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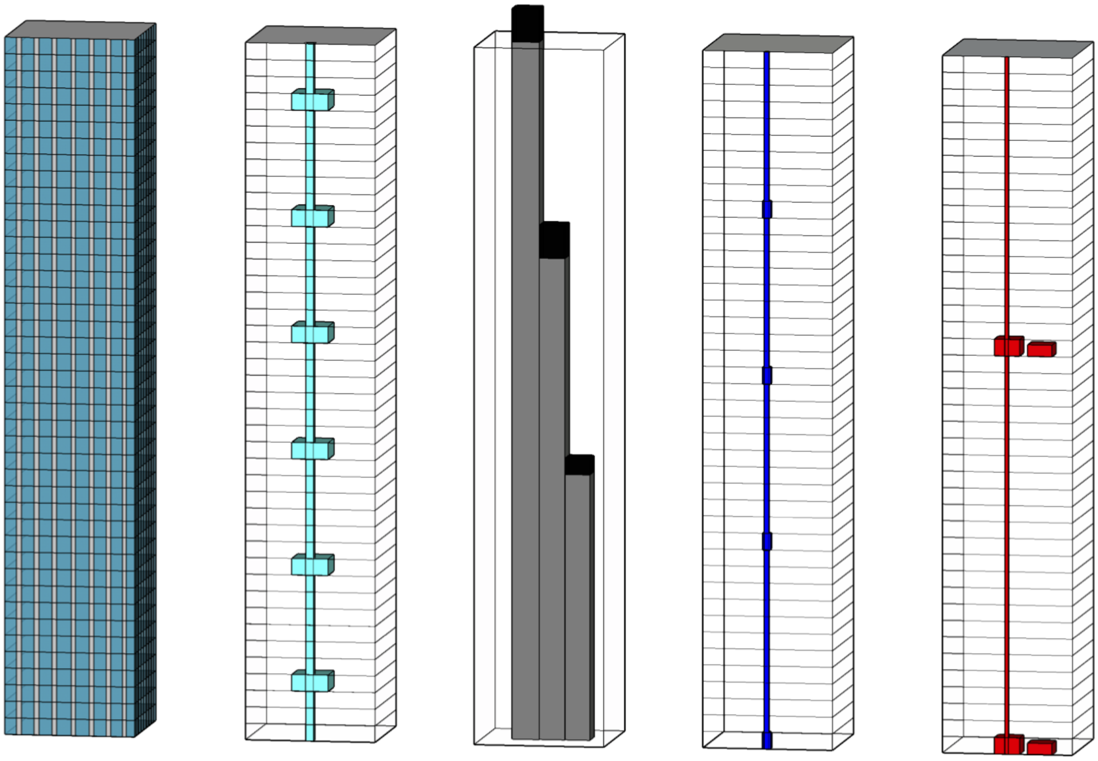

Space Efficiency of Technical Installations in Tall Office Buildings

An early stage analysis based on HVAC, elevators, water distribution and fire safety design

Master's thesis in Structural Engineering and Building Technology

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Master's Thesis ACEX30-19-38
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Cover: Visualization of a tall building with technical systems made in SketchUp.

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Abstract

Tall buildings are becoming more common in Sweden and the progress will require knowledge within the field. This thesis is aimed at an early stage analysis and investigates the technical systems for HVAC, elevators, water distribution and fire safety design in tall office buildings with focus on space efficiency and the distribution of the systems. The thesis is meant to illustrate the importance of design choices rather than to provide optimized solutions.

Information about relevant system choices was gathered through a literature study and by interviewing professionals within the field. A case study was performed where three fictitious buildings of increasing height were investigated. For each of the mentioned systems, a number of possible configurations were tested in all three buildings to investigate the effects of increasing height and design choices on the space efficiency and the distribution of the systems.

The results show that the space efficiencies of the studied systems are affected differently by the building height and that some design choices are more beneficial with respect to space efficiency. It was also evident that some of the systems have a greater potential of space saving than others. Additionally, it was seen that the distribution and sectioning vary between the systems depending on the requirements and prerequisites of each system.

While it is recognized that many aspects need to be taken into account in a building project, the results in this report is considered to have the potential of being a support in an early stage analysis of tall office buildings.

Keywords: Tall office buildings, high-rise, space efficiency, HVAC, water distribution, elevators, fire safety

Yteffektivitet hos tekniska installationer i höga kontorsbyggnader
En analys i tidigit skede baserad på VVS, hissar, vattendistribution och brandsäkerhet
HENRIC ERNTOFT
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Sammanfattning

Höga byggnader blir allt vanligare i Sverige och utvecklingen kommer att kräva kunskap inom området. Detta arbete riktar sig mot ett tidigt analysskede och undersöker de tekniska systemen för VVS, hissar, vattendistribution och brandsäkerhet i höga kontorsbyggnader med fokus på yteffektivitet och sektionering av systemen. Arbetet avser att illustrera vikten av designval snarare än att förse optimerade lösningar.

Information gällande relevanta systemval samlades genom en litteraturstudie samt intervjuer med yrkesverksamma inom området. En fallstudie genomfördes där tre fiktiva byggnader med ökande höjd undersöktes. För de nämnda systemen testades ett antal olika konfigurationer i de tre byggnaderna för att undersöka hur en ökad byggnadshöjd och designval påverkar yteffektiviten och sektioneringen av de tekniska systemen.

Resultaten visar att yteffektiviteten hos de undersökta systemen påverkas olika av den ökande byggnadshöjden och att vissa designval är mer fördelaktiga med avseende på yteffektivitet. Det var även tydligt att vissa system har en större potential för besparing av yta än andra. Vidare noterades att fördelningen och sektioneringen varierade mellan de olika systemen beroende på systemens krav och förutsättningar.

Samtidigt som det inses att många aspekter måste tas hänsyn till i ett byggprojekt så bedöms resultaten i denna rapport ha potential att vara en bidragande del i ett tidigt analysskede av höga kontorsbyggnader.

Nyckelord: Höga kontorsbyggnader, höghus, yteffektivitet, VVS, vattendistribution, hissar, brandsäkerhet

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Preface

This master's thesis investigates technical installations in tall office buildings and expresses these in terms of space efficiency and distribution within the building. The idea for the master's thesis was proposed to us by GICON Installationsledning AB and the study was conducted at their office from January to June, 2019.

First and foremost we would like express our gratitude to our supervisors. We thank Göran Andersson at GICON for sharing his expert knowledge with us and for all the valuable and interesting discussions that have advanced both the master's thesis and our understanding of buildings overall. We thank Jan Gustén at Chalmers for all the encouragement and guidance during the master's thesis work. In moments of doubt we always felt that we were back on track after our discussions.

Secondly, we would like to thank to our opponent, Inga Sierpinska, for the valuable input that a fresh pair of eyes can provide in combination with knowledge on the subject.

Lastly, we would like to thank the entire staff at GICON for their help and especially for making these months an enjoyable time.

Gothenburg, June 2019

HENRIC ERNTOFT
TOR LUNDBERG

Abbreviations

AHU - Air handling unit
BA - Building area
BBR - Boverket´s building regulations – mandatory provisions and general recommendations (Boverkets byggregler)
BBRAD - The Swedish National Board of Housing, Building and Planning's general recommendations on the analytical design of a building's fire protection (Boverkets byggregler analytisk dimensionering)
GEA - Gross external area
HVAC - Heating, ventilation and air conditioning
HWC - Hot water circulation
KPI - Key performance indicator
MER - Mechanical equipment room
MWC - Meter water column
NIA - Net internal area
NPP - Neutral pressure plane
OH - Ordinary hazard
PA - Premises area
PBF - Plan and building regulations (Plan- och byggförodningen)
PBL - Plan and building act (Plan- och bygglagen)
PPD - Percentage of people dissatisfied
PRV - Pressure reducing valve
SBF - The Swedish Fire Protection Association (Svenska Brandskyddsföreningen)
SFP - Specific fan power

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1 Introduction

The definition of a tall building varies depending on who is asked. It could be a specific number of floors or a height. It can also be that the height creates a need for certain solutions. In this report emphasis will be put on the latter. Some buildings will be referred to as high-rises, although the chosen term in most cases will be ”tall”. The definition is explained in Section 2.1.1.

Tall buildings differ from lower buildings in several aspects. To accommodate the needs of the occupants in a tall building there are several services that should be provided. Transportation up and down via elevators have to be solved in a way that ensures acceptable travel-time as well as not taking up too much space. The ventilation system in combination with heating and cooling equipment has to provide a pleasant indoor climate at the same time as it does not make to much noise or take up too much space. To provide water it has to be pumped from the bottom of the building. For a building of a couple of a hundred meters this will require pumping in steps. Another aspect that requires extra attention in tall buildings is the fire safety. Both extinguishing the fire and evacuating the building is more difficult. To provide functional and feasible solutions to these systems requires knowledge and cooperation between the different disciplines involved in a building project. The spaces needed for technical installations will be affected as a building gets taller and this will inevitably affect the economy of the project.

The results of this thesis is intended to provide information on tall building technical installations at an early stage of the design process.

1.1 Background

There are several reasons for building tall and it has been done successfully in many parts of the world since the 19th century. Most well known for their tall buildings is the United States but tall buildings are seen in several other countries as well. Currently the tallest building, the Burj Khalifa, is situated in the middle east in the United Arab Emirates.

The reason for building tall can be to densify an area, to turn a profit on expensive land or to create a landmark and tourist attraction. Regardless the reason, knowledge and experience is needed in order to be successful in the endeavour.

Tall buildings are in a sense multiple buildings stacked on top of each other, but it is not as simple as that. The technical installations has to be positioned and divided in a way that makes sense both functionally and economically. Unfortunately, there is not an optimal solution that can be applied in all buildings, it will differ depending on which system is regarded and the local conditions.

Many disciplines are involved in a building project and the project will benefit from good cooperation at an early stage.

Tall buildings are becoming more common in Sweden as dwellings, hotels and offices. Turning Torso in Malmö has been the tallest building in Sweden since 2005 with its 190 m but is to be surpassed by the 245 m tall Karlatornet in Gothenburg in 2021. The knowledge in Sweden is growing within the field of tall buildings as more are being built and the documentation and distribution of the knowledge will be important for the future of tall building development in Sweden.

1.2 Purpose and aim

The purpose of this thesis is to investigate the technical installations in tall office buildings and describe them in terms of space efficiency and distribution in the building.

The aim of this thesis is to gain insight on what affects the design of the technical installations and how they affect the building design. The outcome of the thesis should provide insight on the space efficiency and distribution of the chosen technical systems and hopefully facilitate the early stage analysis process of future tall office buildings.

1.3 Objectives

In order to fulfill the purpose and aim of this master thesis the following questions should be answered:

- What are the difficulties and challenges regarding building height and technical installations?
- What are the possible and relevant technical solutions for tall buildings?
- At what height are the breaking points and what are the important levels of each system?
- How is the space efficiency affected by the building height?

1.4 Delimitations

There are many possible aspects and topics that can be discussed and investigated regarding tall buildings. This master's thesis focuses on technical installations of tall office buildings and is intended as support for early stage analysis rather than a design guide. Focus has been on space efficiency and questions such as energy performance and sustainability have not been considered although they have a great importance in real projects. The key values for each technical system is chosen according to perfect conditions. The results are an outcome of the specific choices that have been made throughout the report.

The master's thesis has its main focus on the technical installations regarding HVAC, elevators, water distribution and fire safety. Structural and building physics aspects will be treated indirectly, to a very limited extent, in order to support the main focus of the report. Economy will be discussed in the project, since it will serve to bring relevance to the different technical solutions that will be investigated, but only to a limited extent. Three fictitious buildings with realistic settings inspired by existing solutions are modeled for the case study but no real buildings are investigated or modeled.

The following issues will be dealt with in this master's thesis:

- HVAC
- Elevators
- Water distribution
- Fire safety

1.5 Previous work and knowledge in the field

The non-profit organization *Council on Tall Buildings and Urban Habitat (CTBUH)* provides studies and information on tall buildings. The organization is considered an authority on official height of tall buildings (CTBUH, 2019a).

Akbar Tamboli published *Tall and Supertall Buildings: Planning and Design* in which gives extensive overviews of some of the tallest buildings in the world and also explains tall building systems in general (Tamboli, 2014).

Peter Simmonds has in cooperation with *American Society of Heating, Refrigerating and Air-Conditioning Engineers* published *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems* that cover most fields involved when planning and designing tall buildings and emphasis is put on the HVAC systems (Simmonds, 2015).

In the master thesis *Space Requirements for Technical Systems in Office Buildings – Air handling plant room model*, from 2015, Emil Kvist investigates the connection between the size of the air handling plant room and the SFP and airflow. The impact that different shaft solutions and sizes has on the gross external area in a building is discussed. It is explained how different fan solutions work and how they differ from each other and also how this might affect the design in terms of area. It is shown that there is a space efficiency potential in designing well which also implies that there are economical benefits (Kvist, 2015).

Grundfos did a study comparing roof tanks with pressurized systems for water supply in tall buildings. The systems are evaluated over a 20 year period based on energy cost, initial cost, maintenance cost and lost revenue. Dividing the system into zones was proved energy efficient as it was possible to keep lower pressures (Nielsen & Nørgaard, 2018).

Lutfi Al-Sharif published the article *The Design of Elevator Systems in High Rise Buildings* which describes elevator solutions available for tall buildings and some approaches on how to simulate or calculate the right elevator number and configuration (Al-Sharif, 2017).

1.6 Disposition

The areas which will be dealt with in this thesis that are listed in the delimitations overlaps to some extent which will be seen throughout the report. Water distribution is a large part of the fire safety and a part of the HVAC as well. However, the disposition within each chapter is considered appropriate given the content of the report.

The general disposition of the report is described below.

Chapter 2 - Theory

This chapter presents information regarding tall buildings, technical systems and factors that are important for tall building design.

Chapter 3 - Method

This chapter describes what has been considered for the technical systems and also how the case study has been conducted.

Chapter 4 - Analysis

This chapter presents the results and reflections of the case study. Also, possible sources of error and ideas of further stuides are mentioned.

Chapter 5 - Conclusion

This chapter presents a summary of the analysis and also concludes the report.

2

Theory

The theory chapter gives the information regarding tall buildings and technical installations that is of importance for this thesis. Many factors that are important for tall building design is described. However, all that is covered in this chapter is not included in the analysis due to limitations in terms of time and resources.

2.1 Tall buildings

Tall buildings are increasing in numbers as well as in height in many parts of the world. The definition of a tall building is somewhat changing with time and prefixes such as ”super” and ”mega” are added as the limit is being pushed. This chapter will give an explanation of the general conception of what a tall building is and what is considered in this thesis. The chapter will also explain the main reasons for building tall and give a brief history of tall buildings.

2.1.1 Definition

There is no *one* definition of a tall building. The term has different meaning in different parts of the world and has changed over time. When talking about tall buildings there are a couple of expressions that are used, such as high-rise, skyscraper and tower.

Some definitions simply state a required height or number of floors while some definitions include that the height affects the planning or use. In a Swedish dictionary a high-rise is defined as a house with many floors, usually at least five (SAOL, 2009). This provides a hint as to which buildings could be high-rises but the term is still rather wide.

Emporis standards gives the definition that a structure with an architectural height of between 35 and 100 meters is a high-rise building. Alternatively, a building can be regarded as a high-rise if it has a minimum of 12 floors and less than 40 floors (Emporis, n.d.-a).

According to CTBUH the height relative to the surrounding buildings, the proportions of the building as well as the functions in the building will be determining whether or not a building is tall. If the building is considered tall in one or more of these aspects then it it tall. Also, 14 floors or 50 m could be regarded as thresholds of where a building becomes tall. Furthermore, three levels of tall are identified as tall (<300m), supertall (>300m) and megatall (>600m), see figure 2.1 (CTBUH, 2015b).

In this thesis the term "tall" will be used as it is considered to cover all of the said expressions. A tall building can be identified by its height or the number of floors but what will be of importance is if the design of the building is influenced by the fact that it is a tall building, and that is how the concept of tall buildings will be approached in this thesis.

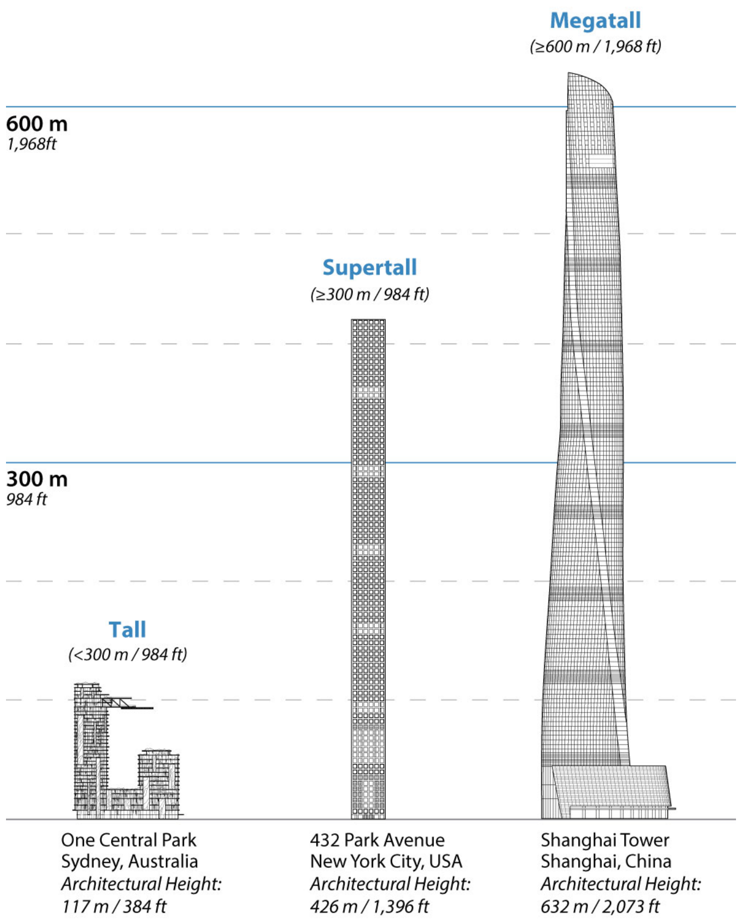

Figure 2.1: Tall, supertall and megatall buildings illustrated with examples (CTBUH, 2015b).

2.1.2 Why tall buildings?

There are several factors and motivations for tall buildings and how these differ will affect the design of the building.

Urbanisation is one factor that motivates tall buildings. When people on a large scale move into areas that are already densely populated it is necessary to utilize the available areas in an efficient way. As of 2018 as much as 55 % of the total world population are living in urban areas and it is projected to increase to 68 % by the year 2050 (UN, 2018). When choosing to build tall it is possible to provide housing or work places for people on these limited spaces. There is an argument that to densify a city is to make sustainable choices both environmentally and socially. The necessary means of conveyance are already present which makes for a decreased car dependency. Densification also increases the probability of spontaneous encounters which is valued in terms of social sustainability. Furthermore, a denser city can be a means to reduce segregation and increase security in a city (Boverket, 2017b). When choosing to densify a city more of the surrounding land is left preserved which is also of value. There are also economic aspects such as increased possibility of finding work and decreased transportation costs (Patrik Höstmad, 2012).

There are of course arguments against densification as well. Green areas are often sacrificed to serve the purpose of densification which is of course seen as negative by the surroundings. With more buildings there is also the risk of overshadowing others and preventing access to daylight which can have consequences on the well being of people. At the same time as it can be advantageous to utilize the already existing infrastructure and other services there is a risk of overloading which will create problems for the citizens of the city (Boverket, 2017b). There are also arguments that tall buildings have an alienating effect on people, due to the separation from the streets, and is thus not good for human health and social functioning (Villegas, 2018). Nevertheless, tall buildings does serve the purpose of providing space for many people on a limited area.

Land prices also affect the choice to build tall. In certain areas the prices are at such high levels that the buildings are required to have a large number of floors in order to be profitable (Alex Block, 2014). This is what the architect of the Woolworth building, Cass Gilbert, was expressing in the year 1900 when he referred to high-rise buildings as "the machine that makes the land pay" (Sun, Architecture, & Planning, 2016). Within this formulation is that the land price is what it is and whether the price is worth it is up to the property developer, meaning that the design choices are of the essence. Although, it is not as simple as increasing the height and thereby turning a profit. A "height threshold" will be reached where the cost of construction and systems is greater than the potential profit (Wood, 2006).

Prestige is perhaps the reason for the most famous tall buildings in the world. In history this can be seen with the pyramids and presently with the Burj Khalifa. This can of course be in combination with densification and high land prices but when motivated by prestige the building often looks very different compared to more "rational" reasons. In these cases the buildings are often very costly (Langdon & Watts, 2010). In connection to the prestige, there is also the aspect of placemaking in which tall buildings play an important role in their built environment. They can help by improving the identity of a city and by asserting its position on a global scale (Al-Kodmany & Ali, 2012). This is very much the case with the Burj Khalifa in Dubai, which the city is very well known for. Antony Wood of the CTBUH points out that the trend has gone from having company names (e.g. Woolworth or Sears) on tall buildings to having the city name (e.g. TAIPEI 101 or Shanghai Tower) (Wood, 2006).

2.1.3 History of tall buildings

The tallest buildings of today are constructed with advanced technology but tall structures can be seen even when looking back in history. A famous example is the pyramids in Egypt, where the tallest one, the pyramid of Khufu, reaches 139 m (Emporis, n.d.-b). In its time it was a considerable height and the structure is still impressive.

In modern time the first tall buildings are found in the United States and was made possible partly as a result of the invention of the elevator safety braking system in 1852 (Mowrey Elevator, 2018). With the elevator it could be motivated to have buildings with more than a couple of floors. Another invention to have a large impact on tall buildings was the steel frame construction which enabled a slender yet sturdy structure (Marshall, 2015).

The first skyscraper is said to be the Home Insurance Building built in Chicago 1885 by William Le Baron Jenney. This was not the tallest building in the world but it is considered the first skyscraper due to the new way of construction, with the steel and iron frame making it more slender. Initially the building consisted of 10 floors but an additional 2 floors were added later on, making it reach 55 m high (Marshall, 2015).

The highest buildings in the world during most of the 20th century could be found in the US, most of them in New York City. Every couple of years a higher building was built that took the record title. The Empire State Building had the title the longest (1931-1972) with its 381 m. It was not until 1998 that a building outside of the US was the tallest. This was the Petronas Towers in Kuala Lumpur, Malaysia, with its 452 m. Presently the tallest building in the world is the 828 m high Burj Khalifa in Dubai, United Arab Emirates (CTBUH, 2015a). In 2013 the construction of the Jeddah Tower started in Saudi Arabia, the completion is said to be in 2021. The building is planned to be the highest in the world, possibly higher than 1000 meters (CTBUH, 2019b). The dominating geographic locations of tall buildings from 1930 to 2018 is seen in Figure 2.2.

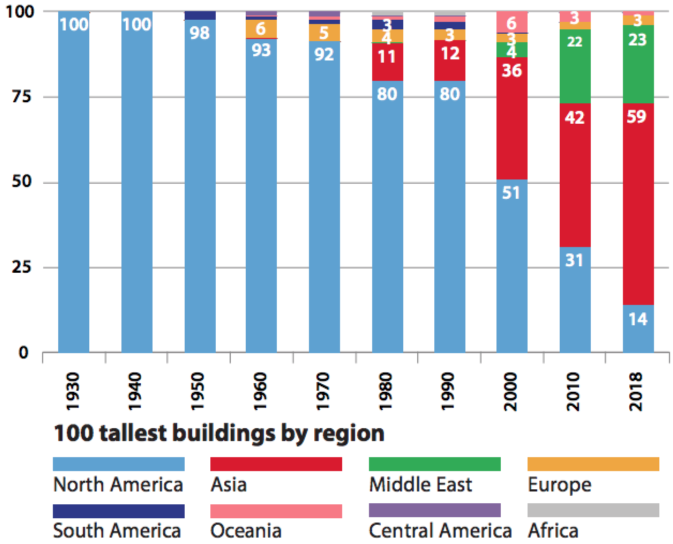

Figure 2.2: Tall buildings through history in percentages per region (CTBUH, 2019c).

As can be seen in Figure 2.2 there is a clear trend of more tall buildings being built in Asia. Although several Asian countries are building tall China represents the larger part of the statistics. Figure 2.3 below shows the buildings built in 2017 that are above 200 meters (Beedle, 2018).

