67 & Hollow core slab	580 mm x 580 mm	590 mm x 590 mm	600 mm x 600 mm

The reinforcement of the beams is estimated by calculating $\frac{M_{ed}}{b*d^2}$ and taking the belonging reinforcement percentage from the table.

Table 31: The beam reinforcement.

Structural material & Floor type:	50 m high	100 m high	150 m high
Cast in-situ C35/45 & Flat slab	ρ = 2.11%	ρ = 2.35%	ρ = 2.44%
Cast in-situ C35/45 & Hollow core slab	ρ = 1.81%	ρ = 1.02%	ρ = 2.19%
Prefab C55/67 & Hollow core slab	ρ = 1.81%	ρ = 1.02%	ρ = 2.19%

Columns

The column cross section size is calculated using LC2 (because this load combination is normative) and a strength check. Column 1 (C1 in figure 1) is normative for the facades with two columns and Column 2 (C1 in figure 1) is normative for the facades with three columns in the façade..

Strength check:

$$F_{own\,weight+live\,load} \leq f_{y,concrete} * A_{column} * 0.9$$

Table 32: The column cross section.

Structural material & Floor type:	50 m high	100 m high	150 m high
Cast in-situ C35/45 & Flat slab	C1: 210 mm x 210 mm C2: 180 mm x 180 mm	C1: 230 mm x 230 mm C2: 200 mm x 200 mm	C1: 240 mm x 240 mm C2: 210 mm x 210 mm
Cast in-situ C35/45 & Hollow core slab	C1: 170 mm x 170 mm C2: 150 mm x 150 mm	C1: 190 mm x 190 mm C2: 170 mm x 170 mm	C1: 200 mm x 200 mm C2: 180 mm x 180 mm
Prefab C55/67 & Hollow core slab	C1: 140 mm x 140 mm C2: 130 mm x 130 mm	C1: 150 mm x 150 mm C2: 130 mm x 130 mm	C1: 160 mm x 160 mm C2: 140 mm x 140 mm

The reinforcement of the beams is estimated by calculating $\frac{N_{ed}}{f_{cd}*A_c}$ and taking the belonging reinforcement percentage from the graph. For every column the graph gave that no reinforcement is needed. This is caused by the fact that only a compressive normal force works on the columns.

Core

Just like Lankhorst (2018) assumed, all cores will be made of cast in-situ concrete (C35/45). The strength check using load case LC1 and LC2:

$$\frac{n_{2nd\ order} * M_{wind}}{W_{core}} + \frac{N_{own\ weight}}{A_{core}} \leq \frac{\frac{C35}{45}}{1.5} * 0.9$$

Tension check using load case LC3:

$$-\frac{n_{2nd\ order} * M_{wind}}{W_{core}} + \frac{N_{own\ weight+live\ load}}{A_{core}} > 0$$

Deflection check using LC1:

$$\frac{n_{2nd\ order} * q_{wind} * H_{building}^{4}}{8 * EI_{core}} \leq \frac{H_{building}}{1000} * 0.9$$

The maximum deflection is H/500. Half of this deflection can be caused by the foundation, so the building is only allowed to deflect H/1000.

Also, *n2nd order* is for every high rise variation between 1.0 and 1.2.

Table 33: The core thickness.

Structural material & Floor type:	50 m high	100 m high	150 m high
Cast in-situ C35/45 & Flat slab	Core thickness: 200 mm Normative check: Strength C35/45	Core thickness: 500 mm Normative check: Deflection	Core thickness: 2000 mm Normative check: Deflection
Cast in-situ C35/45 & Hollow core slab	Core thickness: 100 mm Normative check: Strength C35/45	Core thickness: 550 mm Normative check: Tension	Core thickness: 2000 mm Normative check: Deflection
Prefab C55/67 & Hollow core slab	Core thickness: 100 mm Normative check: Strength C35/45	Core thickness: 550 mm Normative check: Tension	Core thickness: 2000 mm Normative check: Deflection

Because of the deflection the core of the high rise variations of 150 m high became very thick and thus the netto floor area smaller than 75%. The height were the deflection becomes much more important than the strength of the concrete lies between 100 m and 120 m. In the graphs showing the cost, construction time and the environmental cost, the *core* will thus have a maximum height of 120 m.

To calculate the reinforcement for the cores in the table above, a comprehensive computer model is needed. Because of limited time, no computer model is used, but the results from Lankhorst (2018) are used to estimate the amount of reinforcement. Lankhorst calculated how much concrete and reinforcement is needed when different stability systems are used. His '*core combined with a rigid frame*' is the closest to this situation here of *'only a core'*. He calculated that the core needs averagely 0.54% reinforcement. The same percentage of 0.54% will be used to estimate the amount of reinforcement of the cores in the table above.

F.4. Total amount of material

Using the results from section 0 the total amount of material has been calculated on 50 m high, 100 m high and 150 m high for the stability system: *Core* (Table 34). The amount of material needed for the floor is calculated by taking the amount of floor needed to cover the plan of 150 m high building (calculated by

Lankhorst) and using the ratio between the 150 m building and the other buildings.
So combination of the Core+Rigid Frame, Cast in-situ concrete and the Flat slab floor needs 30030075 kg concrete C35/45 in the floor for a 150 m high rise building. This means the 100 m high rise building needs:

$$\frac{30030075*28.5^2*26}{30^2*40} = 17739540$$

Using this, the total direct cost and total environmental cost can be calculated.

Table 34: The total amount of material needed for a *Core* at the height of 50 m, 100 m and 150 m.

				Amount		
			Height:	50 m	100 m	150 m
Stability system:	**Material:**	**Floor type:**	**Width & Depth:**	27 m	28.5 m	30 m
Core + Rigid frame						
	Cast in-situ concrete	Flat slab floor				
			FLOOR	kg		
			Concrete C35/45	7960680	17739540	30030075
			Reinforcement FeB500	250193	557528	823824
			STRUCTURE	m3		
			Concrete C35/45	837	3058	13935
			Reinforcement FeB500	22	35	106
	Cast in-situ concrete	Hollow core slab				
			FLOOR	kg		
			Concrete C20/25	1291905	2878874	4903200
			Concrete C45/55	2918158	6502809	11088000
			Concrete FeB500	88705	197669	335188
			PT Steel	36392	81095	135065
			S355	68234	152053	257143
			STRUCTURE	m3		
			Concrete C35/45	586	3047	13616
			Reinforcement FeB500	16	27	121
	Prefab concrete	Hollow core slab				
			FLOOR	kg		
			Concrete C20/25	1291905	2878874	4903200
			Concrete C45/55	2918158	6502809	11088000
			Reinforcement FeB500	88705	197669	335188
			PT Steel	36392	81095	135065

	S355	68234	152053	257143
	STRUCTURE	m3		
	Concrete C35/45	176	2163	12160
	Concrete 55/67	406	867	1428
	Reinforcement FeB500	16	27	121

G. Calculation of high rise with *Shear walls* as stability system

The measurements of the structural elements nine variations of high rise buildings are calculated. The nine variations are four heights (50 m, 100 m, 150 m, 200 m), mixed with three different material and floor combinations (Cast in-situ C35/45 & Flat slab, Cast in-situ C35/45 & Hollow core slab, Prefab C55/67 & Hollow core slab).

G.1. Measurements

The width and depth of the buildings are the same (square plan). The depth is based on a few existing buildings by Lankhorst (2018). The core size is chosen, such that the netto floor area doesn't drop below the 75%, because the buildings requires a netto floor area of 75% or higher to be economically profitable (Sarkisian, 2016).

Table 35: The heights used to calculate the *shear walls* and the belonging measurements.

Height building	Width building	Size core	Amount of floors	Slenderness	Netto floor area
49.4 m	27 m	9 m x 9 m	13	5.6	*Depends on wall thickness*
98.8 m	28.5 m	10.5 m x 10.5 m	26	9.5	*Depends on wall thickness*
152 m	30 m	12 m x 12 m	40	12.5	*Depends on wall thickness*
197.6 m	31.5 m	13.5 m x 13.5 m	52	14.6	*Depends on wall thickness*

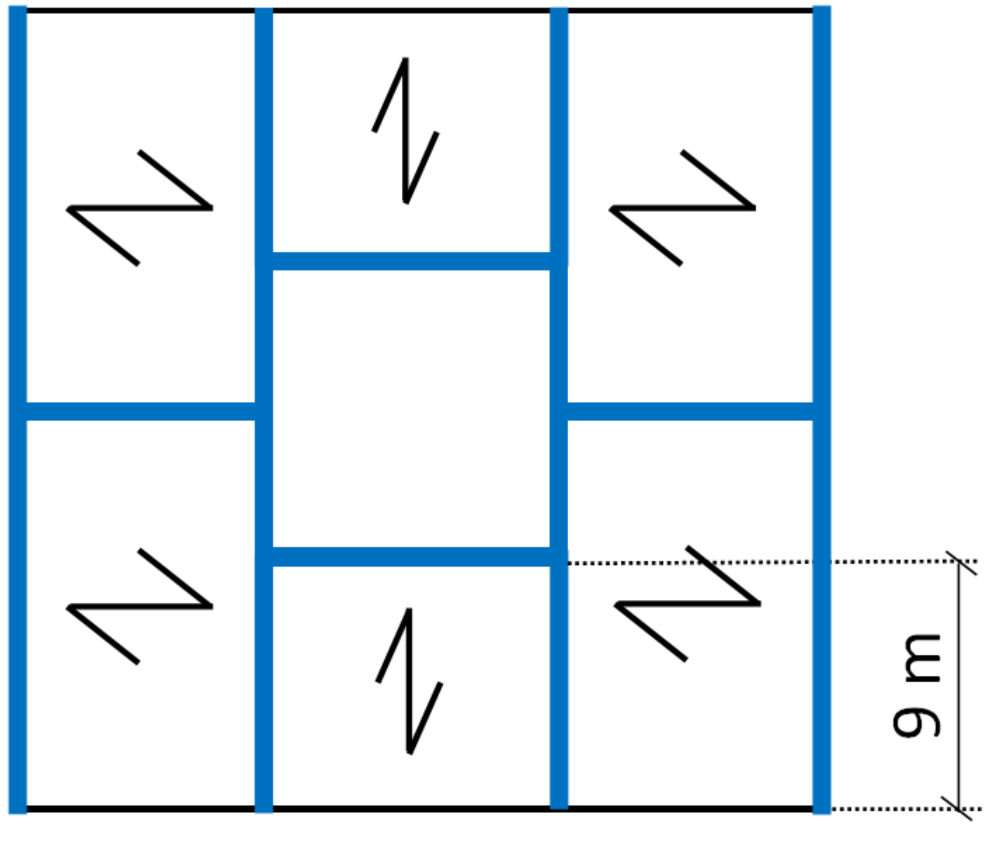


Figure 27: The measurements of the plan used for a high rise building with a *Shear walls* as stability system.

This is the lay-out of all the high rise variations. The blue lines are the shear walls. The distance between the core and the façade is always kept at 9 m, to maintain a netto floor area of 75% or higher. The size of the building plan and core is different for all three heights.

G.2. Loads

For the high rise buildings safety class CC3 is valid.
Qo is the office live load; Qw the wind load. Ψo = 0.5 and Ψw = 0.0

The load combinations belonging to CC3:

ULS
LC1: 1.32 * G + Ψo * 1.65 Qo + 1.5 * Qw
LC2: 1.49 * G + Ψo * 1.65 Qo
LC3: 0.9 * G + 1.65 * Qw
SLS
LC4: G + Ψo * Qo + Qw
LC5: G + Qw

Table 36: The loads used in the calculations.

Load	Value [kN/m2]
Wind load: *(50 m, 100 m, 150 m)*	1.8, 2.2, 2.5
Live load:	2.5*1
Own weight:	Total = 4.5
Partition walls	*1.0*
Mechanical installations and ceiling	*0.3*
Finishing top floor	*1.3*
Facade	*2.0*
Floor type:	
Flat slab (315 mm)	8.8
Hollow core slab (260 mm)	3.8

*1: The live load of office buildings is larger than the live load of housing, so the live load of office is used.

G.3. Cross section and reinforcement

The resulting cross section profiles and amount of reinforcement of the shear walls are shown below.

Shear walls

Lankhorst (2018) assumed, all cores will be made of cast in-situ concrete (C35/45). Because the walls and the core and seen as *one* stability system for this calculation, this assumption can’t be applied here. This means the all the shear walls (core and walls) are either made of cast in-situ concrete or prefab concrete.

