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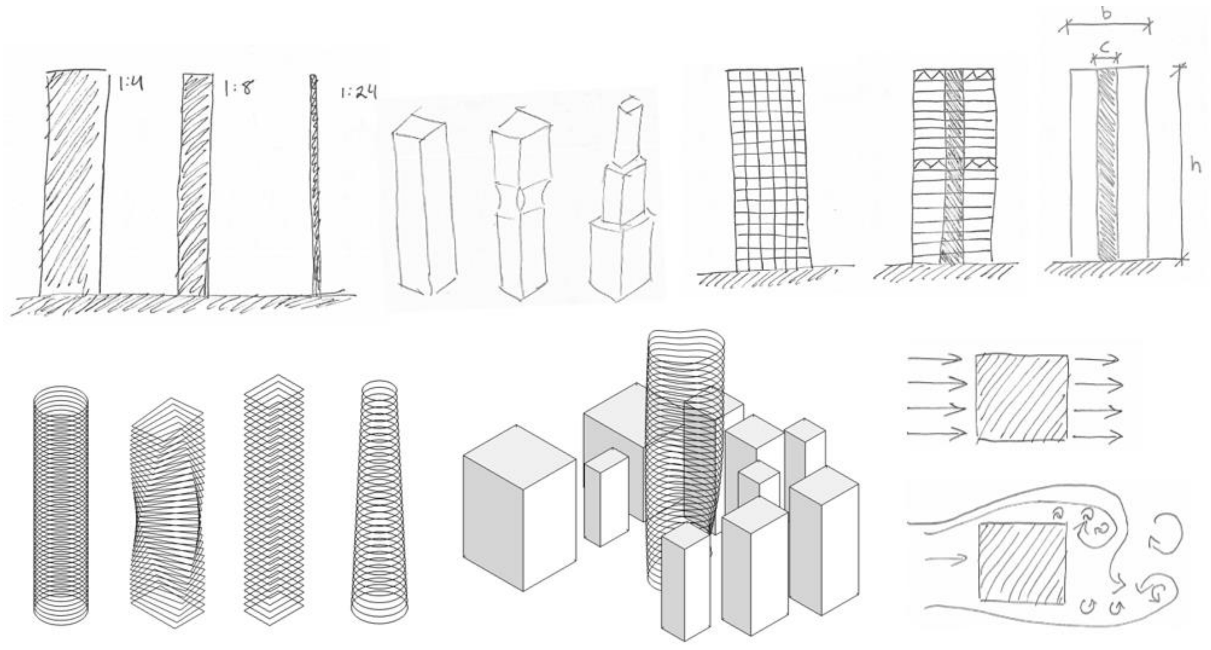

Conceptual High-Rise Design

A design tool combining stakeholders and demands with design

Master's thesis in Structural Engineering and Building Technology

JOHANNA RIAD

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

MASTER’S THESIS 2016:62

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Sketches from the report of a selection of different aspects of high-rise design.

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Abstract

High-rise buildings are becoming more common in Sweden, with several projects planned in the next few years. Experience in tall building design is limited in Sweden, which can be problematic considering the complexity of this type of projects. There are many aspects to take into consideration, such as economy, sustainability, wind performance and vertical transportation. It is difficult to make design changes at late project stages to adapt to aspects that have been overlooked. Therefore, early design choices are very important in order to achieve a satisfactory building performance.

The purpose of this thesis is to provide aid in the conceptual design process for designers with limited experience of high-rises. Their understanding of the demands on high-rise buildings and the implications design choices have is vital. A tool incorporating key stakeholders such as residents, client and citizens and their demands gives a good general idea of high-rise design and the challenges it entails.

To gain an understanding of high-rise projects, a literature study was conducted and interviews were made with several stakeholders and high-rise experts on different aspects of high-rise design. The nature of the information collected was analysed and a suitable way of conveying it through a design tool was developed. The design tool is a parametric computer code programmed in Grasshopper for Rhinoceros 3D. It takes design parameters like building height, shape, function and slenderness as input values. It then processes the information and gives the user feedback on the design with regards to different demands, such as daylight, economy and structural efficiency.

It was found that working with a computational design tool is a good way to give instant feedback on design and help the designer in their process. The design tool displays comprehensive information that is directly connected to the current design concept, which makes the information very accessible. However, creating an intuitive user interface proved a challenge. Programming the information into a tool takes time and depending on the project, modifications of the tool may be needed.

The most important stakeholders, demands and design aspects have been treated in this thesis project, and they are discussed within the report. A design tool has been constructed and verified through a case study. Although not all features have been implemented, the results are promising and the design tool is a working prototype that can be used as it is or as a base for further development.

Key words: high-rise buildings, tall buildings, architectural design, structural design, conceptual design, parametric modelling, design process, design tools

Konceptuell design av höghus
Ett designverktyg som kopplar samman intressenter och krav med design
Examensarbete inom Konstruktionsteknik och Byggnadsteknologi
JOHANNA RIAD
Instutitionen för tillämpad mekanik
Avdelningen för Material och beräkningsmekanik
Chalmers tekniska högskola

Sammanfattning

Riktigt höga hus börjar bli vanligare även i Sverige och flera höghusprojekt planeras de kommande åren. I Sverige är erfarenheten av höghusbyggande begränsad och det finns många aspekter att ta hänsyn till som inte är relevanta i vanliga byggnader. Om man missar viktiga faktorer i ett tidigt stadie är det ofta för sent att tänka ut ett nytt koncept när problem väl upptäcks. I bästa fall kan man hitta en kompromiss så att byggnaden fungerar ändå men i sämsta fall blir resultatet sämre än man önskat.

Syftet med det här arbetet är att skapa ett designverktyg som kan användas då erfarenheten av höghusprojekt är begränsad. Genom att man förstår de olika aspekterna av höghusbyggande och vilka följder ett designbeslut får kan man hitta ett bra koncept från början istället för att behöva kompromissa med sitt koncept i senare stadier.

En litteraturstudie gjordes och intervjuer gjordes med flera olika intressenter och experter inom höghusbyggnad. Informationen analyserades och ett lämpligt sätt att redvisa den utvecklades. Resultatet blev ett digitalt designverktyg som tar designparametrar såsom byggnadens höjd och form som indata. Användaren får därefter återkoppling på den aktuella designen med analyser av bland annat dagsljus, ekonomi och byggnadssystem.

Att använda ett designverktyg visade sig vara ett bra sätt att få en överblick och förståelse för projektet. Designverktyget visar information som är direkt sammankopplad med det aktuella konceptet, vilket gör att den blir lätt att tillgå. Däremot är det svårt att skapa ett lättförståeligt användargränssnitt och det tar lång tid att programmera. För olika projekt kan olika versioner av designverktyget behövas.

De viktigaste intressenterna, kraven och designaspekterna har behandlats i det här arbetet och de diskuteras i rapporten. Ett designverktyg har skapats och verifierats genom en fallstudie. Trots att inte alla delar av verktyget har implementerats har resultaten hittills verkat lovande. Designverktyget är i nuläget en fungerande prototyp som kan utvecklas vidare.

Nyckelord: höghus, skyskrapor, arkitektur, konstruktionsteknik, konceptuell design, parametrisk modellering, designprocess, designverktyg

Contents

Preface

High-rise buildings interest me, and so does the design process used in building design. In this thesis project I have had the chance to work with these interesting topics and have developed my knowledge in the area. The idea for this study was partly my own, and partly the result of rewarding conversations with professor Morten Lund and structural engineer Dmitri Jajich last year.

The study was conducted at Chalmers University of Technology and at structural engineering consultant's office VBK. Interviews were conducted with people from many other organizations and an independent literature study was performed.

First of all, I would like to thank my supervisor Erik Beets at VBK and examiner Mats Ander at Chalmers for their guidance and support throughout this study. I am also grateful to everyone I have interviewed for taking the time and effort to assist me in this project. A special thank you is directed to my opponent Ellen Simonsson for invaluable comments and advice.

Göteborg, August 2016
JOHANNA RIAD

1 Introduction

This master's thesis is a study of how design choices affect high-rise building performance and how the design process can be adapted to incorporate information about different design aspects at an early conceptual design phase. Stakeholders, demands and design parameters in a high-rise project are studied and described. A design tool combining all these aspects is created, in order to display the information in a way that can aid designers in the early conceptual design phase.

1.1 Background

High-rise buildings have become increasingly popular in the last few decades. In Gothenburg the Karlatornet Gothenburg tower, which is to become Sweden's tallest building, is planned for the city's 400th anniversary. As high-rises are becoming more common in Sweden, it is important to understand the challenges and opportunities they entail, which are unique to this type of building. There are many different stakeholders, demands and design aspects to consider and the experience in designing high-rises is relatively limited in Sweden. High-rises are complex buildings and it is difficult to overview the effects of design choices, as many different aspects are likely to be affected. It is also a great challenge to achieve good communication and understanding between the many different professional groups involved in designing high-rises. Ill-considered early design choices may lead to poor performance or large expenses in later stages and it is therefore vital that all necessary aspects are considered and well understood early in the conceptual design phase.

There is a lot of experience and information in the different aspects of high-rise design, such as structural design, vertical transportation and fire safety. However, this knowledge is difficult to access, especially since there is usually a separate source of information for each design aspect. In a high-rise project, dozens of different consultants can be involved, each with expertise and focus on their own part of the design. It is therefore difficult for designers to use previous knowledge at an early design stage, where there is not enough time or resources available to collect all the information needed to make informed design choices. Consequently, ill-informed design choices are likely to be made and since the early choices greatly influence the final design, the negative consequences of these choices can be large. Finding a way of using previous experience and expertise in high-rise design is vital for future high-rises in Sweden to become well-performing buildings.

1.2 Purpose

The purpose of this project is to investigate tall building design from a holistic viewpoint and determine how different design aspects relate to each other. The link between architectural and structural qualities and other aspects of performance, such as environmental and economical, will be illustrated in a design tool.

The design tool should be of help to designers in the early conceptual design phase of tall buildings in Sweden. The aim is for the design tool to be comprehensive for all parties involved in the design process and to be a guide in creating a successful design concept.

Objectives

- Identify the most important stakeholders, demands, design aspects and design choices in a high-rise project

- Investigate how stakeholders, demands, design aspects and design choices are interrelated
- Display this information in a useful and intuitive way through a design tool that can aid in creating a successful high-rise design.

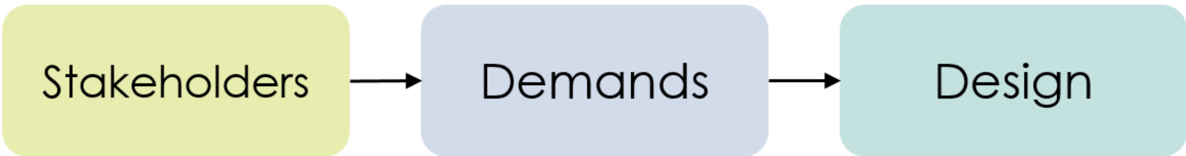
Delimitations
This thesis focuses on the early concept design phase of high-rise design. Therefore, simplifications and guidelines are used rather than more detailed studies. Some design aspects, such as ventilation design and foundations, are left out due to time constraints.

Questions concerning building context are treated only to a small extent since a specific site is not chosen for the study. Most stakeholder interviews are conducted with stakeholders in the Karlatornet Gothenburg project. The thesis focuses on high-rise design in Sweden even if much of the content is general. Swedish regulations and recommendations are used.

1.3 Method

Describing High-Rise Projects
In this study, high-rise projects are described in terms of project stakeholders, demands and design. The stakeholders are the groups or individuals who form the project as well as those who are affected by it. Demands are requests and wishes from stakeholders as well as technical requirements. Design is described in terms of parameters such as building height, slenderness and shape.

This approach was chosen since it captures a broad range of perspectives, giving a comprehensive view of high-rise projects. It gives a structure that is useful for understanding and categorizing information and is a widely accepted approach within the building sector.



Collecting Information
To gain further knowledge in the area, literature studies were conducted. This included studying built high-rises in Sweden and other parts of the world as well as learning about the design and construction process and practices used in Sweden.

Different stakeholders in a high-rise project were identified. Demands from these stakeholders as well as technical demands were then identified and the most important were selected to investigate. These demands were then used when investigating and evaluating design aspects.

Interviews were conducted with architects, engineers, clients and other potential stakeholders, to gain a better understanding of their respective viewpoints. Information was collected in a broad and semi-structured way at first to understand the subject better. When enough information was gathered to understand the core questions more specific questions were asked in structured interviews and by complementing earlier interviews.

Some of the most important demands were found to be the building's stiffness and its ability to carry gravitational loads. Different structural systems were investigated and the advantages and limitations of each were studied. The effects of wind forces proved to be an especially important issue to consider and suggestions on how to adapt the building to high wind forces were explored.

Design Tool

It was decided at an early stage that some type of design tool should be created to give easy access to the information collected and discovered through this thesis project. What this tool should look like was not determined, as it depended on the nature of the information that was gathered in the literature study and through interviews.

Existing design tools were studied and the method best suitable for this thesis project was chosen. It was important that the tool should not be too complicated or time-consuming to create. It was also important that changes and additions should be easy to make as more information to be incorporated was collected in parallel with creating the tool.

Some of the options were a computational tool, a flow chart, a written report or some type of a guide book. In the end, it was decided to create a computational tool that uses this written report for reference and more in-depth information. The program was written in Grasshopper, which is a parametric programming tool inside the 3D modelling program Rhinoceros.

As a further step, multi-objective optimization was studied in order to find if it could be useful for creating designs in a reversed process, described in chapter 6.3. Some trials made would need to be studied more in-depth.

Case Study: The Karlatornet Gothenburg Tower

The Karlatornet Gothenburg project in Gothenburg was used as a case study. How the design was done for this project was compared to the information gathered from the study and the design tool was implemented to see what was done well in the Karlatornet Gothenburg project process and what could be improved. The case study was also used to check how the design tool works. There was an intention to test the design tool on other projects, for example the Turning Torso, but unfortunately there was not enough time to do so.

2 Introduction to High-Rises

2.1 What is a High-Rise Building?

That high-rises are complex projects with many disciplines involved becomes clear from the definition of a high-rise. There is no absolute definition of what a “tall building” is, such as a height limit or slenderness value. The Council on Tall Buildings and Urban Habitat mention height relative to context, proportions and tall building technologies as factors which can determine whether the building can be classified as a “tall building”. If the building displays high-rise qualities in any of these categories it is a “tall building” (Council on Tall Buildings and Urban Habitat, 2016). Some examples of high-rise definitions found in literature are listed below.

“A building which is primarily influenced by wind loads” – Structural Engineers definition, Council on Tall Buildings and Urban Habitat (Gane & Haymaker, 2010)

“A building with height at least three times the width” – American Society of Heating, Refrigeration and Air-Conditioning Engineers (Gane & Haymaker, 2010)

“A building which is considerably higher than surrounding buildings” (Kloft, 2003)

“Buildings in which the floor of at least one occupied room is more than 22 m above the natural or a prescribed ground level” – German consensus (Kloft, 2003)

In Sweden, any building above around 16 stories can probably be considered a high-rise according to most definitions. However, in this thesis project, it has not been important to choose an exact definition to work with.

2.2 Success in High-Rise Projects

One of the aims of this thesis is to create a design tool that can aid designers in inventing successful high-rise design concepts. In order to do this, one must first understand what characterizes a successful design.

Project stakeholders are, as will be described in chapter 3, defined as a person or group that has an interest in a project. In a complex project, there are a number of different stakeholders and they each have different requirements. The success of a project may be expressed in terms of the happiness of these stakeholders, which in turn depends on the fulfillment of their demands. It is difficult to fulfil all demands since they are often in conflict with each other. Therefore, demands and stakeholders need to be prioritized, which can be done using stakeholder mapping, see Figure 3. Minimizing critical unhappiness among stakeholders or optimizing value in a project are two different views on how to define project success. Managing stakeholders and their requirements in a project is usually a worthwhile task since it avoids some of the most common causes of project failure. (Maylor, 2010).

Management researchers Dvir and Lechler, in their study of how planning affects project success, choose to define success as customer satisfaction combined with project efficiency. Customer satisfaction is by far the most important single factor for measuring success but there are several studies that show that it has a strong correlation with project efficiency (Dvir & Lechler, 2003). In a high-rise project, of course, it is more appropriate to switch customers for stakeholders.

Using the stakeholder and demand approach of defining success is considered suitable in this thesis, since it is easy to understand and provides a structured way of viewing project success. It also aligns with the way projects are described in this thesis.

2.3 Why Tall Buildings?

High-rise buildings as we see them today are not the first or only tall structures created by man. The pyramids of Giza, ancient church towers and the Eiffel Tower are all examples of tall buildings designed for different purposes, but with the common denominator of being highly symbolic structures. They are certainly not the most practical or economical buildings in a normal sense but still serve their respective purposes.

There are several possible reasons why a high-rise is built. It is important to understand what the driving force behind the building is, as it decides what is central in the design. Building as economically as possible is a quite different starting point from wishing to create a new icon in the city.

Historically, high-rise buildings were developed in response to increasing land prices and the wish to reside close to the city centers. In large cities where land prices are very high, such as New York and London, this is a viable reason today. Flatiron building, New York is an example of where the high prices in the city made a difficult plot economic to use for a tall building (Rem, 2016).

Another reason to build tall is the wish to create a denser city. This enables more people to live closer to their work places and amenities, which decreases the need for transport. It gives people the ability to have more sustainable lifestyles. High-density areas also have the amount of people needed for an efficient public transport system. A high-rise building is planned for the Chalmers campus. Joakim Wallin and Åke Thunberg of Chalmers Studentbostäder state that one of the main reasons for building tall is to fit as much student accommodation as possible onto the attractive site (Thunberg & Wallin, 2016).

A common aim is also to create a new iconic building. It may be an icon of a country, a city, an organization or an individual. There are many examples of this and in many regions, cities compete to build even taller than their rivals do. An iconic building gets publicity and can serve marketing purposes and symbolize power.

A related reason that is not to be neglected is that many are fascinated by high-rises. They are prepared to pay a premium to live in or have their office in a high-rise. This fascination can be seen from the comments in the case study, see Figure 61.

The main reasons to build tall can be summarized as:

- Economic gain in areas with high land prices
- Building a denser city
- Publicity
- Fascination

These reasons will be discussed more thoroughly in the chapter about demands, 4.

2.4 History

In the late 19th and early 20th century, the first high-rises were constructed in America, mainly in New York and Chicago. The very first skyscraper is generally credited to William Le Baron Jenney with his Home Insurance Company Building, built in 1885. High-rise buildings were developed when rising real estate prices and the demand from businesses to stay close to city centers made it desirable to build tall. These buildings were enabled by the development of cast iron and steel, and made feasible by inventions such as the security elevator and mass-produced building elements (Fazio, et al., 2008).

The first skyscraper boom culminated in the 443-meter high Empire State Building, which was completed in 1931. It would take until the 1960's before high-rises again became popular. Engineers had then developed the tube structure, where load-bearing outer walls carry vertical and horizontal loads. This enabled a very material efficient structure where the amount of steel used could almost be halved compared to earlier structures. Examples of buildings in this style are John Hancock Center and Sears Tower in Chicago, designed by engineer Fazlur Kahn and architect John Graham. John Hancock Center is constructed as a huge truss, see Figure 1, and Sears Tower has nine tubes consisting of stiff frames bundled together to form the tower.

Figure 1 Left: Home Insurance Building Right: John Hancock Center

Other structural options have also been explored in the last few decades. The world's tallest building as of now, Burj Khalifa, is constructed using a symmetrical Y-shaped plan with stabilizing struts in three directions. It was built partly in concrete, which is a very common construction material in high-rises.

In Sweden, with its old city centers and history of lower buildings, high-rise buildings have not started to appear until the last few decades. The tallest building in Sweden as of today is the Turning Torso in Malmö, reaching 190 meters above the ground. It is designed by Santiago Calatrava and completed in 2005. Outside Stockholm the Kista Science Tower (124 m) by White Arkitektkontor AB, and Scandic Viktoria Tower (117 m) by Wingårdhs Arkitektkontor AB are two other high-rises from the early 21st century (Samuelsson, 2015).

Figure 2 Left: Turning Torso by Santiago Calatrava Right: Scandic Viktoria Tower by Wingårdhs

In his investigation of the suitability of building high-rises in Gothenburg, Professor Claes Caldenby (Caldenby, 1990) identifies a clear difference between American and European high-rises. In the USA, the first high-rises originated from a practical and economical need. In Europe, however, tall buildings have always been viewed as elements in city planning. In Sweden, at least so far, the reason for building high-rises is not purely economical.

3 Stakeholders

Stakeholders are defined as “any individual or group with an interest in the project process or outcome”. They can be divided into internal and external stakeholders, where internal stakeholders are directly involved in the project and external stakeholders are people or groups affected by the project process or outcome. Different stakeholders have different levels of interest in and influence over the project. When there are many stakeholders involved, it may be difficult to understand how each of them should be managed. A way to keep track of stakeholders and monitoring them is stakeholder mapping, where stakeholders are ranked according to their interest and influence, see Figure 3 (Maylor, 2010).

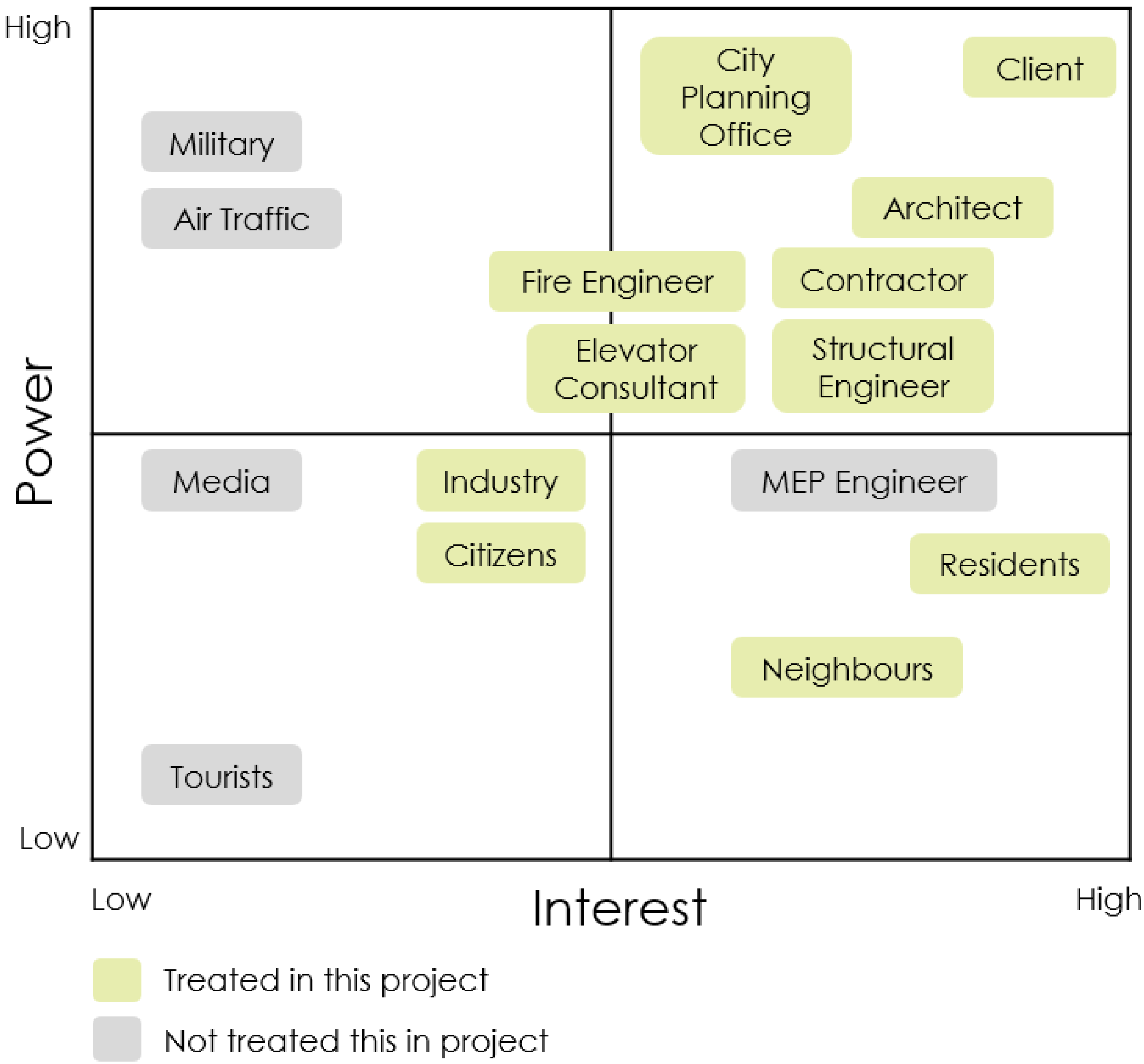


Figure 3 Mapping of possible stakeholders in a high-rise project. The ones considered most important in the early design stages were selected for further studies.

Studying the stakeholders in a project is a good way to understand the background of the project. Knowing who they are and what they want is vital in order to achieve a successful project outcome, as described in chapter 2.2. Therefore, it is important to get a good overview of the stakeholder landscape. According to Maylor, this is vital to avoid the most common causes for project failure (Maylor, 2010).

There are many more stakeholders in a high-rise project than in a smaller building project. Therefore it is of great importance to identify and manage stakeholders throughout a building project. In this thesis, possible stakeholders in a high-rise project were identified and ranked according to interest and influence. The most important stakeholders are those who have a high interest in the project and high power to influence it. An initial stakeholder mapping is shown in Figure 3. Since the thesis is aimed at the early stages of design, only stakeholders important to this stage were chosen to be investigated. Some stakeholders considered less important were not included in this study and some that were too similar to others were also excluded. This chapter describes the chosen stakeholders and what their role in the high-rise project is.

Stakeholders investigated are:

- Client
- Architect
- City Planning Office
- Consultants
- Residents
- Neighbors and Citizens
- Industry

3.1 Client

In this thesis, the person or organization that initiates a high-rises project is titled “the client”. They are the driving force behind the project and to a large extent choose what other designers and consultants to involve. By direct decisions and by choosing who to work with, they are one of the most important decision makers in the high-rise design. Since they are responsible for the economy in the project, they usually have the final say in the most important decisions, while less central issues are delegated.

In Sweden, construction companies are quite often the initiators of building projects. Caldenby is of the view that in Sweden, construction companies have a very strong position compared to other stakeholders. The city planning office used to be more influential in the planning process but today commercial companies have a leading role in building projects (Caldenby, 2016).

Clients have a very high interest in the project since the ultimate responsibility of projects lies with them. They can make good profit and gain publicity with a successful high-rise project whereas a failure can have serious consequences both economically and for their reputation. A high-rise building has many unknowns and there is less experience with high-rises than more regular buildings, especially in countries with very few tall buildings, such as Sweden. Charlotte Petzell at construction company Serneke believes that a tall building project can be considered high risk to sell compared to many other projects (Petzell, 2016).

The client is interested in fulfilling the requirements of the future residents, since they are dependent on finding tenants to be able to go through with the project. It is common that a certain ratio of apartments in a residential building has to be sold before construction can begin. It is therefore extremely important for the client to be able to convince future residents of the qualities of the building.

Many companies have a wish to be viewed as sustainable. Whether sustainability itself is important to a company is difficult to know, but it definitely gives good publicity. In Sweden, many residents will expect features like being able to recycle waste. Sustainability can also be a strong sales argument for conscious buyers and create good-will among citizens and with the city planning office.

As described, along with high interest, clients have more power over the project than any other stakeholder. Therefore, they can be found at the top right of the stakeholder matrix, see Figure 3.

3.2 Architect

An architect is usually the first designer commissioned by the client. They are responsible for coordinating the project design and together with the client they have the most influence on the design. Their responsibilities include functionality and aesthetics of the building and they are the ones who create the design concept, given a certain brief to fulfil.

Architects are often chosen through architectural competitions, where several architects put forward suggestions for how the project should be designed. The option deemed most promising is then chosen to develop. An architecture firm preferred by the client may also be directly commissioned without a competition. Sometimes several different architects are involved with different parts and stages of a project. A good reputation and project portfolio is very important in the choice of architect. It is likely that a client will require some degree of experience in high-rise buildings to be comfortable with the architect's design.

Architects are responsible for creating good living space for occupants and a positive addition to the city for citizens. Designing movement patterns within and outside the building and making sure that it is accessible are a few more of the architect's tasks. A certain aesthetical expression is usually strived for and different architects have different design philosophies to create a strong design concept. A high-rise building is likely to receive publicity in Sweden and it gives the architect an opportunity to improve their portfolio and gain attention.

According to architect Filip Rem, who worked with architects Wingårdhs proposal for the planned high-rise in Gothenburg, one of the challenges in high-rise architecture compared to other buildings is that a high-rise building will be experienced from both near and afar. An aim should be to create a building which draws advantage of its size, since the size automatically becomes a part of the building's aesthetical expression. Tall buildings also have the negative potential to become inhuman in their scale and size. The vertical layout leads to a risk that the different floors are experienced as isolated from each other. It is a challenge to create a tall building for people to like living or working in, despite the large vertical distances (Rem, 2016).

Architects usually have some knowledge within other disciplines, such as fire safety and daylight analysis. The extent of this knowledge depends on the specialization and experience of the architect. Where there is not enough experience, external consultants need to be hired. In Sweden, there are few architects that have much experience in high-rise architecture.

3.3 City Planning Office

This title encompasses the city planning office, the city architect and city council to the extent they influence the work of the decision making. The city architect's role is to work for the general good of the public in the city. The city planning office creates layout and zoning plans for the city regulating where and how it is permitted to build and the city council is the decision maker that must approve any new zoning plan. These stakeholders have the power to greatly influence high-rise projects.

Björn Siesjö, who is the city architect of Gothenburg, was interviewed about his views of high-rises and their role in the city. He believes that the conditions for building high-rises are similar in all the bigger cities in Sweden. However, the conditions in the Nordic countries are quite different from those in countries further south. In Sweden the sun barely rises above the horizon during several months each year. This means that there is a lack of sun and daylight, and shadows cast by buildings are long. In countries further south conditions are very different. This is an important aspect to consider when placing and designing high-rises in Swedish cities. Another significant issue is the amount of people concentrated to one place. Communications and public transport need to be sufficient or there is a risk that the traffic situation becomes chaotic. A risk when building tall is also that the economy of the project will fail. Constructing high-rises is expensive and smaller profit margins may have to be accepted for the building to be realized (Siesjö, 2016).

