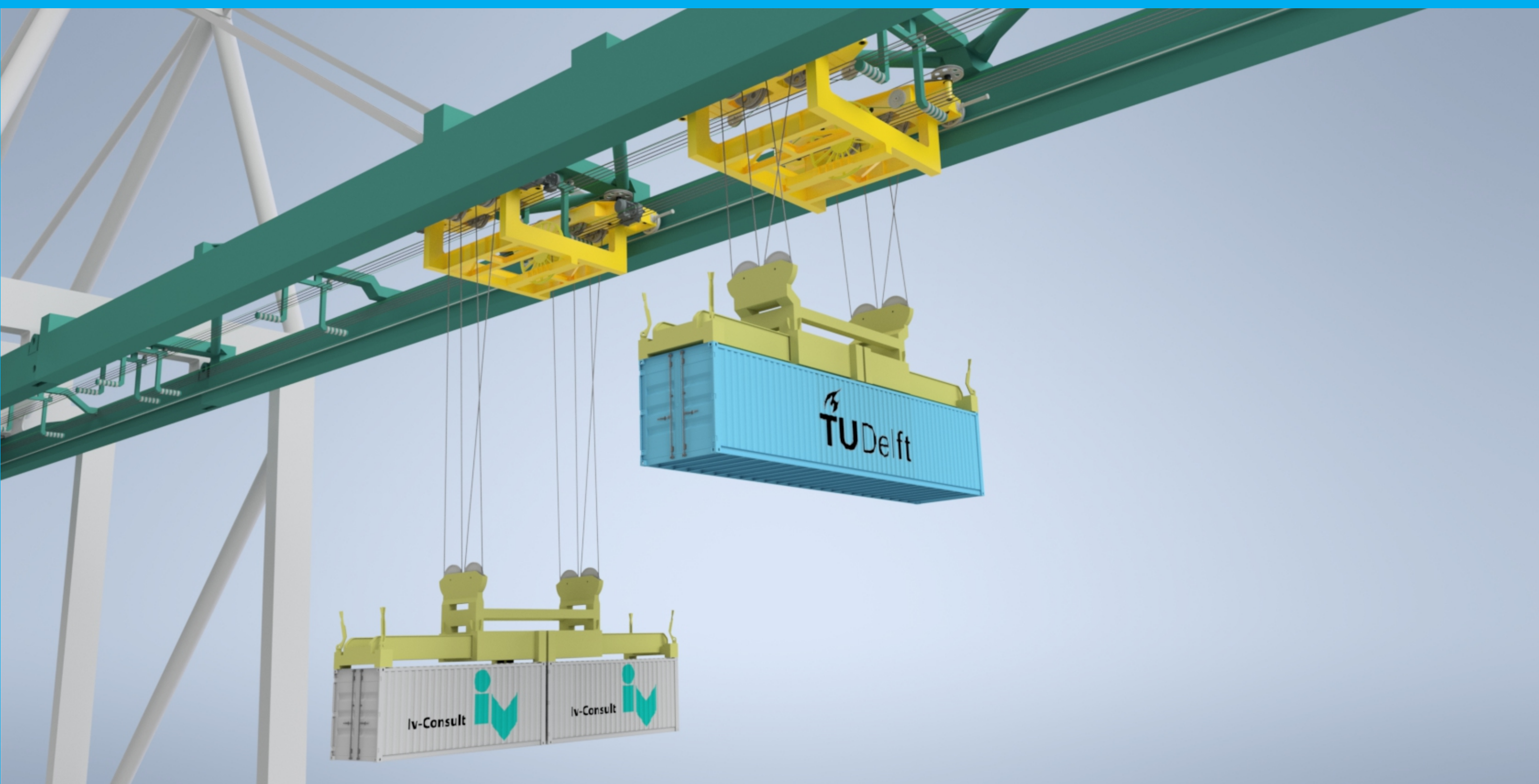
A study into new concepts to simultaneously transport 4 TEU with a ship-to-shore container crane

during loading and unloading of a container ship

L.M. Roest



TUDelft

A study into new concepts to simultaneously transport 4 TEU with a ship-to-shore container crane

during loading and unloading of a container ship

by

L.M. Roest

Master Thesis

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Summary

Container ships are increasingly growing in size. Due to the larger travel distances, the productivity of ship-to-shore cranes drops. Some existing solutions can simultaneously transfer 4 Twenty foot Equivalent Unit containers between the ship and the quay. Because of the limitations that come with these solutions and the demand for higher productivity cranes, this work explores alternative concepts that can simultaneously transfer 4 Twenty Foot Equivalent Unit containers. These concepts have to be designed on a standard ship-to-shore crane structure. Seven concepts are composed. The working principles of these concepts are based on working principles found in (patent) literature. The concepts are compared based on multiple objectives, after which one concept is chosen to realize a concept design. A ship-to-shore crane with two trolleys turns out to be the most suitable concept. In this concept, two trolleys travel on the same rails without being able to pass each other. Both trolleys serve one half of the ship during loading and unloading. As the trolley on the waterside has to drive longer distances, the landside trolley might have to wait before the next cycle can start. In this work, the concept design for the double trolley crane is described. The trolley types, cable support system, cable reeving system, and trolley frames of this concept are all elaborated in this work. The design of the trolleys is based on an existing trolley. It turns out that both trolleys of the double trolley crane need some adjustments compared to a conventional trolley. The reeving system and trolley frames are validated according to the EN 13001 standard. To do so, the trolley frames are examined by means of a finite element analysis.

Samenvatting

Containerschepen krijgen steeds grotere afmetingen. Een gevolg hiervan is dat kadekranen grotere afstanden moeten overbruggen naar de containers op het schip, waardoor de productiviteit van kadekranen afneemt. Een conventionele kraan kan één 40 voets container of twee 20 voets containers tegelijk overslaan (2 TEU). Sommige bestaande containerkranen kunnen het dubbele aantal containers overslaan (4 TEU). Vanwege de beperkingen die deze kranen hebben, en de blijvende vraag naar containerkranen met een hogere productiviteit, wordt in dit verslag onderzoek gedaan naar alternatieve concepten die 4 TEU tegelijk kunnen overslaan. Deze concepten moeten gebouwd kunnen worden op een standaard kadekraan constructie. In totaal worden zeven concepten gevormd. De werkingsprincipes van deze concepten zijn gebaseerd op gevonden literatuur, waaronder patenten. De concepten worden vergelijken op basis van meerdere doelstellingen. Uiteindelijk blijkt het concept met een extra kat het meest geschikt. In dit concept rijden beide katten op dezelfde rails, zonder dat ze elkaar kunnen passeren. Beide katten beperken zich tot één helft van het schip tijdens het overslaan van containers. Aangezien de kat aan de waterkant grotere afstanden moet afleggen, kan het gebeuren dat de kat aan de kadekant moet wachten voordat aan de volgende cyclus begonnen kan worden. In dit verslag wordt het concept ontwerp van de kraan met twee katten uitgewerkt. Het type kat, het kabel ondersteun systeem, de kabel inschering, en beide kat frames worden uitgewerkt in dit verslag. Het ontwerp van beide katten is gebaseerd op een bestaande kat. Het blijkt dat het ontwerp met twee katten wat aanpassingen vereist ten opzichte van de bestaande kat. Het nieuwe ontwerp van de kabel inschering en de kat frames wordt gevalideerd volgens de EN 13001 norm. Voor de validatie van de kat frames wordt de eindige-elementenmethode toegepast.

List of abbreviations

STS	Ship-to-shore
TEU	Twenty-foot equivalent unit
ZPMC	Shanghai Zhenhua Heavy Industries Company Limited
DHT40	Dual-hoist tandem 40
SHT40	Single-hoist tandem 40
LS	Landside
WS	Waterside
IBC	Inter-box connector
MOT	Machinery on trolley
RTT	Rope towed trolley
ULCV	Ultra Large Container Vessel
AGV	Automated Guided Vehicle
LC	Load Combination
ton	1000 kg
Trolley A	The trolley at the LS of the crane
Trolley B	The trolley at the WS of the crane
FEA	Finite Element Analysis

Contents

1 Introduction

1.1. Background

Container ships are increasingly growing in size. Due to these larger ships, the productivity of ship-to-shore (STS) container cranes drops, as the travel distances to the containers on the ship increase. For this reason, there is a need for STS cranes with higher productivity. Increasing the hoisting and trolley travel speeds to improve the productivity has its limitations. To significantly increase the productivity of STS cranes, new concepts with alternative working principles should be implemented. In general, terminal operators are reluctant to implement new STS crane concepts due to the high risks and investment costs, especially when the concepts deviate substantially from a conventional crane design. This is the reason that multiple high productivity crane concepts were never implemented in practice. To decrease this reluctance, high productivity crane concepts should be closely related to the conventional solution.

In practice, some solutions to increase the productivity of STS cranes already exist. These cranes apply tandem lifting to transfer more containers per movement. During tandem lifting, containers are lifted side by side by using a double spreader configuration. In this way, 4 Twenty Foot Equivalent Unit (TEU) containers can be loaded or unloaded, instead of 2 TEU for a conventional crane. To apply tandem lifting, the containers should be positioned in two adjacent rows on the ship. Tandem lifting can both be performed by cranes with a single lifting system (single hoist tandem) and a double lifting system (dual hoist tandem). Both designs can switch to a single spreader configuration when necessary. Whether tandem lifting will be applied depends on multiple factors, like the ship model, stacking plan, and crane operator. Although the theoretical productivity of tandem lifting is high, in practice the percentage of tandem lift operations is often below 20% [1] [2]. Dual hoist tandem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley. Single hoist tandem cranes need to swap spreaders every time there is a switch between single lifting and tandem lifting. On top of that, terminal operators willing to transport 4 TEU simultaneously with a ship-to-shore container crane are limited in their choice. They are often restricted to a single crane manufacturer, which results in high costs.

Because of the just mentioned reasons, a new concept should be developed to provide terminal operators with an alternative to simultaneously transfer 4 TEU between a container ship and the quay. To decrease the risks for terminal operators, the concept should be built on a standard STS crane structure. In the context of an STS crane, transport and transfer have the same meaning, so these terms are used interchangeably in this work.

1.2. Research questions

To exactly define the focus of this work, the following research questions are composed:

- **Main research question**:

    In which way can a new concept to simultaneously transfer 4 TEU during the loading and unloading of a container ship be designed on a standard ship-to-shore crane structure?

- **Subquestions**:
    1. What are the existing solutions for the simultaneous transfer of 4 TEU by an STS container crane?
    2. Which new concepts can be applied for the simultaneous transfer of 4 TEU on a standard ship-to-shore crane structure?
    3. What are the objectives and constraints of an STS crane with a standard STS crane structure?
    4. Which concept is most suitable and feasible for the simultaneous transfer of 4 TEU on a standard crane structure, taking into account the constraints and objectives of an STS crane?
    5. How can a design to simultaneously transport 4 TEU on a standard STS crane structure be realized by applying this concept?

1.3. Report Structure

Chapter 2 first elaborates some general STS crane principles, and subsequently covers the existing solutions for the simultaneous transfer of 4 TEU from and to a container ship with an STS container crane. Chapter 3 discusses multiple non-applied concepts to transport 4 TEU or more with an STS container crane. In chapter 4, the existing patents that describe the simultaneous transport of 4 TEU with an STS container crane are described. Subsequently, chapter 5 elaborates the constraints and objectives that are important for an STS container crane. In chapter 6 seven concepts are formed. A comparison between these concepts and the selection of the winning concept are made in chapter 7. The design of the chosen concept is discussed in chapter 8, although a separate chapter is reserved for the assessment of the trolley frames (chapter 9). Some comments about the consequences of two trolleys on one crane structure are made in chapter 10. The conclusions and discussion can be found in chapter 11.

2

Existing solutions

The problem of the simultaneous transport of multiple containers is already solved in multiple ways. This chapter addresses the existing solutions, with each section covering a different solution. Every design embraces components or aspects that are identical or related to conventional STS cranes. Therefore it is important to discuss several general aspects of STS container cranes before addressing other concepts. In this way every solution covered in this chapter can be compared to conventional STS cranes. For this reason, section 2.1 elaborates multiple general aspects of STS container cranes. The subsequent sections cover existing designs for the simultaneous transport of 4 TEU. The existing solutions most applied in practice are depicted in figure 2.1. It shows the conventional single hoist crane, a single hoist tandem crane and a dual hoist tandem crane. Single hoist tandem lifting is treated in section 2.2. Dual hoist tandem cranes are addressed in section 2.3. Other addressed concepts are the secondary trolley (section 2.4), triple lifting (section 2.5), and vertical tandem lifting (section 2.6). Readers that are already familiar with conventional STS cranes and its working principles can skip section 2.1

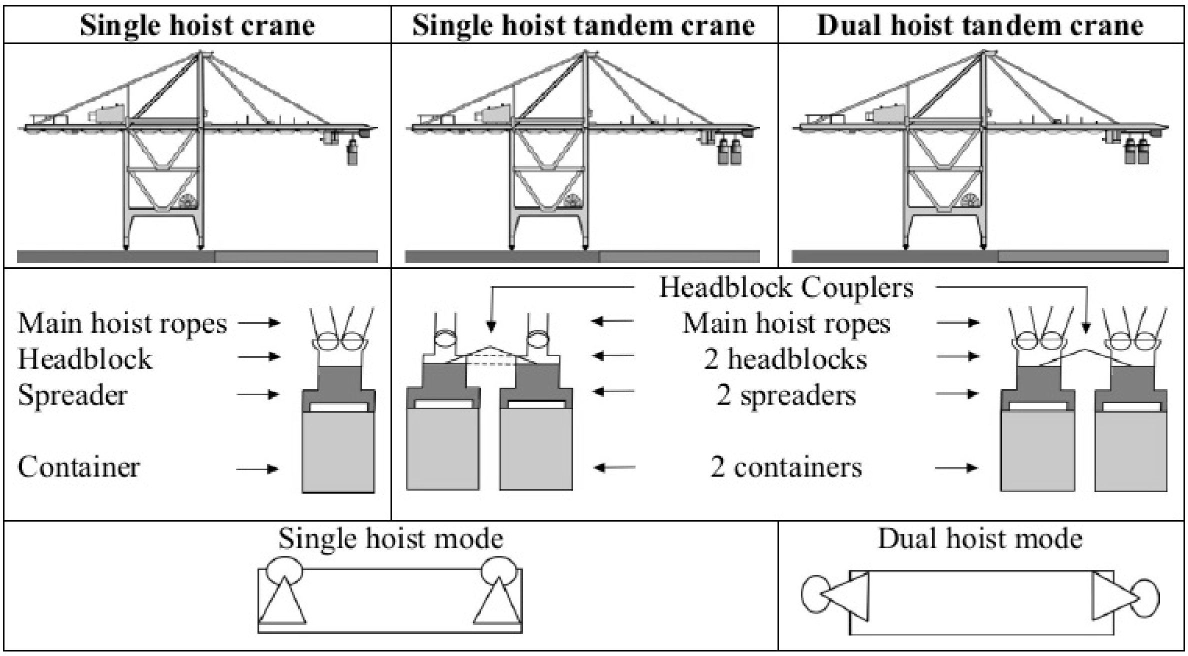


Figure 2.1: Single hoist and dual hoist. From [3]

2.1. General STS crane aspects

2.1.1. Standard crane structure

In this subsection, the definition of a standard crane structure as employed in this work will be elaborated. To start off, a difference can be made between high profile and low profile STS crane structures. These cranes have a different boom mechanization. The boom of a high profile crane tips up to enable large ships to moor, while the boom of a low profile crane can move horizontally. The high profile crane has the advantage of having lower costs and wheel loads compared to the low profile cranes [3]. Due to the disadvantages of low profile cranes, they are only used when less height is required, i.e. in the vicinity of airports. The profiles can be seen in figure 2.2 and figure 2.3. When speaking of a conventional single-hoist crane in this work, a high profile crane like figure 2.2 is meant. This is because this is the dominant design in contemporary STS container cranes. The waterside (WS) of the crane structure is the side where the ship is berthed, while the landside (LS) is the side of the quay. These abbreviations will be frequently used in this work.