The strength check using load case LC1 and LC2:

$$\frac{n_{2nd\ order} * M_{wind}}{W_{core}} + \frac{N_{own\ weight}}{A_{core}} \leq \frac{\frac{C35}{45}}{1.5} * 0.9$$

Tension check using load case LC3:

$$-\frac{n_{2nd\ order} * M_{wind}}{W_{core}} + \frac{N_{own\ weight+live\ load}}{A_{core}} > 0$$

Deflection check using LC1:

$$\frac{n_{2nd\ order} * q_{wind} * H_{building}^4}{8 * EI_{core}} \le \frac{H_{building}}{1000} * 0.9$$

The maximum deflection is H/500. Half of this deflection can be caused by the foundation, so the building is only allowed to deflect H/1000.
Also, *n2nd order* is for every high rise variation between 1.0 and 1.2.

Table 37: The shear wall thickness.

Structural material & Floor type:	50 m high	100 m high	150 m high	200 m high
Cast in-situ C35/45 & Flat slab	Core thickness: 150 mm *(Netto floor area: 87%)* Normative check: Strength C35/45	Core thickness: 300 mm *(Netto floor area: 82%)* Normative check: Strength C35/45	Core thickness: 350 mm *(Netto floor area: 80%)* Normative check: Strength C35/45	Core thickness: 500 mm *(Netto floor area: 76%)* Normative check: Strength C35/45
Cast in-situ C35/45 & Hollow core slab	Core thickness: 150 mm *(Netto floor area: 87%)* Normative check: Strength C35/45	Core thickness: 250 mm *(Netto floor area: 83%)* Normative check: Strength C35/45	Core thickness: 300 mm *(Netto floor area: 80%)* Normative check: Strength C35/45	Core thickness: 350 mm *(Netto floor area: 77%)* Normative check: Strength C35/45
Prefab C55/67 & Hollow core slab	Core thickness: 100 mm *(Netto floor area: 87%)* Normative check: Strength C35/45	Core thickness: 150 mm *(Netto floor area: 84%)* Normative check: Strength C35/45	Core thickness: 250 mm *(Netto floor area: 81%)* Normative check: Strength C35/45	Core thickness: 300 mm *(Netto floor area: 78%)* Normative check: Deflection

Above 200 m the shear walls thickness becomes more than 500 mm and the netto floor area drops below 75%. In the graphs showing the cost, construction time and the environmental cost, the *shear walls* will thus have a maximum height of 200 m.

To calculate the reinforcement for the cores in the table above, a comprehensive computer model is needed. Because of limited time, no computer model is used, but the results from Lankhorst (2018) are used to estimate the amount of reinforcement. Lankhorst calculated how much concrete and reinforcement is needed when different stability systems are used. His '*core combined with a rigid frame*' is the closest to this situation here of *'shear walls'*. He calculated that the core needs averagely 0.54% reinforcement. The same percentage of 0.54% will be used to estimate the amount of reinforcement of the cores in the table above.

G.4. Total amount of material

Using the results from section 00 the total amount of material has been calculated on 50 m, 100 m, 150 m and 200 m high for the stability system: *Shear walls* (Table 38Table 34). The amount of material needed for the floor is calculated by taking the amount of floor needed to cover the plan of 150 m and 200 m high building (calculated by Lankhorst) and using the ratio between the 150 m and 200 m building and the other buildings.
So combination of the Core+Rigid Frame, Cast in-situ concrete and the Flat slab floor needs 30030075 kg concrete C35/45 in the floor for a 150 m high rise building. This means the 100 m high rise building needs:
$\frac{30030075 * 28.5^2 * 26}{30^2 * 40} = 17739540$

Using Table 38, the total direct cost and total environmental cost can be calculated.

Table 38: The total amount of material needed for a *Shear walls* at the height of 50 m, 100 m, 150 m and 200 m.

				Amount			
			Height:	50 m	100 m	150 m	200 m
Stability system:	Material:	Floor type:	Width & Depth:	27 m	28.5 m	30 m	31.5 m
Core + Rigid frame							
	Cast in-situ concrete	Flat slab floor					
			FLOOR	kg			
			Concrete C35/45	7960680	17739540	30030075	43053053
			Reinforcement FeB500	250193	557528	823824	1131895
			STRUCTURE	m3			
			Concrete C35/45	1067	4535	8618	12996
			Reinforcement FeB500	6	24	47	70
	Cast in-situ concrete	Hollow core slab					
			FLOOR	kg			
			Concrete C20/25	1291905	2878874	4903200	137923
			Concrete C45/55	2918158	6502809	11088000	340342
			Concrete FeB500	88705	197669	335188	9197
			PT Steel	36392	81095	135065	4492
			S355	68234	152053	257143	7321
			STRUCTURE	m3			
			Concrete C35/45	1067	3779	7387	9097
			Reinforcement FeB500	9	32	62	76
	Prefab concrete	Hollow core slab					
			FLOOR	kg			
			Concrete C20/25	1291905	2878874	4903200	137923
			Concrete C45/55	2918158	6502809	11088000	340342
			Reinforcement FeB500	88705	197669	335188	9197
			PT Steel	36392	81095	135065	4492

	S355	68234	152053	257143	7321
	STRUCTURE	m3			
	Concrete C35/45	711	2267	6156	7798
	Concrete 55/67	6	19	52	65

H. Parameter for cost calculation: Construction time

The construction time influences the indirect cost. To be able to calculate the indirect cost of the twenty-six *combinations* from Table 13 (Chapter 8), first the construction time of these twenty-six *combinations* needs to be calculated.

H.1. Definitions

Some important definitions regarding construction time are explained below. This information will then be used to calculate the construction time of the twenty-six *combinations* from Table 13 (Chapter 8).

Building time and critical path

The building time of a project consists of two phases: the preparation time and the construction time (Cederhout & Sterken, 2002). During the preparation time the design of the building is made. During the construction time the design is built by the contractor. This distinction is important, because prefabricated elements need more preparation time than cast in-situ concrete.

Figure 28: The definition of 'Building time' that will be used in this thesis.

In a high rise building the phases follow each other. The contractor first checks which activities need to be finished before other activities can start. For example, often the core is a few floors ahead of the frame and the frame a few floors ahead of the façade. When an activity delays, the other activities following that activity delay too.
The line of activities which takes the longest to construct is called the *critical path*. The critical path determines the construction time of the project. If a delay happens in the critical path, the construction time will become longer. If a delay happens in other activities, this line of activities might surpass the construction time of the *former* critical path and it will become the *new* critical path (Antill & Woodhead, 1990). The critical path is important when decisions are made about time reducing measures. For example, when time reducing measures are applied on the load-bearing structure, the load-bearing structure must be part of the critical path. If not, using expensive measures is not economical, because other activities will still result in a longer construction time (Sterken & Timmermans, 1988).
Often the load-bearing structure is part of the critical path and thus indicates the construction time of a high rise building.

Building phases and intervals

Calculating the required construction time of a high rise building is done using intervals. When constructing a building one activity can often only start after another has finished. An interval is the time difference between the start of two activities that follow each other. These activities can be divided into five building phases (Flapper, 1995):

1. Start-up phase: readying the building site.
2. Substructure phase: building the foundation below ground level.
3. Superstructure phase: the structure above ground level.
4. Façade/Roof phase: the roof and the façade (2 floors behind the structure).
5. Finishing phase: the finishing on the inside, after the floor has been made wind- and airtight (2 floors behind the façade).

The book '*Bouwplanning*' of Flapper (1995) has several standard interval times for each building phase. Each standard interval belongs to a certain building method and structural material. Some of these standard intervals are used to calculate the construction time for several high rise buildings.

When it comes to high rise, the Superstructure phase, Façade/Roof phase and Finishing phase include *all* the floors. This means these phases have overlap; the Façade/Roof phase can start a few floors below the Superstructure phase, even though the Superstructure phase is not yet finished.

Planning in months

A cycle is the amount of time it takes to finish a floor. The goal of most contractors is to finish one floor per week. This means one weekend per floor. When the cycle time becomes more than a week, more weekends are needed per floors, which significantly increases the construction time. Also, when cast in-situ concrete is used, the advantage is that the concrete can dry in the weekend. Table 39 show the amount of days can be used to build per year.

Table 39: The netto amount of days per year that can be used to build.

Total days per year	365
Weekend	104
Holidays	6
Vacation days	27
Total workdays per year	**228 (19 days per month)**
Frost	9
Rain	15
Wind	12
Production days	**192 (16 days per month)**

When creating a planning, the free days, weekends and lost days (because of frost, rain, wind) need to be taken into account. For building phase 1 to 4, only the 192 days per year can be used. For building phase 5, the 228 days per year can be used, because this phase doesn't suffer from lost days due to frost, rain, wind. The amount of construction days (N), that are calculated by adding al the intervals of the five building phases, can be changed into months with the following formula:

$$\frac{N-60}{16}+\frac{60}{19}=N-10=\text{Amount of months}$$

Formula footnote:
10 is a correction factor for the fact that the Finishing phase use more days per year (228 days). When the interval time of the Finishing phase is much longer or shorter than 60 days, this factor needs to be adapted.

H.3. Chosen intervals and construction time formulas

Table 40 shows the standard interval times for each building phase from the book *Bouwplanning* that will be used. For each building phase *one*, most common standard interval has been selected. Only the Superstructure phase has three standard intervals: one for prefab concrete, cast in-situ concrete and steel high rise buildings. The structural material and the amount of floors thus create a variation of construction times for the twenty-six *combinations*. The calculated construction times for each of the twenty-six *combinations* on their belonging height points are shown in H.4. Calculation construction time

The construction times for each of the twenty-six combinations are calculated at the chosen height points and are shown in table below. These construction times are calculated, using the formulas shown in the previous paragraph.

Table 41.
Important to note is that the calculated construction times are very long. In practice the construction time becomes shorter, because the construction process is optimized. The ratio between the construction times of the twenty-six *combinations* however are still accurate. These 'longer' construction times can thus still be used to calculate the indirect cost and see the differences in cost (direct and indirect) between the different twenty-six *combinations.*

Table 40: The standard interval times that are used to calculate the construction time of the twenty-six

	Building phase	Standard interval

1	Start-up phase	AL-03: With piling: *20 days*
2	Substructure phase	OB-05: With cellar and elevator building pit: *38 days*
3	Superstructure phase	• BB-01: Prefab concrete elements: *5 days per floor* • BB-06: With cast in-situ high rise: *14 days per floor* • BB-07: With steel: *10 days per floor*
4	Façade/Roof phase	GD-10: High rise with roof + slope *Façade: 18 days per floor* *Roof: 25 days* (this coincides with the *Finishing phase* of the second last floor, which is also 25 days, so *the Roof* is not influencing the construction time)
5	Finishing phase	AB-04: System walls + Ceilings: *25 days per floor*

The following formula's are thus used to calculate the construction time of each of the twenty-six combinations:

Prefab concrete: $20 + 38 + 5 * all\ floors + 5 + 18 + 5 + (25 - 5 * a) * (\frac{all\ floors}{a} - 1) + 25$

Cast in-situ concrete: $20 + 38 + 14 * all\ floors + 5 + 18 + 5 + (25 - 5 * a) * (\frac{all\ floors}{a} - 1) + 25$

Steel: $20 + 38 + 10 * all\ floors + 5 + 18 + 5 + (25 - 5 * a) * (\frac{all\ floors}{a} - 1) + 25$

The amount of floors at which can be worked during the Finishing phase: a=2

There are two floors between the Superstructure phase and the Façade/Roof phase; *and* between the Façade/Roof phase and the Finishing phase. This causes the two fives in the formulas above. For the Finishing phase a limitation in capacity is assumed: contractor can only work at two floors at the same time (*'a'* in the formulas). This causes the big gap between phase 4 and 5 in Figure 29.