A high-rise can symbolize success and belief in the future. Siesjö refers to Turning Torso in Malmö which has become an icon for Malmö and Västra Hamnen, the district where it is placed. However, the design of the building affects its potential to become iconic and well-known. The shape cannot be too simple and the proportions and façade materials need to be of good architectural standard. These are demands that will be placed on any future high-rise in Gothenburg. A prequalified international competition is a way to ensure that the design of a planned high-rise is of a high standard. This can be a requirement from the planning office in order to go ahead with the building plans (Siesjö, 2016).

While smaller decisions are delegated to the city building committee, the city council makes the final decision on any plans that have a great public interest. A high-rise building, at least in Sweden, can be viewed as such. Often there is some type of unofficial agreement between parties so that unnecessary work on a project is not carried out. If a plan has little chance of being accepted, it is not economic to spend a lot of time on it. Since there is no paperwork on these early unofficial agreements, it is difficult to know what agreements have been made and why.

3.4 Consultants

In a big and complex building project such as a high-rise, everything from cleaning windows to disposal of garbage becomes issues that require some level of expertise to solve. Many different consultants are involved in high-rise projects. In this master's thesis, some of the most important consultants are treated, but there are many more involved in different stages of the project.

Generally, consultants are involved in a specific part of a project and have their own respective areas of responsibility. Their tasks in the project may be more or less extensive. Sometimes their work is independent of other groups' work but most often, the different tasks overlap and depend on each other. For example, the size of the ventilation ducts affects the architect’s layout and the required ceiling height, which in turn affects the structural engineer’s work, and so on.

Consultants are concerned with completing their own part of the work well. However, often different areas of responsibility are in conflict with each other and the easiest and best solution for one particular consultant may not be the best for the project as a whole. This means that willingness to compromise, clear goals and understanding of the project complexity are vital for the project to succeed. This is true for smaller projects as well but especially important for large and complex projects such as tall buildings.
The consultants most important at an early conceptual design stage in a project were selected to investigate further. The consultants treated in this thesis project are listed and described briefly below. Their respective areas of responsibility are discussed in more detail in chapter 4.

Structural Engineer
The structural engineer is responsible for the structural safety and performance of the building. This is one of the most crucial tasks in a high-rise project and structural engineers get involved relatively early in the design process. Dmitri Jajich, who is a structural engineer and high-rise expert at SOM, believes the best results are achieved if advice from structural engineers is taken into account from the beginning of the architect’s conceptual design phase (Jajich, 2016). In a high-rise project, expertise is required in dynamics and there are effects that are not important in smaller buildings that need to be considered when designing high-rises.

Vertical Transportation Expert
The amount and type of elevators needed is critical in a high-rise building. The amount of space elevators take up makes it crucial to optimize elevator performance. Experts in vertical transportation, who can simulate people flow and elevator capacity are often hired to design the vertical transportation system.

Fire Safety Consultant
Fire safety is a difficult issue in high-rise design, since in the event of a fire there are a lot of people to evacuate and the evacuation routes to the ground are relatively long. Special rules apply to buildings that reach certain heights and elements of design not needed in regular buildings are often essential in high-rises. Hiring a consultant with knowledge in high-rise fire safety and conferring with local authorities is often necessary in a tall building project.

3.5 Contractor

The contractor is responsible for the fabrication and assembly of the building. In Sweden, it is common for the client company to do the construction, but it may also be a separate construction company.

Predictability and ease of construction are some of the most important demands for a contractor. Different structural systems require different methods of construction and some are more complex than others are to construct. High-rise expert Mark Lavery, who works at Buro Happold in Dubai, believes that local labour cost and experience have a large impact on what design is more suitable. For example, in the Middle East, concrete can be sourced locally and labourers are experienced with the material, whereas steel has to be imported and is less well known. This information speaks in favour of using concrete in Middle East buildings (Lavery, 2016).

In Sweden, there are not many companies with experience in high-rise construction. Therefore, this type of project cannot be seen as the most predictable for the contractor and it may be difficult to find a construction company with enough knowledge and resources to carry out the work required in a high-rise project. However, the chance of getting good publicity through a high-rise project can also be a factor to take into account for potential contractors.

3.6 Residents

Residents can be considered external stakeholders. They buy or rent spaces in the completed building and usually do not take active part in the design process. However, their demands are carefully considered and they are sometimes asked to give their opinion during the different design stages. Residents have a very high interest in the building since they will live, work or run their business in it. If resident requirements are not met, there is a risk that it will be difficult to find people interested in buying or renting spaces in the building. Not being able to sell or let enough space results in economic failure since the income from the project is then too low. Often, a certain ratio of the floor space needs to be sold before construction starts, since the client cannot afford to have an empty building.

Residential high-rises, office buildings and hotels have a range of different requirements, though some demands are common to all potential occupants.

Jimmie Andersson (Andersson, 2016), who used to live in one of the tallest residential towers in Dubai, and Anna Svahn, who has lived in the Turning Torso tower in Malmö, were interviewed about their views on living in a high-rise. They both stated having great views as the best thing about living in a high-rise. Svahn also enjoyed the great light in her apartment (Svahn, 2016).

Neither of them could see many downsides to living in a high-rise but Svahn points out that she knew people who moved out of the building because it was too similar to living in a hotel. Andersson says that he recognized people from his floor and those with the same habits as himself, but it was impossible to know everyone who lived in the building. If this anonymity is perceived as a problem seems to vary from person to person. Svahn enjoyed the sense of privacy. Waiting for elevators could be a problem if they were not properly designed for the building and some people claimed to feel the building vibrating uncomfortably. It was also worrying to think of storms or fires (Andersson, 2016) (Svahn, 2016).

In Turning Torso most residents are single with a high income and academic background while in Elite Residence where Andersson (Andersson, 2016) lived there was a mix of families, couples and flat-sharers. In Elite Residence the facilities included swimming pool, gym, conference rooms, a play room and a room with pool tables. Turning Torso is more focused on the luxury market with wine cellars and party rooms among the facilities. This is also reflected by the layout of one of the apartments Svahn (Svahn, 2016) lived in, which was a 1-bedroom flat with two bathrooms at 104 m^2. Both buildings had a 24-hour concierge.

A survey among people interested in buying flats in Karlatornet Gothenburg, conducted by Serneke, gives some further ideas on what is important to high-rise residents. Many are attracted by the sense of luxury and uniqueness in a high-rise, and a trendy life-style seems to be an important concept to many of the survey participants.

Living in a High-Rise Building	
Advantages	**Disadvantages**
+ Views + Daylight + Facilities + Privacy + Trendiness	- Anonymity - Vibrations - Waiting for elevators - Safety concerns - Unsuitable for pets

Table 1 Table showing some advantages and disadvantages of living in a high-rise compared to a regular residential building.

In office buildings, many demands are similar to those of residential buildings. It should be noted that more ventilation and a higher ceiling height is required in order to fulfill comfort criteria. Another factor to bear in mind is that office buildings have a much higher occupant density than residential buildings, which puts higher demands on for example the vertical transportation.

3.7 Neighbors and Citizens

Both neighbors of the building and citizens are external stakeholders in a high-rise project. Their interest in the project varies and their individual power over the project is limited. However, the gathered public opinion can be relatively important in influencing the decisions of the city council, and a positive opinion among the public is to prefer.

In Swedish conditions, which this master's thesis focuses on, a new high-rise building brings a relatively large change to an area. Compared to Manhattan or Dubai, where a new high-rise is not likely to get much attention, a tall building in Sweden is a big deal to a city. Therefore, the opinions on the building are likely to be quite strong.

High-rises evoke strong feelings among the public and those living in the vicinity of the building. The opinions on tall buildings are divided and some people are against any type of tall building. High-rises are different from other types of buildings in the sense that they can be seen from afar. At least in Nordic cities, where high-rises are still uncommon, a high-rise can be seen from large parts of the city. Some people think this is intrusive and that the high-rise spoils other parts of the city by its presence (Petzell, 2016). In Gothenburg there have been views that the historical port area will be ruined once the new Karlatornet Gothenburg tower is raised (Siesjö, 2016). Others are positive to the publicity and change a high-rise will bring to an area and think that tall buildings are exciting and modern.

The people living close to the high-rise site are most affected by both the construction process and the completed building. Some people are afraid of changes to their city, especially neighbors who may be more directly affected with changed value of their property (Siesjö, 2016). For example, the new building may block their view. Since a high-rise project has the potential to change the status of an area, people who rent their accommodation may fear higher rent in the area in the long-term perspective.

On the other hand, development of the area may also raise house prices, which is beneficial for homeowners. The potential of a high-rise building to lift the status of the area and give life to the neighborhood can be considered mostly an advantage. Neighbors are likely to welcome new restaurants and shops as well as better public transport, which the increase in people are likely to lead to.

Concerning the design of the high-rise, it is important that the climate around the building is comfortable. Protection from the wind and no uncomfortable glare and reflections from the building are important design aspects (Thunberg & Wallin, 2016). The shadows cast by the building must also be considered and the design needs to be adapted to achieve a pleasant outdoor environment near the building.

Siesjö believes that a high-rise should add value not only for the residents, but also for the public. This is a way for the building to "give back" to its environment and compensate for the space and attention it will crave. A public area at the top of the building gives the public the chance enjoy the spectacular views. Other functions that benefit the public can also be incorporated into the design (Siesjö, 2016).

To sum up, the most important thing for the public is that a new high-rise is well placed, designed and adapted to its surroundings, that it is aesthetically pleasing and that its design is iconic enough to create good publicity for the area or city.

3.8 Industry

Local industry and commerce has a high impact on the city economy. Even if they have no direct power over building projects, it is likely that they have significant indirect power. For them it is important for building projects not to disturb their work. Good publicity is of course important for them, and a high-rise building that draws attention to the city or area is of advantage.

In Gothenburg, Chalmers University are planning to build a high-rise on campus. One of the reasons for building a high-rise is to create publicity and an icon for the university. Large organizations and companies in the city can initiate high-rise projects for this purpose and they are likely to have a positive opinion on high-rises in their city or area.

Since they are very important to the city, the large industries and companies are likely to have a relatively large influence on council politicians.

4 Demands

Each of the stakeholders have certain demands, or requirements, on the project process and outcome. For example, a high-rise building resident probably requires nice views and a comfortable indoor climate, as well as other things. Demands may also be of a more technical nature, such as the building's ability to carry certain loads. In this chapter some of the most important demands on a tall building will be described.

It is relatively easy to control that fire safety demands have been fulfilled, while it is more subjective whether the building is comfortable to live in. Some demands can be considered *measurable* while others are *immeasurable*. Neither is more important than the other but focus tends to be put on measurable qualities as they are much easier to monitor. In this thesis both measurable and immeasurable demands are discussed.

A range of demands in high-rise projects have been identified with the help of literature and stakeholder interviews. The most relevant in the early design phases have been selected as the ones to investigate. Some of the demands have been rephrased during the process to make them easier to understand and more useful. There are some demands important for the finished product that do not need to be considered in the early stages. Examples of this is interior design and window specifications, both of which will greatly affect the indoor comfort. There are also demands that are related to the city planning around the tower, and not the building itself. These types of demands have not been considered in this report.

Investigated demands:

- Publicity
- Views
- Daylight
- Vertical Transportation
- Economy
- Manufacture and Assembly
- Environmental Impact
- Gravitational Load Capacity
- Stability
- Fire Safety

Examples of other demands:

- Layout of apartments
- Services and Facilities
- Outdoor Environment
- Building Operations
- Accidental Loads
- Social Sustainability
- Ventilation

Some demands are absolutely necessary to fulfil while others are preferable to fulfil but not essential. It is, for example, compulsory to comply with fire safety demands and to design the building to withstand wind loads. Creating iconic value is important to many stakeholders but it is not necessarily demanded for the project to be completed, even if it adds to its quality. This is a *desired* quality rather than a *required* quality. Many of the demands discussed in this theses are required to fulfil up to a certain standard but above that standard it is a question of added quality. For example, it is required by law to have certain daylight factors in residential spaces, but even better daylight qualities than are required may be desired in the project.

Different Types of Demands	
Required Demands	**Desired Demands**
Daylight (minimum)	Publicity
Vertical Transportation (minimum)	Views
Economy (minimum)	Daylight (good)
Gravitational Load Capacity	Vertical Transportation (good)
Stability (minimum)	Economy (good)
Fire Safety	Environmental Impact
	Manufacture and Assembly
	Stability (good)

Table 2 Table dividing the demands into absolutely necessary demands and the desired demands. Some demands have a required minimum standard and a desired higher standard.

Some demands are important only to one of the stakeholder groups while some are common for many different stakeholders. Some demands are closely related to each other while some are completely independent. It can be helpful to know where demands originate, and how they are connected to the different stakeholders, in order to understand what is to be prioritized and why. One way to get an overview of this is through mapping the key stakeholders and demands graphically. See Figure 4 on the next page for a mapping of demands and stakeholders in a high-rise project.

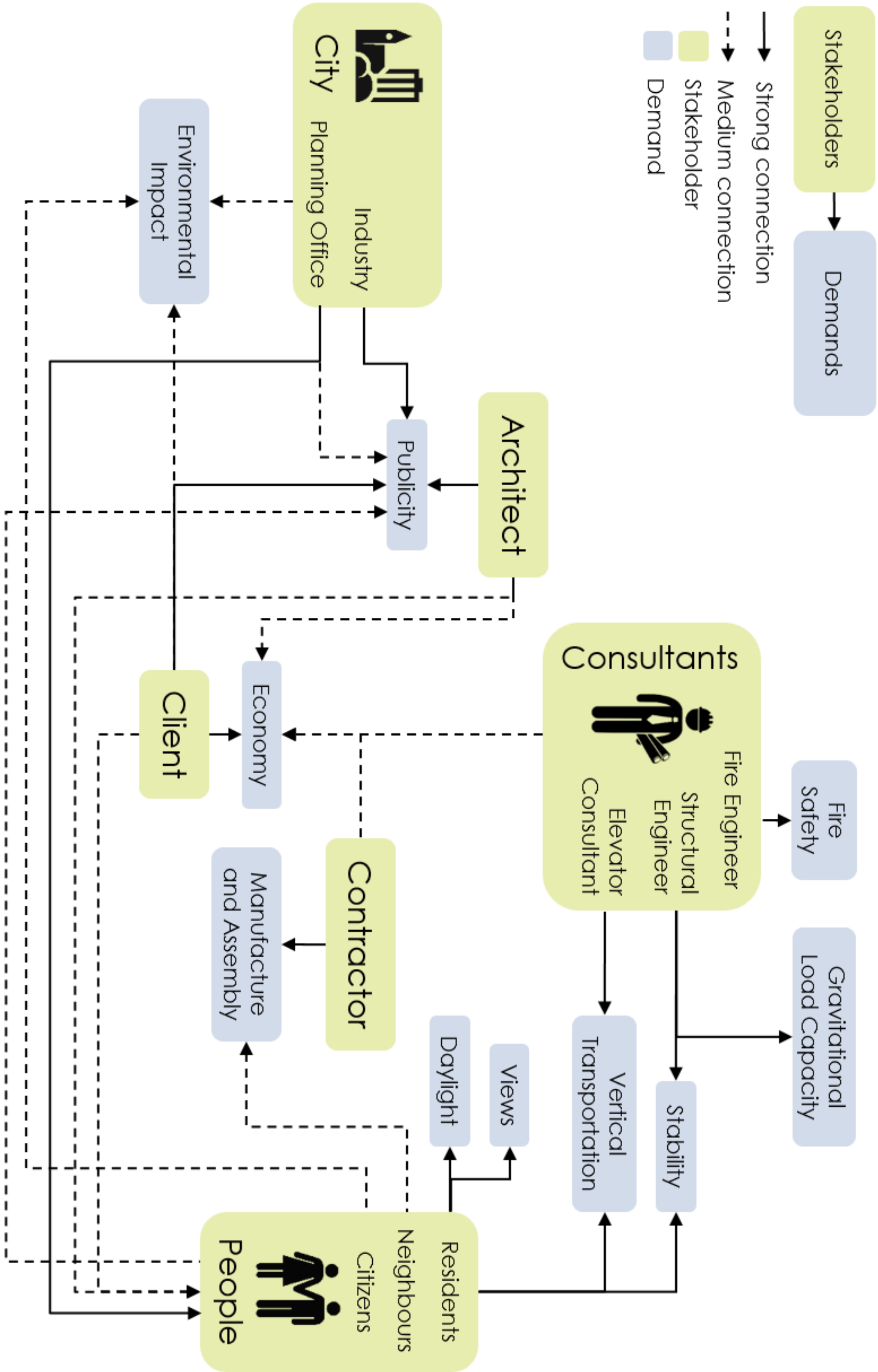


Figure 4 *Map of what demands different stakeholders have on a high-rise project. Stakeholders are also connected to each other. For example, architects are very concerned with the "People" category and therefore also with the demands connected to them.*

4.1 Publicity

Obtaining publicity and creating an iconic building that becomes a symbol for a person or organization is one of the most important motivations for building high-rises. Caldenby compares modern high-rises and their image to the way churches rose above the city and displayed the power of the church in the previous centuries (Caldenby, 2016). The symbol of power and knowledge that a high-rise can become is appealing to many organizations that want to draw attention to themselves.

Not all high-rises achieve iconic status. Siesjö refers to the shape, proportions and façade as important factors to work with in order to achieve a spectacular building (Siesjö, 2016). Iconic buildings express something and they are a response to their context. High quality and iconic status are two completely different things and the building does not need to function well to be iconic. WSP's article about iconic high-rises concludes that being iconic is about catching people's imagination and doing something in a new and different way (WSP Group, 2014).

A building does not need to be tall to be iconic, but the tallest building in a city is likely to be iconic as it catches the light in a special way and acts like a vertical sculpture. Another way to stand out can be to contrast in aesthetic expression with the surrounding buildings.


Figure 5 Left: 30 St Mary Axe, commonly known as "The Gherkin" by Foster + Partners Right: The Shard by Renzo Piano

The 30 St Mary Axe, or "The Gherkin" as it is commonly called, designed by Foster and Partners has received much publicity even before it was built (Kloft, 2003). It is now a well-known landmark and icon in London. In this case, the structural system has been used as part of the expression. Another London icon is The Shard, designed by Renzo Piano.

It is worth noting that, while being significantly taller than the surrounding buildings, both of these towers are less than half the height of the tallest buildings in the world. "The Gherkin" does not even reach the top-100 list. This shows that the shape and expression of the building are more important than height to create iconic buildings. A certain height is important, however, for the tower to be able to function as a landmark. This is part of the iconic value of high-rises and only works if the building can be seen from afar.

To get publicity internationally for its height, the building needs to compete with the top tallest buildings in the world. To get a lot of attention in Sweden, it needs to be approaching the 200-meter mark, since that is the maximum height in the Nordic countries today. If the building does not reach those heights, it needs other aspects to make it interesting.

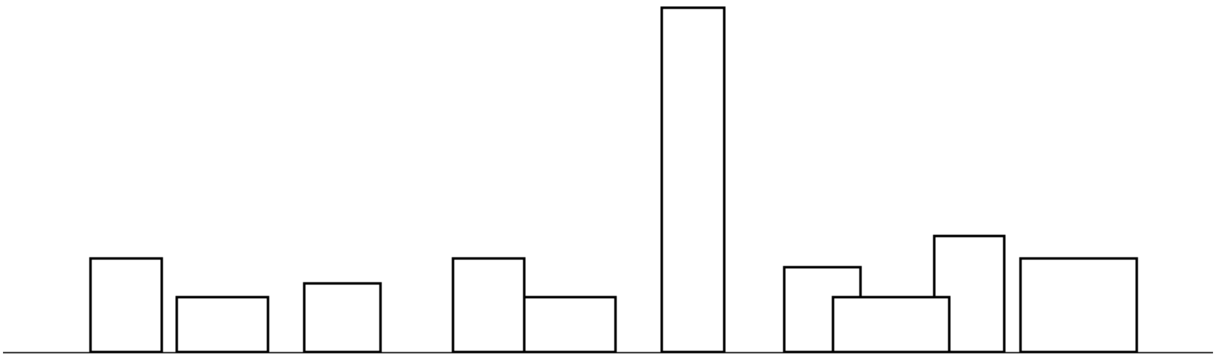


Figure 6 In order for a tower to function as a landmark it needs to be considerably higher than the surrounding topology.

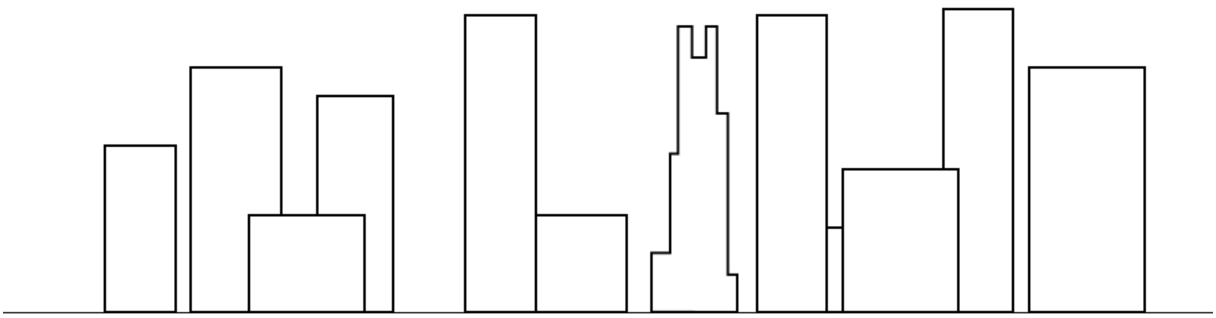


Figure 7 To achieve publicity, a building does not necessarily need to be higher than surrounding buildings. Having a different shape or aesthetic expression is also efficient.

Publicity is an immeasurable demand and difficult to monitor and predict. There is also the risk of obtaining negative publicity, especially in places where high-rises are uncommon, such as Sweden. This makes publicity one of the most difficult demands to understand and monitor.

4.2 Views

Great views is the number one most important reason for people to wish to live in a high-rise. Information collected when preparing the Karlatornet Gothenburg project clearly stated this (Petzell, 2016) and it is confirmed by the interviews conducted with former high-rise residents (Svahn, 2016)(Andersson, 2016). A tall building can give views unavailable anywhere else in the city, especially if there are few natural differences in elevation that can give the same effect. Since they are unique to the building, the views give a sense of exclusivity

Square meter prices usually rise the further up the building one gets and views are assumed to be the best at the top of the building. This is certainly the case in Manhattan, where many high-rises are placed in near proximity to each other and the views from lower floors are likely to be of the façade of the next building. The super-slender buildings being constructed in New York with base-to-height ratios of up to 1:24 are designed very tall and slender so that as much of the floor area as possible is situated above the surrounding buildings (WSP Group, 2014).

However, worth noticing is that views do not necessarily become better further up the building. In creating images intended for selling apartments in the Karlatornet Gothenburg tower, views from the mid sections of the tower were used This was where the views were thought the most attractive for sales materials. When further up there is a feeling of disconnection that can perhaps be experienced as negative (Petzell, 2016). This is confirmed by architect Filip Rem, who thinks that the feeling of isolation that height creates is a much larger challenge to overcome than the technical challenges in building a high-rise (Rem, 2016).

Figure 8 *View from a high-rise building. The sense of privacy created from the height is considered an advantage by some residents, while some feel isolated.*

Views cannot be directly measured but the ratio of good views is assumed to increase with increasing height and slenderness of the building. The views are also affected by the shape of the floor plan and layout of apartments, as well as the chosen structural system, which may interfere with views. Views are of course affected by the site and the height of the buildings and topography around the tower. They are also affected by the size and type of windows used. In Sweden, it is very popular to have a balcony to make the most of sunny days and nice views. However, it is difficult to provide a comfortable outdoor climate on a high-rise balcony, mostly because of high winds and the noise it creates. It is also difficult to achieve a good sense of safety.

4.3 Daylight

Daylight is an important feature for well-being in spaces where people spend a lot of time, for example homes and offices. In a high-rise building, it is common for functions without daylight requirements to be placed in the center of the building. This includes elevators, stairs, ventilation shafts and corridors. This layout enables the space closer to façades to be used as quality rentable space. However, there are other options where vertical transportation is allocated to the outside of the building, to create large, open floors.

There is a limit to how many meters an apartment can stretch from the façade before it starts being perceived as dark. In residential buildings, a guideline for good daylight is a 6-meter maximum “depth” from façade to inner wall of a room (Rem, 2016). According to a rule of thumb often used, residential apartments can be up to 10 meters deep, with dark rooms like bathrooms being placed at the back and 14 meters maximum depth is the corresponding value for offices, where the layout is generally more open. The slenderer the tower is, the more open the layout and the more glass in the façade, the more daylight will be let in. The shape of the tower also affects the amount of daylight reaching the center of the building. Svahn mentions that one of the things she appreciated most living in Turning Torso was the great daylight in the apartments (Svahn, 2016).

In Sweden, different regulations apply to apartments larger than 55 m^2, between 35 m^2 and 55 m^2 and smaller than 35 m^2. Rooms or separate parts of rooms for more than temporary use should have windows towards the outdoors. Smaller apartments and student apartments have less strict regulations but any living space should always have good access to daylight (Boverket, 2015). Daylight factor calculations can be done to make sure a room has enough daylight. The calculations are relatively complex and will not be described in this study. An estimate may be used in certain conditions stating that there should be a window area equivalent to at least 10% of the floor area of the room (Boverket, 2015).

Computational daylight analyses are usually conducted to determine the daylight performance within a building. However, running thorough analyses is relatively time-consuming and in the early stages of conceptual design the information needed has not been developed yet. In this study a simplified approach is used. A maximum value for how far the light will reach from the façade is set. This value is set to 8 meters for residential buildings and hotels and 14 meters for offices. See Figure 9 for pictures of analysis methods.

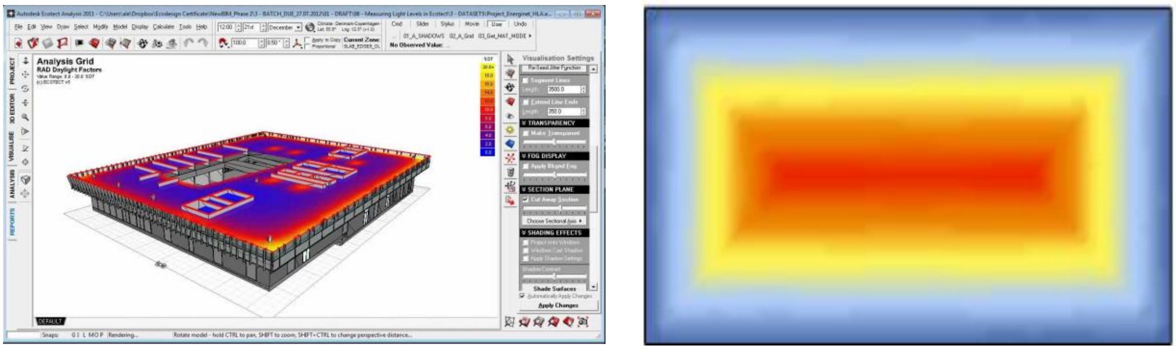


Figure 9 Left: Thorough daylight analysis in software Right: Simplified approach using estimate values for daylight penetration

In the Nordic countries, as opposed to locations further south, shadows from tall buildings become much more dominant (Siesjö, 2016). With a low sun, how to provide suitable shading and indoor lighting climate also differs from locations with a higher sun. The colder climate also means a difference in how to view cooling and heating options. In many countries, cooling is more critical than heating, but it is usually the opposite in Sweden, at least in residential buildings.

4.4 Vertical Transportation

The taller a building is the more space needs to be allocated to vertical transportation. A high-rise needs elevators, emergency elevators and staircases. These functions require a much higher floor area ratio in a tall building than in a regular building. The exact amount and size of elevators required is difficult to predict as it depends not only on known factors, but also a lot on the behavior of people. Behavior is different for residents, hotel guests and office workers and varies with individual behavior because of factors such as age, culture, weight and so on (Scott, 2016). Patrik Albertsson, who was involved in the design of high-rise hotel Gothia Towers in Gothenburg gives as example that a person with a suitcase takes up much more space and is slower than a person without one (Albertsson, 2016).

Elevator speed and size is also important when designing elevators. High-rise resident Jimmie Andersson (Andersson, 2016) mentions bad elevator access as a large potential drawback of living in a tower and Albertsson (Albertsson, 2016) describes how the Gothia Towers hotel had to install extra elevators as a result of guest complaints. In Gothia Towers, the limited height and unusual floor plan enabled adding elevators after building completion, but installing extra elevators at such a late stage is usually practically impossible. The cost of the elevators themselves is quite negligible (Scott, 2016), but the space they take up in the building means lost rentable area. This in turn means that having elevator overcapacity is very expensive. Designing elevators properly from the beginning is therefore of great importance.

Adam Scott is an expert in vertical transportation and works at Sweco UK, with projects such as the Karlatornet Gothenburg tower. He describes elevator design as a complex field of study, where many factors influence the design. It is first of all very important to know what type of building one is dealing with. Office, residential and hotel high-rises all have, as mentioned, very different movement patterns and densities and this is the most important division to make at an early stage (Scott, 2016).

In high-rises it is common to work with several different elevator sets that serve different floors. In some cases one might even need to change elevator on the way to a certain floor. There are also examples where two elevators operate in the same shaft. Because of the complexity of the factors influencing design, it is difficult to provide accurate guidelines on what number and type of elevators that are needed for a certain building. However, some estimates can be calculated before using the more advanced people flow analyses that are required to get a better understanding. These benchmark values should give an idea of reasonable elevator capacity, at least for buildings that are not super tall, see Table 3 (Scott, 2016).

There are different standards to aim for when designing elevators. The standards are based on waiting time and travel time. Depending on expected values for these times, the elevator system receives a grading, where service time is “excellent”, “good”, “satisfactory”, “acceptable” or “not acceptable”. Interestingly, opinions are divided on whether it is better to minimize waiting or total service time. Some mean that it is psychologically easier for passengers to accept a longer service time as long as the waiting time is short. Some mean that it is better to have a longer waiting time if it makes the total service time shorter.

