PRODUCTIVITY AND TOTAL COST ANALYSIS OF VERTICAL LOGISTICS FOR HIGH-RISE BUILDINGS

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Foreword

This master's thesis has been conducted during the spring of 2020 as the final chapter of our time as students of the engineering program Communication, Transport and Infrastructure at Linköping University. The thesis focuses on logistics with a numerical perspective, in regard to methods used within the construction industry.

We would like to thank first and foremost the involved companies, Alimak, Brunkeberg and SSM, as well as the representatives who have helped us out. Special thanks to Henrik Falk (Brunkeberg) and Urban Lundberg (Alimak) for all the time you spent helping us with this study. We would also like to show our gratitude to Petter Haglund and Martin Rudberg, our supervisor and examiner here at the university. Thanks for your support and compliance, as well as the flexibility when scheduling supervision meetings. Martin, thanks also for the coffee and gingerbread cookies we got to enjoy during our startup meeting.

Finally, we should also take a moment to thank ourselves for tolerating each other 20 weeks isolated in a 10 m^2 office during these odd times. With a strict diet of candy bars, cheap coffee, pastries and social distancing, we managed to conduct this study within the planned time frame. Just like it's been for the past 4 1/2 years – and might be for the next 40.

Norrköping, 29 of May 2020.

Simon Istgren

Gustav Sedvallson

"No goal regardless of how small can be achieved without adequate training"
– Taiichi Ohno

Abstract

There is a need for more affordable residences in densely populated areas, which is why production costs in new construction projects are required to be kept at a minimum. Tellus Towers is a construction project with an idea to make affordable apartments. Two suppliers of vertical transportation, Alimak and Brunkeberg, have different solutions for how to manage vertical transportation in the Tellus project. These two methods, referred to as scenarios, were in this study compared with a Base scenario, made up of traditional solutions for vertical transport. The scenarios were studied from a total cost and productivity perspective, since changes in logistics solutions often mean changes in total costs and productivity.

The purpose of the study was therefore to *"from a productivity and total cost perspective, evaluate three different scenarios for vertical construction logistics in the construction phase of the Tellus Towers project"*. This purpose was fulfilled through the formulation of 4 research questions, which were answered by first using literature, divided into the two areas *Construction of high-rise buildings* and *Logistical change processes*. Process maps for the scenarios have then been introduced; which have been implemented to identify costs, activities, resources, etc. used as input for a total cost and productivity analysis. As part of the study a feasibility analysis has also been conducted to evaluate how applicable and realistic each scenario is for the construction project. Data for the analysis has been collected from involved companies though interviews, meetings and email conversations. The result of the study shows that Brunkeberg is 25% cheaper and 31% more productive than the base scenario, Alimak where 2% cheaper and 2% more productive than the base scenario.

This study presents both a recommendation and a conclusion. The recommendation is strictly directed to which solution should be applied on Tellus Towers, while the conclusion is presented on a more general level for the construction industry. This study recommends Brunkebergs solution for Tellus Towers and has drawn a general conclusion of high-rise construction that low variable costs are to prefer over low fixed costs. As the biggest cost and productivity drivers are based on working hours, a correlation between low variable cost and high productivity has been identified.

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Glossary

This section summarizes a list of terminology used in this report which may not be obvious to the reader, and/or which play a particularly important role in the study.

Core structure – The skeleton of a building, designed to bear loads and ensure stability. The structure for high-rise buildings is usually made in steel or concrete.

Cost items – A way to divide and structure the total cost analysis depending on the category and type of cost which is examined.

Jump lift – A self-climbing lift which can be used during construction through dedicated suspension points within the lift shaft of the building.

Logistics center – A distribution center used to consolidate material transports to the end destination. Typically used to maximize fill rates and reduce the total amount of transports, something which is particularly valuable in a city environment.

Relief station – Used by Brunkeberg as an unloading method for incoming trucks from the logistics center. The Relief station consists of a horizontal rail system which moves containers or façade elements to the building.

Vertical logistics – The planning and execution of vertical transportation of material and personnel in a construction project.

1. Introduction

This introduction chapter contains a problem background describing the context of the study, as well as a problem describing the purpose of the study as well as research questions needed to achieve this purpose. The chapter is finalized through a description of the scope as well as delimitations.

1.1. Background

240 out of 290 municipalities in Sweden have reported shortages of housing (Hyresgästföreningen, 2019). However, according to Boverket (2012) the reported shortage is misleading since Sweden does not lack residential buildings overall, but instead of residential buildings matching the needs of the customer. The market is generally demanding smaller and cheaper housing, which there currently is a lack of (Boverket, 2012). Still, during 2018 a total of 52 900 dwelling constructions started, 63 700, in 2017 and 61 100 in 2016 (SCB, 2019). This data is not unique for Sweden, the worldwide market according to BBC Research (2018) is estimated to grow with a compound annual growth rate (CAGR) of 10.3 percent during the period of 2017-2022. According to (Boverket, 2019a) the urbanization is still growing and has never been of such high level of growth as before. This leads to a new way of constructing cities, where we start to build higher instead of wider. Sweden is one of many countries with a handful cases of high-rise construction projects (Drozdz, et al., 2017).

For construction of high-rise buildings there is a challenge of not only organizing large amounts of building material and resources to and from the construction site, but also to effectively plan for transporting the material and resources vertically as the building gets taller. As stated by Cheng, et al. (2014) and Beliakov (2018), the construction process is long, the complexity is high and good coordination of resources is essential. This requires high levels of safety, communications and vertical transport (Cheng, et al., 2014). Vertical transport of material and personnel in high-rise buildings, in this study referred to as vertical logistics, traditional methods may be too ineffective in both a time and cost perspective.

Tellus Towers is an example of a high-rise construction project, with challenges much like the description above. The Tellus Towers project (also referred to as the Tellus project) comprises of two residential buildings located near the city center of Stockholm. Due to the lack of experience of high-rise construction among Swedish clients and contractors, a detailed evaluation of vertical logistics solutions is of interest for the project owner of Tellus Towers, SSM Living and the suppliers of these solutions. This study will use Tellus Towers as a foundation to evaluate different logistical solution for transporting material, since the unique characteristics Tellus Towers provide in term of being a high-rise construction.

1.2. Problem definition

The current lack of experience in construction projects like Tellus Towers means that the project will be particularly challenging in terms of achieving effective vertical logistics. If the methods of transporting material are ineffective, bottlenecks may arise delaying the construction. Avoiding this problem may shorten the total production time and can generate higher productivity (Oskarsson, et al., 2013). This can give especially large effects in construction projects since these are often sensitive to time-overruns and have high material and labor costs (Zhai, et al., 2017). Without effective logistics the large costs of a prolonged construction project may result in higher pricing on the market, contributing to the issue existing in the housing market today. Therefore, there is a need to evaluate vertical logistics solutions in high-rise construction projects, in order to use a solution which can offer high productivity at low costs.

Two suppliers of vertical transportation, Alimak and Brunkeberg, have different solutions for how to manage vertical transportation in the Tellus project. These two methods, referred to as scenarios, will in this study be compared with a base scenario, made up of traditional solutions for vertical transport. For this reason, the Alimak and Brunkeberg scenarios will be compared with this base scenario (henceforth referenced to as the Base scenario) to study the effects from a total cost and productivity perspective, since changes in logistics solutions often mean changes in total costs (Oskarsson, et al., 2013) and productivity (Proverbs, et al., 1999a). Following this, a feasibility analysis will be conducted to evaluate how applicable each scenario is for the construction project. Ultimately, the study will offer a recommendation to the project owner as to how the vertical logistics should be handled.

The following chapters aim to further define the task of this study. First, based on the background and description above, the purpose of the study is presented. The breakdown of the purpose then leads to the formulation of the research questions which are to be answered in the study.

1.2.1. Purpose and research questions

Evaluating the scenarios will be done using productivity and total-cost analysis. The research questions of the study are divided into four main questions with sub-questions. Since the study aims to compare three different scenarios, the main questions are structured as follows. The first three main questions relate to each scenario separately and consist of sub-questions needed to describe these scenarios. After each of these three main questions have been answered, the fourth research question will be used to compare the scenarios. This fourth question will consist of sub-questions which will relate to the sub-questions answered in previous research questions.

The main research questions of the study are derived from the purpose, which in this study is defined as the following.

The purpose of the study is to, from a productivity and total cost perspective, evaluate three different scenarios for vertical construction logistics in the construction phase of the Tellus Towers project.

In order to make this evaluation, a detailed description of each scenario is needed in order to make a detailed and righteous comparison. As is mentioned by Oskarsson, et al. (2013) and LaLonde & Pohlen (1996), a first step is to analyze the logistics processes by making a detailed description of these processes and breaking each process down into activities. Due to this, an important first step in this study is to map the processes in each of the three scenarios. Since the purpose of the study also includes making the evaluation based on total cost and productivity, reflections upon these factors need to be taken into consideration in connection to mapping the processes in each scenario. As the Base scenario is used as the starting point in the study, to which the other two scenarios will be compared, the first research question is formulated as follows:

1. ***How is the Base scenario outlined in terms of logistical processes?***

To answer this question a few sub-questions are needed. First, outlining the scenario requires a detailed process map of activities and resources. Activities can be defined by *"a description of the work that goes on within an organization and consumes resources"* (LaLonde & Pohlen, 1996). Process mapping is an important step in any study that has to do with analyzing supply chain processes, according to LaLonde & Pohlen (1996). The first sub-question needed to be answered is therefore:

1.1 Which activities and resources exist in the Base scenario, and how are these connected?

As mentioned, the purpose also includes that the evaluation will be conducted from a total cost and productivity perspective. To make the evaluation, sub-questions that bring up the cost and productivity perspective need to be included when outlining the scenarios. For example, when describing an activity, it could also be of interest to find a unit cost associated with this activity and the cost item this belongs to (for example transportation or administrative cost) (Oskarsson, et al., 2013). This lays the foundation of the total cost analysis to be done when comparing the scenarios (see research question 4). In the same sense, for the productivity analysis, productivity measurements need to be done in the Base scenario for comparing with the other scenarios. The remaining two sub-questions are therefore formulated as:

1.2 Which cost elements are connected to the processes in the Base scenario, and how large are these costs?

1.3 What is the level of productivity in the Base scenario?

To make a fair comparison between each scenario, the same structure of research questions follows for the Alimak and the Brunkeberg scenarios. Therefore, research question two and are formulated as:

2. ***How is the Alimak scenario outlined in terms of logistical processes?***
3. ***How is the Brunkeberg scenario outlined in terms of logistical processes?***

The sub-questions used to answer these two questions are the same as the ones presented for the first research question, i.e. 1.1, 1.2 and 1.3. Using the same sub-questions in this way enables a

fair and clear comparison, where the Alimak and Brunkeberg scenarios will be compared with the Base scenario one at a time. This set-up is also in accordance with the way that the total cost model is proposed by Oskarsson, et al. (2013), where one alternative solution at a time is compared to the current situation (in this case the Base scenario). The fourth main research question is therefore:

4. ***How do the proposed scenarios from Alimak and Brunkeberg compare to the Base scenario?***

A comparison of scenarios can be done based on several factors, but as the purpose of this study is to evaluate based on total cost and productivity, these are the areas which are analyzed. Therefore, two sub-questions are formulated as:

4.1 How does the total cost differ between the scenarios?
4.2 How does the productivity differ between the scenarios?

In order to make a fair and reasonable evaluation, a qualitative discussion about the feasibility of each scenario is included. The final sub-question is therefore:

4.3 How feasible are the scenarios?

1.2.2. Summary of research questions

The research questions that were derived from the purpose in the previous chapter are presented together with each sub-question in Figure 1. Note that the three sub-questions are the same for research question 1-3.

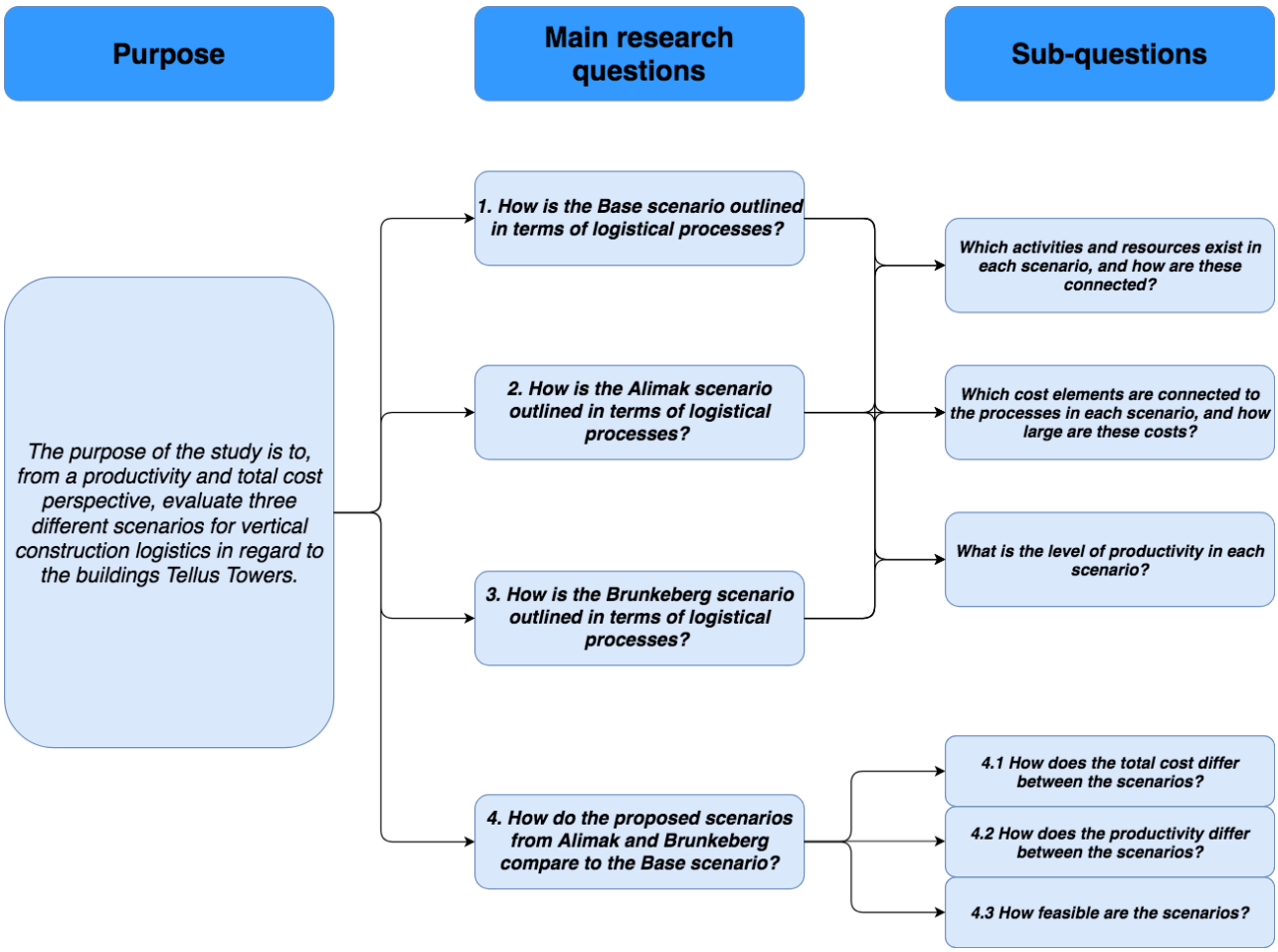

Figure 1 – Presentation of research questions

1.3. Scope of study

With the project companies and scenarios introduced, this chapter moves on specifying the task by describing the overall scope of the study. To clarify, as the term scope is a broad term, the chapter is divided into two separate areas – one describing where the study is within the construction process, the other describing the scope in regard to the physical flow of material and information during the actual construction of Tellus Towers. This second area is what will also be referred to as the studied system.