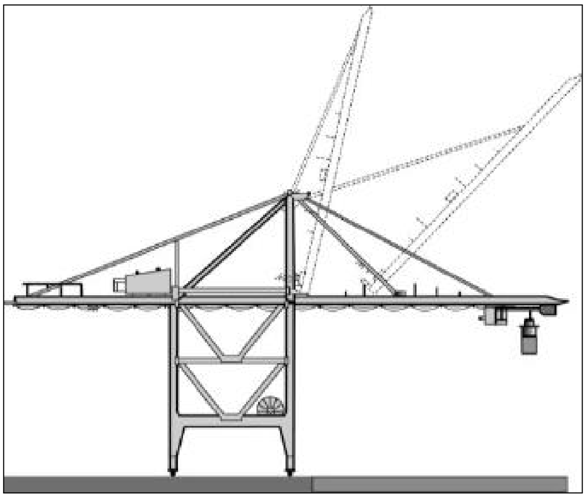


Figure 2.2: High profile STS crane. From [3]

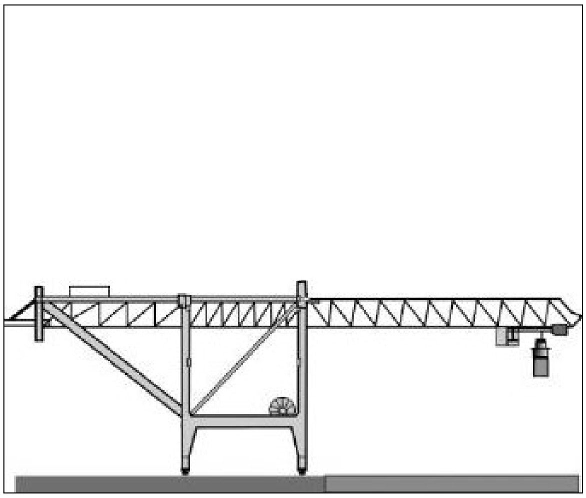


Figure 2.3: Low profile STS crane. From [3]

Figure 2.4 shows a schematic overview of a conventional STS container crane. The terms indicated in the schematic overview will be implemented in this report. These terms can be used regardless of the exact girder type. When speaking of a "standard STS crane structure" in this work, the following characteristics are meant:

- A high-profile crane structure comparable to figure 2.2 and figure 2.4. This structure can have different girder types for the boom and trolley girder (see subsection 2.1.2).
- A maximum width of 27 meters to provide enough space for adjacent cranes.

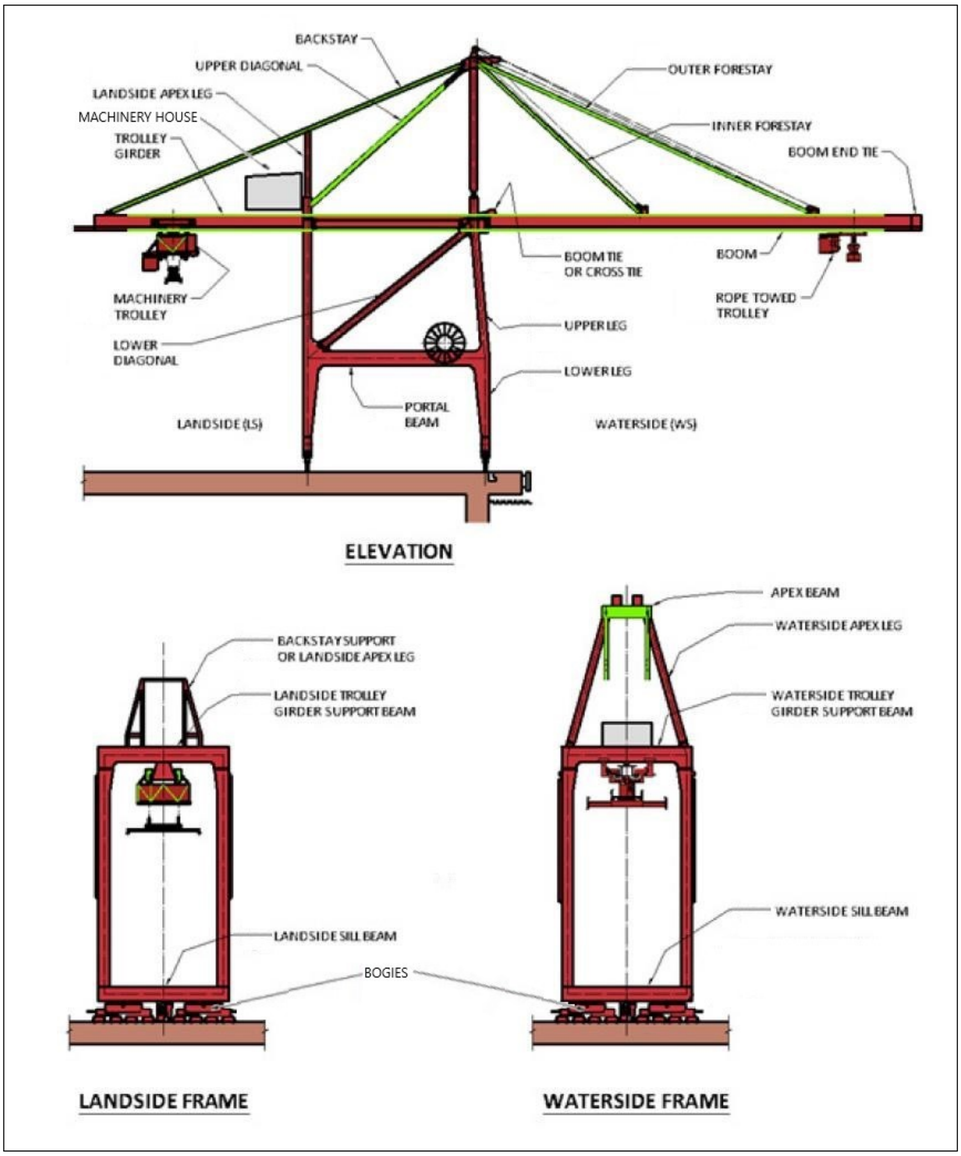


Figure 2.4: Schematic overview of an STS container crane. From [4]. The enumeration from the original publication of this figure is removed. The descriptions for "machinery house" and "bogies" were added later.

2.1.2. Girder types

A distinction can be made between several girder types. The different types of boom girders are explained by Vette [5] and summarized in this paragraph. First of all, there is the mono girder boom (figure 2.5 and figure 2.10), which has the simplest construction of all boom types. Due to this simplicity, production costs are reduced. The flexibility of this design is a disadvantage of the mono girder boom. The trolley is positioned below the girder, while the rails are located on the top side. Synonyms for this boom type are single boom, mono-box boom or mono-box girder. An alternative boom design is the twin girder boom, which can be seen in figure 2.6 and figure 2.9. As the name suggests, two girders are placed in parallel. This layout results in more strength, but also comes with a more complex and heavier construction. The trolley drives in between the two girders. Other names for this design are double box girder, double boom and twin box boom. The last design is the lattice boom (or truss boom). This boom is the most complex of all types, and requires a lot of welds. Due to this structure, the boom is affected less by wind and the weight is decreased. It is also possible to have a boom girder that differs from the trolley girder. An example of this is shown in figure 2.8, where the trolley girder is a monobox and the boom has a lattice structure.

Figure 2.5: Mono girder boom. From [5]

Figure 2.6: Twin girder boom. From [6]

Figure 2.7: Lattice or truss boom. From [4]

Figure 2.8: Crane with monobox trolley girder and lattice boom. From [6]

2.1.3. Trolley types

There are multiple types of trolleys, for which the location and operation of the hoist and trolley drives differ. Every trolley type has its own properties and (dis)advantages. The information about trolleys in this subsection was obtained from Bartošek, Marek, et al. [3], Hans van Ham [7] and Verschoof [8]. The findings of the sources agreed well with each other, and are summarized below. A distinction can be made between a rope-towed trolley (or full rope trolley), machinery trolley, and semi rope trolley (or fleet-through machinery trolley).

Rope towed trolley (RTT)
For the full rope trolley, both the hoist and trolley are driven by wire ropes from the machinery house on the trolley girder. In this way the trolley can be lightweight, as there is no need to place the hoisting and trolley travelling mechanisms on the trolley. Because of this arrangement many components are easily accessible for maintenance. Components can be easily replaced and ropes can be re-reeved. However, due to the extra sheaves and wire ropes more maintenance is required. Also, with the increasing travelling distances of the trolley, the rope sag became a problem for the wire ropes towing the trolley. Therefore arrangements should be made to limit sagging, for example by implementing auxiliary catenary trolleys. The extra wire ropes also result in less responsiveness when adjusting the trolley position. A positive aspect of the RTT is that the trolley wheels will not slip, and therefore a high acceleration is possible. On top of that, the festoon system to the trolley is relatively small-sized, as the trolley drive and main hoist do not have to be powered via the festoon cables. An example of a RTT can be seen in figure 2.9.

Machinery trolley (MOT)
The machinery trolley (MOT, from Machinery On Trolley) has both the hoisting mechanism and trolley travel mechanism installed on the trolley itself. Consequently, no drive ropes to a machinery house on the trolley girder are needed. This is also the case for the main hoist ropes. Because the main hoist is installed on the trolley itself the ropes can be shorter. The configuration of trolley drive and main hoist also leads to a great reduction in number of sheaves. The reduction in components leads to less spare parts that are required to keep the crane operational, and results in a higher maintainability. Due to the simple reeving the crane reacts more accurately on the operators actions. However, the festoon cable system will be more substantial, as power is required for the main hoist and trolley drive. The main downside of MOT is the increased weight, with larger loads on the main girder. Also the wheel loads on the quay increase. Another negative aspect of the MOT is the possibility of slipping trolley wheels. The acceleration of the trolley partly depends on the friction between the trolley wheels and the rails. In figure 2.10 the machinery trolley can be seen. Also the trolley in figure 2.8 is a machinery trolley.

Semi rope trolley
The semi rope trolley is a combination of the RTT and MOT. The main hoist winches are positioned in the machinery house on the trolley girder, just like the RTT concept. However, the trolley travel mechanism is positioned on the trolley, just like in the MOT design. As a consequence, the semi rope trolley has less components than the RTT, but more than the MOT. Self-evidently, the hoisting behaviour is comparable to the RTT and the trolley drive behaviour is comparable to the MOT. Because the trolley drive is placed on the trolley itself the semi rope trolley can also have the problem of wheel slip. This trolley concept is slightly heavier than the RTT. The semi rope trolley is not applied very often compared to the RTT and MOT.

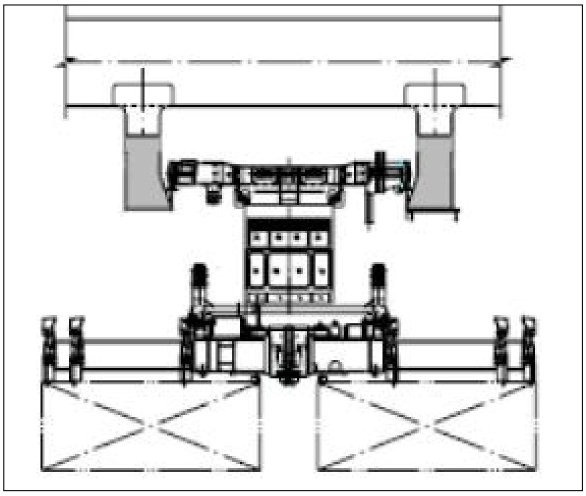


Figure 2.9: Full rope trolley on twin girder. From [3]

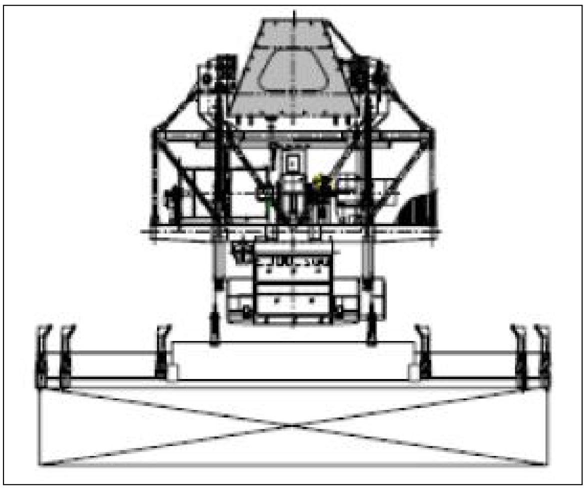


Figure 2.10: Machinery trolley on mono girder. From [3]

An alternative trolley type is the semi machinery trolley [8, p. 161], which is in some sense also a combination of the RTT and MOT designs. Contrary to the semi rope trolley, the semi machinery trolley has the main hoist installed on the trolley, while the trolley travel mechanism is installed in the machinery house on the trolley girder. However, because of the limited presence of this concept in practice it is not further elaborated. The most important difference between the different trolley types listed above is the weight. The machinery trolley is the heaviest, the most lightweight trolley is the full rope trolley, and the weight of the semi rope trolley is in between the other two types. The RTT and MOT are both frequently applied in practice. While discussing the concepts of RTT and MOT, van Ham and Rijsenbrij wrote the following statements in 2012: "The present day crane dimensions, the increased attention for environment and maintenance cost and the demand for productivity (and thus load control) have not resulted in one outspoken choice for one of these concepts" [7, p. 145], and "In general, the rope driven trolley still is the dominating concept, although both concepts are selected depending on local conditions and demands (preferences)" [7, p. 146].