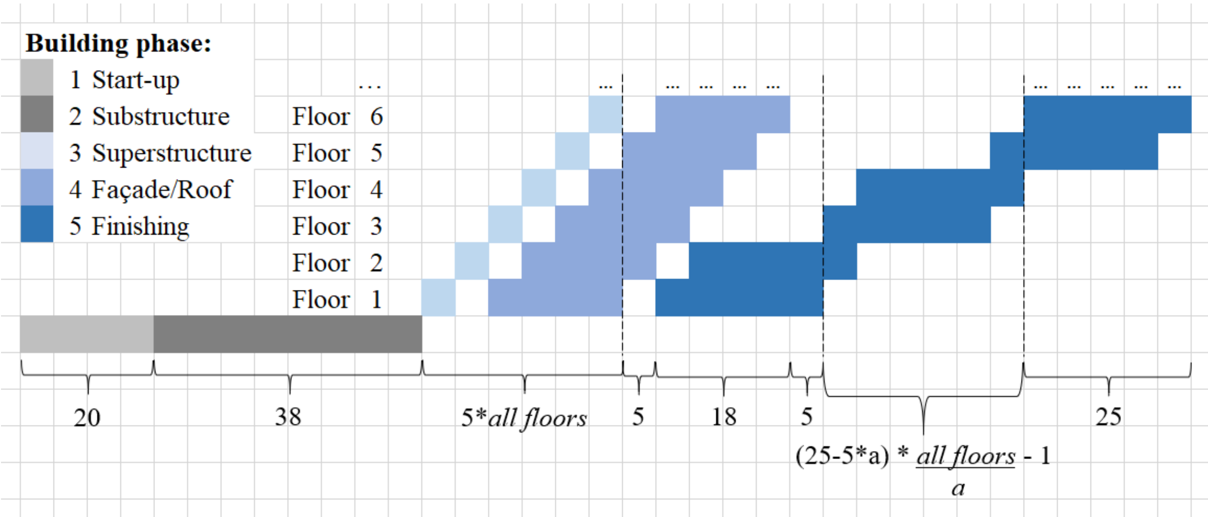


Figure 29: Illustrating the formula for prefab concrete. The other formulas are created in the same way. Each cell is approximately 5 days.

H.4. Calculation construction time

The construction times for each of the twenty-six combinations are calculated at the chosen height points and are shown in table below. These construction times are calculated, using the formulas shown in the previous paragraph.

Table 41: The construction time for each of the twenty-six *combinations* are shown.

Stability system	Structural material	Floor type	Construction time [in months]				
Core		**Height points:**	**50 m**	**100 m**	**150 m**		
	Cast in-situ concrete	Flat slab floor	19	32	46		
	Cast in-situ concrete	Hollow core slab	19	32	46		
	Prefab concrete	Hollow core slab	13	21	29		
Shear walls		**Height points:**	**50 m**	**100 m**	**150 m**	**200 m**	
	Cast in-situ concrete	Flat slab floor	19	32	46	60	
	Cast in-situ concrete	Hollow core slab	19	32	46	60	
	Prefab concrete	Hollow core slab	13	21	29	37	
Core + Rigid frame		**Height points:**			**150 m**	**200 m**	
	Cast in-situ concrete	Flat slab floor			46	60	
	Cast in-situ concrete	Hollow core slab			46	60	
	Prefab concrete	Hollow core slab			29	37	
	Steel	Composite floor			39	49	
	Steel	Hollow core slab			39	49	
Outrigger		**Height points:**			**150 m**	**200 m**	**250 m**

	Cast in-situ concrete	Flat slab floor			46	60	73
	Cast in-situ concrete	Hollow core slab			46	60	73
	Prefab concrete	Hollow core slab			29	37	45
	Steel	Composite floor			39	49	60
	Steel	Hollow core slab			39	49	60
Tube: frame		**Height points:**			**150 m**	**200 m**	**250 m**
	Cast in-situ concrete	Flat slab floor			46	60	73
	Cast in-situ concrete	Hollow core slab			46	60	73
	Prefab concrete	Hollow core slab			29	37	45
	Steel	Composite floor			39	49	60
	Steel	Hollow core slab			39	49	60
Tube: braced		**Height points:**			**150 m**	**200 m**	**250 m**
	Steel	Composite floor			39	49	60
	Steel	Hollow core slab			39	49	60
Tube: diagrid		**Height points:**			**150 m**	**200 m**	**250 m**
	Prefab concrete	Hollow core slab			29	37	45
	Steel	Composite floor			39	49	60
	Steel	Hollow core slab			39	49	60

H.3. Figures

The construction time of each of the twenty-six combinations is plotted figures (see figures below). These figures are created by taking the calculated construction time at the height points (form Table 41) and plotting an exponential line through them within the height range of each of the stability systems. The colours of the exponential lines indicate the structural material: prefab concrete, cast in-situ concrete or steel.

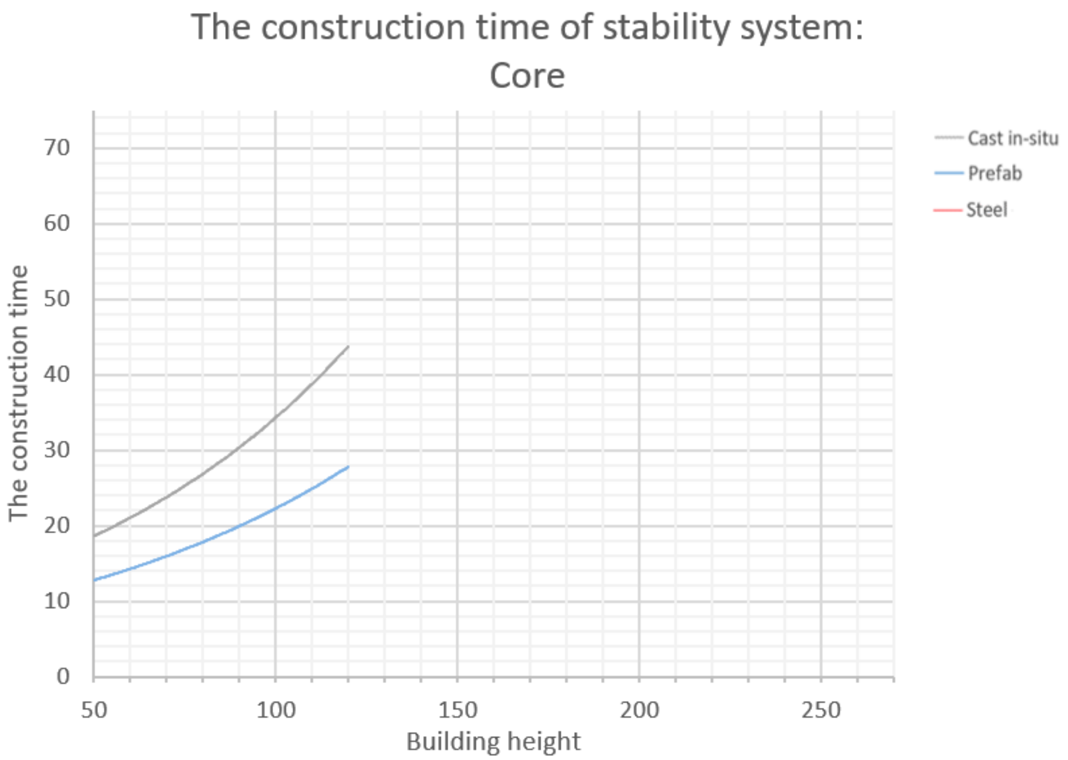


Figure 30: The construction time in months plotted against the building height for a Core stability system.

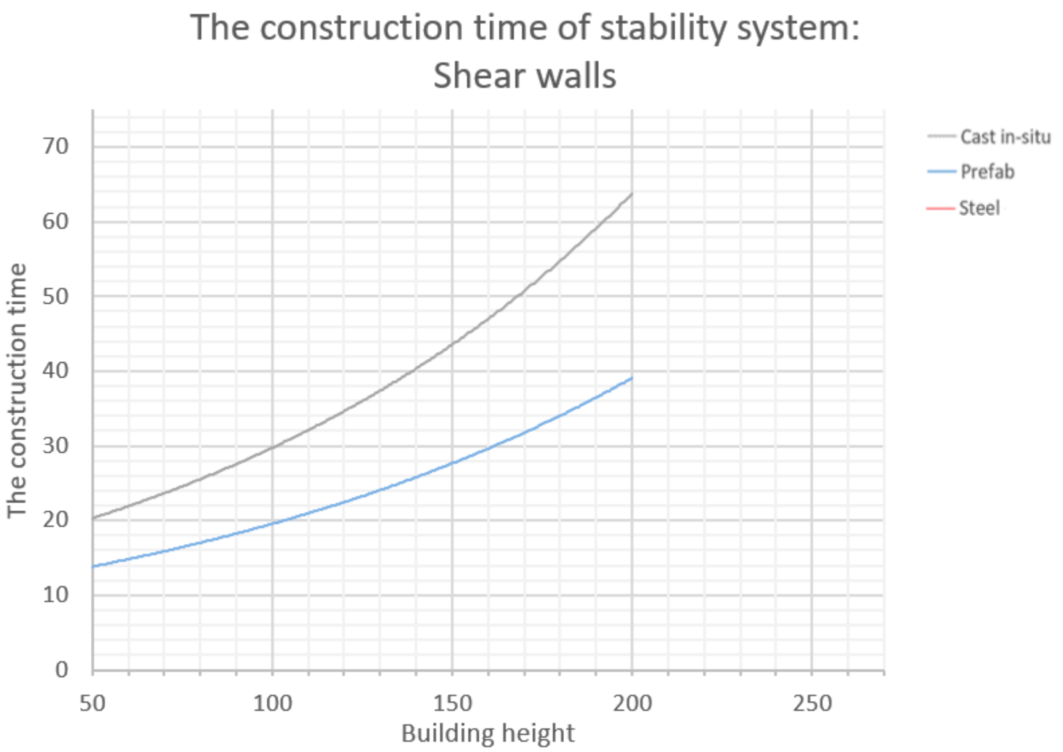


Figure 31: The construction time in months plotted against the building height for a Shear walls stability system.

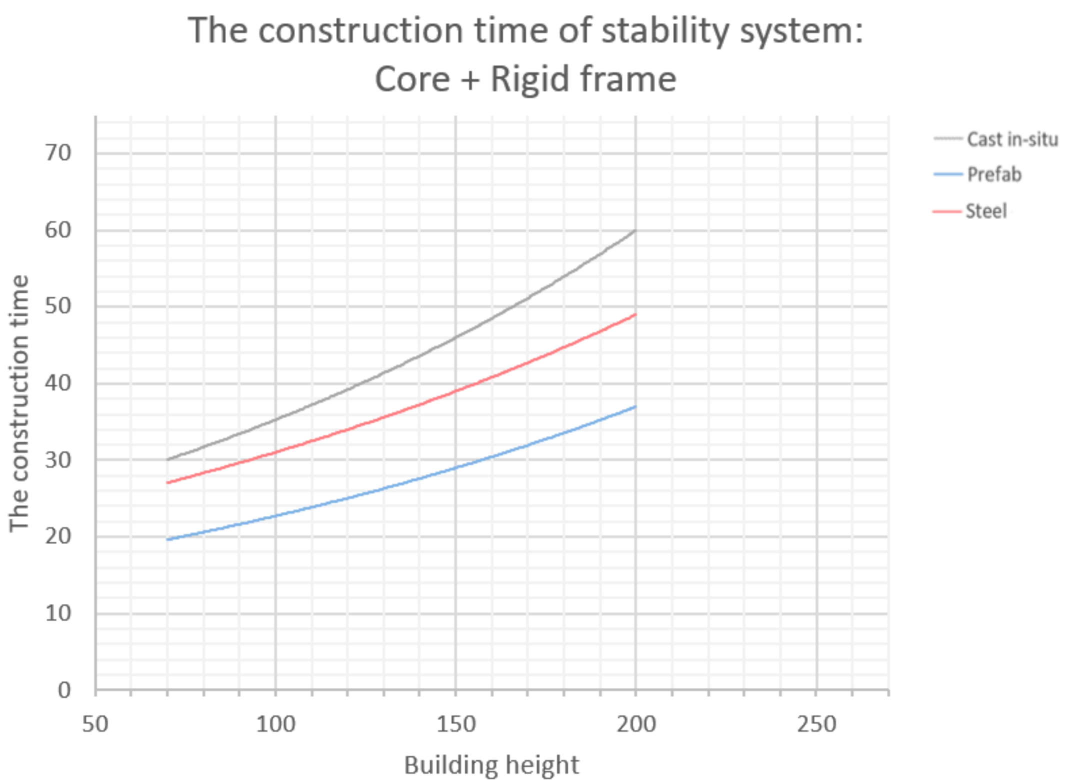


Figure 32: The construction time in months plotted against the building height for a Core + Rigid frame stability system.