1.3.1. Scope regarding the construction process

In order to understand where we are in the construction process, a brief overview of the general construction process will first be presented. Broadly speaking, the construction process according to Nordstrand (2008) can be divided into four main phases. The first three phases have to do with the actual production of the building and are also mentioned by Sears (2015) as being the key project phases within construction. Initially, the owner decides to go through with the project,

which Sears (2015) refers to as the *planning and definition* phase. The project owner is the person, company or organization which decides on having the construction project carried out (Nordstrand, 2008; Sears, 2015). The second phase is the *design* phase, which involves more detailed planning of the architectural and engineering design. This phase also involves details regarding which methods to use during construction. This is followed by the third phase, *procurement and construction*. This is the time period in which the actual construction takes place, which is when flow of material and information to and from the construction site occurs. Normally, especially for larger construction projects, the owner does not carry out the actual construction in the project. This is instead handled through the use of contracting, where the art of the contract and number of contractors varies from one project to another (Nordstrand, 2008; Sears, 2015). Since the companies Alimak and Brunkeberg offer solutions for handling vertical logistics at the construction site, the construction phase will be the main focal point of this study.

The general construction process presented above is summarized and visualized in Figure 2. The first three phases are the ones related to the actual construction process, as described by Sears (2015). The last phase, *product usage*, is also included as a part of the construction process by Nordstand (2008). This phase involves the use of the building after the construction has been finished. This final phase may have been of interest to include in this study, since according to Brunkeberg their rail system can also be used for maintenance applications such as façade cleaning and recladding (Falk, et al., 2016). However, as the analysis focuses on the process up until construction is completed, it is not included in the scope of this study. The dashed area in Figure 2 shows the phases in the construction project which are included in the scope – *procurement and construction*, as well as a small part of the *design* phase. The design phase is partially included since the study involves the choice of material and methods used at the construction site, a decisions which are done before the third phase (Révai, 2012). In this study, the choice between using the Base, Alimak or Brunkeberg scenario is what lies within the design phase.

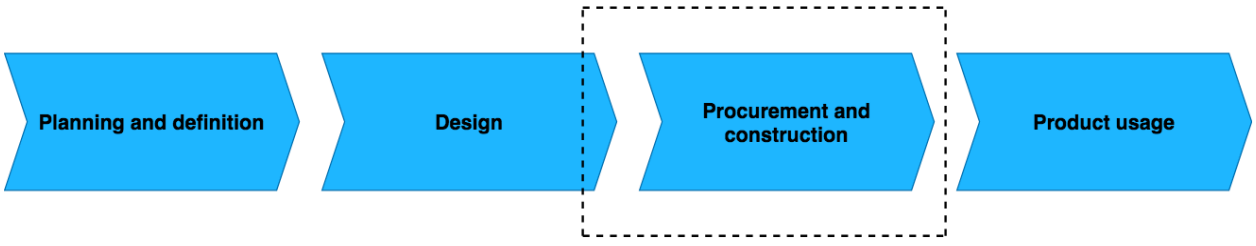

Figure 2 – Studied phases of the Tellus project

1.3.2. Studied system scope

This leads us into the studied system of the study. Below in Figure 3 is an overall flowchart describing the studied system. For all three scenarios the flowchart within this studied system will

differ when studying more thoroughly since the activities and resources, for example activities at the *Logistics center* and at *Tellus Towers* may vary depending on the which scenario is studied.

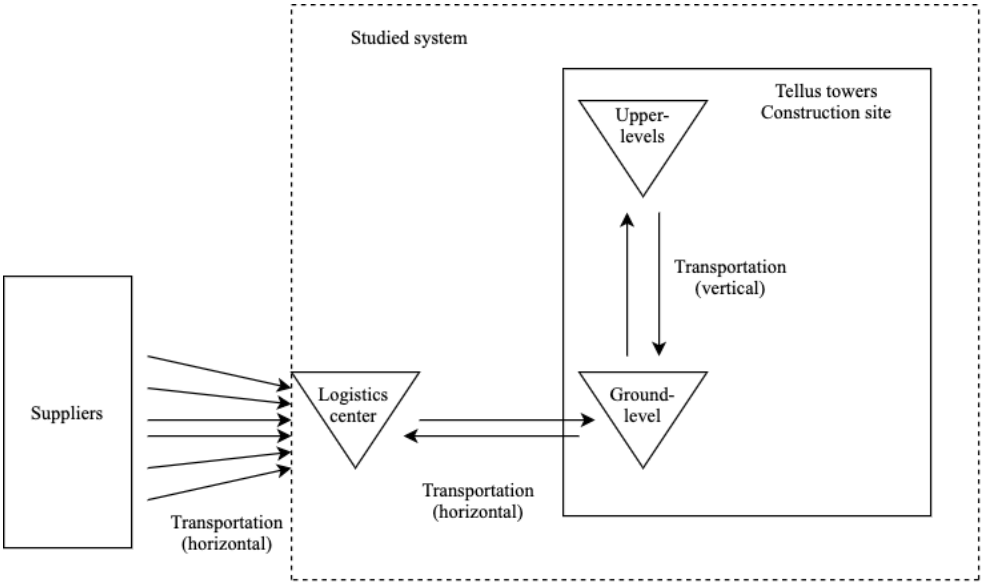

Figure 3 – Studied system

1.3.3. Delimitations

To make the study feasible 9 delimitations are in this chapter presented, as time is a limited factor in any project. The delimitations in the study are the following.

- As the time interval for the study will be limited and the aim of the project is to only analyze the actual construction, the study will not take into account any sort of logistics that might be required after construction is complete. In addition to this, the life span of the apartment interiors and its quality is not taken into consideration.
- The study will focus on the three scenarios previously presented and will not include any other solutions for handling vertical logistics.
- Since the Brunkeberg system transports façade elements and interiors for apartments, this is the only type of material which is studied in all scenarios. Costs related to the frame of the building, as well as activities not related to interiors and façade, will therefore be neglected from the study.
- As mentioned in the purpose, the study will evaluate three scenarios based on productivity, cost and feasibility. Perspectives like social or environmental aspects are not evaluated, these perspectives are instead briefly discussed based on findings during the study.
- Another delimitation is that the focus of the study will begin after the foundation of Tellus Towers has been completed, as the construction scenarios will not differ until five floors have been built. This implies that the analysis in the study will be based on all activities from the logistics center to Tellus Towers (ground level and upper levels), *after* these first

floors have been completed. For more information on the floor setup at Tellus Towers, see *Appendix 1 – Tellus Towers, illustration of floors.*

- Tellus Towers will mostly consist of residential apartment floors of identical material requirements, which is why the study is based on every floor being identical. This is the case even though the buildings will consist of a few floors having other material requirements (ex. technical/maintenance floors, see *Appendix 1 – Tellus Towers, illustration of floors*).
- As can be understood from Figure 3 in the previous chapter, the studied system does not include the suppliers of the material that is sent to the logistics center, and therefore excludes the costs related to producing this material.
- In connection to material, the study does not take into consideration any potential material damages which may occur between the logistics center and the construction site. This is because it is difficult to estimate, and no significant differentiation can be made across the studied scenarios for a fair comparison to be made.
- For most construction projects, there is often a learning curve for construction workers when it comes to the time duration of a certain task. This means that the more times an activity is done, the faster the construction time per activity becomes (Révai, 2012). In this study however, it is assumed that the time requirement of an activity is constant throughout the entire construction project, i.e. an "average" time duration is estimated for each activity.

2. Case description

In this chapter the project Tellus Towers is presented followed by a presentation of the involved companies SSM Living, Alimak Group and Brunkeberg Systems. After this, the three different scenarios of the study are presented.

2.1. Presentation of construction project and involved companies

In order to specify the task of this study, a brief introduction to the studied project is needed. Along with the project owner of Tellus Towers, SSM Living, there are a couple of other companies that are involved in the study. These will also be presented below.

2.1.1. Tellus Towers

As was briefly mentioned in the background of this study, Tellus Towers is a high-rise construction project which is to be carried out at Telefonplan, southwest of Stockholm's city center. The buildings will consist of 82 and 62 floors respectively, and will offer around 1200 apartments (SSM Living, 2020a) – meaning that they will be the tallest residential buildings in the city. The buildings will consist of both rental and condominium apartments. Figure 4 shows a view of how the two towers will look when completed, presented by the project owner SSM Living (2020a).

Figure 4 – Tellus Towers (SSM Living, 2020a)

Apart from the differences in height, the two towers will have the same dimensions (26x26 meters) and will have similar requirements in the form of transported materials. Figure 5 shows the area on which the towers will be built, with the train station Telefonplan located just beside the construction site (at the bottom of the figure). The buildings will in this study be referred to as

Building 1 and Building 2, which is also visualized in the figure below. The building referred to as Building 1 is the one which will consist of 82 floors, while Building 2 will have 62 floors in total.

Figure 5 – Visualization of the Tellus Towers construction area

Although the buildings will consist of 82 and 62 floors in total, a number of these will be below ground, making the actual height of the buildings 78 and 58 floors above ground level. The bottom five floors of the buildings are planned to consist of other things than apartments, such as storage areas, garbage rooms, cafés and a reception. This, together with the standard floor plan of the buildings, is visualized in *Appendix 1 – Tellus Towers, illustration of floors*. The standard floor plan is what all calculations in the study are based upon.

Most apartments in the two buildings will be identical in terms of layout and furnishing and there will not be any customization of individual apartments, which in accordance with Sacks & Goldin (2007) makes the design and construction process of a high-rise building less complex. The Tellus Towers will be built with so called curtain wall façade, which means that the buildings will not consist of bearing walls which otherwise is quite normal for residential buildings in Sweden. The façade elements for the Tellus Towers are prefabricated in factory lines, however according to Abdul-Mohsen, et al. (2014) it is not uncommon for construction of curtain wall systems to take place at the construction site.

2.1.2. Alimak Group

Alimak Group AB was founded 1948 in Skellefteå and is now a world leader of vertical transport solutions for construction and the industrial sector, with headquarters in Stockholm. The company is divided into 4 businesses; Construction equipment, Industrial equipment, after sale and rental. This study will focus on the area Construction equipment. Alimak has its business in more than

100 countries worldwide. The company's products are described as having high quality, sustainability and good security. (Alimak Group, 2020)

Alimak's hoists will be used in the first scenario, and the company will also provide their optimized solution for the Tellus Towers through the second scenario. The company will in the second scenario deliver a solution which has been specially selected for the study.

2.1.3. Brunkeberg Systems

Brunkeberg Systems AB is a relatively young company with a concept enabling vertical transportation of façade elements and building interiors. The concept started with an idea on how to decrease installation time for façade. The idea then evolved to a concept where both the façade and other material can be transported faster and safer compared to traditional solutions. So far the façade installation concept has been tested during a case study conducted in 2015, but the container solution has not yet been tested (Prolog, 2015). The Tellus Towers project is the first real potential project where the Brunkeberg solution can be applied. In *Appendix 2 – Brunkeberg's system* the idea of the system is illustrated, when containers are unloaded, and façade elements installed.

The third scenario in this study will evaluate Brunkeberg Systems concept and how the vertical logistics is affected based on their solution.

2.2. Description of scenarios

With the companies introduced, this chapter moves on to present the three scenarios which are to be compared in this study. The base scenario of the study is as previously mentioned used as an initial starting point in the project, which Alimak's and Brunkeberg's more specialized scenarios can be compared to. Two tower cranes will in all scenarios be used for vertical transport of material. The material that is transported using the cranes varies depending on the phase of the construction project, however the cranes are at an early stage primarily used for transporting material related to making the foundation of the buildings (such as reinforcement bars and material that is necessary for casting). Material of any kind which is time critical may also be granted access for transport by crane, however it is assumed that none of the material in this study requires transportation by tower cranes.

All three scenarios use a logistics center off-site, from where incoming material can be consolidated and transported to the construction site. The idea of a logistics center is to enable a "last mile" transportation into the city center (in this case to the construction site). The last mile transportation simplifies the ability to conduct Just-in-time (JIT) deliveries due to a shorter distance is required to transport since most of the transportation has been done in beforehand (Taniguchi & Thompson, 2014). JIT-transportation is more or less an essential transportation to the construction site since only a buffer zone is located at the construction site. A set of activities are carried out at the center, for example storage and repackaging. Although the logistics center is originally a part of the Brunkeberg solution, it is included in all scenarios in order for the

comparison to clarify implications of differing factors at the construction site. The location of this logistics center is in Skärholmen, around five kilometers southwest of the construction site.

2.2.1. Base scenario

Contractor choice solely based on procurement price is a big issue in construction projects and so is also often the case when it comes to the choice of equipment (Alarcón & Mourgues, 2002; Zedan & Skitmore, 1998). The Base scenario is for this reason used as a reference point in this study, where the construction of Tellus Towers is done with a focus of minimizing the purchasing cost for the equipment. Having this scenario used as a reference point makes it possible to then assess the implementation of Alimak's and Brunkeberg's more specialized solutions. The resources in the Base scenario are part of the Alimak product portfolio, chosen based on a low procurement cost. Although this may initially be a less costly option, it might however result in larger costs which occur during construction.

