Guideline

Advisory tool
stability system, structural material and floor type
for high rise buildings between 50 m and 250 m

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Company: Arcadis, Rotterdam
Period: October 2019 – June 2020

Defence: 10th of July, 2020

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Short thesis summary

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?
By gaining insight in differences between theory and practice in the decision-making process, this thesis tries to identify the main issues arising in the structural material choice process and tries to offer a solution for these issues. The following two differences between theory and practice are combined and addresses together by creating an advisory excel-tool:

- 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.
- 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.

This excel-tool gives the structural engineer early in the design process of a high rise project insight in the influence of the structural typology (stability system and floor type) and the structural material choice on two chosen factors: Cost (direct and indirect costs) and sustainability (environmental costs).

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.

This document is a guide for the *Advisory tool stability system, structural material and floor type for high rise buildings between 50 m and 250 m*.
This advisory tool is an excel-tool that is part of the master thesis "*Rationalising the Structural Material Choice Process for High Rise Buildings in the Netherlands*" by E. (Esmee) M.R. Koopman (2020).

Reading guide

I start this guide for the excel-tool with a reading guide. The reading guide shows you which chapters are most suitable for you to read depending on how much in depth you want to go in the excel-tool. Figure 1 (at the next page) shows a flowchart of all the calculations that were performed to create the excel-tool.

Read Chapter 1: *Interface*	
If you want to know which parameters are included in the tool.	➢ Paragraph 1.1.: *Parameters*
If you want to get a more extensive description on which input and output can be found in the tool (*besides the description that can be found in the excel-tool*) and how the tool operates.	➢ Paragraph 1.2.: *Input* *and* Paragraph 1.3.: *Output*
Read Chapter 2: *Calculations*	
If you want to know which assumptions and measurements have been used in the calculations of *Cost* and *Sustainability* in the tool.	➢ Paragraph 2.1.: *Height points* *and* Paragraph 2.2.: *Chosen output parameters* *and* Paragraph 2.3.: *Measures*
If you want to know how the *Cost* of each structural combination (stability system, structural material, floor type) is calculated.	➢ Paragraph 2.4.: *Cost*
If you want to know how the *Sustainability* of each structural combination (stability system, structural material, floor type) is calculated.	➢ Paragraph 2.5.: *Sustainability*
Read Chapter 3: *Testing of the tool*	
If you want to know where the uncertainties lie and how well the calculations from the tool match the reality.	➢ Chapter 3: *Testing of the tool*
Read Chapter 4: *Recommendations*	
If you want to know how the tool can be improved and what the ultimate goal for the tool can become.	➢ Chapter 4: *Recommendations*
Read Chapter 5: *Literature list*	
If you want to know which sources have been mentioned in this document.	➢ Chapter 5: *Literature list*
Appendix A and B	
If you want to know how the amount and type of material for the stability system *Core* and *Shear walls* are calculated.	➢ Appendix A and B
Appendix C	
If you want to know how the construction time – that serves as input for the indirect costs – for each structural *combination* (stability system, structural material, floor type) is calculated.	➢ Appendix C
Appendix D and E	
If you want get extra insight in the numbers and graphs – about Cost and Sustainability – that serve as input for the excel tool.	➢ Appendix D and E

For a complete explanation I refer to my master thesis.

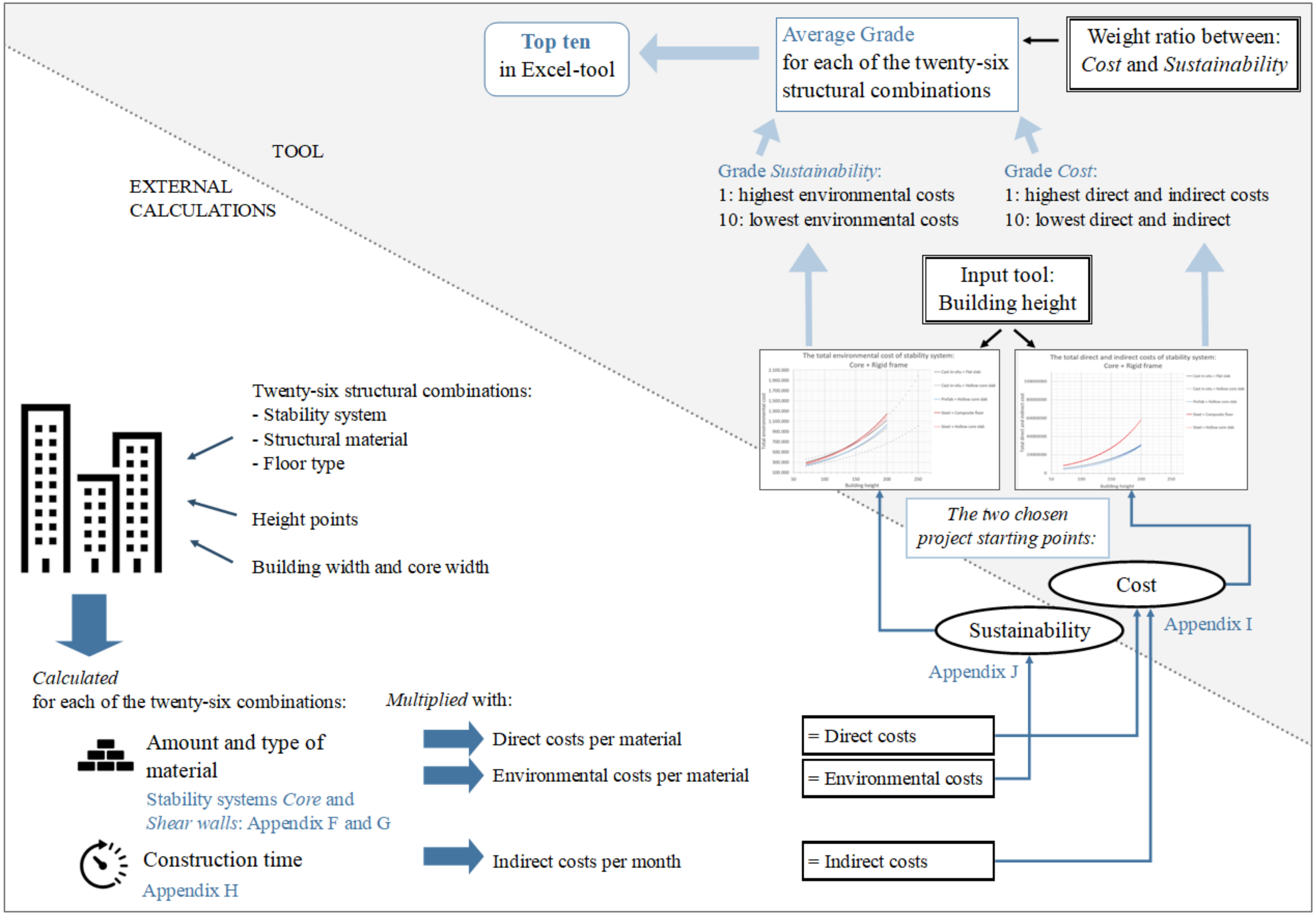

Figure 1: This flowchart shows all the external calculations that served at input for the excel tool (white area); and the calculations that are part of the excel-tool (grey area). The calculations that are part of the excel-tool will be described in detail in Chapter 1. The external calculations will be described in detail in Chapter 2.

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1. Interface

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. 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.

1.1. Parameters

The following output parameters are included in the tool:

- 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 optional twenty-six structural *combinations* of structural typology and structural material that will be shown as a result in the tool are shown in Table 1.

Table 1: 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

1.2. Input

As input only the height of the high rise project is needed (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 9m 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 simple input – only the height of a high rise project – 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.

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 your building is an office, you can exclude *Shear walls*.
Cell J28 to J34 show the height ranges belonging to the stability systems. Why these height ranges were chosen is explained in Table 2.

Table 2: 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 A).
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 B).
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.

Cost (direct and indirect) and *Sustainability* (environmental cost) are used to rank the twenty-six *combinations* from best to worst. 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.
How these *Cost* and *Sustainability* were calculated exactly, can be found in Chapter 2 of this manual.

1.3. Output

After the button "*(re)Calculate*" is pushed, a top ten combinations of stability system, structural material and floor type is shown. 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 from row 72 to 102 and sub-results of *Sustainability* are shown from row 104 to 134. Each of these tables shows the complete ranking of the twenty-six *combinations* based on *Cost* and *Sustainability*.

2. Calculations

The *Cost* and *Sustainability* of each of the twenty-six structural *combinations* shown in Table 1 is calculated and serves as input for the excel-tool. How the *Cost* and *Sustainability* of each of these *combinations* has been calculated is explained in this chapter.

This tool partially builds on the thesis of Lankhorst (2018) were he calculates how sustainable different structural typologies for high rise are. The goal of this tool 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 (Appendix A and B).

2.1. Height points

Within the height range of each stability system (explained in Table 2), several *height points* are appointed. Figure 2 shows the height range of each stability system with a black line and the blue triangles show are the height points. The height points are the heights at which the *Cost* and *Sustainability* of each of the twenty-six *combinations* is calculated. The calculated cost and sustainability at these height points are used per *combination* to draw an exponential cost and sustainability line through, covering the height range. These exponential functions are eventually used in the excel-tool to calculate which structural combination is the cheapest and the most sustainable.

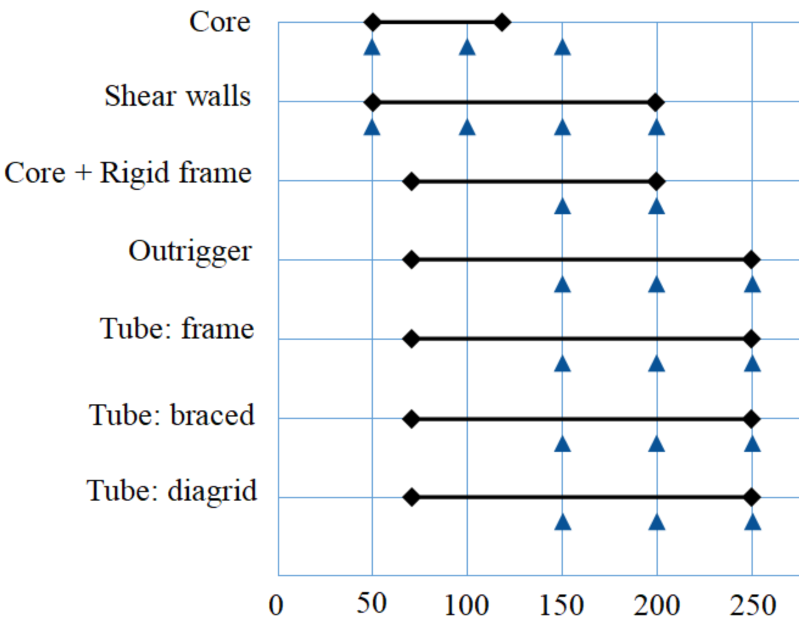

Figure 2: The height range of the stability systems used in this thesis are shown in black. The blue triangles indicate at which height cost and sustainability calculations are performed.