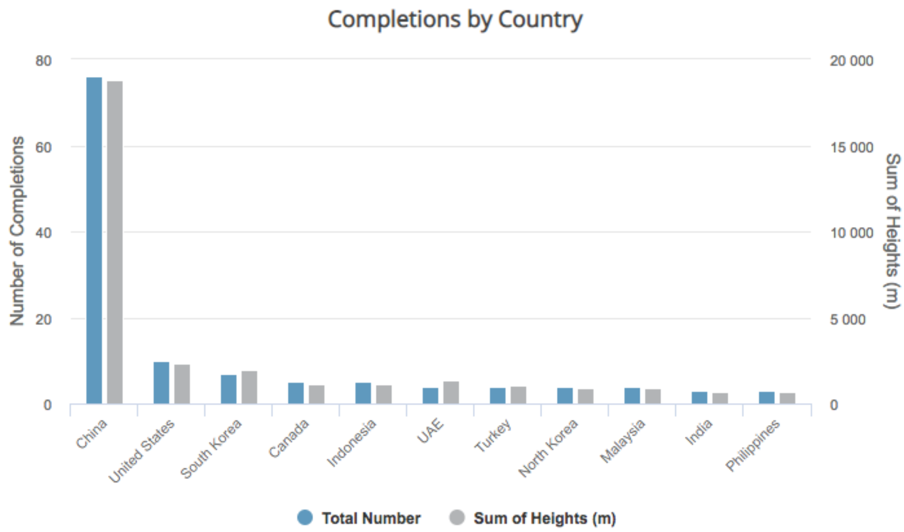

Figure 2.3: Number of completions and sum of heights(m) in 2017. Only buildings above 200 meters are shown(CTBUH, 2019c).

2.1.4 Space efficiency

Space efficiency (or area efficiency) is important for all building projects but it can be more difficult to have a good space efficiency in some projects. Tall buildings are generally more difficult to get a high space efficiency in due to the increasing dimensions of both the technical installations and the load bearing structure (Sev & Özgen, 2009). When looking at some existing tall buildings the ratio between net internal area and gross external area could be below 0.8 (Sev & Özgen, 2009). In a couple of tall buildings in Sweden it can be seen that the ratio is somewhere around 0.8.

Space efficiency is important because it can be the difference between if a project will be feasible or not. Since the cost of construction, materials, operational costs and more is to be paid for by renting or selling the built space, all space that can be used for this purpose will be important. The space efficiency of buildings is different depending on the country. Different regulations apply which dictate e.g. the needed daylight factor. Different climates will also have an affect on how the building can be designed (Sev & Özgen, 2009). Many factors will ultimately be determining whether a building project will be feasible or not, space efficiency is one of them.

In this thesis, the space efficiency will be expressed as percentages of the gross external area (GEA). The GEA and other area definitions are explained in 2.1.9.

2.1.5 Room height

The building height is directly affected by the regulations regarding the room height. The room height differs depending on the use of the room. The expression ”room height” refers to the height from the floor to the ceiling (not from floor to floor). For office rooms intended for longer use the minimum height is 2.4 m. In rooms that are only occupied temporarily it can be as low as 2.1 m in certain areas and 1.9 m if the roof is sloping. In cases when the room is intended for a large number of people the required room height is 2.7 m. The general aim of the minimum height is for people not to experience inconvenience. For communication areas such as hallways, stairs and doors the minimum height is 2.0 m (Boverket, 2018c).

For this thesis the height used for floor to floor is set to 3.6 m with a room height of 2.7 m for the office areas. The distance in between is for the slab, pipes and ducts.

2.1.6 Technical rooms

All of the technical installations will require certain space were the machines, pumps, fans and other equipment is located. These rooms will naturally need to house the equipment itself but also provide enough space around the equipment to enable maintenance work, possibility to change parts etc. For the different systems there will be natural places for these rooms that depend on the limits and planning of each system. This might result in each system having its own technical room and they might be spread out on different floors throughout the building.

If the equipment of the different systems could share spaces then the needed room for maintenance could be reduced. It would also be easier for the mechanics to have much equipment gathered as opposed to having is spread in the building.

2.1.7 Building dimensions

As explained in 2.1.1, a contributing factor to why a tall building is perceived as tall is its proportions, the ratio of the total building height to the gross external area. Table 2.1 shows the height:area ratio for some of the tallest buildings in the world. These ratios are the basis of the ratios of the example buildings seen in Chapter 3.

Table 2.1: Height to gross external area ratios of tall buildings. Source: (Sev & Özgen, 2009).

	Height [m]	**GEA [m^2]**	**Ratio**
Taipei 101 Tower	509	2650	0.192
Shanhai WFC	492	2500	0.197
Petronas Towers	452	2150	0.210
Jin Mao Tower	421	2800	0.150
Two International Finance Center	415	2800	0.148
CITIC Plaza	391	2230	0.175
Shun Hing Square	384	2160	0.178
Central Plaza	374	2210	0.169
Bank of China	367	2704	0.136

2.1.8 Stack Effect

Stack effect is always present in buildings, but even more so in tall buildings. The stack effects main driver is the air temperature difference between the indoor air temperature and the exterior air temperature. The difference between the exterior and interior temperature could be both positive and negative depending on which temperature is the highest. A typical hot summer day or a cold winter day, the pressure inside the building will be different. Somewhere along the height of the building the interior pressure and the exterior pressure will be equal, this is called the neutral pressure plane (NPP). In Figure 2.4 stack effect and reverse stack effect is explained and also how the negative pressure changes to positive pressure above the NPP.

The facade of the building could be of poor quality, not completely airtight, which enables air infiltration or exfiltration depending on the differential pressure. The infiltration or exfiltration will affect the resulting pressure and the resulting pressure will affect the technical installations. The design challenges in tall buildings due to the differential pressure are, elevator- and swing doors could be difficult to open, uncomfortable air flow, heating and cooling system not working properly because of cold or hot air that in- or exfiltrates, the in- and exfiltration could cause noise and the fire strategy could change due to changed pressure differences since controlling the spread of fire is often done by controlling the pressure differences between rooms.

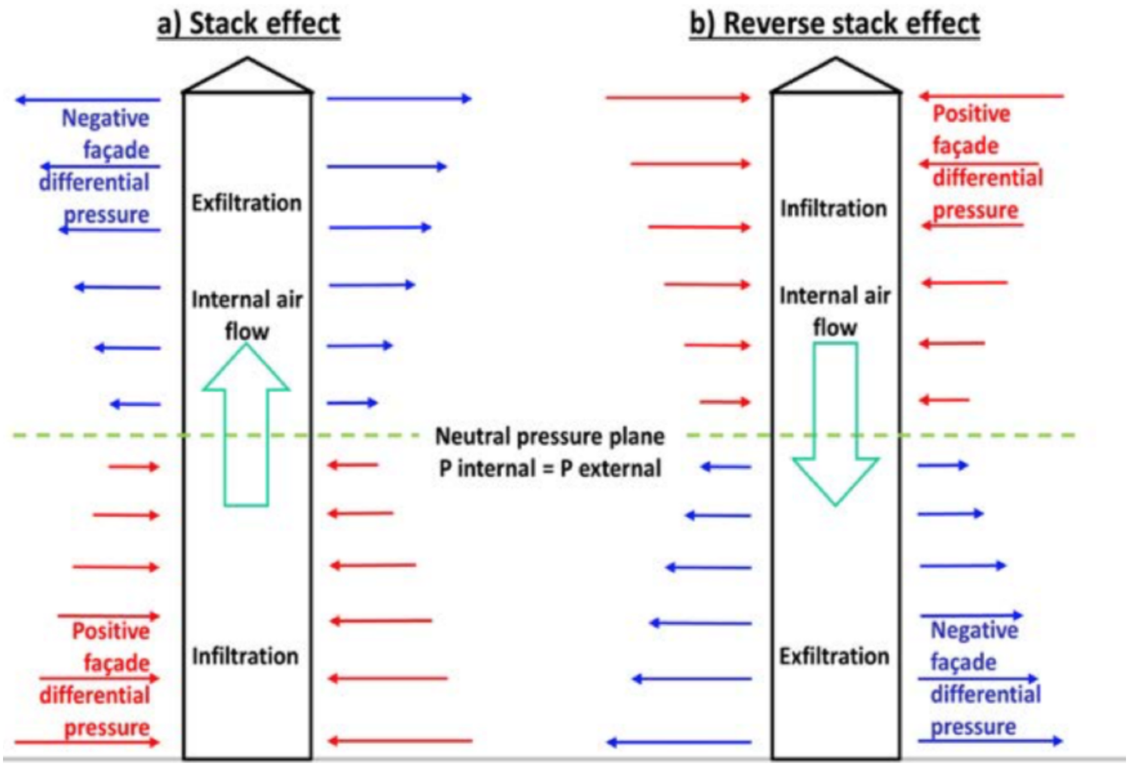

Figure 2.4: Positive and negative pressure differences and location of the neutral pressure plane.

Apart from the stack effects in tall buildings, a large pressure effect is created by the wind. The wind pressure increases with the height of the building, but it also differs depending on the surrounding environment. How the wind speed increases with the height can be seen in Figure 2.5. The sum of both wind pressure and stack effect will give an indication about the resulting pressure.

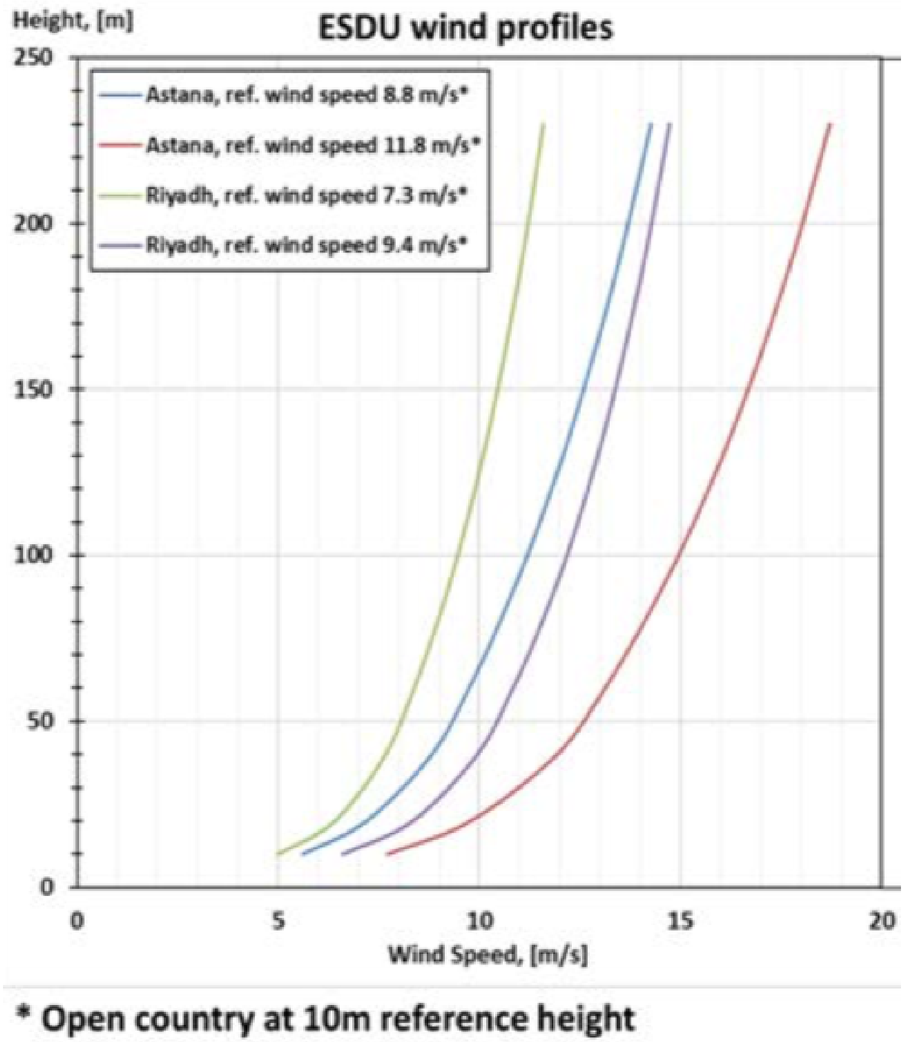

Figure 2.5: Wind speeds over the height of the building, wind speed depends on geographical location and type of landscape.

2.1.9 Building areas - definitions

In Sweden the definition of floor areas are defined in the Swedish Standard (SS) 21054:2009 which is used in the design process of non-residential and residential buildings. It is important to have a definition of each building area as different countries have different definitions, in this report the Swedish Standard is used.

Net internal area (NIA) is the area which is usable for the resident, the net internal area together with the sub-area gives the buildings total area. All area of the building cannot be utilized in the same way, this is why the total area is divided in sub-area and net internal area . The net internal area is measured between the outer walls, the inner walls should also be included as seen in Figure 2.6. All of the floor's area should be included in net internal area except a floor that has a sloping roof where special rules need to be taken into account. The net internal area equals the Swedish living area (BOA) is specified for measuring value (Jagemar, 1996).

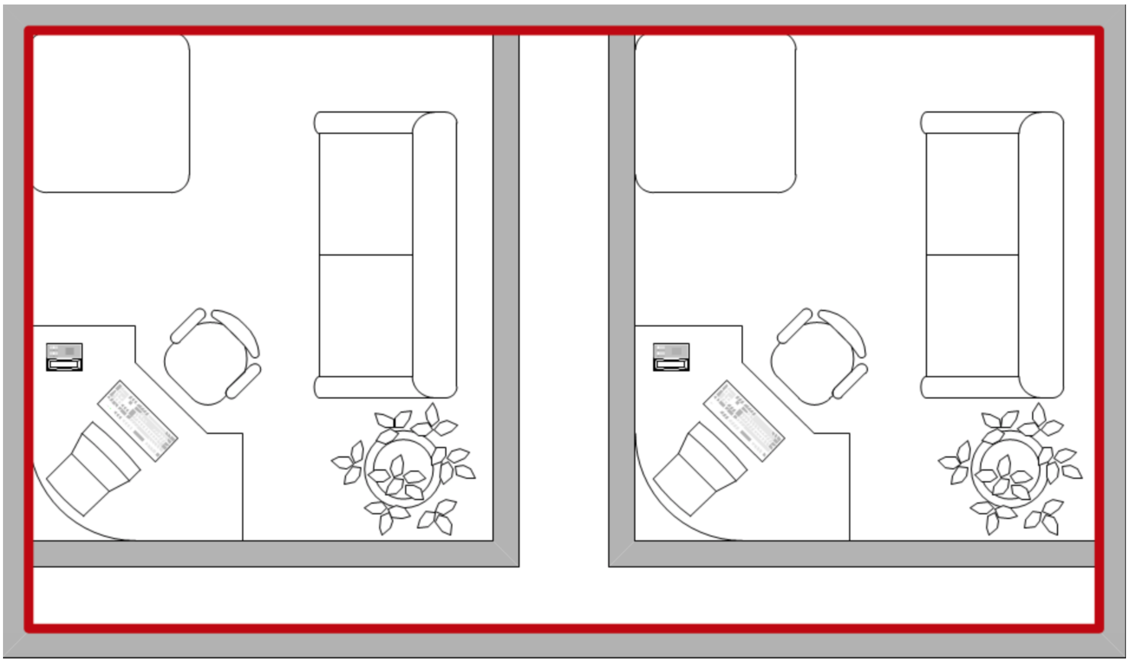

Figure 2.6: The area within the red boundary illustrates the net internal area which is measured between the outer walls of the building.

Gross external area (GEA) is the total floor area and is only limited by the buildings facade. The entresol of the building is also included in gross floor area but the openings in the floor construction is not included in gross floor area. Gross floor area is used in many cases such as house valuation and rent regulations. The gross floor area equals the Swedish gross area (BTA) (Jagemar, 1996).

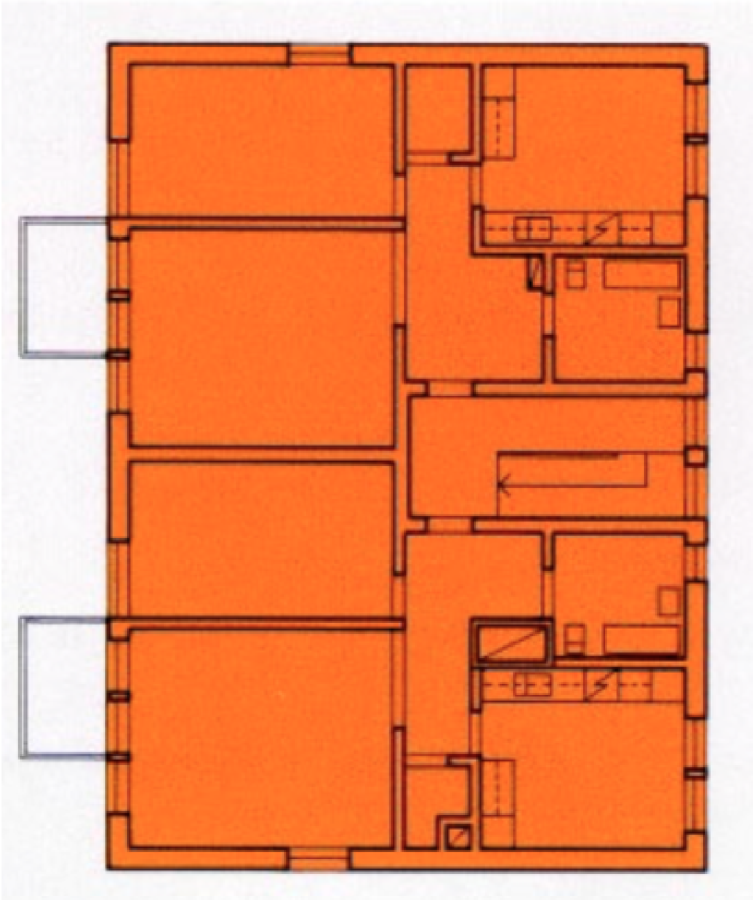

Figure 2.7: Gross external area (GEA). The orange area characterizes gross external area.

Building area (BA) the area of which the building affiliate. The building area is independent of the building height and is often used in detailed development plan. Parts of the facade which is protruding is not included in the building area nor balconies that are higher than 3 meters (Jagemar, 1996).

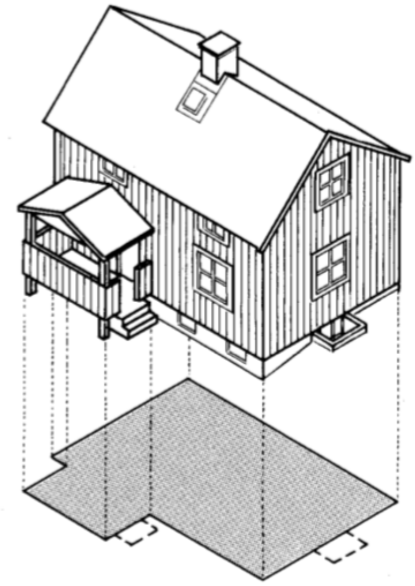

Figure 2.8: The area underneath the building characterizes building area.

$\mathbf{A_{temp}}$ is an abbreviation for tempered area, which is the area within the building heated above 10 °C e.g. floor plan, attic floor and basement floor. Garage, shafts, internal and exterior walls are not included in A_{temp}, which is illustrated in Figure 2.9 (Boverket, 2014).

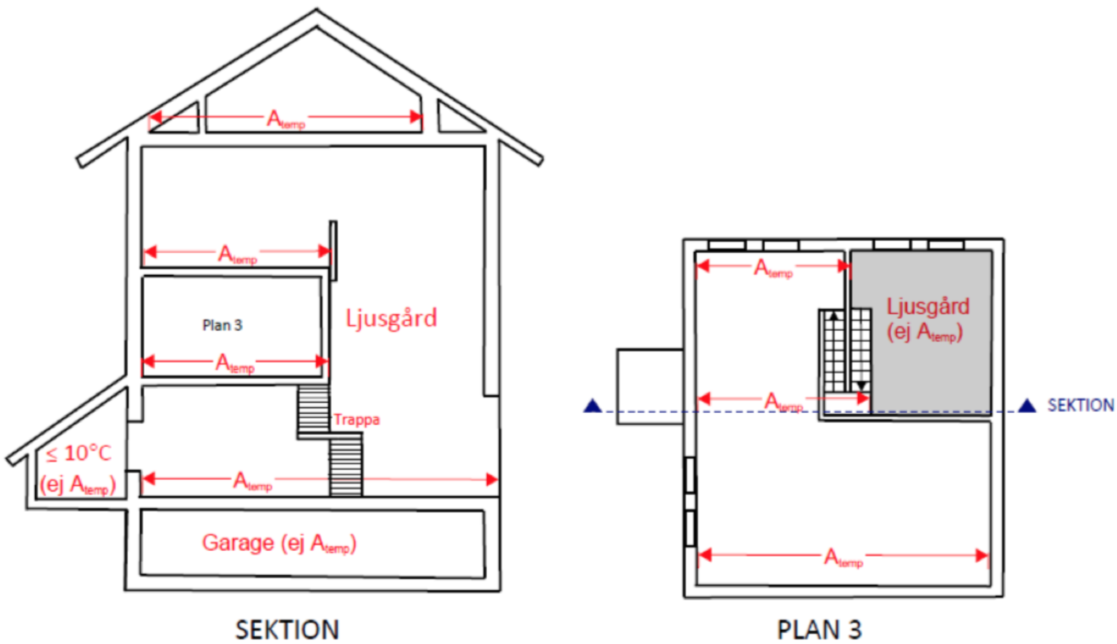

Figure 2.9: Examples of areas in a building which are defined as A_{temp}.

Premises area (PA) in Sweden (LOA) includes premises area for business LOA(V), premises area for personnel (toilets, cloakrooms etc.) LOA(P), premises area for horizontal access between premises on the same floor, mainly corridors LOA(K) (Jagemar, 1996). The connection between different floor areas is shown in Figure 2.10.

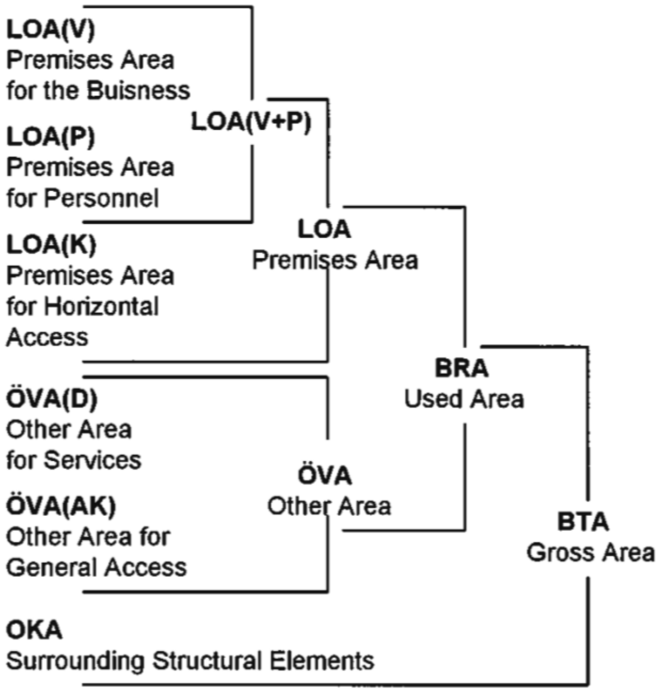

Figure 2.10: The different areas of a building and their connection to each other.

2.1.10 Key performance indicators

A performance indicator or key performance indicator (KPI) is a type of performance measurement. KPI could be both of technical or economical meaning depending on the context, the border between technical- and economical key performance indicators may be very small, this is described in 2.1.10.1 and 2.1.10.2.

2.1.10.1 Economical key performance indicators

Premises area and gross external area are both technical and economical key performance indicators due to the fact that they both describe technical space and ratio between revenue-generating area, premises area and gross external area. Higher ratio between premises area and gross external area indicates that the building has a larger floor area that is revenue-generating. Another TKPI is kr/m^2 which describes how much something costs per square meter, it could be e.g land price or production cost.

2.1.10.2 Technical key performance indicators

Different floor ratios could be explained through technical key performance indicators, the floor ratios is of importance when talking about revenue-generating area, the different floor areas is explained in 2.1.9. Other important TKPI is cooling need which is how much of cooling is needed per square meter, W/m^2. The cooling need is connected to how much heating surplus the building has which correlates to higher or lower demand on the air- or waterborne cooling systems. The TKPI often tells something of importance which has consequences on the technical systems which in turn affects the economy.