It is easy to assume that faster elevators can solve service time problems in taller buildings. However, a limiting factor in elevator design is passenger comfort. Even if higher maximum speeds can technically be reached, the discomfort felt when the acceleration of the elevator car is too high limits this method. An acceleration of 1.4 to 1.6 m/s^2 is the maximum that can be used without passengers feeling uncomfortable. The maximum speed in today's elevators is about 17-18 m/s. This means that it takes around 100 meters for the elevator to reach its maximum speed and the same distance for it to slow down to a stop. It is quite unlikely that it will reach this speed very often, as it has to make stops along the way. In tall buildings, "express" elevators that do not serve the lower floors can be used and in this case, a high elevator maximum speed is beneficial.

Elevator Guidelines		
Office	**Residential**	**Hotel**
1 elevator per 200-250 people Average 1 person per 10 m^2 net area Not more than 8 elevators per set 1 service lift if net area is over 10 000 m^2, 2 if over 30 000 m^2.	Minimum 2 elevators Over 20 floors, 3 elevators Over 40 floors, 4 elevators Over 55 floors, 5 elevators or more	1 elevator per 100 rooms 1 service lift per 2 passenger lifts

Table 3 Table showing guidelines for elevator design for different building functions.

4.5 Economy

There are hundreds of factors that influence the economy of a tall building project, many of which are difficult to accurately predict in the early stages. The economy of a project depends on how much is spent but also on the quality of the completed product, which affects how much people are willing to pay for it. Therefore, economy is closely related to the demands of the occupants. This thesis will not attempt to cover all economical aspects, only a few which are relatively important and which can give an early indication on the economy of a high-rise project.

Area Efficiency

Area efficiency is important in any project. It can be measured as the ratio between rentable space and total space. Its importance is confirmed both by Joakim Wallin and Åke Thunberg (Thunberg & Wallin, 2016) at Chalmers Studentbostäder and Anna Tirén at Serneke (Tirén, 2016). "We're looking for every square centimeter to utilize in our project" says Tirén. Only the rentable space will give any revenue and therefore this ratio needs to be as high as possible. Depending on the function of the building, different values are possible to achieve. As an example, an aim for a residential building may be to reach a ratio of at least 0.75 between rentable space and total space.

Buildings with apartments all around the perimeter and staircase and elevator shafts placed in the center can usually reach a high area efficiency (Thunberg & Wallin, 2016). In taller buildings, however, more of the space is taken up by functions such as vertical transportation and ventilation shafts. Columns and walls also need to be thicker. From an area efficiency point of view, large floor plates are preferable, see Figure 10. Even if the population increases with an increased floor area the space for functions only needs to increase a marginally compared to the rentable area gain. However, there are disadvantages connected to large floor plates, such as poor daylight qualities.

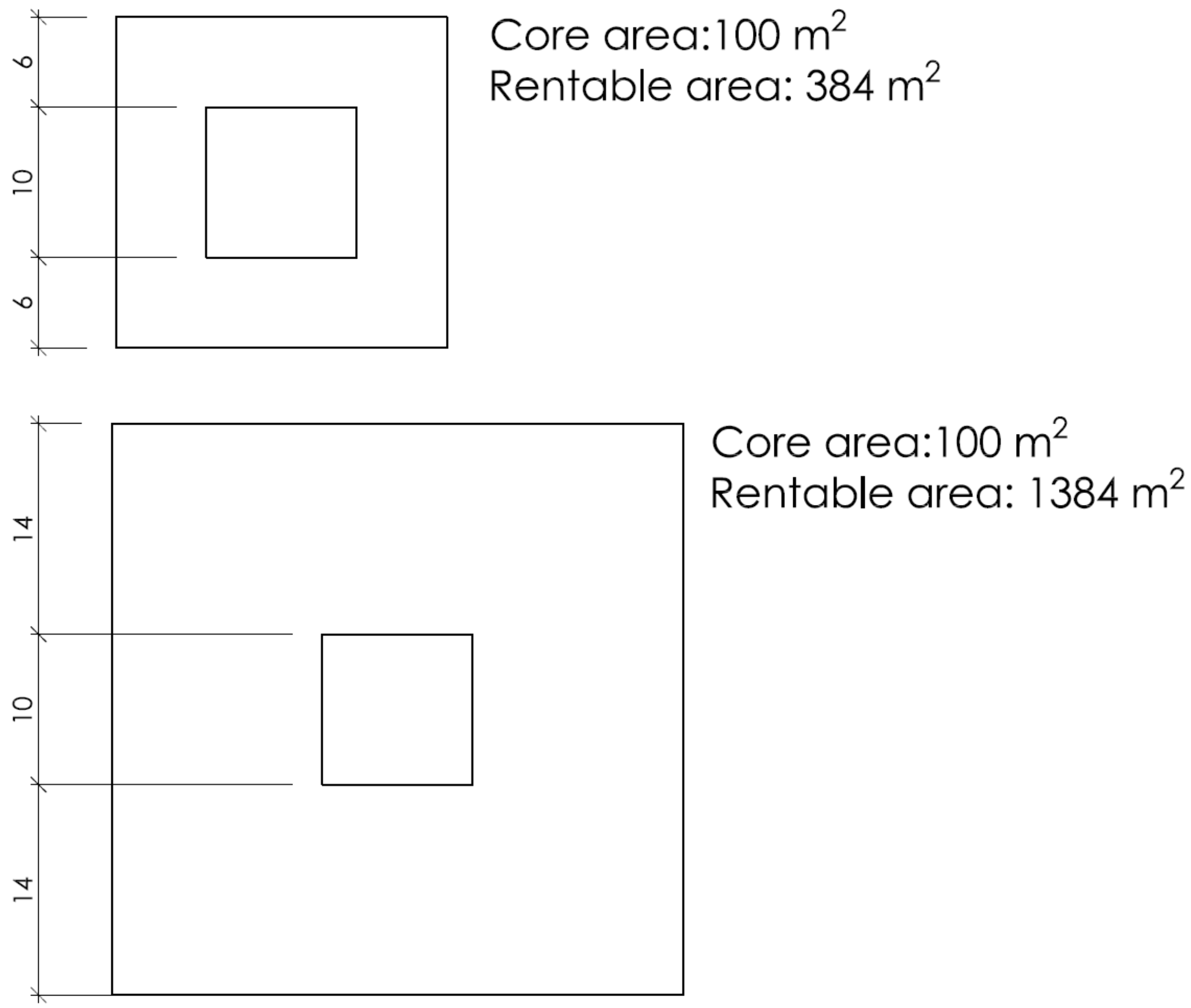


Figure 10 *Picture showing the principle of different area efficiencies. The lower floor plate has a much higher efficiency ratio than the top one.*

Repeatability

High repeatability in a project improves its possibility to be economically sustainable. The degree of repeatability is something Chalmers Studentbostäder (Thunberg & Wallin, 2016) look for in any project to indicate economic soundness. In many building projects repeatability means many of the same unit being placed next to each other, but in a high-rise it can mean having many units stacked on top of each other, see Figure 11. Symmetry is also a type of repeatability.

In the structural system for example, the column and wall sizes are not structurally optimized for the loads on each floor. This would not be economical since it would be more complicated to keep track of all the measurements and new formwork would have to be built for each floor. Instead, the floors are divided into sets of perhaps ten, and all the floors in each set are made identical. The same principle can be used for apartment layouts and other aspects of the design.

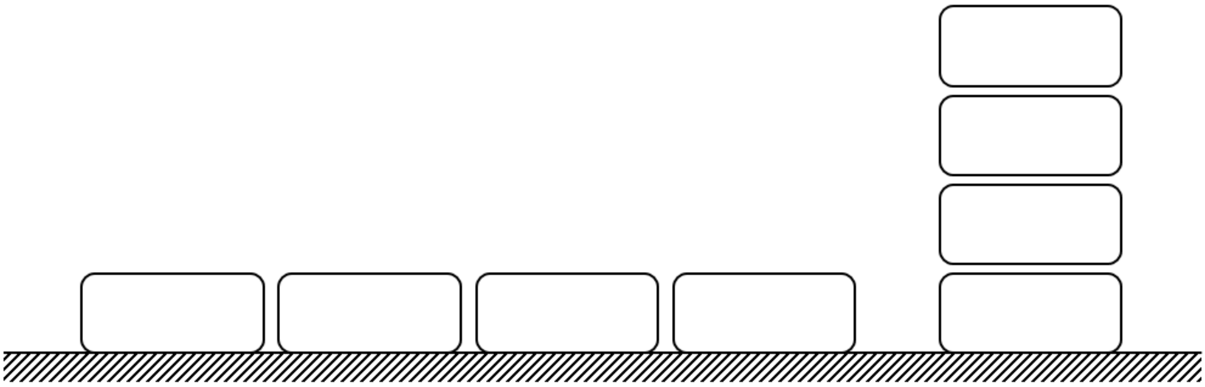


Figure 11 Repeatability with units placed next to each other, which is common for low-rise developments, and on top of each other, which is the case for high-rises.

Compliance with Demands

People are usually willing to pay more the better the quality of the product they are buying is. A high-rise is an expensive building and floor area in it will not be cheap, even in an economically efficient project. It is therefore of great importance to create good value for money so that people will be willing to pay a premium.

For example, in an office building it is important not to compromise too much on the ceiling height, as this is a noticeable disadvantage and makes the building more difficult to let (Albertsson, 2016). The cost savings of decreasing the ceiling height must therefore be balanced against the decreased value.

Structural and Material Efficiency

One way to achieve an economic building is using as little material as possible. This strategy saves money and is also beneficial from a sustainability viewpoint. Most of the newer high-rises from the 1960's and forward use a significantly lower amount of material than the older ones. The differences can be as large as 40%. Subsequently, the savings made can be high. However, a more efficient structural system will often require a more complex geometry, with diagonals as well as horizontal and vertical elements. This increases cost as connections are expensive to fabricate and more complex to put in place.

Cost of labor is an important factor in the choice of structural system. Mark Lavery, high-rise engineer at Buro Happold in Dubai, states that labor is cheap in the Middle East, making concrete buildings popular, whereas in Europe and America steel can be more attractive (Lavery, 2016). Dmitri Jajich at SOM agrees; "Production and labor are generally much more expensive than the raw material itself. For steel, the cost of the raw material is only about a quarter of the cost of the finished product" (Jajich, 2016).

Generally, concrete is becoming the most common material in high-rise buildings (Jajich, 2016). However, according to Samuelsson in his book on the art of engineering, concrete is near its practical limit when it comes to building height with the Burj Khalifa This is due to the fact that with increasing height, columns need to increase in size and the design ultimately becomes too inefficient to build (Samuelsson, 2015). This can be argued but it is true that super tall buildings in concrete have very poor area efficiency compared to other buildings. Taller structures are of course possible to create if factors like economy are disregarded.

4.6 Manufacture and Assembly

How to manufacture and assemble the building is another important aspect of high-rise design. It is closely related to economy as different production methods have different costs attached to them. It is also closely linked to the choice of structural system, since different production methods are suitable for different systems

As high-rises are usually built in cities the sites can be very limited and logistics play a limiting role in the success of the project. Important to consider is the degree of prefabrication. A high level of prefabrication can shorten the building time and ease site logistics by reducing the amount of work being carried out on site. This means a less crowded site, which is beneficial for control and safety.

Transporting large prefabricated elements to the site and putting them in place may however be a problem, and in some cases cause a safety issue. Some mean that prefabricated concrete elements are not suitable in tall buildings because of the difficulties and dangers in moving them into place. The operating time for the crane also increases when there are many building elements that cannot be transported in elevators or, as in the case when using fresh concrete, pumped in fluid form to the right height. Pumping concrete to large heights also comes with problems. Very high pressure is needed and the concrete mix needs to be adapted to get the concrete to flow.

4.7 Environmental Impact

In his book about the environmental impact of high-rise buildings, architect Ken Yeang states: "Right at the outset, we should be clear that the skyscraper is not an ecological building type. In fact it is one of the most un-ecological of all building types" (Yeang, 2009). High-rises are, in many respects, a very inefficient building type. They need a lot of structural material per square meter, as will be explained in chapter 4.8. In addition, building operations tend to be energy consuming, with vertical transportation and cooling as two of the big issues.

There are, however, different aspects to consider when designing high-rises to make them more sustainable. It is also interesting to look at the building's environmental impact from a city planning viewpoint.

Designing an Efficient High-Rise

There are ways to make a tall building more energy efficient. High-rises often have large windows or wholly glazed facades in order to let daylight in and make the most of the views from the building. The balance between letting daylight in and keeping glare and heat from the sun out is one of the key issues in the design, at least in warmer climates. This question becomes more complex in the colder Swedish climate where heat from the sun may be beneficial in the colder months. There is also a difference depending on the function of the building. Office buildings generally need more cooling than residential buildings. When the sun is low, as it often is in Sweden, it can cause uncomfortable glare. This is also an issue that needs to be dealt with in the design.

Sun shading can be placed inside or outside the façade depending on if added heat is beneficial or not. If shading is placed outside windows, direct heat is blocked as well as glare. If it is placed on the inside, glare is blocked but heat is let in. Blocking the sun when it is low in the sky is impossible without obstructing views, which makes a system that can adapt throughout the day preferable. Letting a lot of daylight into the building decreases the need for artificial lighting. Occupancy sensors, daylight sensors and other controls can be installed in offices to decrease energy consumption.

Using natural or forced ventilation as well as type of lighting system are also choices that affect the energy performance. Lighting systems can be added and the ventilation system can be improved at later stages. It is, however, important to think about the ducts being large and simple enough at an early design stage. The BREEAM or LEED system can be used to aid the design for both the whole building and separate parts of it.

There are some examples of putting plants or wind turbines on buildings to improve sustainability performance, but it is often the case that the net effect of this type of solution is adverse.

Added Density

Dense cities are good from a sustainability viewpoint, since the need for transportation is decreased. A high density makes it possible for service functions to establish close to people's homes and a good public transport system becomes feasible. Citizens can live more sustainable lifestyles in this type of city. High-rise buildings add to the density of an area, whether they are residential, hotel or office buildings. Thanks to their height, they can fit many people onto a small footprint. It is arguable whether high-rises are the best way to achieve high density. High-rises are difficult to place close to each other without interfering with the outdoor environment too much. Therefore, medium-height buildings, which may be spaced more closely, are an alternative to consider.

The net effect of the environmental impact of a high-rise during its lifetime is very difficult to estimate when complex effects like these should be taken into consideration. People tend to focus on the construction phase since it is easier to monitor, but to understand the whole picture more thorough investigations are needed.

4.8 Gravitational Load Capacity

Disregarding everything else except material efficiency, it is always more efficient to build a single-story building, rather than several stories (Jajich, 2016). Stacking floors on top of each other means an increase of loads on the lower stories and therefore an increased amount of material needed in vertical load-bearing elements. The area covered by columns and walls on each floor is costly, regarding both structural material and lost floor space. The taller the building is, the larger this problem becomes.

The effect is illustrated in Figure 12, where the same loads are applied to a conceptual single-story building and a four-story tower, with the same total floor area. As can be seen, the total loads on the lower stories in the tower become increased, since the loads from above are added. The vertical load-bearing elements will therefore need to be bigger in the tower than in the single-story building. The columns on a given story in a high-rise need to carry the weight of all the stories above. This includes the loads from floor slabs, installations and other materials as well as people, furniture and movable elements. They also need to carry the weight of all columns on floors above.

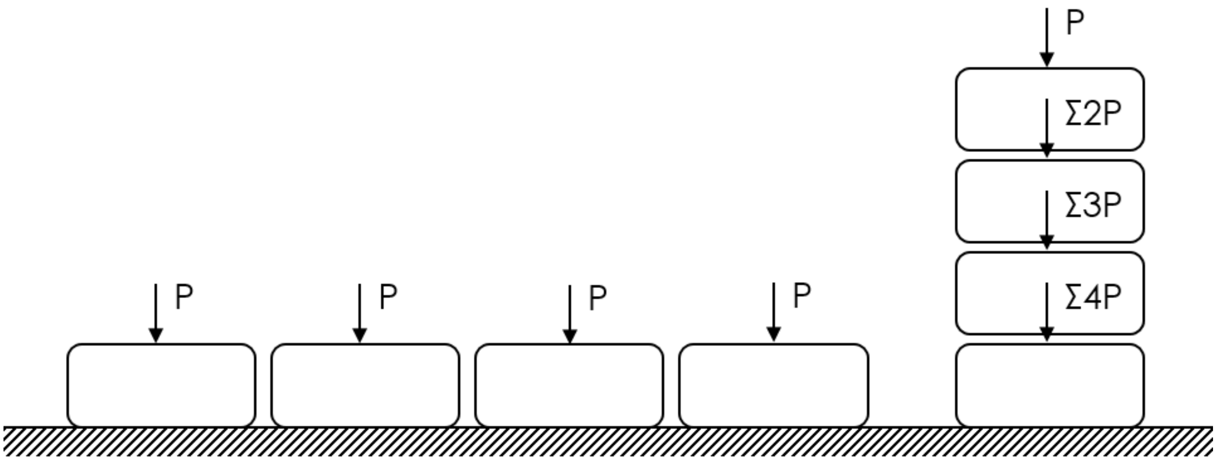


Figure 12 The difference in loads between a 1-story and 4-story building with the same total floor area.

To design vertical elements in a simplified manner, the self-weight and imposed load on each story can be calculated. Then the loads from stories above can be added to those of the story in question to get the total load to design the columns for.

However, the weight of the columns above can be very large at the lower stories of a tall building. This is because the columns need to increase in size the further down the tower they are placed, in response to the increasing loads from above. To accommodate this effect in the design, an iterative calculation is needed, described below and in Figure 13.

The first step is to size columns according to simplified loads, then the weight of these columns can be calculated and added to the loads on each floor. Then the column size can be re-calculated with better precision. More iterations can be made to get even more accurate results, but one iteration is probably enough, even for more detailed design. This is because a very precise solution is unnecessary, since it is unlikely that columns will be sized individually for each floor. Optimizing the column sizes with regards to material only is not the most economic solution, since there are other factors, such as formwork and connections, to consider. In the Karlatornet Gothenburg tower, the columns change cross section every 10 to 15 floors.

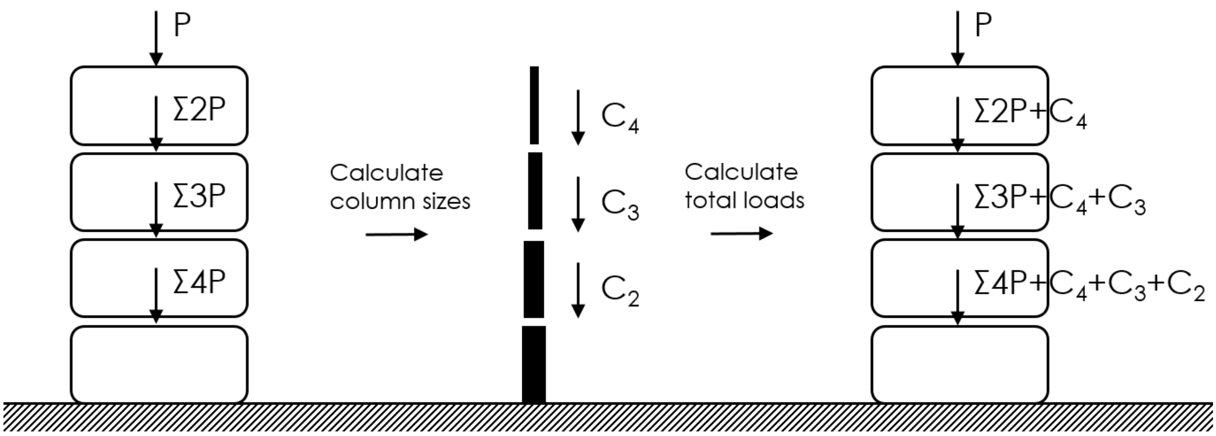


Figure 13 The accumulated loads on each floor are used to calculate needed column sizes. Then the weight of the columns is added to the other loads to get the total loads on each floor.

As explained, much of the loads and mass are concentrated to the lower part of a high-rise building. If the building is reduced in height it structurally means that the bottommost part is removed, which means losing much of the loads. A relatively small reduction in height can therefore save a lot of material. Figure 14 below shows a diagram of vertical loads, which can be approximated as linearly distributed over the height of the building. The figure shows that reducing the building to 7/10 of its height means reducing the vertical loads to half.

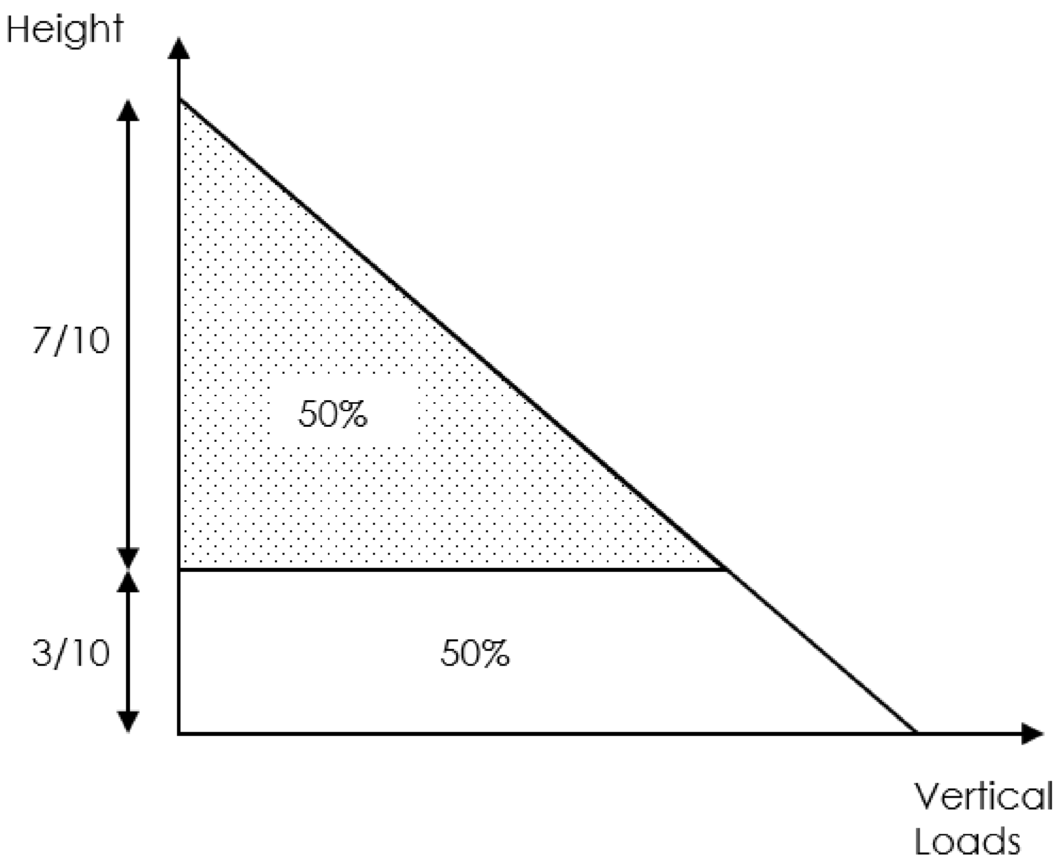


Figure 14 The vertical (gravitational) loads are distributed approximately linearly over the height of the building, see Figure 12. Reducing the building to 7/10 of its original height results in reducing the vertical loads by half.

4.9 Stability

High-rise buildings are, as earlier mentioned, sometimes defined by structural engineers as "A building which is primarily influenced by wind loads" according to the Council on Tall Buildings and Urban Habitat (Gane & Haymaker, 2010). Tall buildings are exposed to very strong winds since winds are stronger high up from the ground. For tall buildings, wind loads are so large they are often more critical than the gravitational loads. At what building height wind loads become more important than gravitational loads varies depending on location and building design. The building's capability to handle wind loads is one of the most important structural demands. The capability to withstand seismic loads is also critical in earthquake zones.

Figure 15 shows a diagram of the amount of steel needed for buildings of different heights. Note that the steel needed for wind bracing is dominant for taller buildings while floor framing and columns are dominant for lower buildings.

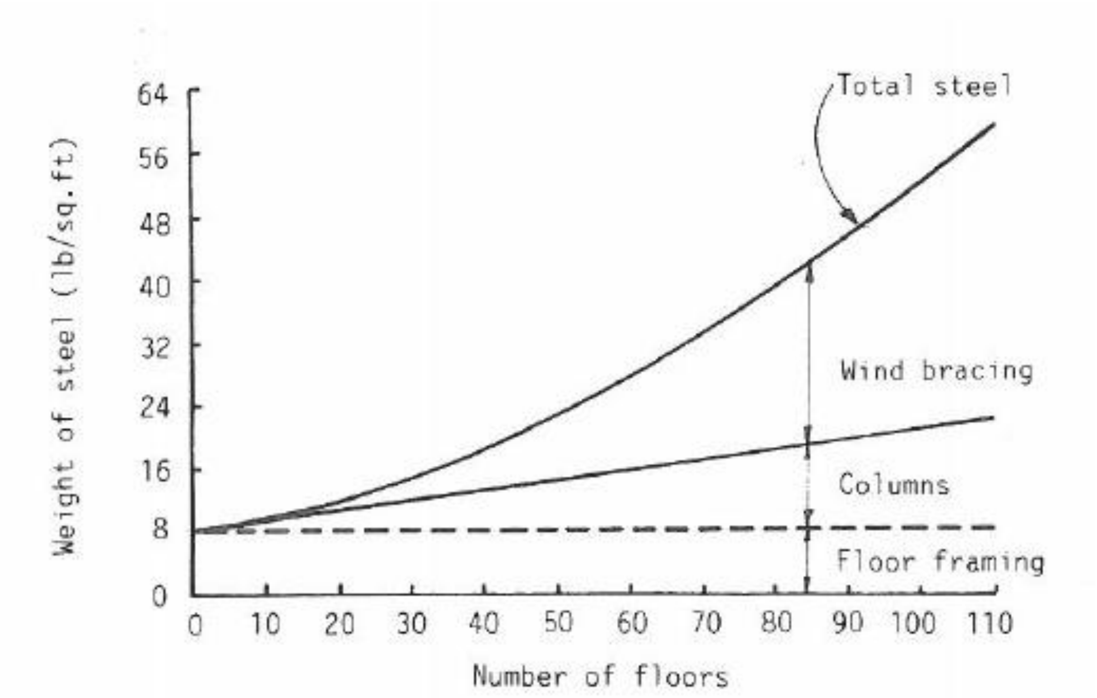


Figure 15 *Amount of steel needed related to number of floors according to Smith and Coull (Stafford Smith & Coull, 1991).*

Wind Effects

Simple calculations can be used to estimate the static wind force at a certain location and for a certain building height. The wind force, F_w is calculated through the following method:

$$F_w = c_s c_d c_f q_p(z_e) A_{ref} \ [N]$$

$c_s c_d c_f$: coefficients taking different effects into account
A_{ref} $[m^2]$: area
$q_p(z_e) = c_e(z) q_b$ $[N/m^2]$
$c_e(z)$: exposure factor
$q_b = v_b^2/1600$ $[N/m^2]$
v_b $[m/s]$: basic wind velocity

The wind force increases with increasing building height, as is illustrated in Figure 16, which shows the wind exposure factor, $c_e(z)$ for different terrain categories.

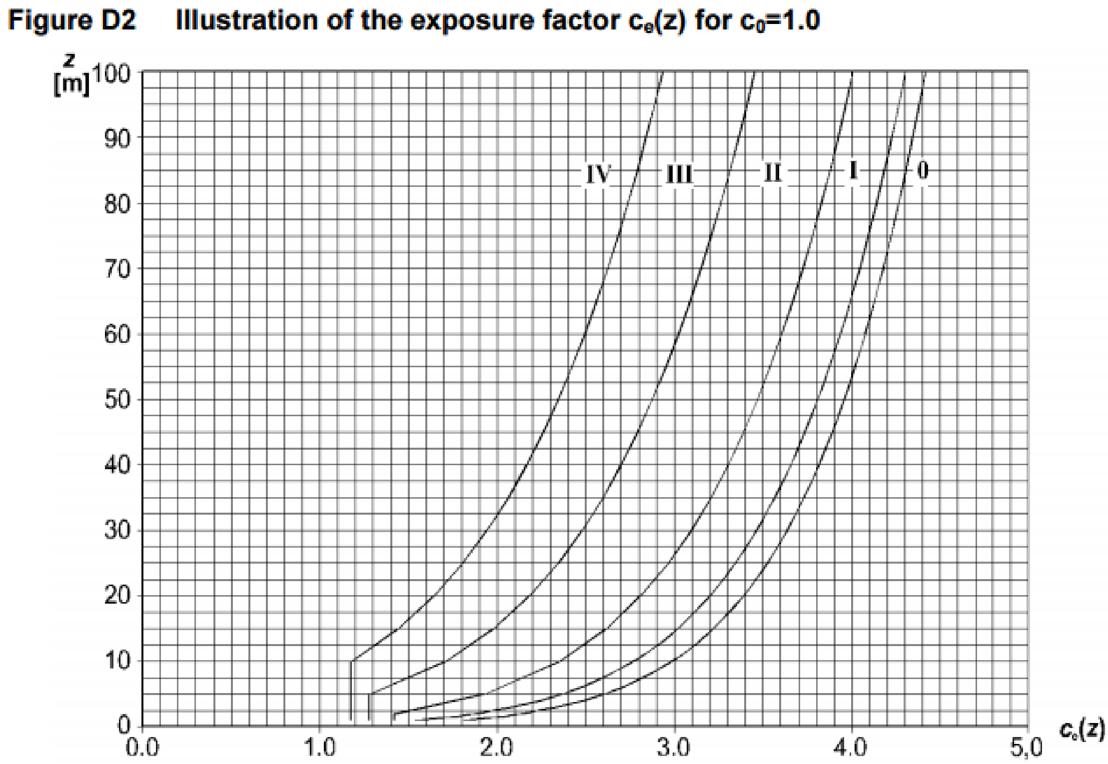


Figure 16 *Diagram showing the wind exposure factor up to 100 m above the ground.*

For high-rises, other more critical wind effects than the static wind force affect the building. The most critical effect is the so-called vortex shedding, a phenomenon that causes large forces in the direction perpendicular to the wind direction. Vortex shedding occurs when the wind flows past a building. A pulsating force that pushes the building from side to side at a regular frequency is generated, even though the wind speed is constant. There is no simple way to calculate the forces caused by this effect. There are some estimations in building codes that can be used but since they have a large error margin it is common to use wind tunnel testing to predict vortex shedding effects at different wind speeds and directions.