2.2. Chosen output parameters: Cost and Sustainability

This thesis has stated that *Cost* would include direct and indirect cost and *Sustainability* would be expresses in environmental cost.

Both the direct costs and environmental costs will be calculated by using the total amount and type of material used (Figure 3). Lankhorst has already determined from *combination* 7 to *combination* 26 from Table 1 how much and what type of material is needed. This thesis has added the *Core* and *Shear walls* (*combination* 1 to 6). The calculation for the amount and type of material needed for the *Core* and *Shear walls* can be found in Appendix A and B. Eventually the amount of material will be multiplied with the direct cost per material and the environmental cost per material.
The indirect costs are calculated by multiplying the construction time with the indirect cost per month

construction time (Figure 3). The construction time is calculated, by using the book *Bouwplanning* (Flapper, 1995) (see Appendix C).

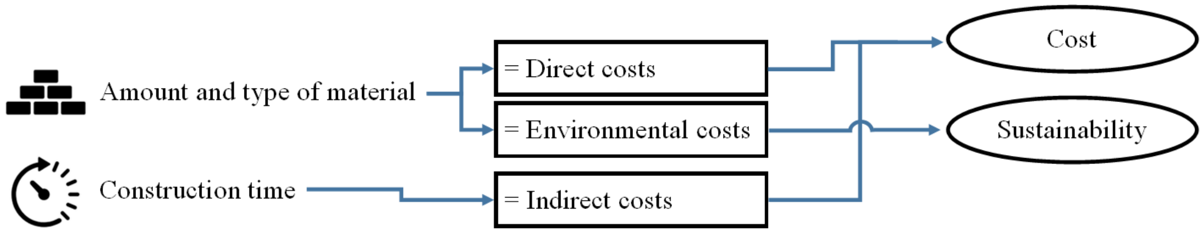

Figure 3: The calculation flow chart, showing how the direct costs, indirect costs and environmental costs of each of the twenty-six structural *combinations* have been calculated.

2.3. Measures

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 3. These measures were based on the measures of existing high rise buildings – as already mentioned in Paragaph 1.1 – and were used to determine the amount of material that is needed to have a structurally working building.
Table 4 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 has compared several geometries of each stability system (Outrigger, Tube: frame, Tube: braced, Tube: diagrid) with 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 5. Of the *Core* and the *Shear walls* only one geometry has been calculated by this thesis.

Table 3: 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	*If applied:* Amount of outriggers
49.4 m	27 m x 27 m	1.8	13	9 m x 9 m	89%	*Not applicable*
98.8 m	28.5 m x 28.5 m	3.5	26	10.5 m x 10.5 m	86%	*Not applicable*
152.0 m	30.0 m x 30.0 m	5,1	40	12.0 m x 12.0 m	84%	1
197.6 m	31.5 m x 31.5 m	6,3	52	13.5 m x 13.5 m	82%	2
243.2 m	33.0 m x 33.0 m	7,4	66	15.0 m x 15.0 m	79%	3

Table 4: 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

Table 5: The most sustainable geometries of each stability system are shown below, together with the limits of each stability system.

Stability system	Geometry
Core	1 core and 4 columns in the façade in one direction and 5 columns in the façade in the other direction (Appendix A)
Shear walls	1 core made of shear walls 2 walls in the façade and 2 around the core in one direction and 2 walls in the other direction, connecting the façade walls to the core walls (Appendix B)
Core + Rigid frame	1 core and 8 columns per façade
Outrigger	1 core and 8 columns per façade 2 storey high outrigger in both directions with a Belt truss
Tube: frame	1 core and 11 columns per façade
Tube: braced	1 core and 11 columns per façade
Tube: diagrid	1 core and 71° angle for the trusses

2.4. Cost

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.

The direct costs are calculated by multiplying the cost per m^3 with the amount of that material. Lankhorst (2018) has calculated the type and amount of material needed of *combination* 7 to 26. This thesis has also calculated the type and amount of materials needed when only a *Core* or *Shear walls* (combination 1 to 6) 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 A and B).
Table 6 shows the direct costs per floor type [€/m^2] and Table 7 shows the direct costs per material [€/m^3]. The resulting total direct costs of each of the twenty-six *combinations* can be found in Appendix D.

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 [€/m^3]
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 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 4 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 4 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 4 at 150 m height matches the total indirect costs shown in Table 8.

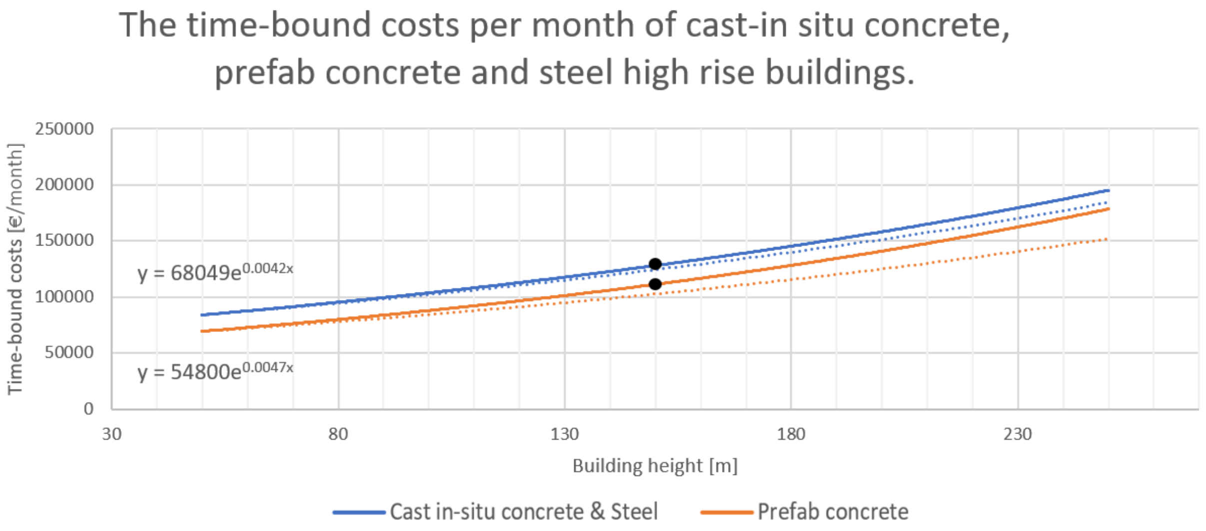

Figure 4: The time-bound costs per month for each building height and structural material. The thick lines (and the belonging formulas) are the indirect costs per month given by Arcadis (Bunk, 2020). The dotted lines are the indirect costs per month as stated by Oss (2007).

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**

For each of the twenty-six *combinations* the direct and indirect costs have been calculated within the height ranges shown in Table 2, using the mentioned height points. The direct costs are calculated using the type and amount of material needed for each of the twenty-six *combinations*. The indirect costs are calculated using the construction time of each of the twenty-six *combinations*.

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 5 is one of these plotted figures. In Appendix D 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 (as already mentioned in Chapter 1).

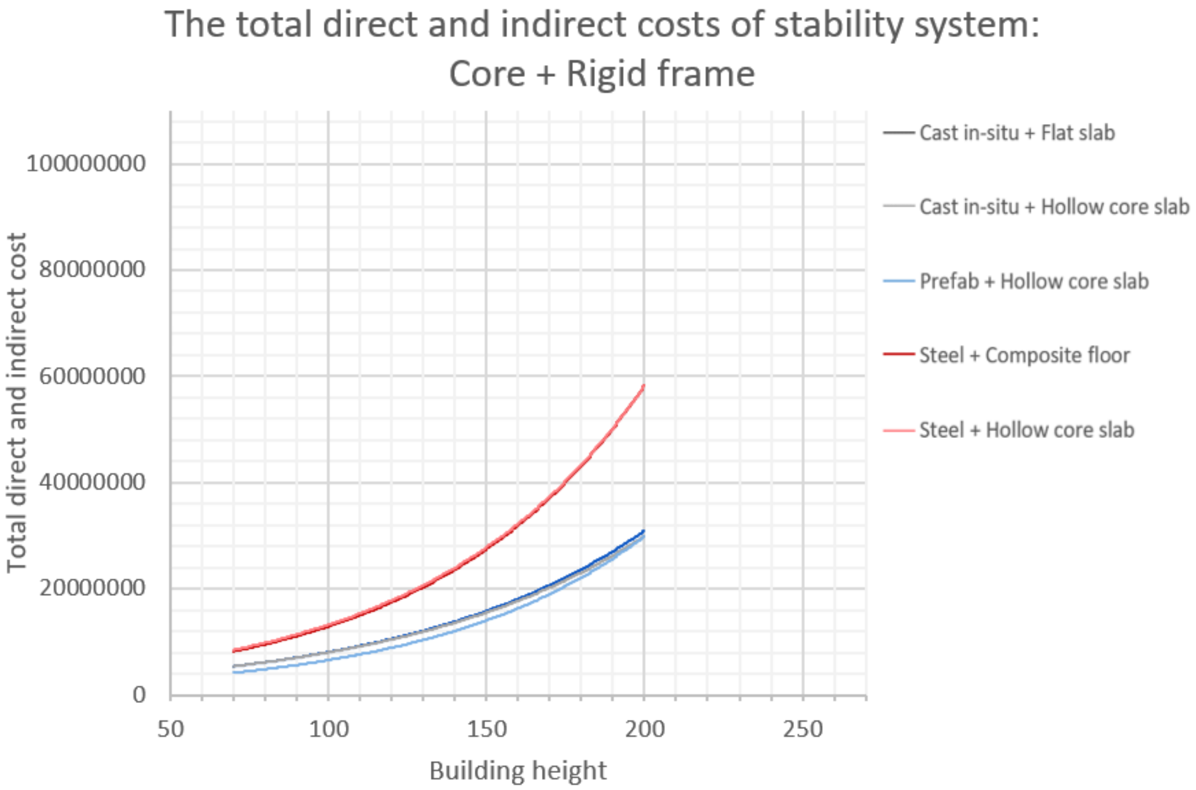

Figure 5: The total direct and indirect costs plotted against the building height for a Core + Rigid frame stability system.