2.2 HVAC

There are several acquis to consider when designing the ventilation system for a building. The regulations for ventilation are mainly found in the Swedish National Board of Housing, Building and Planning (Boverkets Byggregler, BBR). Additional regulations are given by the Swedish Work Environment Authority (Arbetsmiljöverket), the Swedish Environmental Code (Miljöbalken) and the Public Health Agency of Sweden (Folkhälsomyndigheten). Sveby provides a compilation of the regulations with focus on energy use. The compilation suggest values of e.g. temperatures and air flows.

The general minimum ventilation flow is 0.35 l/s·m^2 and 7 l/s·person. For offices the basic ventilation rate is around 1.3 to 1.6 l/s·m$^2 A_{temp}$ (Sveby, 2013). The maximum velocity is between 0.15 - 0.20 m/s (Arbetsmiljöverket, 2018). The set-points for heating and cooling should be 22 ± 2 °C and 24,5 ± 1.5 °C for winter and summer respectively to be within PPD $\leq$ 10%(*Sveby*, 2013).

2.2.1 Cooling demand

The cooling need differs vastly depending on a number of factors such as activity, level of insulation, type of windows and geographic location. The type of activity that has been considered in this thesis is office work. Dwellings, hotels and similar are not investigated. Three levels of cooling need has been chosen for offices to account for some variance in activity. 20, 30 and 40 W/m^2 have been used as the office's cooling needs based on interviews with professionals within the field. For offices this cooling need is due to the internal heat gains from people, light, computers, sun load and other equipment.

2.2.2 Means of cooling and ventilating

There are several approaches to handle the cooling need in a building. Two main categories can be identified as airborne and waterborne (Tamboli, 2014). An air flow could be supplied at the needed rate and appropriate temperature to ensure a good indoor climate. Another approach is to utilize the cooling effect of water by installing e.g. chilled beams. In this case the supplied air flow would only need to satisfy the hygienic needs. The different approaches are described below.

To better understand what is described in this section see Equation 2.1:

$$Q = \rho \cdot C_p \cdot \Delta T \cdot V \tag{2.1}$$

Q - effect [W]
ρ - density [kg/m^3]
C_p - specific heat capacity [J/kg°C]
ΔT - temperature difference [°C]
V - volume flow [m$^3/s$]

2.2.2.1 Airborne cooling

When looking at equation 2.1, the cooling need is Q. To handle the cooling need of a building, supplying the right amount of air is a very viable solution in many cases. If the building in question is not densely occupied and the internal and external heat loads are at a reasonable level the cooling need is likely to be met by only ventilating with air that has only a small temperature difference (ΔT) to the room. Should the cooling need be higher, a means of handling this is to increase the volume flow of air (V). Although, at a certain point the air flow will give velocities at the air diffuser that are too high and can cause both noise and draught which will be unpleasant for the occupants of the building. Also, with increased air flows the whole system will have to be larger which will encroach on other areas in the building that could be put to better use.

Low-tempered air

A means of handling a high cooling need with air while still keeping the air flows small is by supplying low-tempered air, i.e. using a large ΔT. As seen in Equation 2.1, an increased ΔT can be used instead of an increased V. This means that the air flows can be kept at a moderate level while still handling the cooling need. The main parts of the ventilation system, such as the AHU and ducts, can be of smaller dimensions and the space saved can be utilized for other purposes. The low-tempered air does however require other cooling equipment than what would be required to supply a normal temperature. As large temperature differences as 16 °C can be used (Simmonds, 2015). Too large ΔT:s can result in occupants experiencing draught from the low temperatures and the air flow still has to be kept high enough to ensure a good air quality. With a well-chosen air diffuser the low-tempered air will not result in any draught.

2.2.2.2 Waterborne cooling

An effective way to handle the heat surplus is to use waterborne cooling systems as chilled beams in the office space. The chilled beams could be of passive or active cooling which is explained below. The temperature of the water in the active chilled beam should not be too low, a very low water temperature in combination with a high humidity will result in condensation on the pipes. The difference between supply- and return water from the chilled beam could be from 2°C to 10°C depending on the indoor climate and cooling need. The waterborne cooling takes advantage of both the cooling capacity of water and air which is seen in Equation 2.1 where the specific heat capacity and density must be changed to air or water. If there is a large cooling need waterborne cooling is an effective choice compared to airborne cooling where the dimensions of the ducts gets very large if not a very large air flow or low temperature is used. The return water from the chilled beam needs to be cooled down to supply temperature before returning to the chilled beam again, this heat surplus needs to be removed either by having cooling towers on the roof of the building or by using district cooling.

Active and passive cooling

There are different ways to achieve comfort cooling in a building, passive cooling or active cooling could be used to reduce the heating surplus. A first step to reduce the heating surplus could be by decreasing the solar gains with awnings or sun blinds, changing the lightning system to a more energy efficient or have enough of insulation in walls and roof. All of these alternatives prevent the building from being heated in the first place. If these solutions are not enough, then passive or active cooling could be an alternative to achieve a pleasant indoor climate. The point with passive cooling is to use cold sources such as a nearby lake, groundwater or a borehole. The cold water is circulated through a circuit in a building or only certain rooms which takes away the heat surplus, the coldness could also be diffused by a fan-radiator (Thermia, 2019). If the passive cooling is not enough to reduce the heat surplus, active cooling could be an alternative. Active cooling could be achieved by using a heat pump which is inverted and therefore works as a refrigerator. This could be achieved by reversing the cooling circuit in the heating pump, or by switching over the primary and secondary connection on the pump (Viessmann, 2019). A common choice regarding cooling is to use active or passive chilled beams, the active chilled beam is connected to both ventilation supply air ductwork and the chilled water system. The passive chilled beam has no supply air connected to it, but it has a cooling battery which works due to natural convection. The air is cooled which changes the density of the air and therefore the cooled air drops, the air gets heated by the surroundings which changes the density of the air and the air rises, this procedure continues over and over again. Due to the natural convection, passive chilled beams are not suitable over working spaces but the cooling effect from the beam could be rather large (Flaktwoods, 2008).

2.2.3 Centralized and decentralized ventilation systems

In Sweden most types of ventilation systems are centralized, the owner of the building is responsible for all of the technical installations and their functions. The tenant has no responsibility regarding the technical installations, the rent from the tenant should cover the costs for the maintenance which the owners pays for (Nathan, 2018). A central air handling unit (AHU) is distributing the supply air via the ductwork. The base demand in the meaning of air temperature and air humidity is distributed by the AHU, if a certain room or area have a different demand this could be achieved by adding a cooling or heating coil in the ductwork before the supply air enters the room or area. In other countries as USA decentralized systems are more common compared to Sweden (Nathan, 2018). It is common that the tenant has their own AHU, the tenant could choose which solution of air handling system that fulfills their requirement of indoor climate. In this case the owner has no responsibility regarding the air handling system, both the cost of AHU and maintenance is the tenants responsibility, but there are several ways to solve the problem with AHU and its costs.

Shared responsibility - The costs for the HVAC system is shared between the landlord and the tenant. Often the maintenance and repairs is paid by the tenant and the replacement of the AHU is paid by the landlord (ASHRAE, 2016).

Tenant pays all - The tenant has responsibility for maintenance, repair and replacement if needed. The landlord will not cover any costs, it is a good deal for the landlord but it could occur problems when the lease is going to end, the tenant might not tell the truth about the condition of the AHU (ASHRAE, 2016).

Limited responsibility - The total cost of an AHU is divided by its service life (15-25 years), this is how much the AHU costs per year for the landlord. If the tenants wants to end the lease in advance the yearly cost of the AHU is billed to the tenant for the remaining time of the contract (ASHRAE, 2016).

In tall office buildings the position of the plant room could be different, a very large AHU could supply many floors but a smaller AHU supply fewer. The distribution of the plant room is analysed in Chapter 4 where space efficiency is in focus. An AHU supplying many floors will need more space than a smaller AHU but the amount of smaller AHU:s will be higher. The position of the plant room will also affect the space efficiency which is discussed in the analysis chapter but the aim is to use as few square meters as possible. The distance from floor to ceiling will limit the height of the AHU which limits how many floors could be supplied, an alternative is to use two floor heights for plant rooms. The advantage of using centralized ventilation system is that the building owner could design the building in an efficient way which could give more space over for rental.

2.3 Elevators

According to the plan and building regulations (PBF) buildings with more than one floor should be equipped with an elevator or equivalent lifting equipment if it is required to ensure accessibility. It is further stated that dwellings with up to three floors is not required to have an elevator. It should however be possible to install in the future (Boverket, 2019b).

Boverket's building regulations (BBR) provides information on when two elevators are required and when a rescue elevator is needed. The latter should be possible to install in dwellings with four floors or more. The dimensions for certain sizes of elevators are regulated and BBR refers to the Swedish Standards Institute for the measurements of those. At ten floors two elevators are required, one of these needs to be a rescue elevator (Boverket, 2019b). If the floor area exceeds 900 m^2 two rescue elevators should be installed (Boverket, 2019a).

A very important component in tall buildings is the elevator system. Tall buildings depend on a well-functioning elevator system that combines a high capacity with space efficiency. There are several possible solutions for this and the solutions can differ depending on the building in question.

When a building increases in height (and in size) a higher capacity is required from the elevators. Traditionally this has been equivalent to simply increasing the number of regular elevators but modern technology provides alternatives on control, machine room size, cable material and configuration.

The required capacity of an elevator system is determined based on the population (number of employees), the level of occupancy (presence/simultaneousness) and the peak demand (indicative traffic flow peak) (Wit, 2007). For offices the lunch peak is dominant (J. Wit, personal communication, February 12, 2019).

2.3.0.1 Control

The main types of control are **conventional** control and **destination** control. Conventional control means that the user requests an elevator with the push of an "up" or "down" button. The user then chooses the desired floor when inside the elevator. Destination control means that the user at the point of requesting the elevator specifies which floor is desired. The destination control reduces the total time, although the waiting time increases compared to the conventional system

(Wit, 2007). Destination control is preferred when more than four elevators are installed (L.G. Sergerlind, personal communication, April 1, 2019).

2.3.0.2 Machine room

Machine room size can differ depending on the characteristics of the elevator. It is even possible to remove the machine room (Elevatorpedia, n.d.). Different machine room solutions can be seen in Figure 2.11 and it is evident that the choice will affect the space efficiency of the system.

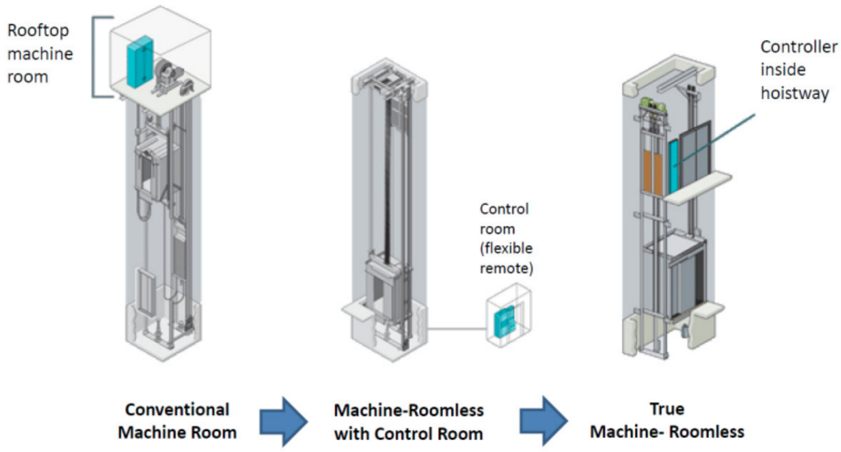

Figure 2.11: Machine room, machine room-less (Al-Kodmany, 2015).

2.3.0.3 Configuration

The standard elevator solution which is sufficient for most buildings is to have an elevator group with a couple of single-deck elevators on conventional control. This solution works well up to a certain height and size of the building, after that other solutions are required.

Zoning of elevators can be used to manage the people flow when a building increases in height. Zoning means that different groups of elevators serve different floors (zones) in the building. For a building of 45 floors it could mean that one elevator group serves floors 1-15 (zone 1), one elevator group serves floors 15-30 (zone 2) and one elevator group serves floors 30-45 (zone 3). Each group would then only stop at its designated floors and have an express zone passing the zones below. An illustration of zones can be seen in Figure 2.12.

When the building height continues to increase the zoning approach will require a fairly large number of elevator groups. Since all elevator groups start at the ground floor and continues to each designated zone it will claim a high percentage of the floor area, especially at the lower floors. At a certain point there is a need for a different approach. ASHRAE identifies two main elevator approaches for supertall (>300m) and megatall (>600m) buildings; the **sky lobby** approach and the **double-deck** system (Simmonds, 2015). These solutions can be applied in buildings lower than 300 m as well. These two approaches are illustrated in Figure 2.12. The double-deck system has two elevator cabs in the same shaft. This is a very costly solution but in projects where area and space efficiency is of the essence it is a viable solution. When applying the double-deck solution it affects the design of the rest of the building. As there are two cabs on top of each other you might arrive at a level above or below your destination depending on your initial choice of cab. This can be solved with escalators to easily reach your wanted floor, see Figure 2.13. The idea of the sky lobby approach is to have two separate elevator systems that meet at the sky lobby level. The first system serves the floors from ground to sky lobby while the second system serves the floors from the sky lobby and above. As can be seen in Figure 2.12 there is also shuttle elevators from the ground level to the sky lobby. The shuttle elevators travel directly from the ground floor to the sky lobby and a transfer to the upper zones is made there.

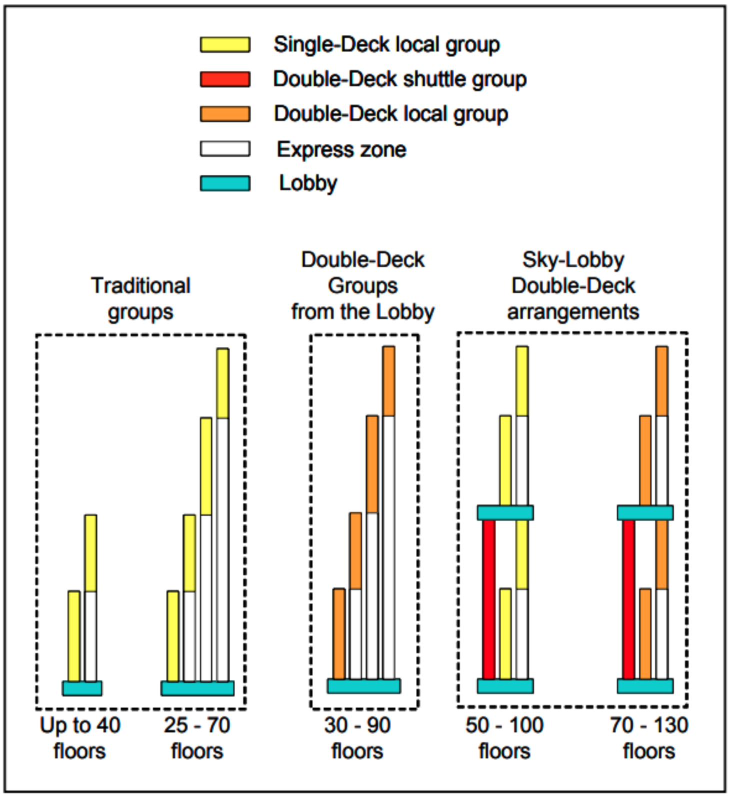

Figure 2.12: Elevators with different configurations. Zoning choices, double-deckers and sky lobbies are illustrated (Jong, 2008).

The company Thyssenkrupp has developed a similar concept to the double-decker but instead of connecting two cabs on top of each other there are two independent cabs moving within the same shaft. The concept is called TWIN and can potentially save 25 % of space according to Thyssenkrupp themselves (Thyssenkrupp, 2019). The company has also developed a new type of elevator system which is based on the technology of magnetic levitation that makes ropes unnecessary. The system is called MULTI and will have vertical and horizontal shafts with several cabs in each. The capacity will be significantly increased but at a cost around five times as high compared to a conventional solution (Maglev, 2017).

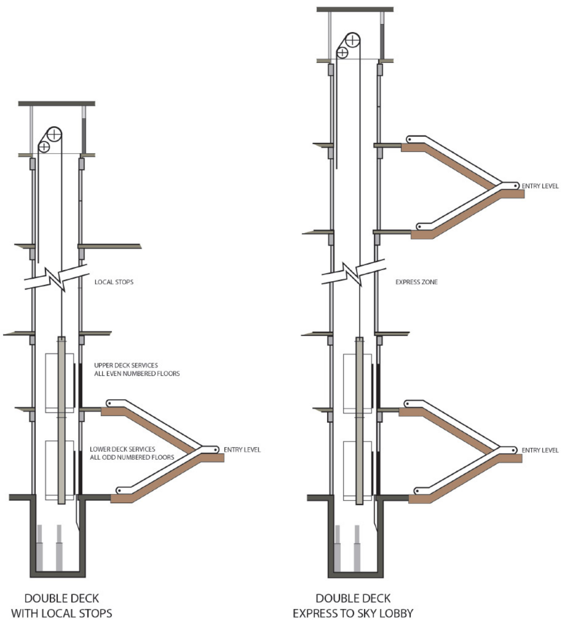

Figure 2.13: Double-deckers with escalators (Simmonds, 2015)

2.3.0.4 Elevator rope

A component that has been limiting the travel height for elevators is the elevator rope. The material of choice has traditionally been steel due to the high tensile strength. However, steel is relatively heavy and there is a height limit at around 550 m where the elevator rope can no longer carry its own weight. Steel ropes also have issues with sway that arises as an effect of wind acting on the building (de Jong, 2014). The new KONE Ultrarope allows longer elevator travel distances up to 1000 m by utilizing carbon fibres which are both light weight and strong (KONE, 2013). Due to the lower weight the energy use will decrease and the effect of rope sway is significantly reduced due to the high natural frequency in the rope.

2.3.0.5 Rescue elevator

A rescue elevator is required in buildings with more than ten floors. The rescue elevator is meant to be used by the emergency personnel in case of fire or other emergencies. The shaft of the rescue elevator needs to be its own fire cell and the elevator needs to fulfil the same fire requirements as the shaft. The inner dimensions of the rescue elevator are 1.1 X 2.1 in order to be able to carry a stretcher. The area outside of the elevator should be a fire lock and be large enough to fit the stretcher with personnel (Boverket, 2019a).

2.3.1 Stairwells

In lower buildings stairwells are the main means of vertical transportation whereas in taller buildings the elevators are the choice of transportation. Stairwells are an alternative to the elevators and important to the fire escape strategy.

The dimensions of the stairwells are partly chosen by the architect and partly regulated by fire safety restrictions. For stairs with <150 persons the minimum width is 0.9 m. For stairs with >150 persons the minimum width is 1.2 m. In most cases it is considered worthwhile to use the larger dimensions (H. Rosenqvist, personal communication, March 29, 2019). The number of people specified does not refer to the total number of people in the building but to the number of people who are planned to evacuate at the same time.

More information on stairwells is found in Section 2.5.

2.4 Water distribution

The distribution of water is dependent on minimum and maximum pressure in pipes and taps. The water is pumped through the building and different systems need different pressures. The building could be divided into different sections which is dependent on the differential pressure. When building tall there is a need of pumps which adds pressure to incoming water, if the building is very tall many pump stations will be needed. The amount of pumps is also depending on the water flow together with desired pressure.

2.4.1 Water pressurization system

In tall buildings there is a need of water in many forms e.g. tap water, water to toilets, showers and sprinkler system. In the municipal water supply network the tap water pressure of 4-6 bar is available, 4-6 bar can be compared to 40-60 MWC (Lundagrossisten, 2018). If there is a need of higher pressure than 4-6 bar, it has to be pressurized by a water pump. The pressure of 4-6 bar is enough for many residential buildings and offices but some are higher than 40-60 meter. The water is distributed from water towers or other kinds of reservoirs. The reservoir is depending on the height of the reservoir location in relation to the place of consumption.

The minimum pressure for tap water is 1 bar and it might occur problems if the pressure is too low such as no water through the tap. The maximum working pressure is between 4-5 bar depending on the tap. The recommended value of 1-5 bar as working pressure is from manufacturers of tap water installations. The pipes should be able to handle 16 bar according to (Boverket, 2011). Pumping water one meter up in the air is equal to one meter of water column (MWC) which is the same as 0.1 bar. Friction losses in the pipes is depending on water flow and pipe size and have to be taken into account when design the pressurization system. Too high water pressure will result in wear in pipes and too high pressure at the tap. The pressure losses in the tap water system are from friction and difference in height. The probable water flow for an office of 1000 m^2 is 0.7 l/s and the velocity should not exceed 2 m/s (VVS Företagen, 2013). The number of worker is 1 per 15 m^2 according to (Sveby, 2013).

There are many possible solutions for solving the problem with distributing water to tall buildings. Possible systems for solving the distribution are, single booster system, zone divided system, roof top tank system, series connected intermediate break tanks and series connected system (Nielsen & Nørgaard, 2018). One solution which is commonly used in USA is to pump up the water to gravity feed tanks on the roof, the water is then distributed downwards from the tank with the help of gravity (Nielsen & Nørgaard, 2018). When distributing the water from the tanks on the roof high speeds could occur which creates noise in the pipes, well-insulated pipes is a possible solution but the water also creates large forces which needs to be taken care of with special vents (Nielsen & Nørgaard, 2018). Another problem is the floors close to the tank could get too low water pressure, to solve this an extra water pump needs to be installed. It can be considered counterproductive to pump the water to the top of the building and then pump it downwards to provide sufficient pressure for the top floors. Another solution is to have tanks in series which distributes water to surrounding floors. The pump does not need to pump the water a great distance, but instead it pumps the water to a lower level and from this level to the next level. Instead of one giant water pump there are several small water pumps. The requirements of the pump is lower for the case with smaller pumps in the meaning of pressurizing the system and special pipes due to high water pressure. Either the building is divided into pressure levels or the entire building functions as a pressure zone. Dividing the building into pressure zones is a more energy efficient solution but especially a space efficient solution. In the report from Anders Nielsen and Jens Nørgaard, pressurizing zone-systems are superior compared to roof top tank system.

The total cost during a time period of 20 years is lower for the pressurizing zone-systems compared to the roof top tank system, but the loss of revenue for the roof top tank is not the worst compared to the other water distributing systems. The system which affects the revenue-generating area the most in a negative way is "series connected systems with intermediate break tanks". The life cycle cost for the 5 different water distributing systems is shown in Figure 2.14. The choice of water distributing system is explained in the method chapter.

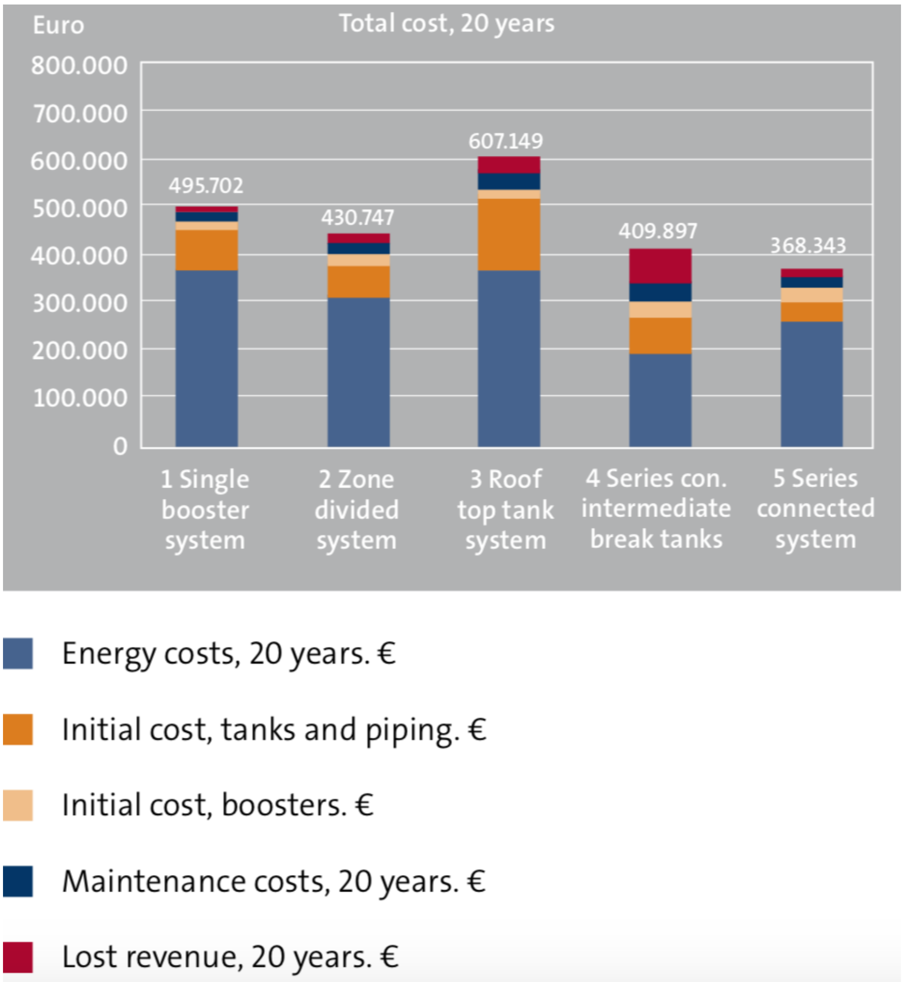

Figure 2.14: Total cost over 20 years for different water distribution systems (Nielsen & Nørgaard, 2018).