2.1.4. Main hoist

As explained in the previous subsection, in most cases conventional cranes have either a RTT or MOT. The main hoist works differently for these trolley types. For cranes with a MOT, less wire rope length is required for the main hoist. In figure 2.11 a typical hoisting winch on a MOT is depicted. By fixing the rope ends to the trolley, the load on the winch is reduced. Self-evidently, the semi rope trolley has the same hoisting system as the RTT. In figure 2.12 a commonly used main hoist wire rope reeving for conventional single-hoist STS cranes with RTT is shown. The drums are located in the machinery house on the trolley girder. The wire ropes run from the drums to sheaves located at the landside side of the crane, to the trolley and headblock, and to the waterside (WS) end of the boom. Another example of a hoist wire rope reeving of a RTT is depicted in figure 2.13. This reeving is used when the crane has a continuous rope support system (see subsection 2.1.6).

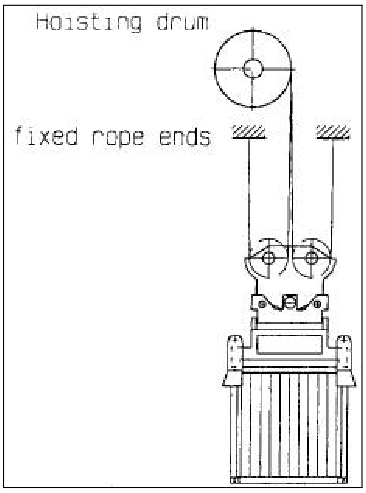


Figure 2.11: Hoisting winch on machinery trolley. From [8]

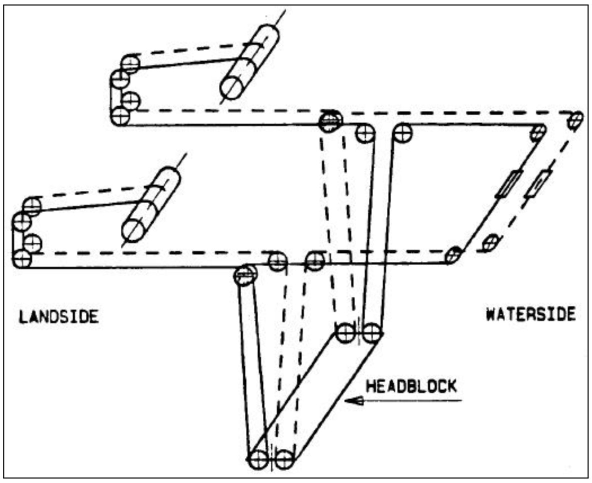


Figure 2.12: Normal hoisting wire rope scheme. From [8]

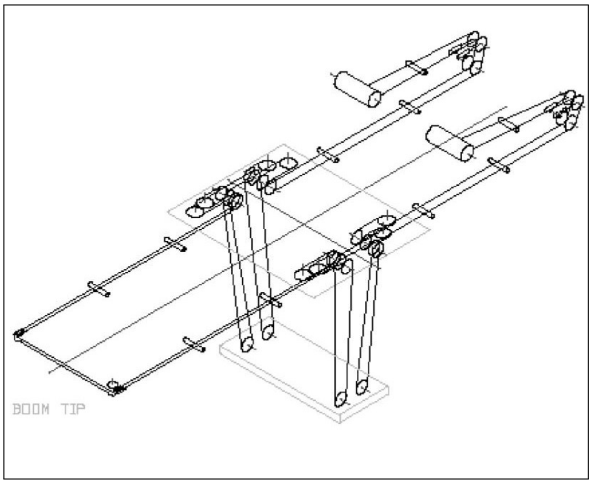


Figure 2.13: Hoisting wire rope scheme. From [9]

2.1.5. Trolley travel

The wheels of a machinery trolley and a semi rope trolley are directly driven via multiple motors and gearboxes that are installed on the trolley. A rope towed trolley is towed via wire ropes that run from the machinery house to the trolley. In figure 2.14 the wire rope reeving for the trolley travel can be seen.

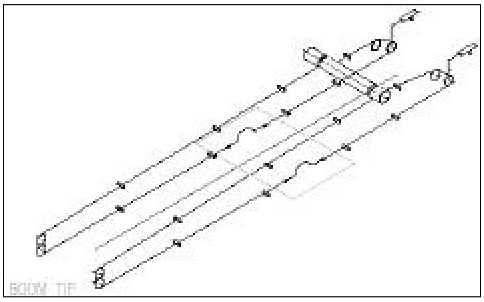


Figure 2.14: Trolley travel reeving. From [9]

2.1.6. Rope support

Because of the large outreach of modern cranes with a RTT (and semi rope trolley), the wire ropes should cover a large distance. This can result in substantial rope sag. For this reason, a rope support system needs to be installed on the crane to support the wire ropes. The support of the wire ropes can be achieved by two different systems. To start off, the wire ropes can be supported by catenary trolleys. This are two smaller trolleys that drive simultaneously with the main trolley at half the speed. Figure 2.15 shows the wire rope reeving of the catenary trolleys, together with the main trolley travel reeving and the hoisting reeving system. An example of a catenary trolley can be seen in figure 2.16.

The second option to prevent the rope sag is a continuous rope support system. This system has stationary rollers that support the wire ropes, which can be passed by the trolley. In figure 2.13 the supports are depicted. Figure 2.17 shows a situation where this principle is applied in practice.

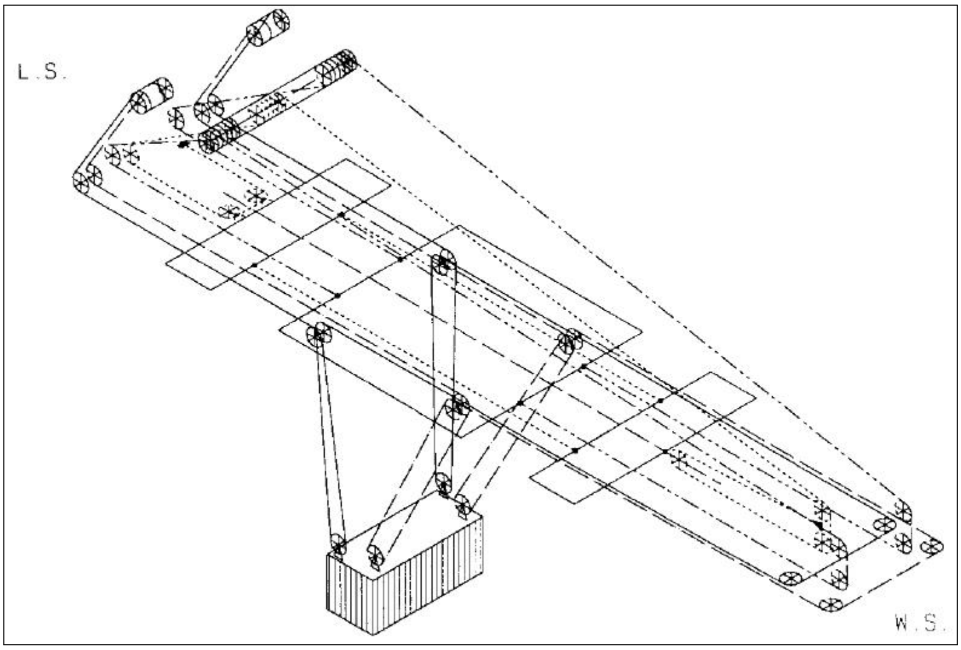


Figure 2.15: Hoist and trolley wire rope reeving of a rope towed trolley with two catenary trolleys. From [8]

Figure 2.16: Catenary trolley. From [6]

Figure 2.17: Continuous rope support system. Photo is made by the author.

2.1.7. Spreaders and headblocks

To be able to lift a container, an STS crane needs equipment that can be attached to the corners of a container. To do so, a spreader is used. A spreader connects to the corner casting of a container by using twistlocks. By rotating with 90 degrees the twist lock is fixed to the container corner. A wide variety of spreaders exist. Although traditionally spreaders were designed to lift a single size of containers, contemporary spreaders often have the capabilities to lift multiple container sizes. This is done by adjusting the distance between the twistlock connectors of the spreader, often described as telescopic spreaders. Another feature some modern spreaders have is the ability for twin lifting. Twin lifting is lifting two containers simultaneously end by end. To do so, extra twistlock connectors in the middle of the spreader are required. Well-known spreader manufacturers are Bromma, Stinis and RAM. Figure 2.18 shows a single lift RAM spreader capable of lifting 20', 40' and 45' containers, but without the possibility for twin lifting. In figure 2.19 a Stinis twin spreader is shown, which has the capability to twin lift two 20' containers. Larger container sizes can be handled in single lift mode. Most spreaders have flippers installed on the corners of the spreader to help position the twistlocks on the container corner castings. Power is required to drive multiple components on the spreader, i.e. for moving the telescopic beams, rotating the twistlocks, activating the flippers, moving down the twin lift twistlocks, and for separating two containers in twin lift mode [10]. Self-evidently, this depends on the functions the respective spreader has. Figure 2.10 and figure 2.9 also show a single lift and twin lift, respectively. Spreaders can be both hydraulically or electrically powered, but traditionally spreaders are powered hydraulically. In this report the single and twin lift spreaders are considered conventional spreaders, in contrast to tandem lift spreaders. Tandem spreaders will be addressed in section 2.2.

Figure 2.18: RAM 2400 Hydraulic single lift spreader. Load possibilities: 20', 40', 45'. From [11]

As explained above, a spreader connects to the container. However, the hoisting cables that run from and to the trolley are not directly connected to the spreader. Instead the hoisting cables run through sheaves on the

Figure 2.19: Stinis long twin. Load possibilities: 1×20', 1×30', 1×40' 1×45' and 2×20'. From [12]

headblock. The headblock is in its turn connected to the spreader. This configuration enables the possibility to switch between different spreaders while maintaining the same headblock. For conventional STS cranes, a single set of wire rope falls runs to a single, conventional headblock. Figure 2.18 shows a headblock (in light red) positioned on top of the spreader. In figure 2.12 a simplified representation of the headblock and its sheaves can be seen. This figure explicates how the headblock (and thus the spreader) is lifted.

2.1.8. Motors and drives

In this subsection, the main hoist and trolley travel drives of conventional STS container cranes are discussed. In the past, various types of motors and drives were used. Examples of drive systems used in STS container cranes are the squirrel cage motor with fluid coupling, the slipring motor, the Ward-Leonard drive, and direct current full-thyristor systems [8]. However, the dominant drive system in contemporary STS container cranes is the asynchronous alternating current motor with variable frequency control [5, p. 23] [13, p.25] [14, p. 27]. These AC motors have a simple design and reduce the required maintenance compared to other motor types. An introductory guide from Nidec [15] gives a useful overview of approximated motor powers of STS container cranes. As for this project the trolley and hoist motors are most interesting, these are listed in table 2.1.

Table 2.1: Typical values for motor power for main hoist and trolley travel. Data obtained from [15]

	Panamax	**Post panamax**	**Super post panamax**
Hoist motors	200-400 kW	400-600 kW	660-800 kW
Hoist overload	180%	180%	180%
Trolley motors*	22-30 kW	37-55 kW	55-75 kW
Full rope trolley	-	1x220 kW	1x300 kW
Trolley overload	170%	170-200%	170-200%

* Power per motor. Two or four motors in total

2.2. Single hoist tandem lifting

The most simple and straightforward way to simultaneously transport 4 TEU is single hoist tandem lifting, which is visualized by the middle hoisting configuration in figure 2.1. Cranes with this arrangement are called single hoist tandem 40 cranes, abbreviated as SHT40. The simplicity comes from the analogy to conventional single hoist cranes. Most aspects of SHT40 cranes are the same as conventional cranes. The major difference is a specialized headblock-spreader system. The construction of SHT40 cranes can be reinforced to cope with the larger forces that come with tandem lifting, but this is not always the case. Further modifications that can be applied to a SHT40 crane to handle the larger loads are larger motors, brakes, sheaves, wire ropes, and other reinforced components. Due to the analogy to conventional single hoist cranes, SHT40 cranes have a main hoist reeving with only one set of falls, analogue to the system in figure 2.12.

The specialized headblock-spreader system of SHT40 cranes is able to lift in tandem mode. With tandem, side by side lifting is meant, instead of end by end lifting which is the case for twin lifting as explained in subsection 2.1.7. Multiple container combinations can be lifted in tandem mode. The exact load combinations possible depend on the capabilities of the respective spreader(s). Single hoist tandem lifting can be done in several ways, depending on the manufacturer of the headblock and spreader(s). First of all, a specialized tandem spreader can be connected to a headblock. In this case, the spreader cannot be separated and should always be utilized as a whole. The second option is a specialized headblock that connects to two conventional spreaders. Both ways are used in practice, and in the following subsections the solution applied by several manufacturers will be elaborated. However, in either case the spreader configuration of a SHT40 crane needs to be changed when switching between single lifting and tandem lifting. This is time intensive when a lot of switches occur.