In terms of construction site equipment for transporting interior, personnel, and façade transports, the Base scenario consists of a combination of four hoist cars for each building. The hoists are placed on two of the sides of each building, as is visualized in Figure 6. The two sides are chosen since they enable entry into the buildings where there is the least amount of concrete walls, making access to each apartment an easier thing to accomplish (this is also visualized by the floor plan in the buildings in Figure 6). As the figure also aims to show, the hoist cars are installed in pairs of two – having a shared hoist tower which needs to be extended and secured every three floors. The entire hoist configuration on each side of the buildings will span the width of the middle three apartments on each floor.

The type of construction hoists used in the Base scenario is Alimak's Scando 45/30 FC II and Scando 45/30 FC SP II. Scando 45/30 FC II is a closed case hoist with a carrying capacity of 2000 kg and hoisting speed of 0.63 m/s. The car size is 1.4x3.0x2.0 meters (depth, width, height). The difference between the two hoist models is that Scando 45/30 FC SP II has a lower carrying capacity (1900kg) but can instead travel above 200 meters which is needed for Building 1. These models are chosen for the Base scenario since it according to Alimak is a realistic occurrence when the customer prioritizes a lower price. When installing façade elements in the Base scenario, this will be done by using a mobile crane placed on the floor above where the façade element is to be installed. The façade elements need therefore to be transported through the interior of the buildings and use the construction hoists like other material. Façade elements can also in traditional construction be installed using a tower crane. However, as the aim is to only send material by tower crane which cannot be sent in other ways, façade transport by tower crane is neglected in this study.

2.2.2. Alimak scenario

The set-up of the Alimak scenario is similar to the Base scenario in the sense that the equipment used is also based on the Alimak product portfolio. The chosen set-up for the scenario is also similar as the same location and number of hoists is used, as visualized in Figure 6. The same set-

up is chosen to make it easier to see the logistical effect of investing in more expensive equipment. However, as previously mentioned, this scenario is a more optimized version where the equipment used is not necessarily the least expensive. The chosen products are instead based on the more specific requirements of the Tellus project, meaning that if for example more space is needed for some material to be transported – larger hoists may be installed for the vertical transport. For installation of façade elements, this will like in the Base scenario be done by using a mobile crane placed on the floor above the installation point. The hoist type studied in the Alimak scenario is Scando 650 II FC, with a vertical speed of 0.9 m/s. The carrying capacity of the hoist is 3200 kg, and the size is 1.5x3.9x2.3 meters (depth, width, height).

Figure 6 – Rough sketch of hoist configuration in Base and Alimak scenario

2.2.3. Brunkeberg scenario

The Brunkeberg scenario is based on Brunkeberg's own solution for vertical logistics, where the idea is to replace the construction hoists with a rail system, both horizontally around the building and vertically. According to Brunkeberg Systems (2019), the solution entails a reduced lead time and reduced number of construction site workers. The Brunkeberg system would in the Tellus project be introduced after completion of the fifth floor, as the system requires a building foundation in order to be installed.

In the Brunkeberg scenario, the material is at the logistics center repacked in specially designed containers and thereafter loaded onto a truck which in turn transports the containers to the construction site. When the truck arrives at the construction site the truck drives into a so-called

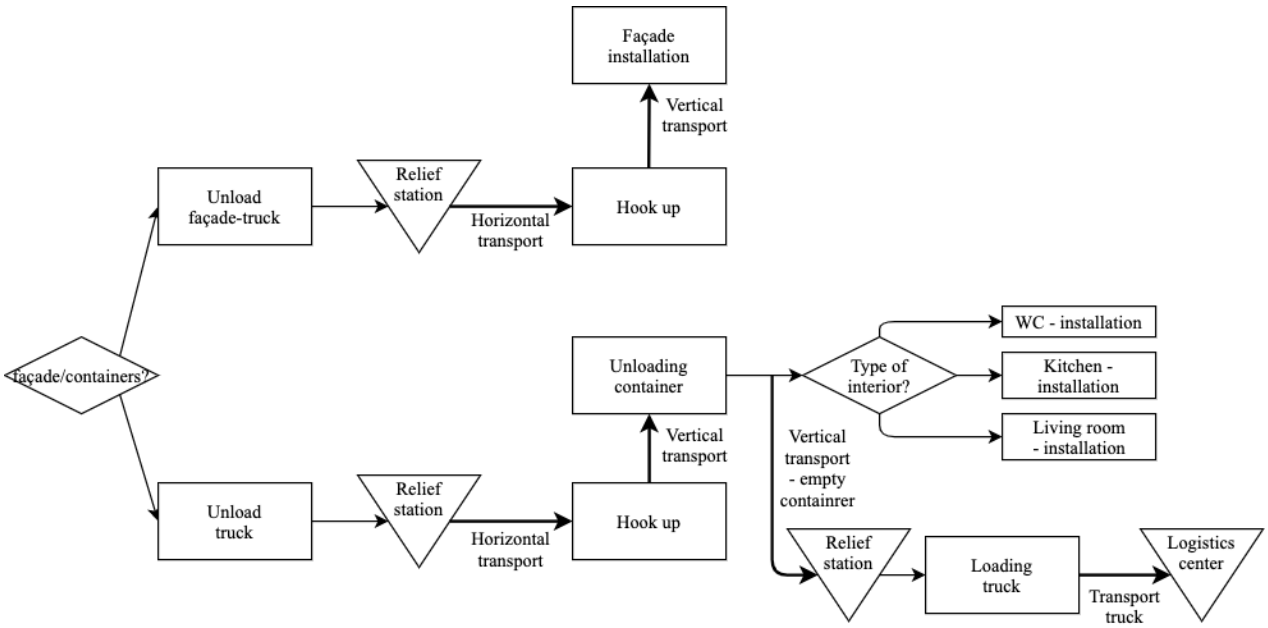

Figure 17 – Flowchart of Brunkebergs process at the construction site

When a container is requested it is moved by hand (by 1 construction worker). After passing ¾ of the first building a switch is located which either keeps steering the container around the building or to the next one (illustrated in Figure 18). Since the horizontal transportation only works counterclockwise the material must be moved all the way around the buildings, meaning that the distance of the transport only differs depending on the desired building for the material. For the nearest building, *Building 1* in Figure 18, the total transport distance (to and from the desired room) is 104 meters and for *Building 2* this distance is 245 meters. The worker transporting the container is estimated to walk at a speed of 0,83 m/s. When the container has been transported horizontally to the desired position the crane hook-up time is 0.034 hours. The lifting distance varies between 3-213 meters for *Building 1* and 3-159 meters for *Building 2*. Unloading each container takes 0.167 hours and requires 2 construction workers. Installation time of the interiors is presented in *Appendix 5 – Installation time in Tellus apartments*. After the container has been fully unloaded it is sent back to the Relief station. Every tenth container is filled with packaging material, which takes 0.083 hours. These are then handled identical to an empty container and therefore not presented separately in the flowchart. When containers have been unloaded and returned to the station, they are loaded onto a truck to the logistics center.

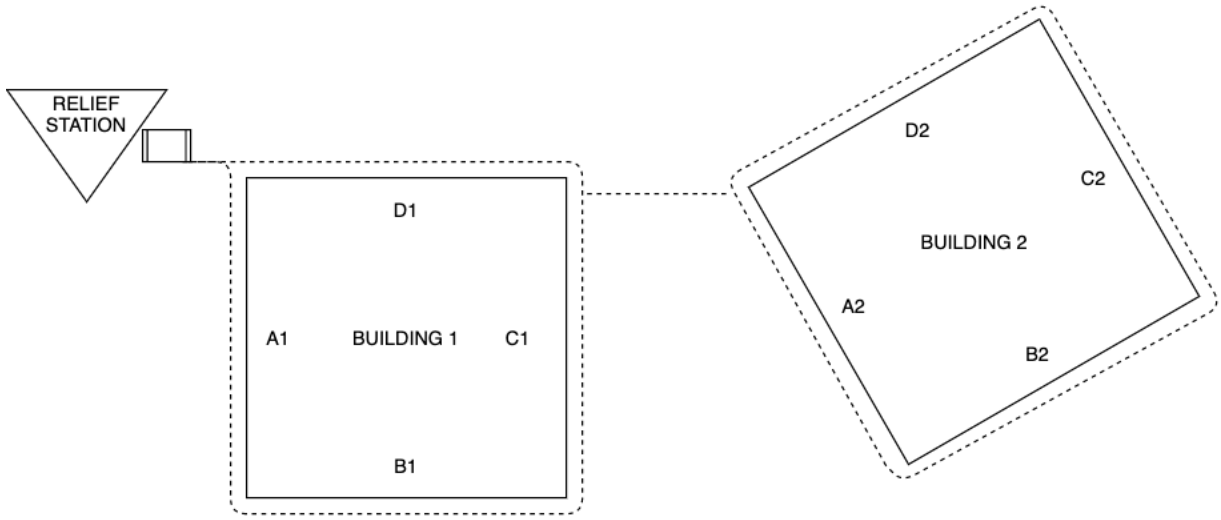

Figure 18 – Rough topological draft of Brunkebergs system around Tellus towers

The process is similar when it comes to façade elements. The element is unloaded from the truck at the Relief station, requiring three workers and taking 0.783 hours. The element waits at the Relief station until a room has been filled with interiors from the containers. The façade element is transported the same way as the containers. The installation takes 0.034 hours and requires 3 construction workers. When the element has been installed the crane is moved (takes approximately 0.067 hours) to the next room where it waits for new material.

5.3. Summary of activities and time durations

This chapter summarizes the activities which have been mapped in the chapters above. Note that the unit times presented in this chapter do not include waiting times, which are instead added when summarizing the total time durations in the construction project.

5.3.1. Summary of Base and Alimak scenarios

Table 3 presents a summary of activities, workers and time durations for the Base and Alimak scenarios.

Table 3 – Summary of activities in the Base and Alimak scenarios

Activity	Duration of activity (h)	Number of workers	Worker type
Assemble interiors pallet	0.25	2	LC worker
Load truck with interiors	0.5	2	LC worker
Load truck with façade	0.5	2	LC worker
Transportation with truck	0.1667	1	Truck driver
Unloading truck with interiors	0.5	2	Construction worker

Unloading truck with façade & Transport to buffer zone*	0.5	2	Construction worker
Transport to construction hoist	0.018	1	Construction worker
Loading of pallets on hoist	0.05 Base, 0.066 Alimak	1	Construction worker
Loading of façade on hoist	0.05 Base, 0.0042 Alimak	1	Construction worker
Vertical transport	0.0189-0.1859 Base, 0.0178-0.087 Alimak	1	Construction worker
Unloading of hoist	0.05 Base, 0.066 Alimak	1	Construction worker
Floor transport	0.0183-0.0256	1	Construction worker
Façade installation	0.3	5	Construction worker
Handling time of return goods	0.0552-0.2294 Base, 0.0541-0.1305 Alimak	2	Construction worker
Loading of return truck with pallets	0.5	2	Construction worker

* = Activities are carried out simultaneously and therefore presented together.

5.3.2. Summary of Brunkeberg scenario

In Table 4 and Table 5 below is a summary of activities and time durations for containers and façade elements in the Brunkeberg scenario.

Table 4 – Summary of activities for containers

Activity	Time duration (hours)	Number of workers	Contractor type
Fill containers with interior	0.4167	2	LC worker
Load containers onto truck	0.2500	2	LC worker
Transportation with truck	0.1667	1	Truck driver
Unload truck	0.1667	3	Construction worker
Horizontal transport	0.035	1	Construction worker
Hook up	0.034	1	Construction worker

Vertical transport	0.001-0.118	2	Construction worker
Unloading container	0.167	2	Construction worker
Vertical transport – empty container	0.001-0.118	1	Construction worker
Loading truck	1.667	2	Construction worker
Transport truck	0.1667	1	Truck driver

Table 5 – Summary of activities for façade elements

Activity	Time duration (hours)	Number of workers	Contractor type
Load façade onto façade truck	0.2500	2	LC worker
Transportation with truck	0.1667	1	Truck driver
Unload façade truck	0.783	3	Construction worker
Horizontal transport	0.035	1	Construction worker
Hook up	0.034	1	Construction worker
Vertical transport	0.001-0.118	2	Construction worker
Façade installation	0.034	2	Construction worker

6. Total cost analysis

This chapter aims to present the cost comparisons in the study by first presenting the cost inputs, followed by the total cost model used in the study. Secondly, the costs in the Alimak and Brunkeberg scenarios are compared to the ones in the Base scenario. Finally, a sensitivity analysis is presented based on the results presented in the comparison chapters.

6.1. Cost inputs

In Table 6, the hourly costs for different resources are presented, chosen based on hourly costs approximated by Kostnadsguiden (2020). The cost for forklift is acquired from Vångell (2013). In the column "*Used cost*" the cost that has been used in this study is presented, which is based on the average cost per hour. The cost of 40 EUR per construction worker is used in the Base and Alimak scenarios, whereas construction workers in the Brunkeberg scenario are assigned an hourly cost of 50 EUR (due to specifications given by Brunkeberg).

Table 6 – Hourly cost for resources (Kostnadsguiden, 2020; Vångell, 2013)

Resource type	**Cost per hour**	**Used cost**
Plumber	45-60 EUR/h	52.5 EUR/h
Floor layers	35-60 EUR/h	47.5 EUR/h
Construction worker	30-50 EUR/h	40 EUR/h
Forklift (excl. driver)	90 EUR/h	90 EUR/h

In Table 7, costs for the logistics center are presented. The number of months the logistics center will need to be used differs between the scenarios, and have been calculated based on the duration requirements for the logistics. A percental safety lead time of 10% has also been applied to cover for uncertainties.

Table 7 – Cost for the logistics center

Cost type	**Cost**
Rent	5 200 EUR / month
Logistics center personnel	40 EUR / h per person
Logistics center manager	6000 EUR/month

In Table 8 the cost for the transportation between the logistics center and Tellus Towers is presented.