2.4.2 Wastewater treatment

In BBR chapter 6 section 6:641, installations for wastewater, there are two types of flows, standard flow and probability flow (Boverket, 2011). Standard flow is dependent on kind of sewage unit, a water closet has a flow of 1.8 l/s and a bathtub 0.9 l/s (Lindblad & Lindström, 1996). The sum of all sewage units will give a total standard flow, this flow is not utilized to 100 % due to the fact that every sewage unit is not used at the same time. Probability flow is a function of all connected sewage units standard flows which could be seen in Figure 2.15. The numbers in Figure 2.15 is depending on what kind of building that is investigated. There is a difference between residential buildings, hospitals and schools (Lindblad & Lindström, 1996).

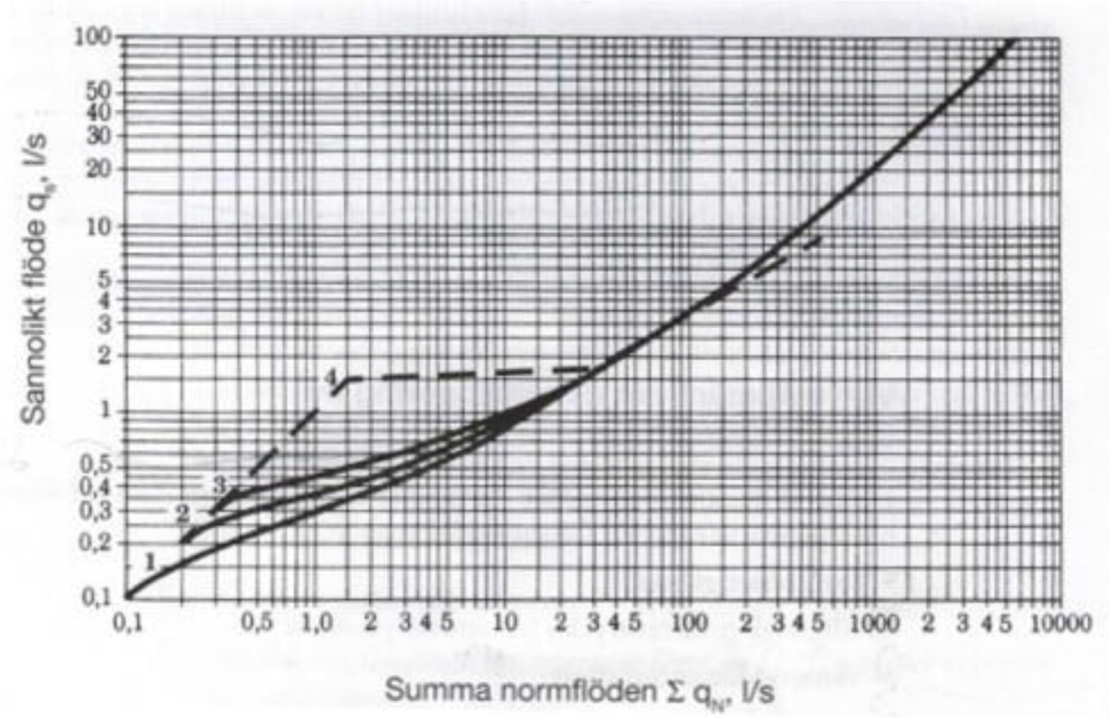

Figure 2.15: Probability flow and its relation to standard flow.

Wastewater pipes should be designed to fulfill the requirement of being able to handle 150 % of the standard flow to reduce the possibility of flood (Boverket, 2011). Bad smell should not be able to be spread through the wastewater system, this is usually solved by a siphon which separates the air masses on different sides of the siphon. High velocities in the wastewater system could create noise which has to be considered, a possible solution to reduce the noise is to use well-insulated pipes. Regardless if the building is 100 meter or 300 meter the velocity of the water will not increase due to the air resistance that is generated by the falling water. The terminal speed of the water is not depending on the height of the building (Böhm, 1989).

Most water treating systems have separate systems for urban runoff and wastewater as in Figure 2.15. The reason for this is to lower the amount of water that goes to treatment plants, the urban runoff leads to nearby lakes or streams if possible (Klimatanpassningsportalen, 2016). Even though the buildings roof area in relation to the building height is low it cannot be neglected that the roof area is large due to the large circumference of the building. The roof will collect a large amount of water which has to be taken care of. It is not desired to have gutters and downpipes on the facade but a possible solution is to lead the water inside the building in a separate water system. Another solution that is used is to lead the water through the building a couple of floors and then lead the water through the facade out from the building as rain. The amount of water collected on the roof is reduced if the design of the tall building is acute, the rain will not stay on the roof in this case, instead it will slide down on the facade.

2.5 Fire safety

Fire safety in tall buildings is different from in low buildings. In a low building the fire can be fought from the outside either from the street or from a fire truck. In a tall building this is not possible above a certain height, the fire has to be fought from inside the building. This means that apart from enabling the occupants to escape, the firefighters have to be able to access the building.

The rescue elevator is seen in the figure below, as it is connected to fire safety, but is explained in 2.3.0.5.

The Swedish fire safety aquis are found in PBL, PBF, SBF, BBR and BBRAD. The latter is an extension of BBR with focus on analytical dimensioning (AD) of the fire safety.

Buildings are divided in BBR into different building classes depending on the need for safety measures. There are four classes; Br0, Br1, Br2 and Br3. Br0 requires the highest level of safety and Br3 the lowest. As seen in Figure 2.5 buildings with more than 16 floors are classified as Br0-buildings and will require analytical dimensioning. Other important fire safety levels are marked in the same figure. The heights in Figure 2.5 are given in number of floors at the vertical axis. This is due to that the regulations for elevators and building classes are specified for number of floors. For risers and ladders the limits are given in meters as well since the floor height can vary.

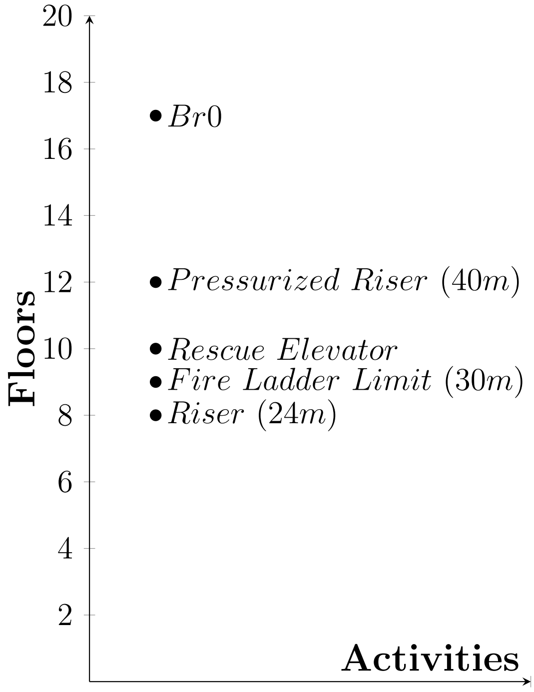

Figure 2.16: Heights relevant to fire safety.

2.5.1 Stairwells and evacuation

BBR states that there should be two available escape routes but in certain cases it can be allowed to have only one escape route. Table 2.2 shows what stairwells can be applied for the activity class (verksamhetsklass) Vk1 which pertain to offices. The type of dimensioning required is also seen.

There are two types of classifications of stairwells that are of importance with respect to fire safety; Tr-1 and Tr-2. Tr-1 is to fulfil the highest fire safety demands and Tr-2 the second highest. The demands specify connected areas and time that fire should be resisted. The specifications can be found in BBR chapter 5 (Boverket, 2018b).

Table 2.2: The fire safe stairwells required for offices at certain number of floors if one stairwell is considered sufficient.

Offices (Vk1)		
Number of floors	Stairwell	Dimensioning
2 - 8	Tr2	Simplified
8 - 16	Tr1	Simplified
16 -	Tr1	Analytical

As seen in Table 2.2, the specified stairwells can be used as a single fire escape route for the given activity classes if the solution is satisfactory. The general advice of what is deemed satisfactory for simplified dimensioning is given in BBR 5:322 and depends on number of people and distance to the fire escape route. For buildings with more than 16 floors, BBR gives no recommendation, instead BBRAD is to be used. The aim should be that an analytical dimensioning provides the same safety as what would be possible if simplified dimensioning could be applied. What is stated is that buildings with more than 16 floors, as Br0-buildings, are to have one Tr-1 stairwell and additional stairwells should be at least Tr-2 (Boverket, 2018b).

2.5.2 Alternative means of evacuation

Traditionally, the evacuation route is from your floor through the fire escape (stairwell in a tall building) to the outside. In very tall buildings the evacuation route can be very long which results in both significant evacuation times and possibly exhaustion of the evacuees. Some occupants of the building might not be able to use the stairs and will be in need of other solutions. In super- and megatall buildings it can be considered if refuge areas and/or fire escape elevators can be used during evacuation (Simmonds, 2015).

The idea of a refuge area is that it is unoccupied during normal operation so that it is ready to be used and it is an own fire cell with a separate ventilation system. The solution is very costly as it claims space both for the refuge floor itself and for the extra technical installations needed for the floors.

To enable evacuation, the evacuation route and the rescue elevator has to be free of fire and smoke. A way to ensure this is to pressurize the stairwells and elevator shafts as explained in 2.5.4.

2.5.3 Fire ladders

Fire ladders reaches a maximum of approximately 30 meters (9 floors) and at 10 floors a rescue elevator is required in accordance with BBR (Eskilsson, 2019) (Boverket, n.d.).

2.5.4 Pressurization of shafts and stairwells

To control the air flows and pressures during a fire in a tall building there is need for pressurization of certain areas.

In tall buildings, elevators are used as the main vertical transportation during normal operation. In case of fire however, the main means of escape is not the elevators but the stairs. Due to this the stairwells need to be pressurized to prevent smoke and fire from entering. There is a minimum and a maximum to this pressure difference, 20 Pa and 80 Pa respectively (Jensen, 2005). The minimum is to ensure that the smoke and fire is kept out and the maximum is to not have too high pressure differences on doors which would prevent them from opening. There is no height limit on stairwells with regards to pressurization (Henrik Rosenqvist, personal communication, March 29, 2019). The pressurization of the stairwell is provided by a fan that supplies air at even levels at approximately every third floor (Simmonds, 2015).

Pressurization of stairwells in tall buildings has to be done with analytical dimensioning but the commonly used solutions does not provide the same safety as the simplified dimensioning does. The problem in these solutions is not with the fans but with the dampers, counterbalance dampers or pressure sensors (Runefors & Persson, 2017). One aspect that makes pressurization difficult is wind. Since the value of the pressure in the stairwell is the value of the pressure difference between inside and outside of the stairwell this will fluctuate depending on the pressure outside of the stairwell.

2.5.5 Pressurization of pipes

There are no regulations mandating sprinklers in tall buildings. It is however common practice to have sprinklers as part of the fire safety design in tall buildings. The use of sprinklers can be a costly solution but is often considered worthwhile especially in tall buildings where the fire safety can be more difficult to assure. Sprinklers also provide benefits such as less strict fire requirements on structural parts. Traditional sprinkler systems need large amounts of water in the pipe system and there could be a need of water tanks if it is not possible to get water from a nearby lake or from the municipal water pipeline network. The water mist system is a high pressure system but does not need as much water as the sprinkler system. The water mist also removes oxygen from the air which counteracts the fire. For the firefighters there is a need of water risers, depending on the height of the building the riser needs to be pressurized or not.

2.5.5.1 Sprinkler pressurization

The sprinkler system has pressure losses at the sprinkler head and in the pipes as friction losses. The friction losses in the pipes is dependent on the water flow and the size of the pipe, as seen in Figure 2.17. The main distribution pipes have dimensions of 65 to 150 mm, the range pipes are 50 to 25 mm and the pipes supplying the nozzle is 25 mm (Fogtec, n.d.). The friction loss occurs from the pump to the sprinkler head furthest away from the pump. The friction loss has been calculated by adding the vertical distance of the pipes with the distance from the center of each floor plan to the corner of the building. Each building has the geometry of a square and therefore the distance from the center to the corner is calculated as $\sqrt{GEA} \cdot \frac{2}{2}$ m.

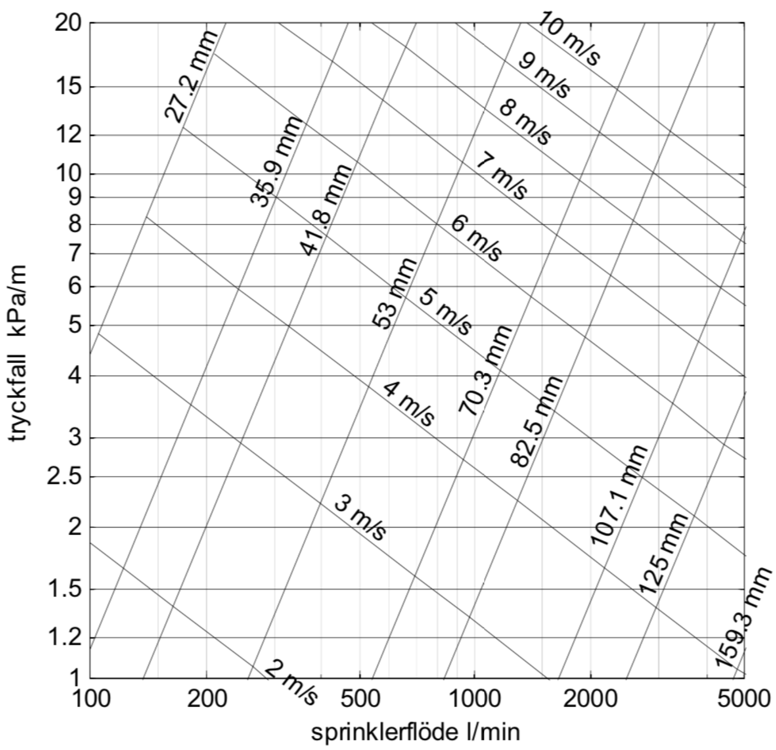

Figure 2.17: The pressure loss is dependent on the water flow through the sprinkler and velocity of the water.

The pressure loss at the sprinkler head depends on the water flow through the head and the size of the sprinkler head. The conditions for the calculations is dependent on the type of building e.g if it is an office- or a residential building. Office buildings has a lower hazard group than residential buildings or warehouses. The hazard group determines the working area for the sprinklers and the value of design density. The design density gives the total water flow in the unit mm/min. The hazard group also decides how large the water tanks have to be, if the water tanks should be able to supply water to the sprinkler system for 30 or 60 minutes (Standard, 2004).

The pressure loss over the sprinkler head is calculated by using Equation 2.2 (Standard, 2004). The constant K depends on the sprinkler head but for office buildings which is in hazard group 1 a value of 80 or 100 is recommended (Standard, 2004). The minimum pressure at the sprinkler head to function is 0.35 bar and the maximum pressure is 12 bar (Standard, 2004). The friction loss together with the pressure loss over the sprinkler head and minimum pressure over the furthest away sprinkler results in the total pressure for the pump to overcome.

$$Q = K \cdot \sqrt{P} \tag{2.2}$$

Q - water flow [l/min]
K - constant [(l/min)/$\sqrt{bar}$]
P - pressure [bar]

2.5.5.2 Water mist pressurization

For the water mist system the lowest required water mist pressure is 60 bar at the highest point (Fogtec, n.d.). High-pressure pumps of 140 bar is able to pressurize the system to heights of 600-700 meters depending on pressure losses in the pipe network. The main distribution pipes have dimensions of 28 to 42 mm and the pipes supplying the nozzle is 12 mm (Fogtec, n.d.). High water pressure and reduced water consumption gives smaller pipe dimensions for the pipe network. The water needed depends on the hazard class but for offices the design density is 2.2 mm/min (Fogtec, n.d.). This value is lower than for sprinkler design which is due to that water under high pressure expands when exiting the system into the air (LU, 2006). The water tanks do not need to be as large as for traditional sprinkler design because of the volume expansion of water mist. The water tanks should be able to supply the water mist system with water for 60 minutes (Standard, 2004).

2.5.5.3 Risers and pressurized risers

At heights above 24 meters (8 floors) water risers should be installed and above 40 meters (12 floors) the water risers need to be pressurized to ensure sufficient water pressure for the fire fighters (Boverket, 2018a). The Swedish Fire Protection Association has in SBF 504:1 provided information on how risers can be designed in accordance with BBR for systems that are automatic and water filled (Brandskyddsföreningen, 2018).

The maximum pressure is not to exceed 20 bar except for in express risers supplying higher areas, which will be the case in tall buildings. The pressure at outlet fittings is to be between 8 and 12 bar. Outlet fittings are to be placed on at least every other floor starting from the third floor. The distance between an outlet fitting and the farthest place it is to reach shall not exceed 50 m. For every stairwell that is intended for fire safety use there needs to be a riser. The minimum riser dimension is DN 100 and the minimum water flow is 900 l/min. The risers are to be connected to two pumps, a primary and a secondary for back-up. Lower floors can be supplied by a municipal water pipe while higher floors will need water tanks. The required water flow needs to be supplied for at least 45 minutes (Brandskyddsföreningen, 2018).

3

Method

The thesis work has mainly consisted of the case study of the three fictitious buildings and the technical systems of those. Information was gathered by studying literature and previous work within the field, some of which is mentioned in Section 1.5. As a help to attain more information, professionals within the field have provided their knowledge and assistance.

3.1 Case study

What has been investigated is how the design choices of the chosen technical systems affect the space efficiency of a tall building. The approach has been to look at each system individually to identify important characteristics and levels specific to the system in question. For pipes and ducts the focus has been on the vertical distribution.

As explained in the introduction, the buildings of interest are tall office buildings and the data for the modeling has been chosen to comply with the activity of office buildings. Three fictitious tall buildings have been used to investigate the different systems. The buildings have been given values on height, areas etc. and the systems have been adjusted to fit the chosen buildings. The characteristics of the fictitious buildings have been based on existing buildings in order for the system solutions to have relevance to real projects.

The parts that are presented for the case study are:

- HVAC
- Elevators
- Water Distribution
- Fire Safety

The example buildings that have been used are seen with their data in Table 3.1 and the buildings are illustrated in Figure 3.1 and Figure 3.2.

Table 3.1: Example buildings with data

	Building 1	Building 2	Building 3
Total height [m]	151.2	252	352.8
Gross external area (GEA) [m^2]	800	1100	1700
Number of floors	42	70	98
Floor to floor [m]	3.6	3.6	3.6
Net internal area (NIA) [m^2]	640	880	1360
NIA/staff	15	15	15
Staff/floor	43	59	91

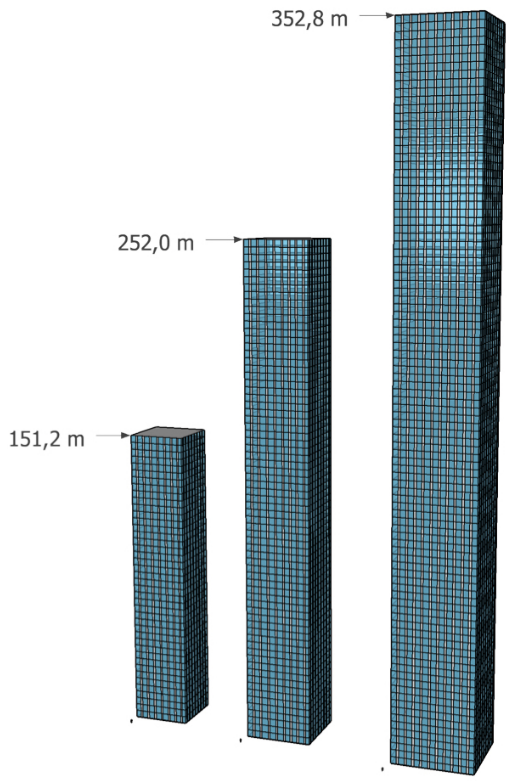

Figure 3.1: The three buildings next to each other. The height of each building is given and a person is placed at the bottom left of each building for scale.

The height and GEA of the buildings are chosen to have similar ratios as those shown in Table 2.1. With more tall buildings being built in Sweden the height is increasing as well. The heights of the chosen example buildings are chosen as plausible heights for future Swedish tall buildings. The three GEA-values are chosen as a result of building rules and practices. At 900 m^2 two rescue elevators are required and at 1250 m^2 it should be investigated if a floor should be divided into more than one fire cell. The floor to floor height is based on a number of tall buildings found in Sweden. In the U.S. or Asia it is common to have higher values. The NIA is set as 80% of the GEA based on existing tall buildings and is used as a basis for how many occupants each building has. To simplify the case study the NIA and the A-temp have been considered as the same. This is due to that all areas that are considered and used in calculations are office space with its associated activity. No parking garages or similar areas are considered which could be an example of where NIA and A-temp differs.

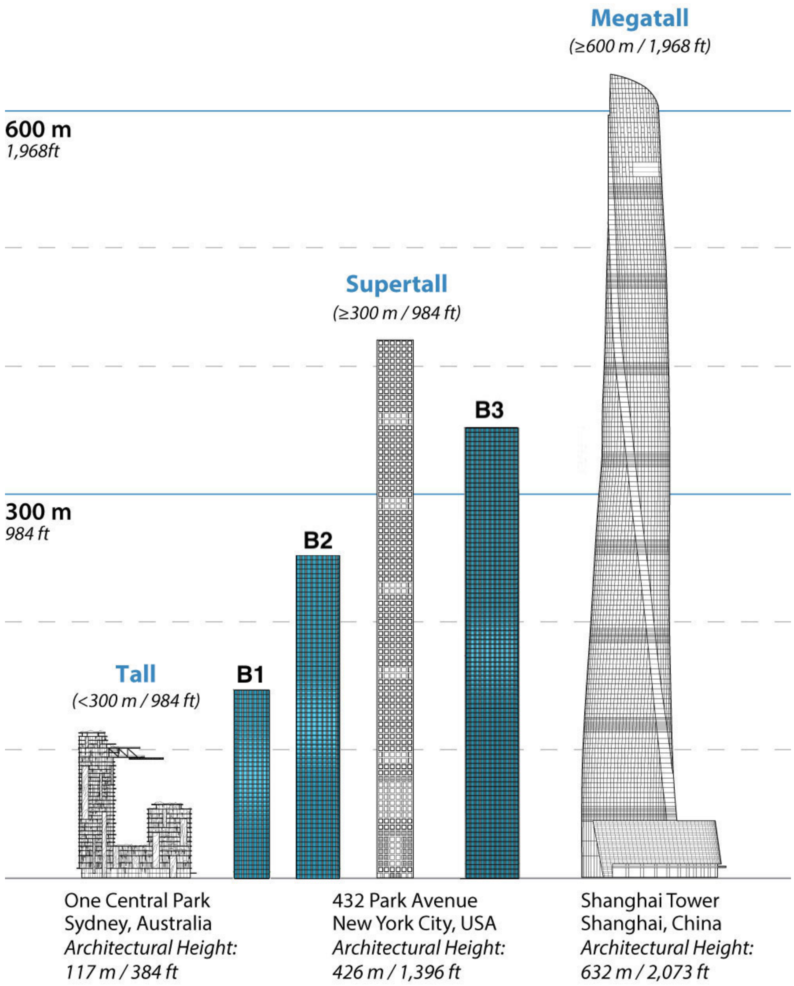

Figure 3.2: The example buildings next to existing tall buildings. Original graphic from (CTBUH, 2015b).