2.5. Sustainability

First, Lankhorst (2018) has calculated the type and amount of material that is needed for *combination* 7 to 26. Next, he has calculated the environmental cost of those *combinations* from Table 1, excluding the *Core* and *Shear walls*. The environmental cost of these two stability systems have been calculated by this thesis.

In his calculation Lankhorst only included the production phase (green in Figure 6), not the construction, user and demolition phase (red in Figure 6). 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).

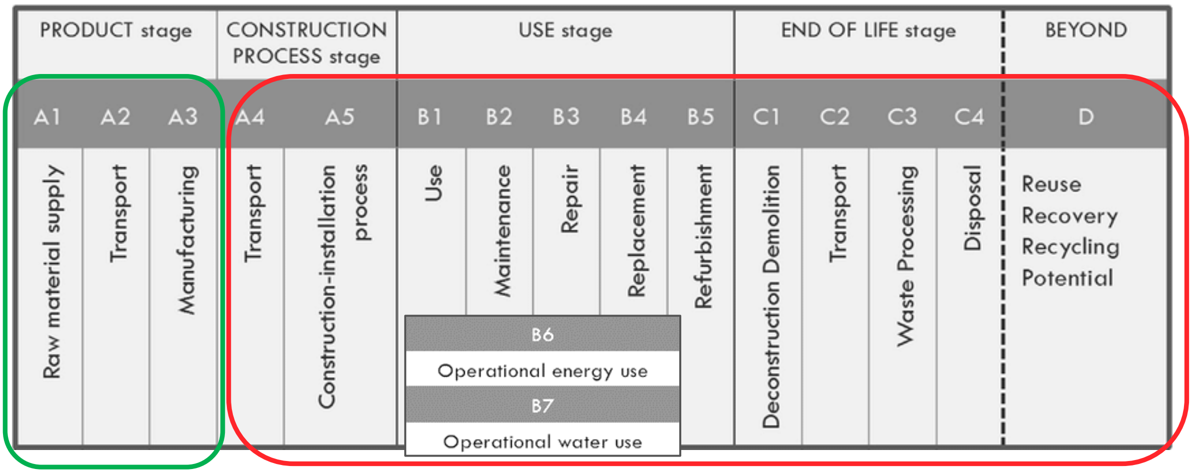

Figure 6: All the building phases in an LCA calculation (Wolf, et al., 2017).

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. The environmental cost of each material used in the twenty-six *combinations* from Table 1 can be found in Table 9.

Table 9: 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	Shadow price
Cast in-situ concrete	C35/45	0.00750 €/kg
Prefab concrete	C55/67	0,00898 €/kg
Steel	S355	0,06750 €/kg
Reinforcement	FeB500	0,24711 €/kg
Fire safety insulation	Gypsum sheet	0.069241 €/kg

This thesis also has calculated total environmental cost when only a *Core* or *Shear walls* are applied by multiplying the amount of material (Appendix A and B) with the environmental cost of that material. The results can be found in Appendix E

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 cost of each *combination* on each height. Figure 22 is one of these plotted figures. In the Appendix D 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.

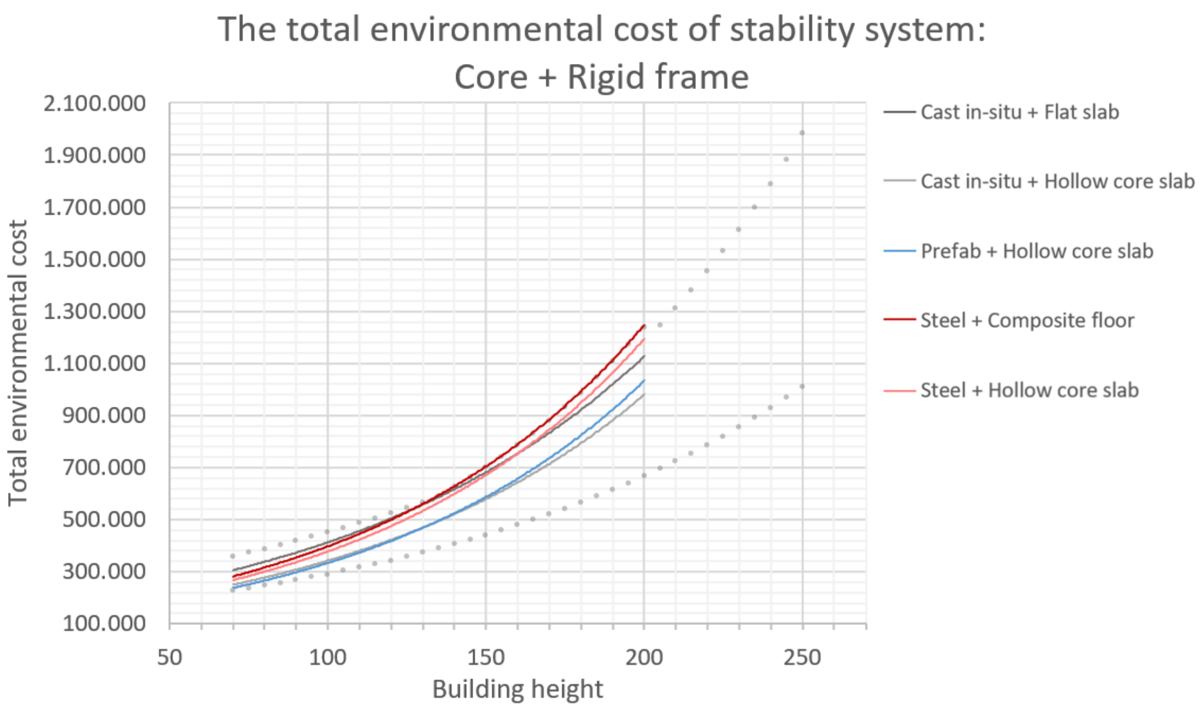

Figure 7: The total environment costs plotted against the building height for a Core + Rigid frame stability system.

3. 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.

3.1. 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*.

3.2. Verification

During the verification the content of the tool will be compared to reality. Figure 8 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.

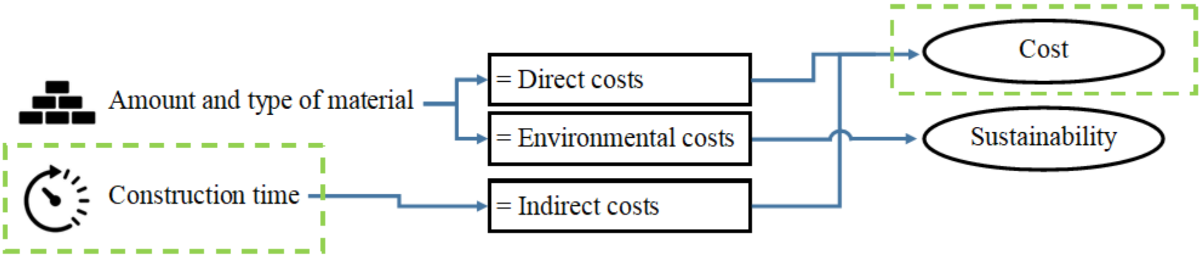

Figure 8: The two points in the calculation process of the tool that will be validated: construction time and cost.

Construction time verification

Table 10 shows the verification of the *construction time*. The last column

Table 10 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 10: 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. 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 11).
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 11: 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 12 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 12: 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%**

3.3. Validation

The 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.

3.4. 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.

Table 13: 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)*

4. 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 calculated construction time used for the indirect cost calculation is now based on '*Bouwplanning*' by Flapper (1995). This book is often used for the planning of buildings, but with the increasing demand for high rise the information taken from this book needs to be compared to real high rise in the Netherlands.
- 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, 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.

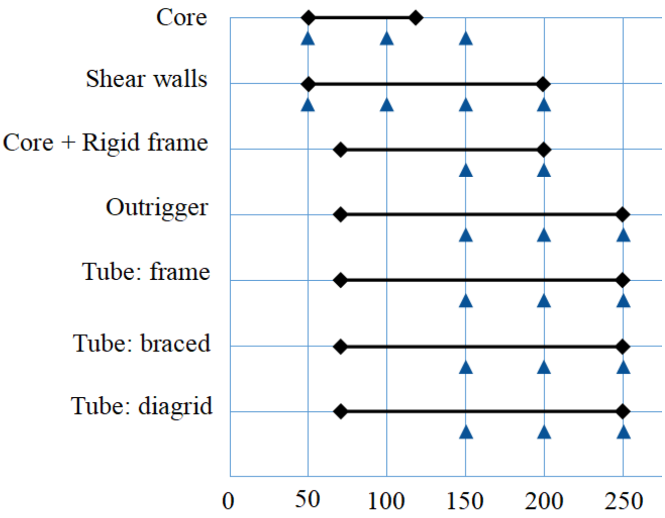

Figure 9: The height range of the stability systems used in this thesis are shown in black. The blue triangles indicate at which height cost and sustainability calculations are performed.

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 9 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 there's a lack of blue 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 10, 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.