It is important to take all wind aspects into account at an early stage in order to be able to optimize the building. Resonance effects may cause problems in high-rise buildings and this needs to be investigated in addition to the pressure and suction caused by wind in order to achieve a well-functioning and efficient building (Gerhardt, 2003).

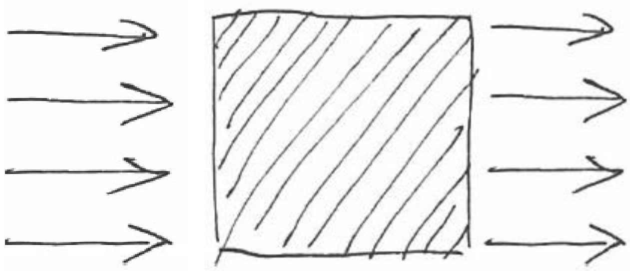


Figure 17 *The wind force acts in the direction of the wind as pressure and suction.*

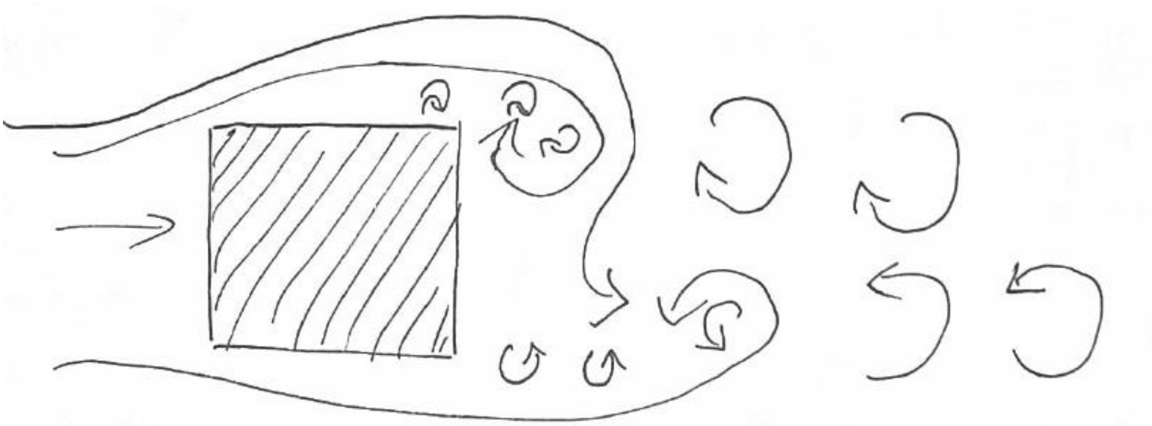


Figure 18 Vortex shedding is an oscillating flow that occurs when the wind flows past the building at certain velocities. The effect varies with the size and shape of the building.

Tall buildings need to be very stiff. This is in order to avoid uncomfortable motions for the occupants of the building and deformations that can cause windows and other building components to crack (Addis, 2007). Giving the building stability enough to avoid uncomfortable swaying can often be the limiting factor when designing high-rises. Therefore, the *Serviceability Limit State*, which concerns demands related to comfort and practicalities, is often more critical than the *Ultimate Limit State*, related to collapse of the structural system.

Wind Tunnel Testing

Because wind flows are very complex, it is almost impossible for wind engineers to make suggestions on building solutions without the aid of wind tunnel tests. Using CFD analysis is not enough to calculate the wind flows acting on buildings accurately, due to the enormous complexity (Cammelli, 2016).

Wind tunnel tests can establish what type of vortex shedding will happen and the type of wind (frequency and magnitude) that can cause the building to start oscillating. It needs to be made sure that the natural frequency of the building does not match those conditions (Addis, 2007). The building can be detuned so that the eigenfrequencies are moved outside the critical range. This is mainly done through changing the mass distribution in the building. Passive or active dampeners can also be used to reduce oscillations (Wörner & Nordhues, 2003). Different versions of the building can be modelled and tested to see if there is a certain shape or position of the building that is better suited. Cammelli mentions examples where rotating the floor plan of a building was enough to solve serious wind issues. The wind tunnel testing may in many cases be seen as a design aid (Cammelli, 2016).

A wind tunnel test comprises of two parts. The first is making a physical model and using the wind tunnel to determine airflow effects and forces. The second is a mathematical processing of the data from the wind tunnel test in order to "translate" it to useful data for engineers to analyze. It is possible to test different building stiffness distributions with this mathematical method. The stiffness distribution with the best results can then be chosen and the building be modelled in accordance to this (Jajich, 2016).

It has become common practice to do wind tunnel tests for almost all taller buildings, according to Jajich (Jajich, 2016). Mark Lavery, who is a tall building expert at Buro Happold in Dubai, agrees; "The cost and speed at which wind tunnel tests can be done now means there is no sensible reason not to do one" (Lavery, 2016). Lavery adds that any building that is deemed dynamically sensitive or has a natural frequency over around 4 Hz should be investigated more closely. Any building over 300 meters is definitely governed by wind. Cammelli gives an estimate of a slenderness of around 1:5 as a limit where consulting an expert is appropriate while Jajich says anything over around 40 stories should go into a wind tunnel (Cammelli, 2016), (Jajich, 2016).

One key issue is to find whether the building's natural frequency is close to the frequency of the wind and its effects. The Canadian and Australian building codes have some preliminary calculations that can be performed to investigate the likelihood of the building having performance issues due to dynamic response (Lavery, 2016).

Figure 19 shows an early study done in the Karlatornet Gothenburg tower design. The critical width of the building at different wind speeds was compared to the actual width of the building. The critical width is defined as the width of the building at a given height at which the frequency of vortex shedding would match the first mode of vibration of the building. This study shows that the building is likely to have large dynamic response at very high wind speeds (1000 year return period).

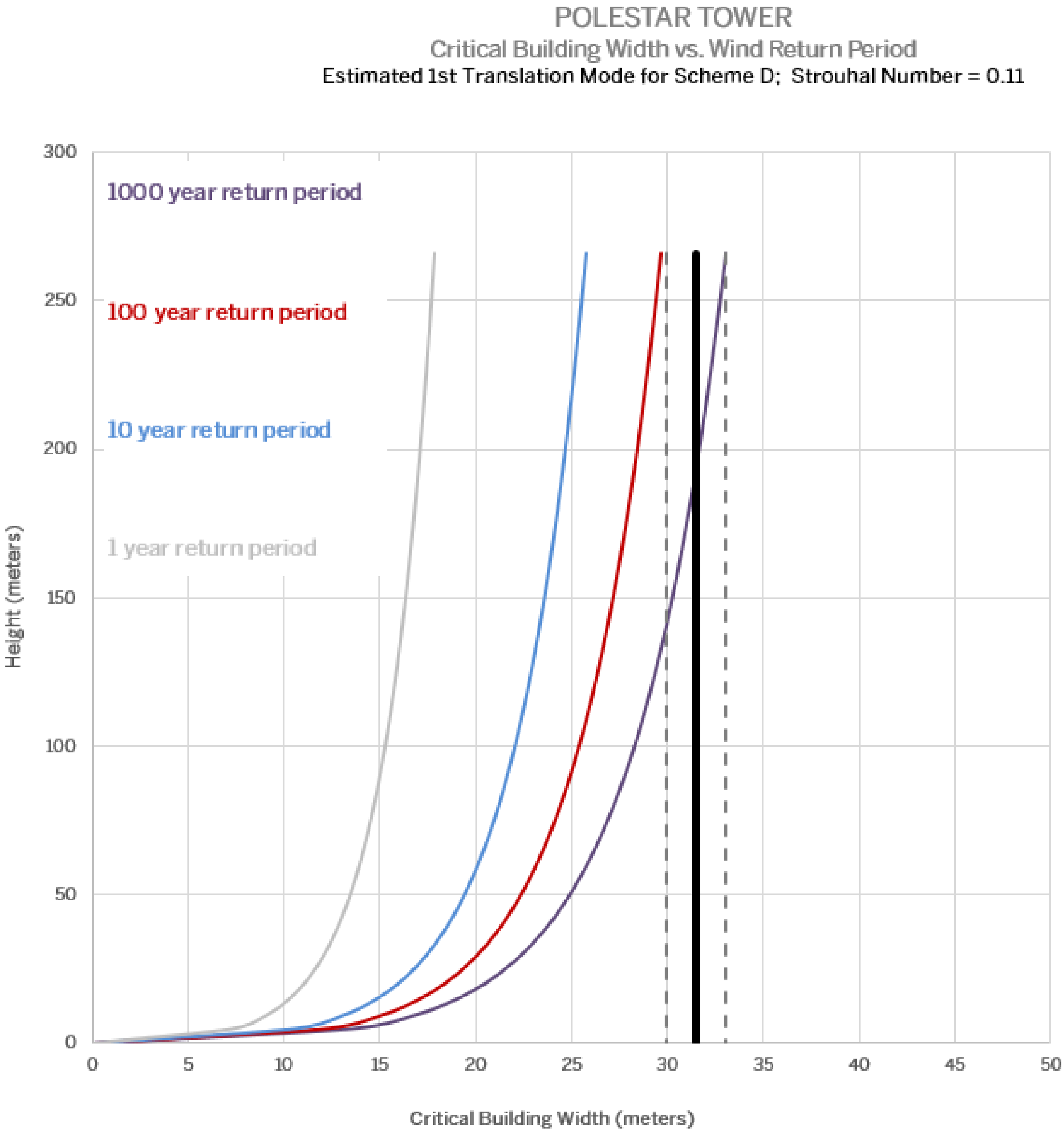


Figure 19 *The critical width of the building for different wind speeds and heights compared to the actual width. The picture is from the Karlatornet Gothenburg project.*

The Beam Model

There are some preliminary estimations that can be used in the early design phase to get an idea of the building design. A common guideline to use is that the maximum horizontal displacement due to static wind loads should be no more than the building height divided by 500 (Jajich, 2016). This calculation can be done quite easily knowing the building stiffness distribution.

In a very simplified manner, one can model a high-rise building as a cantilevering beam fully restrained to the ground (Jajich, 2016). The bending stiffness of this "beam" can be calculated from the buildings structural system and materials. Its deformations due to horizontal loads can then be calculated, as a first estimate. Figure 20 shows a model of a cantilevering beam.

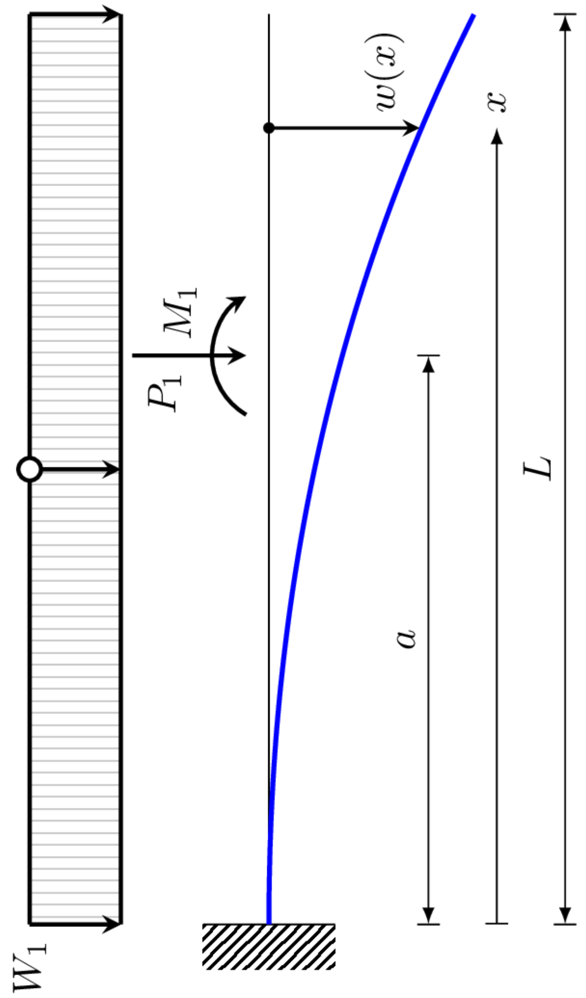


Figure 20 *Diagram showing a high-rise building modelled as a beam. The wind load can in a rough analysis be simplified to the uniformly distributed load W_1.*

The horizontal displacement at the top of the building can be computed as:

$$p_1 = \frac{W_1 L^4}{8EI}$$

Where EI corresponds to the bending stiffness of the building due to its materials and cross section. Despite the simplicity of this model, it can be useful to understand some of the most basic concepts in high-rise design. It is worth noticing that the displacement is related to the height of the building by a power of four. This means a small increase in height gives a large added displacement. Therefore, an increase in height inevitably means a substantial increase in the amount of material used to give the same displacement.

The horizontal deflection in the building is a combination of flexural and shear deformations. Structural systems and materials handle these two types of deflection to a varying degree of efficiency.

In this study, three different types of cross sections of the building have been studied, see Figure 21. These are the core, the core with outriggers, and perimeter systems. The different versions of these systems studied are described more thoroughly in chapter 5.4. The material in columns and core walls is here assumed to be concrete, but it is possible to change the material to steel or another material, since the same principle applies regardless of the material used. The building is assumed to have the same cross section throughout its height and the different columns and walls are assumed to act together as one interconnected cross section.

The combined moment of inertia, I can be calculated with the help of Steiner's theorem:

$$I = \sum I_n + A_n a_n^2$$

A_n $[m^2]$: area of cross-section element *n*
a_n $[m]$: distance of cross-section element *n* to cross-section center

Where, for rectangular elements, the moment of inertia I_n can be calculated as:

$$I = \frac{bh^3}{12}$$

b $[m]$: width
h $[m]$: height

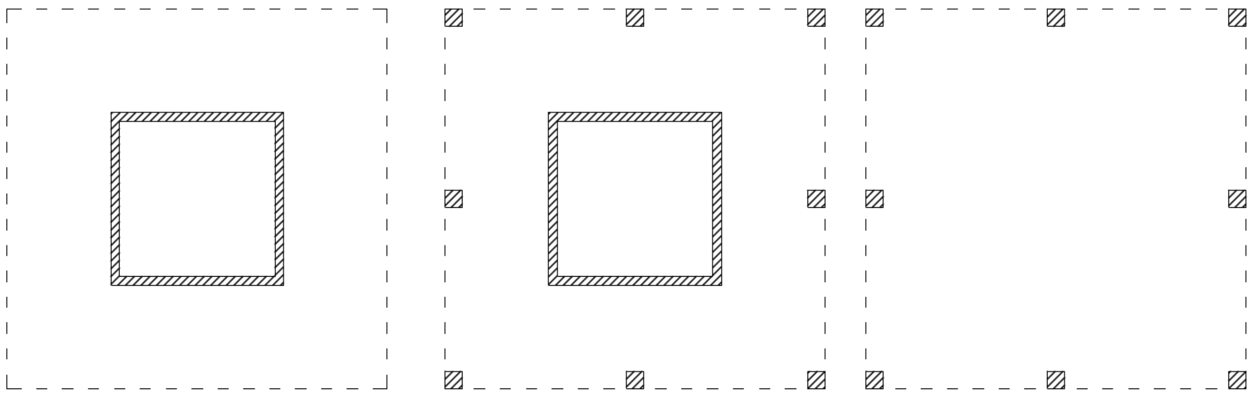


Figure 21 Simplified cross sections of core, core and outrigger and perimeter structural systems.

There are some measures that can be taken in the design to improve the possibility of good wind performance. Generally, a heavier structure will perform better. It is also important to avoid sharp corners. Softening the edges decreases vortex shedding. It is also advisable to avoid regular extruded shapes as large regular areas increase vortex shedding. This is especially important at the top third of the building as this is where the effects of vortex shedding can be most critical (Cammelli, 2016).

Combined Loads
Both gravitational loads and wind loads contribute to the forces in the vertical load-bearing elements. Therefore, load combinations need to be used in order to design for the combined effect of different loads. Checks need to be made for serviceability limit state as well as for the ultimate limit state. Other issues, like buckling and dynamic response, also need to be taken into consideration.

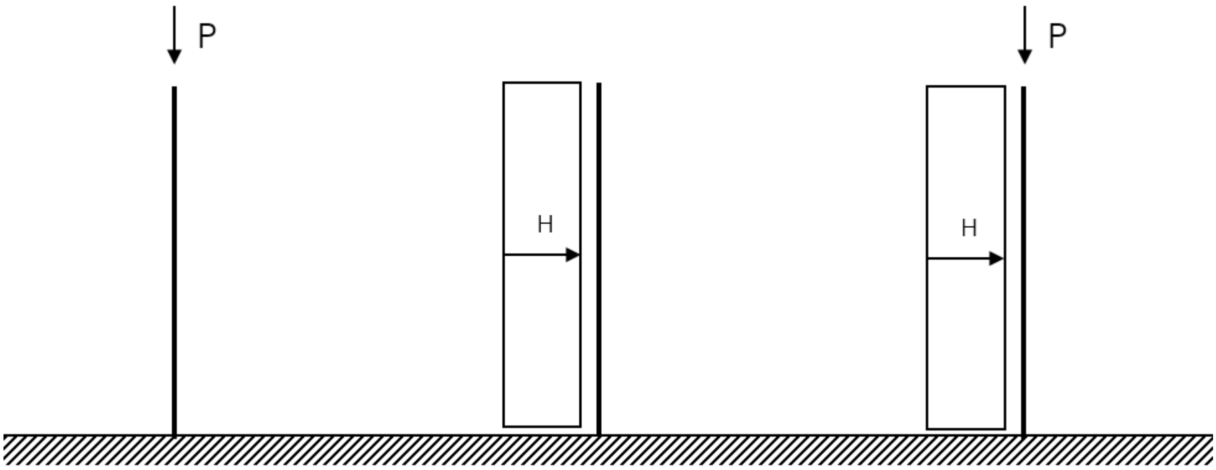


Figure 22 *Beam model of a high-rise with different loads. Left: Only vertical load Middle: Only horizontal load Right: Vertical and horizontal loads*

Figure 22 shows the different loads in a simplified manner. In this analysis gravitational loads and wind loads are studied separately (left and middle), while in reality they act at the same time as a combined load (right).

Navier's formula gives the stress in each point of the beam:

$$\sigma = \frac{N}{A} + \frac{M}{I} z$$

The stresses due to vertical loads, due to horizontal loads and the combination of the two can be seen in Figure 23, from left to right. This corresponds to the first term on the right-hand side of the equation, N/A, the second term on the right-hand side of the equation, Mz/I, and the combined stress σ.

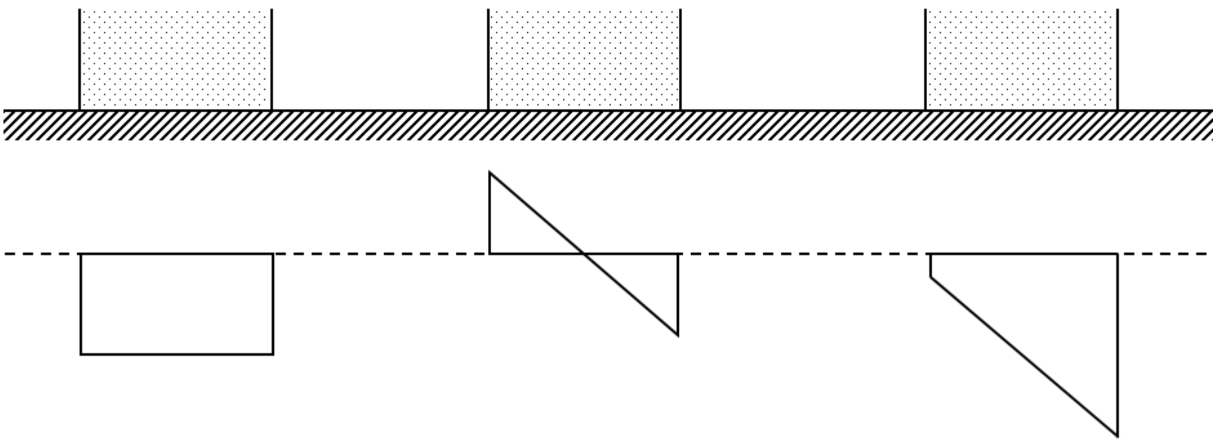


Figure 23 *Stress distribution of the beam at the connection to the ground for the load cases in Figure 22.*

As can be seen in the middle figure of Figure 22, the wind loads generate both compression and tension stresses in the structure. Often it is of interest to limit the tension stresses since these can give difficulties in the structure itself as well as the foundations of the building. Depending on the relative magnitudes of gravitational and wind loads, tension forces may or may not arise. A heavier structure that gives large gravitational forces counteracts tension forces and can be preferable from this viewpoint. In Figure 24, the combined stresses in a heavier building are shown on the left. The stresses varies throughout the cross-section but are always compressive. The stresses in a lighter building are shown on the right. Here there is a tensional component as well as a compressive.

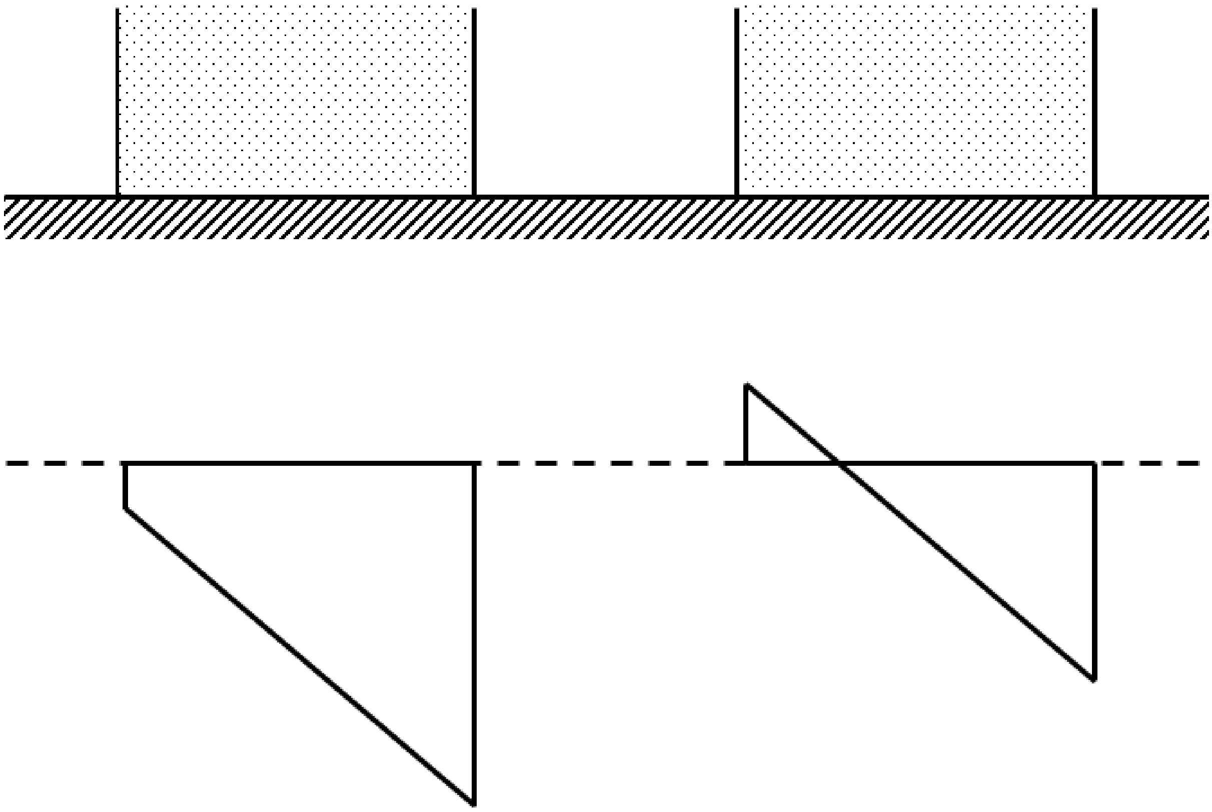


Figure 24 Depending on the size of the vertical loads compared to the horizontal loads, tension may arise in parts of the ground connection. If so, the structural system needs to be adapted to handle these loads.

Structural Efficiency
One way of estimating the efficiency of the structural system in a concrete building is to determine the ratio between the concrete volume and the floor area. This gives an idea of the material efficiency and subsequently the cost of the structure. The concrete volume is the added volume of the slab and columns. For a one-story building, columns are negligibly small and the volume is only the volume of the slab. The taller the building is the larger is the contribution from the columns and walls.

$$\frac{V}{A} = \frac{0.25m * 1m^2}{1m^2} = 0.25$$

For a slab of 0.25 m, this ratio can be no less than 0.25, see the simple calculation above. This is if the columns are negligibly small. According to Dmitri Jajich at SOM, a value to aim for in a high-rise may be about 0.35. If the ratio is above 0.5, the building is starting to become very inefficient (Jajich, 2016).

4.10 Fire Safety

Fire safety issues influence high-rise design to a large extent. Evacuating a tall building takes a long time since there are many flights of stairs to descend and a long way to the ground. The emergency routes need to be safe from fire and smoke. It is also very complicated to extinguish a fire far up in a high-rise. It is difficult to reach the higher floors from the outside and on the inside a safe elevator is needed for firefighters to reach the fire. To have access to enough water to put out a fire, there has to be a system to pump water to the upper floors at a high enough pace.

Figure 25 A Dubai high-rise on fire.

Forensic analysis shows that the reason the World Trade Center towers collapsed was not the impact itself and the façade columns destroyed but rather the fire that came after (Addis, 2007). In Dubai there have been several major fires in the last few years. According to an article about these fires, flammable materials were used for insulation and stricter rules apply for new buildings (Walker, 2016). However, a fire may arise in any building and the structural system needs to well protected in order to avoid a major collapse and the fire must be prevented from spreading. Especially when designing steel buildings, a lot of fire protection is needed for the structural system, as steel deforms disastrously at high temperatures.

Fire safety elevators are regulated by local codes and laws, rather than individually designed for each building (Cammelli, 2016). For example, in Sweden, a safety elevator is required in all buildings higher than 10 floors. An enclosed space is required outside the elevator to give firefighters a safe way to exit the elevator (Boverket, 2015). If the building is taller than 16 stories, a second emergency exit route is required.

In this thesis project, fire safety issues are not treated in depth but noted as an important factor to take into consideration when designing since fire safety regulations have a large impact on the design.

5 Design

There are many different factors and design choices that affect the completed building in a high-rise project. There is an almost unlimited amount of smaller decisions to be made and all choices somehow have an effect on the final result. Some choices, however, have bigger impact than others and are difficult to change in a later stage of the project. For example, it is impossible to change the story height once construction is underway, but whether to put in parquet or carpets is a later decision. Both story height and floor cladding have large impact on how a room is, but story height is the more important choice during the early conceptual design stage. The design factors chosen all affect the end result to a great extent and are interesting to investigate. Many other factors are mentioned and discussed in the project but these are the most critical design choices to understand.

The design factors chosen for investigation in this project are:

- Height
- Structural system
- Function
- Slenderness
- Shape

Height and slenderness are numerically measurable design factors. Structural system, function and shape each have a set of different options. For example, the function can be either residential, hotel or office. The table below shows if each demand is affected by each design factor. If there is a connection between a design factor and demand, it is marked with "**x**". For height and slenderness, it also shows whether the demands are improved (↗) or decreased (↘) with an increasing value in height or slenderness.

Demand \ Design	Height	Slenderness	Shape	Structure	Function
Views	↗	↗	x	x	
Daylight		↗	x	x	x
Elevator Access	↘				x
Economy	↘	↘	x	x	
Environmental Impact	↘				
Gravitational Load Capacity	↘			x	x
Wind Loads/Stability	↘	↘	x	x	
Publicity/Iconic Value	↗		x		
Ease Manufacture/Assembly	↘		x	x	
Population/Added Density	↗	↘			x
Fire Safety	↘				x

Table 4 *Table of how design variables affect demands. The symbols used can be explained with examples: ↗ Views increase with increasing height, ↘ Stability decreases with increasing height,* ***x*** *Economy is affected by structural system.*

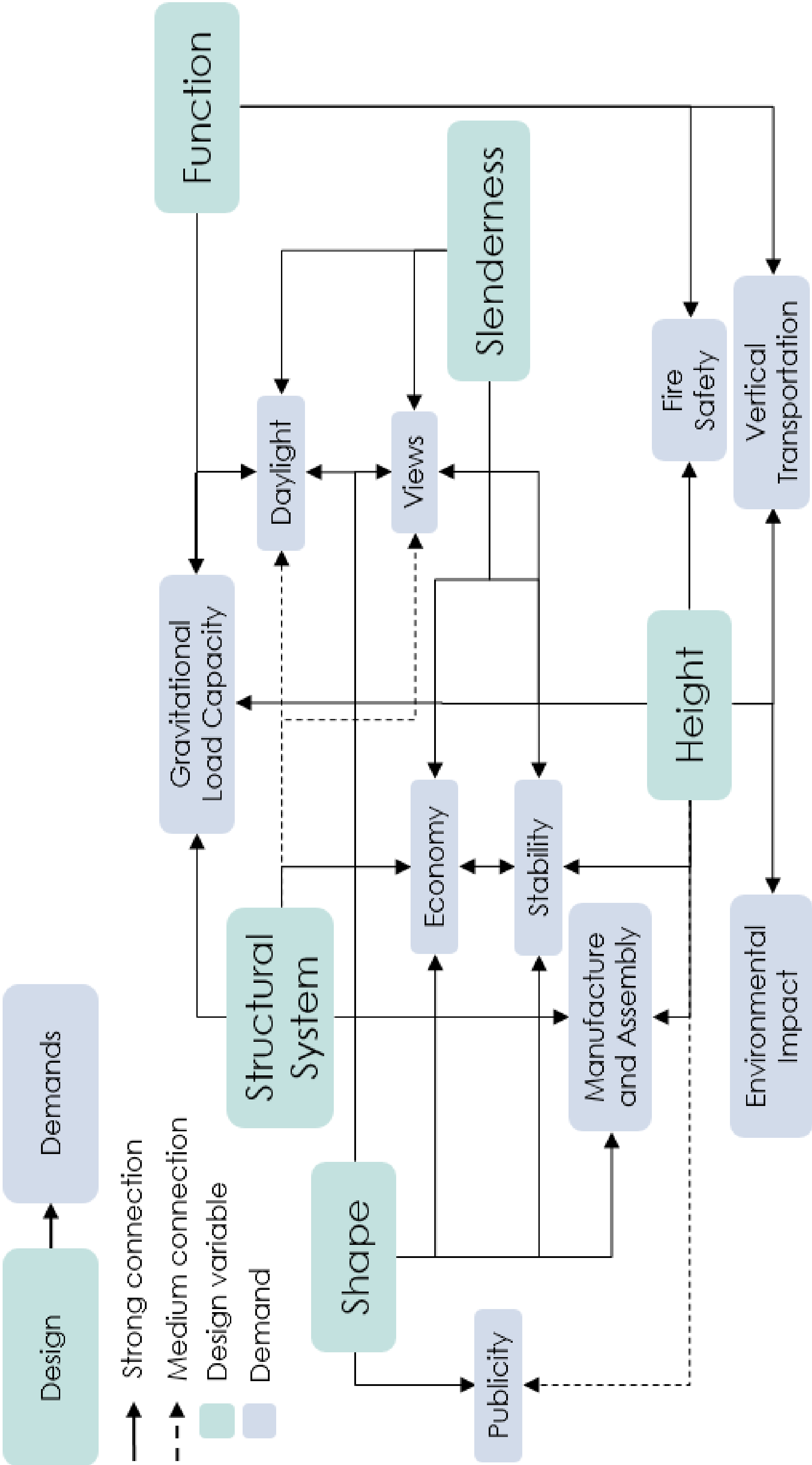


Figure 26 *Map showing how the design variables affect the different demands. The design variables studied in this project all affect several different demands.*

5.1 Height

The building height is the first thing people are interested to know in a high-rise project. Tall buildings fascinate people and in high-rise projects, there is a tendency to design a building as tall as possible. However, when designing a high-rise, the height greatly affects factor such as economy, sustainability and views. Changing the height by a few meters may have large implications and relations between height and other factors tend to be exponential rather than linear. This chapter aims to explain the major implications of building height.