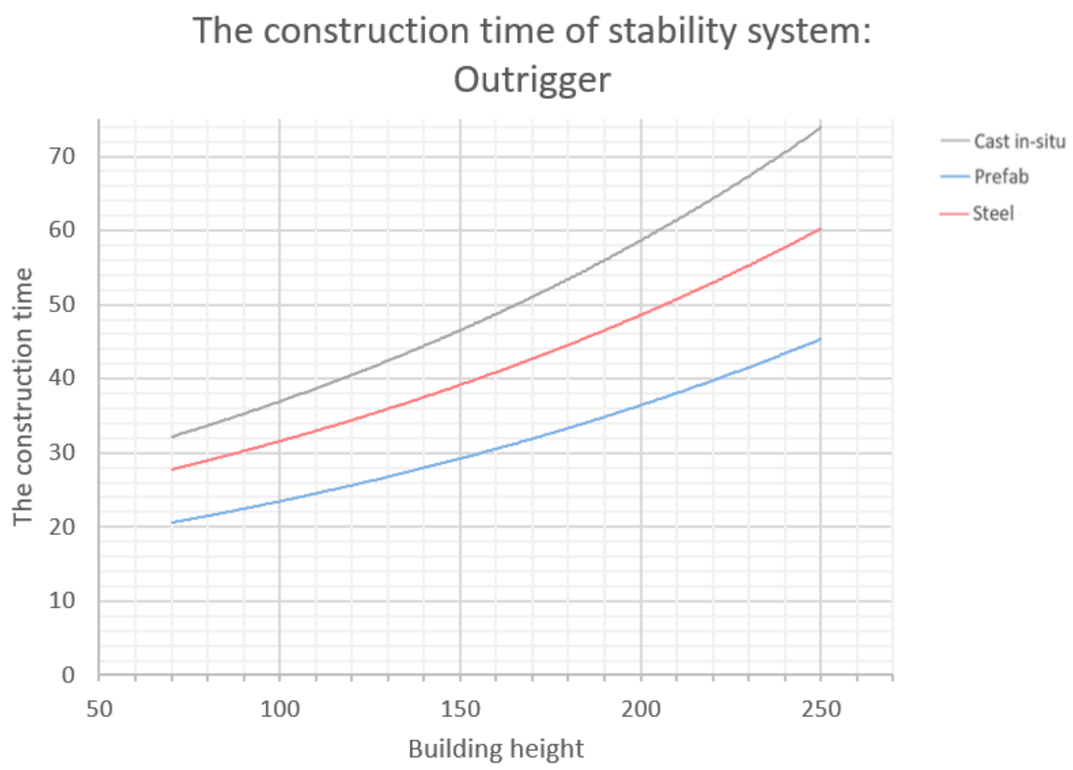


Figure 33: The construction time in months plotted against the building height for a Outrigger stability system.

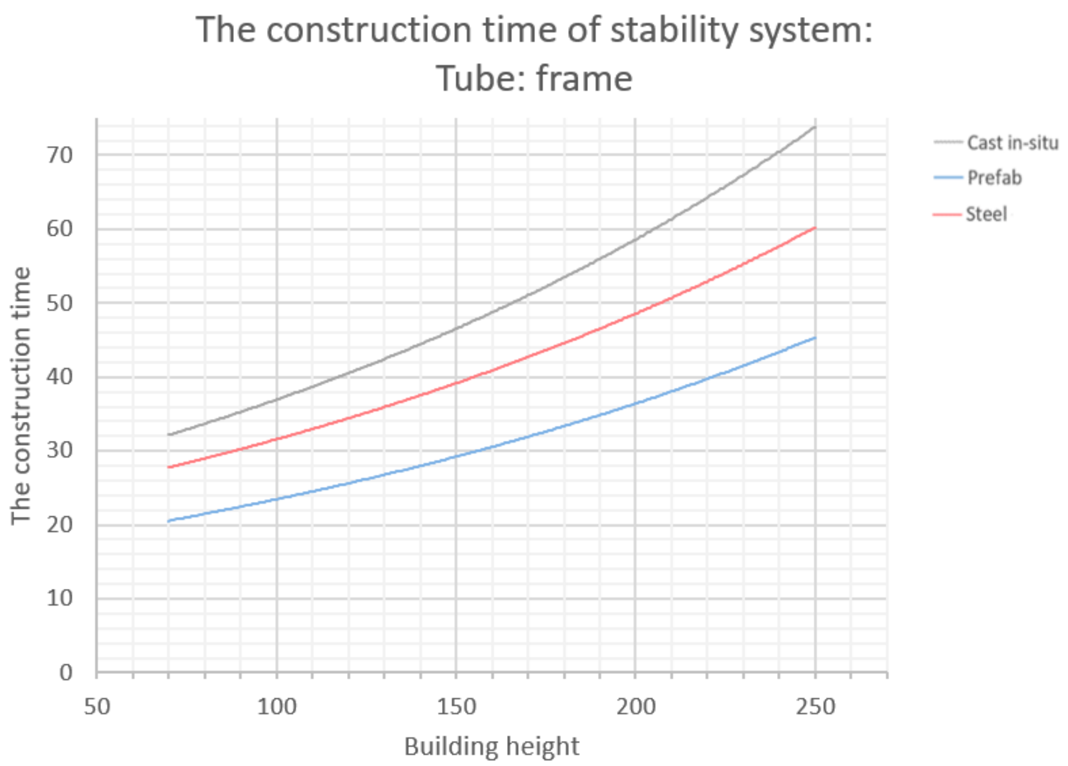


Figure 34: The construction time in months plotted against the building height for a Tube: frame stability system.

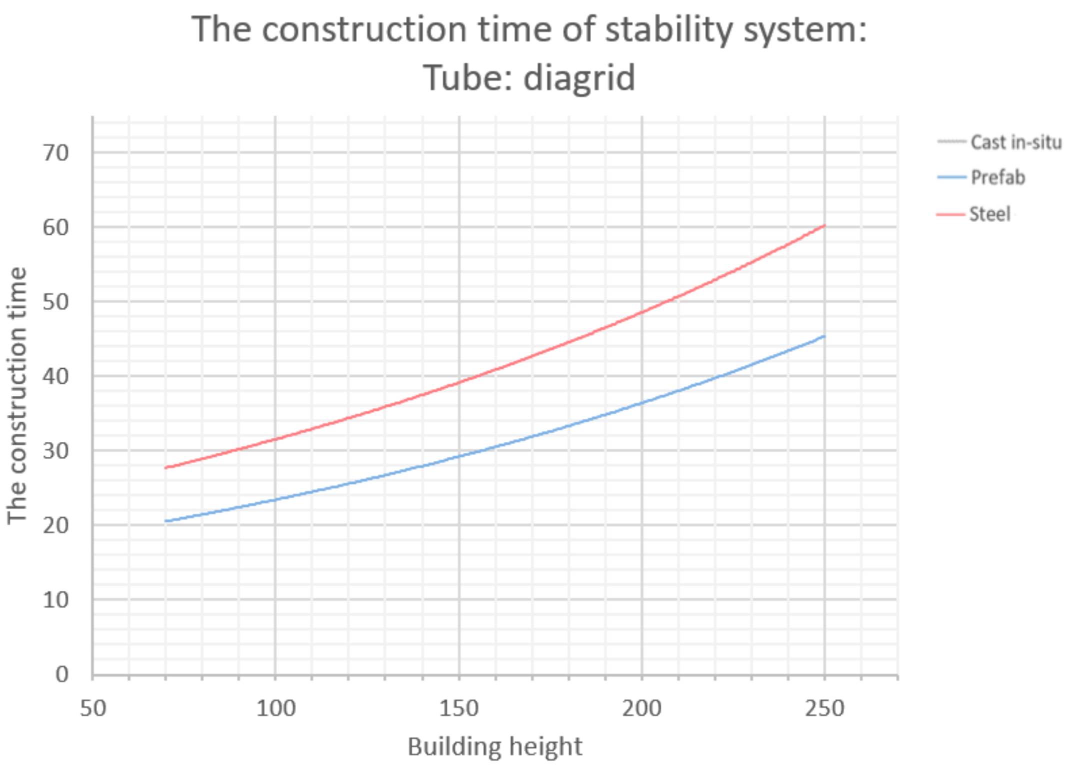


Figure 35: The construction time in months plotted against the building height for a Tube: diagrid stability system.

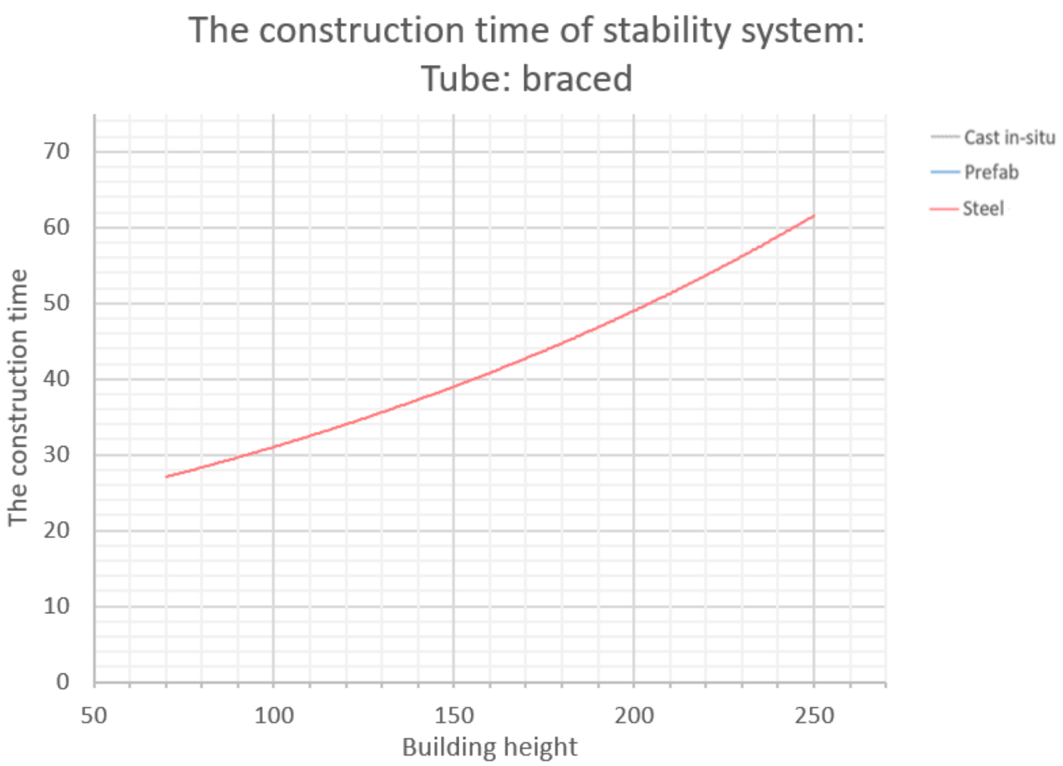


Figure 36: The construction time in months plotted against the building height for a Tube: braced stability system.

I. Input excel tool: direct and indirect costs

First, the calculated direct and indirect costs are shown in tables. Then these cost are added and plotted figures. The function plotted through the height points is then used in the excel tool.

I.1. The calculated costs: direct and indirect

Table 42: The direct costs [€] of each of the twenty-six *combinations.*

			Height				
Stability system	**Structural material**	**Floor type**	50 m	100 m	150 m	200 m	250 m
Core							
	Cast in-situ concrete	Flat slab floor	922374	3182855	14518040	X	X
	Cast in-situ concrete	Hollow core slab	668878	3196863	14224145	X	X
	Prefab concrete	Hollow core slab	672272	3193783	14219210	X	X
Shear walls							
	Cast in-situ concrete	Flat slab floor	1236668	4891220	9192870	13804064	
	Cast in-situ concrete	Hollow core slab	1236668	4097609	7900110	9710324	
	Prefab concrete	Hollow core slab	863204	2510387	6607350	8345744	
Core + Rigid frame							
	Cast in-situ concrete	Flat slab floor			9948798	21246077	X
	Cast in-situ concrete	Hollow core slab			9664334	20307558	X
	Prefab concrete	Hollow core slab			10820354	24538278	X
	Steel	Composite floor			22490205	50412909	X
	Steel	Hollow core slab			22826726	50433804	X
Outrigger							
	Cast in-situ concrete	Flat slab floor			9659056	15433916	X
	Cast in-situ concrete	Hollow core slab			7024146	14483252	28989033
	Prefab concrete	Hollow core slab			7788065	18444067	33794014
	Steel	Composite floor			12607260	27966536	52533669
	Steel	Hollow core slab			13299166	28152301	53052993
Tube: frame							
	Cast in-situ concrete	Flat slab floor			14699420	17401712	X

	Cast in-situ concrete	Hollow core slab			7652942	16940529	34662844
	Prefab concrete	Hollow core slab			6173326	13247058	25635765
	Steel	Composite floor			21326578	48355709	87691710
	Steel	Hollow core slab			22247201	48848094	87874287
Tube: braced							
	Cast in-situ concrete	Flat slab floor			X	X	X
	Cast in-situ concrete	Hollow core slab			X	X	X
	Prefab concrete	Hollow core slab			X	X	X
	Steel	Composite floor			12607260	27966536	52533669
	Steel	Hollow core slab			12701080	28152301	53052993
Tube: diagrid							
	Cast in-situ concrete	Flat slab floor			X	X	X
	Cast in-situ concrete	Hollow core slab			X	X	X
	Prefab concrete	Hollow core slab			4229267	8342542	16121474
	Steel	Composite floor			9448028	16107232	27809835
	Steel	Hollow core slab			9537276	16127455	27839238

Table 43: The indirect costs [€] of each of the twenty-six *combinations*.