3.1.1 HVAC

What has been investigated for the ventilation and cooling is the effects that certain design choices have on area efficiency. For each of the possible choices in Table 3.3 the three AHU choices seen in Section 3.1.1.3 have been tested. As an example: airborne cooling at a cooling need of 40 W/m^2, ΔT of 10°C is supplied with air by one AHU that is limited to the ceiling height. Depending on the choices a varying number of floors can be supplied with air and different percentages of the GEA will be claimed by the ventilation system resulting in different efficiencies.

No fan or ventilation calculations are done for the pressurization of shafts. That part is treated in the theory chapter.

3.1.1.1 Ventilation

The ventilation rates used in the case study has been based partly on Svebys recommendations and partly on common values used by professionals within the field. However, what has been dimensioning for the ventilation rate has been the cooling need. The values can be seen in Table 3.2 below.

Table 3.2: Ventilation rates for water and airborne cooling for different cooling needs.

	Ventilation rates [l/s·m^2]	
Cooling need [W/m^2]	**Waterborne**	**Airborne**
20	**1.8**	**1.7**
30	**2.0**	**2.5**
40	**2.2**	**3.3**

3.1.1.2 Cooling

The ventilation and cooling is based on cooling needs that was found when looking at a number of tall office buildings in Sweden. Higher values could potentially occur as well, but these are the values that have been used; 20, 30 and 40 W/m^2. Two different design approaches are tested for the cooling. The first is waterborne cooling which is to have a hygienic ventilation in combination with active chilled beams. The second is airborne cooling which is to have only ventilation that provides sufficient amounts of air as well as removes the excess heat. For the first case 5°C is used as a temperature difference for the air and for the second case 10°C is used as temperature difference.

The different cooling needs represent different activities as explained in Section

2.2.1 and the idea is to test which type of system could be better suited at a given cooling need. The aim is not to do an optimization but to illustrate the importance of design choices. Table 3.3 illustrates the configurations that have been tested.

Table 3.3: Waterborne and airborne cooling configurations.

	Waterborne	**Airborne**
Cooling need [W/m^2]	**20** **30** **40**	**20** **30** **40**
ΔT [°C]	**5**	**10**

3.1.1.3 Air handling plant room size

As mentioned in Section 1.5 a previous study on the connection between SFP, air flow and plant room size has been of help when testing the different configurations. Data has been available for one AHU per plant room and two AHU:s per plant room with a range of air flow between around 4-40 m^3/s.

While it is understood that an optimal size of the plant room is not always possible it is assumed that the plant room areas used in this thesis have the potential of being as well planned as possible since an early stage of the planning process is considered.

An SFP of 1.5 kW/(m^3/s) has been chosen for this master's thesis as it is a commonly used value when designing. This has been established by interviews with professionals within the field, it is also the value suggested by BBR (Boverket, 2017a). The type of heat exchanger that has been chosen is a rotary heat exchanger. This does take up more space than the alternatives but is more common for the intended use and is hence the most realistic choice.

As previously mentioned the example buildings have been given certain measurements. The restriction in ceiling height has given a restriction when choosing the ventilation system as a larger air flow will generally require a higher ceiling height. Three different configurations have been tested when choosing the ventilation system with regards to ceiling height. What has been investigated is how many floors can be ventilated and how much of the GEA is taken depending on the following configurations:

- Configuration 1: One AHU within the ceiling height
- Configuration 2: One AHU within double the ceiling height

- Configuration 3: Two AHU:s within the ceiling height

As seen in Table 3.1 the floor to floor height is 3.6 m for all three buildings. For the office spaces the ceiling height is assumed to be 2.7 m. However, for the plant rooms it is assumed that the ceiling height is 3.3 m and that is the height that can be utilized for the plant rooms. The ceiling height in the plant room data that has been used accounts for 0.4 m of space above the AHU to make room for water pipes, meaning that the AHU itself is maximum 2.9 m high, unless two ceiling heights are being used as in configuration 2.

3.1.1.4 Ducts and shafts

The only ducts that have been dimensioned are the vertical ducts in the shafts. The dimensions of the ducts have been chosen as consistently as possible based on air flow, air speed and pressure drop. The air speed and pressure drop have been chosen as approximately 10 m/s and 1 Pa/m respectively. Naturally, there have been some variance due to that standard dimensions have been chosen for the ducts. Ducts have only been dimensioned for the vertical shafts and the large air flows have resulted in rectangular ducts. The size of the ventilation shafts have been chosen as twice the size of the supply and return duct with insulation included. This is both due to enable maintenance work and provide room for flexibility.

3.1.2 Elevators

Very advanced technology is mentioned in Section 2.3 and all of it will not be part of the solutions that are tested in this thesis due to the intricacy of the systems and the limitations of the software. What has been tested in this thesis is the influence of zoning choices and also the use of one or several sky lobbies. Destination control has been used for all of the calculations as it is preferred when there are more than four elevators (LG Segerlind, personal communication, April 1, 2019).

The programs that have been used to model the elevator configurations are KONE Quick Traffic and KONE Planulator. Quick Traffic allows the user to provide data on type of building (office) and type of use (multiple tenant, flexible working hours) as well as zone information such as travel distance, number of floors served and occupants per zone. Estimated speed and size per elevator is suggested and depending on the choices a certain number of elevator cars will be required. The program has a predefined limit of ”time to destination” which is from when the user requests a floor to when the elevator doors open on the requested floor. The chosen elevator configuration has to fit within the given time. Planulator allows the user to choose number of people per elevator and elevator speed among other things and then provides required dimensions of an elevator shaft. As understood when consulting the KONE-support the Quick Traffic program uses the full population value and that is what has been entered in the calculations. It is assumed that the entered type of use ”multiple tenant, flexible working hours” accounts for any variance in occupancy. The default setting for the peak handling capacity has been kept at 14% of the population/5 minutes.

The program provides the option of changing the elevator size in the sense that the number of occupants per elevator can be chosen. However, it is not possible to choose a rescue elevator which would have its own closed off shaft with certain dimensions. Hence, the use of rescue elevators is merely treated in the theory part of the thesis.

The two programs have been used together to find realistic configurations and measurements that could be used for the example buildings. The intention is not to optimize the solutions and give conclusive answers to what is the best solutions but rather to illustrate the importance of design choices.

When using the programs it is assumed that all floors have the same activity and number of occupants. This is not likely to be the case in reality but had to be assumed to use the programs.

3.1.3 Water distribution

Distribution of water in tall buildings is a question of pressure levels. The water pressure has to be in range of minimum and maximum pressure and these levels are depending on what kind of water pressure system is used. Pumping water a great vertical distance costs a lot of energy but it is achievable if the water flow together with desired water pressure suits the pump curve. It is a balance between energy consumption and space needed for pump rooms. The water distribution system that is chosen according to Figure 2.14, is a combination of energy- and space efficient system resulting in a series connected system. Tap water demand in an office building is low when comparing with residential buildings but is of great importance. The water usage per worker is multiplied by the total number of workers and then divided on the number of pumps to get a specific flow per pump. The pump should be able to distribute the total water flow to all desirable floors, the pumps have then been evaluated to see if the water flow could be pumped to the highest floor within the sectioning. The same procedure has been done for wastewater but the system does not need any pumps it is just the dimension of the wastewater pipes that is of importance.

The water pressure should be between 1-5 bar for the installations to work correctly. The friction loss in the pipes depends on the water flow and pipe size but a pressure loss of 0.0125 bar/m has been used in the calculations. The minimum pressure at the tap is 1 bar, this means that the differential pressure is 4 bar which is around 40 meters.

The size of the water and sewage shaft has been calculated by using the definition of a standard shaft in Sweden, this is seen in Figure 3.3. The dimensions of the ducts depends on the water- and wastewater flow but the insulation thickness and the distance between the ducts is chosen according to the Figure 3.3.

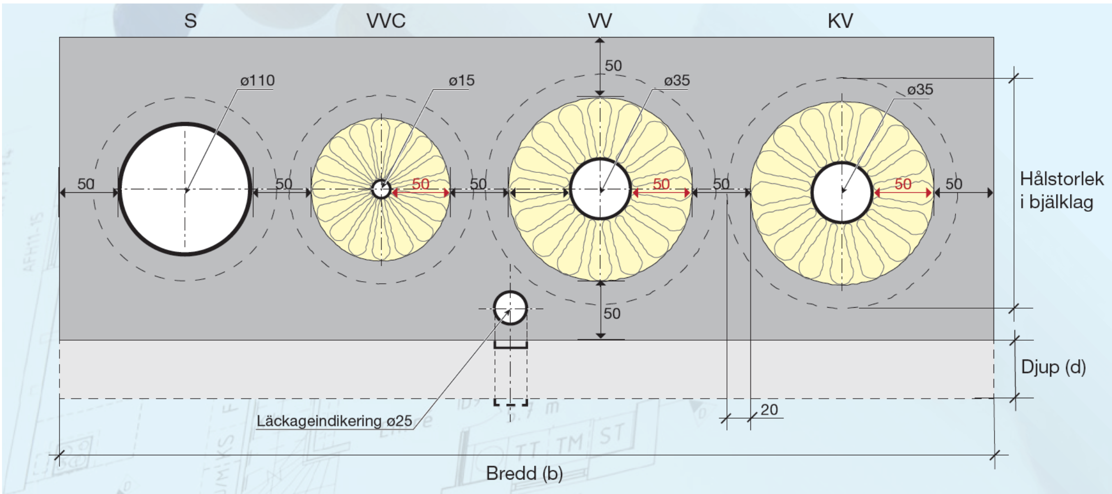

Figure 3.3: Shaft for tap water, wastewater and hot water circulation.

To get the pipe dimensions for tap water the flow for cold and hot water is used and the same principal for wastewater duct dimensions. The hot water circulation has not been investigated but the dimensions of the pipes are very small compared to the insulation thickness and other pipe dimensions. The shaft area should be multiplied with a factor 3 to get the area needed for service personnel to be able to repair and maintain the ducts. The pump also need extra space for service and therefore extra space of 300 mm from the nearest side wall, 500 mm from the wall behind the pump and at least 1000 mm in front of the pump (Magnus Johansson, personal communication, April 8, 2019)

3.1.4 Fire safety

For the sprinkler system the pressure losses in the system is from friction loss in pipes and pressure loss at sprinkler heads. The friction losses in the pipes occur from the pump to the sprinkler head furthest away from the pump. The pressure loss at the sprinkler head is depending on the water flow and size of head. For ordinary hazard group 1 (OH1) the K-factor is 80 l/min/$\sqrt{bar}$, the pressure drop over the sprinkler head is calculated by using Equation 2.2 which gives a pressure drop of 0.56 bar. The minimum pressure at the sprinkler head is 0.35 bar and the maximum pressure is 12 bar and this pressure needs to be fulfilled for the sprinkler to function (Fogtec, n.d.). The required water flow at the sprinkler is dependent on the classification of the building, if it is e.g an office, hotel or restaurant. In this case it is an office building which has the lowest demand (Standard, 2004). The water flow should be spread over an area which is dependent of the hazard type. A sprinkler head could handle 8-12 m^2 floor area, the floor area is divided on 8-12 m^2 and the result is the amount of sprinklers (Standard, 2004). For OH1 the design density is 5 mm/min and the working area for the sprinkler is 72 m^2. The total water flow for a floor is then working area times the design density. The maximum amount of floors for each sprinkler central is a combination of the water flow and required water pressure. The water tanks should have enough water to supply the sprinkler system with water for 60 minutes (Standard, 2004). The area needed for a sprinkler room to function is 30 m^2 (Fogtec, n.d.). The room should be sufficiently large for service staff and for the firefighter to use it.

For the water mist system the available pressure is much higher than for the sprinkler system, using high-pressure pumps with a pressure of 140 bar. The needed pressure at the head is 60 bar which means that 80 bar is left for vertical transport of the water and to handle pressure losses. Depending on the pressure losses a height of 600-800 meter is attainable, in the thesis the buildings are lower than this and usage of a water mist system is therefore considered. The design density for the water mist system is 2.2 mm/min and the water tanks should be able to supply the system for 60 minutes. The area needed for a water mist room to function is 24 m^2 (Fogtec, n.d.).

4

Analysis

This chapter presents the results and reflections from the studied example buildings. As described in the method chapter, three fictitious buildings have been used to investigate possible solutions for HVAC, elevators, water distribution and fire safety. The result for each technical system is presented below and the result should be seen as alternative solutions which does not need to be the best. In reality each project has to be treated individually to find what is best suited.

4.1 HVAC

Presented below is the results for the ventilation and cooling followed by reflections.

4.1.1 Results

The results for the different ventilation and cooling solutions will be presented as percentages of how much area each solution claims of the gross external area. As presented in Tables 3.2 and 3.3 three cooling needs are used as basis for the ventilation rates and both waterborne and airborne cooling is investigated. For waterborne a temperature difference of 5 °C is used whereas for airborne a temperature difference of 10 °C is used.

Tables 4.1, 4.2 and 4.3 presents how much of the gross external area is taken by the three ventilation configurations expressed in percentages (C1, C2 and C3 as described in Section 3.1.1.3). It is also shown how many floors are supplied by each plant room. Included in the ventilation area is the area of the plant rooms and the area of the ventilation shaft on each floor.

Since the number of floors have been decided for each building and the number of floors supplied by each plant room should be maximized it will for some of the cases result in that the last plant room supplies a smaller number of floors. These floors will be marked in parenthesis in the result tables. This is less than optimal but does not have a significant effect on the results. Some deviations in choices regarding this approach has been done as well and is further discussed in Section 4.1.2.

After each table of results there are illustrations of the three ventilation configurations next to each other. The illustrations show only a couple of the possible configurations and it is stated in the figure text which it is.

Table 4.1: Area taken by the ventilation solutions for Building 1 expressed in percentages. Shown also is the number of floors supplied from one plant room. In parenthesis is the number of odd floors.

Building 1						
42 floors **151.2m** **800 m^2 GEA**						
Waterborne cooling		**ΔT 5 [°C]**	Plant room area [m^2]	Shaft area [m^2]	Vent.Area/ GEA	Floors/ Plant room
Cooling need [W/m^2]	20	C1	315	109	**1.3 %**	**8** (+2)
		C2	559	203	**2.3 %**	**21**
		C3	276	166	**1.3 %**	**14**
	30	C1	371	109	**1.4 %**	**7**
		C2	599	240	**2.5 %**	**21**
		C3	302	203	**1.5 %**	**14**
	40	C1	403	109	**1.5 %**	**7**
		C2	632	284	**2.7 %**	**21**
		C3	324	203	**1.6 %**	**14**
Airborne cooling		**ΔT 10 [°C]**	Plant room area [m^2]	Shaft area [m^2]	Vent.Area/ GEA	Floors/ Plant room
Cooling need [W/m^2]	20	C1	304	109	**1.2 %**	**9** (+6)
		C2	532	203	**2.2 %**	**21**
		C3	219	203	**1.3 %**	**19** (+4)
	30	C1	454	109	**1.7 %**	**6**
		C2	695	284	**2.9 %**	**20** (+2)
		C3	379	203	**1.7 %**	**12** (+6)
	40	C1	614	109	**2.2 %**	**4** (+2)
		C2	947	284	**3.7 %**	**14**
		C3	495	203	**2.1 %**	**9** (+6)

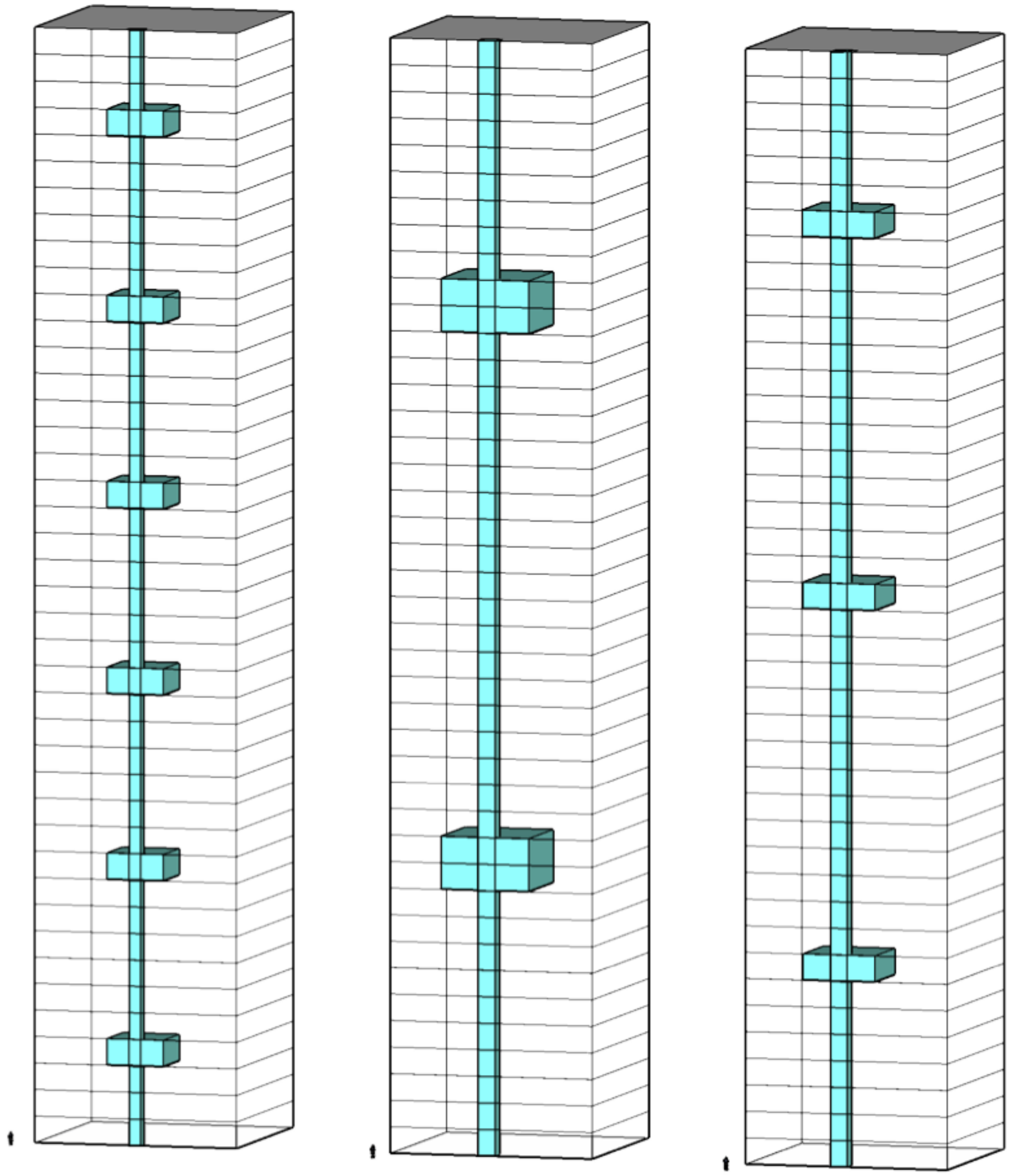

Figure 4.1: Building 1 with the three ventilation configurations for waterborne cooling at 30 w/m^2. Marked in blue is the plant rooms and ventilation ducts. A person is placed at the bottom left of each building for scale.

Table 4.2: Area taken by the ventilation solutions for Building 2 expressed in percentages. Shown also is the number of floors supplied from one plant room. In parenthesis is the number of odd floors.

<table>
<tr><td colspan="7">Building 2</td></tr>
<tr><td colspan="7">70 floors
252m
1100 m^2 GEA</td></tr>
<tr><td colspan="2">Waterborne cooling</td><td>ΔT 5 [°C]</td><td>Plant room area [m^2]</td><td>Shaft area [m^2]</td><td>Vent.Area/ GEA</td><td>Floors/ Plant room</td></tr>
<tr><td rowspan="9">Cooling need [W/m^2]</td><td rowspan="3">20</td><td>C1</td><td>761</td><td>182</td><td>1.2 %</td><td>6 (+4)</td></tr>
<tr><td>C2</td><td>1203</td><td>473</td><td>2.2 %</td><td>20 (+10)</td></tr>
<tr><td>C3</td><td>617</td><td>339</td><td>1.2 %</td><td>12 (+10)</td></tr>
<tr><td rowspan="3">30</td><td>C1</td><td>842</td><td>182</td><td>1.3 %</td><td>5</td></tr>
<tr><td>C2</td><td>1292</td><td>473</td><td>2.3 %</td><td>18 (+16)</td></tr>
<tr><td>C3</td><td>684</td><td>339</td><td>1.3 %</td><td>11 (+4)</td></tr>
<tr><td rowspan="3">40</td><td>C1</td><td>1093</td><td>182</td><td>1.7 %</td><td>6 (+4)</td></tr>
<tr><td>C2</td><td>1453</td><td>473</td><td>2.5 %</td><td>16 (+6)</td></tr>
<tr><td>C3</td><td>741</td><td>339</td><td>1.4 %</td><td>10</td></tr>
<tr><td colspan="2">Airborne cooling</td><td>ΔT 10 [°C]</td><td>Plant room area [m^2]</td><td>Shaft area [m^2]</td><td>Vent.Area/ GEA</td><td>Floors/ Plant room</td></tr>
<tr><td rowspan="9">Cooling need [W/m^2]</td><td rowspan="3">20</td><td>C1</td><td>690</td><td>176</td><td>1.1 %</td><td>7</td></tr>
<tr><td>C2</td><td>1035</td><td>473</td><td>2.0 %</td><td>21 (+7)</td></tr>
<tr><td>C3</td><td>553</td><td>339</td><td>1.2 %</td><td>14</td></tr>
<tr><td rowspan="3">30</td><td>C1</td><td>1050</td><td>182</td><td>1.6 %</td><td>4 (+2)</td></tr>
<tr><td>C2</td><td>1610</td><td>473</td><td>2.7 %</td><td>14</td></tr>
<tr><td>C3</td><td>830</td><td>339</td><td>1.5 %</td><td>9 (+6)</td></tr>
<tr><td rowspan="3">40</td><td>C1</td><td>1418</td><td>182</td><td>2.1 %</td><td>3 (+2)</td></tr>
<tr><td>C2</td><td>2186</td><td>473</td><td>3.5 %</td><td>10</td></tr>
<tr><td>C3</td><td>1105</td><td>339</td><td>1.9 %</td><td>7</td></tr>
</table>

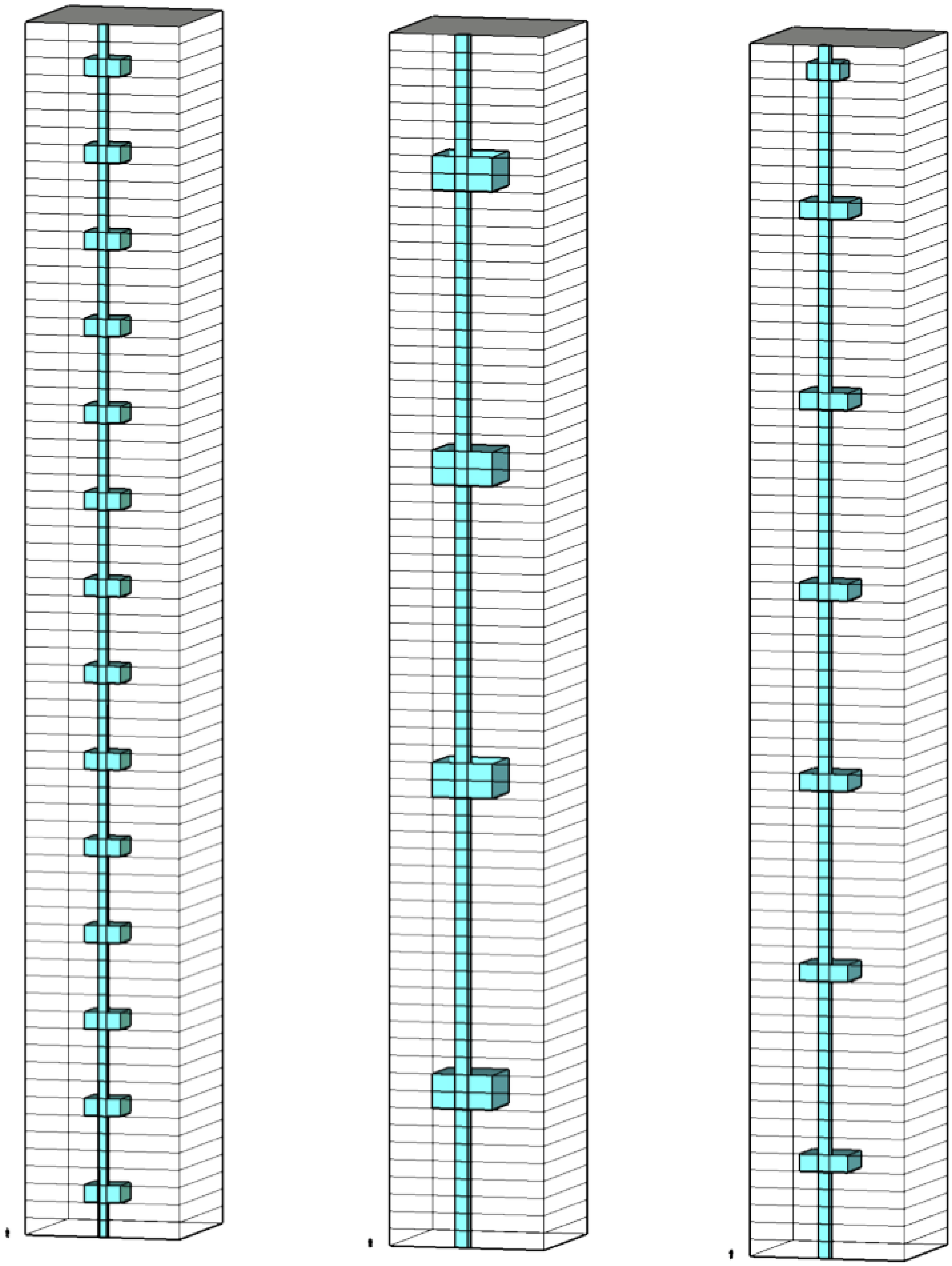

Figure 4.2: Building 2 with the three ventilation configurations for waterborne cooling at 30 W/m^2. Marked in blue is the plant rooms and ventilation ducts. A person is placed at the bottom left of each building for scale.