The height of the building quite obviously affects the views. The surrounding topography also has a major impact on views. As mentioned in chapter 4.2, the views may not necessarily be the best at the top of the building. Lower stories may have great views as long as they are situated above the surrounding topography. The most important values needed to estimate quality of views are the height of the high-rise and the height of surrounding buildings and topography.

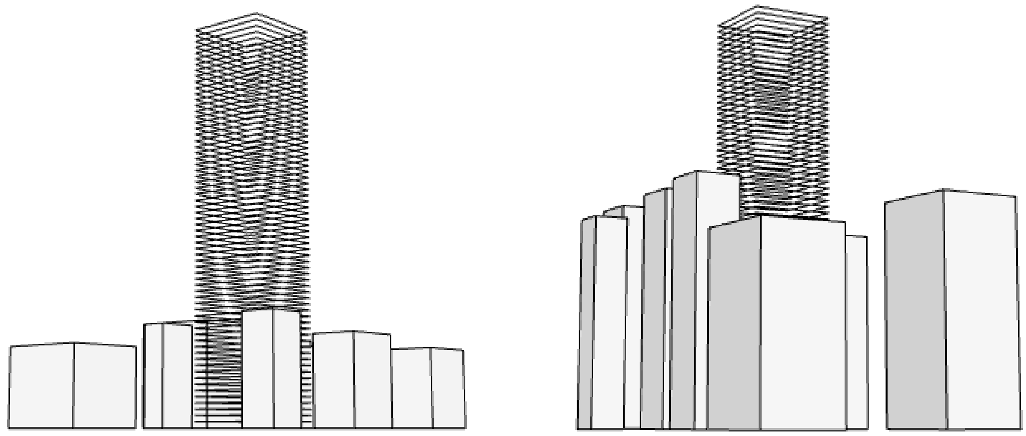


Figure 27 Views are affected by the building height as well as the height of surrounding buildings and topology. A percentage of building area above average surrounding building height can be used as a measure of views.

The building height is also closely related to the economy of the project. Generally, it can be stated that lower buildings are cheaper to construct per area unit of floor space. The costs associated with high-rise building technical demands are high, and the lower area efficiency due to vertical transportation, ventilation shafts etc. makes the cost/m^2 ratio increase with increasing building height. Cost tends to be exponentially rather than linearly related to building height, see Figure 28.

However, when land prices are high it may be more economic to build tall. In New York City it is more economic to build relatively tall buildings, according to structural engineer Dmitri Jajich (Jajich, 2016). It is also well established that residents are prepared to pay a premium for higher floors, which makes the top floors in a high-rise very valuable. In the Karlatornet Gothenburg tower the apartments on the lower stories cost about 50 000[1] SEK/m^2 while at the top the cost may be as high as 150 000 SEK/m^2 (Petzell, 2016).

[1] In the initial interview with Charlotte Petzell the prize 50 000[1] SEK/m^2 was given as the lower limit but has since then changed to around 65 000[1] SEK/m^2

It is difficult to predict an exact optimum height of a building concerning economy, as there are so many unknown factors. However, a reasonable height span can be predicted for the project in question. What height span that is viable depends on the site and project conditions, such as land price, building function and sale prices in the area. Figure 28 shows how building cost, land cost and predicted income are related.

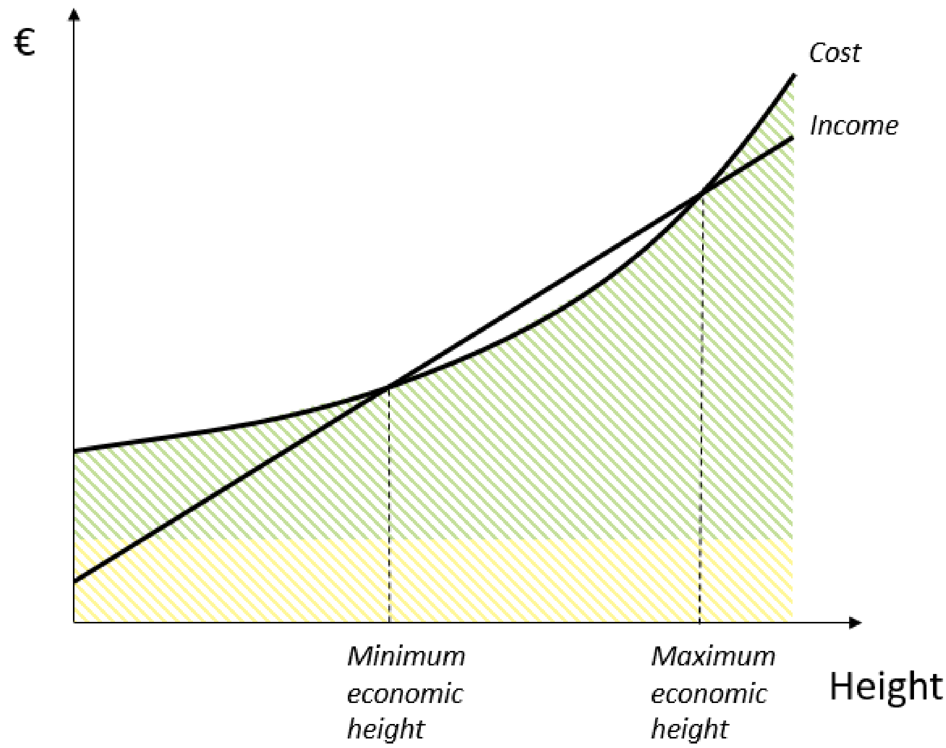


Figure 28 Sketch of possible economic conditions for a high-rise building. There is typically a minimum and maximum building height that is economic to build, but these values vary from project to project.

The environmental impact from the building increases with increasing height, while the added density effect may argue for a taller building from a sustainability viewpoint, see chapter 4.7. As discussed in chapter 4.8 and 4.9, the loads on the building increase with increasing height. Both the vertical and horizontal load capacity therefore need to increase.

Height Advantages
The taller the building, the better the views and daylight properties and the better the chances are of creating a building with iconic value and landmark status. The added population density leads to benefits from a sustainability perspective.

Height Disadvantages
The taller the building, the more difficult it will be to provide elevator access, fire safety and achieve good economy in the project. It will also become structurally more complicated and is bound to become less sustainable as a building and more difficult to construct.

Approximate Height Breakpoints

16 stories	Two exit routes are required
100 meters	A central core is probably not enough to stabilize building

40 stories	Wind tunnel testing definitely needed (Jajich, 2016)
190 meters	Height of Turning Torso, Sweden's tallest building
200 meters	Eurocode is not applicable
300 meters	Definitely a wind governed building, unless in seismic area (Lavery, 2016)
828 meters	Height of Burj Khalifa, world's tallest building

Height, Story Height and Number of Stories
In a 200 m tall tower the number of floors that can be accommodated depends on the floor height, see an example in Table 5. A change in story height in a tall building adds up over many instances and the story height needs to be chosen carefully.

	Floor-to-floor height	**Number of stories**
Residential	2.7 m	74
Residential, extra height	2.8 m	71
Office	3.5 m	57

Table 5 How many stories a 200-meter tower contains depends on the story height. A small change in story height in all the stories makes a significant difference.

As can be seen in Table 5, changing the floor height with only 10 centimeters means a difference of three stories in a 200-meter tower, which gives significant extra area to sell or let. Occupants notice a change of 10-20 centimeters in ceiling height though, and making the floors too low can mean false economy as the rentable spaces become much less attractive (Albertsson, 2016).

5.2 Slenderness

Slenderness is a very important factor to consider in high-rise construction. It is here defined as the base width to the height of the building. Note that it is the width at the base of the building that is most appropriate to consider when looking at slenderness. Tapered high-rises, like the Burj Khalifa, appear to be slenderer than they really are from a structural viewpoint.

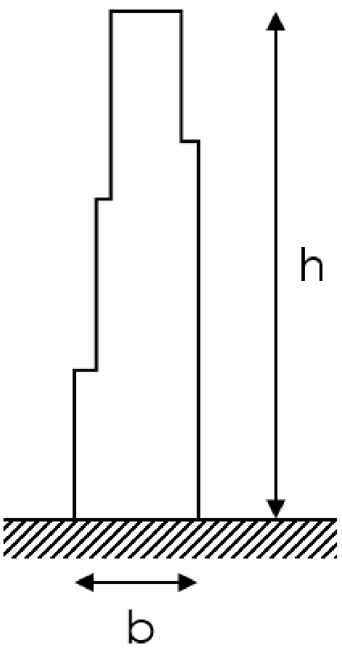


Figure 29 *The slenderness ratio is defined as the base width, b, to the height, h*

Slender buildings have good daylight properties since the distance from the façade to the center of the building is relatively short. The views from the building are also better since the smaller floor plates give easier access to views in all directions.

Slenderness ratios in high-rises vary. Until recently, the thinnest buildings have had a ratio of about 1:9 or 1:10. However, in the last few years, buildings with ratios of 1:15 and 1:24 have been constructed or are in the process of being built in New York City. One of the most important reasons for making these buildings so slender is that most of the floor area should be situated above neighboring buildings, to give better views. Even if consequences are difficult structural solutions and less floor area, the views are important enough to prioritize in these luxury buildings (WSP Group, 2014).

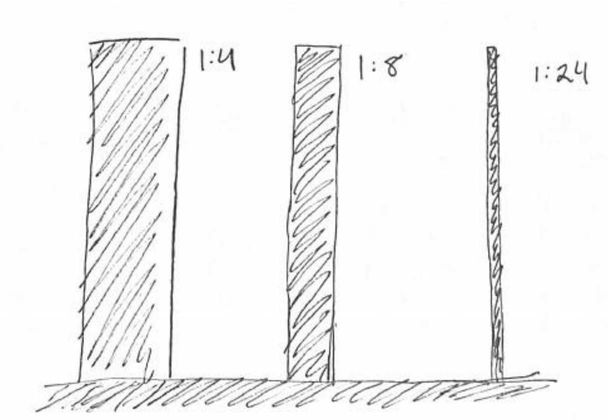


Figure 30 Sketch of different slenderness ratios. A slenderness ratio of 1:8 is common while the most slender buildings designed today have a ratio of up to 1:24.

The slenderness ratio, together with the context, is what decides when a thorough wind analysis has to be conducted. When the slenderness ratio is somewhere around 1:5, consulting a wind expert should be considered (Cammelli, 2016). Slenderness is more critical than the actual height of the building. For example, a wind analysis may be needed on a 20-meter thin chimney but not on a 40-meter tall building with a large floor plate. Slenderness is considered a positive value aesthetically and slender buildings are often perceived as beautiful (Rem, 2016).

Figure 31 Left: 432 Park Avenue with a slenderness ratio of 1:15 Middle and right: 30 Rockefeller Plaza which has different ratios in different directions. It has a wide base and tapered top which makes it appear more slender than it is.

5.3 Shape

The variations on possible shapes for a high-rise are practically unlimited. Here “floor shape” and “vertical variation” will be used as simplifications to describe tower shapes. This is an appropriate simplification as these two aspects are the most influential for the building performance.

Floor Shape

Floor shapes in high-rises are commonly rectangular, but there are many examples of circular, triangular and irregular floor plans in high-rise buildings. Rectangular shapes are easy and cheap to manufacture and it is easy to create functional and efficient floor plans from a rectangular floor plate. Other shapes are less straightforward to design but have other advantages.

To achieve good capacity to handle wind, sharp edges should be avoided. Softening the edges means that vortex shedding will decrease and the building will perform better (Cammelli, 2016). Rounded buildings are therefore preferable compared to square or rectangular from a wind perspective.

From an economic viewpoint, square/rectangular buildings with 90-degree angles and standard elements are usually the most economic (Thunberg & Wallin, 2016). They are easier to manufacture and assembly and therefore save a lot of time and money even if the material amount is roughly the same. However, compensating for a shape which is problematic from a wind viewpoint, with added structural mass or dampeners, may prove very expensive. In the case of needing to use dampeners, two or three stories at the top of the building may be lost as rentable space (Cammelli, 2016).

To get publicity a more unusual shape is preferable, since it is only the more spectacular buildings that receive a lot of attention. It is however possible to create a rectangular building which is unique in other aspects, for example façade solution. The building shape also affects views and daylight properties.

Vertical Variation

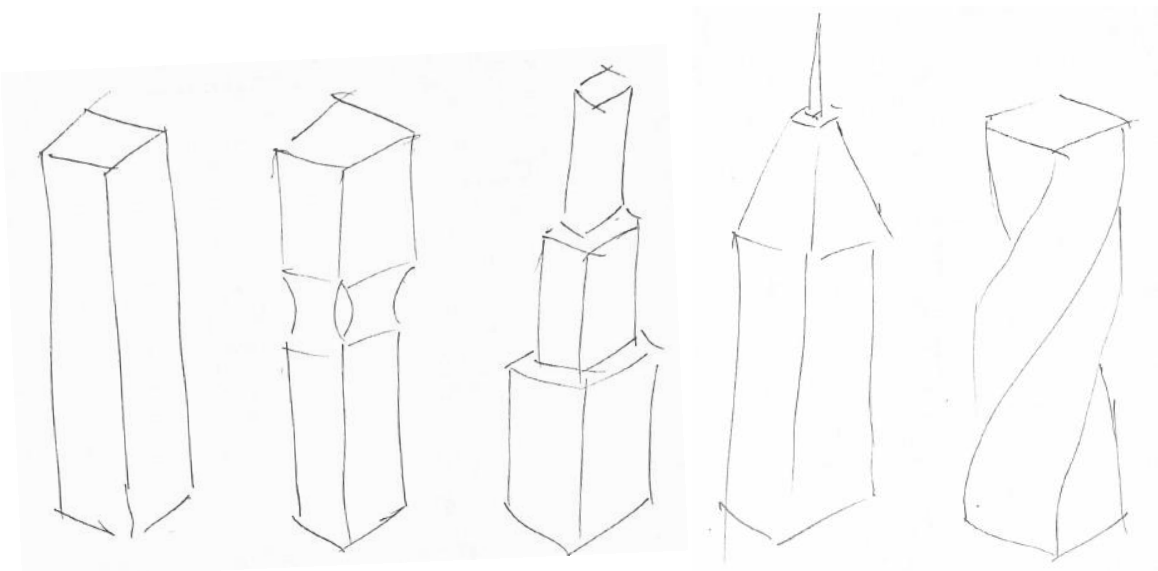


Figure 32 Examples of vertical variations in high-rises. Vertical variation is important for the aesthetics of the building as well as wind properties.

Very regular extruded shapes should be avoided to achieve good wind performance. Large regular areas mean that vortex shedding will arise continuously over large areas, which increases the effect. Avoiding regularity is especially important at the top 1/3 of the building where vortex shedding can potentially cause major problems (Cammelli, 2016). See chapter 4.9 for more information on wind effects.

Some kind of vertical variation is usually needed to achieve an interesting visual impression. At Wingårdhs, architects strive for a concept that gives a maximum visual impression without being too complex (Rem, 2016). That the building is recognizable and gives a strong visual impression is important to create an iconic building.

Repeatability is usually strived for to achieve good economy (Thunberg & Wallin, 2016) but in high-rises seemingly simple and efficient structures can, as mentioned, have issues with wind performance. Cammelli (Cammelli, 2016) mentions 432 Park Avenue by Rafael Viñoly in New York City as an example of a building where a great deal of damping had to be used. This building has the simplest possible geometric shape, an extruded square. Cammelli states that it was extremely costly to stabilize the building through damping. and this is certainly an example of a problematic design stability perspective. Interestingly, Filip Rem (Rem, 2016) brings up this building as an example of aesthetically pleasing architecture.

An example of where vertical variation is used to avoid vortex shedding is in the design of industrial chimneys. Putting a spiral profile on the top part of a thin, circular chimney is a common way to ensure enough variation to “trick the wind”. The regular air flow is disturbed by the helical strakes that break up the vortices and change the time they come around, instead of letting a vortex form over the entire length of the chimney.

Interestingly, the strakes add to the drag forces on the chimney but since vortex shedding is the most critical phenomenon in these structures they are still very useful. As can be seen in Figure 33 below, only the top part of the chimney is designed with helical strakes. In fact, adding strakes on just the top 1/3 of the chimney is usually optimal to reduce oscillations, which is consistent with Cammelli’s (Cammelli, 2016) estimate of where vertical variation is needed in high-rise buildings.

Figure 33 Left: 432 Park Avenue by Rafael Viñoly under construction Middle: Shanghai World Financial Center Right: Spiral on an industry chimney

Twisting the building is a way to keep the same floor plan but still achieve a more interesting shape. It also has potential to be good for avoiding wind-induced swaying. Examples of this is the Turning Torso in Malmö and the Cayan Tower in Dubai. To achieve a more slender-looking tower the floor area can be decreased as the building rises towards the sky. This gives the stability benefits of having a large base, while at the same time achieving a light expression. This design has been used both in Burj Khalifa in Dubai and The Shard in London. There are other types of vertical variations such as the Taipei 101 and the Gherkin in London. These two examples are both strong images that are easy to recognize.

Figure 34 Examples of vertical varitation. Left: Taipei 101 with a repeatable vertical pattern Right: Burj Khalifa with decreasing floor area along its height.

5.4 Structural System

Throughout the years, various structural systems have been used in high-rise design. In the first decades of high-rise construction, traditional systems with columns and beams were used, resulting in layouts with many internal columns. In the 1960's, engineers started to come up with other, more efficient structures (Samuelsson, 2015).

All buildings need to be structurally designed both for vertical and horizontal loads. However, while in most building types the vertical loads are much more critical than the horizontal, the opposite is true for high-rises. Engineers need to put much of their focus on how the building can withstand wind loads, and be stable enough to be safe and comfortable to reside in. In earthquake regions, the building also has to be able to withstand earthquakes. Building components such as shear walls and trusses are useful to make the building stiffer.

The choice of what structural system to use depends on several different factors. Building height, context, ground conditions as well as human factors such as knowledge of engineers and local laborers are some of the variables that affect what system is the most suitable for the project. The structural system is also very dependent on what demands are prioritized in the project. For example, sometimes there is a wish to use the structural system as an architectural expression. Sometimes the system should be as quick to construct as possible and sometimes a certain system is chosen because of local building traditions and expertise. In any tall building project, there is always a combination of several different demands. The structural system needs to be chosen to suit all the different demands in the project as well as possible.

The variety between different structural systems is limited in high-rises compared to other constructions, because of their height (Wörner & Nordhues, 2003). Therefore, there are many similarities between the systems used and often principles from several different systems are used in the same project. Some of the most typical current structural systems will be described in this chapter, with a discussion on their advantages and disadvantages. The structural systems chosen to investigate are stabilising core, stabilising core with outriggers, façade tube structures, truss tube structures and space structures, see Figure 35.

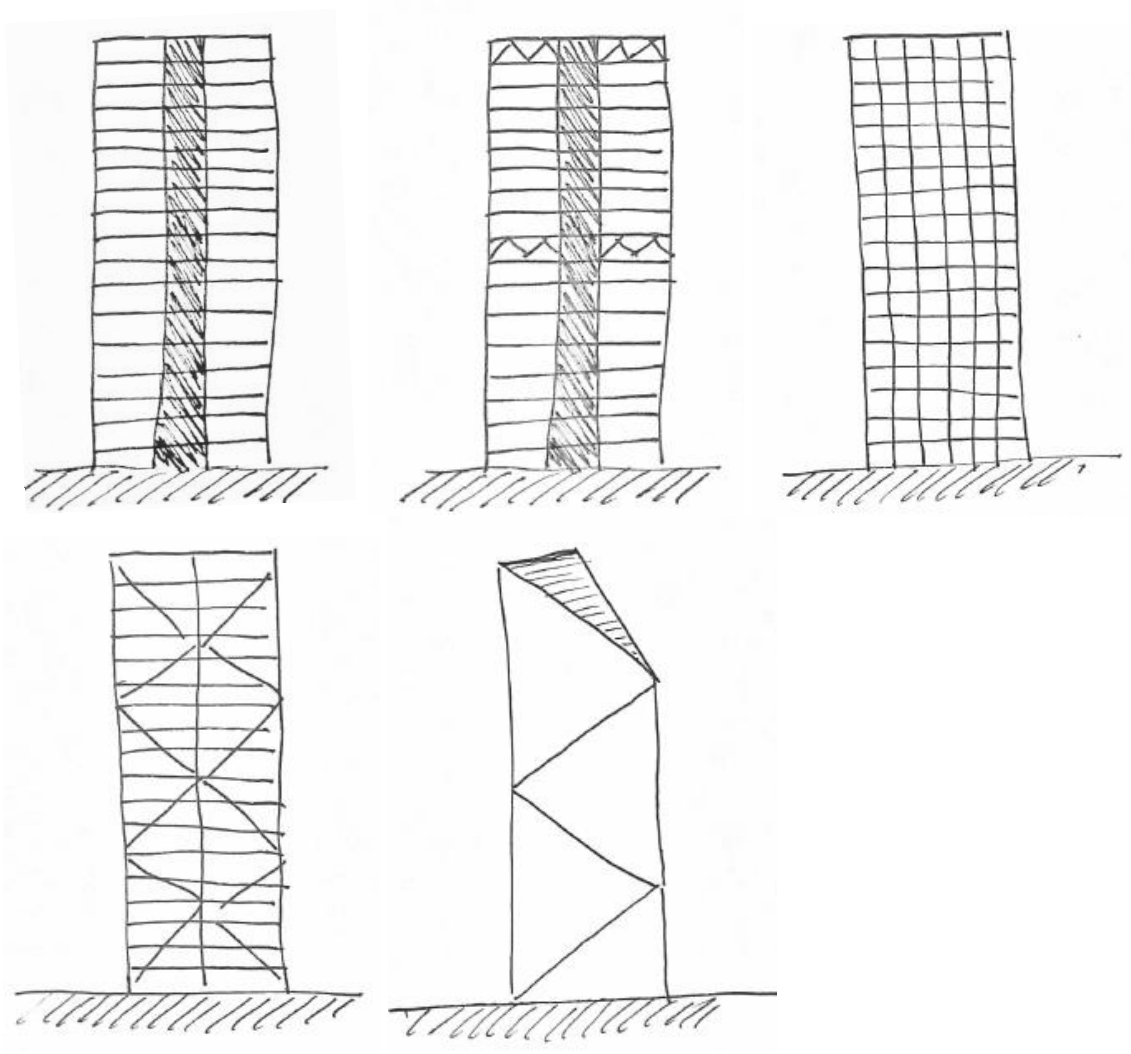


Figure 35 The structural systems chosen to investigate are stabilizing core, stabilizing core with outriggers, façade tube structures, truss tube structures and space structures.

There is a correlation between building height and suitable structural system. Some systems are more suitable for very tall buildings while some are better for lower buildings. However, there are many factors that influence what system is most suitable for a project, and there are usually several different options for a building of a certain height. There are guidelines in literature on what systems are suitable for certain heights, but between sources, these guidelines vary a lot.

Developing a structural concept in a complex project such as a high-rise project is an iterative process. Many different options and scenarios are modelled in order to gain better understanding of the design space. Rough calculations and models are an aid when choosing a suitable system, and can later be used when developing the chosen design.

Certain parts of the building are more critical than others. At an early stage, sensitivity analyses are conducted on these critical parts in order to make sure that they can be handled in the design. With experience, engineers know what the most important areas to investigate are. Once critical parts have been established and modeled, the structural system can be optimized and risks mitigated (Jajich, 2016).

Stabilizing Core

A common system for buildings up to about 30 stories is a stabilizing core to resist lateral forces and columns and walls to carry vertical loads. The core is usually placed centrally in the building. This is preferable from a structural viewpoint since it gives symmetry as well as suitable architecturally, since it contains functions that do not require daylight, such as ventilation shafts and staircases. This system is rational, well tried and works well for smaller heights.

The walls of the core act as a cantilevering beam, with two sides acting as webs and the other two acting as flanges depending on the wind direction. The size, configuration and material properties of the core affects the stability. The concrete core is most often cast on site. Using prefabricated elements is problematic because of the difficulty in achieving strong enough joints between the elements (Albertsson, 2016). The other parts of the building may be either prefabricated or cast on site.

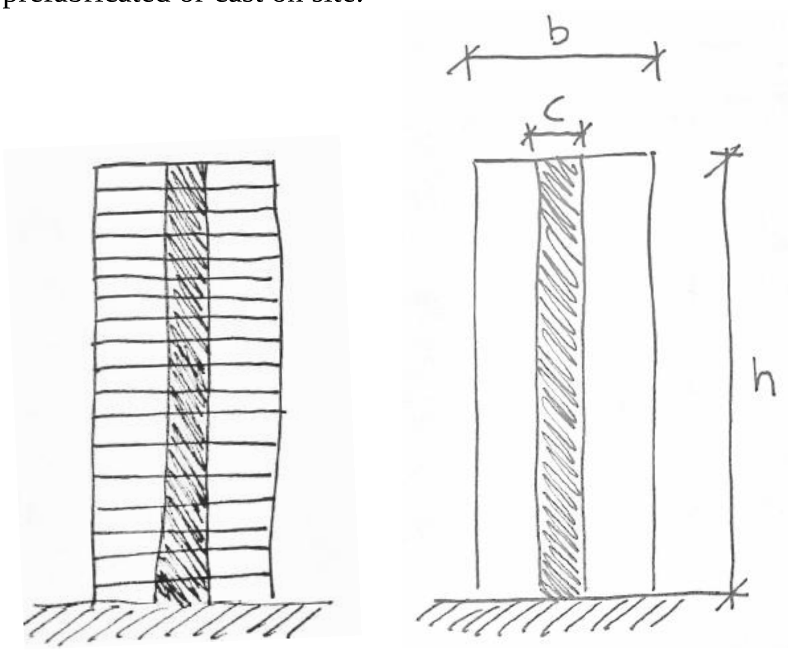


Figure 36 Left: Schematic view of the stabilizing core concept. Right: The ratio between the core width, c and the building height, h is critical for lateral stability since only the core provides lateral strength.

Advantages: Rational, well tried, cheap

Disadvantages: Limited stability, structurally inefficient
Examples: Gothia Towers

Because only the core provides lateral stability, this system is not the most efficient from a stability viewpoint. The width of the whole building is not used for stabilizing the building. Therefore, it is the slenderness of the core that is critical for wind load capacity rather than the slenderness of the whole building, see Figure 36.

Stabilizing Core with Outriggers

At a certain height, a central core is not enough to stabilize the building. One way of adding stability to the building is using one or more "outriggers". An outrigger is a stiff element that can transfer loads between the core and the façade columns. An outrigger is usually one or two stories tall and a building may have one or several outriggers depending on what is necessary in the particular case.

Outriggers give a longer lever arm for the elements resisting the lateral forces and thereby greater stability. Smith and Coull suggest that outrigger systems are suitable for buildings higher than 40 stories (Stafford Smith & Coull, 1991).

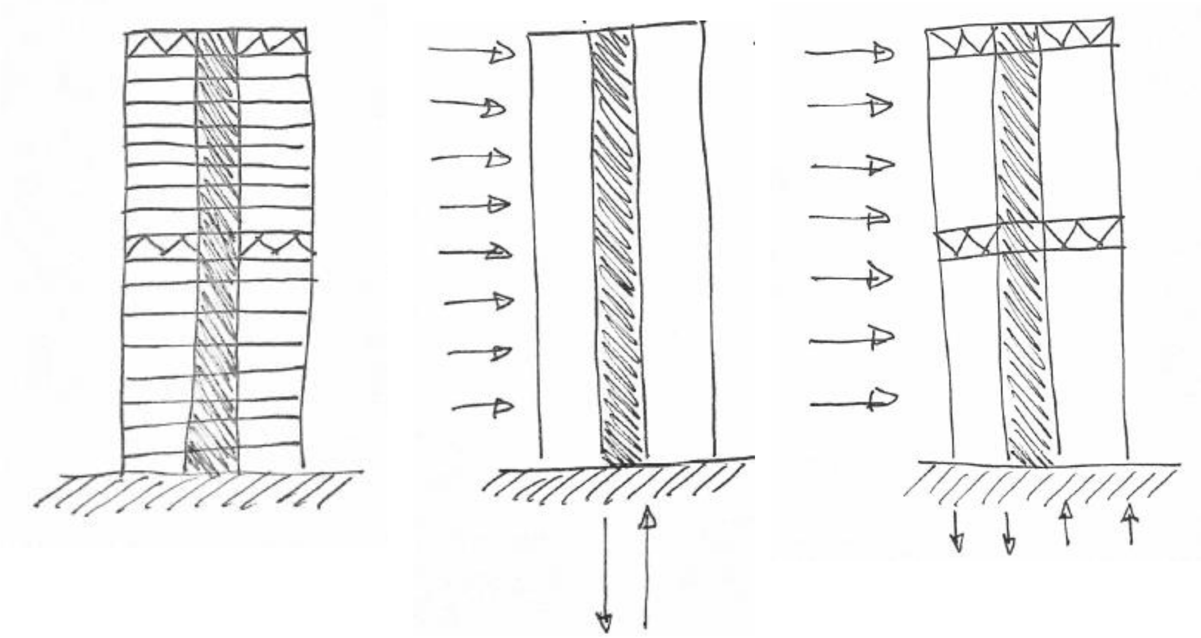


Figure 37 Left: Schematic view of a stabilizing core with outriggers Middle: A stabilizing core without outriggers has to withstand all the lateral loads in the core Right: Outriggers transfer forces to the perimeter columns so that the moment induced by lateral loads is divided by the core and perimeter columns.