2.2.1. Bromma

Bromma developed a tandem headblock and spreader system [10] [16]. The Bromma tandem headblock is able to position the sheave wheels in both a wide and narrow configuration. The narrow sheave wheel configuration is applied when a conventional single or twin lift spreader is connected. When a tandem spreader is connected, the sheave wheels are positioned in the wide configuration. This mechanism allows for quick shifting between both conventional and tandem spreaders. Both configurations can be seen in the left of figure 2.20. On the right side of the same figure the tandem headblock can be seen. Brommas' tandem spreaders consist of two separate spreaders connected to an adapter frame with chains, and this relatively simple design makes that the system is only able to adjust the spreader gap adjustment, skew, and height difference between the two spreaders [1, p. 109]. Several tandem spreader types are manufactured by Bromma, with different possible load configurations. All Bromma tandem spreaders can at least lift two 40' containers in tandem mode. In figure 2.21 the Bromma Quattro spreader can be seen, which can handle various combinations of 20', 40' and 45' containers.

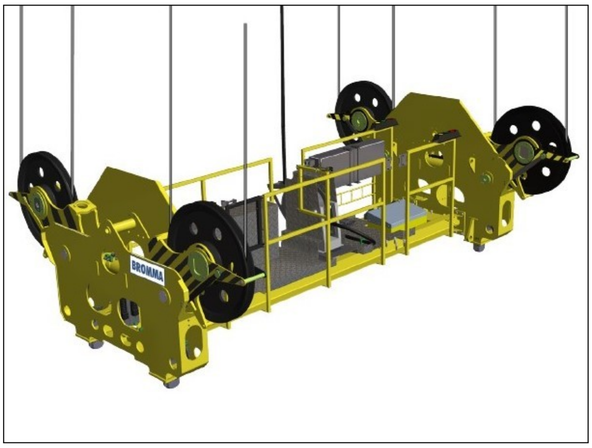


Figure 2.20: Bromma tandem headblock. From [16]

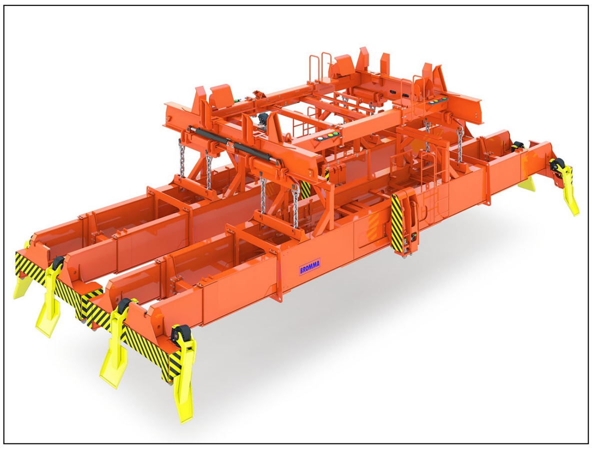


Figure 2.21: Bromma Quattro spreader. Possible container combinations: 20´, 40´, 45´, 4×20´, 2×40´, 2×45´, 2×20´+ 1×40´, 2×20´+ 1×45´. From [10]

2.2.2. Stinis

Stinis developed a specialized headblock for single hoist tandem lifting, which is called the split headblock. This headblock, which can be seen in figure 2.22, utilizes four hydraulic cylinders to control the spreaders. A specialized tandem spreader is not needed: the split headblock is connected to two conventional spreaders. The cylinders of the headblock are able to control the gap between the spreaders, the side shift, the height difference between the spreaders, and the skew. Figure 2.23 shows the split headblock during operation with two conventional spreaders. Different Stinis spreaders, like the long twin spreader shown in figure 2.19, can be connected to the headblock. Also a single conventional spreader can be connected to the headblock to enable single and twin lifts. The Stinis split headblock is not compatible with other brands' spreaders. The technical properties of the Stinis split headblock are rated above other comparable products [1, p. 109].

Figure 2.22: Stinis split headblock. From [17]

Figure 2.23: Stinis split headblock with two separate spreaders. From [7]

2.2.3. RAM

RAM developed the SingFlex headblock, which can be seen in figure 2.24. Just like the Stinis split headblock, the RAM SingFlex headblock is capable of connecting to conventional single or twin spreaders. Also the SingFlex headblock is able to adjust the gap between the spreaders, the side shift, the height difference between the spreaders, and the skew. An advantage of the RAM SingFlex headblock is the compatibility with other brands spreaders, in contrast to the systems developed by Bromma and Stinis. Just like it's competitors, the RAM SingFlex can also connect to a single spreader for single or twin lifting.

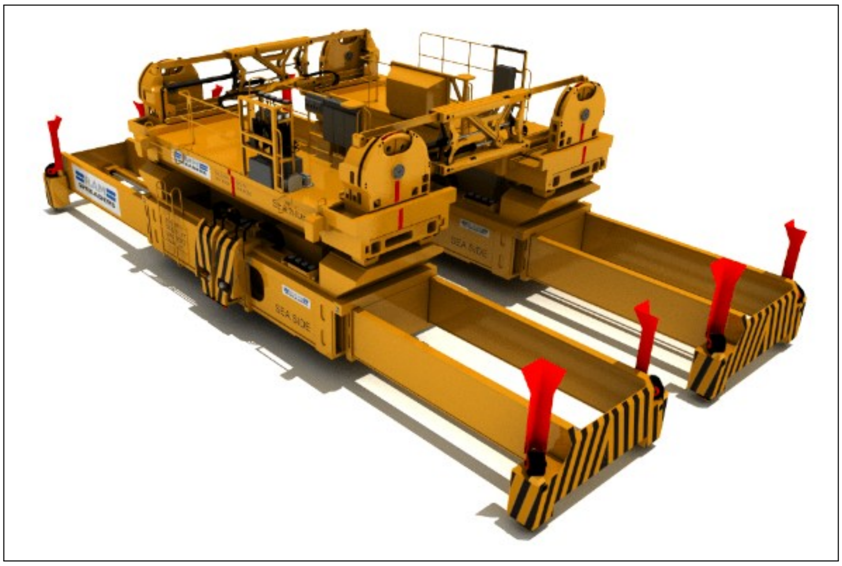


Figure 2.24: RAM SingFlex headblock with conventional spreaders. From [11]

2.3. Dual hoist tandem lifting

An alternative to single hoist tandem lifting is dual hoist lifting. Dual hoist cranes can lift containers in tandem mode, while using two hoisting mechanisms. Another way to call these cranes is dual hoist tandem 40 (abbreviated as DHT40), which indicates that two 40' containers can be lifted in tandem mode by two hoists. Although DHT40 cranes have two hoists, only one trolley is used. At the right side of figure 2.1 the dual hoist tandem crane is depicted. Some photographs of this system in practice are shown in figure 2.25 and 2.26. According to Michael Jordan, the ZPMC crane in Shanghai, China, is the first DHT40 crane ever built [18]. The first DHT40 crane was developed in 2004 according to Yi, Zhiyong, and Xiaofeng [1]. Back in 2007, ZPMC was the only manufacturer of dual hoist tandem cranes and McCarthy, Jordan, and Wright [19] expected other crane manufacturers to follow. However, to this day ZPMC is still the only manufacturer to have delivered dual hoist cranes. As a result, terminal operators depend on a single crane manufacturer when they prefer this working principle. Nowadays multiple terminals apply dual-hoist tandem lifting. For example in Dubai Port Authority, Yantian international container terminals, and other PRC terminals [19].

Figure 2.25: Dual hoist tandem lifting. From [20]

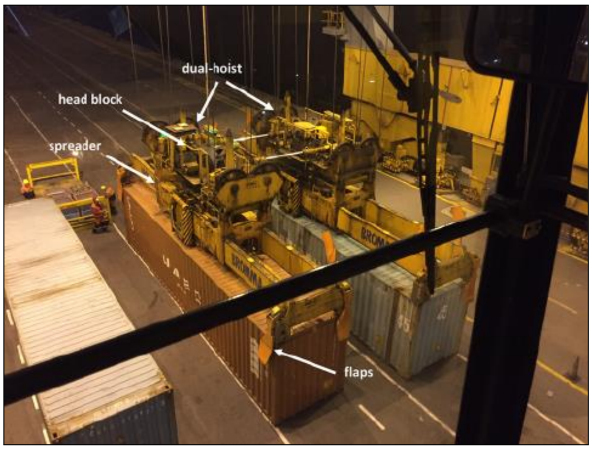


Figure 2.26: Dual hoist tandem lifting. From [21]

With the two hoisting mechanisms come two sets of falls and sheaves. The two sets of main falls operate independently, which means the ropes run in parallel. This can clearly be seen in figure 2.27. The reeving system in figure 2.27 is a duplex of the reeving system of a conventional crane shown in figure 2.12. The vertical position of both headblocks is controlled by a separate pair of drums, which enables both spreaders to operate individually.

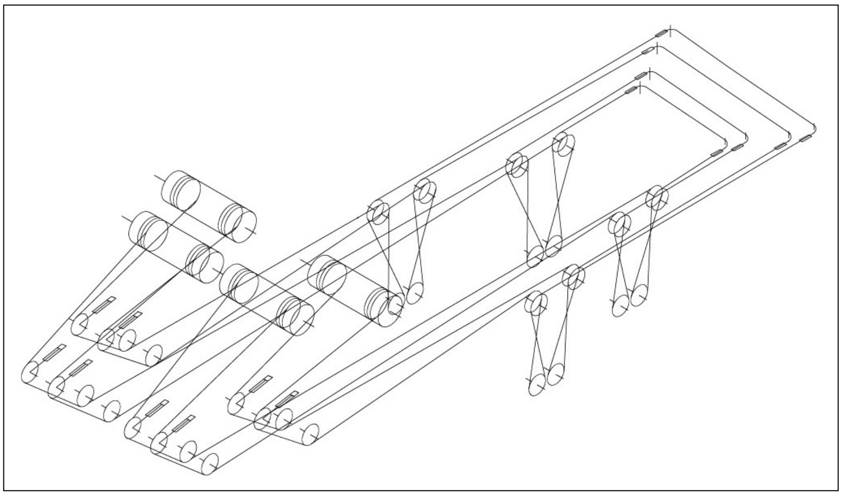


Figure 2.27: Main hoist reeving in a ZPMC DHT40 crane. From [2]

Although in single hoist tandem lifting a single headblock is used, DHT40 cranes have two separate headblocks. The headblocks, both equipped with conventional spreaders, have a set of sheaves, and either of them is connected to the falls of one of the hoisting systems. However, the reciprocal movement of both headblocks is not unlimited. Although the headblocks of dual hoist cranes are closely related to conventional headblocks, they differ from conventional headblocks by having the ability to be laced together. The coupler can correct the relative position of the headblocks. By lacing both headblocks together with a headblock coupler, they cannot collide and the difference in vertical position is limited. The couplers are only disconnected in certain situations, e.g. when picking up containers from a ships' cells, or when one of the headblocks is out of service. By lacing together the headblocks they will move simultaneously and side by side, which are characteristics of tandem lifting. Bromma and ZPMC designed a headblock system that can be used during dual hoist lifting [20, p. 7]. Figure 2.28 shows the general arrangement of a dual hoist crane produced by ZPMC. The machinery house is fixed and located at the trolley girders. The wire ropes run from the machinery house towards the landside, and then turn through sheaves towards the waterside to the trolley. This configuration allows for the control of trim, list and skew and protection against snags [19, p. 3]. Although DHT40 cranes are designed to simultaneously use both headblocks, they can also be used in single

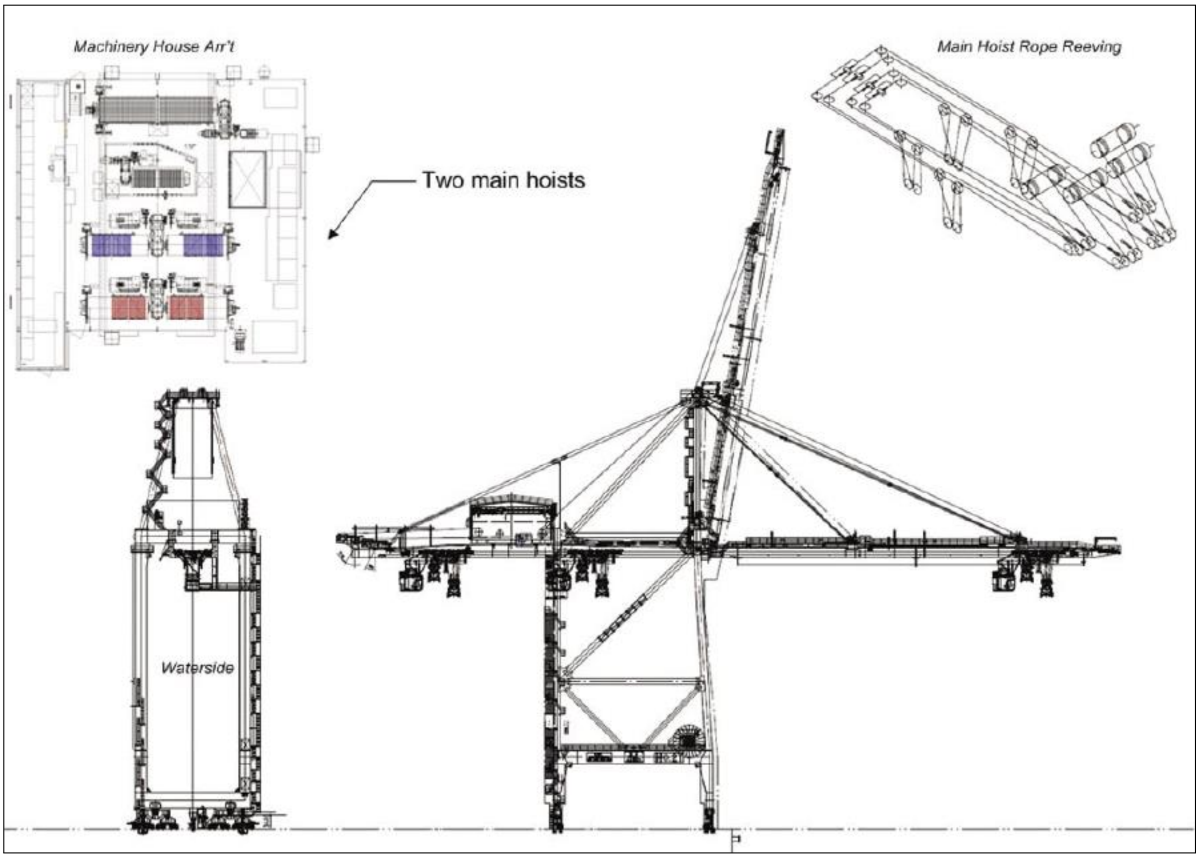


Figure 2.28: General arrangement of DHT40 crane. From [19]

hoist mode. In this situation, one of the headblocks is stowed underneath the trolley. A stowed headblock can be seen in figure 2.30. Dual hoist tandem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley. Self-evidently, the headblock coupler is disconnected when the crane is operating in single hoist mode. When lifting or lowering in dual hoist mode, the headblock coupler is connected. In this way, collision is prevented and it is controlled how the headblocks are positioned relative to each other. An important property of the coupling system is to automatically disconnect in case of a snag or extreme relative motion. In general, the headblock coupler is engaged when lifting in tandem mode and the containers hang above the wharf or ship. Some ships require the coupler to disengage when containers below deck are loaded or unloaded. However, the coupler should be engaged again before the headblocks leave the ship. Both the latched and unlatched configuration of a headblock coupler can be seen in figure 2.29.