Table 4.3: Area taken by the ventilation solutions for Building 3 expressed in percentages. Shown also is the number of floors supplied from one plant room. In parenthesis is the number of odd floors.

Building 3						
98 floors **352.8m** **1700 m^2 GEA**						
Waterborne cooling		**ΔT 5 [°C]**	Plant room area [m^2]	Shaft area [m^2]	Vent.Area/ GEA	Floors/ Plant room
Cooling need [W/m^2]	20	C1	1637	247	**1.1 %**	**4** (+2)
		C2	2554	662	**1.9 %**	**12** (+2)
		C3	1324	474	**1.1 %**	**8** (+2)
	30	C1	1837	212	**1.2 %**	**3** (+2)
		C2	2838	662	**2.1 %**	**11** (+10)
		C3	1463	474	**1.2 %**	**7**
	40	C1	2007	255	**1.4 %**	**3** (+2)
		C2	3137	662	**2.3 %**	**10** (+8)
		C3	1640	474	**1.3 %**	**6** (+2)
Airborne cooling		**ΔT 10 [°C]**	Plant room area [m^2]	Shaft area [m^2]	Vent.Area/ GEA	Floors/ Plant room
Cooling need [W/m^2]	20	C1	1510	255	**1.1 %**	**4** (+2)
		C2	2298	662	**1.8 %**	**14**
		C3	1200	388	**1.0 %**	**9** (+8)
	30	C1	2241	247	**1.5 %**	**3** (+2)
		C2	3505	662	**2.5 %**	**9** (+8)
		C3	1807	474	**1.4 %**	**6** (+2)
	40	C1	3014	255	**2.0 %**	**2**
		C2	4595	662	**3.2 %**	**7**
		C3	2462	474	**1.8 %**	**4** (+2)

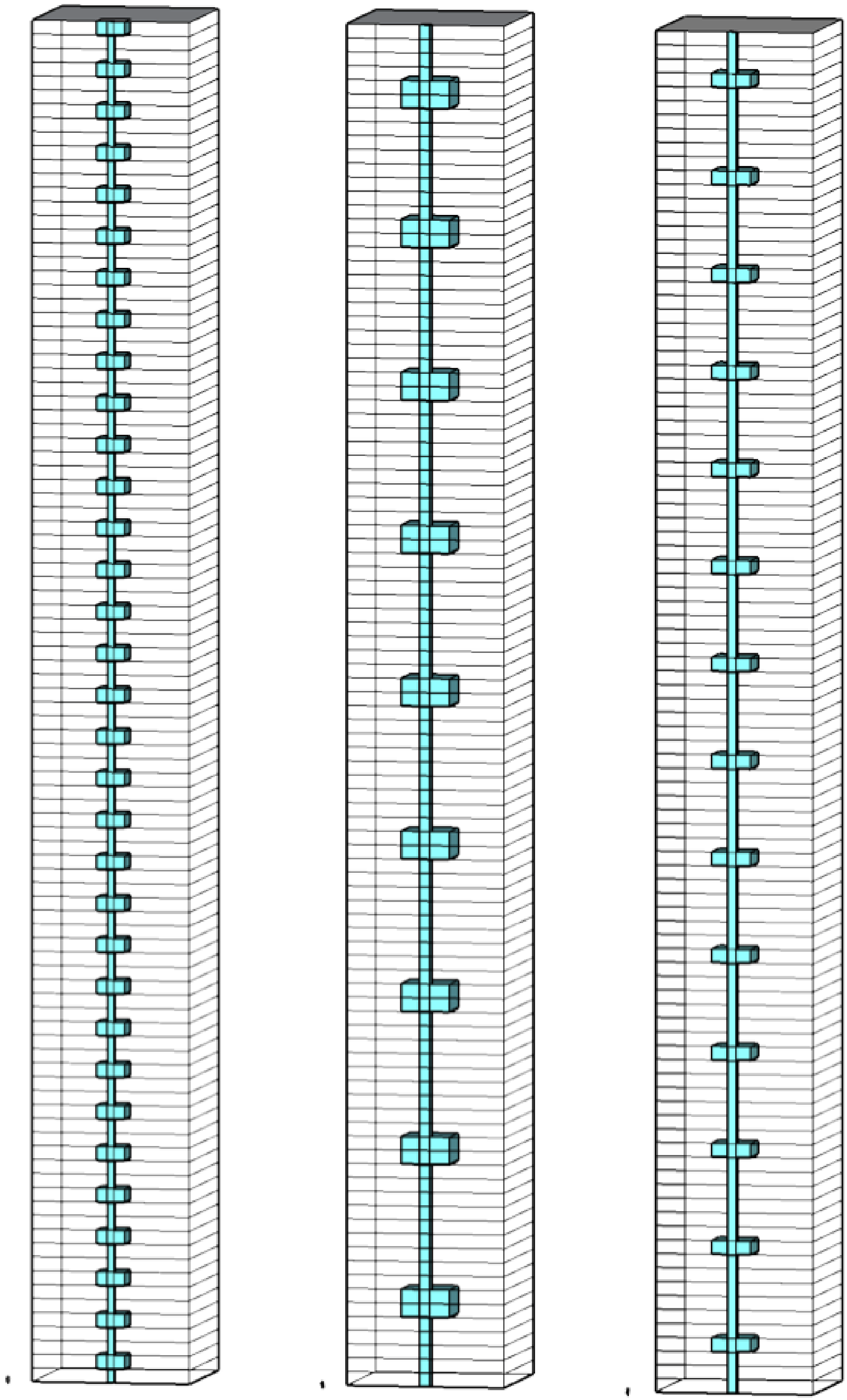

Figure 4.3: Building 3 with the three ventilation configurations for waterborne cooling at 30 W/m^2. Marked in blue is the plant rooms and ventilation ducts. A person is placed at the bottom left of each building for scale.

4.1.2 Reflections

All three cooling needs that have been used in the case study require a larger air flow than what is needed to satisfy the hygienic air flow which means that the hygienic air flow is provided in all cases.

When increasing the height of a building there are no drastic changes in how the ventilation system is designed. The outside air can in many cases be taken from the same height as the air handling plant room is at, which means that a plant room at floor 5 can look the same as on floor 50. Although, in some cases the risk of getting in polluted or dirty air will require the outside air to be taken from another floor than the one of the AHU. This would result in large ducts taking up extra space on several floors.

In Table 4.1 the floors per plant room seem much more evenly distributed compared to the other buildings. For C2 there could actually have been more than 21 floors supplied by one AHU but it was chosen to divide the floors evenly on two plant rooms, 21 floors for each. Otherwise one plant room would have taken perhaps 30 floors and the other 12. The second plant room that would supply 12 floors would still have to use the double ceiling height which in total would result in a less space efficient solutions. For buildings 2 and 3 seen in Tables 4.2 and 4.3 this was not an issue.

4.1.2.1 Space efficiency

As can be seen in Tables 4.1, 4.2 and 4.3, C2 (one AHU, double ceiling height) is least space efficient in all cases. When looking at C1 (one AHU, regular ceiling height) and C3 (two AHU:s, regular ceiling height) the results are less conclusive. The relation between C1 and C3 are not always the same when comparing the Vent.Area/GEA for 20, 30 and 40 W/m^2 for both waterborne and airborne cooling. In some cases C1 is more space efficient and in some cases C3 is. This is interesting because at first glance it might feel natural that C3, that has two AHU:s in the same plant room and can utilize that space more efficiently, will be more space efficient overall. In Figure 4.1 C1 (left) and C3 (right) for waterborne cooling at 30 W/m^2 in Building 1 are seen. C1 has six plant rooms, i.e. six AHU:s. C3 has three plant rooms, i.e. six AHU:s. The number of AHU:s are the same but it is clearly seen in Table 4.1 that C3 takes up less space for the plant rooms. Based on simply the plant rooms C3 is more space efficient in every comparison. However, it is not that simple. Due to the fact that C3 can supply more floors from one plant room the flow from each room will be larger, which results in larger ducts and shafts.

With the plant rooms and shafts considered, C1 and C3 takes up basically the same amount of space. The model that the plant room areas are based on is considered to be valid and thus the areas are trusted to be valid as well. However, it should be said that the plant room model is a bit of a best-case scenario and all plant rooms might not be as space efficient. The areas for the shafts are based on calculations of the required flows, assumed thickness of insulation, shaft walls and space needed for maintenance. Although the shaft calculations and assumptions are believed to be true to real solutions the space assumed for maintenance might be smaller or larger in real buildings depending on what is prioritized.

4.1.2.2 Waterborne vs. airborne cooling

The two main means of cooling that was used in the case study was waterborne cooling and airborne cooling. Which of them that is best in terms of space efficiency depends on the cooling need. What was found is that at a cooling need of 20 W/m^2 waterborne and airborne were quite even in terms of space efficiency. This is due to that the low cooling need was satisfied almost entirely by the basic ventilation and very little extra cooling was required. At cooling needs of 30 and 40 W/m^2 however, waterborne cooling was more space efficient since the airborne solution required a lot larger air flows. The space taken by cooling towers, chilled beams and connecting pipes are not taken into account in this comparison.

4.1.2.3 Distribution

The distribution of the system, the number of plant rooms and the number of floors that can be supplied with air by one plant room, depends on the required air flow and the type of configuration (C1, C2 or C3). With the chosen floor to floor height of 3.6 m the maximum floor per plant room for each configuration is seen in the results tables. There is of course the possibility of having fever floors supplied by each plant room than what is presented here, the tables simply show the limits. The choice of configuration is in reality not as simple as choosing the one that takes the least space. Other factors have to be taken into account, e.g. the cost of the ventilation system itself as well as the rent price. The number of floors supplied by each plant room could also be increased in reality. The ceiling height for the plant rooms was set to 3.3 m which resulted in the presented distributions. However, this distribution would look different if the ceiling height changed. The distribution could also look different if other configurations had been used. If for example 3 AHU:s were put in one plant room, or if 2 AHU:s utilized double ceiling height. Another possibility is to increase the ceiling height of only the floors that have technical rooms. This would give the possibility to increase the number of floors supplied by each plant room without increasing the total height drastically. The distribution depends on the prerequisites of the project and will be a result of the choices made.

4.2 Elevators

Presented below are the results on the elevator calculations followed by reflections.

4.2.1 Results

As mentioned in Chapter 3, the elevator configurations are found with the help of certain software and with guidance from previous work. It should be understood that the configurations presented in this section is not meant to be optimized as it is recognized that elevator design is very complex. This is meant to illustrate the importance of design choices and the effect it has on the space efficiency of tall buildings and also to illustrate possible levels that can be relevant for the elevator systems. With that said, the configurations are believed to be fairly close to real solutions as the programs have been used in accordance with the instructions.

The percentages presented account for the elevator shafts with the needed machine rooms, not entire structural shafts. As can be seen in the elevator illustrations in this chapter the machine rooms (marked in black in the figures) vary in height depending on the shaft. This is related to the speed at which the elevator travels. A lower speed will result in a smaller machine room.

The overall size of the elevator shafts presented in the figures are proportionate to what is presented in the tables. However, all shafts have been made square while the real shape would be more rectangular. Also, the positioning of the shafts is merely meant to show how it could look, not to show exactly how it should look.

Rescue elevators that have specific requirements on size and safety have not been taken into account in the modeling due to that it was not possible to add in the programs.

Tables 4.4, 4.5 and 4.6 shows possible elevator solutions for the three buildings. The tables present number of zones, number of floors per zone, area per floor taken by each elevator shaft, total area taken by each shaft, total area taken by all shafts together and how much of the GEA is taken by the shafts. The Figures 4.4, 4.5 and 4.6 are meant to help the understanding of the tables. No marks are shown in the figures to illustrate the floors but the tables explain what floor pertain to what zone and shaft.

Table 4.4: Building 1. Possible elevator configurations and the area taken by each, expressed in percentages of the GEA.

B1	**Zone**	**Floors**	**Area /Floor [m^2]**	**Area [m^2]**	**Total Area [m^2]**	**Total Area /GEA**
C1	1	1-22	45.4	1089		
	2	22-42	51	2144	3233	**9.6 %**
C2	1	1-16	29	493		
	2	16-29	31.1	964		
	3	29-42	34.7	1458	2915	**8.7 %**
C3	1	1-12	22.3	289		
	2	12-22	24.5	588		
	Sky lobby		23.4	560		
	3	22-32	22.3	289		
	4	32-42	27.5	577	2303	**7.1 %**

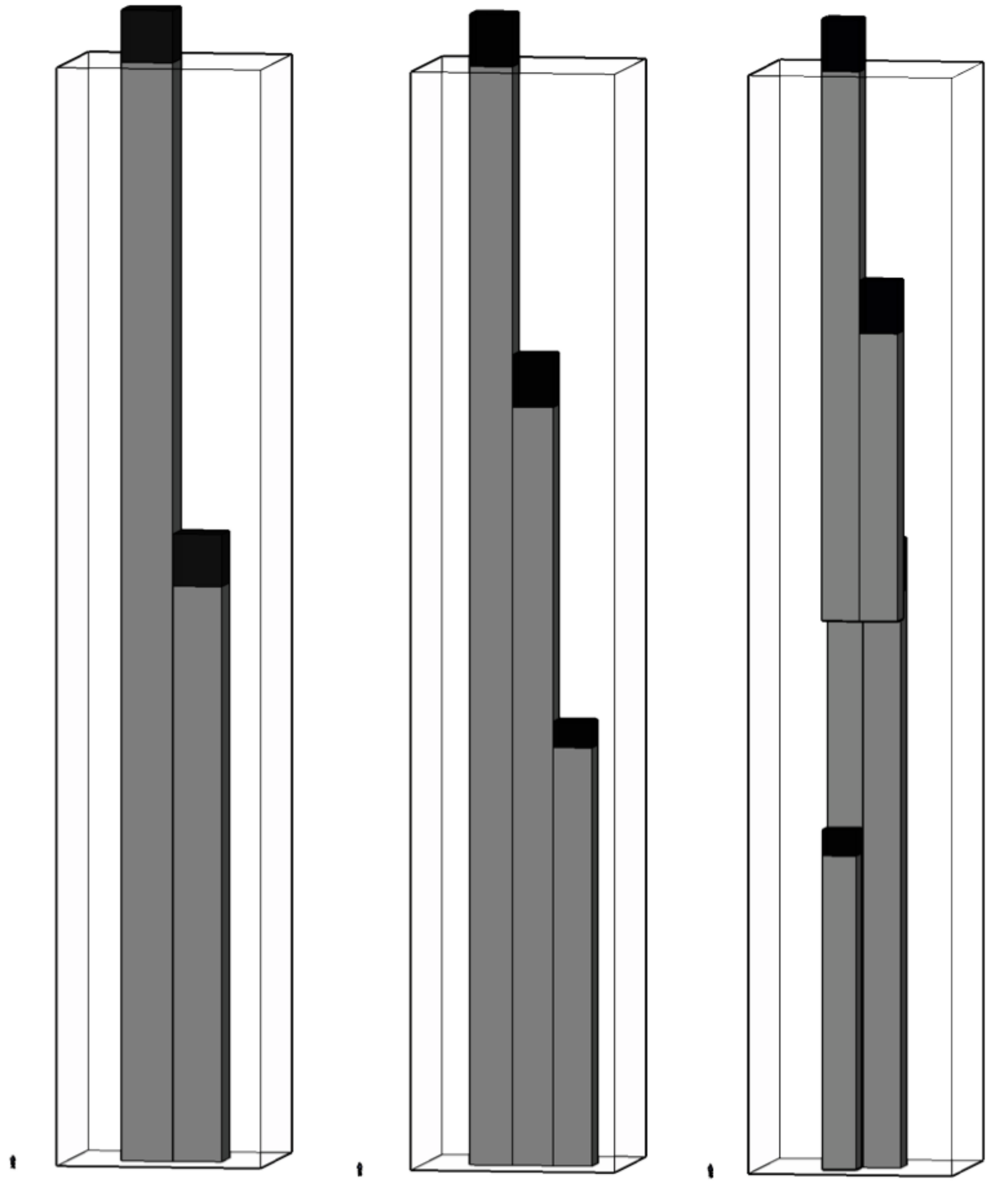

Figure 4.4: Building 1 with its three elevator configurations, C1, C2 and C3 from left to right. The elevator shafts are marked in grey and the mechanical rooms are marked in black. A person is placed at the bottom left of each building for scale.

Table 4.5: Building 2. Possible elevator configurations and the area taken by each, expressed in percentages of the GEA.

B2						
	Zone	**Floors**	**Area /Floor [m^2]**	**Area [m^2]**	**Total Area [m^2]**	**Total Area /GEA**
C1	1	1-30	82.7	2648		
	2	30-52	72.5	3916		
	3	52-70	83.7	5859	12423	**16.1 %**
C2	1	1-16	40.7	692		
	2	16-30	40.5	1295		
	3	30-44	44.7	2054		
	4	44-57	53.2	3139		
	5	57-70	53.2	3725	10905	**14.2 %**
C3	1	1-16	40.7	692		
	2	16-30	40.5	1295		
	3	30-44	44.7	2054		
	Sky lobby		53.2	2446		
	4	44-57	38.5	616		
	5	57-70	40.5	1133	8236	**10.7 %**

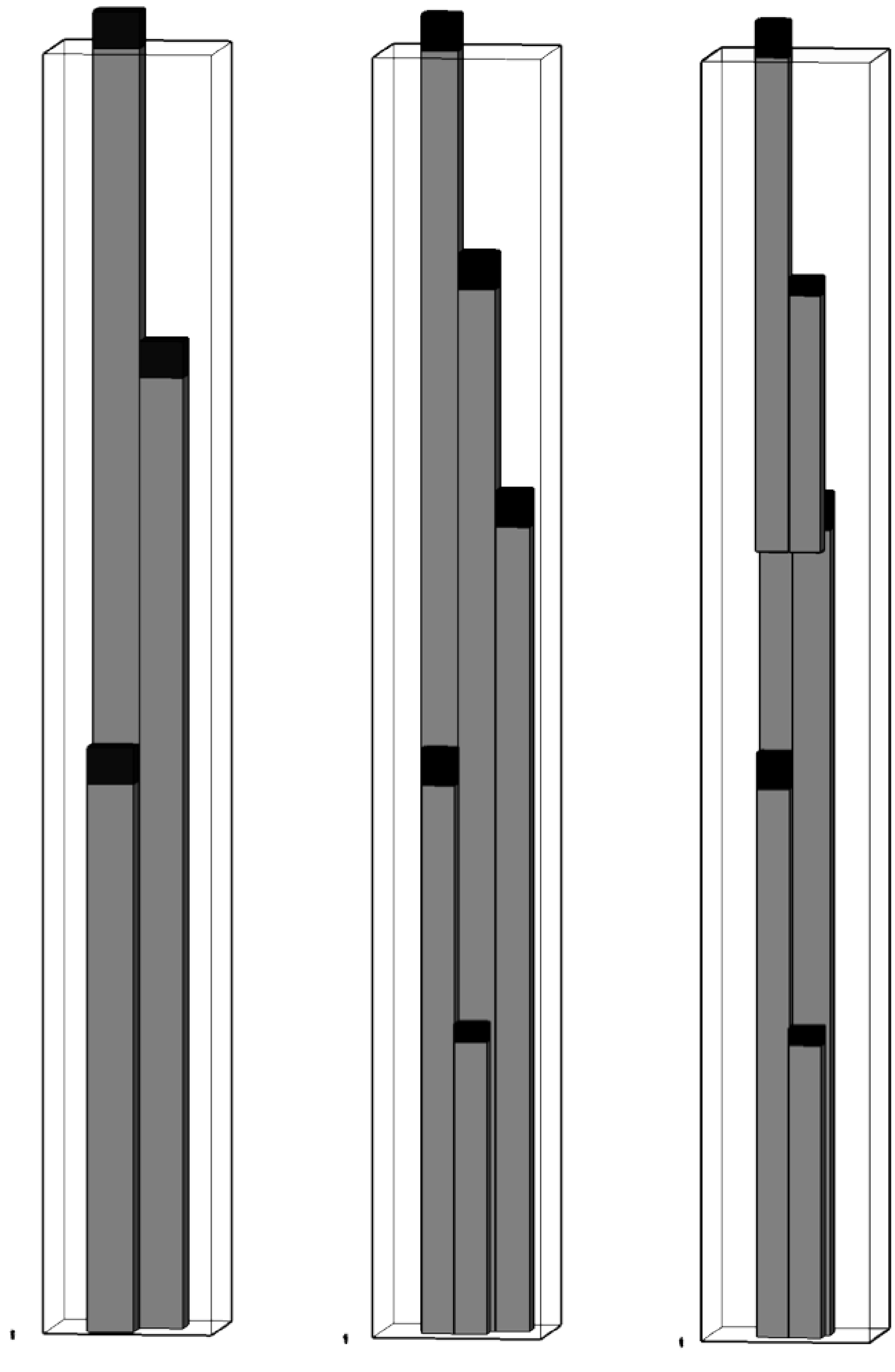

Figure 4.5: Building 2 with its three elevator configurations, C1, C2 and C3 from left to right. The elevator shafts are marked in grey and the mechanical rooms are marked in black. A person is placed at the bottom left of each building for scale.

Table 4.6: Building 3. Possible elevator configurations and the area taken by each, expressed in percentages of the GEA.