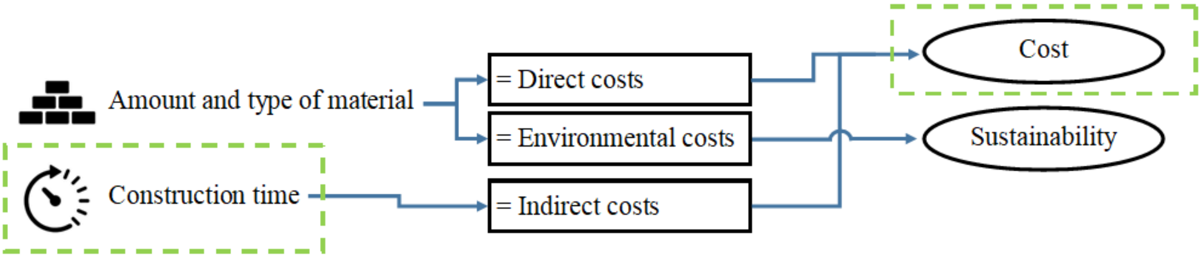

Figure 10: The calculation flow chart, showing how the direct costs, indirect costs and environmental costs of each of the twenty-six structural *combinations* have been calculated. The two points in the calculation process of the tool that were validated are circled with a green square: construction 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.

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.

5. Literature list

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APPENDICES

A. 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.

A.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 14: 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%

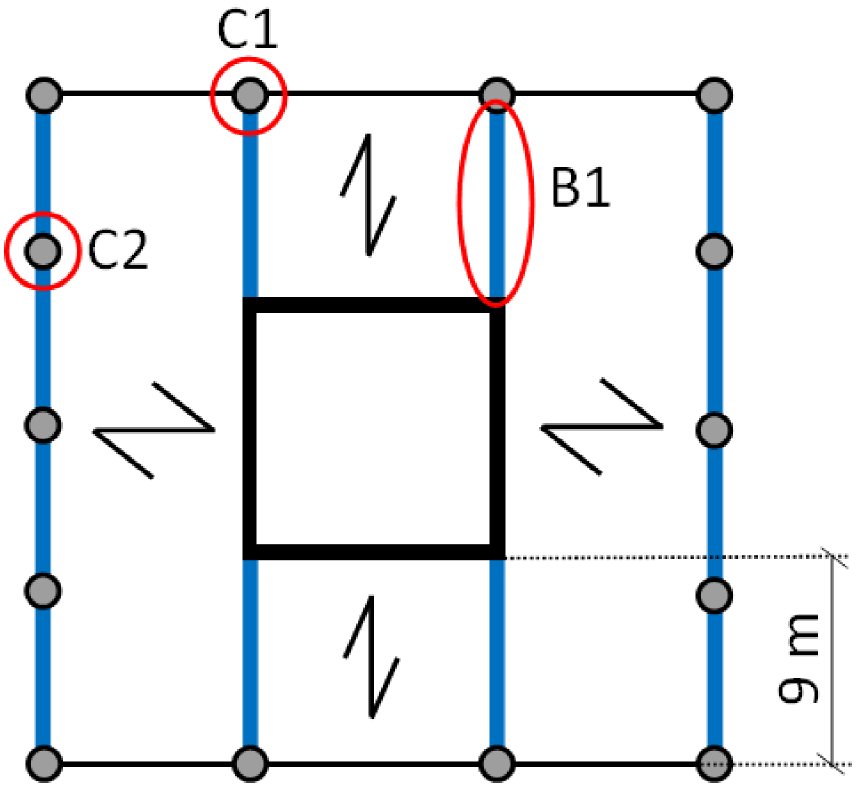

Figure 11: The measurements of the plan used for a high rise building with a *Core* as stability system.

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.

A.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 15: 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.

A.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 11) 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 16: 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 17: 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 18: 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 19: 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.

A.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 20). 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 20: 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

B. 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).

B.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 21: 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*

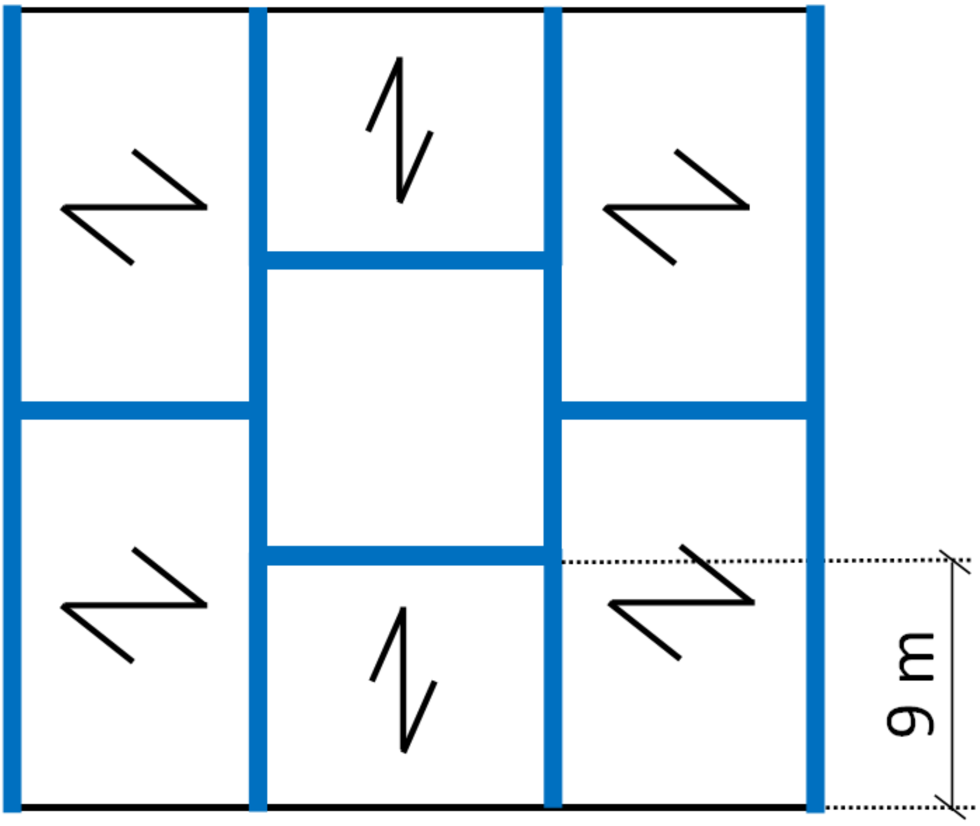

Figure 12: The measurements of the plan used for a high rise building with a *Shear walls* as stability system.

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.

B.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 22: 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.

B.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:

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

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 23: 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.

B.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 24Table 20). 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 24, the total direct cost and total environmental cost can be calculated.

Table 24: 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

C. 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 1 (Chapter 1) the construction time of these twenty-six *combinations* needs to be calculated.

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 25 show the amount of days can be used to build per year.

Table 25: 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:

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

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.

C.3. Calculation construction time

Table 26 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 Table 27.
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 26: 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*
5	Finishing	AB-04: System walls + Ceilings: *25 days per floor*

Table 27: 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	26	43	62		
	Cast in-situ concrete	Hollow core slab	26	43	62		
	Prefab concrete	Hollow core slab	25	42	61		
Shear walls		**Height points:**	**50 m**	**100 m**	**150 m**	**200 m**	
	Cast in-situ concrete	Flat slab floor	26	43	62	79	
	Cast in-situ concrete	Hollow core slab	26	43	62	79	
	Prefab concrete	Hollow core slab	25	42	61	78	
Core + Rigid frame		**Height points:**			**150 m**	**200 m**	
	Cast in-situ concrete	Flat slab floor			62	79	
	Cast in-situ concrete	Hollow core slab			62	79	
	Prefab concrete	Hollow core slab			61	78	
	Steel	Composite floor			61	78	
	Steel	Hollow core slab			61	78	
Outrigger		**Height points:**			**150 m**	**200 m**	**250 m**
	Cast in-situ concrete	Flat slab floor			62	79	96
	Cast in-situ concrete	Hollow core slab			62	79	96
	Prefab concrete	Hollow core slab			61	78	95

	Steel	Composite floor			61	78	96
	Steel	Hollow core slab			61	78	96
Tube: frame		**Height points:**			**150 m**	**200 m**	**250 m**
	Cast in-situ concrete	Flat slab floor			62	79	96
	Cast in-situ concrete	Hollow core slab			62	79	96
	Prefab concrete	Hollow core slab			61	78	95
	Steel	Composite floor			61	78	96
	Steel	Hollow core slab			61	78	96
Tube: braced		**Height points:**			**150 m**	**200 m**	**250 m**
	Steel	Composite floor			61	78	96
	Steel	Hollow core slab			61	78	96
Tube: diagrid		**Height points:**			**150 m**	**200 m**	**250 m**
	Prefab concrete	Hollow core slab			61	78	95
	Steel	Composite floor			61	78	96
	Steel	Hollow core slab			61	78	96

D. Input excel tool: direct and indirect cost

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.

D.1. The calculated costs: direct and indirect

Table 28: 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 29: 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	377000	967500	1891000	X	X
	Cast in-situ concrete	Hollow core slab	377000	967500	1891000	X	X
	Prefab concrete	Hollow core slab	1102500	3263400	6789300	X	X
Shear walls							
	Cast in-situ concrete	Flat slab floor	44772	56196	68964	80388	X
	Cast in-situ concrete	Hollow core slab	44772	56196	68964	80388	X
	Prefab concrete	Hollow core slab	27300	38724	51492	62916	X
Core + Rigid frame							

	Cast in-situ concrete	Flat slab floor	68964	80388	X
	Cast in-situ concrete	Hollow core slab	68964	80388	X
	Prefab concrete	Hollow core slab	51492	62916	X
	Steel	Composite floor	68292	79716	X
	Steel	Hollow core slab	68292	79716	X
Outrigger					
	Cast in-situ concrete	Flat slab floor	68964	80388	X
	Cast in-situ concrete	Hollow core slab	68964	80388	91812
	Prefab concrete	Hollow core slab	51492	62916	91140
	Steel	Composite floor	68292	79716	91812
	Steel	Hollow core slab	68292	79716	91812
Tube: frame					
	Cast in-situ concrete	Flat slab floor	68964	80388	X
	Cast in-situ concrete	Hollow core slab	68964	80388	91812
	Prefab concrete	Hollow core slab	51492	62916	91140
	Steel	Composite floor	68292	79716	91812
	Steel	Hollow core slab	68292	79716	91812
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	68292	79716	91812
	Steel	Hollow core slab	68292	79716	91812
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	51492	62916	91140
	Steel	Composite floor	68292	79716	91812
	Steel	Hollow core slab	68292	79716	91812

D.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.