Table 8 – Costs for transportation between the logistics center and Tellus Towers

Cost type	**Cost**
Trucks in traditional construction	100 EUR/h
Container transport (Brunkeberg solution)	100 EUR/h
Façade transport (Brunkeberg solution)	100 EUR/h

6.2. Total cost model

To enable total cost analysis between the scenarios, the costs in the system need to be connected to a cost item included in the adapted total cost model. As was discussed in chapter *3.2.2 - Total cost analysis*, making an adapted cost model first entails costs to be adjusted or removed depending on their relevance to the specific study. Therefore, Table 9 below shows a summary of the thought process when adapting the general total cost model in this study.

Table 9 – Presentation of relevant cost items

Cost item	**Included?**	**Explanation**
Warehousing costs	Yes	Included as inventory and handling costs
Inventory carrying costs	No	Neglected, minor to no difference
Transportation costs	Yes	Divided into horizontal and vertical transport
Administration costs	No	Neglected, minor to no difference
Other costs	Yes	Includes packaging- and return pallet handling

Oskarsson, et al., (2013) uses *administration* as one of the five main categories in total cost model, but costs for administration is neglected from this study as it is assumed that no notable difference would exist between the scenarios. The one area where administration time could arise is at the logistics center with order handling. However, since the workers know what will be transported each time it is assumed that this can be neglected.

The category *warehousing* is placed in a cost category called *inventory/handling*. In this category, the cost for carrying inventory is neglected since the quantity and cost for material is similar across all three scenarios. Even though Brunkeberg's solution offers prefabricated material the same unit price is achievable due to the size of the construction project. The cost category *inventory/handling* however includes the costs of utilizing the logistics center, as well as handling material during loading and unloading activities. Handling costs through transport of material is included in the *horizontal transport* category.

Transportation costs includes transportation with truck, pallet truck and with hoist/crane. Transportation with truck and pallet truck is categorized as *horizontal transport* while hoist and crane transportation are categorized as *vertical transport*. Since this study mainly focuses on vertical transportation this form of transport is placed in a separate category.

Equipment is a cost category incurred by the different vertical transportation solutions. Example of equipment in this study is the Relief station in the Brunkeberg scenario as well as the hoists in the Base and Alimak scenarios. The equipment costs are placed as a separate cost item since the equipment plays a large role in the differentiation of the scenarios. The equipment costs also include the set-up as well as work required to maintain the equipment during construction (for example extending Alimak hoists).

The installation category contains costs for installation of the apartments. As the installation time is the same in the Base and Alimak scenarios, due to the same material being transported, this cost item only becomes of interest when evaluating the Brunkeberg solution.

Other costs in this study includes packaging and return pallet handling. These costs do exist but are placed in this category as they are seen to have less significance than other cost items when comparing between the scenarios. The packaging costs are calculated as the time it takes for handling the packaging material during apartment installation. The costs for the actual packaging material are assumed to be included in the purchasing cost of apartment interiors, and since these costs are similar across all scenarios the packaging material costs are also neglected.

Figure 19 illustrates the development from the general total cost model to the cost model used in this study.

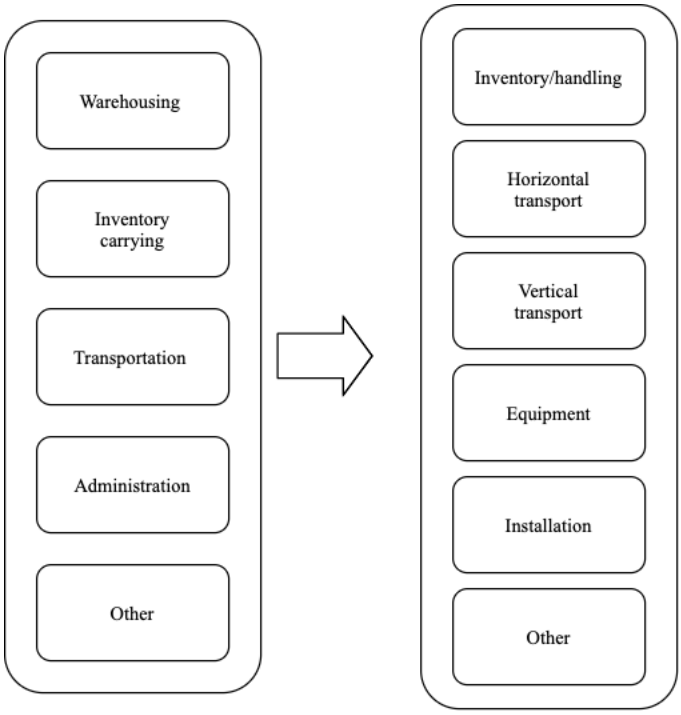

Figure 19 – Development of total cost model

6.3. Alimak and Base cost comparison

This chapter is divided into 7 sub-chapters, the first 6 chapters represents each cost item and the last chapter summarizes the total cost. Tables in the following sub-chapters represent the cost differences between the Base and Alimak scenarios. In the case a cost item contains several categories the result has been presented in tables, otherwise the difference is simply presented in the text.

6.3.1. Inventory and handling costs

In Table 10 below the differences for the categories which generate inventory and handling costs are presented. As can be seen, *Rent of logistics center and Cost of manager* are the only categories which differ between the scenarios. This entails a total inventory and handling cost difference of 26%, where the Alimak scenario is cheaper.

Table 10 – Inventory and handling costs, Base and Alimak

Category	**Cost difference, Alimak compared to Base**
Rent of logistics center	-30%
Cost of manager	-30%
Cost of assembling interior on pallets	No difference

Cost of loading interior	No difference
Cost of loading façade elements	No difference
Cost of loading return transports	No difference
Cost of unloading at construction site	No difference
Total	-26%

6.3.2. Horizontal transport costs

Since horizontal transport with truck is treated identically in the two scenarios, the cost related to this does not differ. The cost is therefore not presented here but is taken into consideration when calculating the total cost. However, due to the differing hoist capacity in the scenarios the horizontal transportation on site is more efficient, thereby lowering the transport cost to both the hoists as well as the desired room on each floor. This leads to a lower cost of 7% in the Alimak scenario, which also entails a lower total cost for horizontal transport with 6%.

6.3.3. Vertical transport costs

As the Base and Alimak scenarios use different hoists, the cost differs due to differences in speed and loading capacity. The hoists used in the Alimak scenario transports at a higher speed and can also transport a larger number of pallets per trip, making the scenario 63% cheaper.

6.3.4. Equipment costs

Even though there are 4 hoist set-ups in the Base and Alimak scenarios, it is assumed that only half will be sufficient for handling the material included in this study – meaning that half of the total hoist cost is accounted for in the analysis. The hoists are in both scenarios purchased and then sold for 75% of the purchasing price. The purchasing price is 55% higher in the Alimak scenario compared to the Base scenario. This also entails that the sale price and the actual cost for the hoists is 55% higher for the Alimak scenario.

The cost for performing hoist set-up is the same in both the Base and Alimak scenarios, as this only is based on time and does not depend on hoist type. The extent to which different activities affect the total set-up cost is shown in Table 11 (note that this table does *not* compare the two scenarios, as the set-up time is the same).

Table 11 – Hoist set-up cost, Base and Alimak

Category	**Fraction of total cost**
Cost for first 15 meters	7%
Cost for installing landing doors	28%

Cost of extensions	65%
Sum	100%

6.3.5. Installation costs

Installation costs in the apartments are the same in both scenarios and represent 69% of the total cost in Base scenario and 70% in Alimak scenario. As installation is the most time-consuming category this becomes a large contributor to the total cost.

6.3.6. Other costs

In Table 12 the cost difference for the cost item *Other costs* is illustrated. As can be seen, *Cost pallets, rooms to buffer zone* is reduced 100% in the Alimak scenario since this activity is only carried out in the Base scenario. Return pallets from each room are handled when they have been unloaded, meaning that the cost for this instead is included in the cost for horizontal and vertical transport.

Table 12 – Packaging handling costs, Base and Alimak

Category	**Cost difference, Alimak compared to Base**
Cost pallets, hoist to buffer zone	-100%
Cost packaging, rooms to buffer zone	-15 %
Cost loading return transport	No difference
Total	-19%

6.3.7. Summarized cost comparison

Table 13 below presents the cost differences of the 6 cost items studied, and Figure 20 displays the cost items for both scenarios relative to the Base scenarios total cost. The figure is used to illustrate the impact of each cost item on the total cost. A big difference between a cost item does not necessary lead to a big impact of the total cost, if the cost item only constitutes a smaller part of the total cost.

Equipment is the only cost item which is more expensive in the Alimak scenario and *Installation* is the only one where no difference exists. All other cost items benefit the Alimak scenario which in turn makes the Alimak scenario 2% cheaper.

Table 13 - Cost differences of the cost items between Base and Alimak scenario

Cost difference of all cost items	**Cost difference, Alimak compared to Base**
Inventory/handling	-22%
Horizontal transport	-6%
Vertical transport	-63%
Equipment	+38%
Installation	No difference
Other	-19%
Total cost	**-2%**

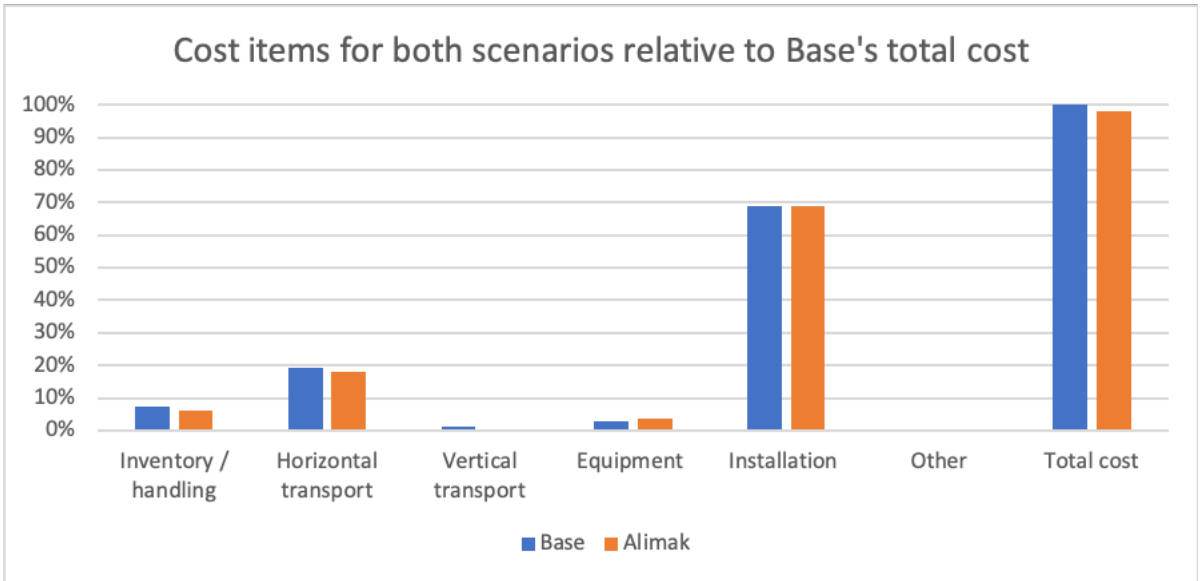

Figure 20 - Cost items for Base and Alimak scenarios relative to the Base scenario's total cost

6.4. Brunkeberg and Base cost comparison

This chapter moves on to study the comparison of costs between the Base and Brunkeberg scenarios. The same logic has been used regarding presenting data in text or tables, meaning that tables are only used when several sub-categories of a cost item are affected between the scenarios.

6.4.1. Inventory and handling costs

Table 14 shows the difference in inventory/handling costs between the Base and Brunkeberg scenarios.

Table 14 - Inventory and handling costs, Base and Brunkeberg

Category	**Cost difference, Brunkeberg compared to Base**
Rent of logistics center	-50%
Cost of manager	-50%
Cost of assembling containers/pallets	-83%
Cost of loading containers/pallets	-73%
Cost of loading façade elements	-67%
Cost of handling return transports	+413%
Cost of unloading at construction site	No difference
Total	-66%

6.4.2. Horizontal transport costs

Table 15 shows the difference in horizontal transport costs related to truck transports between the logistics center and the construction site.

Table 15 - Horizontal transport with truck, Base and Brunkeberg

Difference in truck transports	
Number of transportations, interior	+230%
Number of transportations, façade elements	-33%
Total time for truck transportation	+210%
Total	+210%

Costs for horizontal transport on site differs in the amount of time spent by personnel carrying out the activity. The cost difference here is 80%, in favor of the Brunkeberg scenario. Weighed together, the cost for all horizontal transport is 66% less in the Brunkeberg scenario.

6.4.3. Vertical transport costs

The difference in vertical transport costs arise due to the volume capacity as well as the speed of the hoist. These differences amount to a cost difference of 123%, making the Brunkeberg system more expensive than Base.

6.4.4. Equipment costs

The category *equipment costs* differs between the Base and Brunkeberg scenarios due to both equipment price as well as set-up time of this equipment, generating cost differences presented in Table 16 below.

Table 16 – Equipment and set-up costs, Base and Brunkeberg

Equipment	**Cost difference, Brunkeberg compared to Base**
Purchase/rental costs	+245%
Set-up costs	-28%
Total	+161%

6.4.5. Installation costs

The installation costs are directly related to the installation time and personnel requirements when installing interiors and façade elements in the Tellus apartments. The cost differences between the Base and Brunkeberg scenarios is visualized in Table 17.

Table 17 - Installation costs - Base and Brunkeberg

Installation	**Cost difference, Brunkeberg compared to Base**
Façade	-89%
Interiors	-16%
Total	-25%

6.4.6. Other costs

Packaging handling costs, although only constituting a small fraction of the total cost, differs by a total of 88.44% favoring the Brunkeberg scenario over Base.

6.4.7. Summarized cost comparison

Table 18 below represents the cost differences of the 6 cost items studied, and Figure 21 displays the cost items for both scenarios relative to the Base scenario's total cost. Note the cost item *Other* is displayed as 0% for Brunkeberg, this is due to its low cost.

As can be seen in the table, the cost item *Other* differs the most with -88%. However, as illustrated in **Error! Reference source not found.** this cost item barely contributes to the total cost in respectively scenario. In summary is the Brunkeberg scenario cheaper with 29%.