B3						
	Zone	**Floors**	**Area /Floor [m^2]**	**Area [m^2]**	**Total Area [m^2]**	**Total Area /GEA**
C1	1	1-25	98.7	2667		
	2	25-46	93.0	4461		
	3	46-65	93.0	6227		
	Sky lobby		104.6	7010		
	4	65-82	68.0	1360		
	5	82-98	68.3	2324	24049	**14.4 %**
C2	1	1-14	50.6	758		
	2	14-26	50.2	1406		
	3	26-38	59.7	2388		
	4	38-50	63.3	3292		
	Sky lobby		109.1	5673		
	5	50-63	60.0	900		
	6	63-75	50.2	1406		
	7	75-87	60.4	2416		
	8	87-98	63.3	3102	21341	**12.8 %**
C3	1	1-12	32.1	418		
	2	12-22	38.1	914		
	3	22-32	40.2	1366		
	4	32-42	43.7	1921		
	Sky lobby		74.5	3279		
	5	42-52	38.5	462		
	6	52-61	40.3	887		
	7	61-70	40.5	1254		
	Sky lobby		94.8	6825		
	8	70-80	38.5	462		
	9	80-89	40.3	887		
	10	89-98	40.5	1173	19848	**11.9 %**

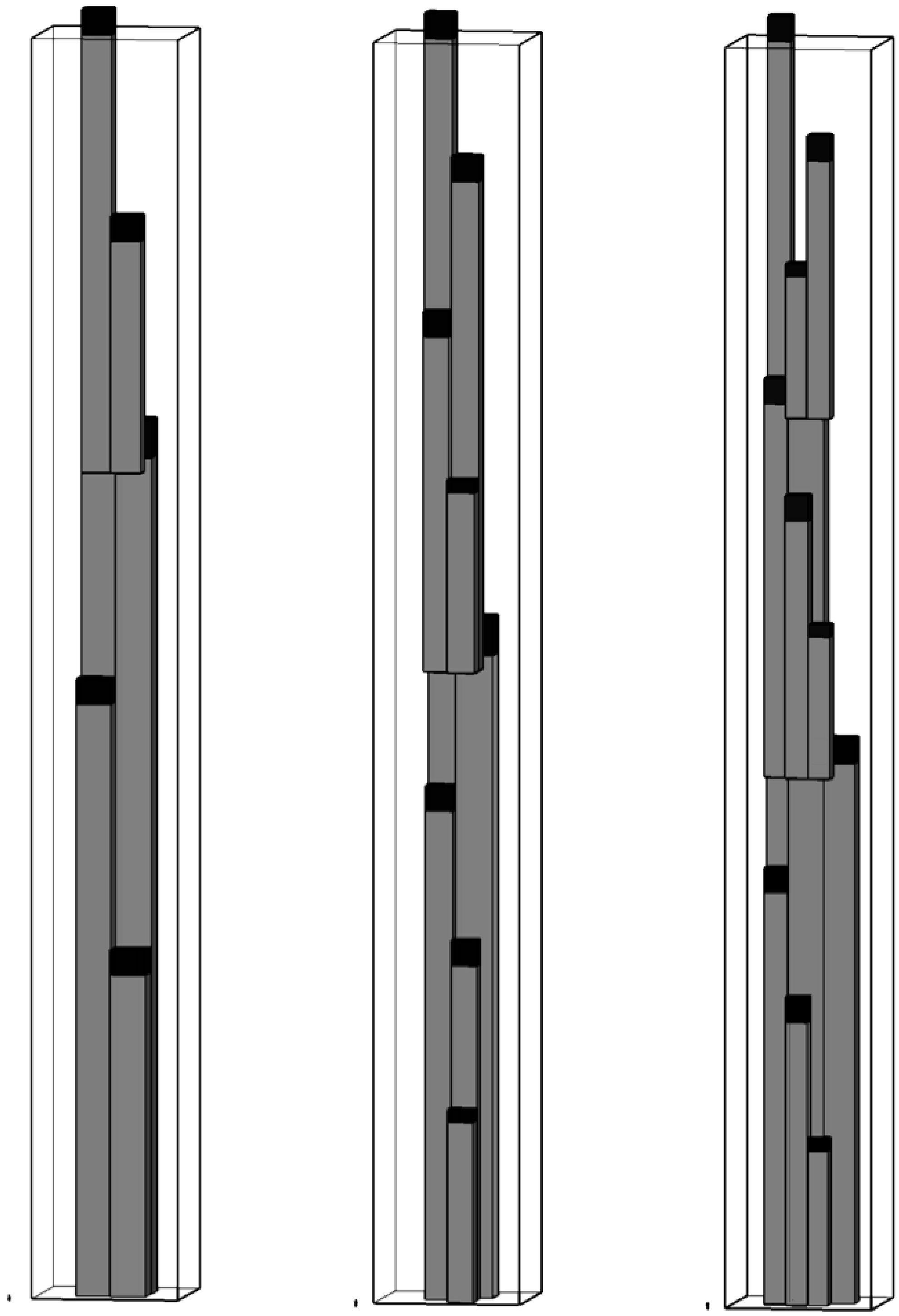

Figure 4.6: Building 3 with its three elevator configurations, C1, C2 and C3 from left to right. The elevator shafts are marked in grey and the mechanical rooms are marked in black. A person is placed at the bottom left of each building for scale.

4.2.2 Reflections

Elevators do take up a significant amount of space in tall buildings which means that there is a large potential to save space by well-planned design. When looking at the ventilation configurations it was noted that the area claimed by the system was not dependent on the height of the building but the choice of floors supplied by each plant room. In the case of elevators the system is much more affected by the building height due to that most of the elevator shafts take up space even on floors that they do not serve. See C1, zone 5 in Table 4.5 for example. The elevator group serves floors 57-70 but takes as much space from each floors it serves as each floor it does not serve. Thus, with increasing height there will be more ”dead space” taken by elevator shafts.

4.2.2.1 Zone choices

Choosing the number of zones and number of floors per zone will have a large effect on the total area claimed by the elevators. In Table 4.4 it can be seen that when increasing from two zones to three the total area taken by the elevators decreases even though it essentially means adding another elevator shaft. The main reason for the decrease in area taken by the shafts is that with one more zone each zone serves fever people which requires a lower capacity and thus smaller dimensions of the shaft. It is seen clearly in Figure 4.4 that C1 (left) has larger dimensions of the shafts than C2 (middle). The same can be seen for Building 2 and 3 as well.

4.2.2.2 Sky lobbies

It is evident for all three buildings that the use of sky lobbies has the potential of decreasing the space taken by the elevator system. When searching for information and looking at existing tall buildings and their elevator solutions sky lobbies was not seen in buildings at similar heights as Building 1 (151.2 m) which would suggest that it is not realistic to have in a building of that height. An explanation to this could be that it is not as easy as space saved equals money saved.

For the taller buildings however, the use of sky lobbies is more common. This could be partly because of the physical limitations that arise when reaching certain heights, but also that when a building increases in height much of the elevator shaft will be ”dead space” as discussed previously and sky lobbies will counteract this.

4.3 Water distribution

Results for distribution of tap water is evaluated and analysed below but also reflections how sectioning of the systems could be done and what limitations the systems have.

4.3.1 Results

The distribution of tap water has fewer floors per pump room than sprinkler, this is due to the pressure range. The minimum pressure is 1 bar and the maximum pressure is 5 bar at the tap. The pump needs to overcome the pressure losses as static losses and friction losses. The differential pressure could maximum be $\sim$ 4 bar if no pressure reducing valves is used. The static loss is 0.1 bar/m and the friction loss is 0.0125 bar/m, the static loss will be 0.36 bar/floor and the friction loss 0.045 bar/floor which is seen in Table 4.7. This results in a sectioning of maximum 10 floors per pump room. In this case for building 1, 2 and 3 a sectioning of 10 floors per pump room is chosen. This sectioning results in 4, 7 and 10 pump rooms for building 1, 2 and 3.

Table 4.7: Water pressure and pressure losses for tap water.

Floor	**Static loss** [bar]	**Friction loss** [bar]	**Total pressure** [bar]
1	0.36	0.045	0.41
2	0.72	0.045	0.81
3	1.08	0.045	1.22
4	1.44	0.045	1.62
5	1.80	0.045	2.02
6	2.16	0.045	2.42
7	2.52	0.045	2.84
8	2.88	0.045	3.24
9	3.24	0.045	3.65
10	3.60	0.045	4.05

A probable water flow is calculated by using the value of 1000 m^2, this gives a water flow of 0.7 l/s and the maximum velocity of 2 m/s results in a pipe dimension. The same calculations have been done for wastewater to get a dimension of the pipes, the results are shaft dimensions of 0.3, 0.35 and 0.4 m^2. The shaft goes from the bottom to the top of the building and a shaft area of 0.9 m^2/floor, 1.05 m^2/floor and 1.2 m^2/floor is needed for building 1, 2 and 3. The increase of shaft area is due to extra area for service personnel. The required tap water pump for building 1 will be of a smaller kind than for building 2 and 3, the size of pump 1 is 1050x1460x828 mm and 1350x1460x828 mm for pump 2. The total area needed for pump rooms is shown in Table 4.8. The pump needs an area of 3.1 m^2 for building 1 and 3.8 m^2 for building 2 and 3. The total area required for water distribution is small compared to the GEA of the buildings as seen in Table 4.9.

Table 4.8: Pump area, shaft area and total area for buildings 1,2 and 3.

Building	**Pump area [m^2]**	**Shaft area [m^2/floor]**	**Total area [m^2]**
1	3.1	0.9	50.4
2	3.8	1.05	100.4
3	3.8	1.2	156

Table 4.9: Space efficiency of water pump area.

Building	**GEA [m^2]**	**Pump+Shaft area [m^2]**	**(Pump+Shaft area)/GEA [%]**
1	33600	50.4	0.15
2	77000	100.4	0.13
3	166600	156	0.09

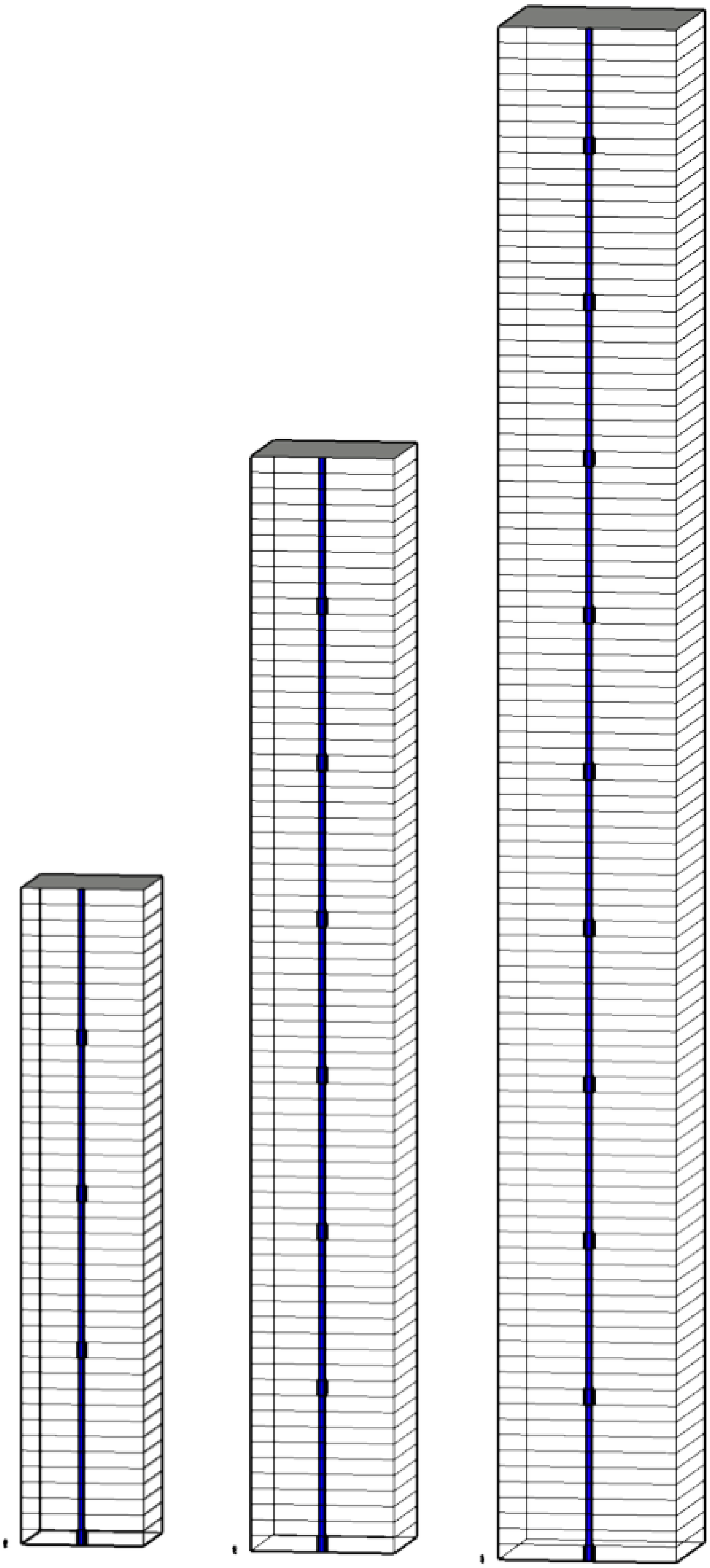

Figure 4.7: Buildings 1,2 and 3. Water distribution. The pump rooms and pipe shafts are marked in blue. A person is placed at the bottom left of each building for scale.

4.3.2 Reflections

The sectioning of 10 floors per pump room implies that no pressure reducing valves (PRV) is used, it is a possible solution to use pressure reducing valves at floors which has too high pressure, this would result in more than 10 floors per pump room. Theoretically, it is possible to pump water extremely high if the water flow matches the pump curve, perhaps only one pump room would be needed but on the other hand many PRV:s are needed and the solution would not be energy efficient but could be more space efficient. Tap water distribution is a very important function for the building, the space needed for tap water compared to plant room or elevators is very low. To save space it could be a good idea to let pump rooms coincide with sprinkler rooms or if possible air handling plant rooms. The chosen tap water distribution system is, as explained before, a series connected system where water is pumped through the building from one zone to another. The system entails that no water tanks are required which saves space and no PRV:s is needed because of the sectioning. The water pressure from the municipal water pipe network could be used to get the water a number of floors up in the building before pressurizing the water with pumps. The municipal water pressure is between 4-6 bars which could supply 8-10 floors, after this point a water pump will be needed, this could save space by removing one pump room. As seen in Figure 4.7 the tap water distribution is solely a duplication of pump rooms with a distance of 10 floors between each pump room. The distribution system looks the same for building 1, 2 and 3, only shaft and pump areas differ. Also, a difference which has to be mentioned is for building 1 where the first pump room takes care of 12 floors instead of 10 floors. Building 1 has 42 floors which should result in 5 pump rooms, the last pump should then distribute water to 2 floors which is a space inefficient solution.

4.4 Fire safety

Results for pressurization of sprinkler- and water mist system is evaluated and analysed below but also reflections how sectioning of the systems could be done and what limitations the systems have are presented below.

4.4.1 Results

Presented below are the results for sprinkler- and water mist systems followed by reflections.

4.4.1.1 Sprinkler system

As mentioned in Chapter 2 the water distribution is calculated by adding friction losses with static losses and pressure losses. The pressure from the pump needs to overcome the total pressure loss in the system and deliver a minimum pressure at the sprinkler head or at the tap. The minimum pressure for the sprinkler head is 0.35 bar and the maximum pressure is 12 bar. In Table 4.10, the maximum allowable total pressure occurs at floor 25, the total pressure is 11.68, 11.76 and 11.88 bar for building 1, 2 and 3 which is below the maximum pressure. The sectioning for the sprinkler system could maximum be each 25th floor with the prerequisites of the office building.

Table 4.10: Water pressure at the 25th floor.

Building	Total pressure [bar]	Floor
1	11.68	25
2	11.76	25
3	11.88	25

As seen in Table 4.11 the needed area for building 1, 2 and 3 is 116, 174 and 232 m^2. In the total area it is included a water tank of 70 m^3 per sprinkler room, the area needed for the water tank is 28 m^2 with the chosen tank height of 2.5 m.

Table 4.11: Area needed for sprinkler rooms. The tank height is chosen as 2.5 m. The sprinkler area is for each floor that a sprinkler room is located and the water tank area is for each floor that a water tank is located.

Building	**Sprinkler area [m^2]**	**Water tank area [m^2]**	**Total area [m^2]**
1	30	28	116
2	30	28	174
3	30	28	232

The area needed for sprinkler rooms in the buildings are quite small compared to the GEA of the buildings, which can be seen in Table 4.12. The shaft area needed for water distribution for sprinkler is not included in the sprinkler room area, the shaft size has not been investigated and therefore it is not taken into account. Looking at the shaft size for tap water distribution the area needed is not large, the same thing could apply to sprinkler. The pipes is only in one direction and there is no need for insulation which reduces the shaft area needed.

Table 4.12: Space efficiency for sprinkler rooms.

Building	**GEA [m^2]**	**Total area [m^2]**	**Total area/GEA [%]**
1	33600	116	0.35
2	77000	174	0.23
3	166600	232	0.14

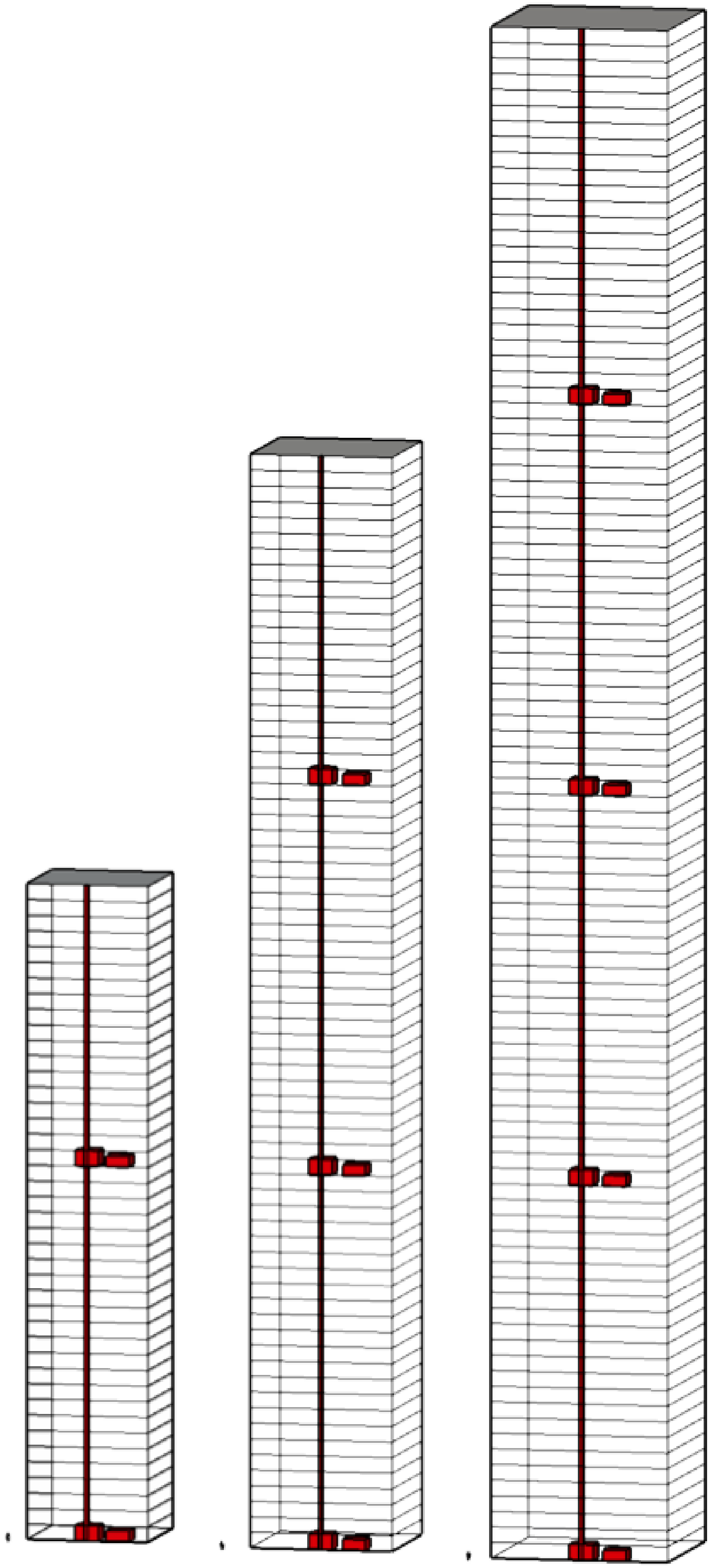

Figure 4.8: Buildings 1,2 and 3. Sprinkler sectioning with pump rooms and water tanks marked in red. A person is placed at the bottom left of the building for scale.

4.4.1.2 Water mist

According to (Fogtec, n.d.) high-pressure pumps with 140 bar pressure could be used in a water mist system, the pressure at the furthest away head should be minimum 60 bar. 80 bar of pressure losses as friction loss and vertical pressure loss is then acceptable, this results in a sectioning of 600-700 meter per water mist central. The water mist central is 24 m^2 which is 6 m^2 smaller than the sprinkler central. The water tank needed has the volume of 22, 36 and 50 m^3 for building 1, 2 and 3. The water tanks have the area of 9, 13 and 20 m^2, this means that the needed area for building 1, 2 and 3 is 33, 37 and 44 m^2 which is seen in Table 4.13. The water tanks for the sprinkler system have constant volume for building 1, 2 and 3 due to the sectioning of the buildings being the same. One sprinkler room each 25th floor, but for the water mist system the water tanks are depending on the number of floors in the building due to that only one water mist room is used, this results in three different tank volumes and areas. In Table 4.14 the total area of the water mist room is divided with the GEA. The space taken by the water mist room is 0.1, 0.05 and 0.03 % for building 1, 2 and 3 which is very low comparing with other technical rooms for e.g. elevators and ventilation.

Table 4.13: Area needed for water mist room. The tank height is chosen as 2.5 m. The water mist central area is for each floor that has a central and the water tank area is for each floor that has a water tank.

Building	**Water mist central [m^2].**	**Water tank [m^2]**	**Total area [m^2]**
1	24	9	33
2	24	13	37
3	24	20	44

Table 4.14: Space efficiency for water mist rooms.

Building	**GEA [m^2]**	**Total area [m^2]**	**Total area/GEA [%]**
1	33600	33	0.1
2	77000	37	0.05
3	166600	44	0.03

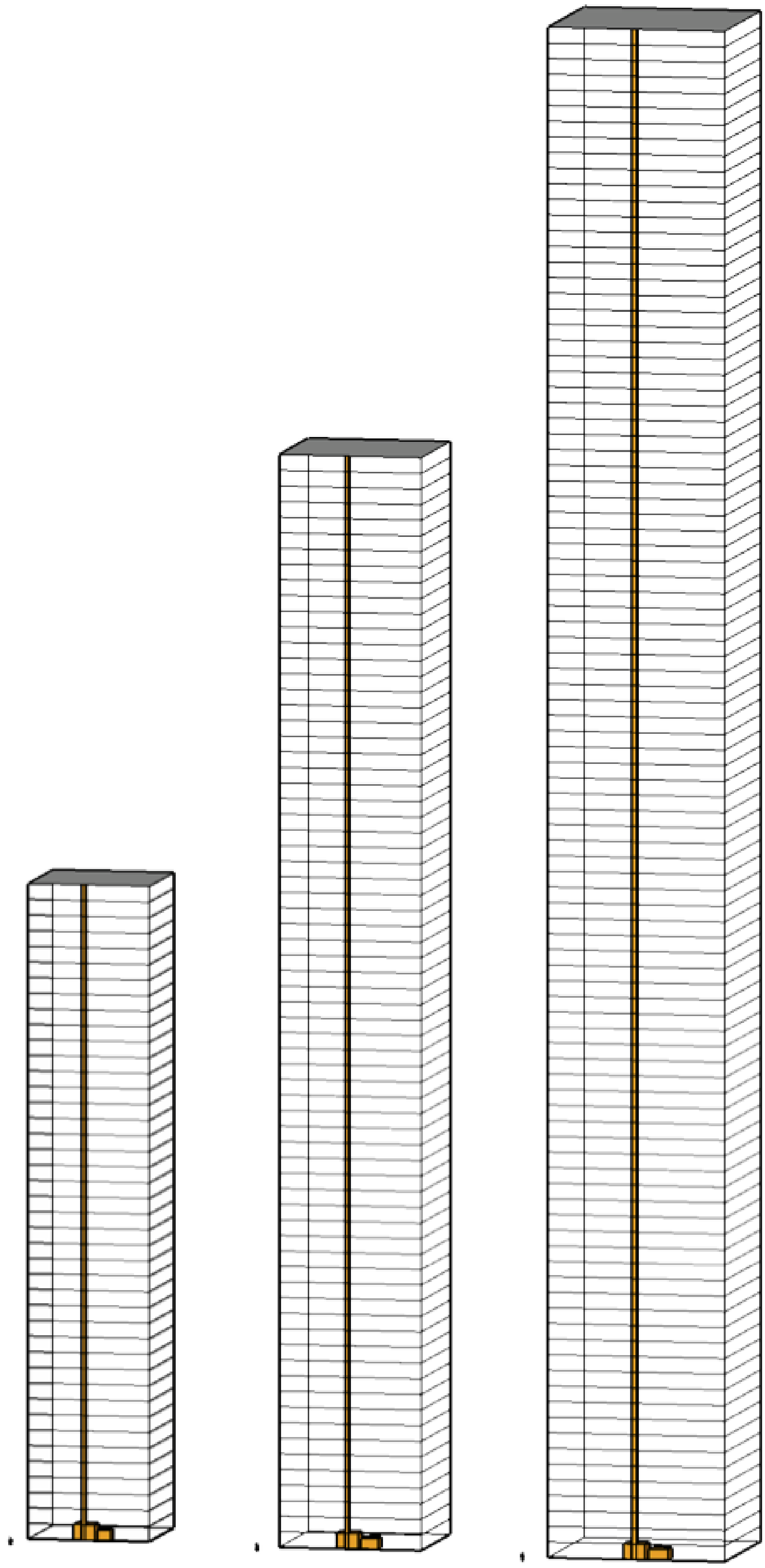

Figure 4.9: Buildings 1,2 and 3. Water mist. The pump rooms and pipe ducts are marked in yellow. A person is placed at the bottom left of each building for scale.