Advantages: Rational, similar to stabilizing core system, good stability
Disadvantages: Loss of rentable area on outrigger floors, limited shear capacity
Examples: Karlatornet Gothenburg

The most efficient placing of the outriggers from a structural viewpoint depends on the distribution of wind forces and whether stiffness or resistance is dimensioning. The base moment and maximum lateral deflection were studied in Nawar Merza and Ashna Zangana's thesis from 2014 (Zangana & Merza, 2014). The optimal location of one outrigger in a 245-

meter building was discovered to be at 75% of the building height if the aim is to minimize deflections. If the aim is minimizing base moment, the best location is at about 50% of the building height. In their investigation, a trapezoidal wind load was used, which is a common way to model wind.

A weakness with using an outrigger system is that the floors where outriggers are situated can usually not be used as rentable area. The structural elements needed to connect columns and core disrupt the floor plan and limit the amount of windows. Outriggers can be coordinated with technical floors where open floorplans and daylight are not required. This may however mean moving the outriggers to less than optimal locations.

Outriggers are effective in adding flexural capacity but shear strength is not improved and shear has to be handled by the core.

Rectangular floor plans that are as similar to conventional floor plans as possible are easier to let. Therefore an outrigger system is often preferable to a perimeter system as it does not interfere with the floor plan (except on the outrigger floors) and does not limit window size (Jajich, 2016).

Framed-Tube Structure

Placing the stabilizing system in the façade maximizes the cantilever arm between stabilizing elements, see Figure 38. This leads to smaller stresses and a more stable building and is preferable to a core structure from a structural efficiency viewpoint. A tube structure acts as a large cantilevering beam with two sides acting as webs and the other two acting as flanges depending on the wind direction. For the façade to be stiff enough, this building type needs columns to be closely spaced. Normal column spacing is 2-4 meters center to center and large girders join the columns together (Stafford Smith & Coull, 1991).

This provides a very stiff building but the openings between columns are quite small, limiting daylight. Because openings are small and the columns quite thick, views become obstructed as well. In some buildings of this type, the ground floor is modified to provide easier access to the building. Using larger columns and girders means that openings between columns can be larger.

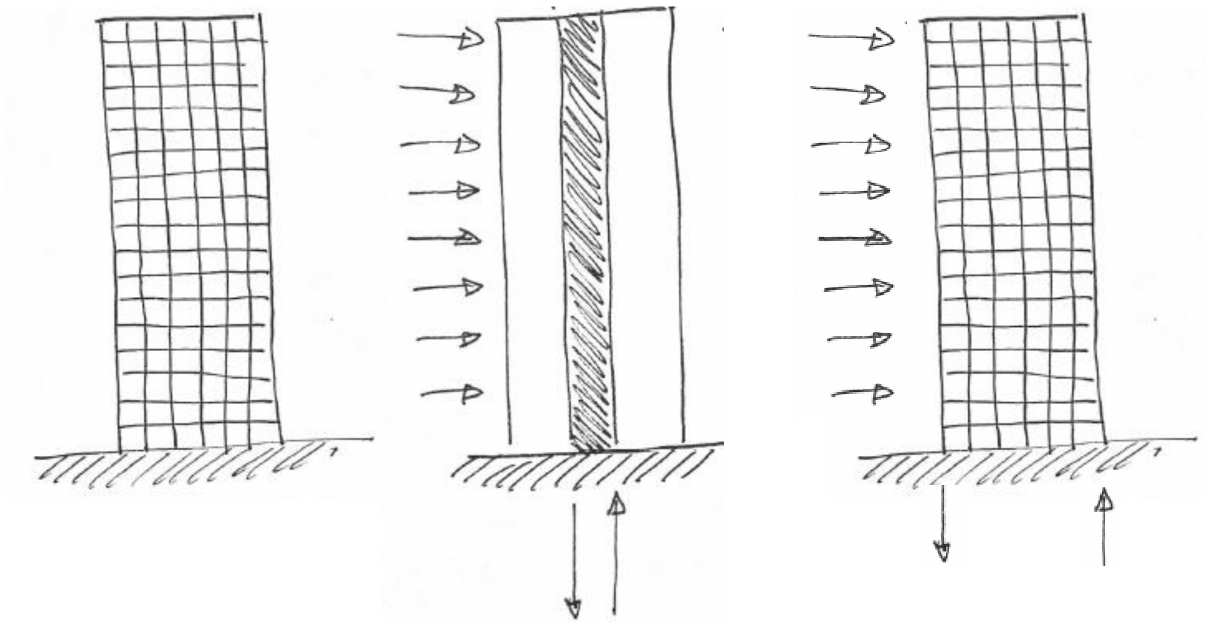


Figure 38 Left: Facade tube structure with columns closely spaced in the façade Middle: A core system has a relatively short cantilever arm for stabilising against lateral loads, leading to large stresses in the core Right: A façade tube structure has a longer cantilever arm, which decreases stresses.

Advantages: Use of the whole building width increases stability, freedom in planning the interior, high repeatability in construction
Disadvantages: Small windows, using only vertical and horizontal members is inefficient structurally
Examples: World Trade Center towers

There are variations on this structural system. Putting several tubes together into a bundle is a method used in the Sears Tower in Chicago. There are also examples of buildings with a second tube placed inside the larger perimeter tube. The tube system has been used for buildings from around 40 stories to more than 10 stories (Stafford Smith & Coull, 1991).

Braced-Tube Structure
This is a version of the tube structure, with the same advantage as the framed-tube structure of having the load carrying material placed at the perimeter of the building. Instead of using solid or rigid-framed tubes, this type of building uses a bracing system in the facades. This is much more structurally efficient and allows for a more slender structure. Shear lag, which is problematic in framed-tube systems, is almost eliminated and the building acts more like a braced frame. This enables larger windows and an even distribution of loads between columns (Stafford Smith & Coull, 1991).

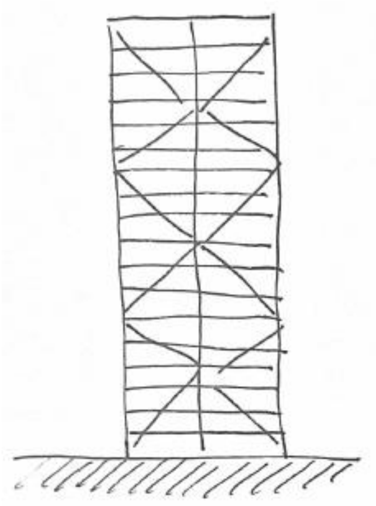


Figure 39 The diagonals in a braced-tube structure makes it structurally more efficient than a framed-tube structure.

Pros: Use of the whole building width increases stability, material efficient
Cons: Diagonals may obstruct views, complicated to build
Examples: John Hancock Building

One of the disadvantages of this system is the decreased repeatability compared to other systems. This makes the construction process more complicated and expensive. Another disadvantage is that the diagonals to some extent obstruct views and openings in the façade.

Space Structure
A space structure is a 3D triangulated frame system. As opposed to the braced-tube system, a space structure is triangulated in the horizontal plane as well as in the façades. This makes the whole structure work as one truss, which makes this structural system very efficient. Buildings using this system often have a light and interesting appearance.

However, this type of structure is very complex to design and construct. The repeatability is low and connections between elements difficult to create. Floor plans may become awkward from the sharp angles created by the triangular shapes in the structural system.

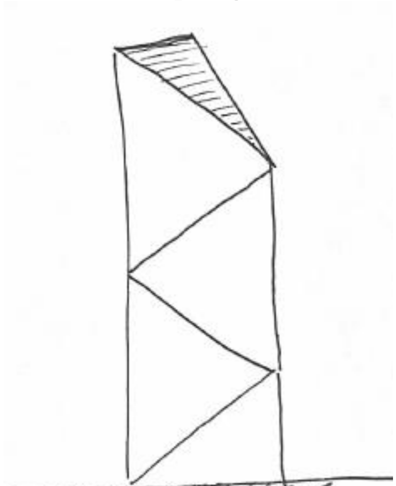


Figure 40 A space structure is essentially a 3D truss beam cantilevering from the ground.

Pros: Material efficient, aesthetically interesting
Cons: Very complicated to design and construct
Examples: Bank of China

5.5 Function

High-rises can be divided into four different functional categories: residential, commercial, hospitality and mixed use (Gane & Haymaker, 2010). Depending on its use the building population, layout, economy etc. change. It is therefore very important to consider what type of function the building is going to be used for when making design choices. Some of the implications of building function will be discussed in this chapter.

High-Rise Function Categories

- Residential
- Office
- Hospitality
- Mixed use

Daylight

Residential and office buildings both require good daylight properties. The layout of a building decides how much daylight reaches each rooms. As described in chapter 4.3, an interesting value to look at is the distance from the façade to the center of the building.

In residential buildings a guideline is a 6-meter maximum "depth" from façade to inner wall of apartments (Rem, 2016). Offices are often open-plan, which allows them to be deeper than apartments. A common limit is 14 meters as a maximum depth for offices. Patrik Albertsson (Albertsson, 2016) use 8 meters for "shallow" offices and up to 16 meters for "deep" offices in the "Region City" project in Gothenburg. These guidelines show that office buildings can have substantially bigger floor plates, which leads to less slender buildings.

Windows are not needed in some rooms, such as bathrooms and storage areas. In a hotel building the service functions and corridors can be placed centrally as they do not require daylight.

Story Height

The story height is also different for different building functions. In Sweden the required ceiling height is 2.40 m for residential buildings and office rooms. However, 2.70 m is needed for rooms intended for several people, which is the layout in many offices (Boverket, 2015). Larger loads and ventilation needs in offices further add to the floor-to-floor height. Experience suggests setting a preliminary floor-to-floor height of 2.70 m for hospitality and residential stories and 3.60 m for offices (Albertsson, 2016).

Vertical Transportation

The amount and type of elevators requires is also affected by the function of the building, see chapter 4.4. Peak hours are different for offices, residential buildings and hotels (Albertsson, 2016).

Loads

The loads are different depending on function. Residential areas have relatively low loads while offices and hotels have higher loads. Restaurants, bars, swimming pools etc., which are associated with hotels, can add even higher loads. It is common to have a restaurant or bar placed at the very top of a building, and the added loads are considerable.

6 Design Tool

At an early stage in the thesis project, it became apparent that the information in the report needed to be displayed in a comprehensive way in order to be useful in the design process. Therefore, the decision was made to create a design tool.

Initially, it was not decided what type of design tool should be created. Whether it should be digital, integrated with computational models or in a report format was decided about halfway through the project. The nature of the information and the design process made it suitable to create a parametric tool integrated in a 3D-modelling program. After information on high-rise design had been collected and interviews conducted, the development of a design tool started. The work with the report and design tool was then carried out in parallel, with new information acquired being integrated into the design tool as well as written in the report.

6.1 Why a Design Tool?

For a well-integrated design process, the information collected in the previous chapters in this report needs to be displayed in an intuitive way. A designer should be able to get direct feedback on their design, based on existing knowledge and information. This enables improving the design through quick explorations of the design space and iterations of the chosen design.

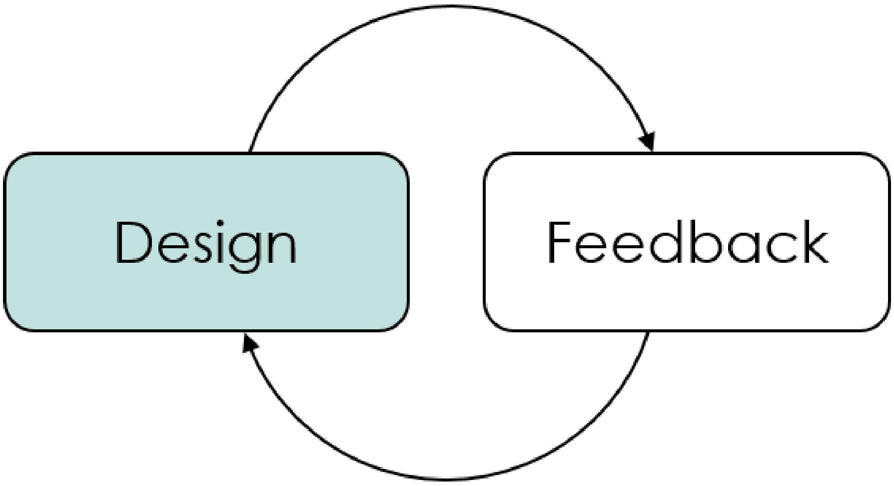


Figure 41 For a great design, it is vital that the designer can analyse different design options and get feedback. The feedback loop needs to be as quick as possible.

Ian Keough, creator of the parametric Revit plug-in tool Dynamo (Keough, 2016), in his lecture at the Smart Geometry conference 2016, raises the question of why designers have to start from a "blank page" with every building project, when there is so much experience and expertise available from previous projects.

As mentioned, there is a lot of information available on high-rise building design. However, having to ask an expert on each area for advice on every design option is time-consuming and only a few design alternatives can be investigated in this way. Of course, expert opinions are invaluable and a design tool cannot replace expertise. It can, however, allow the designer to get direct access to information which may lead the design in one direction or the other in the early stages. Basic knowledge in each area of expertise can be incorporated into a design tool, which can be useful for determining the design space, giving preliminary feedback and raising important topics.

Keough, together with Phil Bernstein, vice president at Autodesk, believe that there is a future in design tools which allows the user greater freedom in exploring different design options (Keough, 2016) (Bernstein, 2016). In the currently most common work process, the design space is not thoroughly explored and there is a lack of clarity in evaluating different options. Recent developments at Autodesk include the integration of Dynamo into FE-software Robot and the new design tool Akaba, which lets the user work with several design options in parallel. At McNeel, plugins to Rhinoceros and Grasshopper continue to evolve, making the tools useful for engineers as well as architects. The development of these types of tools is in progress and holistic design tools are not yet used for most building projects but we can probably expect to see more of this in the future.

6.2 Design Tool Options

One way of creating a design tool is through a mind map. This is an efficient way of showing a very broad picture in a visual and comprehensive way. However, mind maps have a tendency to become messy and difficult to read as soon as more information is input. Only a few nodes and connections can be displayed without ruining the simplicity of the diagram.

A traditional report is useful for giving in-depth information but takes time to read. If the whole report is not read the reader needs to know what information to look for and where to find it. Information is given in a linear manner and it is difficult to see connections between different parts of the report when reading only chosen parts.

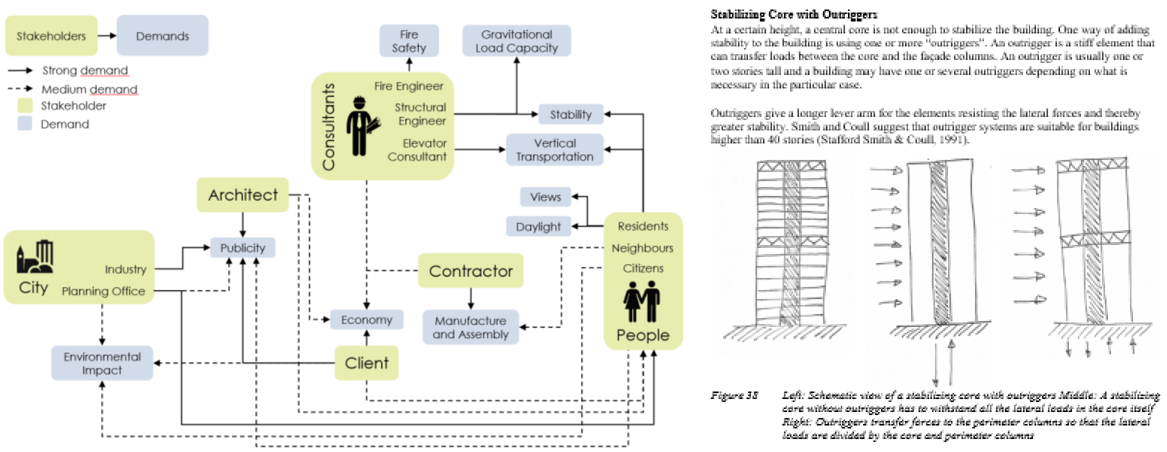


Figure 42 Left: Mind map from Chapter 4, showing the connections between stakeholders and demands. A mind map is useful for displaying schemes and connections Right: A report is suitable for in-depth information

For a high-rise design tool, one of the problems with these two approaches is that they are not directly connected to the current design and there is no two-way communication between user and tool. To be able to explore many different designs the feedback loop, visualized in Figure 42, needs to be as quick as possible. This means that the feedback given should be immediate and easy to comprehend. It needs to be directly related to the design in question.

These requirements led to the choice of creating a computational tool within a 3D-modelling program. The design task of creating a high-rise fits well with a parametric model with parameters such as height, building shape and floor height. High-rise buildings have a relatively limited design space because of their height and the challenges it entails. Therefore, the number of design parameters are limited which means that a high-rise design tool can be relatively simple and specialized.

6.3 Design Tool Description

The design tool consists of three main instances: user input, data processing, and display of results, see the schematic overview in Figure 43. The user has several options to choose from in the design of the high-rise. A 3D-model of the current design is always shown in a separate window. When any input value is changed, the data processing is triggered and the new analysis results are displayed almost immediately. Some analyses are slightly heavier computationally and take longer to run. These analyses can be turned on when needed.

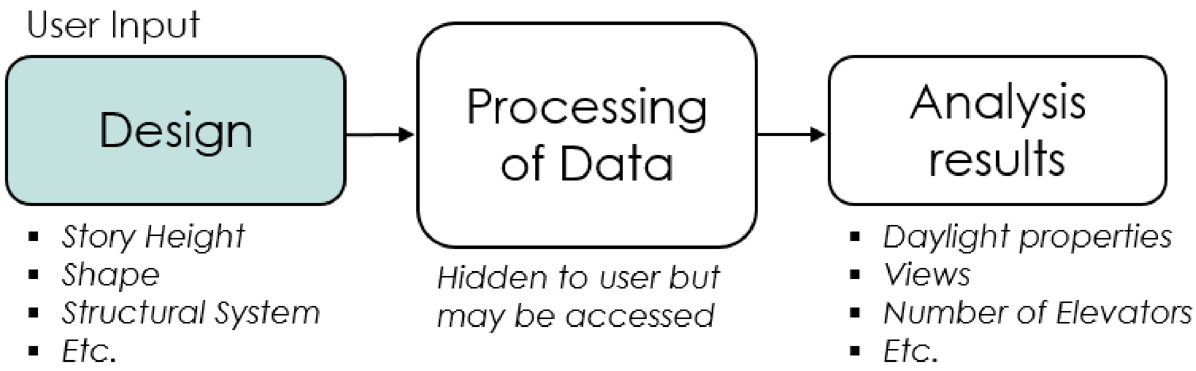


Figure 43 Schematic view of the way the design tool functions. The user inputs the design, which is processed, and the analysis results are displayed to the user

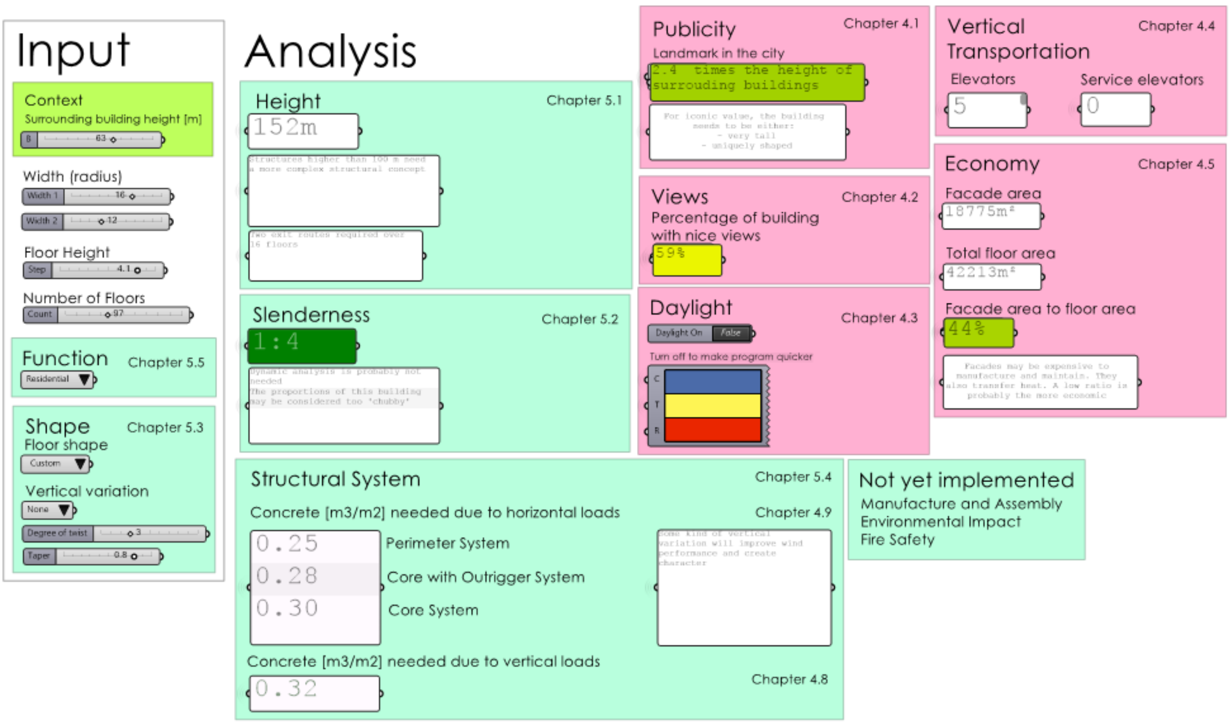


Figure 44 Design tool user interface. Design parameters users can change are in the input box. Some of the feedback is displayed in the analysis on the right, some in the model viewport.

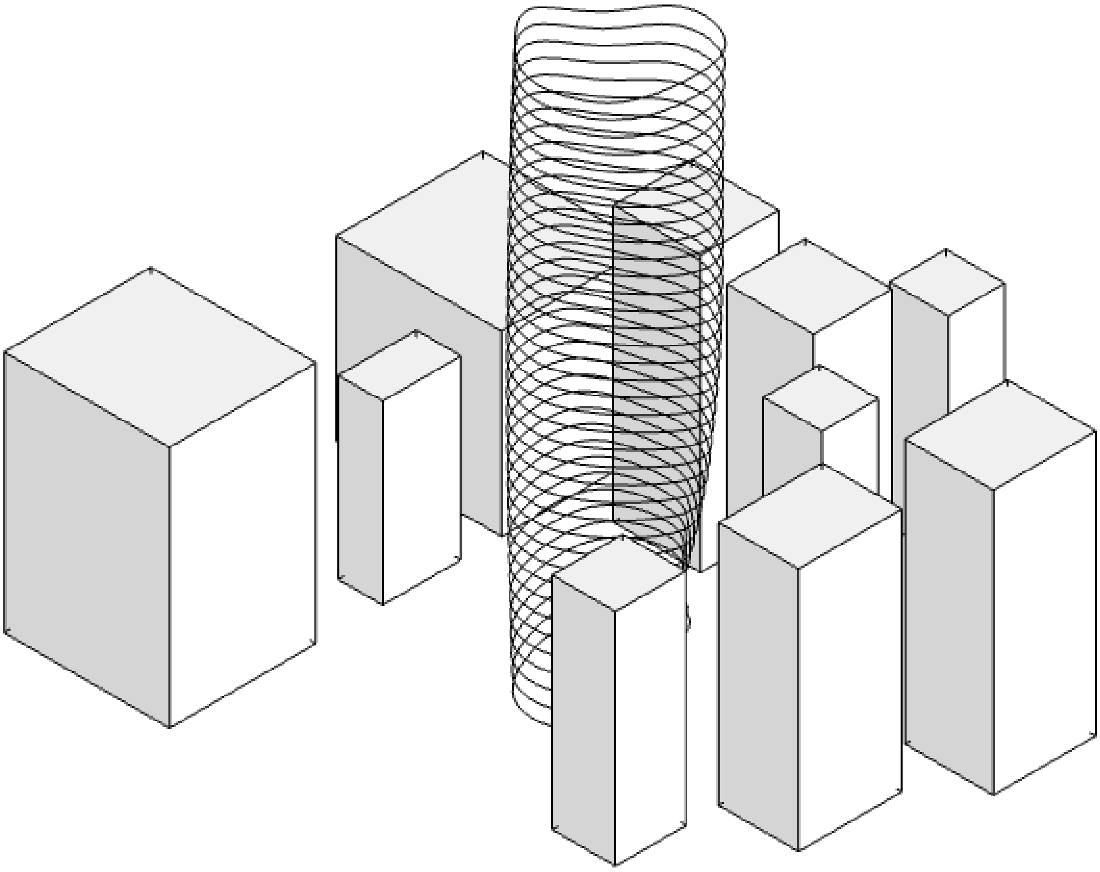


Figure 45 A 3D-model of the high-rise is shown simultaneously to the design tool user interface. In this picture the surrounding buildings have been modelled as well.

The design tool is created in Grasshopper 3D, which is a parametric design plug-in to 3D-modelling program Rhinoceros. The user can select and change parameters like story height, building shape and structural system and get direct feedback on what this means for the design. Graphics, colors, numbers and text are provided as feedback. Figure 44 and Figure 45 show the user interface and the generated 3D model of the building. There are references to this report in the different boxes of the design tool for more information on each topic.

The data processing in the design tool is hidden from the user, but can be accessed if needed. The processing is written in a combination of visual programming language Grasshopper and traditional programming language C#. Users can view, change and add to the code at any time they like. This enables the user to extend the design tool to include new features or information. There is also a possibility to extend the model and do structural analyses within the program, using existing plug-ins. Figure 46 shows the different parts of the data processing that can be found when zooming out from the user interface view.

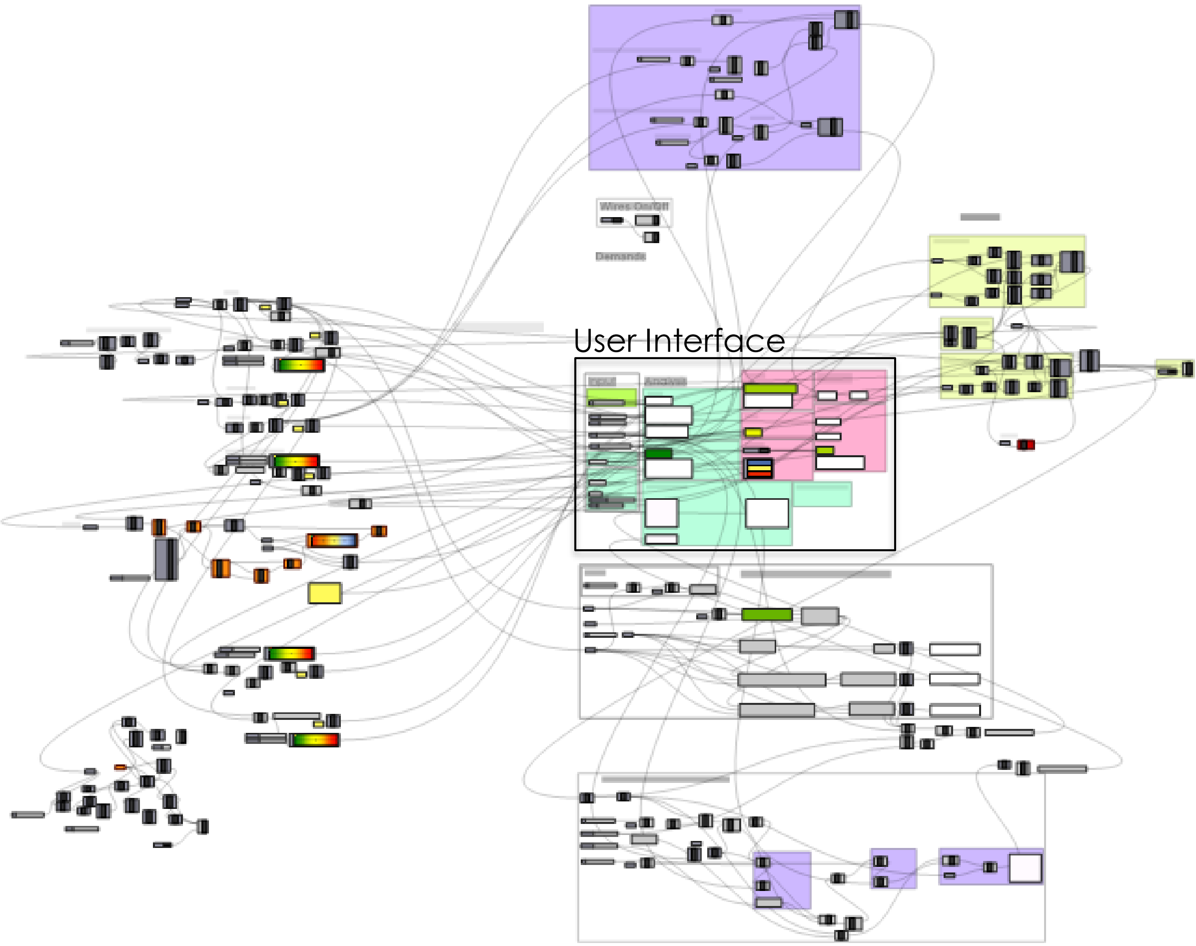


Figure 46 *The data processing is available to view, change or add to when needed, but is for ease of use hidden in the default mode of the design tool.*

Design parameters that are measurable and objective can easily be modelled appropriately. Parameters that are subjective or that have very complex connections, like economy, have in this instance been simplified to a few indicative values like area and material efficiency. With more time and information these parameters can of course be modelled more correctly. However, a limitation of this approach is that immeasurable parameters, like iconic value, are difficult to include. These rely on the judgement of the user.