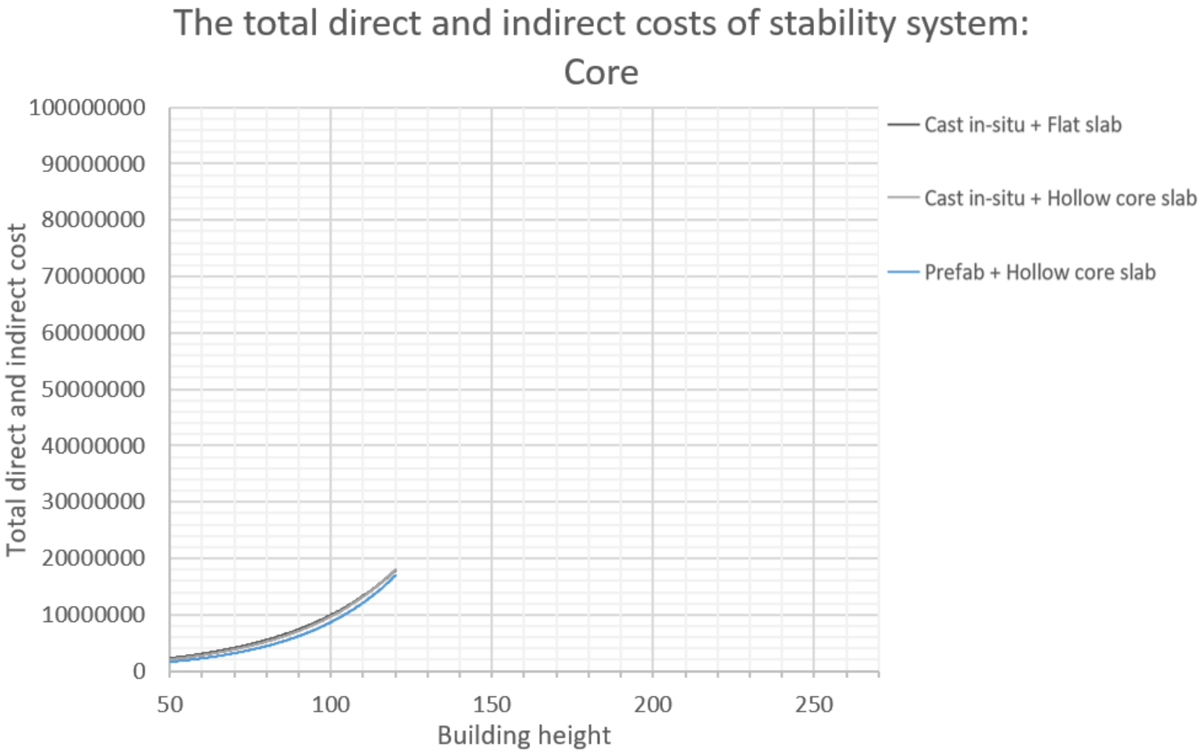

Figure 13: The total direct and indirect cost plotted against the building height for a Core stability system. The light grey line lies behind the dark grey line.

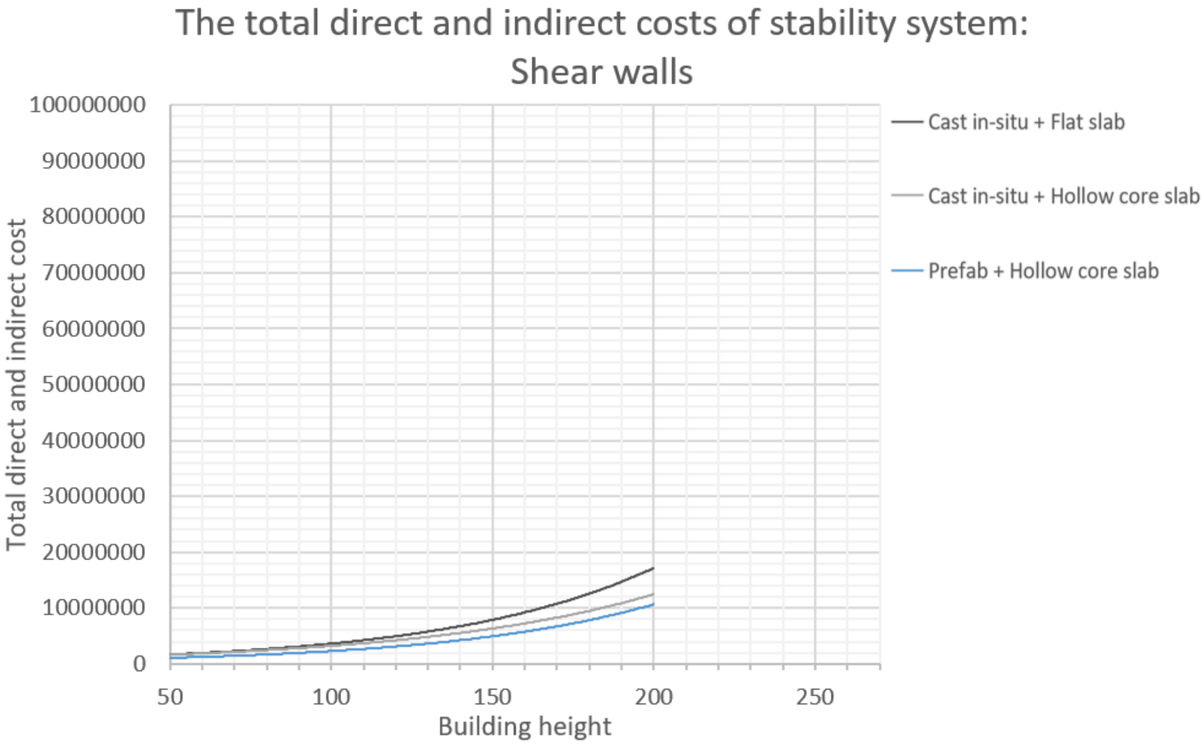

Figure 14: The total environment cost plotted against the building height for a Shear walls stability system.

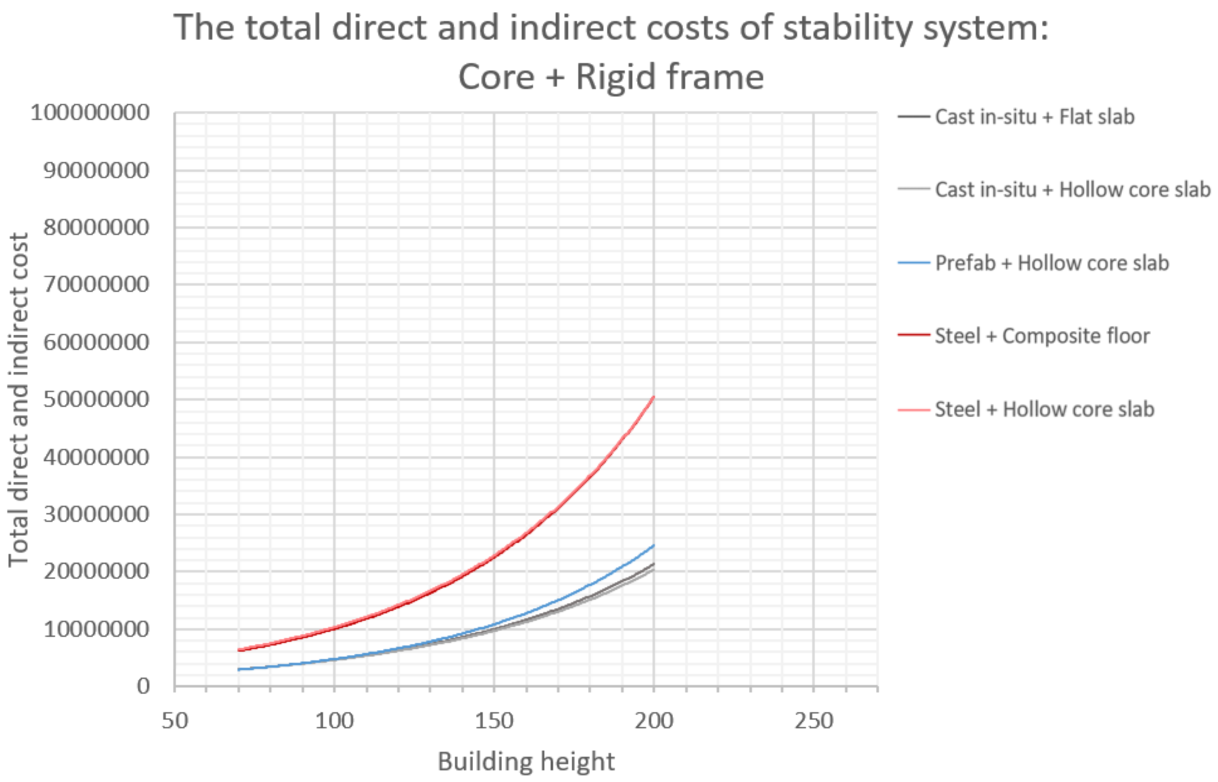

Figure 15: The total environment cost plotted against the building height for a Core + Rigid frame stability system.