4.4.2 Reflections

A sectioning of sprinkler rooms each 25th floor does not imply that it is the most space efficient solution other types of sectioning could be better. For buildings 1, 2 and 3 the number of floors is 42, 70 and 98, this means that if the sectioning of the sprinkler system is each 25th floor, the number of sprinkler rooms are 2, 3 and 4. If the sectioning were each 20th floor the number of sprinkler rooms would be 3, 4 and 5. A sectioning each 20th floor would need 174, 232 and 290 m^2. In this case a sectioning every 25th floor would be more space efficient. The shaft needed for both systems will be of different dimensions, the main pipes for sprinkler- is 65 to 150 mm and 28 to 45 mm for water mist system. The difference in dimensions will not have a large affect on the space efficiency.

Water mist system is a more space efficient solution when comparing traditional sprinkler with water mist system which is seen in Table 4.15. The space difference between the systems are 250, 360 and 370 % for building 1, 2 and 3. It does not need as much area due to the high pressure in the system which is able to distribute water from the bottom of the building to the top and the water tanks does not need to be as large. Due to the high pressure it could occur severe damage if the pipes brake and the investment cost of water mist system is higher than traditional sprinkler system (Fogtec, n.d.). The systems have both pros and cons which have to be compared but just looking at the parameter space efficiency, water mist system could be a better choice. By comparing Figure 4.8 with Figure 4.9 it is seen that the water mist system has less amount of installations than the sprinkler system. It could be a good idea by placing water mist rooms at the same floor as the tap water pumps, which could coincide with the plant rooms to get a space efficient solution.

Table 4.15: A space efficiency comparison between sprinkler- and water mist systems.

Building	**Total sprinkler area /GEA [%]**	**Total water mist area /GEA [%]**
1	0.35	0.10
2	0.23	0.05
3	0.14	0.03

4.5 The value of space efficiency

The value of a square meter depends on the geographical location, different pricing for various cities. The yearly rent for a square meter in an newly built office in Gothenburg is about 3000 kr/m^2 compared to 13000 kr/m^2 in London. An example how much space efficiency could be worth is the difference of space needed for the HVAC system for building 1 with a cooling need of 30 W/m^2 waterborne cooling. Configuration 1 needs 480 m^2 and configuration 2 needs 839 m^2 the difference in area is 359 m^2. The 359 m^2 will be worth 1 070 000 kr/year in Gotenburg and 4 667 000 kr/year in London. Comparing the two configurations is not only about square meters, configuration 1 has more AHU:s than configuration 2, if they are taken into account an investment cost of 3 888 000 kr for configuration 1 and 3 492 000 kr for configuration 2 (AB, 2019). The result will still be profitable if choosing configuration 1 but there are other parameters than just space efficiency that have to be considered.

4.6 Sources of error

The case study is based on key values and research data, the key values as cooling demand and staff density will have a large impact on the technical system. The key values used in the master's thesis is achievable but in real life projects they might be a little optimistic, the conditions for the case study are very good and aims for future tall office buildings. The staff density of the building is according to Sveby reasonable but most office buildings today have different types of tenants which uses the area differently for their staff which could lead to other demands on the technical installations.

4.6.1 HVAC

Regarding what is discussed in Section 4.1.2.1 about the variance between C1 and C3. A contributing factor to the variance is likely that each configuration has been chosen to fit within the restricted ceiling height. The ceiling height will always be the same, but it can be utilized differently. For a required flow there will not always be an AHU that fits perfectly, it might leave some space up to the ceiling. At the same time, there might be an AHU that fits perfectly. The type of AHU that can utilize the full ceiling height will be able to provide a larger air flow (more floors) with fewer AHU:s and will be more space efficient in terms of plant room area.

Another aspect that can make a configuration seem less space efficient is that the number of floors that are supplied by each AHU will add up to a number that requires a smaller number of floors supplied by the last AHU, as illustrated with the numbers in parenthesis in the tables. Since the shaft size will be that which is required by the largest flow this will result in the shaft being unnecessarily large for the last number of floors.

4.6.2 Elevators

When adding the shuttle elevators it was difficult to follow the methods that applies to regular elevators since a shuttle elevator only serves two floors, the bottom floor and the floor of the sky lobby it reaches. This makes is difficult to estimate the number of users of the shuttle elevators and hence the needed capacity. This may have resulted in the number of shuttle elevators and the sizes of the shafts being less true to a real solution than the rest of the elevators and shafts.

Full occupancy was assumed when calculating the needed elevator capacity. This gives the worst-case scenario since the need for elevators is at its highest. The level of occupancy is assumed to be handled by the chosen type of building and the type of use. However, it is not known to which extent the program alters the number of occupants that is given by the user of the program.

4.6.3 Water distribution

The standard value of 0.7 l/s for 1000 m^2 from (VVS Företagen, 2013) has been used as a preliminary value, to get the correct tap water flow a summary of all taps is needed and this design has not been done in the master's thesis. The pipe area depends on the water flow and the velocity in the pipe, however the velocity of 2 m/s is correct and the only parameter that will affect the area is the water flow. The needed pump area for the tap water pump is chosen according to Grundfos product list and other pumps from other companies could be of a smaller size but with the same capacity, they could also be larger. The friction loss in the main tap water pipe has been assumed to be constant even though it will change over the length of the pipe. As for tap water flow the wastewater flow is also taken as a standard value due to that no detailed design has been done in the master's thesis, this could in turn affect the wastewater pipe area. The dimension of the shaft for tap water, wastewater and HWC an insulation thickness is assumed this thickness may be smaller or larger depending on circumstances but in this master's thesis it is designed according to Figure 3.3.

4.6.4 Fire safety

The area for the pipes of the systems have not been accounted for, which is a source of error in the space efficiency calculations. The hazard classification for tall buildings could be higher than OH1, but OH1 is correct according to the Swedish Sprinkler Standard (Standard, 2004). An higher classification would affect the needed water flow for each sprinkler zone which affects the needed pipe area. The height of the water tank is set to a arbitrary value of 2.5 m, a change of this value would affect the area needed for the water tank. The friction loss in the main pipe is assumed to be constant over the total pipe length even though the water flow in the main pipe is not constant. The area needed for the sprinkler- and water mist central is said to be 30 m^2 respectively 24 m^2 these numbers are standard values, may be larger or smaller areas could be chosen at a more detailed design. The maximum pressure in the sprinkler system is 12 bar according to (Fogtec, n.d.) a higher value would increase the sectioning of the sprinkler system, FOFTEC is a German company and the choice of 12 bar as maximum pressure could be according to other guidelines than the Swedish.

4.7 Further studies

As mentioned throughout the report, several aspects have not been considered in this thesis. For further studies it would be interesting to account for the energy use of the system and connect the economy of that with the economy of the space efficiency. It would also be interesting to look further into the building physics aspects and see what measures can be taken to improve the performance of the building on that end.

It would be interesting to investigate what measures could be taken to affect the space efficiency in the vertical direction. In this thesis the floor to floor height of 3.6 m with a room height of 2.7 m was chosen as it complies with the regulations and is used in tall office buildings in Sweden. The 0.9 m is meant to fit both structural elements and technical installations. If this could be decreased to 0.8 m it would for a building of e.g. 70 floors mean a difference of 7 m and for taller buildings the potential for saving space would of course be larger.

It is concluded that C3 is space efficient with its plant rooms but that the number of floors supplied by each plant room increases the dimensions of the ducts so that C1 and C3 are even. If an optimization was to be made it could be interesting to look further into the use of several AHU:s in one plant room and the optimal number of floors supplied by one plant room.

It was seen in the results on the elevator system that there is a great potential of space saving there and it was found in the literature study that double-deckers can have a big influence on the space claimed by the elevator shafts. Therefore, the use of double-deckers could be further investigated to get specific numbers on the potential of them.

5

Conclusion

The height affects the space efficiency of the technical systems differently and the distribution of the systems differ as well. Some of the systems can be stacked on top of each other while some of the systems have to extend from the bottom to the top floor.

When looking at the ventilation system it is seen than C1 and C3 are very even in terms of space efficiency. C3 requires less space for the plant rooms but C1 requires less space for the ducts due to the smaller number of floors supplied by each plant room. This shows that the most space efficient solution will be a compromise between plant room size and duct size. C2 takes the most space both in plant room and ducts and is hence the least space efficient solution. However, C2 is a possible solution if the priority is to increase the number of floors per plant room as much as possible. As the building height increases, AHU:s and ducts will be added to supply air to the added floors, but the space efficiency will not be affected by the increased height. The parts of the ventilation system will simply be stacked on top of each other, as seen in the figures in Section 4.1. When comparing waterborne and airborne cooling it was seen that at 20 W/m^2 the two solutions claimed roughly the same amount of space, while at 30 and 40 W/m^2 the waterborne was more space efficient.

The elevator system differs from the other systems in that the space claimed by the system increases with an increased height of the building. The elevator system is also the most demanding in terms of space as can be seen in the results. Although this is not surprising, the relation seen between the percentages claimed by the elevators and the other systems shows that the space saving potential in elevator design choices is substantial. Zoning choices is observed to have a big influence on the space claimed by the elevator shafts. Shorter zones will generally result in a more space efficient solution although shafts are added for the extra zones. The shorter zones serve fewer people per group of elevators and will result in decreased dimensions of the shafts which in total will result in a more space efficient solution. The use of sky lobbies also show positive effects on the space efficiency. However, sky lobbies might not be used in real building projects with similar heights as the lower ones used in this case study. Nevertheless, from what can be observed in the results it is concluded that the space efficiency can potentially be improved by the use of sky lobbies.

A sectioning of the water distribution system each 10th floor implies that no PRV is needed, it could be a good alternative to use the municipal water pressure before pressurizing the tap water. The sectioning of the water distribution system is independent of the height of the building, and the space needed for the system compared to the total GEA is very low. The series connected system has not the lowest space efficiency but the total cost compared to other water distribution system is the lowest. Single booster system could be an option but the need of PRV is very large because of the high water pressure that will be needed.

The sprinkler system has a sectioning each 25th floor compared to water mist system which has sufficient capacity to supply water to the whole building. It is due to the high pressure that water mist system could handle, the sprinkler system does need more space than the water mist system but none of the system do need much space compared to the total GEA. Water mist system is very space efficient but sprinkler is a very common fire protection method with detailed guidelines, why it is more common.

The focus of this thesis has been on the space efficiency and distribution of the chosen systems. This has meant that many aspects that will have influence in real building projects have not been considered. The intention of the thesis work is that people with a good understanding of the building as a system will be able to understand how to use the results in combination with their knowledge. The results of the thesis is believed to have the potential of being a contributing part in early stage analysis of tall office buildings.

References

AB, W. B. (2019). *Wikells sektionsfakta-VVS 19/20.* Växjö.

Alex Block. (2014). *A machine to make the land pay – City Block.* Retrieved from http://www.alexblock.net/blog/2014/04/02/a-machine-to-make-the-land-pay/

Al-Kodmany, K. (2015). Tall Buildings and Elevators: A Review of Recent Technological Advances. *Buildings*.

Al-Kodmany, K., & Ali, M. M. (2012). Skyscrapers and placemaking: Supporting local culture and identity. *Archnet-IJAR*, *6*(2), 43–64. Retrieved from https://www.researchgate.net/publication/265067165_Skyscrapers_and_placemaking_Supporting_local_culture_and_identity

Al-Sharif, L. (2017). The Design of Elevator Systems in High Rise Buildings. *Lift Report*, *43*, 46–62.

Arbetsmiljöverket. (2018). *Temperatur och klimat - Arbetsmiljöverket.* Retrieved from https://www.av.se/inomhusmiljo/temperatur-och-klimat/

ASHRAE. (2016). *2016 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Systems and Equipment (I-P Edition) - Knovel.* Retrieved from https://app.knovel.com/web/toc.v/cid:kpASHRAEN1/viewerType:toc/root_slug:ashrae-handbook-heating?kpromoter=federation&hierarchy=kt010ZFI92

Beedle, L. S. (2018). The Council on Tall Buildings and Urban Habitat. *CTBUH Journal*, 1968. Retrieved from www.ctbuh.org%7Cwww.skyscrapercenter.com

Böhm, H. P. (1989). A General Equation for the Terminal Fall Speed of Solid Hydrometeos. *American Meteorological Society*. Retrieved from https://journals.ametsoc.org/doi/pdf/10.1175/1520-0469%281989%29046%3C2419%3AAGEFTT%3E2.0.CO%3B2

Boverket. (n.d.). *Räddningshissar - PBL kunskapsbanken - Boverket.* Retrieved from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/brandskydd/raddningshiss/

Boverket. (2011). *BOVERKETS FÖRFATTNINGSSAMLING BFS 2011:6 BBR 18*

(Tech. Rep.). Retrieved from https://www.boverket.se/contentassets/3108c5069a60495380949c906e9c6f0b/bbr-18-ovk.pdf

Boverket. (2014). *Atemp - Boverket.* Retrieved from https://www.boverket.se/sv/byggande/bygg-och-renovera-energieffektivt/Atemp/

Boverket. (2017a). *Boverkets författningssamling BFS 2018:xx BBR xx.* Retrieved from https://www.boverket.se/contentassets/ac528c243fed4ee4ab08cf27e04a7eeb/bfs-2018-xx-bbr-avsnitt-9.pdf

Boverket. (2017b). *Urban Density Done Right* (Tech. Rep.). Retrieved from www.boverket.sehttps://www.boverket.se/globalassets/publikationer/dokument/2017/urban-density-done-right.pdf

Boverket. (2018a). *BBR 26.*

Boverket. (2018b). *Brandskyddade trapphus, Tr1 och Tr2 - PBL kunskapsbanken - Boverket.* Retrieved from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/brandskydd/trapphus/

Boverket. (2018c). *Rumshöjd - PBL kunskapsbanken - Boverket.* Retrieved from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/rumshojd/

Boverket. (2019a). *Räddningshissar - PBL kunskapsbanken - Boverket.* Retrieved from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/brandskydd/raddningshiss/

Boverket. (2019b). *Tillgänglighet - PBL kunskapsbanken - Boverket.* Retrieved from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/tillganglighet/

Brandskyddsföreningen. (2018). *Installation av våt trycksatt stigarledning.* Stockholm. Retrieved from https://www.brandskyddsforeningen.se/globalassets/blanketter/remiss-sbf-504_1.pdf

CTBUH. (2015a). *Burj Khalifa - The Skyscraper Center.* Retrieved from http://www.skyscrapercenter.com/building/burj-khalifa/3

CTBUH. (2015b). CTBUH Height Criteria for Measuring & Defining Tall Buildings. *CTBUH Journal*. Retrieved from http://ctbuh.org/uploads/CTBUH_HeightCriteria.pdf

CTBUH. (2019a). *About the CTBUH | Council on Tall Buildings and Urban Habitat.* Retrieved from http://ctbuh.org/about/about/

CTBUH. (2019b). *Jeddah Tower - The Skyscraper Center.* Retrieved from http://www.skyscrapercenter.com/building/jeddah-tower/2

CTBUH. (2019c). Tall Buildings in Numbers. *CTBUH Journal*(1). Retrieved from http://global.ctbuh.org/resources/papers/4045-Journal2019_IssueI_TBIN.pdfhttp://global.ctbuh.org/

resources/papers/2848-Journal2016_IssueIII_TBIN.pdf

de Jong, J. (2014). Innovative Elevator Technologies To Future Proof Your Building. In *Ctbuh 2014 shanghai conference proceedings* (pp. 817–823). Retrieved from http://global.ctbuh.org/resources/papers/download/1866-innovative-elevator-technologies-to-future-proof-your-building.pdf

Elevatorpedia. (n.d.). *Traveling cable | Elevator Wiki | FANDOM powered by Wikia.* Retrieved from https://elevation.fandom.com/wiki/Machine_room_less_elevatorhttp://elevation.wikia.com/wiki/Traveling_cable

Emporis. (n.d.-a). *high-rise building | Emporis Standards | EMPORIS.* Retrieved from https://www.emporis.com/building/standard/3/high-rise-building

Emporis. (n.d.-b). *History of the World's Tallest Buildings.* Retrieved from https://www.emporis.com/statistics/history-of-worlds-tallest-buildingshttp://www.emporis.com/statistics/history-of-worlds-tallest-buildings

Eskilsson, M. (2019). *Stegbilar | Svensk Utryckningsfordonsförening.* Retrieved from http://utryckningsfordon.se/stegbilar/

Flaktwoods. (2008). *Projekteringshandledning Kyla* (Tech. Rep.). Retrieved from http://resources.flaktwoods.com/Perfion/File.aspx?id=82af80b9-bd71-4dcc-b6cc-4b53100e0b30

Fogtec. (n.d.). *High-rise Buildings Standard sprinkler system High pressure water mist Case Study* (Tech. Rep.). Retrieved from https://fogtec-international.com/files/fogtec_brozura_a4_en_print_rgb.pdf

Jagemar, L. (1996). *Design of energy efficient buildings* (Doctoral dissertation, Chalmers). Retrieved from http://www.enerma.se/wp-content/uploads/2017/02/d34-1996.pdf

Jensen, L. (2005). *Trycksättning av trapphus för utrymning* (Tech. Rep.). Retrieved from https://www.brandskyddsforeningen.se/globalassets/brandforsk/rapporter-2000-2015/trycksattning-av-trapphus-for-utrymning/bf_rapport_330_031-1.pdf

Jong, J. (2008). Advances in Elevator Technology: Sustainable and Energy Implications. In *Ctbuh 8th world congress* (p. 7). Retrieved from http://global.ctbuh.org/resources/papers/download/461-advances-in-elevator-technology-sustainable-and-energy-implications.pdf

Klimatanpassningsportalen. (2016). *Dagvatten och spillvatten | Klimatanpassningsportalen.* Retrieved from http://www.klimatanpassning.se/hur-paverkas-samhallet/vatten-och-avlopp/dagvatten-och-spillvatten-1.107468

KONE. (2013). THE NEXT LEAP KONE high-rise solutions. , 6. Retrieved from http://download.kone.com/ultrarope/assets/download/KONE_high-rise_solutions.pdf

Kvist, E. (2015). *Space Requirements for Technical System in Office Buildings-Air handling plant room model* (Doctoral dissertation). Retrieved from http://publications.lib.chalmers.se/records/fulltext/227252/227252.pdf

Langdon, D., & Watts, S. (2010). High vs Low: An Elemental Comparison. *CTBUH Journal*, *Issue 3*. Retrieved from http://global.ctbuh.org/resources/papers/45-Journal2010IssueIII_TBIN.pdf

Lindblad, N., & Lindström, B. (1996). *Vatten och avlopp, En handbok i anslutning till Boverkets byggregler.* Stockholm: AB Svensk Byggtjänst.

LU, L. U. (2006). *Gaslagar.* Lund. Retrieved from https://www.lth.se/fileadmin/kemigen/pdf/gaslagar.pdf

Lundagrossisten. (2018). *VVS-KUNSKAP* (Tech. Rep.). Retrieved from https://lundagrossisten.se/common/pdf/Utbildningskompendium_VVS_steg_2.pdf

Maglev. (2017). *World's First Maglev Elevator.* Retrieved from https://www.maglev.net/worlds-first-maglev-elevator

Marshall, C. (2015). The world's first skyscraper: a history of cities in 50 buildings, day 9. *The Guardian*. Retrieved from https://www.theguardian.com/cities/2015/apr/02/worlds-first-skyscraper-chicago-home-insurance-building-history

Mowrey Elevator. (2018). *The Evolution of the Elevator | Changes Over The Years | Mowrey.* Retrieved from http://www.mowreyelevator.com/industry-updates/the-evolution-of-the-elevator/

Nathan, S. (2018). 11 Important Tips When Leasing Warehouse Space -. *https://www.austintenantadvisors.com/*. Retrieved from https://www.austintenantadvisors.com/blog/11-important-tips-when-leasing-warehouse-space/

Nielsen, A., & Nørgaard, J. (2018). *GRUNDFOS WATER BOOSTING Introduction* (Tech. Rep.). Retrieved from http://www.pacopumps.com/Documentation/WhitePapers/Roof_Tank_Whitepaper.pdf

Patrik Höstmad. (2012). *Hög tät stad - Yimby Göteborg.* Retrieved from http://gbg.yimby.se/2012/12/hog-tat-stad_3210.html

Runefors, M., & Persson, C. (2017). *TRYCKSÄTTNING AV TRAPPHUS - RISKER OCH MÖJLIGHETER* (Tech. Rep.). Retrieved from http://vpp.sbuf.se/Public/Documents/ProjectDocuments/d7c9c10a-31ed-4d6b-a032-80aa1701ba22/FinalReport/SBUF_13210

_Slutrapport_Trycksattning_av_trapphus.pdf

SAOL. (2009). *höghus | SO | svenska.se.* Retrieved from https://svenska.se/so/?id=21467&pz=7

Sev, A., & Özgen, A. (2009). Space Efficiency In High-Rise Office Buildings. *METU Journal of the Faculty of Architecture*, *26*(2), 69–89. Retrieved from http://jfa.arch.metu.edu.tr/archive/0258-5316/2009/cilt26/sayi_2/69-89.pdf doi: 10.4305/METU.JFA.2009.2.4

Simmonds, P. (2015). *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems.* Atlanta: W. Stephen Comstock.

Standard, S. (2004). *Brand och räddning-Fasta släcksystem-Automatiska sprinklersystem-Utförande, installation och underhåll Fixed firefighting systems-Automatic sprinkler systems-Design, installation and maintenance Provläsningsexemplar / Preview* (Tech. Rep.). Retrieved from www.sis.se

Sun, L., Architecture, C., & Planning, U. (2016). Title : Research on the Effect of High-Rise Commercial Building Construction on Land Value of Shanghai in the 1920s Research on the Effect of High-Rise Commercial Building Construction on Land Value of Shanghai in the 1920s. *International Journal of High-Rise Buildings*, *5*(2), 145–154. Retrieved from www.ctbuh-korea.org/ijhrb/index.php

Sveby. (2013). *Brukarindata kontor* (Tech. Rep.). Retrieved from http://www.sveby.org/wp-content/uploads/2013/06/Brukarindata-kontor-version-1.1.pdf

Tamboli, A. (2014). *Tall and Supertall Buildings: Planning and Design.* McGraw-Hill Education.

Thermia. (2019). *Komfortkyla – aktiv och passiv kyla | Thermia.* Retrieved from http://www.thermia.se/varmepump-kunskap/hur-fungerar-en-varmepump/varmepump-teknik/komfortkyla/

Thyssenkrupp. (2019). *TWIN - elevator by thyssenkrupp.* Retrieved from https://www.thyssenkrupp-elevator.com/uk/products/elevators/twin/

UN. (2018). *2018 Revision of World Urbanization Prospects | Multimedia Library - United Nations Department of Economic and Social Affairs.* Retrieved from https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html

Viessmann. (2019). *Naturkyla och aktiv kyla – kylning med värmepumpar | Viessmann.* Retrieved from https://www.viessmann.se/sv/bostadshus/varmepumpar/naturkyla-och-aktiv-kyla.html

Villegas, L. N. (2018). *The Density Fallacy: Don't Need Towers to add density – lewisnvillegas.* Retrieved from https://lewisnvillegas.wordpress.com/2018/08/15/the-economics-of-high-rise-buildings/

VVS Företagen. (2013). *VVS Företagens Teknikhandbok.*

Wit, J. (2007). *Elevator planning for high-rise buildings.*

Wood, A. (2006). Tall Buildings A Strategic Design Guide. In (p. 8). Retrieved from https://store.ctbuh.org/index.php?controller=attachment&id_attachment=9