Table 18 - Cost differences of the cost items between Base and Alimak scenario

Cost item	**Cost difference, Brunkeberg compared to Base**
Inventory/handling	-66%
Horizontal transport	-66%
Vertical transport	+123%
Equipment	+161%
Installation	-25%
Other	-88%
Total cost	**-29%**

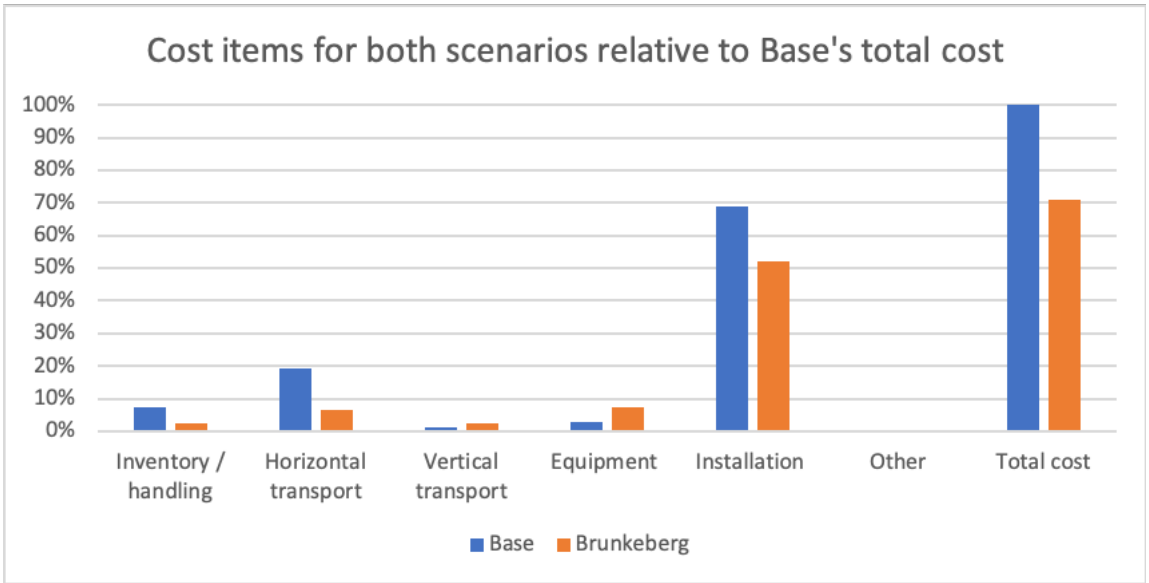

Figure 21 - Cost items for Base and Brunkeberg relative to the Base scenarios total cost

6.5. Summary of cost for both scenarios

In Table 19 are the cost for both the Alimak and Brunkberg scenario presented, it is the same cost as in Table 13 and Table 18 only that it has been combined to illustrate the results between the scenarios.

Table 19 - Cost difference for both Alimak and Brunkeberg scenarios, compared with Base

Cost difference Alimak and Brunkeberg compared to Base	**Alimak**	**Brunkeberg**
Inventory/handling	-22%	-66%
Horizontal transport	-6%	-66%
Vertical transport	-63%	+123%
Equipment	+38%	+161%
Installation	No difference	-25%
Other	-19%	-88%
Total cost	**-2%**	**-29%**

6.6. Cost sensitivity analysis

With the total cost differences calculated, this chapter moves on to study the sensitivity of the calculations and assumptions which have led to the results. In this sensitivity analysis, parameters affecting the total costs are tested one at a time to study their relative impact individually.

A cost item which has proven to contribute a large part to the total costs in all scenarios is the cost for apartment installation. This cost is based on the time for this installation, data which had to be gathered through multiple sources and due to the deviation in provided data this was regarded as unsure. Since the installation time for the Base and Alimak scenarios is identical, only the Brunkeberg scenario is evaluated and compared with the Base scenario. The logic of the analysis is to see to which extent the time can increase before the result of the study will be affected. If the time of the installation would increase by 56% in the Brunkeberg scenario, this would result in approximately the same total cost as the Base scenario. Given the linear relation of cost and time for the installation, this would entail that the total installation time could increase by 13.5 months before the total cost would favor the Base scenario. Even if the calculations are based on uncertain data this shows that it is unlikely that installation time would increase to such extent that it would change the outcome of the study. Worth mentioning is that the data could also be wrong in the sense that Brunkeberg would actually have a lower installation time, this has however not been analyzed since it would only emphasize the already existing outcome.

Another factor which is of interest to study in regards to the cost sensitivity is the extent of waiting times in each scenario. Since no data has been possible to gather when it comes to waiting times in the Brunkeberg scenario, only a 10% downtime for the Brunkeberg crane has been used as a delay factor. An interest could therefore be to see how the costs in the Brunkeberg scenario would be affected if further waiting times were to occur. The waiting time has therefore been studied with the same logic used for the sensitivity of installation time, i.e. to what extent can the waiting time increase before the outcome of the study would be altered. Increasing the transportation time (horizontally and vertically) at the construction site made it possible to see how much the waiting time could increase before the Base scenario became more favorable. The result showed that the transportation time would need to increase by 4653 and 4041 working hours for each building, which is considered unrealistic since it would require waiting times of 80% in the Brunkeberg scenario (compared to the 30% in traditional construction).

Finally, since the handling of material plays a big part in the total cost, the hourly cost of construction personnel is tested based on the found cost span of 30-50 EUR/h. Even though the hourly costs used are lower in the Base and Alimak scenarios (40 instead of 50 EUR/h), further decreasing this to 30 EUR/h is considered interesting since this could mean that the Brunkeberg scenario in total becomes costlier. Applying a decrease to 30 EUR/h in the Base scenario results in the total cost difference changing from 29% to 27%, still favoring the Brunkeberg scenario. If all personnel costs (not just construction workers) were to decrease to 30 EUR/h the resulting cost difference would become 13%. While at the same time being a quite improbable occurrence, this

still favors the Brunkeberg scenario – meaning that the hourly costs are seen as a non-sensitive parameter in this study.

In addition to installation, waiting times and hourly costs; a few more analyses have been carried out on a more basic level and not evaluated as thoroughly. A list of the parameters tested along with the reason these were not evaluated to a greater extent is presented in Table 20.

Table 20 - Parameters which have been evaluated on a basic level

Parameter evaluated on a basic level	**Explanation**
Renting instead of buying hoists	Increases the cost in both Base and Alimak scenario approximately with the same amount, therefore not deemed relevant.
Longer or more costly transports with truck	Increased the cost in all three scenarios with roughly the same amount
Number of pallets that would fit in a hoist	Too small of an impact on the total cost

7. Productivity analysis

The chapter provides a comparison of productivity between the scenarios by first presenting the factors which have affected the labor productivity (total working hours/m^2), and secondly comparing how this affects the time requirements in the construction project. The first sub-chapter presents a comparison between the Alimak and Base scenario and the second sub-chapter compares Brunkeberg and Base.

The productivity is in each comparison analyzed by dividing time durations into the categories *Logistics center, Truck transport, Transport at construction site & equipment set-up, Installation of apartment, Packaging handling* and *Core structure.* These categories are in a way similar to the cost items in the total cost analysis; however, they are slightly altered to enable easier comparisons of time durations. Vertical and horizontal transport at the construction site is for example merged together with the set-up of equipment as these are performed in successive order of one another. In the Base and Alimak scenarios this becomes evident since the hoists need to be extended throughout the course of the project, temporarily delaying the material transport. Furthermore, the time for building the core structure is added in the productivity comparisons since it governs the achievable time span of the construction project. For definition purposes, the core structure is the skeleton of the building which is designed to bear loads and ensure stability.

7.1. Alimak and Base productivity analysis

7.1.1. Difference in labor productivity

Table 21 illustrates the difference of working hours per square meter between the scenarios. As shown in the table only the productivity items *Transport vertical and inside building & set-up of equipment* and *Packaging handling* differ. *Installation of apartment* corresponds to 87% respective 89% of the working hours for the Base and Alimak scenario. This is considered reasonable since the installation cost in the cost analysis was also the dominating cost item. The labor productivity difference between the Base and Alimak scenario becomes 2%, 1.204 working hours/m^2 in the Base scenario and 1.185 working hours/m^2 in the Alimak scenario.

Table 21 - Difference of working hours per square meter, Base and Alimak

Productivity item	**Productivity difference, Alimak compared to Base**
Logistics center	No difference
Transport truck	No difference
Transport at construction site & equipment set-up	-28%
Installation of apartment	No difference
Packaging handling	-11%
Core structure	No difference
Total	**-2%**

7.1.2. Effects on project time span

In Figure 22 below it is illustrated how the working hours on each floor affects the time span of activities in the construction project, depending on which scenario is used. The figure shows the time duration for an arbitrary set of 5 building floors (i.e. 200 hours of core structure progression), as well as the dependencies which activities have during construction. Each section in the chart shows the time spent for a certain building floor, where the time span for installation of apartments was determined by assuming that 10 teams of 2 workers (i.e. 2 per apartment) plus 3 plumbing specialists carried out the installation.

The main difference shown in the figure is that *Transport at construction site & equipment set-up* causes delays in the Base scenario which do not arise to the same extent in the Alimak scenario, affecting the total time for a building floor.

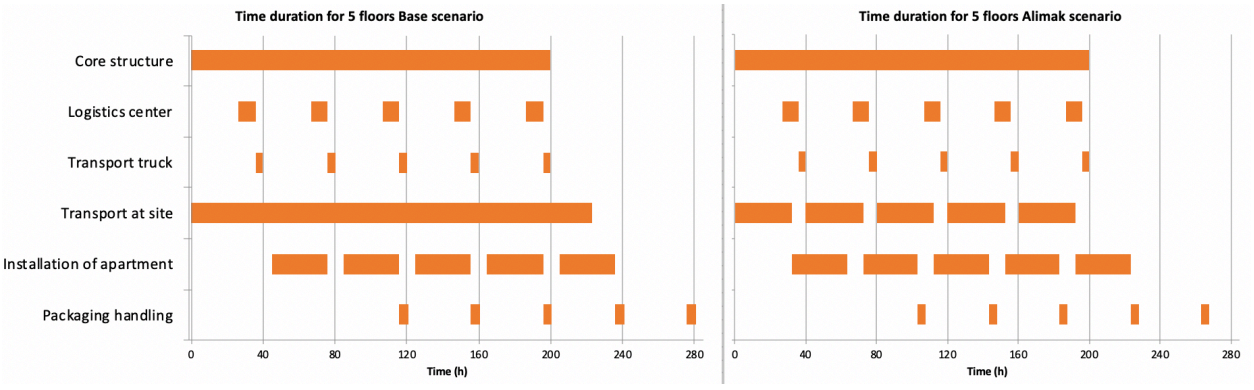

Figure 22 - Differences in time durations, Base and Alimak

7.2. Brunkeberg and Base productivity analysis

7.2.1. Difference in labor productivity

Table 22 shows the differences between the scenarios when it comes to working hours/m^2. The only productivity item which does not differ is *Core structure* since the core is built at the same pace in all three scenarios. As shown the total difference becomes 31% where the Brunkeberg scenario has a lower working hours/m^2 with 0.834 compared to 1.204 working hours/m^2 in the Base scenario.

Table 22 - Difference of working hours per square meter, Base and Brunkeberg

Productivity item	**Productivity difference, Brunkeberg compared to Base**
Logistics center	101%
Transport truck	170%
Transport at construction site & equipment set-up	-50%
Installation of apartment	-34%
Packaging handling	-90%
Core structure	No difference
Total	**-31%**

7.2.2. Effects on project time span

Figure 23 shows differences in time durations for the Base and Brunkeberg scenarios, again studying 5 arbitrary building floors. Installation of the apartments in the Brunkeberg scenario is done by 8 teams of 2 construction workers per team, who also perform the installation of façade elements after the containers have been unloaded.

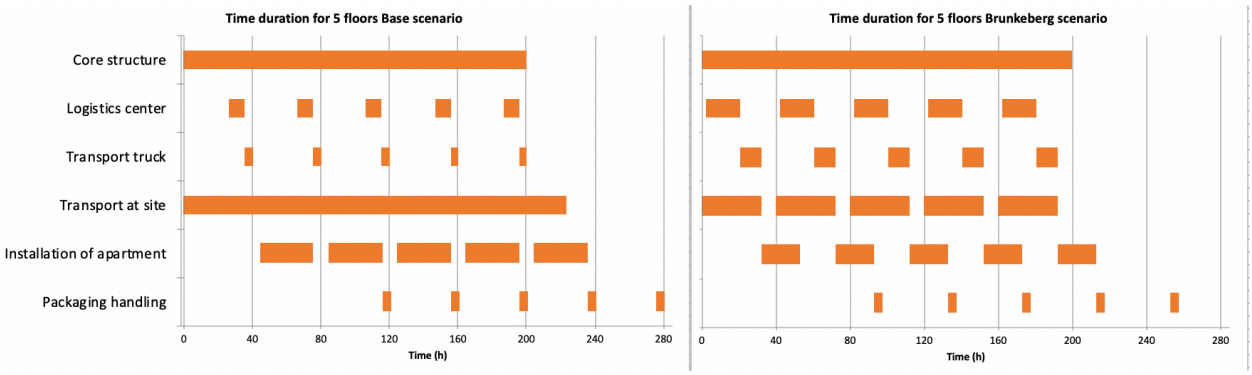

Figure 23 - Differences in time durations, Base and Brunkeberg

Worth mentioning in regard to the figure is that although the logistics center and truck transport requires more time per floor in the Brunkeberg scenario, transport at the construction site is more effective and can enable quicker installation of apartments. The transport at the construction site further benefits from the fact that no equipment needs to be set-up throughout the construction period. This is visible by the *Transport at site* category being a delaying factor in the Base scenario, where in the Brunkeberg scenario it is instead possible to keep up with the pace of the core structure.

8. Evaluation and discussion

This chapter aims to evaluate and discuss the findings. The chapter is divided into three sub-chapters, where the first chapters evaluate each scenario based on the findings of the study. A discussion chapter then proceeds with reflections on the study and what can be said in regards to the studied literature. Finally, some notes about sustainability as well as thoughts on future studies are presented.

8.1. Summarized evaluation

Table 23 illustrates a summary of how the scenarios compare to each other, the table processes the different categories (e.g. different cost items or productivity measures) the study evaluates. The idea of the table is to present an overview of the result which in turn will be used as a foundation for discussions. The different categories have been graded with colors green, yellow and red, where green is the highest grade. The cost category is discussed in chapter 8.2, productivity in 8.3 and feasibility in 8.4.