			Height				
Stability system	**Structural material**	**Floor type**	50 m	100 m	150 m	200 m	250 m
Core							
	Cast in-situ concrete	Flat slab floor	1595061	3314175	5877398	X	X
	Cast in-situ concrete	Hollow core slab	1595061	3314175	5877398	X	X
	Prefab concrete	Hollow core slab	901121	1841273	3216297	X	X
Shear walls							
	Cast in-situ concrete	Flat slab floor	1595061	3314175	5877398	9457587	X
	Cast in-situ concrete	Hollow core slab	1595061	3314175	5877398	9457587	X
	Prefab concrete	Hollow core slab	901121	1841273	3216297	5190618	X
Core + Rigid frame							
	Cast in-situ concrete	Flat slab floor			5877398	9457587	X

	Cast in-situ concrete	Hollow core slab	5877398	9457587	X
	Prefab concrete	Hollow core slab	3216297	5190618	X
	Steel	Composite floor	4983011	7723696	X
	Steel	Hollow core slab	4983011	7723696	X
Outrigger					
	Cast in-situ concrete	Flat slab floor	5877398	9457587	X
	Cast in-situ concrete	Hollow core slab	5877398	9457587	14195602
	Prefab concrete	Hollow core slab	3216297	5190618	7985260
	Steel	Composite floor	4983011	7723696	11667618
	Steel	Hollow core slab	4983011	7723696	11667618
Tube: frame					
	Cast in-situ concrete	Flat slab floor	5877398	9457587	X
	Cast in-situ concrete	Hollow core slab	5877398	9457587	14195602
	Prefab concrete	Hollow core slab	3216297	5190618	7985260
	Steel	Composite floor	4983011	7723696	11667618
	Steel	Hollow core slab	4983011	7723696	11667618
Tube: braced					
	Cast in-situ concrete	Flat slab floor	X	X	X
	Cast in-situ concrete	Hollow core slab	X	X	X
	Prefab concrete	Hollow core slab	X	X	X
	Steel	Composite floor	4983011	7723696	11667618
	Steel	Hollow core slab	4983011	7723696	11667618
Tube: diagrid					
	Cast in-situ concrete	Flat slab floor	X	X	X
	Cast in-situ concrete	Hollow core slab	X	X	X
	Prefab concrete	Hollow core slab	3216297	5190618	7985260
	Steel	Composite floor	4983011	7723696	11667618
	Steel	Hollow core slab	4983011	7723696	11667618

I.2. Input figures

The figures below show the total direct and indirect costs for each height of the following five stability systems: Core, Shear walls, Core + Rigid frame, Tube: frame, Tube: braced, Tube: outrigger.

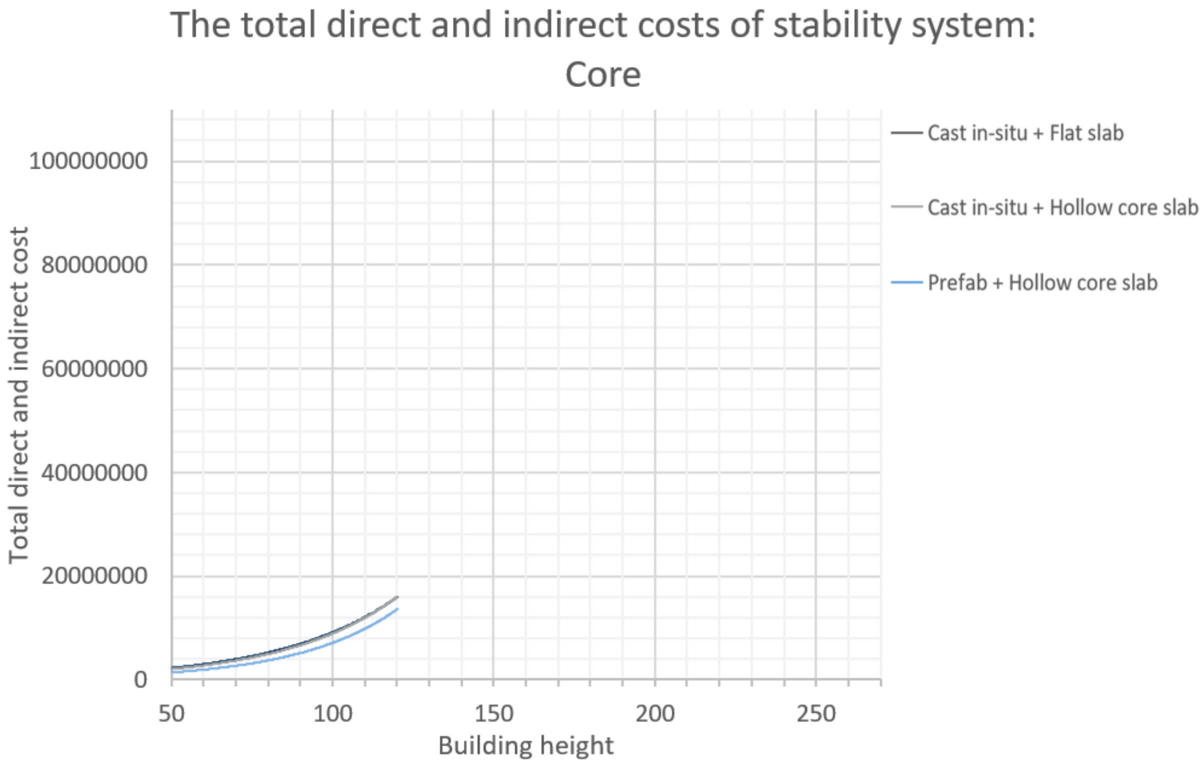


Figure 37: The total direct and indirect cost plotted against the building height for a Core stability system. The light grey line lies behind the dark grey line.

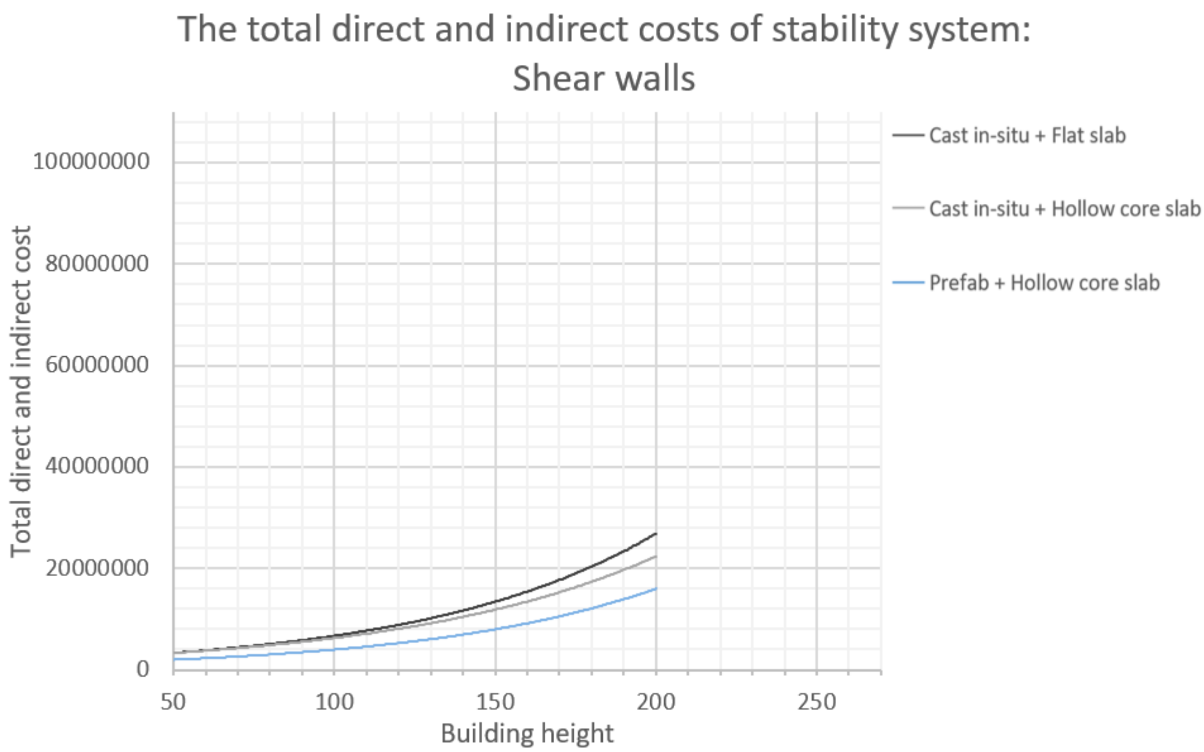


Figure 38: The total direct and indirect cost plotted against the building height for a Shear walls stability system.

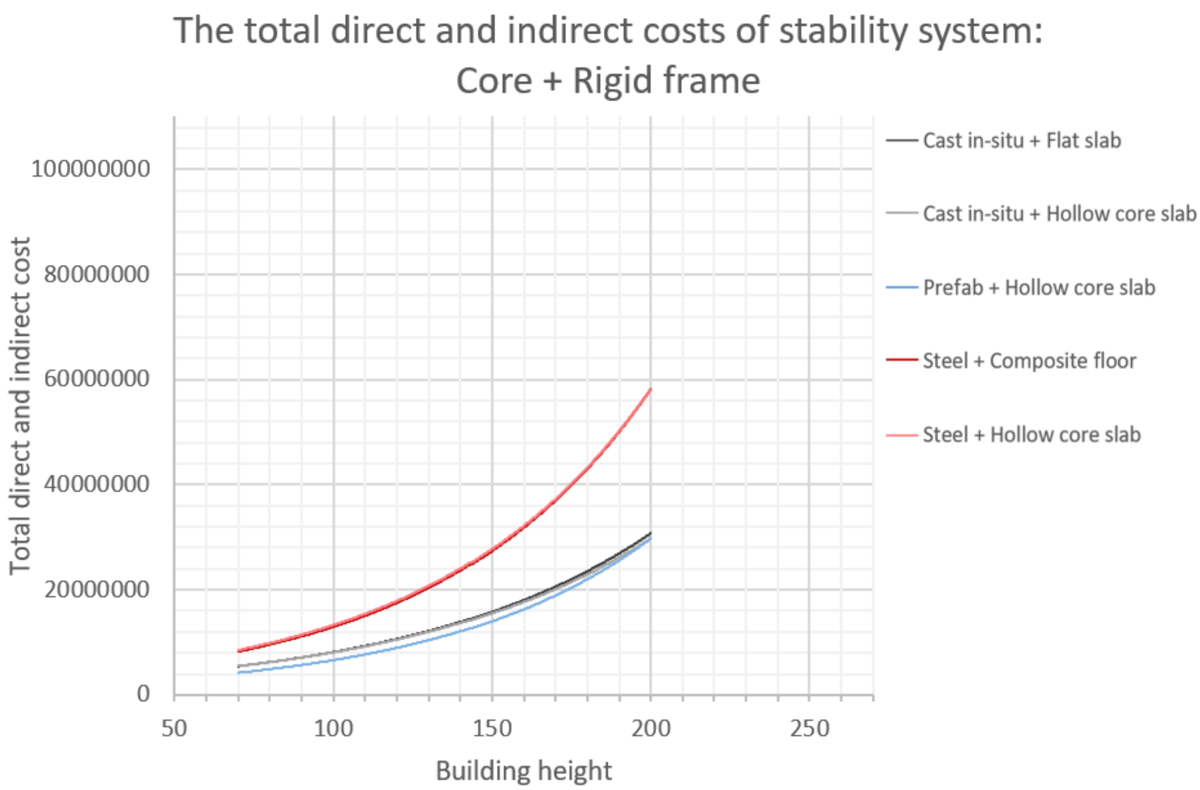


Figure 39: The total direct and indirect cost plotted against the building height for a Core + Rigid frame stability system.