Dual hoist cranes can have either a rope towed trolley (figure 2.31) or semi rope trolley (figure 2.32). The reeving for the RTT travel mechanism is identical to figure 2.14. Due to the heavier trolley that comes with dual hoist cranes, more driving power might be required compared to a conventional crane. To the best of the authors knowledge, DHT40 cranes with a machinery trolley do not exist. DHT40 have catenary trolleys to support the wire ropes.

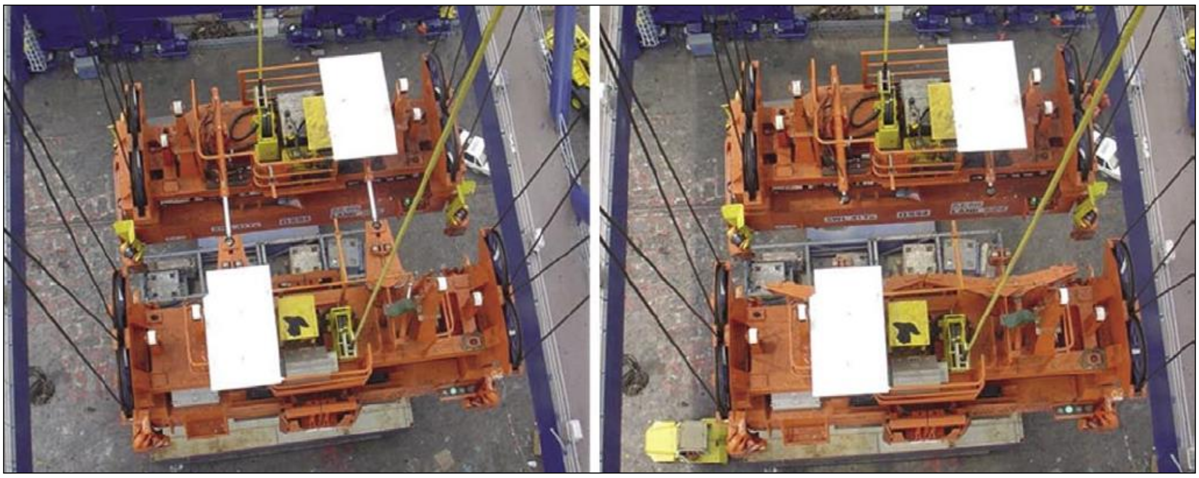


Figure 2.29: Headblock coupler is connected (left) and disconnected (right). From [19]

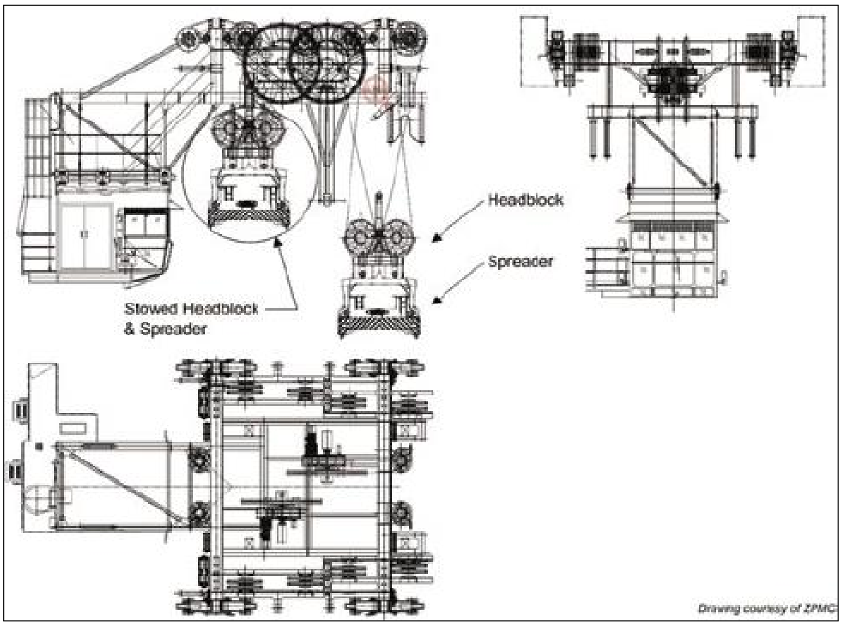


Figure 2.30: Trolley of a dual hoist crane. From [19]

Figure 2.31: Rope towed trolley on a DHT40 crane. From [2]

Figure 2.32: Semi rope trolley on a DHT40 crane. From [19]

Another variation in DHT40 cranes is the machinery house configuration. As previously explained, every DHT40 crane has two hoisting systems, of which both are equipped with two hoisting drums. Consequently, every DHT40 crane has four hoisting drums which need to be driven by motors. A gearbox reduces the rotational speed from the motor to the hoisting drum. DHT40 cranes have two gearbox configurations; either with two separate gearboxes for both hoisting systems or a single, combined gearbox. In case of a combined gearbox, both hoisting systems should always be used simultaneously. This can be problematic in all cases one spreader needs to be moved to another height than the other spreader. Also lifting in single hoist mode is not possible in case of a combined gearbox. On top of that, Soderberg et al. mentioned that "The combined gearbox design cannot be easily converted to a single hoist system" [22]. For the just mentioned reasons, a separate gearbox for both hoisting mechanisms is the better choice. The system with two gearboxes and the system with a combined gearbox are shown in figure 2.33 and 2.34, respectively.

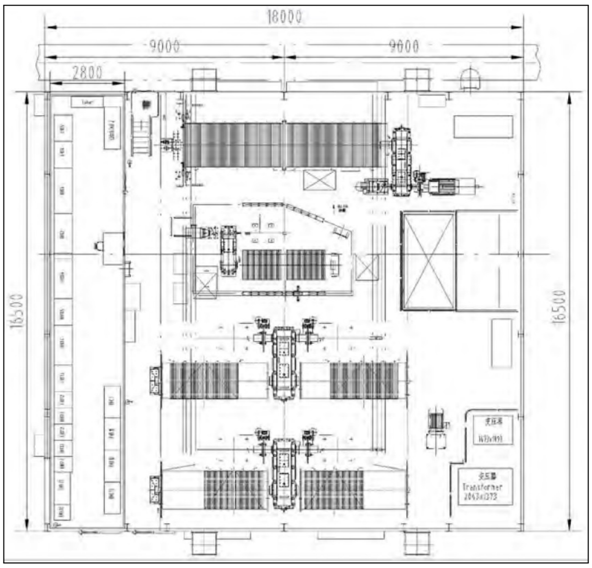


Figure 2.33: Two gearboxes. From [18]

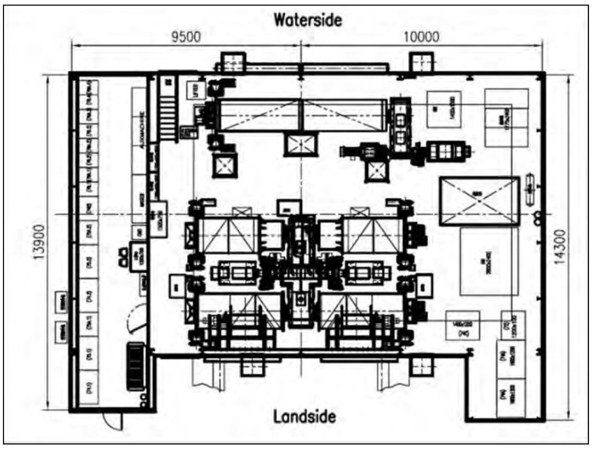


Figure 2.34: Combined gearbox. From [18]

The just explained working principles of a dual hoist tandem crane result in various differences compared to conventional singe hoist cranes. The most important changes that are made to enable two hoisting mechanisms are summarized in the following list, for which the information is obtained from McCarthy, Jordan, and Wright [19] and Bartošek, Marek, et al. [3].

- Two hoisting systems, so the double amount of hoist wire ropes, drums, and sheaves.
- The crane is heavier due to the extra components which results in larger loads on the wheels.
- The operator control is more complex due to the extra hoist system. Additional devices to improve the operators sight are necessary.
- The trolley is larger because two main hoists should fit, and it should provide stowage for unused headblocks.
- The energy consumption is higher for DHT40 cranes.
- The headblock devices of DHT40 cranes are specialized.
- Storm wharf loads are larger due to increased surface area.

2.4. Secondary trolley

Nowadays a considerable amount of modern STS cranes is equipped with an additional (fully automated) trolley on the portal beams. This development started in the late 1970s with manufacturers like Nelcon introducing this separate shore hoist [23, p. 3]. Although the secondary trolley could be regarded as part of general STS crane aspects, a separate section is reserved for this topic as the the second trolley is closely related to this work. On cranes with a secondary trolley the cycle is subdivided in separate sections. First the (manned) main trolley unloads the container(s) on a platform on the crane, and the secondary trolley transfers the container from this platform to the quay. typically, the platform is used to have the IBCs removed by workers, which is safer for the workers than working between vehicles on the quay. In figure 2.35 the configuration of a crane with a second lower trolley can be seen, and figure 2.36 shows an example of a crane with this principle that is currently in use. The configuration with a secondary trolley installed on the lower part of the crane is sometimes also called second trolley or dual trolley. Sometimes, especially in older literature, cranes with a second trolley are called dual hoist cranes, for example in [24] and [25]. This should not be confused with the dual hoist cranes discussed in section 2.3, as this is another concept.

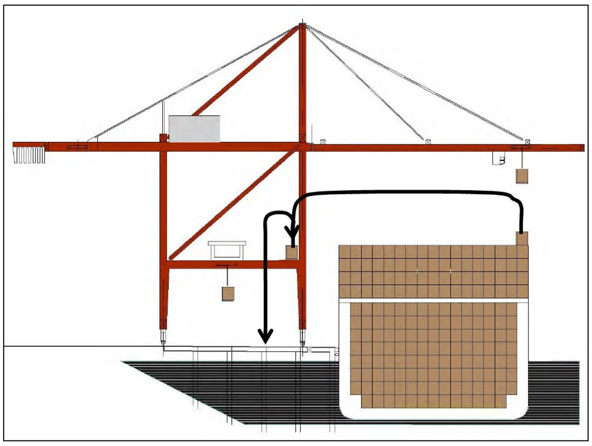


Figure 2.35: Second trolley configuration. From [26]

Figure 2.36: Second trolley configuration at Altenwerder container terminal. From [27]

2.5. Triple lifting

One step further than tandem lifting is triple lifting. Although multiple configurations in which triple lifting can be applied could be possible, the existing variant is basically a combination of single-hoist tandem lifting and dual-hoist tandem lifting. Before reading further, it is insightful to take a look at figure 2.37 and 2.38 for a better understanding of the working principles. The trolley and hoisting mechanisms have the same configuration as dual hoist cranes. However, one set of hoisting wire ropes is connected to a tandem headblock with two spreaders. In this way, in total three spreaders can be used for lifting. The working principles of the tandem headblock-spreader system is already explained in section 2.2, and the configuration of the hoisting mechanism can be seen in section 2.3. Self-evidently, triple lift cranes should have enough lifting capacity to cope with the extra loads. ZPMC engineered a triple lift configuration [20, p. 8] and nowadays the system is used at the Ma Wan Container Terminal in Shenzhen, China [28, p. 8]. However, triple lifting is not extensively used in practice.