A simple example of how the design tool modelling works is shown below in Figure 47. The user through a slider controls the width of the base of the building. When the value of this slider is changed, the slenderness of the building is recomputed and displayed in the panel on the right. As the slenderness becomes more critical, the color of the panel changes.

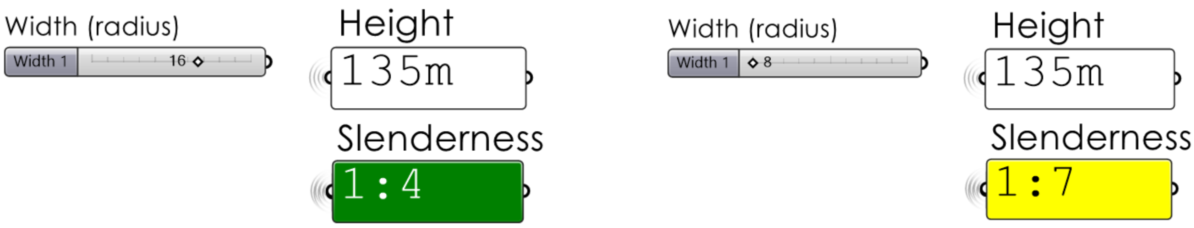


Figure 47 *Changing the value of the "width" slider changes the slenderness of the building.*

Message panels are used to convey messages when certain criteria are fulfilled. These act as information boards with tips or warnings to users. Below, in Figure 48, is an example where there is a message board connected to the slenderness value. Different messages are displayed depending on the slenderness value.

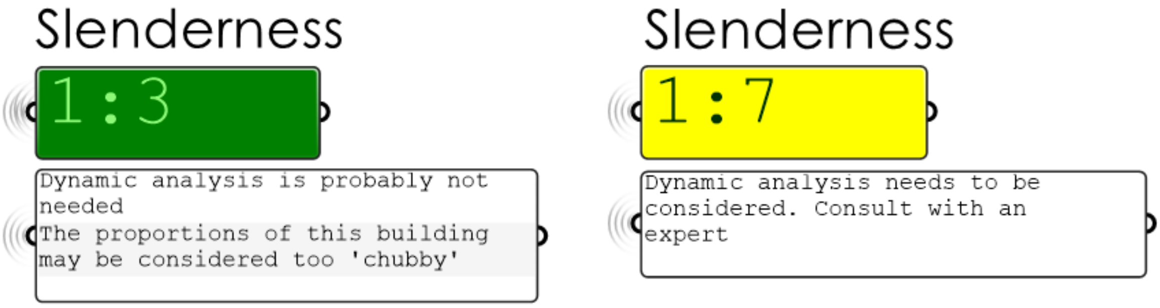


Figure 48 Messages related to slenderness are displayed depending on its value.

The 3D model space gives visual feedback. The building is represented very simply with lines to give an idea of proportions and silhouette. Figure 49 shows six different towers of the same height and their representation as a 3D model. Some analyses, such as how much daylight reaches different parts of the floors, are visualized in this display as well, see Figure 50.

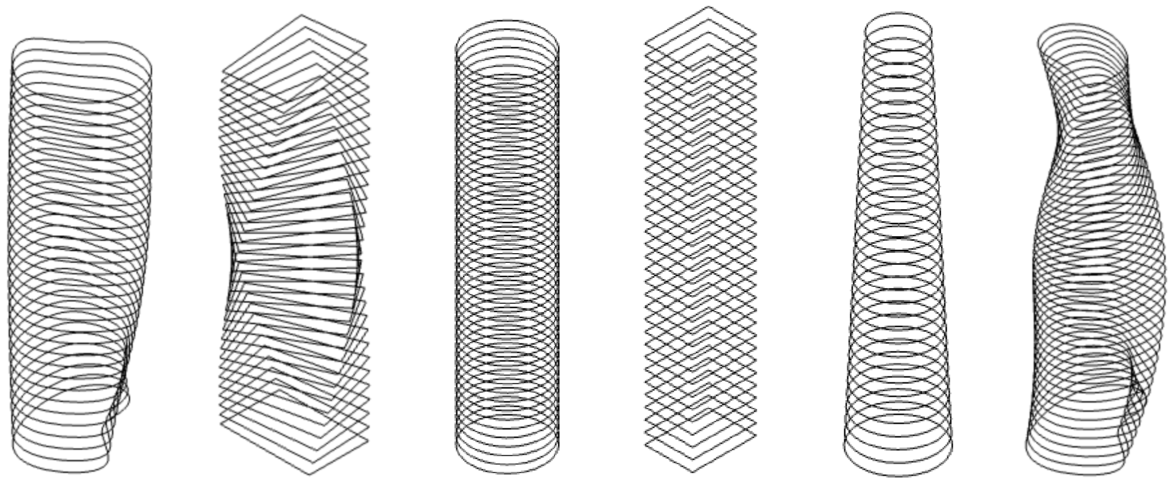


Figure 49 Changing the shape variables results in visually very different towers. They can be viewed from different angles in the 3D viewport.

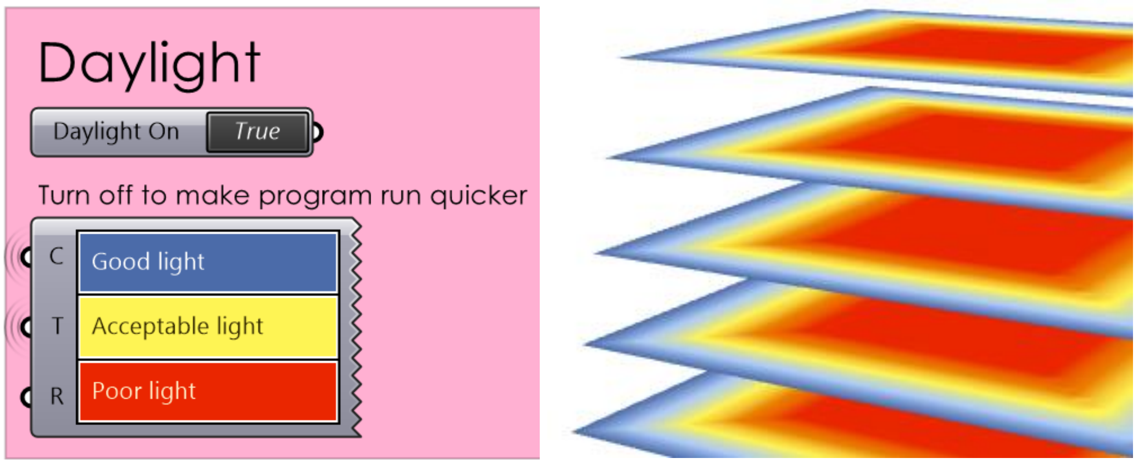


Figure 50 Simple daylight analysis showing how far into the building light can be expected to reach according to guidelines.

6.4 Design Tool Functions and Details

The data processing in the design tool analysis is written according to the information gathered in this report, with the guidelines and information from various sources being put into code. Many parts are relatively straight-forward to understand, while some are a bit more complex. Some more explanation on how parts of the analysis is done can be found below.

Structural Analysis

In this study, concrete is used as material for the columns and slabs. However, the analysis can easily be done for steel or any other material by changing the material properties in the program. The column cross section size is calculated using the load carrying capacity in compression of the material. Other failure modes such as buckling are not considered at this stage.

In this study the sizing of vertical members is done both for vertical and horizontal loads, separately. For horizontal loads, the allowed displacement is used to design the bracing system whereas for the vertical loads the columns are designed for the ultimate limit state. Vertical and horizontal loads need to be studied in combination to get the maximum possible loads. Note that the study in this project is designed to give indications on different properties of the building, not to get accurate sizing values.

The method used for calculating the building efficiency is described in chapter 4.9. Efficiency is here a measure of what volume of concrete needs to be used per square meter of floor area in the building. Figure 51 shows the efficiency section of the design tool user interface. For a given building layout, the efficiency is calculated for horizontal and vertical loads. For horizontal loads, three different structural systems are considered. The values given indicate whether the high-rise design is driven by vertical or horizontal loads. They also give an idea of the comparative efficiency between the three different structural systems. Figure 52, Figure 53 and Figure 54 show how the cross section of the three different systems have been modelled. More information about the beam model can be found in chapter 4.9. The full calculations can be accessed from the design tool if more information is needed.

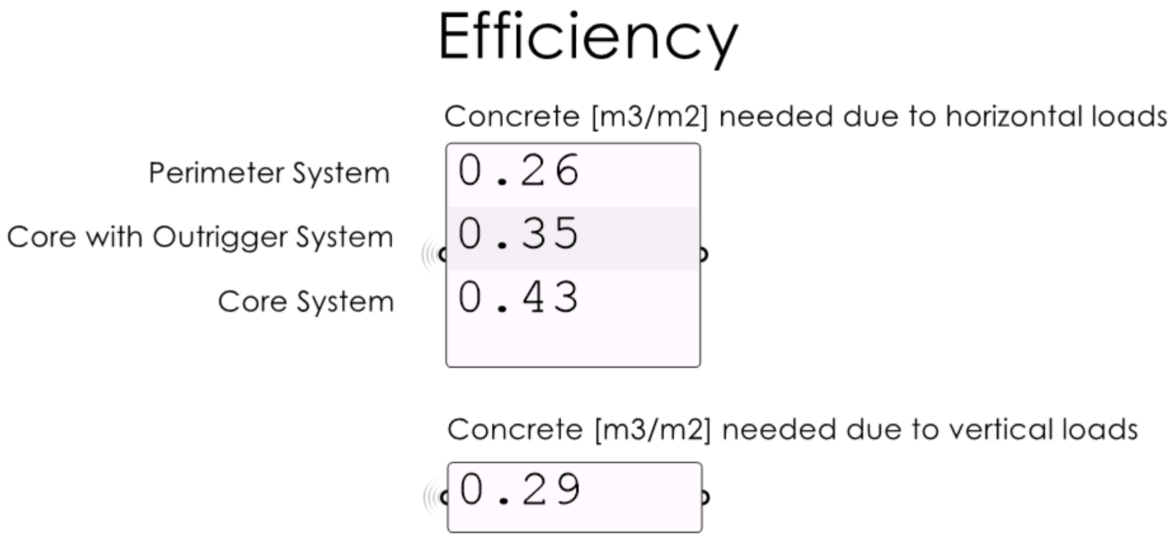


Figure 51 The efficiency ratio for different structural systems due to horizontal loads can be compared to the ratio needed for vertical loads. This gives an idea of what loads are more critical for the building.

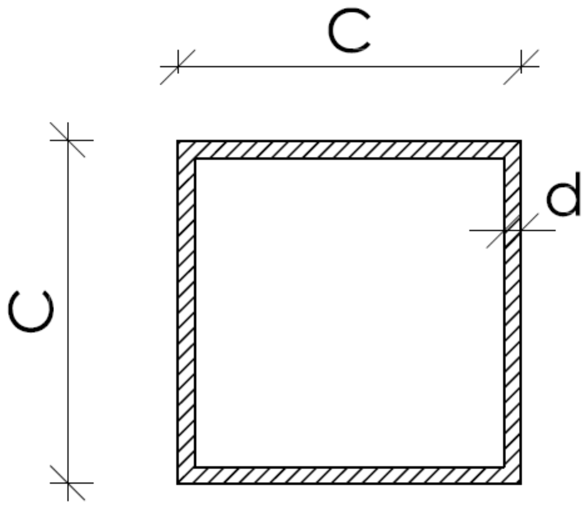


Figure 52 *Core system cross section. The size of the core, C, is set. Then the core wall width, d, is calculated to limit the deformation to a maximum of L/500.*

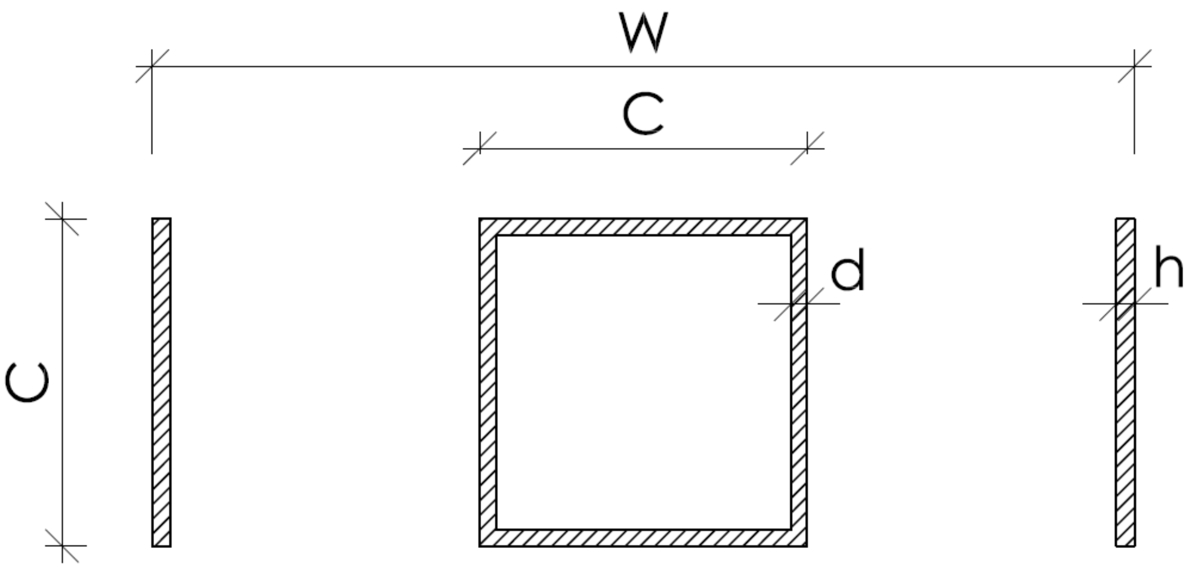


Figure 53 *Core with outrigger structural system, where outrigger columns are modelled as areas at each side of the core. The distribution of stiffness is set so that the outriggers and core each resist half of the wind-induced moment and the core width, C, and building width, W, are set. Then the core wall width, d, and column width, h, are calculated to achieve a maximum deformation of L/500.*

Figure 54 *Perimeter system. The building width, W, is set. Then the column width, h, is calculated to achieve a maximum deformation of L/500.*

Economy
To describe the building's economical potential, different values is used as indicators. The structural efficiency, as described above, indicates whether the structural system will be expensive or not. The façade area of the building is measured and compared to the floor area to give an indication of the relative façade costs. The number of elevators needed can give an idea of area efficiency. More indicators, like building repeatability and shape, can be implemented with more time.

Views
In the design tool this rough estimate is used, where the user inputs average height of surrounding buildings and the percentage of the floors situated above this height is calculated. This measure can also be used to get an idea of whether the building will function as a landmark, see chapter 4.1.

6.5 Reversing the Design Process

With the method in the design tool described previously, the user can change input variables and see what effect changes have on the output. Another way of viewing the design process is to set a desired outcome and have the program calculate what the input values should be to achieve this.

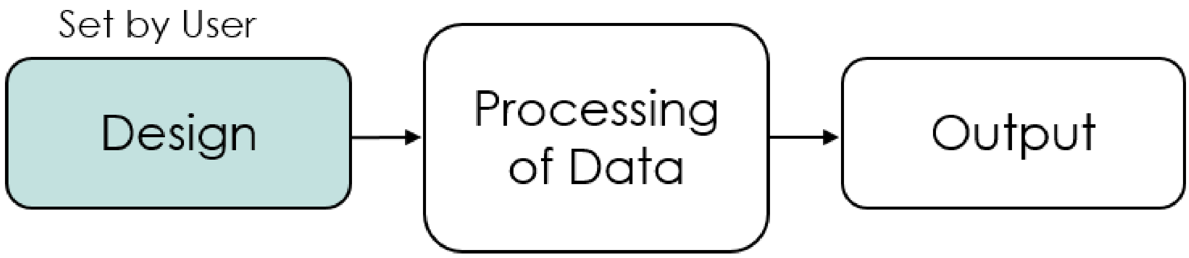


Figure 55 *Normal design process with the design being set by the user and the analysis carried out and displayed with each design change.*

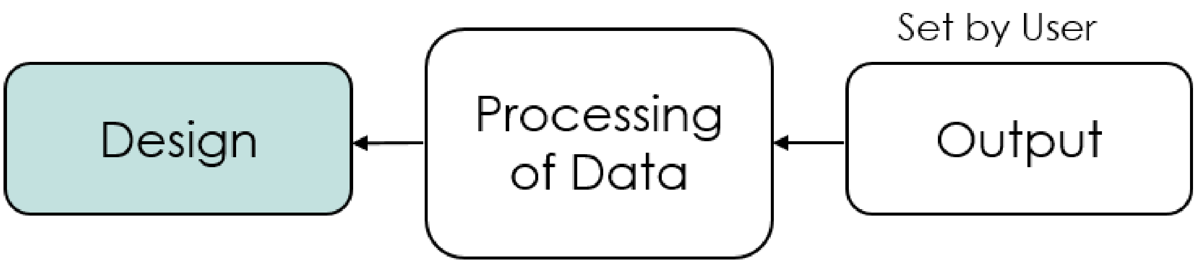


Figure 56 Reversed design process with the user specifying a desired outcome and the analysis being carried out in reverse to find what design option(s) is the best fit

This design logic can be applied to entire design or smaller problems. For example, in a core and outrigger structure, the optimal number of outriggers and their locations can be calculated using this method. There are several options on how to implement this design method. In this project, a genetic solver has been used to test the idea. The solver used is a part of the software Grasshopper which has been used to create the design tool. The genetic algorithm solver can therefore be used directly in the design tool, with only small modifications to the code.

Genetic algorithms will not be explained in this master's thesis, but the figures below show a couple of examples. Figure 57 shows an example of how the genetic algorithm solver in Grasshopper works. The objective of this optimization is to maximize views. The building width, the floor height and the number of floors are given to the solver as changeable parameters. The solver will, in time, find the configuration of these parameters that give the best views.

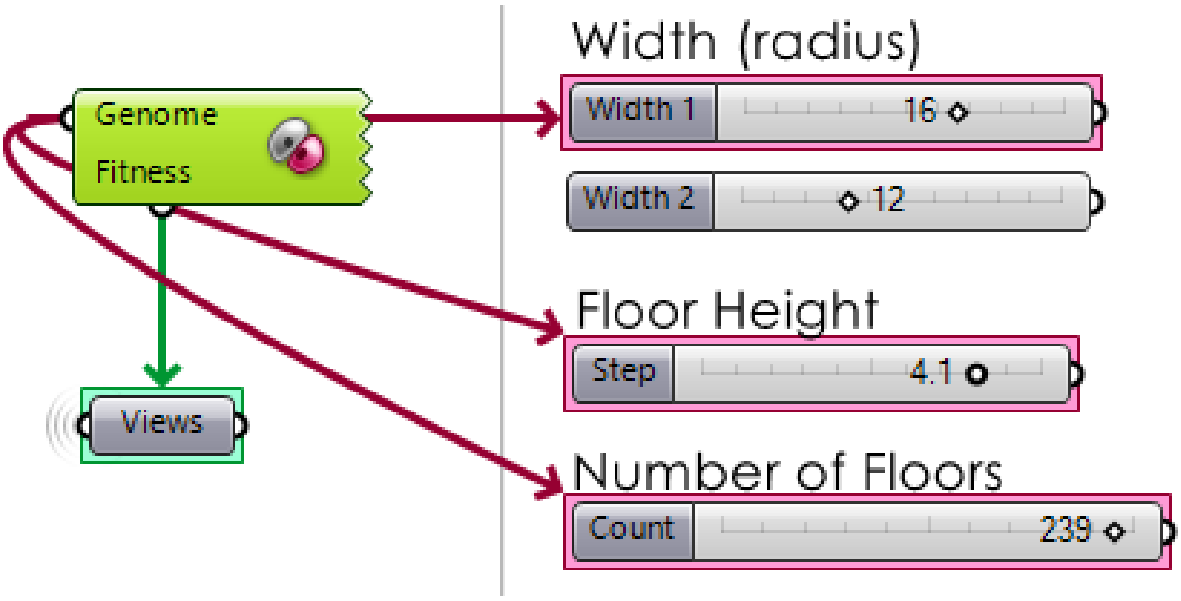


Figure 57 The Galapagos genetic solver can be connected directly to design parameters within the design tool script.

In Figure 58 the slenderness of the building is minimized using the same parameters.

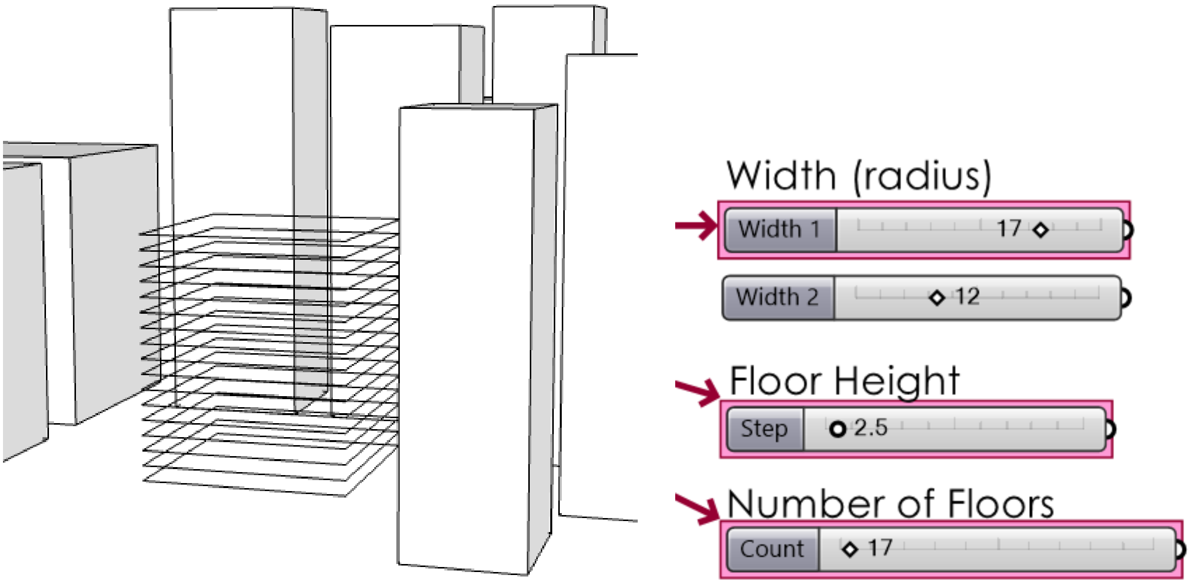


Figure 58 Minimizing slenderness with building width, floor height and number of floors as variables. The resulting building is shown on the left. The optimization was run for around one minute, a more accurate value is gained by running it longer.

In Figure 59 the same solver is used to find what story the outrigger should be placed on to minimize deflections in the structure. In this case a simplified 2D model was built and connected to an FE solver as well as Galapagos.

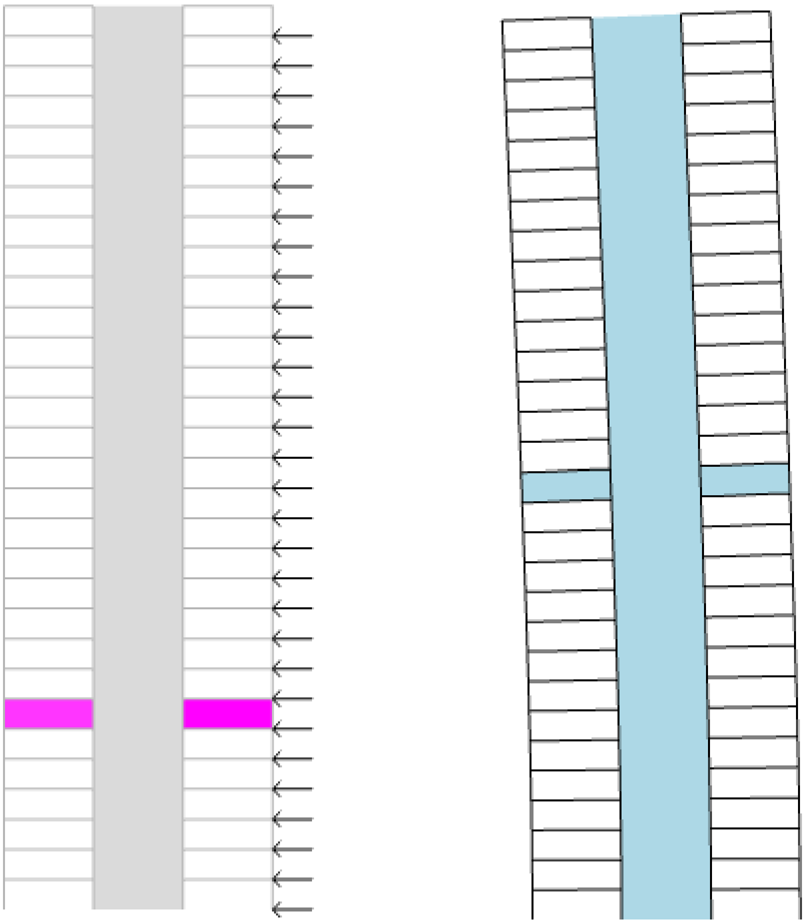


Figure 59 *A building with one outrigger is loaded with uniform horizontal loads. The genetic solver is set to find the story where the outrigger is most efficient, which in this case is halfway up the building.*

Using genetic solvers is not the most efficient time-wise when problems can be solved mathematically. Some problems are easily solved just thinking logically. However, when problems are complex and there is no apparent solution it is necessary to use a solver of some kind. This is often the case and especially if there are many variables. Optimising with several targets is also possible.

7 Case Study: The Karlatornet Gothenburg Tower

A case study has been done to test the ideas in this thesis on a real project. The Karlatornet Gothenburg project was selected to study, as it is a suitable project with information relatively easy to access. The project has been studied by doing interviews with many of the stakeholders involved in the project. The stakeholders, demands and design have been compared to the information gathered in earlier chapters of this report. The tower has also been modelled and tested in the design tool.

The Karlatornet Gothenburg tower is a high-rise building planned in Gothenburg, Sweden. It is planned to be completed by year 2021, which is Gothenburg's 400th anniversary. The project is initiated by Serneke and an architectural competition was conducted with SOM and Entasis as winners.

7.1 Context

The Karlatornet Gothenburg tower will be located in Gothenburg, which is the second largest city in Sweden. It will be built in an area called Lindholmen, which is a newly developed office area in on the north shore of Göta Älv. This area is an old industrial and port area with heritage from shipbuilding. As Gothenburg grows, the north shore of Göta Älv is being transformed from industrial to mixed-use city.

The area where Lindholmen is located, the large island Hisingen, is much less developed than the south shore of Göta Älv. House prices are generally lower on Hisingen and there are several areas with poor social and economic status. In recent years, however, many parts of Hisingen have been developed with new commercial centers and residential areas.

Lindholmen can be reached by ferry from the south shore. Even if it is a quite central part of Gothenburg it is difficult to reach for pedestrians and cyclists since there are no pedestrian bridges to the center. It is easy to reach by car or bus.

The building will be at least twice the height of the tallest building in Gothenburg today (Gothia Towers, 100 meters), and it will be visible from many places in the city. The building site is located on the flat Rivershore but there is a small mountain, Ramberget, close to the site.

Figure 60 Karlatornet Gothenburg

7.2 Stakeholders

It is quite apparent that the project has been initiated and strongly driven by the entrepreneurs, Serneke. Ola Serneke, CEO of Serneke, is the main initiator of the project. Serneke came up with a proposal of a high-rise on Lindholmen where the company owned a plot of land. The site was deemed unsuitable for a high-rise by the city planning office and so Serneke acquired another plot which the city planning office indicated might be more suitable. The city architect Siesjö believes that a high-rise in Gothenburg is a risky and difficult project to take on and is a project that requires personal will. That being said, the project is a great advertising possibility for the company and may very well be hugely profitable in the end. However, the margins in the project are small and Siesjö thinks that this riskiness would not have been acceptable to many entrepreneurs. (Siesjö, 2016). Ola Serneke claims that the cautious attitude many contractors have towards building tall is completely unnecessary. He mentions other high-rises that have been built on budget in other countries (Engström, 2014).

An international architectural competition was held as a requirement from the city planning office who wanted to make sure that the new high-rise would be of good architectural quality (Siesjö, 2016). Serneke states that holding a competition adds value for them as well, as it creates publicity and collects valuable opinions from people with experience in the area. SOM, or Skidmore, Owings & Merrill which is the full name, won the architectural competition for the Karlatornet Gothenburg tower together with Danish architects Entasis. SOM are a Chicago-based company with large experience in high-rise buildings and an international reputation. Ola Serneke, CEO of Serneke, says in an interview 2014 that it feels safe to work with SOM thanks to their extensive experience in high-rise buildings (Engström, 2014).

The city planning office of Gothenburg has traditionally been very hesitant towards allowing tall buildings in the city. Professor Claes Caldenby, who is strongly opposed to high-rises in Gothenburg, means that it is the entrepreneurs that are the strong parties in negotiations, whereas the city planning office takes a passive role in what is being built. Caldenby calls for a policy on high-rise buildings that can be used when proposals are made (Caldenby, 2016). Siesjö thinks that there are some places in the city where a high-rise can add value. He believes that a high-rise can give iconic value and belief in the future (Siesjö, 2016).

The tower is planned as a residential building. The future residents are expected to come from the immediate area as well as other Swedish cities and even from abroad (Petzell, 2016). Interviews with people interested in buying an apartment show that people are attracted by the uniqueness of the project. Figure 61 show some comments from a survey among people who expressed an interest in the tower. The comments are answers to why they are interested in living in Karlatornet Gothenburg.

The area where the Karlatornet Gothenburg tower is being planned is close to many businesses and industries as well as some residential areas. The Chalmers University campus and its science park are close neighbors and other parts of Hisingen have a lot of businesses and industries. To them it is very likely a positive thing for the area to get more publicity and become a closely integrated part of the city. If a high-rise has the ability to contribute to this, they are likely to welcome it.