Table 23 - Summarized evaluation of all scenarios

Category	Subcategory	Base	Alimak	Brunkeberg
Cost	Inventory and handling cost			
	Horizontal cost			
	Vertical cost			
	Equipment cost			
	Installation cost			
	Other costs (packaging)			
	Total cost			
Productivity	Productivity, working hours/m^2			
	Productivity, project time span			
Feasibility	Possibility of implementation			
	Adaptability			

8.2. Cost evaluation

As can been understood from Table 23 and chapter 6.5 the Brunkeberg scenario should be favored when looking at the costs generated. Worth noticing is that the Brunkeberg scenario with its new system has a costlier vertical transport, which is considered interesting since the system is designed

to increase the effectives in this aspect. On the other hand, the increase in vertical costs entails a lower cost in 4 out of 6 cost items which in turns leads a lower cost in total.

Also, worth noticing is the tradeoff between variable and fixed cost between the scenarios. The Base scenario has the lowest fixed cost but with its high variable costs it becomes the scenario with the highest total costs. This turned out to be the opposite for the Brunkeberg scenario, having the highest fixed cost but the lowest total cost. As illustrated in Figure 24 the Brunkeberg scenario would become the least costly alternative after about 25% of the project time span, where 25% represents 31 floors of construction. After about 50% of the project the Alimak scenario becomes more economical than the Base scenario.

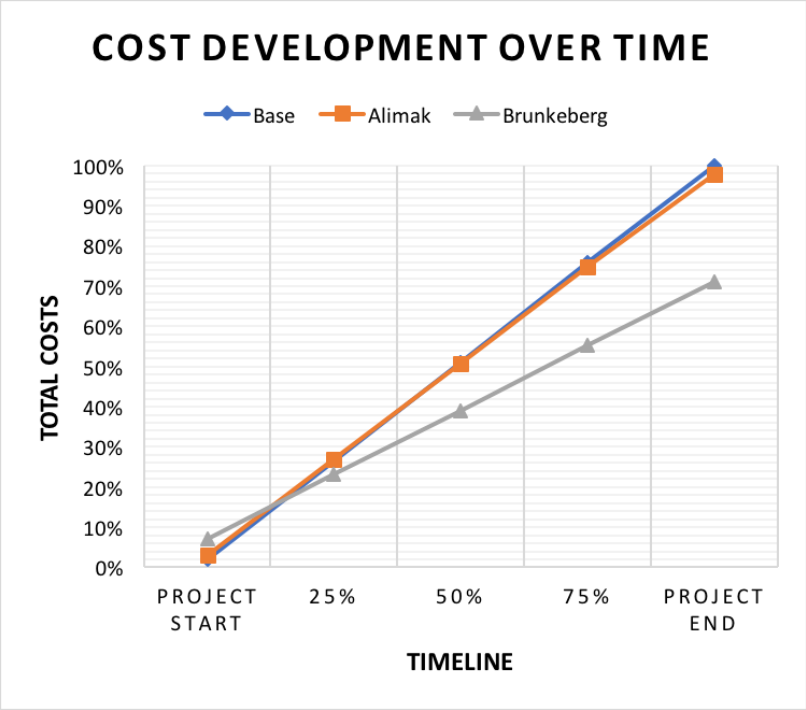

Figure 24 - Cost development for all three scenarios over the project's lifespan

The Alimak scenario offers a lower total cost by 2%, making the solution more favorable than Base despite the use of more expensive hoists. This would however have shown a bigger impact if the study only evaluated Base and Alimak, since according to Oskarsson et al. (2013) only costs that differ should be included in a total cost analysis. The cost item *Installation cost* should by this reasoning not have been included in the comparison. With that said however, the cost item did differ between Base and Brunkeberg, meaning that a fair assessment would not have been provided if the cost items were to differ in the two comparisons. If the cost item however would have been neglected it would have resulted in a 7% cost difference between Alimak and Base, favoring the Alimak scenario further. As illustrated in Figure 25 (where the installation cost has been neglected) this difference is visualized, where it also becomes more clear that the Alimak scenario deviates from the Base scenario the taller the buildings become.

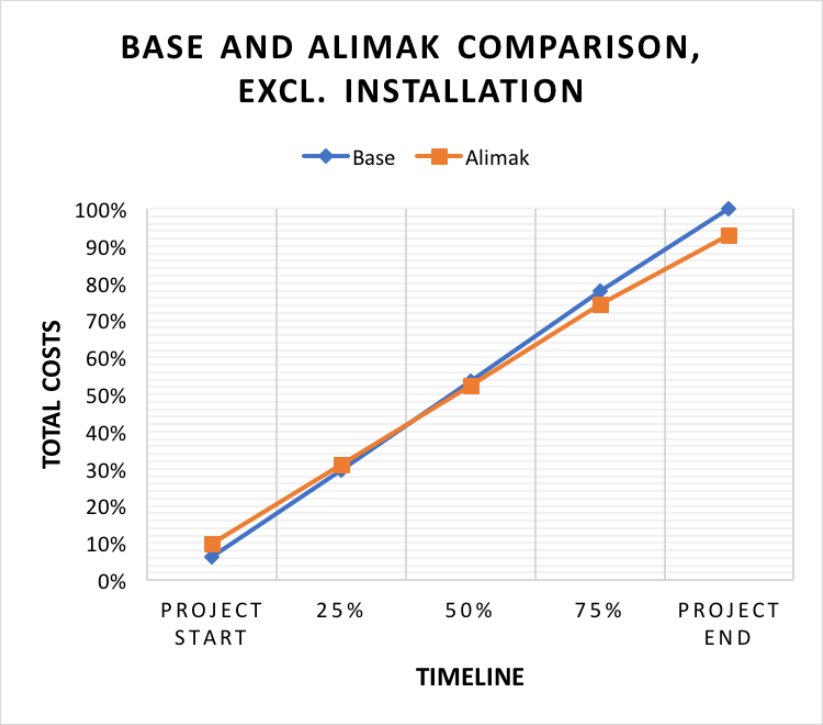

Figure 25 - Base and Alimak cost development, without installation cost

8.3. Productivity evaluation

The productivity analysis which was carried out through comparisons with the Base scenario showed that using an optimized Alimak solution at Tellus can offer material handling at a high pace, which can have a positive effect on the project time plan. This was visualized in Figure 22 when comparing the productivity. However, the study has shown that installation of façade elements and interiors proved to be the single most time-consuming factor in terms of time required per m^2. This means that in order to achieve a substantial productivity impact in the Tellus project, it is necessary to not just optimize the vertical transport but also provide the right prerequisites for the installation within the buildings. This includes being able to transport more prefabricated interiors as well as larger façade elements.

The productivity when looking at the time span of activities showed that the Brunkeberg scenario is capable of completing material supply to the construction site 4 months faster than the Alimak scenario, and a total of 10 months faster than the Base scenario. An important note however is that this does not necessarily mean that the whole construction project can be completed 10 months faster, since this would require the core structure as well as the installation of interiors to be finished within the same time. Since the core structure is built one story per week, this sets the pace for what is achievable on a project level. With this in mind, the Brunkeberg scenario would offer a construction time the span of the core structure progression (18 months) while the Base scenario would need an additional three months to be completed. This is however given that the

pace of the core structure cannot be increased. Depending on the achievable progression of the core structure, it is certain that the Brunkeberg scenario will be between 3-10 months faster than the Base scenario. This time span can therefore be seen as a form of lower and upper bound for the construction of Tellus Towers, where the corresponding time span for the Alimak scenario is between 3-7 months faster than Base (depending on the time requirements for the core structure and other construction activities).

With this possible reduction in total project time, it is possible to again reflect back to costs in the construction project. As reducing the time of construction can result in large benefits in operational costs, both the Alimak and Brunkeberg scenarios can offer further gains through decreased construction costs. As Globerson (2017) mentions, assuming that direct overhead costs represent 15% of the total production costs, a big scale construction project such as the Tellus project can save around 1% of the total production costs for each month the project can be shortened. This would weigh in a lot more than just the costs related to the actual material flow analyzed in this study.

8.4. Feasibility analysis

The feasibility analysis presented below aims to discuss the practical implications each scenario would have in the construction project, as well as how achievable the scenarios would be. The first part of the chapter focuses on the possibility of implementation at Tellus Towers, where the assumptions made in this study are discussed based on how applicable each scenario would be in practice. This is followed by reflections on the adaptability of each scenario in other types of construction projects.

8.4.1. Possibility of implementation

Due to the floor planning of Tellus Towers the study has been affected in terms of the transportation within the buildings, which becomes challenging in the Base and Alimak scenarios. As visualized in *Appendix 1 – Tellus Towers, illustration of floors*, the core structure of the buildings is spread out throughout the entire floor, making it difficult to handle larger material within the buildings. For example, the bed had to be divided into two parts in these scenarios since the hallways are too narrow to support transport of a fully assembled one.

Although the floor planning has been taken into consideration in the study, the feasibility of the Base and Alimak scenarios however needs to be discussed in regard to the practical handling of material. The study is based on assumptions of which material can and cannot realistically be transported within the buildings, but further analysis is required to guarantee that this material transport is feasible. As an example, the pallets containing material may be too large to transport through the building interiors, which in practice would mean that the transport time may be longer than calculated in this study. In this way the feasibility of the result in the Base and Alimak scenarios is impacted negatively.

The feasibility of the Base and Alimak scenarios overall however benefits in the sense that these construction methods have been previously tested and verified. As mentioned, the Brunkeberg system has only been tested on a three-story building prior to this study and most of the data collection regarding façade handling is based on that individual test. The container handling has never been tested before and this study assumes that the handling for containers is similar to the handling of façade elements. If the study were to be conducted after testing the system and more concert data was available, the credibility would have increased since factors could more accurately be taken into account.

Another factor worth mentioning is in regards to the transport of personnel at the construction site. This study has mainly focused on material supply and has not studied the effects the Brunkeberg scenario would have in terms of transporting construction site workers to the building floors. With no regular construction hoists and only the internal jump lifts to provide personnel transports, this factor could affect the productivity to a large extent. With no way of evaluating this in the study it is regarded as a negative feasibility factor for the Brunkeberg scenario.

The feasibility is however weighed up somewhat by the practical use of the logistics center. In this study it has been assumed that a logistics center will be used in all three scenarios, but only the Brunkenberg scenario can guarantee the use of one. The assumption has been made to simplify the comparison from both a cost and productivity perspective. We can however be relatively certain that a logistics center will be used in all three scenarios. The logistic center will enable JIT-transportation and reduce transportation within the urban area (Janné, 2018), which in this case is more or less necessary due to the size of Tellus Towers and its densely populated location. Notable, however, is that there would need to be a company or other actor responsible for the logistics center as this is not a given in the more traditional construction scenarios. For this reason, using a logistics center is regarded as less feasible in the Base and Alimak scenarios.

8.4.2. Level of adaptability

The level of adaptability is based on the three scenarios possibility to be applied on other construction projects. As the Base and Alimak scenarios only differs between the hoists speed, size and capacity (note that cost and productivity is not taken into account when discussing adaptability) will they have the same level of adaptability and therefore be compared together as one solution with Brunkeberg.

Brunkeberg provides a vertical logistic solution for building with similar layout as Tellus Towers. The solution is tailored for buildings like Tellus Towers, buildings with a solidary layout and where the same interior will be used throughout the buildings. As soon as we move away from this type of construction where each room would be more unique, Brunkeberg will most likely start losing its high productivity and become less cost efficient. While the hoists Alimak provides will maintain its level of productivity and cost since they are less dependent on the transported material. However, material needs transportation within the buildings which makes the logistics challenging, shown in the study. On the other hand, is the adaptability of the hoists higher, since

they can transport a wider range of material and makes the solutions more suitable for buildings with a more "normal" layout. Alimak as a corporation has a wide range of hoist set-ups and are able to supply flexible solution for a wide market. If for example a building with another layout would be studied, the solution Brunkeberg has presented with prefabricated material could have been used in all three scenarios. It would thereby remove the cost difference in the cost item, *Installation cost.* This would mean that the study would have neglected the largest cost item from the calculations, thereby improving the result for Base and Alimak in this study.

Brunkeberg's system is designed to be a good match for buildings similar to Tellus Towers. Construction with curtain walls as façade and with low level of apartment customization is where the system performs at its best. The Brunkeberg system is tailored for this type of construction which traditional construction is not. Brunkeberg will however face bigger challenges with less unitary buildings, since material larger than 80x80cm will not fit in the containers. This makes the Base and Alimak scenarios more flexible and susceptible for larger material.

8.5. Discussion

Even though numbers and data used in this study are unique for Tellus Towers, there are still some general discussions to be had when looking at the construction industry as a whole. The results in this study show that the Brunkeberg solution is one which is specialized for a certain type of construction. With a high number of identical apartments, the Tellus project is similar to the type of production found in assembly lines. Here, as brought up by Roy (2005), the most effective system is one which may require a high fixed cost – but is tailored to a large extent to the individual product and can produce at high pace and low variable costs.

Construction projects are nevertheless varying and can require different production methods, which is why it may be essential to clearly define what the product actually is. If one were to study products in the terms of Tellus Towers apartments, Brunkeberg offer the most suitable logistics solution. The degree of standardization in Tellus Towers resembles to non-volumetric pre-assembly (Jonsson & Rudberg, 2014), and the Brunkeberg scenario appears to support this through a more dedicated logistics system. However, if products are seen as entire buildings, Alimak offer vertical transport solutions which are applicable for construction projects with varying characteristics. Alimak's vertical transport solutions are designed to cope with these variations to a higher degree than Brunkeberg's solutions, which could impact each scenario's productivity level. Even though the Tellus Towers consists of high levels of non-volumetric pre-assembly, this is not the case for every construction project. Although as Yazdi, et al. (2019) argues, there is an increasing need of affordable apartments in densely populated areas. A solution to this could be non-varying apartments with similar characteristics to the Tellus Towers, where Bunkeberg's solution might be the most applicable.