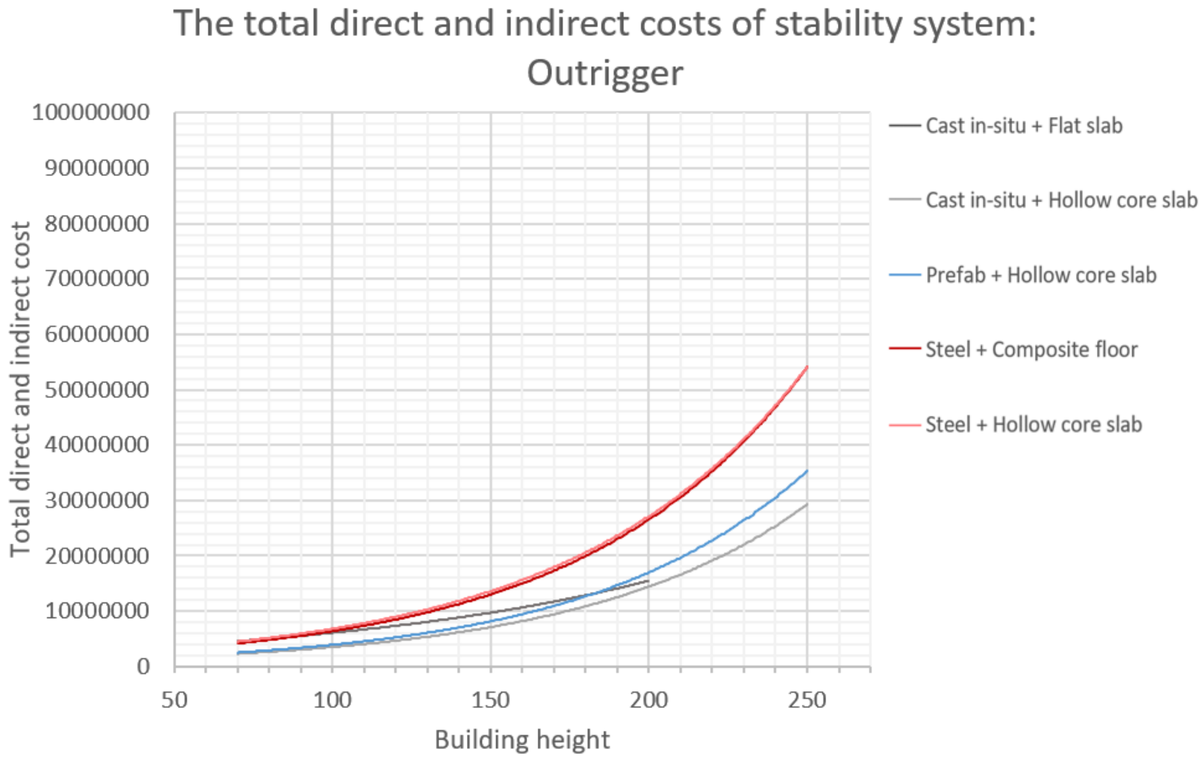

Figure 16: The total environment cost plotted against the building height for a Outrigger stability system. The light red line lies behind the dark red line.

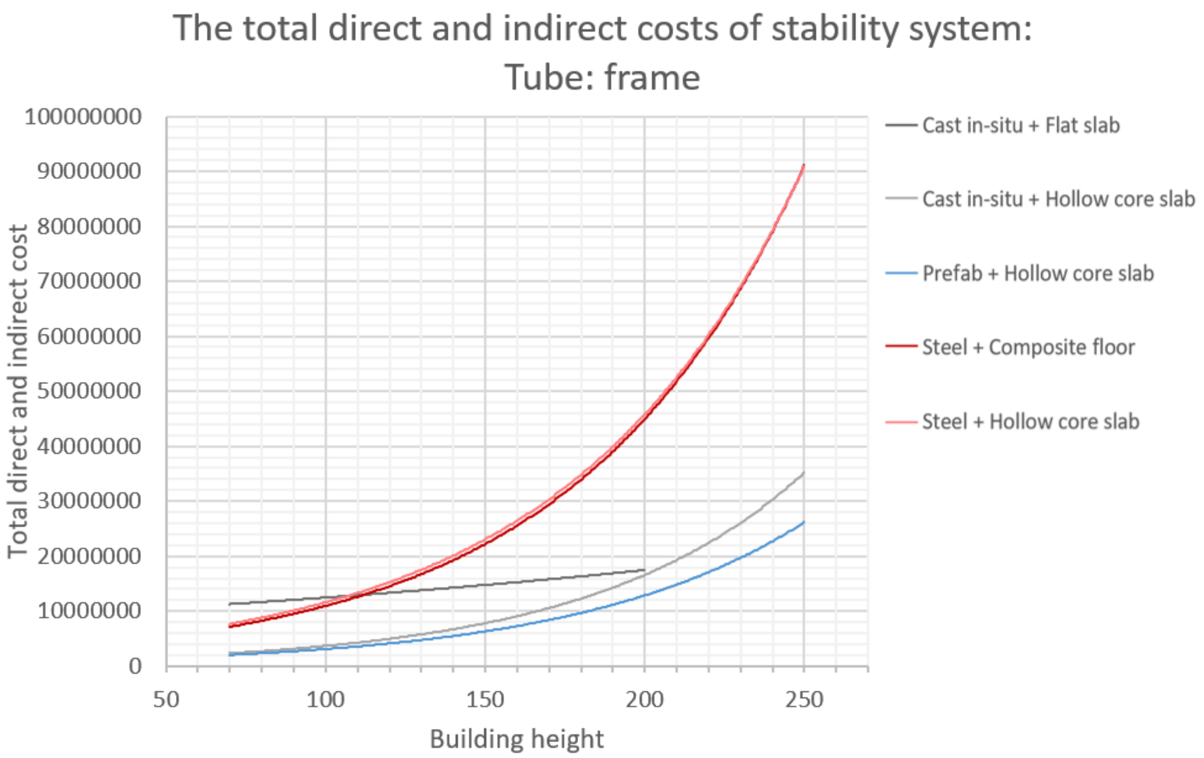

Figure 17: The total environment cost plotted against the building height for a Tube: frame stability system.

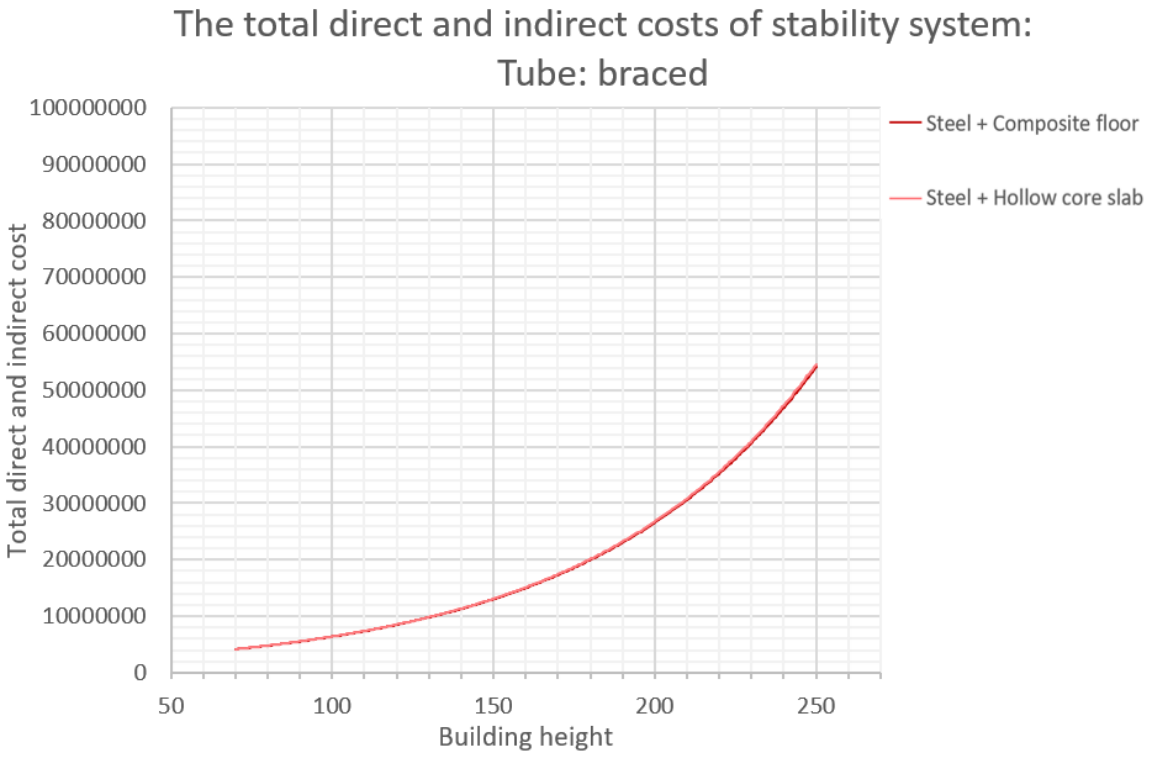

Figure 18: The total environment cost plotted against the building height for a Tube: braced stability system. The light red line lies behind the dark red line.

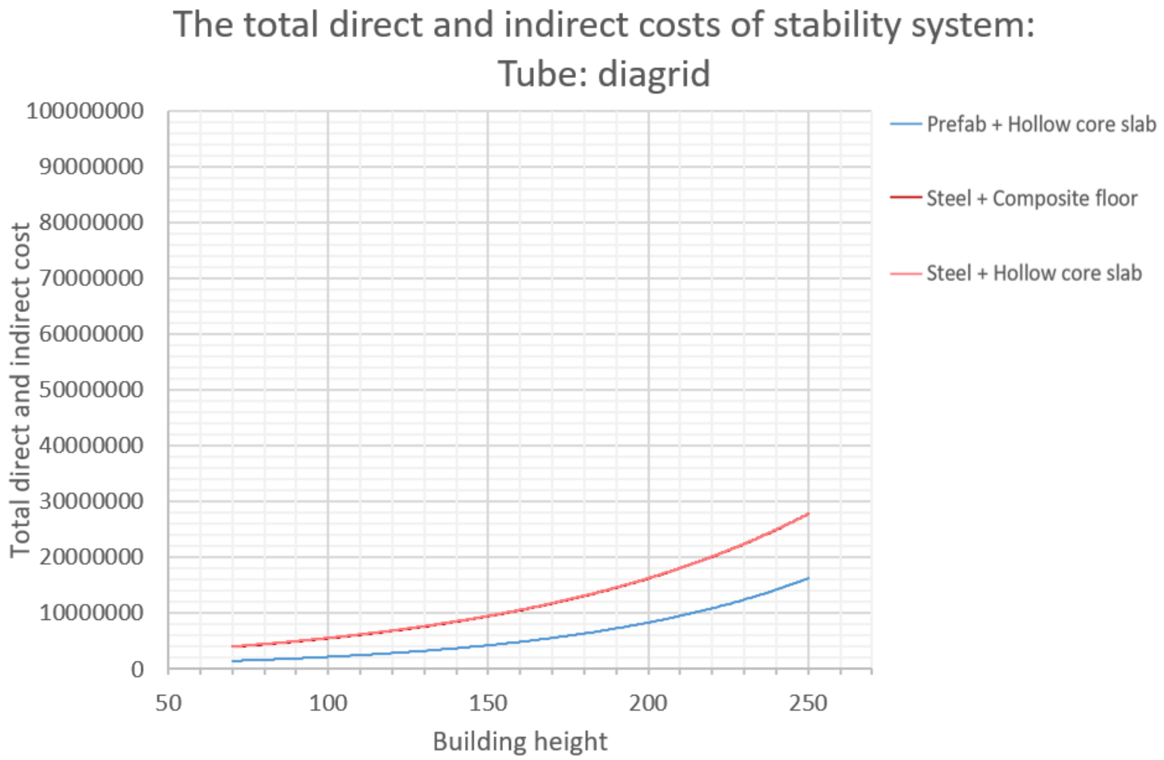

Figure 19: The total environment cost plotted against the building height for a Tube: diagrid stability system. The light red line lies behind the dark red line.