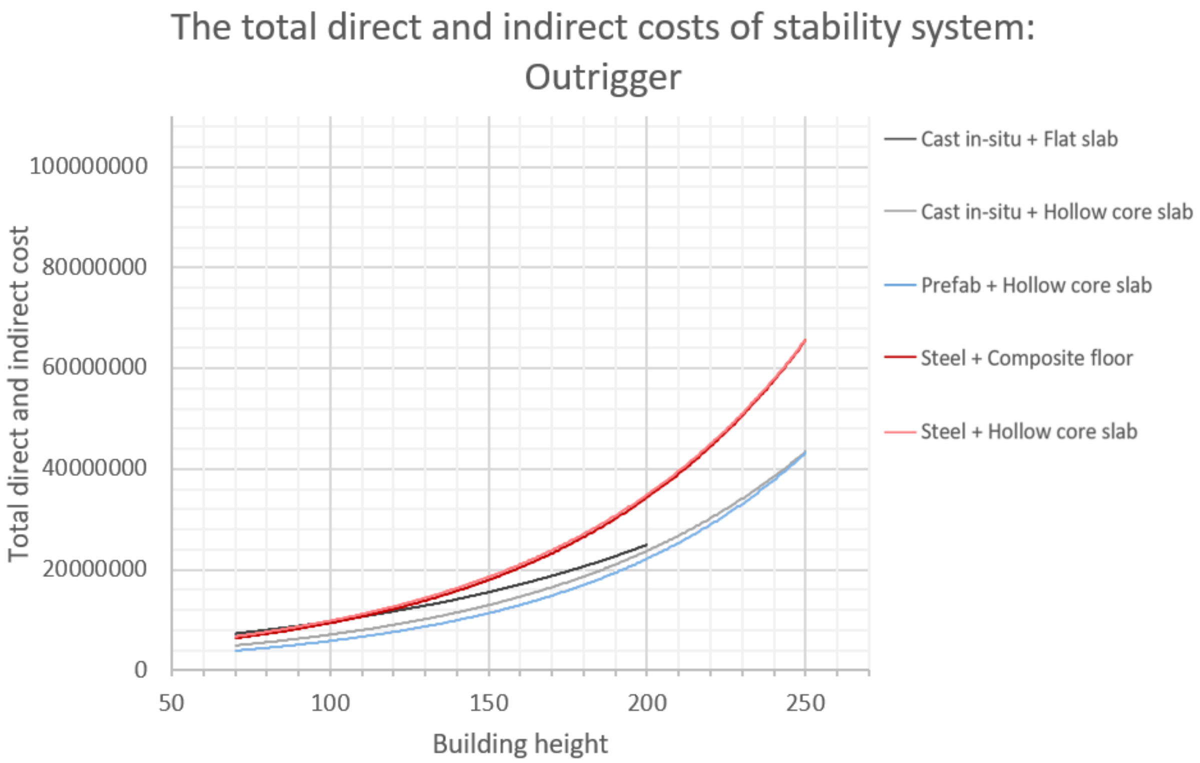


Figure 40: The total direct and indirect cost plotted against the building height for a Outrigger stability system. The light red line lies behind the dark red line.

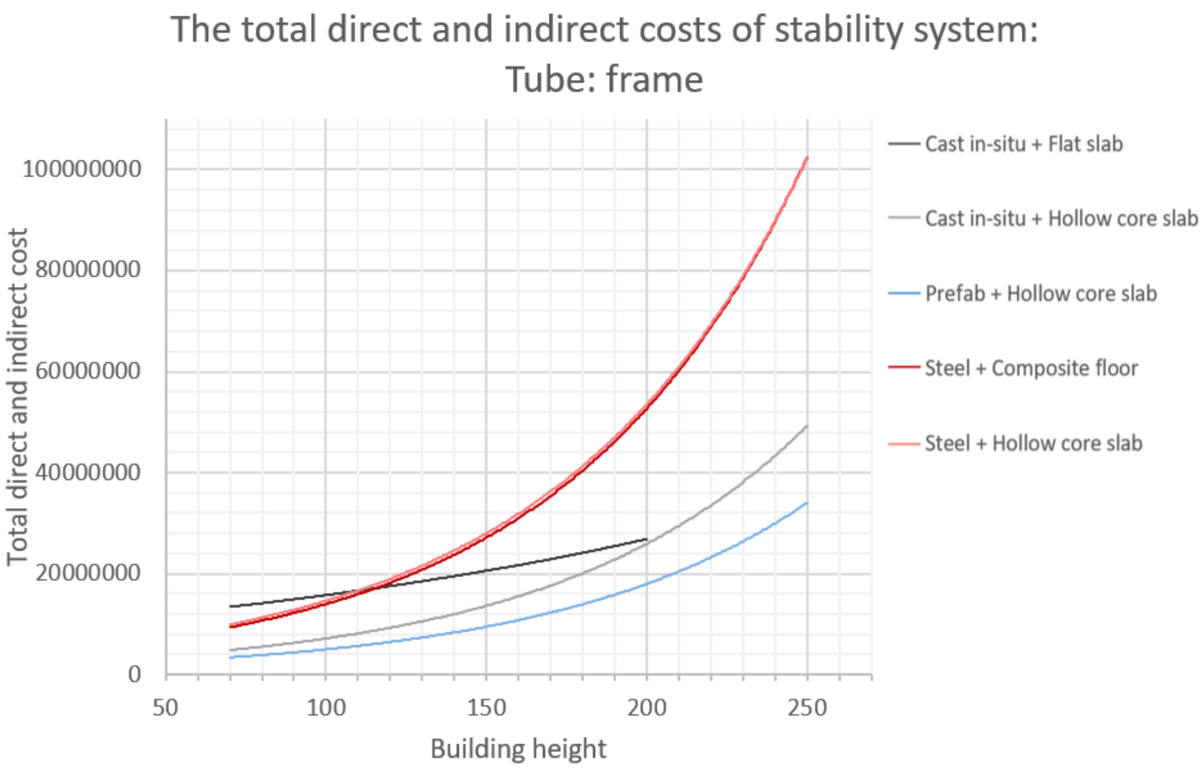


Figure 41: The total direct and indirect cost plotted against the building height for a Tube: frame stability system.

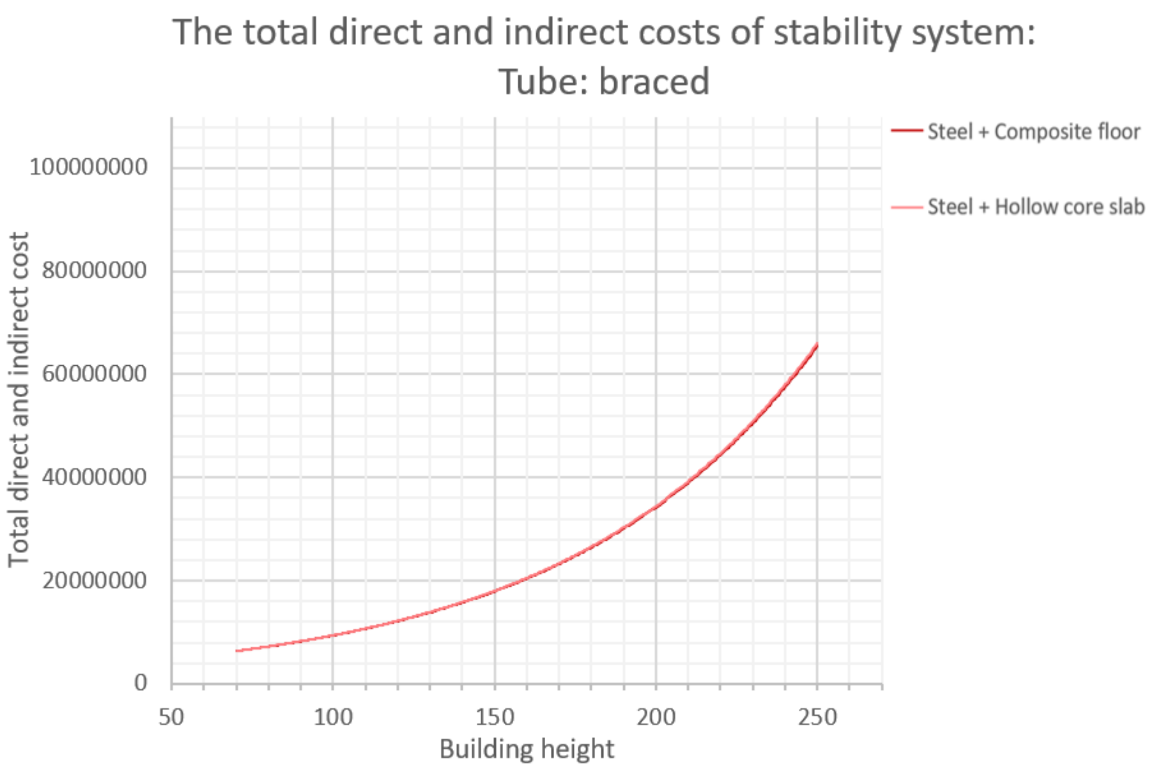


Figure 42: The total direct and indirect cost plotted against the building height for a Tube: braced stability system. The light red line lies behind the dark red line.

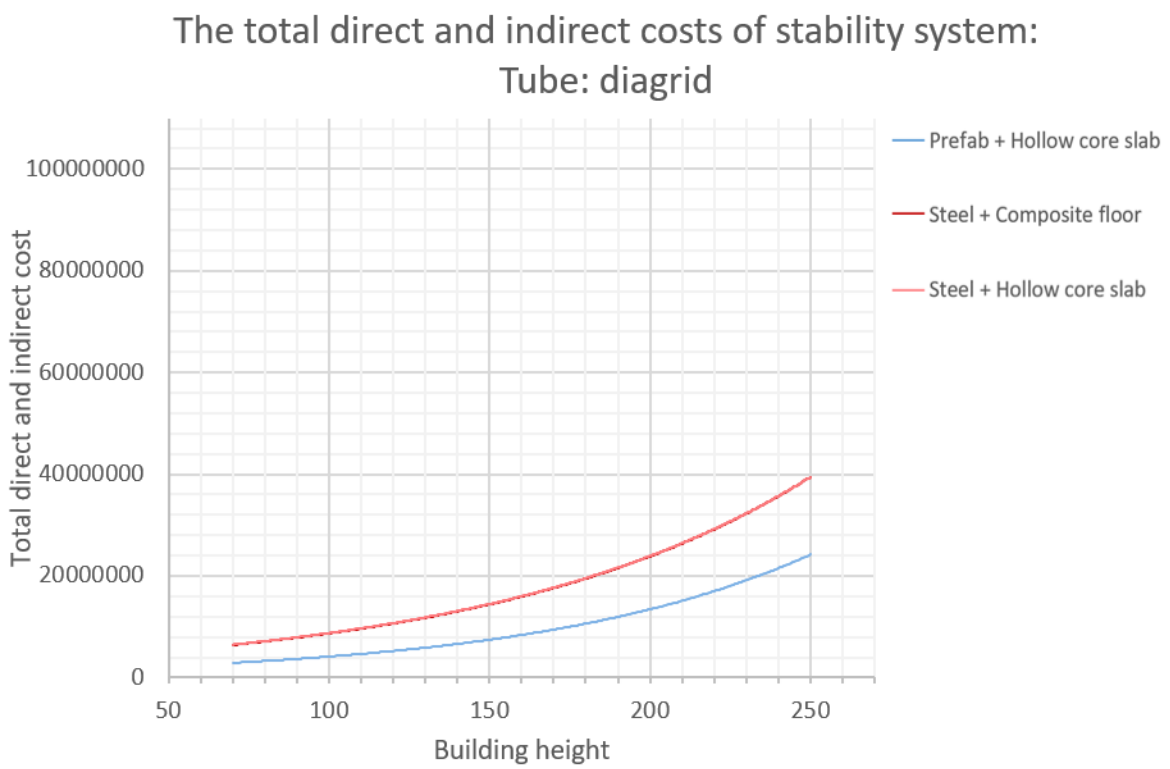


Figure 43: The total direct and indirect cost plotted against the building height for a Tube: diagrid stability system. The light red line lies behind the dark red line.

J. Input excel tool: environmental cost

First, the calculated environmental costs are shown in a table. Then these cost are plotted figures. The function plotted through the height points is then used in the excel tool.

J.1. The calculated costs: direct and indirect

Table 44: The environmental costs [€env] of each of the twenty-six *combinations*.