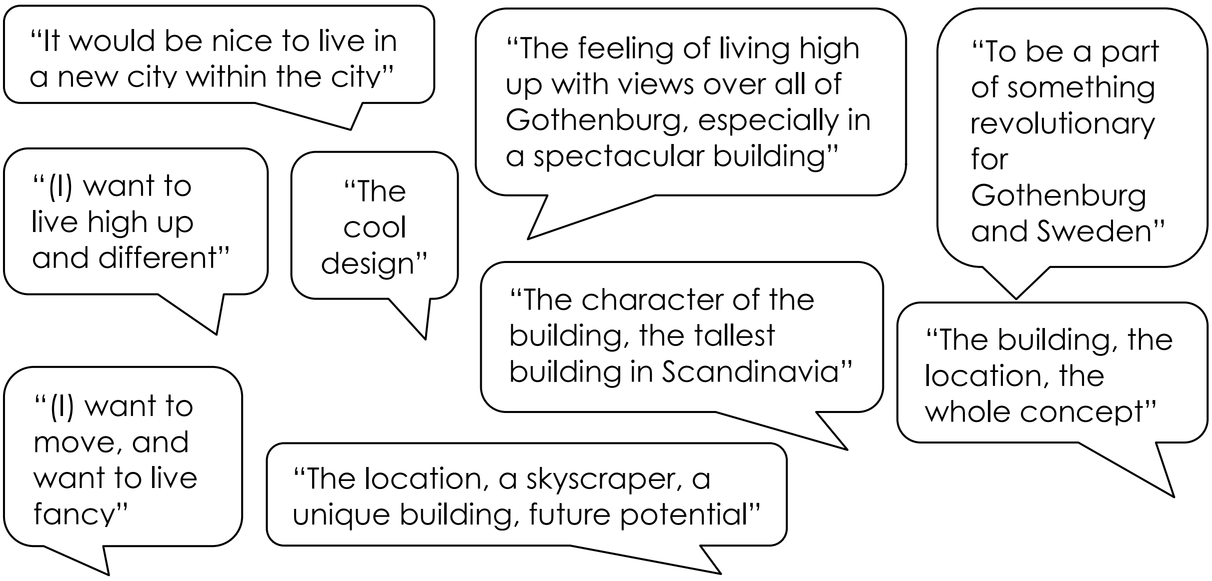


Figure 61 *Comments on why the Karlatornet Gothenburg tower is interesting to live in, taken from an enquiry conducted by Serneke*

7.3 Demands

One of the most important demands for the client is publicity, which is achieved through the iconic value of the project. Economy is, of course, also important to the client. However, the publicity and reputation created from this type of iconic project may be more important than the profits from the project itself. In Sweden land prices are not high enough to make it economically preferable to build tall.

Views is probably the most important demand from residents, but the iconic value of the project is important for residents as well, as can be seen from the comments in Figure 61. Balconies are considered very important by more than half of the people in the enquiry.

Figure 62 *One of the most important demands and best selling points is great views from the building. Picture: Serneke*

The city planning office is mostly concerned with how the building relates to its context. To them it is also important that the building is interesting and beautiful enough to be allowed to rise high above all other buildings.

The citizens of Gothenburg have divided opinions on the tower. Some believe that it should not be allowed at all and that the building will ruin the cultural landscape of the old port. Others welcome a change in the area. However, Siesjö believes that once a high-rise is built in Gothenburg the reactions will be almost only positive, under the condition that it is placed and designed well (Siesjö, 2016). Most citizens are not much affected by the new building but neighbors can be affected by change in house prices, as discussed in chapter 3.7.

Figure 63 View of the tower from the Gothenburg city center. Picture: Serneke

Getting a good economy in the project is difficult. There have been many changes throughout the process and project developer Anna Tirén at Serneke states that every square centimeter of sellable area counts (Tirén, 2016). There are many unknowns in a project of this size and it is a technically difficult project where new ideas are needed to solve problems. This makes it very difficult to estimate costs and to some extent, it is guesswork (Tirén, 2016). There are estimations on how many apartments need to be sold before construction starts, around 70% of the total value (Petzell, 2016).

Features like elevator access seem to be pressed hard due to economy. The standard likely to be reached is “acceptable” rather than “good” or “excellent” (Scott, 2016). This is something residents will notice only when they have moved in and it will probably not have an impact when selling the apartments.

The building will be cast on site. One of the major advantages is that the crane will not need to lift prefabricated concrete elements in place. This saves a lot of time in tall building construction. Serneke, who are the contractors as well as the clients for the tower have had influence in this decision, as well as VBK and SOM.

The maximum allowed deflection at the top of the building has been set to L/500 value and acceleration values have been recommended by the wind consultant.

Environmental impact has been considered to some extent but sustainability has not been used as a driving force in the design. Different certification systems have been discussed and it has quite recently been decided to use a system for certifying the area around the high-rise. However, for the tower itself no system has been used yet and it seems as though it will be difficult to fulfil some of the points for the "Miljöbyggnad" system which has been considered (Tirén, 2016).

7.4 Design and Design Tool Comparison

The height for the competition was set as "above 200 m" and the proposals came in between just over 200 m and 231 m. The height was set to make the building the tallest in Scandinavia. After SOM and Entasis were awarded the project, they changed their proposal to a building with a height of 266 m. That height is not final however, and there are indications that the tower will be shortened to its original height to save money.

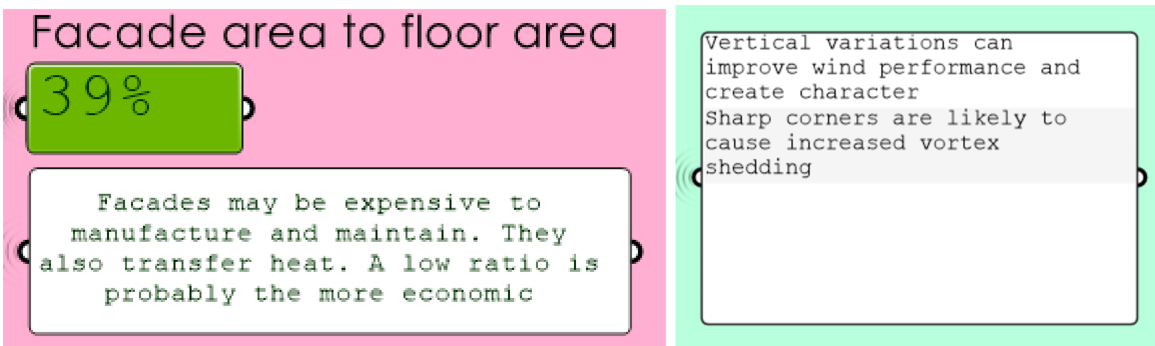


Figure 64 Design tool output concerning the shape and layout of the building

The shape is square, with sharp corners. At one point along the building, there is a twist that gives the building a "waist". The twist is positioned at about 2/3 of the building height. The height and position of this twist has been iterated to optimize building aesthetics, according to the architect. The twist was believed to have positive effects for wind performance, but the wind tunnel test showed these positive effects to be limited. If the twist had been placed higher or on a larger part of the building the improvement might have been bigger. The sharp corners of the building induced problematic vortex shedding.

The square shape of the building is relatively area efficient. The floor area is large compared to the façade area, for a residential building. As can be seen in Figure 65, the daylight reaches most of the apartment floor area. The inner part of the tower, which does not have enough daylight to be used as living space, is used for vertical transportation, corridors and bathrooms.

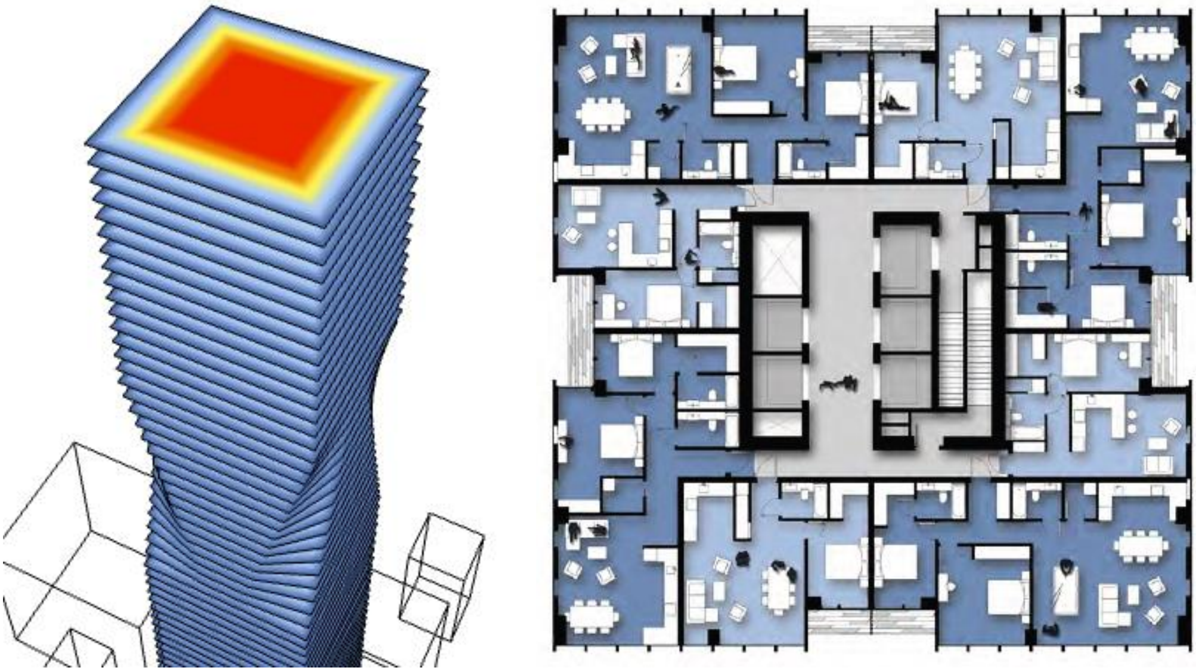


Figure 65 *Left: Daylight analysis of the floor shape Right: Typical floor plans for medium sized apartments. Picture: Serneke*

Most of the apartments in the building will have great views, since buildings and topography around the site are much lower than Karlatornet Gothenburg. It has good chances of getting a lot of publicity since it is much higher than surrounding buildings. The shape is moderately unique, it is not the simplest shape but variations on the theme have been seen before. Compared to Turning Torso in Malmö, this building is much more rational and less sculptural. This is an advantage from an economical viewpoint but the building may not be special enough to attract international attention the way Turning Torso has.

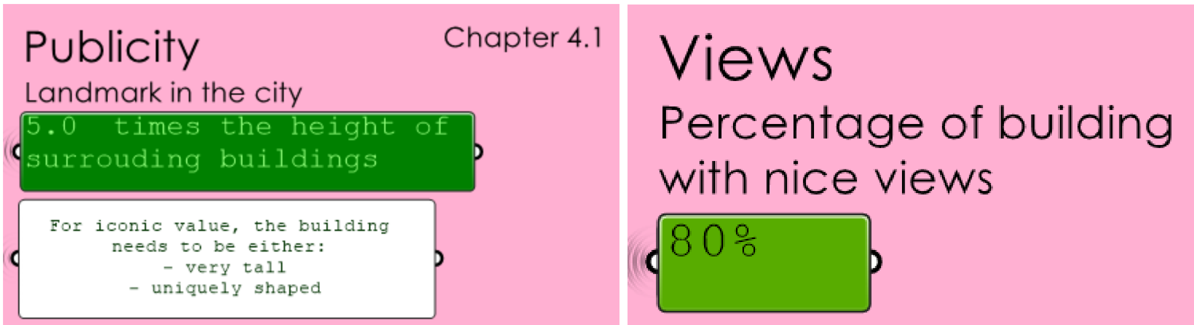


Figure 66 *Design tool output for views and publicity*

There have been changes and adaptions of the building throughout the process to achieve better economy in the project. The shape of the twisting section has been changed to get more floor area and the height has been reduced to save money. There are now indications that the building will have another type of twist that protrudes out from the building in order to get a larger floor area and thereby improving the economy in the project.

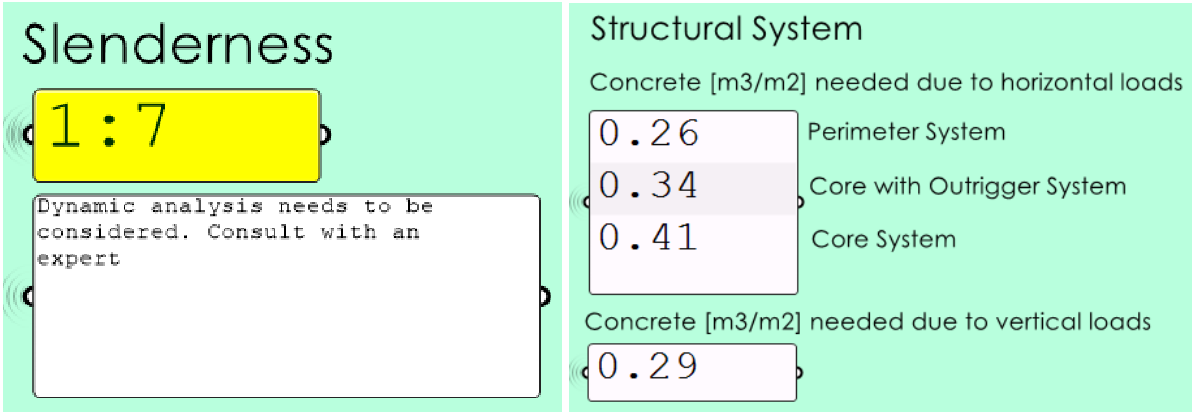


Figure 67 Design tool output for slenderness and structural system

The floor shape of the building is square with sides of approximately 31 meters. This means a slenderness ratio of between around 1:7 and 1:9. The building is relatively slender and dynamic analysis and wind tunnel tests are needed. This has been done in the design process and the input from testing has been very valuable. The initial wind tunnel tests showed problems with the design and adaptions have had to be made.

The structural system is a central core system with two outriggers. One outrigger is located near the top of the tower and the other somewhere around floor 10-12. Each outrigger comprises of a concrete belt wall connected with outrigger walls to the core and spans two stories in height. These stories will be used for mechanical equipment. This set-up with two outriggers was chosen as it saved floor space. Originally, three outriggers were designed but with a lower height only two are needed. The top outrigger is more important for minimizing deflections while the lower one decreases tension forces in the structure. The entire structure with core, columns and floor slabs will be concrete cast in site. Concrete is cheap and has good stiffness, even if columns tend to be quite large and heavy. The floor slabs will be post-tensioned in order to decrease slab height, as they span around 8 meters. As can be seen in Figure 67, the perimeter system would give a considerably more structurally efficient building. However, the core with outrigger system has many advantages and is possible for this building. Only using a core for stability would be very inefficient.

The function of the building is mainly residential, but with a hotel located in the bottom part of the tower and a public viewing deck near the top. There is a mix of apartment sizes, with smaller apartments in the lower part of the tower and bigger at the top. The top apartments will cost around 30 million SEK and the cheapest apartments will cost around 50 000 SEK/m^2 (Engström, 2014). The hotel may be moved to the adjacent building.

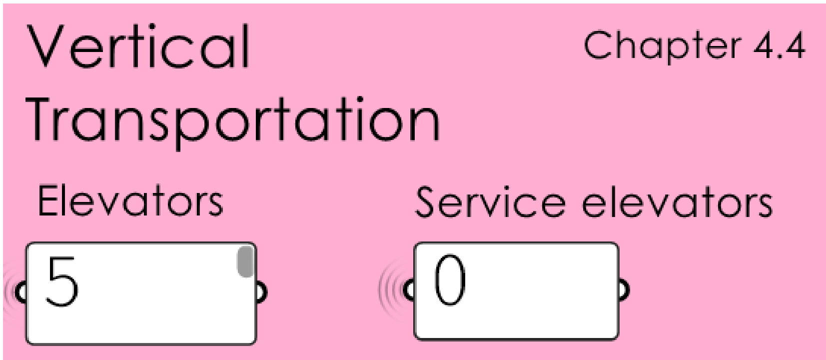


Figure 68 Design tool output for vertical transportation.

The building will have five elevators. The design tool recommends five or more elevators and considering that this building has a public viewing platform at the top which will require higher elevator capacity a higher number might have been chosen. Analyses by the vertical transportation consultants show that the building is not likely to reach a standard better than "acceptable". Of course, adding more elevators would be expensive.

8 Results

The objectives of this thesis were:

- Establish what the most important stakeholders, demands, design aspects and design choices are in a high-rise project
- Find out how stakeholders, demands, design aspects and design choices are interrelated
- Display this information in a useful and intuitive way through a design tool

The results are:

Establish what the most important stakeholders, demands, design aspects and design choices are in a high-rise project
The findings from the literature review and interviews were one of the major results in this study. Many different opinions and perspectives on high-rises were gathered and a better understanding of high-rise design was gained. The findings are exhibited and explained in chapters 3, 4 and 5. For example, publicity was found to be a very strong demand for most stakeholders and structural stability seems to be the most challenging technical demand.

Find out how stakeholders, demands, design aspects and design choices are interrelated
Interrelations between stakeholders, demands and design were found throughout the project process. Some were found already in the literature review and interviews while some where found when creating the design tool. More interrelations were found when testing and using the design tool. Some of the connections are of a more direct nature while some where found to be quite complex.
Examples of interrelations are:

- Designing traditional and efficient floor plans desired by residents and clients often result in a building with less than optimal stability properties
- A high slenderness value means that the daylight properties improve while the structural efficiency decreases

More examples can be found in chapters 3, 4 and 5 and links can be explored with the design tool.

Display this information in a useful and intuitive way through a design tool
A design tool was created and tested and applied through a case study of the Karlatornet Gothenburg Tower in Gothenburg. The concept seems promising.

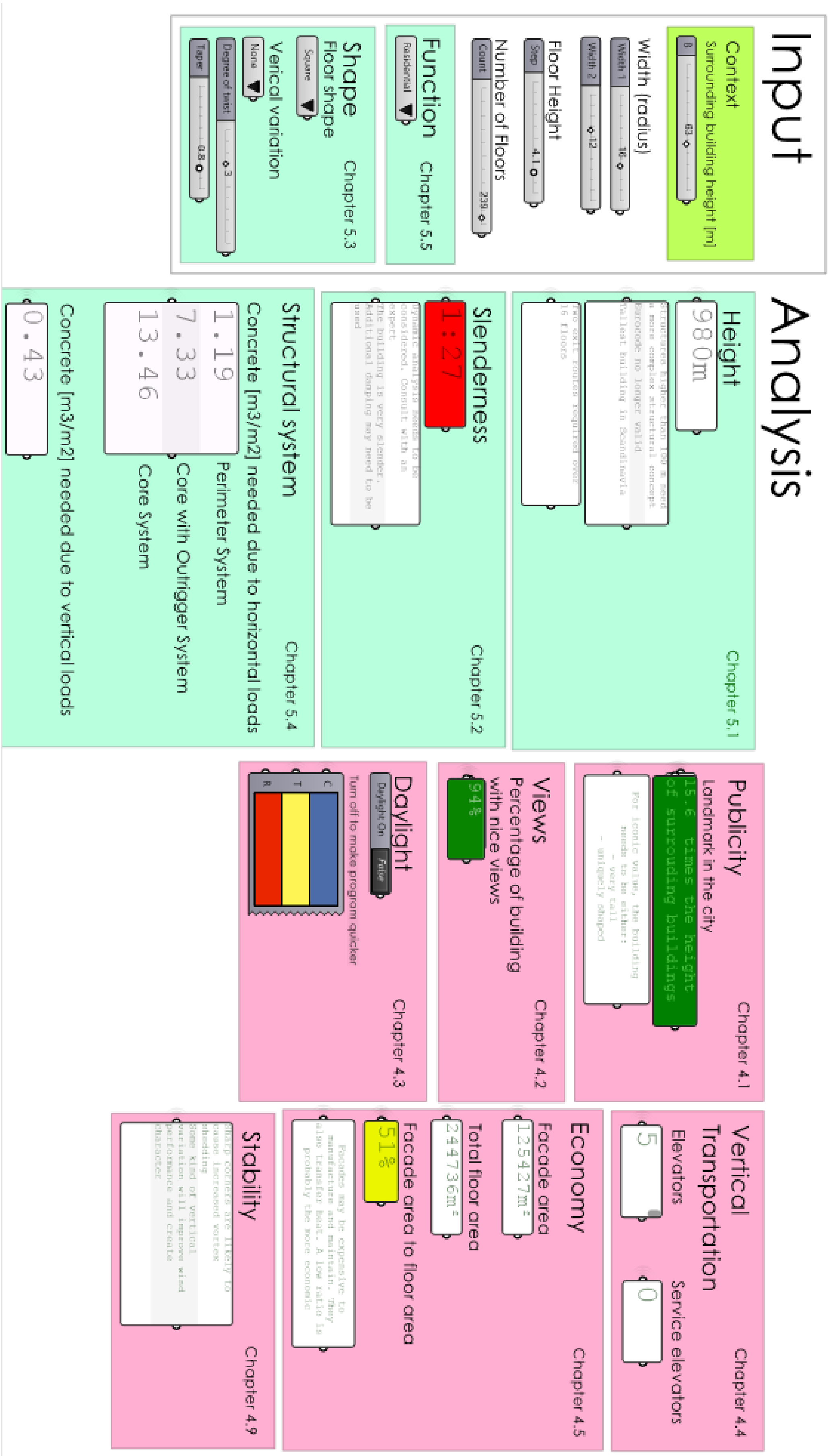


Figure 69 Design tool interface

9 Discussion

Establishing information
Defining the most important stakeholders in a project is relatively straightforward. The stakeholders treated in this thesis were all found to be of value to study, even if a few more could have been treated to give a more comprehensive result. However, the time limitations in this study made the choice suitable.

It is much more difficult to treat demands. First of all, there are hundreds of different demands from different stakeholders. Some are implicit and though never spoken, very important to fulfill. Stakeholders are not always clear when expressing demands and one has to read between the lines to really understand what they mean. Because stakeholders have their own interests to think about, it is also a possibility that they exaggerate or leave out certain information. It would have been very interesting to study the official and unofficial politics of this type of project more closely. This would have given a better understanding of how different demands are prioritized.

One of the most difficult issues in this study was how to treat the demands that need to be fulfilled and those that are preferable to fulfill but not completely necessary. For example, residents may think vertical transportation is very important but they don't think to mention it because they take it for granted that it should be fulfilled to a good standard. In contrast, they put a lot of emphasis on balconies, which they would like but that they know cannot be taken for granted. It is also interesting to consider that some of the demands which stakeholders think are really important beforehand might not be as crucial as they imagine. In the Karlatornet Gothenburg tower investigations, it was found that residents with previous experience of living in high-rises are not as concerned with balconies as those who have no experience of high-rise living. This may be due to the fact that the former are aware of the often windy and unpleasant climate on a high-rise balcony.

Because some demands have to be fulfilled anyway, they may be slightly overlooked in the design concept. In this study, both compulsory and voluntary demands are considered. It is arguable whether they should have been divided and treated separately.

Regarding the design, the design space for a high-rise tower is relatively small because of the height. This means that some of the design aspects are well known and can be predicted to a good degree of accuracy. For example the number of elevators needed can be relatively well predicted. Other aspects are not as predictable and will vary a lot from project to project, for example economy and structural stability. Detailed technical information is difficult to acquire in the early design stages. Experience is needed to assess each specific situation and while some design aspects are common to every high-rise project, some are unique. One of the main difficulties in this study has been to draw the line between being detailed enough to be useful while still being general for all high-rise projects.

Making connections
Stakeholders, demands and design in a high-rise project are related in a complex and intricate manner. They affect each other to different extent but almost all design choices affect several demands and stakeholders. Because of the complexity of high-rise projects, it is difficult to predict how exactly each demand is affected. It varies on so many variables it is difficult to

give general guidelines. Some relations are relatively simple and easy to understand and guidelines can however be given to give a basic understanding and overview. These are discussed in previous chapters and displayed in the design tool.

One of the major benefits of a study like this is to understand that other demands and stakeholders are affected by ones choices, even if it is unclear exactly how. This enables decision makers to see who they need to consult before making design changes or decisions.

It also gives a good idea of the design space and what demands contradict each other and which ones work together. A greater understanding of the building as a whole benefits each stakeholder as they will be more willing to and able to make balanced decisions.

Displaying information

The design tool can be used for two main purposes. First of all as an introduction and a general overview of high-rises and how different demands and design aspects interrelate. Secondly, the design tool can be used as a sort of project management tool to help parties in the project to communicate. Each designer could even build and adapt their own part of the tool for the specific conditions. Ideally, it should be possible to connect the design tool to some kind of data base so that its contents can be updated automatically. The idea is a bit similar to BIM but for early stages and not detailed design.

The design tool created in this project can be seen as a prototype and proof of concept. Not all information is incorporated as it is very time-consuming to gather information and put it into the design tool. The design tool format also has room for improvement. It is relatively comprehensive but requires specific software to use and to understand the data processing one must be familiar with visual programming. It would have been better with a design tool that has the report embedded somehow and that is stand-alone (now it is dependent on a rhino license). However, the idea of achieving direct feedback on a 3D design has proven efficient, and the idea of this type of design tool seems very promising, since complex information really proved possible to display in a comprehensive manner.

The design tool needs to be developed to have more visual feedback and less text and numbers, which are more difficult to read. Understanding the results from the design tool requires some knowledge at this stage, should be made more intuitive. The design tool can easily become quite heavy to run and requires computational power. There are several ways of dealing with this. The aim is to keep the analyses functioning in real time, and this has been managed so far. In this study, more heavy analyses are switched off during design alterations and turned on when needed.

Future Studies

How to create a comprehensive user interface for a design tool is something that needs to be studied. This is a separate issue from high-rises and could be done for all building or even design projects.

Case Study

SOM are experienced high-rise designers and have a lot of expertise available. However, in their early design process it seems as though architects and structural engineers have worked quite separately from each other. Architects have come up with proposals, which the engineers then solve structurally.

For example, the position and shape of the twist was most likely decided from an aesthetical viewpoint by the architects. Perhaps it could have been iterated to give the building better wind performance as well, if wind tunnel tests had been part of the earlier design process. That would have given the twist, which creates some complications in the building layout and extra expenses a better raison d'être.

The buildings on first and second place in the competition were both square towers with a vertical variation at around 2/3 of the tower height. While Filip Rem at Wingårdhs (Rem, 2010) speaks of creating a variation that gives maximum impact with minimum complications, SOM architects speak of a "ribbon in the sea breeze" when explaining their twisting design.

It is difficult to draw conclusions on the design tool from only one case study. Ideally, more case studies should be conducted to verify the design tool results through studying completed buildings. However, since most of the information in the design tool comes from sources with a lot of experience on each respective area, the information is to some extent already verified.

The design tool can predict technical aspects, like number of elevators and daylight properties quite well. With more additions more complex demands like economy and environmental impact can be predicted relatively accurately as well. The most difficult part is to consider aspects like iconic and aesthetical value through a computational design tool. From the case study, these demands seem to have been some of the most important in the project.

Because it is subjective, it makes it even more difficult to put "aesthetics" as a demand. It is closely related to architectural quality. But since so many of the stakeholders talk about is as very important it should somehow be an official demands.

10 Conclusion

From the information gathered and the design tool it can be concluded that from most viewpoints a tall building is not efficient. Publicity and iconic value are really the most important driving forces behind building tall. The reputation of the architect can be of great importance when publicity and iconic value are prioritized demands. A well-known name will inevitably create publicity and if international recognition is sought after an internationally known architect is valuable. In combination with the expertise needed it means that well established high-rise companies can do well.

Improving communication between different stakeholders is probably one of the most important uses for a design tool. It is much easier to communicate efficiently about complex issues with a visualization at hand. The design tool can also help stakeholders with who should be consulted about a certain design issue. The stakeholders most likely to use this tool at an early stage are the client and the architect.

While BIM is a great communication tool for the final stages of design, it is much too slow and clumsy to use in the early phases, when exploring the design space and coming up with a concept. A simple 3D model and tool available to everyone in the project could greatly improve understanding between stakeholders and efficiency in communication. A 3D model should be an aid in improving the design, not just something created at the very end. We should be using the tools available to us to their potential.

While this study was originally about high-rises, the same type of design process can be applied to other types of buildings as well. There is potential in linking together different types of analysis software and having a simple model that can be developed into a BIM model as the project progresses. It would also enable working with several different design options in parallel, which would be made possible if exploring an option was less time-consuming. This type of thinking of course has a lot to do with software development, but it is even more important to consider how we really would like to work. Instead of adapting to the tools and design process available to us, we should request the tools that we need in order to be able to work with a process that we believe in.

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11.2 Interviews and Presentations

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11.3 Figures

Figure 1 *Left:* "HOME INSURANCE BUILDING CHICAGO" (CC BY 2.0) by jasonwoodhead23 https://www.flickr.com/photos/woodhead/15305233828
Right: "John Hancock Center June 6 08 sunlight" By Golbez (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons https://commons.wikimedia.org/wiki/File:John_Hancock_Center_June_6_08_sunlight.jpg

Figure 2 *Left: "Turning Torso Malmo 20110519 0088F" (CC BY 2.0) by News Oresund https://www.flickr.com/photos/newsoresund/8199975684*
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Figure 5 Left: "Gherkin from the Sky Garden 2015" © User:Colin / Wikimedia Commons, via Wikimedia Commons
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Figure 8 "Downtown_Toronto_From_CN_Tower" By Sajeewashaluka (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
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Figure 9 Left: http://i.ytimg.com/vi/EutJCAJNBm0/maxresdefault.jpg

Figure 15 *(Stafford Smith & Coull, 1991), see literature references*

Figure 16 *Eurocode SS-EN 1991-1-4:2005*

Figure 19 *SOM*

Figure 20 *Formelsamling i hållfasthetslära, Magnus Ekh, Peter Hansbo och Jim Brouzoulis, Tillämpad mekanik, Chalmers*

Figure 25 *https://www.youtube.com/watch?v=cs_5QGEq-FU*

Figure 31 Left: "432_Park_Avenue_tower_under_construction_2015" By Steven Lek (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons
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Right: "Spiral Chimney" (CC BY 2.0) by Modern Relics
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Figure 34 Left: "Taipei 101, Taiwan, 20100607" (CC BY 2.0) by daymin
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Right: https://pixabay.com/sv/burj-khalifa-byggnad-dubai-city-1096446/

Figure 60 *Karlatornet Gothenburg, Serneke*

Figure 62 *Karlatornet Gothenburg, Serneke*

Figure 63 *Karlatornet Gothenburg, Serneke*

Figure 65 *Right: Karlatornet Gothenburg, Serneke*