E. 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.

E.1. The calculated costs: direct and indirect

Table 30: 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

E.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.

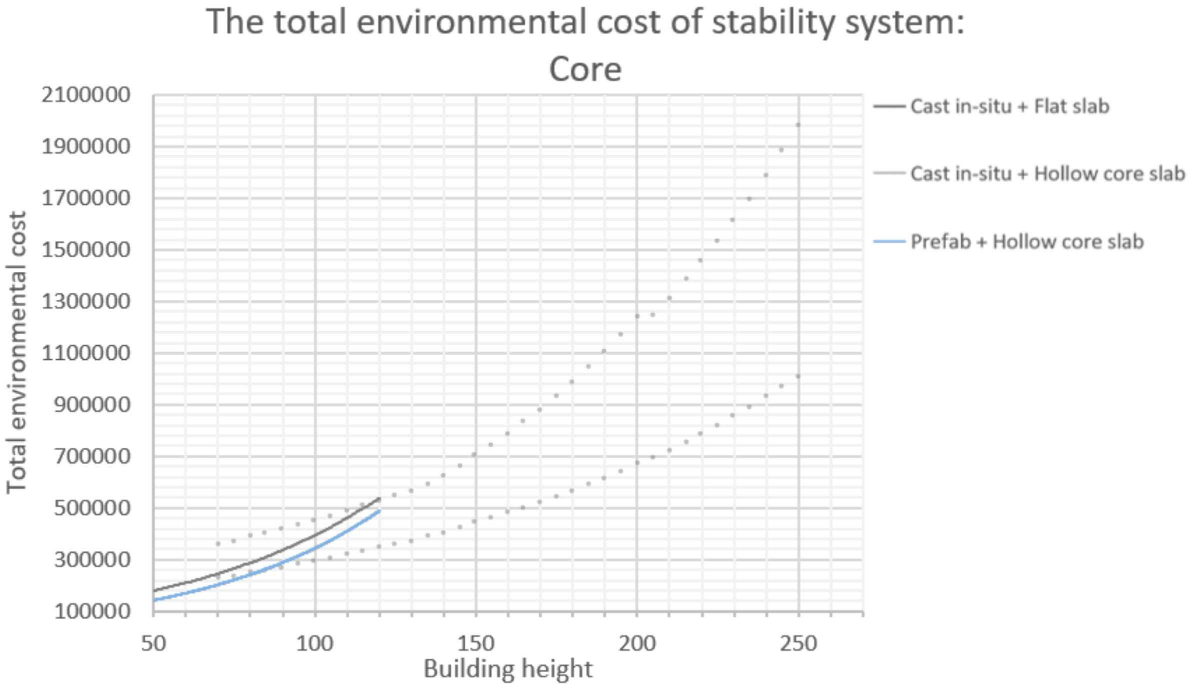

Figure 20: The total environment cost plotted against the building height for a Core stability system. The light grey line lies behind the light blue line.

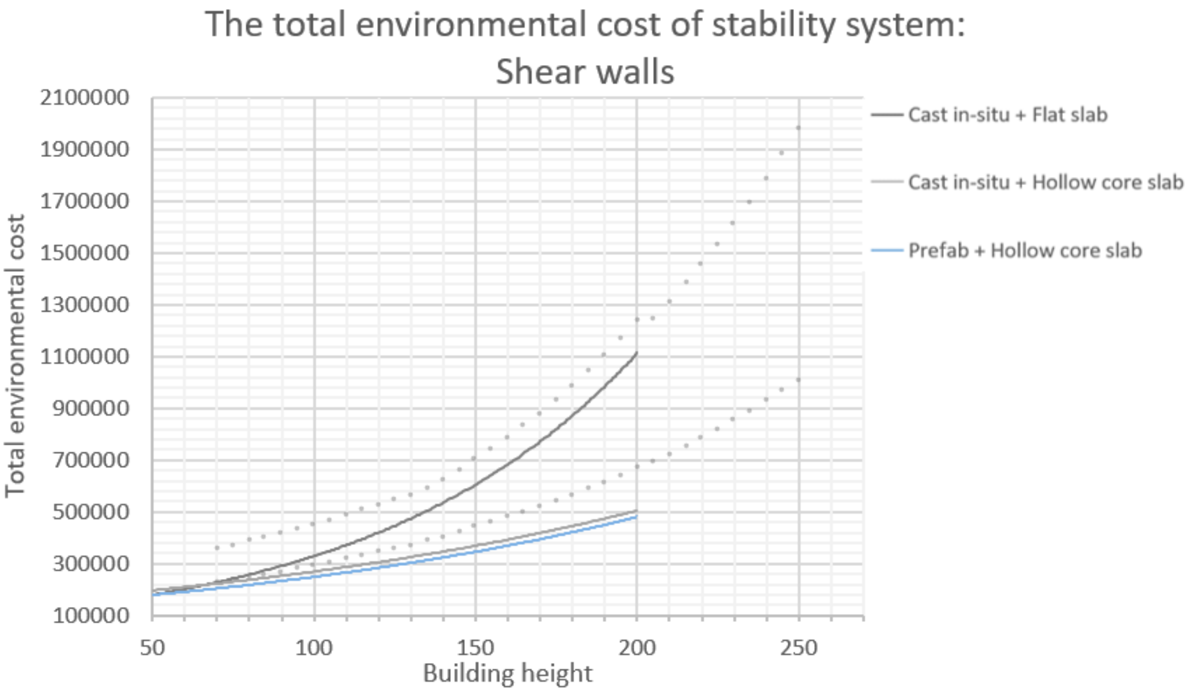

Figure 21: The total environment cost plotted against the building height for a Shear walls stability system. The 'Prefab + Hollow core slab' is completely made of prefab concrete, in contrast to all the other stability systems which always have a core made of cast in-situ concrete.

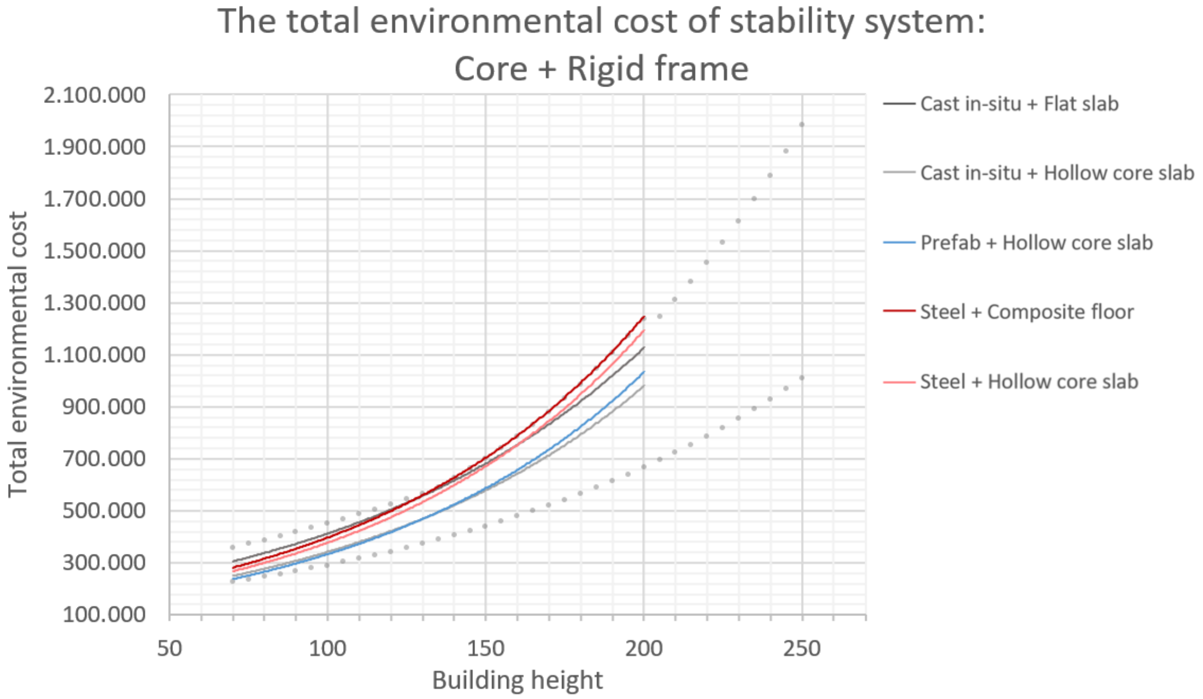

Figure 22: The total environment cost plotted against the building height for a Core + Rigid frame stability system.