			Height				
Stability system	**Structural material**	**Floor type**	50 m	100 m	150 m	200 m	250 m
Core							
	Cast in-situ concrete	Flat slab floor	179244	392703	540000	X	X
	Cast in-situ concrete	Hollow core slab	142624	331139	500000	X	X
	Prefab concrete	Hollow core slab	143978	333899	500000	X	X
Shear walls							
	Cast in-situ concrete	Flat slab floor	151843	399647	673635	971794	
	Cast in-situ concrete	Hollow core slab	137329	353935	633804	322009	
	Prefab concrete	Hollow core slab	127686	310277	613501	305179	
Core + Rigid frame							
	Cast in-situ concrete	Flat slab floor			682320	1126784	X
	Cast in-situ concrete	Hollow core slab			579454	979677	X
	Prefab concrete	Hollow core slab			587458	1033616	X
	Steel	Composite floor			704572	1247890	X
	Steel	Hollow core slab			672116	1194605	X
Outrigger							
	Cast in-situ concrete	Flat slab floor			661820	968148	X
	Cast in-situ concrete	Hollow core slab			502486	798600	1289250
	Prefab concrete	Hollow core slab			504299	819034	1305169
	Steel	Composite floor			568274	949885	1550388
	Steel	Hollow core slab			533552	898894	1484341

Tube: frame					
Cast in-situ concrete	Flat slab floor	664855	1016373	X
Cast in-situ concrete	Hollow core slab	529119	898928	1532101
Prefab concrete	Hollow core slab	533165	917174	1513029
Steel	Composite floor	698465	1230783	1961194
Steel	Hollow core slab	664534	1209212	1888848
Tube: braced					
Cast in-situ concrete	Flat slab floor	X	X	X
Cast in-situ concrete	Hollow core slab	X	X	X
Prefab concrete	Hollow core slab	X	X	X
Steel	Composite floor	672466	1064401	1776283
Steel	Hollow core slab	656606	1066881	1764428
Tube: diagrid					
Cast in-situ concrete	Flat slab floor	X	X	X
Cast in-situ concrete	Hollow core slab	X	X	X
Prefab concrete	Hollow core slab	440417	664463	1009466
Steel	Composite floor	521325	793661	1182390
Steel	Hollow core slab	481697	722612	1110758

J.2. Input figures

The figures below show the environmental cost for each height of the following five stability systems: Core, Shear walls, Core + Rigid frame, Tube: frame, Tube: braced, Tube: outrigger. The dotted lines follow the minimum and maximum values for each height of *all* the stability systems, except Shear walls. Shear walls are often only used in high rise building with as function housing. This means this stability system can't always be used and it thus is not embedded in the dotted minimum and maximum environmental cost lines.

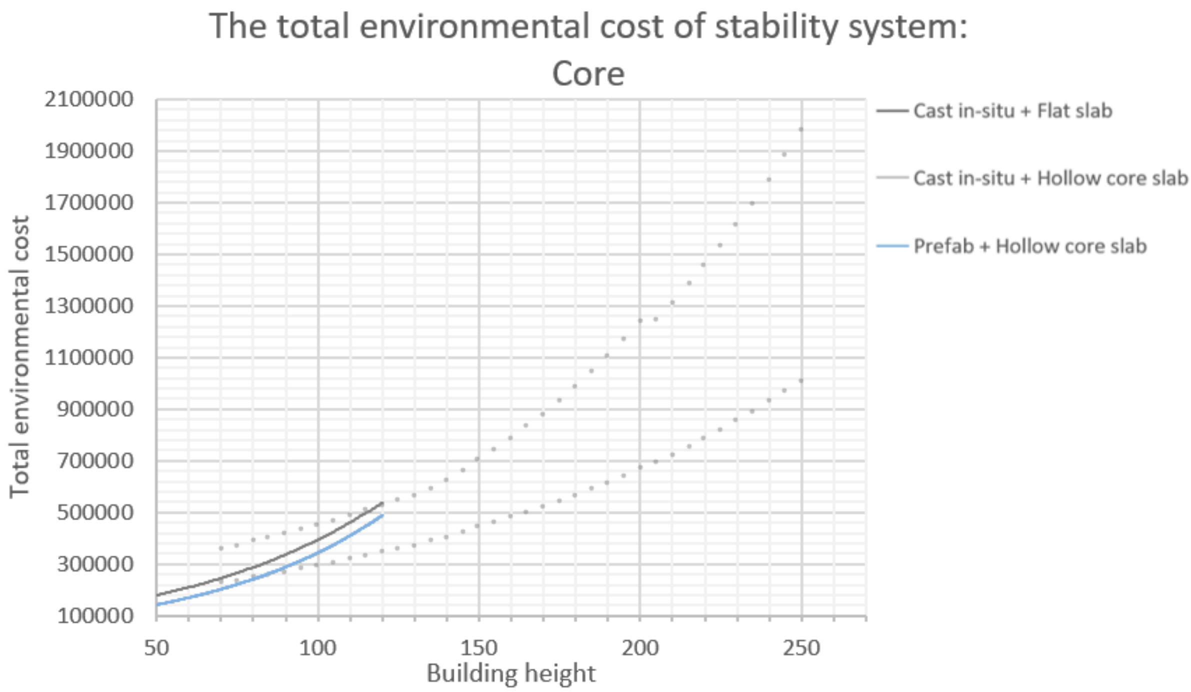


Figure 44: The total environment cost plotted against the building height for a Core stability system. The light grey line lies behind the light blue line.

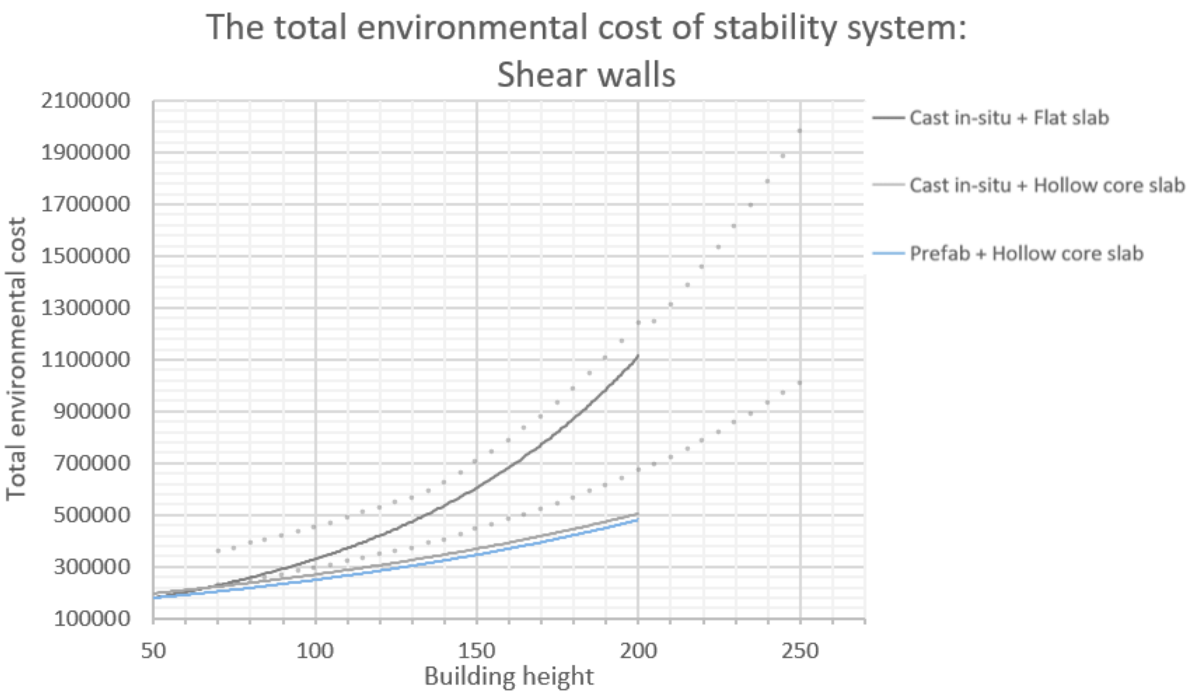


Figure 45: The total environment cost plotted against the building height for a Shear walls stability system. The 'Prefab + Hollow core slab' is completely made of prefab concrete, in contrast to all the other stability systems which always have a core made of cast in-situ concrete.

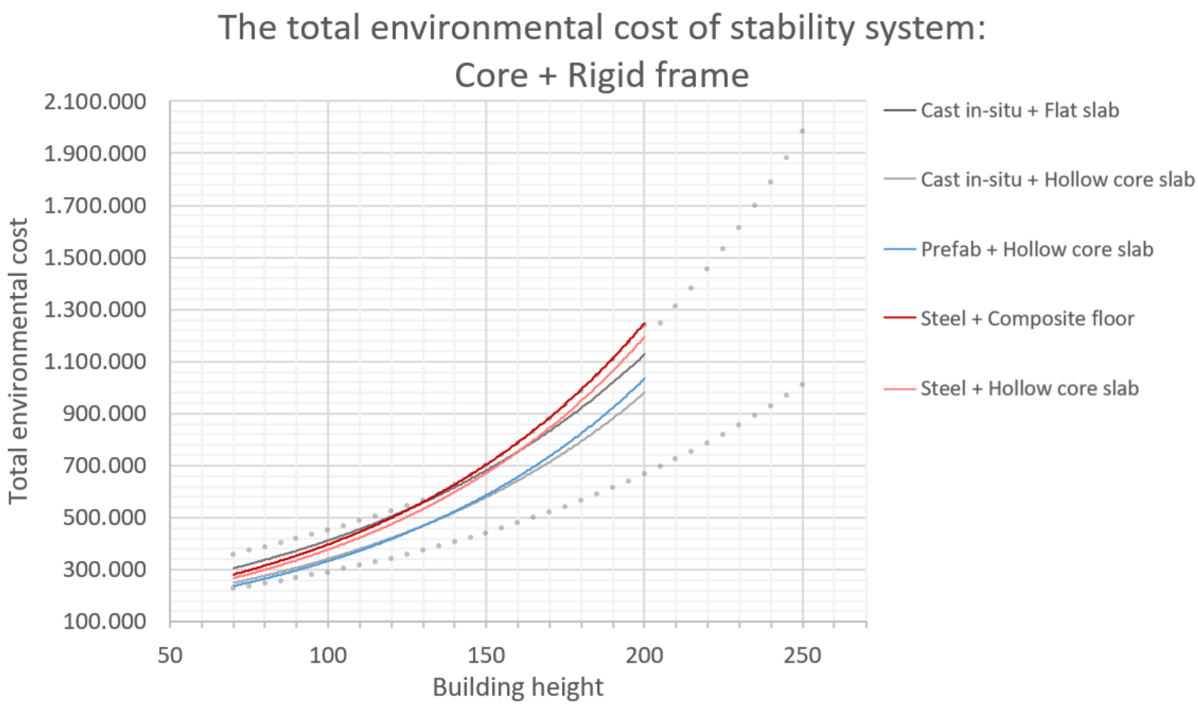


Figure 46: The total environment cost plotted against the building height for a Core + Rigid frame stability system.