The Alimak scenario however showed that if the floor planning had been different, larger hoists could be used to transport even larger material than the Brunkeberg containers. Costs in the total cost analysis which were directly attributed to the design of the building floors were installation

and horizontal transport, which were also found to be the two largest cost and productivity drivers in the Alimak and Base scenarios. Being able to affect these could therefore have the biggest impact, which is underlined by what Coelli, et al. (2005) states about the need to improve activities with the biggest negative effects on productivity. Furthermore, with varying apartment requirements, the Alimak hoists would be more adaptable to manage transports of different material needs. Due to this, when looking at the transition between construction projects, it is more likely that Alimak's construction hoists can serve a wider range of projects. This can provide value benefits to the owners of these projects, as discussed by Grant, et al. (2006).

During the transitions between projects however, it is crucial that cooperation is maintained for effective SCM. It is notable that Brunkeberg is significantly more integrated in a wider range of the project, where the vertical transport is not the sole area of focus. This can be related to Dubois and Gadde (2002), who brings up loose couplings as part of the reason why it is difficult to achieve increasing productivity levels in the industry. Loose couplings can lead to situations where the industry prioritizes individual projects ahead of long-term cooperation. Brunkeberg for example provide a solution where they use a specific supplier for interior so that material can be prefabricated and easier to install in the apartments, and also a logistic center providing material at the right pace. Brunkeberg is integrated in the whole construction supply chain, while Alimak provide a hoist solution based on vertical transport specifications by the main contractor. This is further exemplified by Zijm (2016), who mentions that issues arise when short-term profits are prioritized ahead of long-term supply chain performance. If Alimak were to be integrated earlier in the construction process in terms of floor planning the solution delivered would most likely be optimized to a larger extent for the construction site. For example, by enabling transportation of larger material which usually would have to be transported by tower crane. Less material transported by tower crane would result in a possibility to decrease costs, since according to Briskorn and Dienstknecht (2019) tower cranes are one of the biggest cost drivers at the construction site. With Alimak's ability to provide solutions for all kinds of different construction projects, maintaining performance between different projects can also be achieved. As Abdel-Wahab and Vogl (2011) pointed out, micro level productivity in a certain project does not guarantee macro level productivity in the industry. For this to be achieved, higher supply chain cooperation within construction is required.

Evaluating the construction scenarios using total cost analysis made it possible to more accurately evaluate the costs of the logistics scenarios, an aspect which can be more applicable than just studying procurement price as described by Ellram (1995) and Roda et al. (2019). Although total cost of ownership takes the buyers perspective of a product, they enable a way to study costs which arise outside of the individual company's border. This study has underlined the importance of looking at a wider scope of costs rather than simply purchasing price, which in the construction industry may be difficult due to the temporary supply chains in each project. These solutions can be both costly and less effective, in turn leading to lower productivity levels highlighted as current problems in the industry (Abdel-Wahab & Vogl, 2011; National Academy of Sciences, 2009;

Dubois & Gadde, 2002). By introducing a standard of cooperation these temporary solutions can be avoided and thereby reduce cost and time duration for construction projects. As Mentzer, et al. (2001) points out, trust and information sharing are key factors which need to be worked on in an industry consisting of multiple actors – perhaps partly explaining why purchasing price is still a dominant factor when deciding between different construction methods.

8.6. Sustainability and ethical aspects

The 3 dimensions within sustainability environment, social and economic are discussed in this chapter. First of all, the environmental aspect should be mentioned in regards to the use of a logistics center. As Brunkeberg has to have a logistics center for their solution, this scenario could entail a positive impact on the environmental aspects compared to the other two, since neither of them can guarantee a logistics center. To consolidate goods and thereby transport fully loaded trucks can reduce the number of last mile transportations needed. The use of electrical driven trucks for the façade elements (as explained in chapter *2.2.3 - Brunkeberg scenario*) can further enable positive additions to the environmental aspect, as well as social aspect through reduced noise levels in the urban area.

Regarding further social and ethical aspects, the safety between the different solutions can be discussed. As Ghodrati, et al. (2018) argues there is sometimes a tradeoff between high productivity and safety at construction sites. An increased productivity may entail stress on the construction workers, which in turn may jeopardize the safety of in terms of increased injury risks. As Brunkeberg's solution has the best productivity it could according to Ghodrati, et al. (2018) entail that the solution also has the highest risk for accidents. However, the productivity level in the Brunkeberg scenario is acquired by simplifying the works tasks, which indicates that the safety is not necessarily jeopardized. To give a certain answer this should however be further investigated. For the Base and Alimak scenarios the productivity difference is rather small and is therefore not considered as an implication on how the safety is affected.

Besides the costs which have been analyzed in this study, there are a few other things to mention when it comes to the economical aspect of sustainability. First of all, this can be viewed through the eyes of the owner of Tellus Towers. Through a shorter project time span, it is possible to quicker profit from the selling and/or rental of Tellus apartments. The future property owners or tenants at Tellus Towers can also be positively affected from reduced costs in the project, since these costs might also affect the price set for these apartments.

8.7. For future studies

As in most studies, time if of the essence and somewhere along the line delimitations and assumptions have to be conducted for simplification purposes. This entails work for future studies discussed below.

As for both productivity and cost it would be of interest to study these three scenarios but on other buildings. This would be a way to get a deeper understanding on how these solutions compare to

each other on a more general level. Tellus Towers consist of 82 respective 62 floors but due to the rapidly increasing complexity of the bottom and top floors has 71 and 53 floors been studied. As previously mentioned will the Brunkeberg solution for example face bigger challenges when the material being transported starts varying, this occurs on the top floors of both buildings (see *Appendix 1 – Tellus Towers, illustration of floors*). It would therefore be of interest to compare the solutions when not only apartment interiors are transported but also larger interior for the roof tops.

Since Brunkeberg has never been tested on a larger scale, the data collected in this study is fairly uncertain and with a lack of scientific background. If the system would be used on similar projects like Tellus, data could be collected and used for further studies to ensure a higher credibility. The same goes with the estimation for walking speed, traveling distance, installation time, et cetera. For future studies, actually timing construction workers by observations to ensure correct data would increase the reflection of the reality.

9. Recommendations and conclusion

This chapter aims to present the recommendation for which scenario should be used for Tellus Towers, as well as a conclusion based on the study's purpose.

For Tellus Towers we recommend the third scenario, the Brunkeberg scenario. With that said, this study has shown indications that Brunkeberg should not necessarily be recommended for other buildings with different floor layouts. To give a more general recommendation in this regard the scenarios need to be further studied based on multiple construction projects.

The purpose of the study was to:

"The purpose of the study is to, from a productivity and total cost perspective, evaluate three different scenarios for vertical construction logistics in the construction phase of the Tellus Towers project."

This purpose has been fulfilled by answering research questions which led to the conclusion that the Brunkeberg scenario proved to be the most suitable for the construction project, followed by the Alimak scenario. The first 3 research questions in the study have been answered through process mapping of each scenario. These 3 questions have in turn been used to answer the fourth question, where comparisons of total cost and productivity could be made. In terms of feasibility, the scenarios are seen to have equal levels of achievable implementation depending on the perspective. Based on the collectable data in the study are the Base and Alimak scenarios seen as more feasible, while in terms of floor planning is the Brunkeberg scenario preferable.

A general conclusion for high-rise construction is that low variable costs are to prefer over low fixed costs. As the biggest cost and productivity drivers are based on working hours, a correlation between low variable cost and high productivity has been identified. In order to achieve this to a maximum level, an integration of actors in the supply chain is required. This creates possibilities to design solutions which favor not only vertical transportation but the entire material flow.

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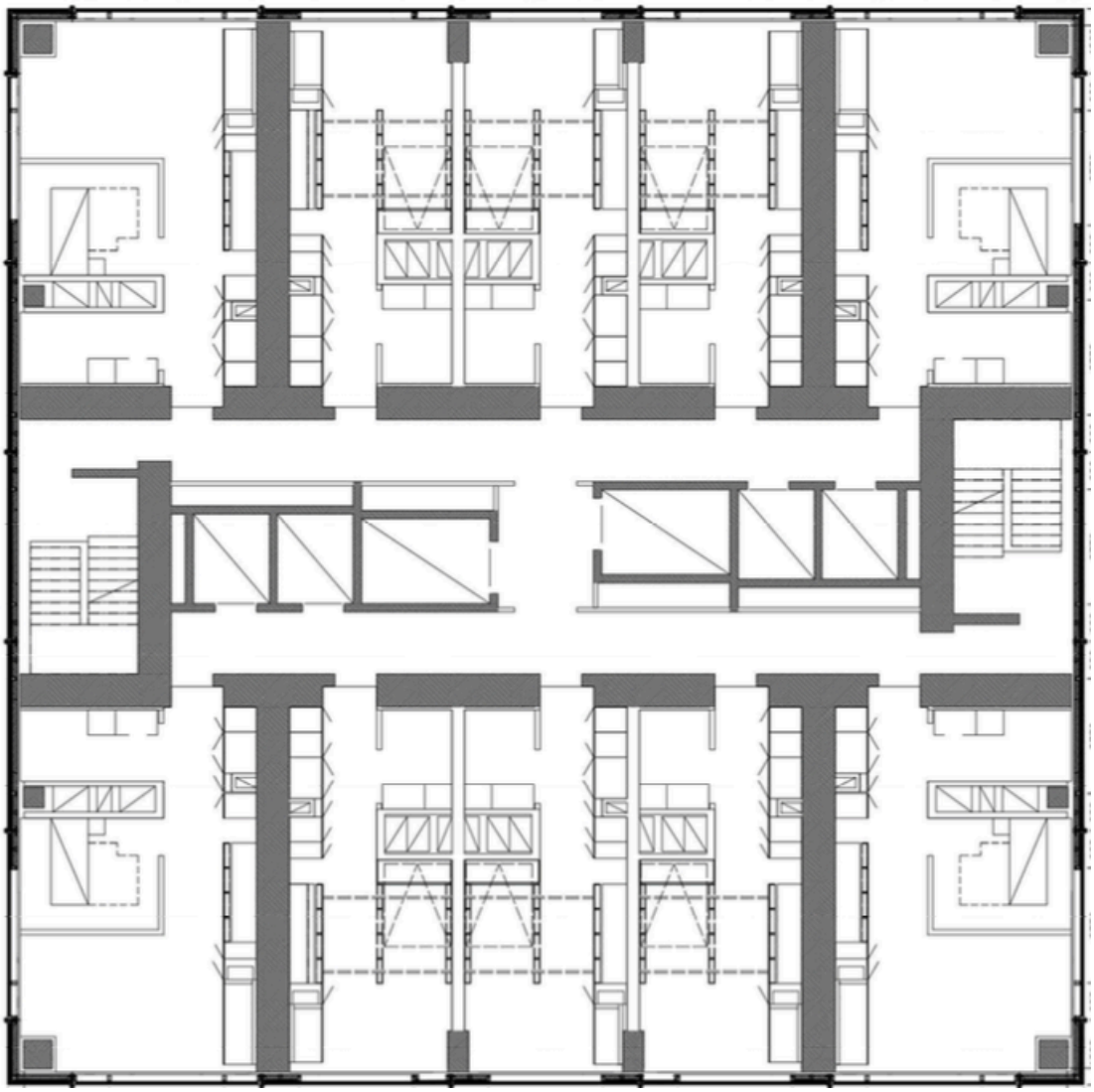
Appendix 1 – Tellus Towers, illustration of floors

height	floor	78 V - Tower	Level
279,7		top of parapet	82
276,7	3,0	roof top	81
273,7	3,0	Roof-Tech/Jacu/Gym	80
269,7	4,0	skybar	79
266,7	3,0	restaurant	78
262,5	4,2	visitor centre /stor	77
259,5	3,0	standard	76
256,5	3,0	standard	75
253,5	3,0	standard	74
250,5	3,0	standard	73
247,5	3,0	standard	72
244,5	3,0	standard	71
241,5	3,0	standard	70
238,5	3,0	standard	69
235,5	3,0	standard	68
232,5	3,0	standard	67
229,5	3,0	standard	66
226,5	3,0	standard	65
223,5	3,0	standard	64
220,5	3,0	standard	63
217,5	3,0	standard	62
214,5	3,0	standard	61
211,5	3,0	standard	60
208,5	3,0	standard	59
205,5	3,0	technic	58
202,5	3,0	standard	57
199,5	3,0	standard	56
196,5	3,0	standard + technic	55
193,5	3,0	standard	54
190,5	3,0	standard	53
187,5	3,0	standard	52
184,5	3,0	standard	51
181,5	3,0	standard	50
178,5	3,0	standard	49
175,5	3,0	standard	48
172,5	3,0	standard	47
169,5	3,0	standard	46
166,5	3,0	standard	45
163,5	3,0	standard	44
160,5	3,0	standard	43
157,5	3,0	standard	42
154,5	3,0	standard	41
151,5	3,0	standard	40
148,5	3,0	standard	39
145,5	3,0	standard	38
142,5	3,0	standard	37
139,5	3,0	standard	36
136,5	3,0	standard	35
133,5	3,0	standard	34
130,5	3,0	standard	33
127,5	3,0	standard	32
124,5	3,0	standard	31
121,5	3,0	standard	30
118,5	3,0	standard	29
115,5	3,0	standard	28
112,5	3,0	standard	27
109,5	3,0	standard	26
106,5	3,0	standard	25
103,5	3,0	standard	24
100,5	3,0	standard	23
97,5	3,0	technic	22
94,5	3,0	standard	21
91,5	3,0	standard	20
88,5	3,0	standard	19
85,5	3,0	standard	18
82,5	3,0	standard	17
79,5	3,0	standard	16
76,5	3,0	standard	15
73,5	3,0	standard	14
70,5	3,0	standard	13
67,5	3,0	standard	12
64,5	3,0	standard	11
61,5	3,0	standard	10
58,5	3,0	standard	09
55,5	3,0	standard	08
52,5	3,0	standard	07
49,5	3,0	standard (special)	06
46,5	3,0	mezz, cellars	05
43,5	3,0	cellars	04
40,5	3,0	com, bicycles	03
37,5	3,0	bicycle	02b
34,7	2,8	technic / cellar	02a
31,9	2,8	cellar	01