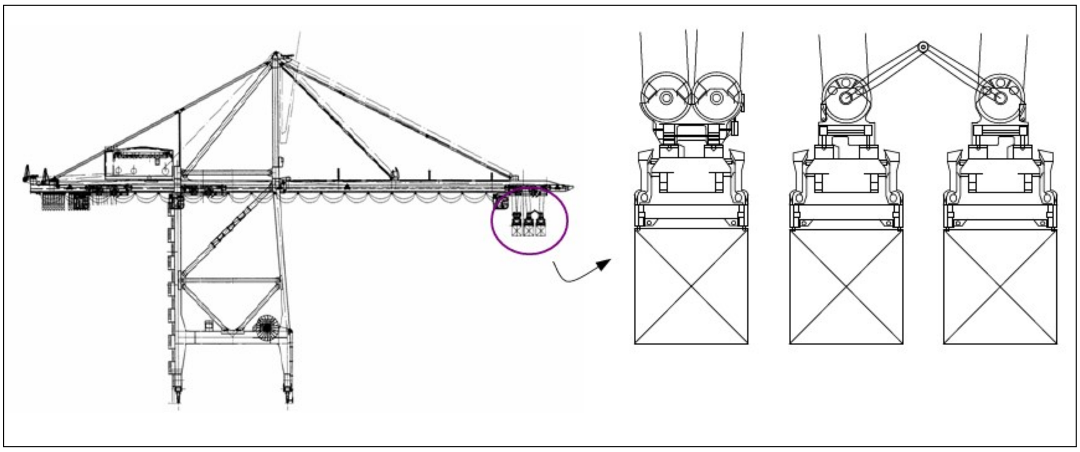


Figure 2.37: Triple lifting concept by ZPMC. From [20]

2.6. Vertical tandem lifting

During vertical tandem lifting, two containers are lifted in the same operation by connecting them vertically by twistlocks (figure 2.39). Vertical tandem lifting is considered an unsafe practice by UK port industry [29], while in the same document it is mentioned that some countries use this principle. This is because the safe operation in vertical tandem lifting depends on the quality of the twistlocks that connect the containers. Also the poor quality of a container could result in hazardous situations. Although lifting equipment is subject to inspection and testing, this same level of inspection might not be the case for containers and twistlocks. Khezripoor investigated whether vertically doubled container lifting would be a possible solution to increase STS crane productivity, and concluded that despite some challenges it could be a viable solution [30]. He concluded that container body structure was the main problem to apply this approach. However, concerning the uncertainties regarding container and twistlock quality, it is not likely that this approach will become an accepted method in container ports around the world.

Figure 2.38: Triple lifting. From [7]

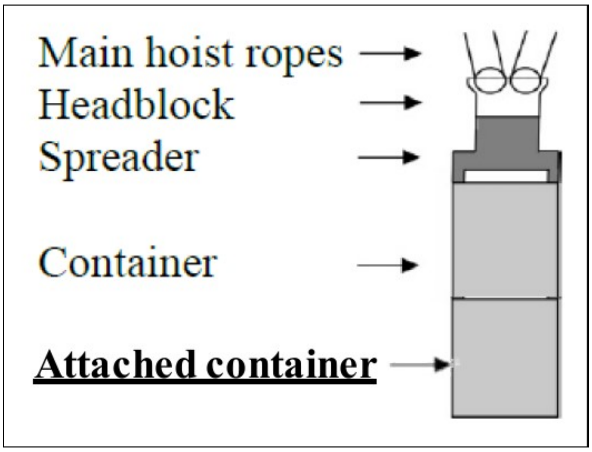


Figure 2.39: Vertical tandem lifting configuration. From [30]

3 Non-applied concepts

This chapter addresses various concepts that increase the productivity of an STS container crane by simultaneously transporting 4 TEU or more. In contrast to chapter 2, the concepts covered in this chapter are not applied in practice. All concepts addressed here have the aim to increase STS container crane productivity by introducing new working principles. Because the addressed concepts were not tested in practice, it is hard to tell how realistic the working principles of every individual concept would be. However, they can be an inspiration for new solutions to be formed in this project. Almost all concepts addressed in this chapter use some type of carrier or transfer vehicle that copes with the horizontal transport between the ship and shore. Typically, the hoisting at the WS and LS is executed by distinct hoisting mechanisms. Furthermore, all concepts have larger quay loads due to the considerable dimensions that come with these concepts.

3.1. TU Delft carrier crane

On behalf of Delft University of Technology, Luttekes and Rijsenbrij [31] made a concept design for a high productivity wide body STS container crane, called the carrier crane. As the name suggests, the TU Delft carrier crane utilizes carriers to move containers. These carriers are used for the horizontal transport from the WS to the LS. The carriers can travel on two different rail levels, which enables them to pass each other. The carriers travel towards the WS on low rail tracks, while the carriers travel to the LS on the higher positioned rail tracks. Both the WS and LS have separate hoists. First, the container is lifted from a ship by a WS hoist. The second step is to load the container from the WS hoist to a carrier that travels on the upper rail tracks. Simultaneously, another empty carrier travels underneath to the WS of the boom and waits to be served next. Once the carrier is loaded, it travels towards the LS and the next empty carrier that just drove underneath takes its place. The carrier that just received a container travels towards the LS of the boom. Here it waits in a queue of other loaded carriers until it can be unloaded by the LS hoist. The queue serves as a buffer to cope with variations in hoisting time. The LS hoist can be a tandem lift, so it can unload two carriers simultaneously. After the carrier is unloaded, it travels towards the LS, and the cycle starts again. One or two WS trolleys can be used. In case of two WS trolleys, every time a container is loaded on a carrier, two other empty carriers travel underneath. Visualizations of the crane, including the carriers, LS hoist and WS hoists, can be seen in figure 3.1 and 3.2.

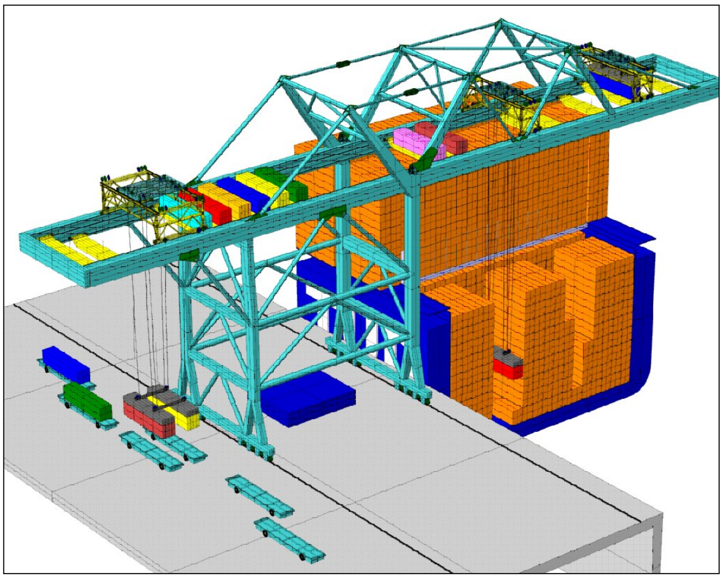


Figure 3.1: TU Delft carrier crane basic design. From [32]

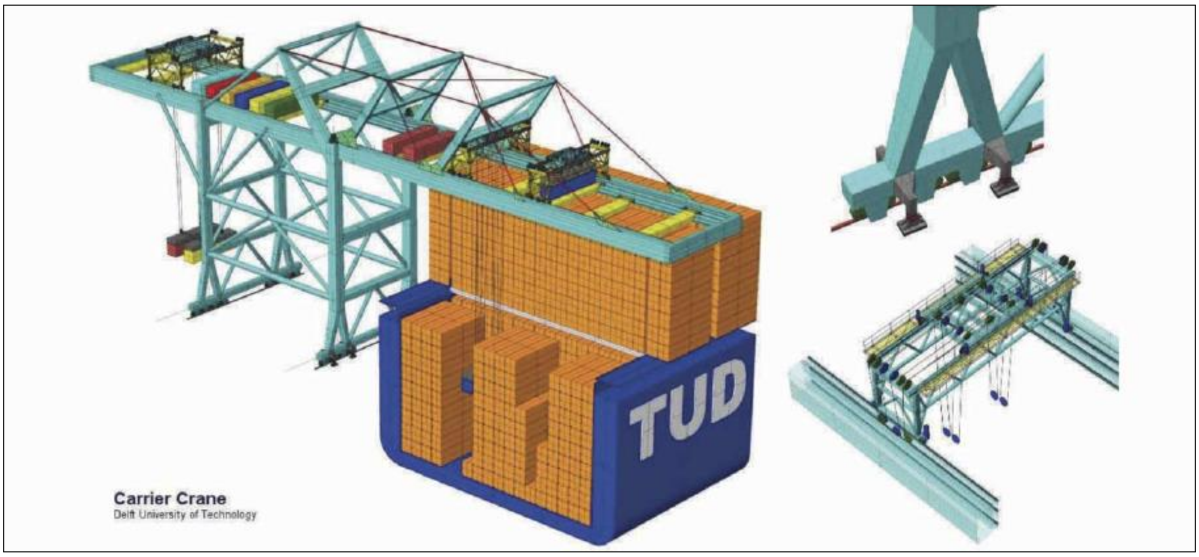


Figure 3.2: TU Delft carrier crane. From [7]

3.2. Liftech Super Crane

The working principle of the Liftech Super Crane is described in multiple sources [24] [33] [23], and the main aspects are described in this section. The Liftech super crane is similar to the TU Delft carrier crane in the sense that they both have multiple main hoists (LS and WS) and carriers to move containers between WS and LS hoists. Also, both concepts have a WS hoist that does not move during loading or unloading. However, the Super Crane has a WS trolley that has the ability to rotate, which is required to position the container on carriers that travel between the boom girders. Once this is done, the carriers travel towards the LS to be unloaded by a LS hoist. Once unloaded, the carriers travel back to the WS via an upper runway, for which they need to be lifted to the overhead rail by an elevator. At the WS another elevator lowers the carrier, so that it can be loaded and unloaded again on the way to the LS. Two carriers are needed to carry a container, one at each end. This configuration results in small, light carriers and makes it suitable for all container sizes. Both a high profile (figure 3.3) and low profile (3.4) version of the Liftech Super Crane can be found in literature. The low profile Super Crane version is covered in more recent literature [23] [33], while the high profile Super Crane is mentioned in older sources [26] [24]. As described by Michael Jordan [33], the low profile version of the Super Crane is a shoot-off of the original (high profile) Liftech Super Crane from 2002. Although the two versions of the Super Crane are somewhat different, the working principles described so far are identical for both types. However, they do differ in some aspects.

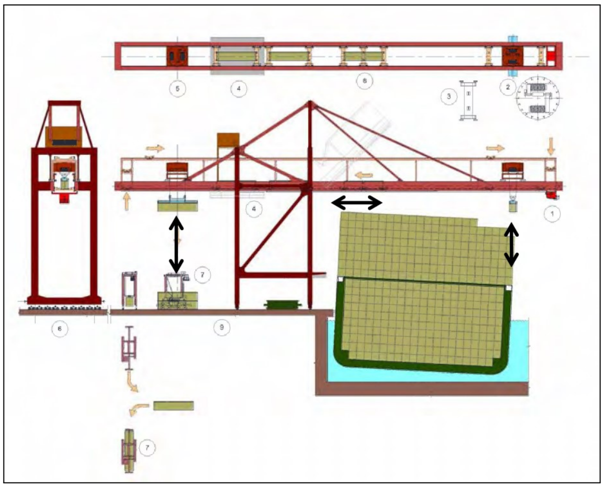


Figure 3.3: Liftech Supercrane. High profile. From [26]

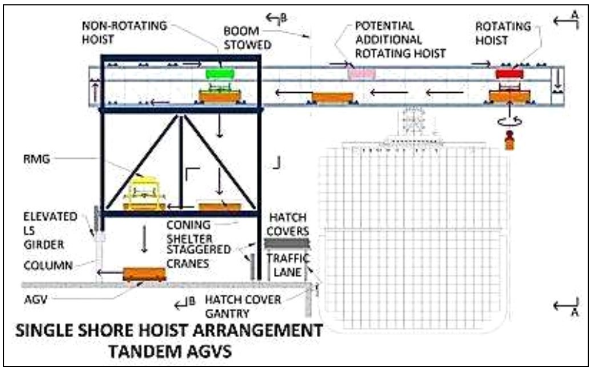


Figure 3.4: Liftech Supercrane. Low profile. From [23]

For both cranes, the carrier is unloaded by a hoisting mechanism that is installed on a trolley at the LS of the main boom. The high profile crane has a rotating LS trolley, while the low profile crane has not. As a result, the low profile crane always positions the containers perpendicular to the quay, having an impact on the processes on the wharf. On top of that, the high profile crane directly lowers the containers on the wharf after the LS hoist unloaded a carrier, while the low profile crane first positions the container on a coning platform on the portal beam. This platform on the low profile version allows the removal of inter box connectors (IBCs). Once the IBCs are removed, they are transferred to the wharf by secondary trolley. The high profile version does not have an extra hoist and coning platform, instead the IBCs can be removed on the carrier runway and the LS hoist directly lowers the container to the wharf. Also, besides the just described configuration the low profile version can have another, second configuration. In this configuration the lower trolley and coning platform in figure 3.4 are excluded and three trolleys with hoisting mechanisms will be installed on the main boom. The middle trolley can be positioned both over the wharf and the ship, depending on the specific situation. This configuration allows for flexible operations.

3.3. CreaTech Technotainer

The CreaTech Technotainer is a unique concept that combines a spreader and carrier into a single component, and is explained by Jordan [24]. The general configuration of the Technotainer can be seen in figure 3.5. Just like the previous concepts, the Technotainer has separate WS and LS hoisting mechanisms. As a first step, the WS hoist raises a container from the ship to the maximum height. Then, both the container and spreader are unloaded to a lower runway on the boom. The spreader is specialized and is able to travel over the runway to carry the container to the LS. Basically, the spreader transforms into a shuttle. Just like in the previously described concepts, a separate WS hoist lowers the container and spreader towards the quay. Once the container is unloaded, the spreader width is reduced to the 20 foot arrangement while being lifted to the boom. The smaller spreader configuration allows to travel through the boom, as can be seen in figure 3.6. The spreader travels towards the WS at an upper runway, which allows the spreaders to pass each other. Once arrived at the WS, the hoist connects to the spreader and the cycle starts again. The main disadvantage of this concept is the complexity of the spreader. To enable the spreader to travel on a runway it should have wheels and accompanying mechanisms. Also the spreader should be towed when driving on the runway which requires additional components.