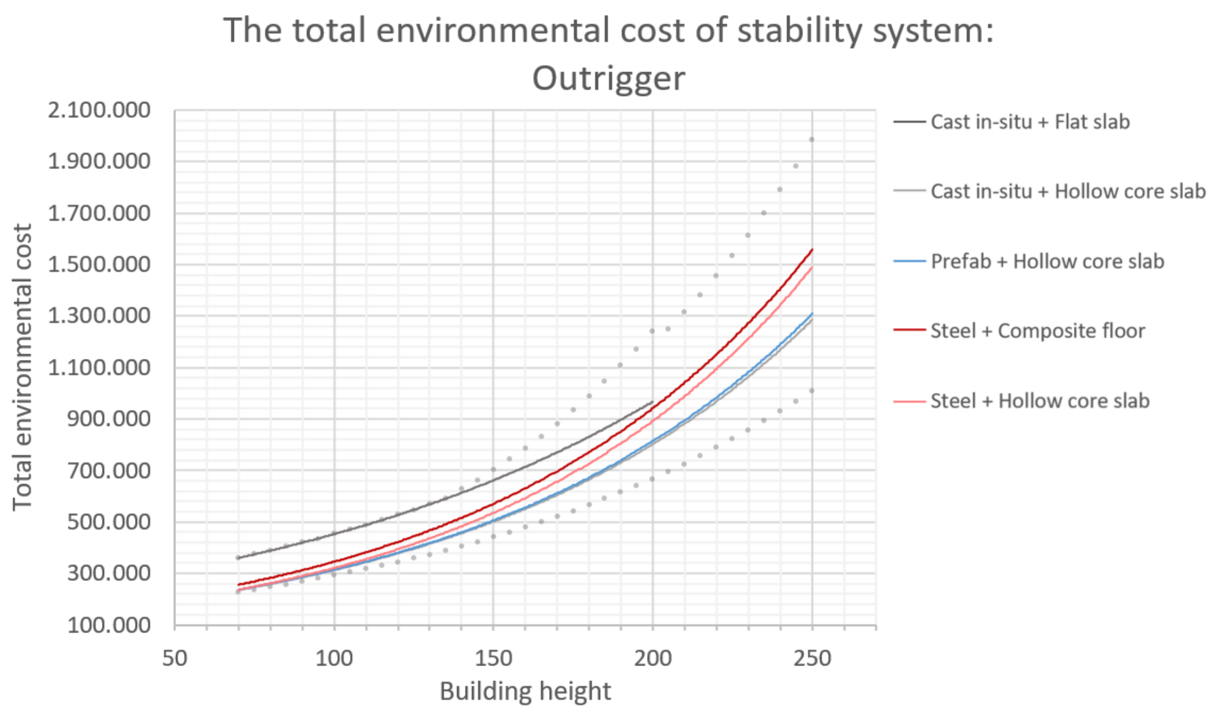


Figure 47: The total environment cost plotted against the building height for an Outrigger stability system.

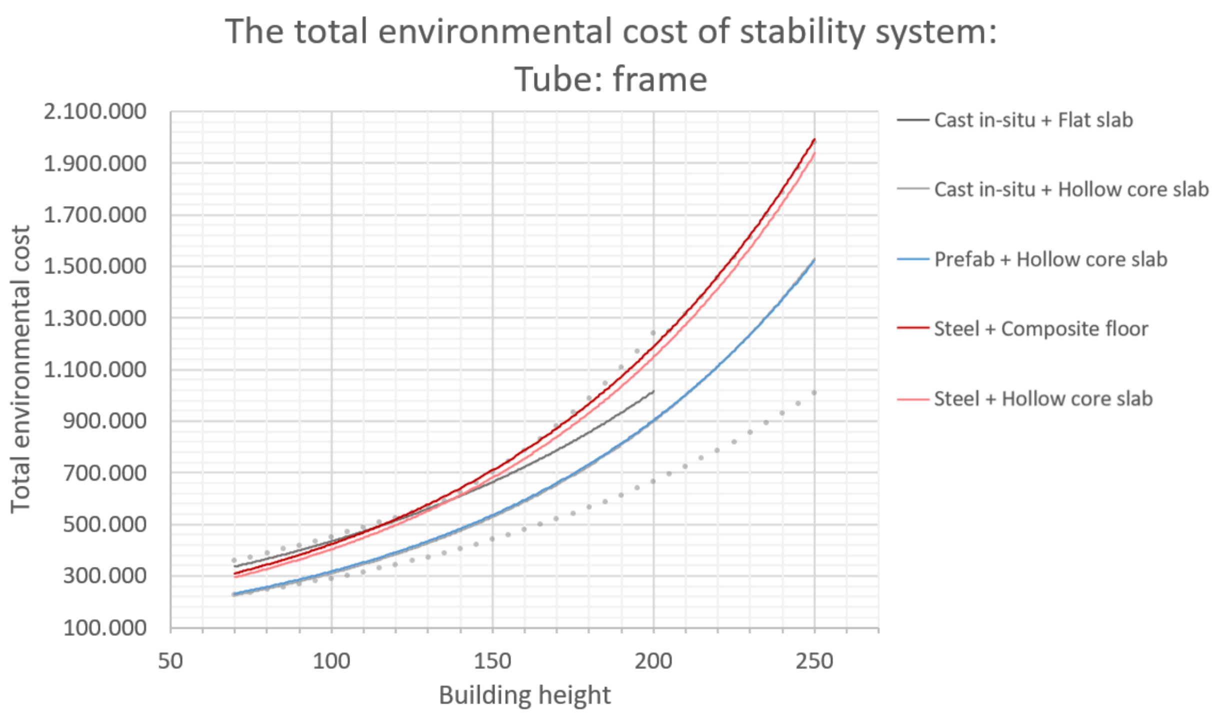


Figure 48: The total environment cost plotted against the building height for a Tube: frame stability system. The grey line lies behind the blue line.

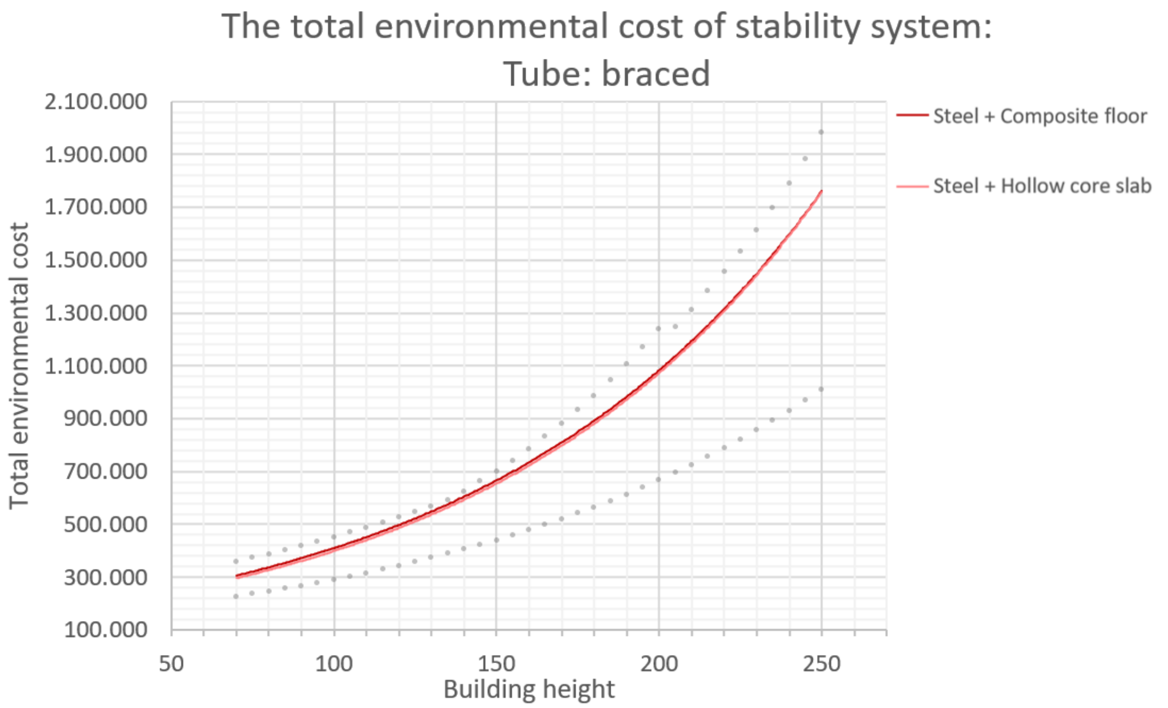


Figure 49: The total environment cost plotted against the building height for a Tube: braced stability system.

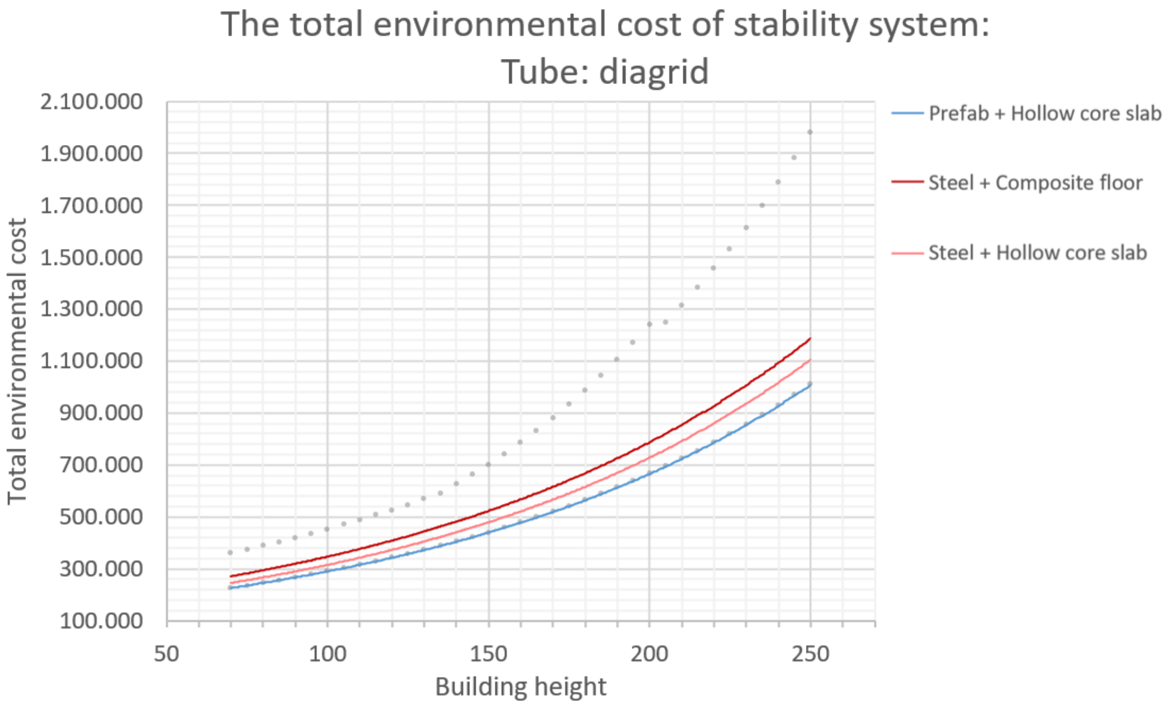


Figure 50: The total environment cost plotted against the building height for a Tube: diagrid stability system.

K. Validation: Results

The Structural Engineering & Design department of the Arcadis office in Rotterdam has been asked to give feedback on different parts of the tool. The average results can be found below.

The 'Read' box

1a. How clear was the content and the lay-out of the 'Read' information block at the top of the tool? Were the instructions clear enough to know what you have to do?

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **3.7**

The 'Input 1' box

2a. How clear was the content and the required input of the 'Input 1' block? Is the building height a clear factor to use as input early in the design process?

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **4.7**

2b. How clear was the information given on the right of the 'Input 1' block? Were the assumptions made to be able to create the excel-tool clear?

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **3.7**

The 'Input 2' box

3a. How clear was the content and the required input of the 'Input 2' block? Was it clear that certain things can be excluded beforehand? For example: an office high rise building probably won't use 'Shear walls' as a stability system.

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **3.9**

3b. How clear was the information given on the right of the 'Input 2' block? Were the height ranges of each stability system clear? And was it clear that the tool will take these ranges into account? So when a height above 120 m is chosen, 'Core' is excluded as a stability system.

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **3.8**

The 'Input 3' box

4a. How clear was the content and the required input of the 'Input 3' block? If for example you find cost much more important than sustainability, you can have that as input here.

Give a score from 1 (very bad) to 5 (very good).

- The average of the scores that were given: **4.4**

The 'Calculate' box

5a. How clear was the use of the green (re)calculate button?
Did you understand that [Yes] needs to be typed again to (re)calculate? Otherwise the results won't be accurately shown.

Give a score from 1 (very bad) to 5 (very good).

- ➢ The average of the scores that were given: **3.6**

Output

6a. How clear was the 'Output'?
Was the ranking clear?

Give a score from 1 (very bad) to 5 (very good).

- ➢ The average of the scores that were given: **3.8**

Sub-results

7a. Did you use the 'Sub-results'?
For example to give you more insight in the calculated cost or sustainability of the shown best solution.

Answer ‘yes’ or ‘no’.

- ➢ ‘yes’ was answered **7** times and ‘no’ **2** times.

7b. How clear were the 'Sub-results'?
Was the ranking clear?

Give a score from 1 (very bad) to 5 (very good).

- ➢ The average of the scores that were given: **3.4**

The goal of the tool
The goal: The tool wants to give the structural engineer early in the design process of a high rise building insight in which stability systems, structural materials and floor types fit the wishes of the design team best. The focus will be on cost (direct and indirect) and sustainability (environmental cost).

8a. How well was this goal achieved?

Give a score from 1 (very bad) to 5 (very good).

- ➢ The average of the scores that were given: **3.3**