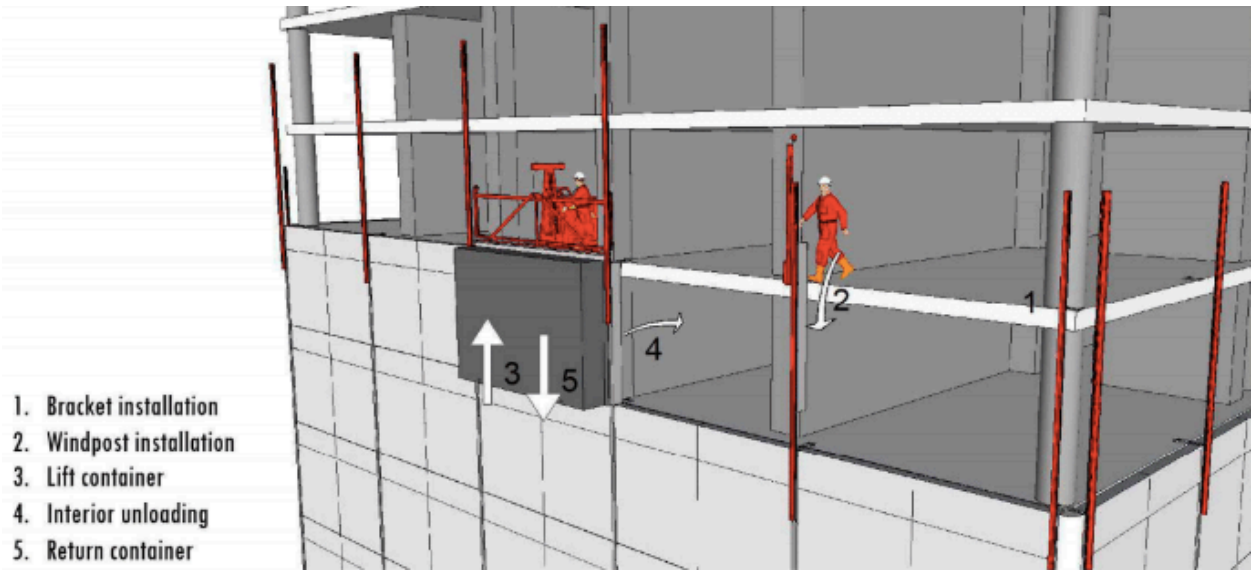
height	floor	58 V - Tower	
217,6		top of parapet	
214,6	3,0	roof top	
211,6	3,0	Roof-Tech/Spa/Jac	
208,5	3,1	special	
205,5	3,0	standard	
202,5	3,0	standard	
199,5	3,0	standard	
196,5	3,0	standard	
193,5	3,0	standard	
190,5	3,0	standard	
187,5	3,0	standard	
184,5	3,0	standard	
181,5	3,0	standard	
178,5	3,0	standard + technic	
175,5	3,0	standard	
172,5	3,0	standard	
169,5	3,0	standard	
166,5	3,0	technic	
163,5	3,0	standard	
160,5	3,0	standard	
157,5	3,0	standard	
154,5	3,0	standard	
151,5	3,0	standard	
148,5	3,0	standard	
145,5	3,0	standard	
142,5	3,0	standard	
139,5	3,0	standard	
136,5	3,0	standard	
133,5	3,0	standard	
130,5	3,0	standard	
127,5	3,0	standard	
124,5	3,0	standard	
121,5	3,0	standard	
118,5	3,0	standard	
115,5	3,0	standard	
112,5	3,0	standard	
109,5	3,0	standard	
106,5	3,0	standard	
103,5	3,0	standard	
100,5	3,0	standard	
97,5	3,0	standard	
94,5	3,0	standard	
91,5	3,0	standard	
88,5	3,0	standard	
85,5	3,0	technic	
82,5	3,0	standard	
79,5	3,0	standard	
76,5	3,0	standard	
73,5	3,0	standard	
70,5	3,0	standard	
67,5	3,0	standard	
64,5	3,0	standard	
61,5	3,0	standard	
58,5	3,0	standard	
55,5	3,0	standard	
52,5	3,0	standard	
49,5	3,0	standard (special)	Canopy
46,5	3,0	mezz, cellars	
43,5	3,0	cellars	
38,7	4,8	com, segregation	GF / Street Level
34,7	4,0	technic / cellar	
31,9	2,8	cellar	

Appendix 1, Figure 1 – Illustration of Tellus Towers levels

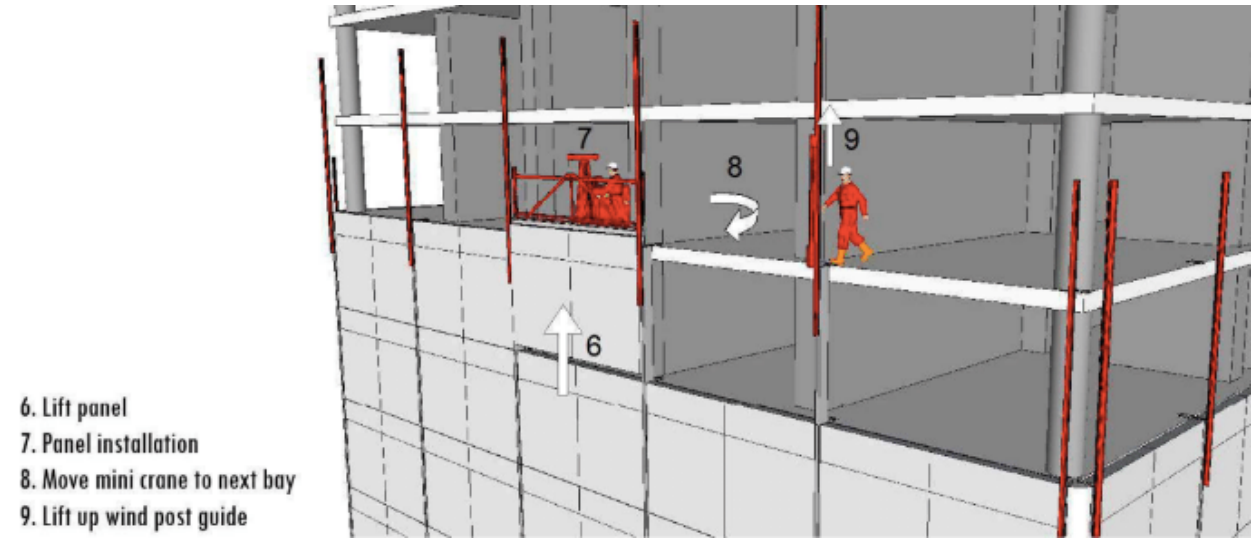


Appendix 1, Figure 2 – Planning on standard floor

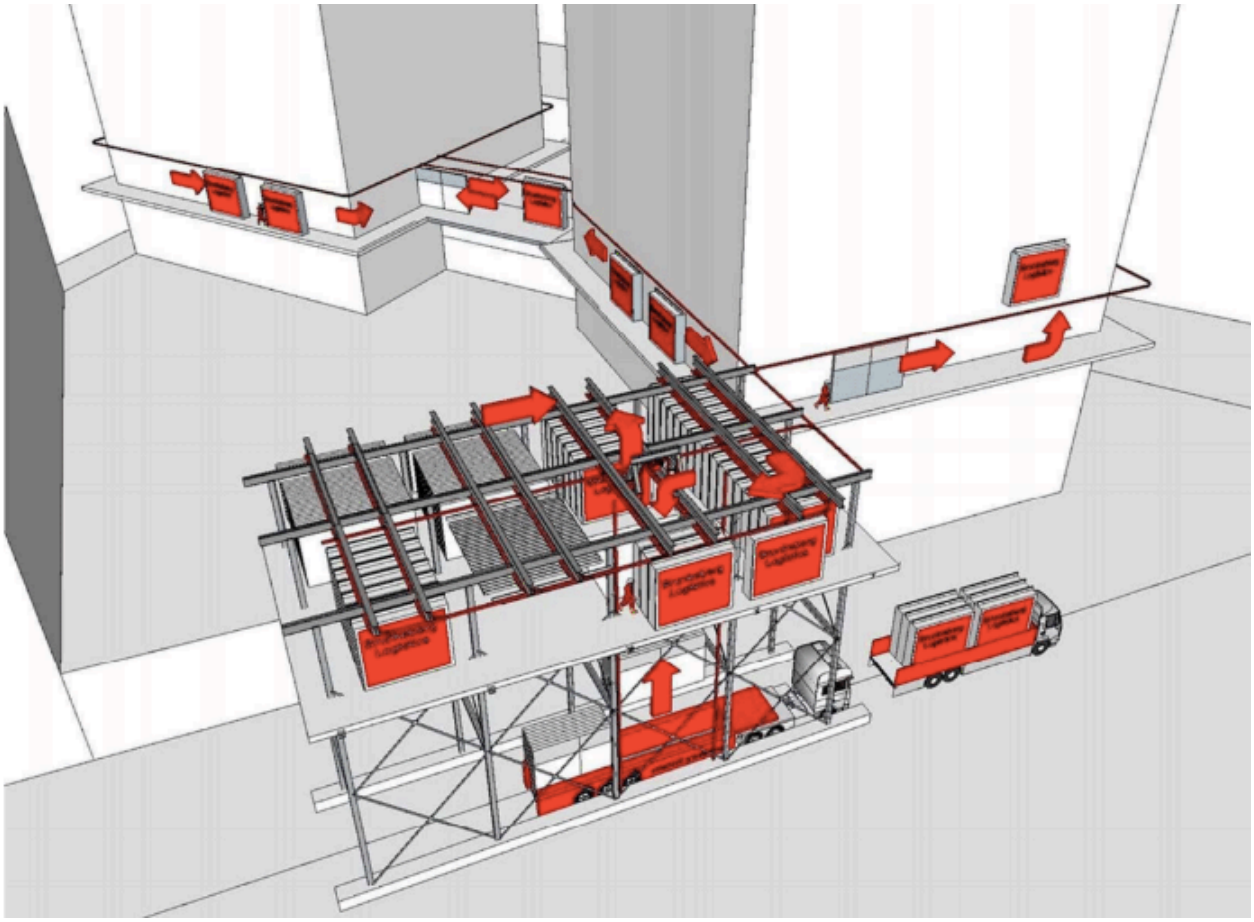
Appendix 2 – Brunkeberg's system



Appendix 2, Figure 1 – Brunkeberg's system for containers



Appendix 2, Figure 2 – Brunkeberg's systems for façade



Appendix 2, Figure 3 – Brunkeberg Relief station at Tellus Towers

Appendix 2, Figure 4 – Truck designed for Brunkeberg façade elements

Appendix 2, Table 1 - List of equipment used in the Brunkeberg system

Equipment	**Rental/purchase**
Brunkeberg crane (x2) with installation tools	Rental
Relief/Offloading station, 24x12m	Purchase
Scaffolding weather protection	Purchase + resell on market
Scaffolding erection	Purchase
Horizontal railway	Rental
Containers (x60)	Rental

Appendix 3 – Brunkeberg data

Below the façade time requirements are presented in each cell, as the number of minutes for each installation point in a building. The numbers along the left-hand side resemble the floor of installation, and the bottom two rows show the horizontal distance and transport time to walk with a façade element from the Relief station to the respective location.

29	11	11	11	11	12
28	11	11	11	11	11
27	11	11	11	11	11
26	11	11	11	11	11
25	11	11	11	11	11
24	11	11	11	11	11
23	11	11	11	11	11
22	10	11	11	11	11
21	10	10	11	11	11
20	10	10	10	11	11
19	10	10	10	10	11
18	10	10	10	10	10
17	10	10	10	10	10
16	10	10	10	10	10
15	10	10	10	10	10
14	10	10	10	10	10
13	10	10	10	10	10
12	9	10	10	10	10
11	9	9	10	10	10
10	9	9	9	10	10
9	9	9	9	9	10
8	9	9	9	9	9
7	9	9	9	9	9
6	9	9	9	9	9
5	9	9	9	9	9
4	9	9	9	9	9
3	9	9	9	9	9
2	8	9	9	9	9
1	8	8	9	9	9
	2	7	11	16	21
	15	20	26	31	37

Appendix 3, Figure 1 – Façade time, installation and transport

Appendix 4 – Material requirements

The tables below present the material requirements for the Tellus apartments, as well as how these are loaded on pallets (Base + Alimak scenario) or containers (Brunkeberg scenario).

Appendix 4, Table 1 – Material requirements for Base & Alimak

Pallet number	**Material loaded on pallet**	**Note**
1	Wardrobes x6, kitchen pantry	Packed as flatpack
2	Stove, kitchen cabinets x9	Cabinets packed as flatpack
3	Fridge, freezer	
4	Bed (disassembled)	Divided into two separate parts
5	Toilet and bathroom sink	This pallet also consists of various smaller items (vents, smaller tubes, etc)
6	Shower, cabinets x5, mirror	
7	Washing machine, tiles, floor	Tiles and floor for bathroom
8	Bathroom door, front door, specialized sliding wall	
9	Floor	Floor for the rest of the apartment
10	Material for plumbing installation (tubes, pipes), kitchen sink	Need to be assembled in each apartment

Appendix 4, Table 2 – Material requirements for Brunkeberg

Container number	**Material loaded in container**	**Note**
1	Prefab plumbing configuration (Uponor)	Quite large, requires a whole container
2	Prefab bathroom floor panel, prefab wall panel x3, washing machine	
3	Toilet, bathroom door, main apartment door, shower, bathroom mirror, bathroom sink	
4	Wardrobes x6 (assembled)	
5	Floor, kitchen	Kitchen involves stove, sink and cabinets
6	Bed (assembled) + specialized sliding wall	The wall is placed beside the bed and can slide to screen off

Appendix 5 – Installation time in Tellus apartments

Appendix 5, Table 1 – Installation time, Base & Alimak scenario

Category	Activity name	Unit time (h)
Plumbing	Water supply, bathroom + kitchen	10
Bathroom	Walls	13
	Mirror	0.5
	Toilet, shower, washing machine, sink	7
Frame supplements	WC door	1.3
	Front/main door	1.3
	Floor (bathroom)	2
	Floor (rest of apartment)	4
Furnishings	Wardrobes + kitchen	8 (x2 workers)
	Bed assembly + installation	8
	Sliding wall assembly + installation	8
	Total working hours	**71.1**

Appendix 5, Table 2 – Installation time, Brunkeberg scenario

Category	Activity name	Unit time (h)
Bathroom	Plumbing (prefab panel), walls+ floor panels	8 (x2 workers)
	Mirror	0.5
	Toilet, shower, washing machine, sink	7
Frame supplements	WC door	1.3
	Front/main door	1.3
	Floor (rest of apartment)	4
Furnishings	Wardrobes + kitchen	4 (x2 workers)
	Bed installation	1
	Sliding wall installation	8
	Total working hours	**47.1**