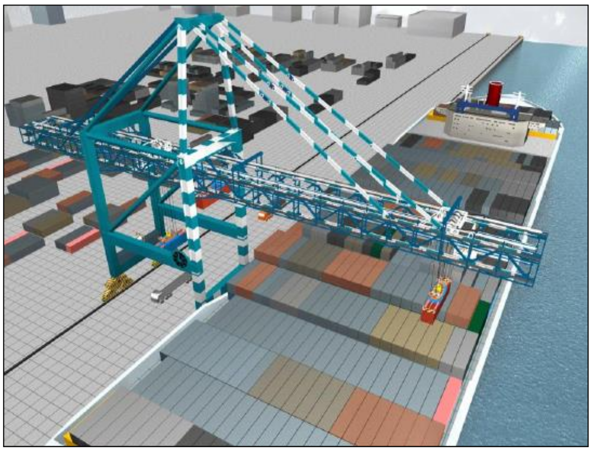


Figure 3.5: CreaTech Technotainer. From [34]

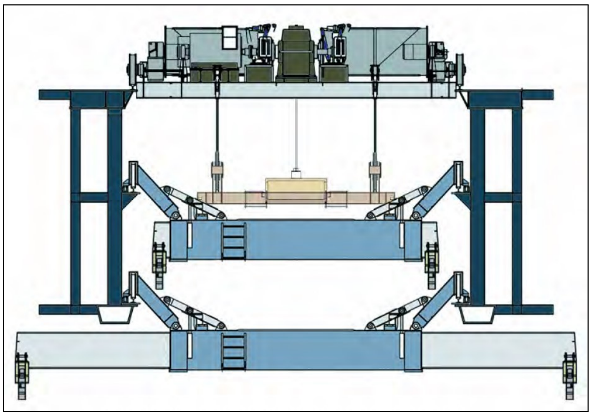


Figure 3.6: Boom section of CreaTech Technotainer. From [26]

3.4. Gottwald multi trolley crane

The Gottwald multi trolley crane also employs carriers and separate LS and WS hoists to load or unload containers. The WS hoist places the container on a transfer platform. A carrier equipped with a spreader transfers the container towards the LS after it is rotated with 90 degrees. A detailed description of the exact working principles of the Gottwald multi trolley crane has not been found in literature. Probably the transfer platform rotates the container, which enables carriers to travel past each other. Lastly, Hans van Ham [7] described that the carriers transfer the rotated containers to the LS, where an unmanned hoist lowers the containers to the quay [7, p. 150].

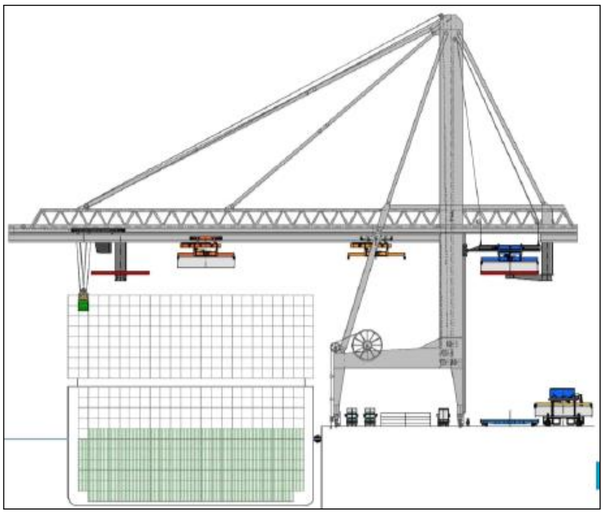


Figure 3.7: Gottwald multi trolley crane. From [34]

3.5. Paceco Supertainer

The Supertainer was introduced by Paceco in 1994 [7, p. 142]. Also the Supertainer has a separate LS and WS hoist, but in this concept only one carrier/shuttle travels back and forth to deal with the horizontal transport of containers. As can be seen in figure 3.8, the carrier is a moving platform with the same width as the boom. When unloading a ship, the WS hoist lifts the container, the shuttle travels underneath the load, and the WS hoist transfers the container to the shuttle. In this way, the WS hoist itself does not need to move towards the LS and can simply stay above the vessel. Once the shuttle moved to the LS, the LS hoist lowers the container to the quay via a funnel guide (the white structure above the quay in figure 3.8) [23]. As a consequence of the wide boom, larger loads on the quay will be apparent. According to Jordan, "The crane will also weigh significantly more than a conventional crane and will overload most existing quays" [24]. The Supertainer has not been realized yet [7].

Figure 3.8: Paceco Supertainer. From [23]

3.6. Regianne Octopus

In 1995, the Italian crane manufacturer Regianne published a concept called the 'Octopus'. Although this concept cannot be considered a single STS container crane, and therefore could be less relevant for this project, it is still interesting to shortly address it. The Octopus consists of multiple cranes built on one structure. As Woxenius describes, "the cranes are not used for lowering the containers all the way to the ground, but only to a roadway elevated 14 m from the ground" [35, p. 150]. In 2012, van Ham and Rijsenbrij stated that "For 15 years, there were no applications but the Fastnet concept published by Maersk during 2008-2011 shows some similarities." [7]. The FastNet concept is explained in the next section.

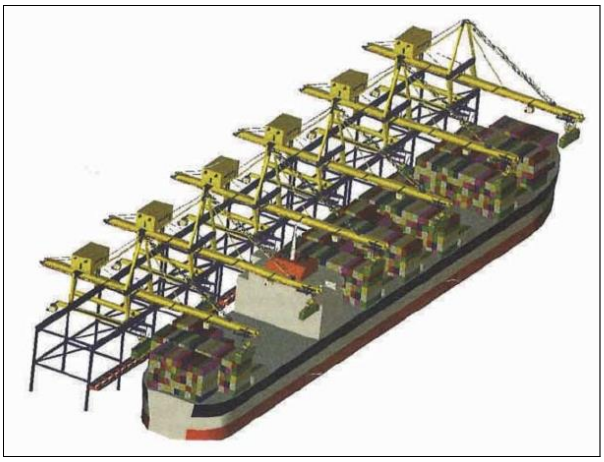


Figure 3.9: Reggiane Octopus. From [7]

3.7. APMT FastNet

APM Terminals patented the FastNet concept in 2008, followed by publications around 2010-2011 [7, p. 151]. The FastNet concept, as can be seen in figure 3.10, is able to assign cranes to adjacent container hatches of a vessel, which is an important advantage. Just like the Reggiane Octopus, the FastNet concept is not a single STS crane, rather it is a system of multiple cranes on a single structure. The main principles are described in multiple sources [23] [36] [33], and summarized here. The main components of the FastNet structure are a WS girder, LS girder, and movable supporting legs. All cranes can travel laterally on the girders, allowing the cranes to move close to each other instead of being blocked by the structure of the adjacent crane as is the case for conventional cranes. The movable supports that carry the girders are also able to move laterally. In this way, the most beneficial position in terms of crane support and accessibility can be obtained. The LS girder is elevated high enough to allow trucks or AGVs to pass underneath. In combination with the movable supports this allows the yard vehicles to easily enter or exit the area underneath the cranes. When a support is positioned somewhere underneath the WS girder, no cranes can operate at this position. In the upper right image of figure 3.10, it can be seen that no cranes are assigned at the positions of the WS supports. As van Ham and Rijsenbrij mentioned, "The concept should be capable of a vessel berth performance of 450 boxes per hour, a very ambitious goal compared with the 150-200 boxes/hr. as state of the art in 2011" [7, p.151].

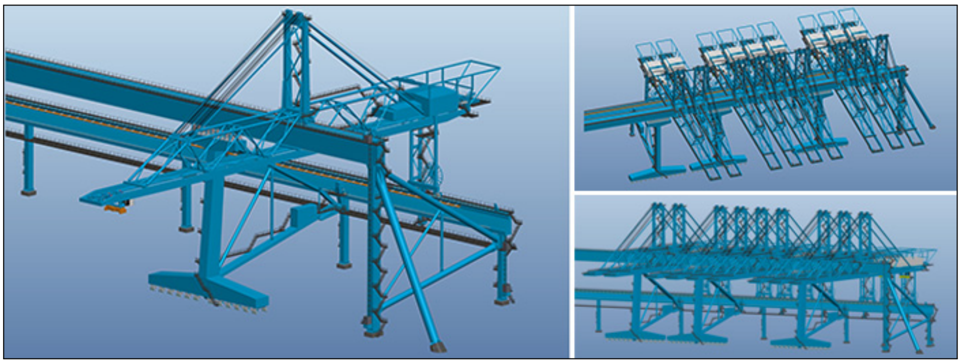


Figure 3.10: APMT FastNet. From [37]

4
Patent study

Besides the existing solutions and non-applied concepts also patents can be interesting to look into. The patent study was executed after the information in chapter 2 and 3 was obtained. In this way concepts or ideas that were not extensively published are still covered. On top of that, it is important to know which ideas are already patented to prevent conflicts. All patents covering concepts for the simultaneous transport of 4 TEU or more with an STS container crane are interesting for this work. Therefore every significant patent found will be addressed. For patents to be covered in this work, they should adhere to the following requirements.

1. The patent should cover a (component of a) ship to shore container crane concept.
2. The working principle described in the patent must allow the simultaneous transfer of 4 TEU or more between a container vessel and the quay.
3. The innovative aspect should be focused on the STS crane instead of the wharf process or stacking equipment. In other words: the crane itself should be innovative.

It is important to notice that not all patented concepts that increase STS crane productivity are covered. Concepts that increase the productivity while not being able to simultaneously carry 4 TEU or more are not included. The patents covered in this chapter can be categorized as:

- Transfer vehicle(s)
- Trolleys passing each other
- Trolleys not passing each other
- Dual hoist
- Circulating systems

The following sections cover these categories. In this chapter only an impression of the working principles described in the patents is given. In Appendix B a complete overview of all discovered patents is given.

4.1. Transfer vehicle(s)

A large amount of patents describe an STS crane on which one or more transfer vehicles transfer containers between the WS and LS. In these concepts, at least one WS trolley and one LS trolley is installed on the crane, which transfer the containers between the ship and trolley, or quay and trolley, respectively. This is comparable with the Paceco Supertainer (section 3.8) and Gottwald multi trolley crane (section 3.7). Table B.1 shows an overview of all patents that contain transfer vehicles that travel back and forth between LS and WS trolleys. This section only covers transfer vehicles that travel along the same path in both ways. Concepts with circulating transfer vehicles are categorized in the "circulating systems" section (section 4.5).

Some exemplary patents will be shown in the current section. A typical transfer vehicle is connected to a set of additional rails on the boom. In figure 4.1 an example of such a typical transfer vehicle can be seen. Some concepts included two levels of rail tracks, where the trolley(s) travel on the upper rails while the transfer vehicles travel on lower rails (see figure 4.2). Other concepts contain multiple transfer vehicles that can pass each other, as is depicted in figure 4.3. In this way the horizontal transfer of containers has a higher capacity.

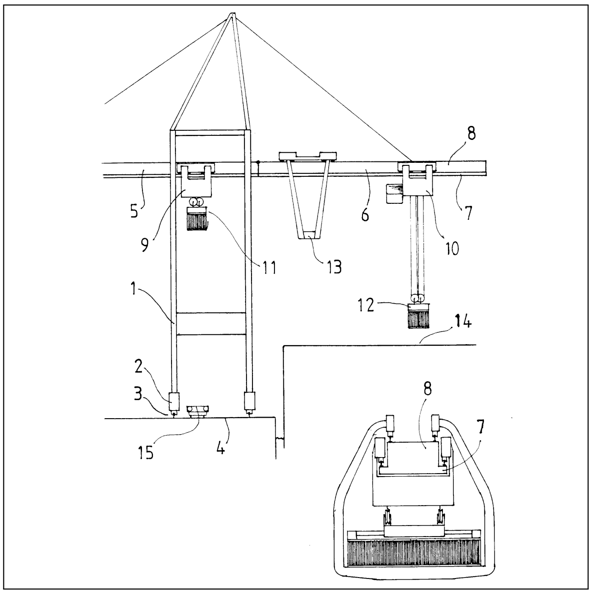


Figure 4.1: Patent DE3837726A1

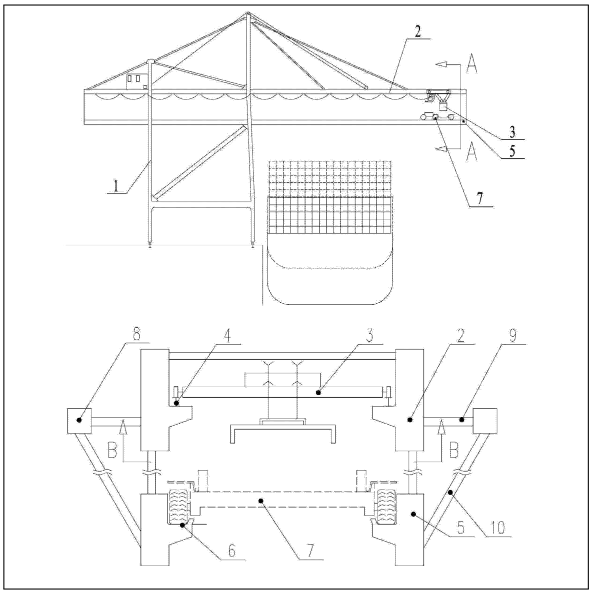


Figure 4.2: Patent CN103303805A

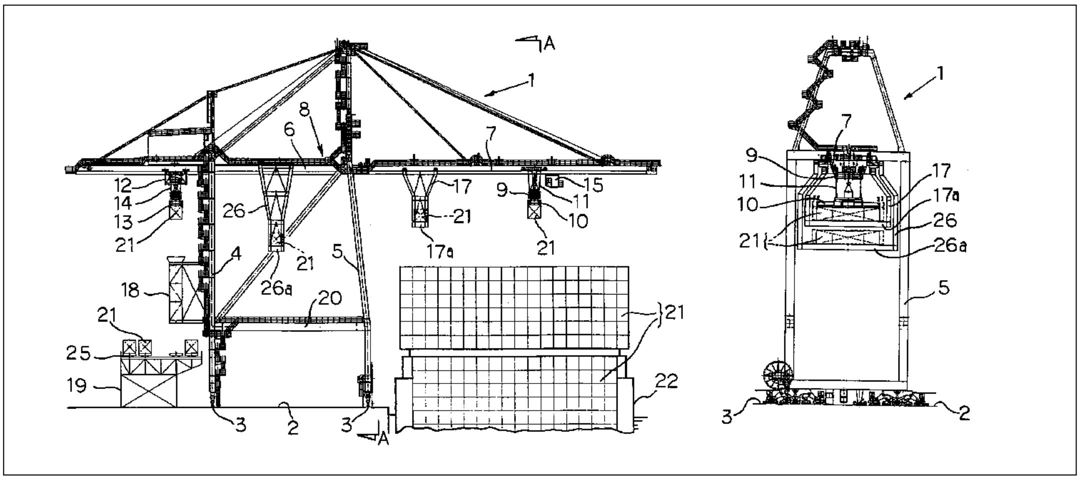


Figure 4.3: Patent JPH11278790A

4.2. Trolleys passing each other

Multiple patents describe an STS crane with two trolleys that can pass each other. In this way, both trolleys can independently load and unload containers, which increases the productivity. In all these patents, one trolley travels underneath the other trolley. To do so, the upper trolley should hoist the load to the highest position. This is clearly depicted in figure 4.4. Some patents describe an alternative configuration, where the container that is carried by the upper trolley is rotated with 90 degrees. This requires the trolley, headblock, or spreader to rotate. An example is shown in figure 4.5.