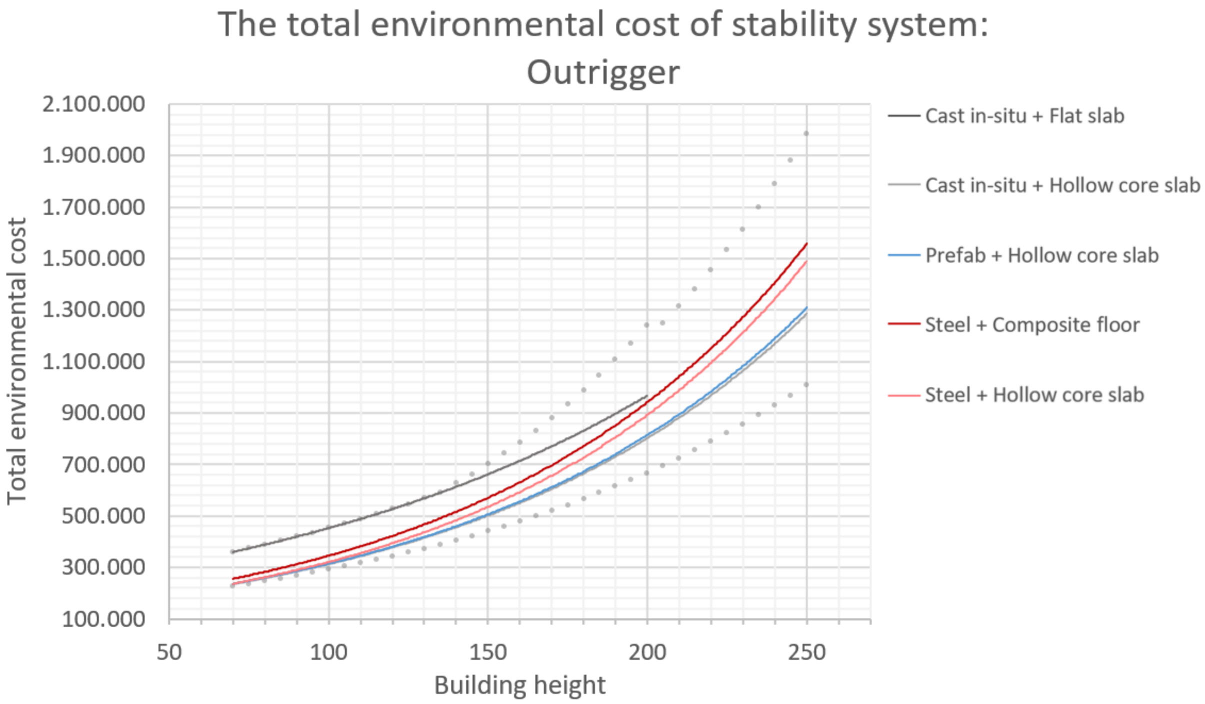

Figure 23: The total environment cost plotted against the building height for an Outrigger stability system.

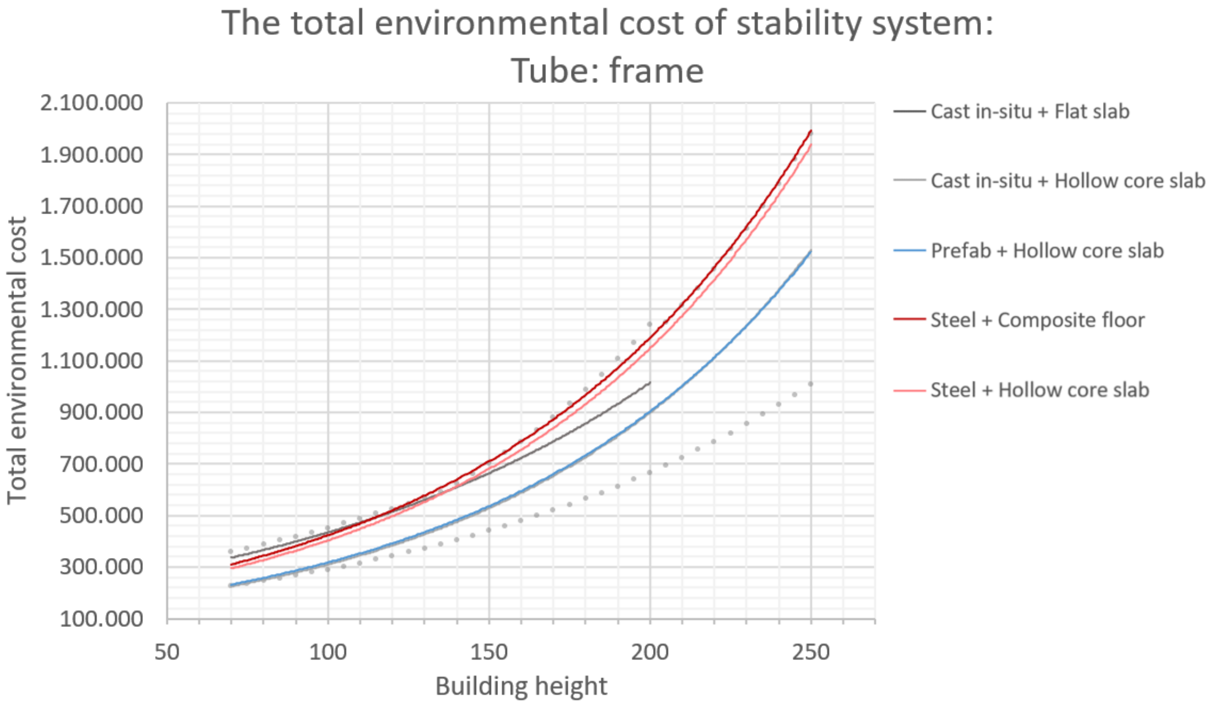

Figure 24: The total environment cost plotted against the building height for a Tube: frame stability system. The grey line lies behind the blue line.

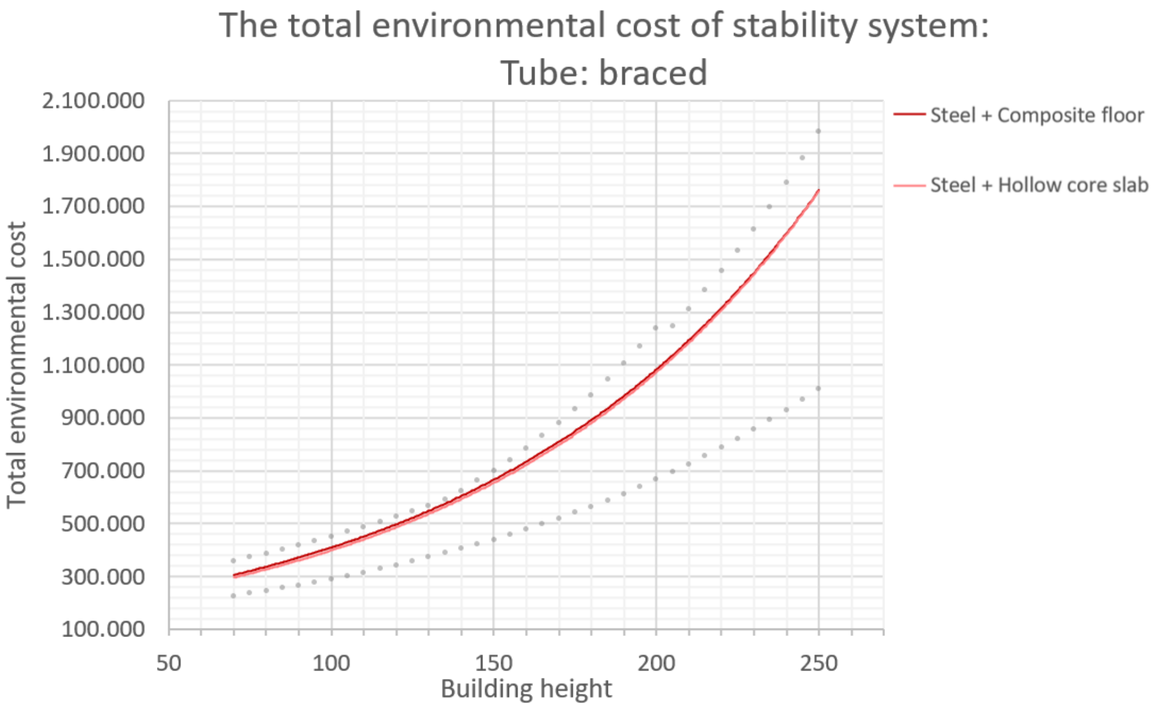

Figure 25: The total environment cost plotted against the building height for a Tube: braced stability system.

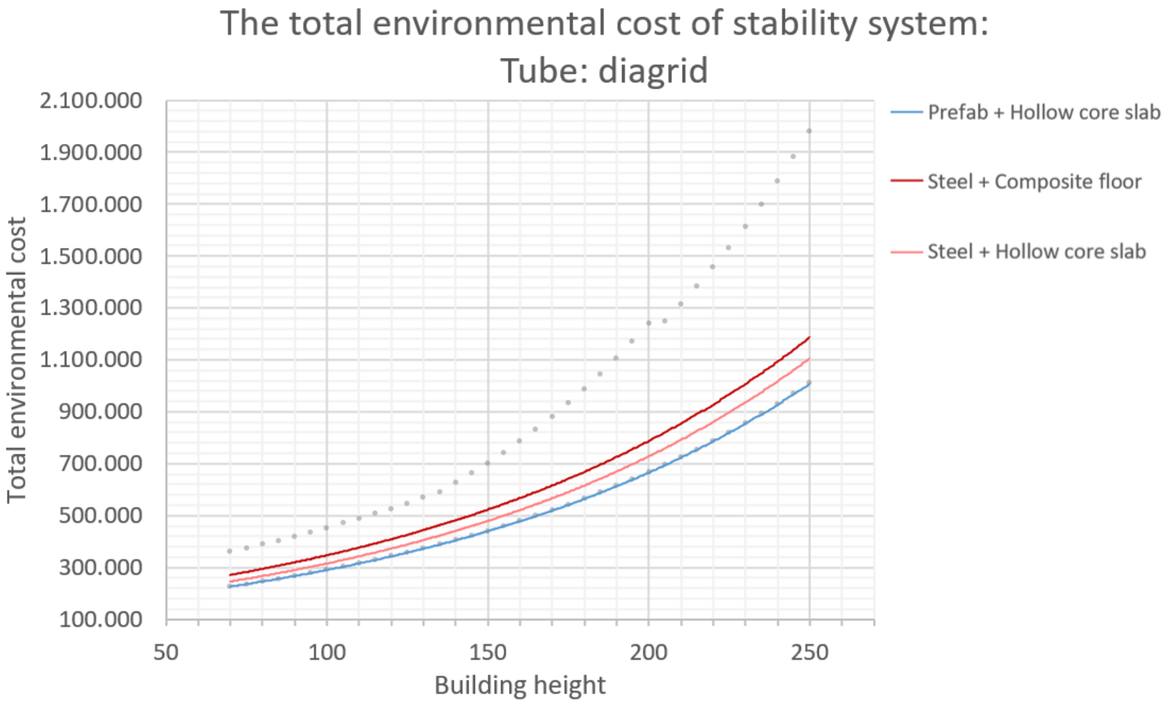

Figure 26: The total environment cost plotted against the building height for a Tube: diagrid stability system.