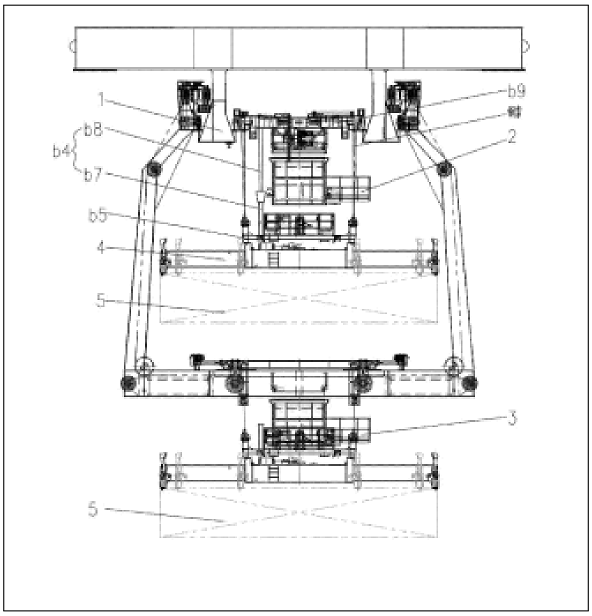


Figure 4.4: Patent WO2020224050A1

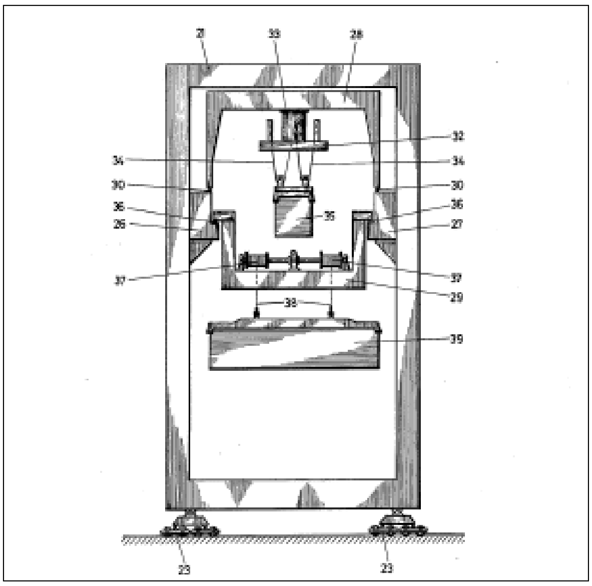


Figure 4.5: Patent US3881608A

4.3. Trolleys not passing each other

Some patents describe STS crane concepts with two trolleys that cannot pass each other. In this case, both trolleys travel on the same trolley rails. Figure 4.6 depicts a crane with two trolleys, that operate independently. Figure 4.7 shows a crane with two trolleys that can be coupled and decoupled. In the coupled configuration the crane operates like a dual hoist crane, while it can also operate as a conventional crane with one trolley by parking one of the trolleys at either the WS or LS.

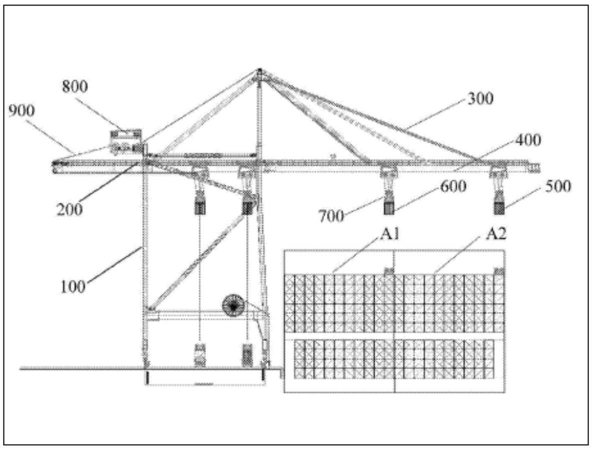


Figure 4.6: Patent CN105000480A

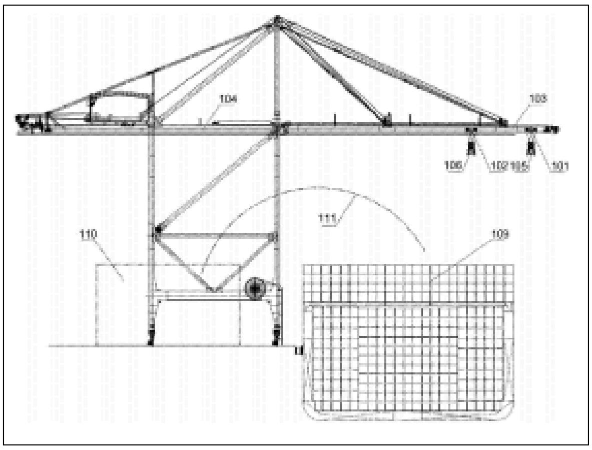


Figure 4.7: Patent CN107285208A

4.4. Dual hoist

The dual hoist working principle is already extensively described in section 2.3. Although this concept is only developed in practice by ZPMC, also some other applicants have patents that the describe the dual hoist working principle (see Appendix B).

4.5. Circulating systems

Circulating systems can be either circulating transfer vehicles or circulating trolleys. Due to the unique working principles of circulating systems, a separate category was formed. The TU Delft carrier crane (section 3.1), Liftech super crane (section 3.2), and CreaTech Technotainer (section 3.3) are examples of circulating systems. However, more patents of circulating systems were found. The exact working principle of these concepts varies. In figure 4.8 a circulating system with elevators on both sides can be seen. These elevators transfer the trolleys from a lower set of rails to a higher set of rails. In figure 4.9 the trolleys can circulate by driving upwards and downwards at both ends of the boom. Another option is to have have a curve in the horizontal plane to pass the other trolley, as can be seen in figure 4.10. A complete overview of circulating systems can be found in Appendix B.

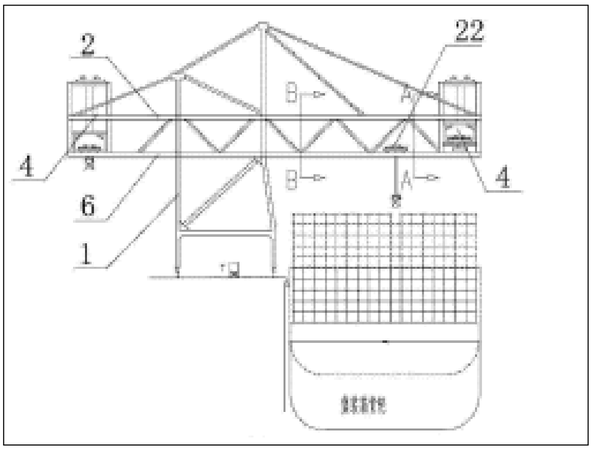


Figure 4.8: Patent CN103395699A

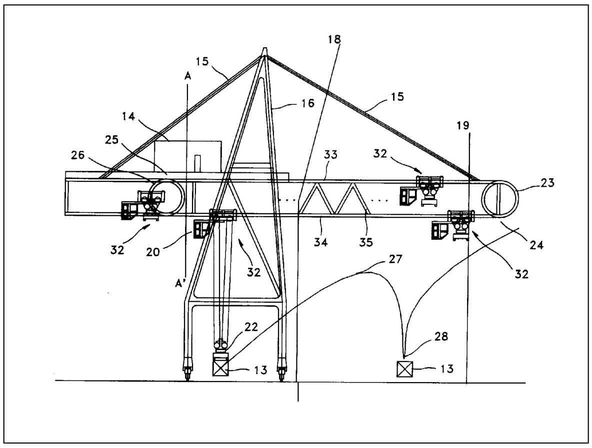


Figure 4.9: Patent KR0143699B1

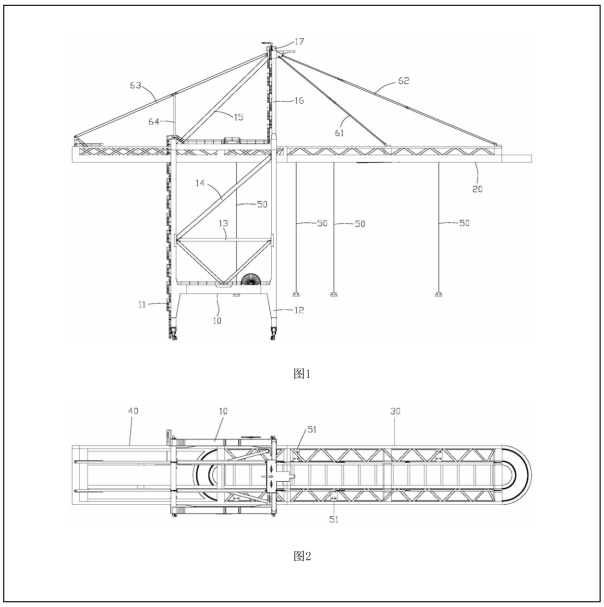


Figure 4.10: Patent CN110877865A

5 Constraints and objectives

As described in the research questions in chapter 1, the concept will have a standard crane structure. Before any further decisions related to the concept design can be made, it should be clear with which constraints and objectives an STS crane with a standard STS crane structure has to comply. Although constraints and objectives might be very straightforward in some cases, their exact definition often depends on personal preference. For this reason, all objectives and constraints are established in consultation with Iv-Consult. In section 5.1 the constraints are elaborated. Section 5.2 describes all the objectives. In some cases the constraints and objectives have some overlap. For instance, although a maximum weight increase can be set in the constraints, it is still beneficial to have a lighter crane. In case of any overlap, this is clearly mentioned in the constraints and objectives sections.

5.1. Constraints

The constraints define the limits or restrictions the design should adhere to. Constraints must be met for a concept to be an appropriate solution. For example, they could depend on the natural limits of materials or compatibility with surrounding elements. The constraints should be clear-cut to enable a sophisticated design process. Accordingly, every constraint is described as explicitly as possible. Table 5.1 lists the constraints, which are explained in the following subsections.

Table 5.1: Constraints for the new concept

Constraint name	Description
Standard	The concept should adhere to the EN 13001 standard.
Weight	Maximum weight increase of 200 tons additional to the standard crane structure
Wind area	Maximum increase of 80 m^2 additional to the standard crane structure
Terminal process compatibility	The concept should be able to operate at at least one existing terminal
Dimensions	Standard crane structure. Large enough to serve ULCVs. Maximum 27 meters wide. Any rail span that is used in an existing terminal. Not obstructing ship or wharf process

Standard

For an STS crane to be employed in practice, it should adhere to a renowned crane standard. The EN13001 standard will be used during the design of the concept. The standard ensures the safety of the design in terms of static strength, fatigue strength, and stability. However, in this stage of the design process, it is hard to predict whether a certain concept will be able to adhere to the standard. For this reason, when selecting a concept it should be roughly estimated whether it is realistic enough to adhere to the standard. In short, a concept will not be excluded as long as there is reason to believe this concept can adhere to the EN 13001 standard.

Weight & wind area

The weight and wind area are discussed simultaneously, as both constraints are related to the maximum corner loads on the quay. The wind area is important as a larger wind area causes larger storm wharf loads. An STS crane cannot be of unlimited weight and size, due to the limited capacity of the quay. On the other hand, Achterberg reported that there are no realistic limits yet on the maximum quay loads for new quays [14, p. 93]. Also, de Gijt describes that the crane loads cover only 2% of the building costs of a quay [38, p. 167]. This means that larger crane loads are not necessarily problematic when a new container terminal is built. There is also a possibility that a quay is overdeveloped [14, p. 93], although this is probably not the case for most terminals. Due to the just mentioned reasons, it is realistic to assume that new concepts are allowed to have larger corner loads than conventional cranes.

To set constraints for the weight and wind area, a percentage of a standard crane structure is taken. A large standard STS crane structure weighs approximately 2000 tons. In this work, the components added to the crane for the new concept may weigh no more than 10% of the crane structure, so 200 tons. It could be that necessary reinforcements of the crane structure result in extra weight. However, in this constraint this is not taken into account. A standard STS crane structure has approximately 1600 m^2 of wind area [39]. In this work, the wind area of the new concept may increase with a maximum of 5%, so 80 m^2. Although in reality the vertical location of the wind area is also of importance, this is simplified in this constraint. These values are chosen in such way that it is still realistic to implement the concept on an existing terminal, without excluding concept that need additional components.

Although the values described above are the maximum values to this constraint, a lighter crane concept with less wind area is still beneficial as more existing terminals will be able to implement the new concept on the terminal. Therefore the terminal compatibility objective in section 5.2 also takes the crane weight and wind area into account.

Terminal process compatibility

One of the constraints is that the concept should be able to operate at an existing container terminal. This constraint is devised to prevent the concept to require the whole wharf process to be adjusted. However, the concept should not necessarily perform at one particular type of container terminal. As long as there is some type of container terminal at which the concept could fit into the process it is sufficient to adhere to this constraint. For instance, an STS crane concept that is unable to load Automated Guided Vehicles (AGVs) will not be excluded as long as it can work together with other ground vehicles like straddle carriers. However, it might be that some concepts are more suitable to fit into a terminal process than others. Therefore terminal process compatibility is also part of the objectives that are addressed in section 5.2.

Dimensions

As the concept will be designed on a standard STS crane structure, the dimensions of the crane are already set to a certain extent. However, some additional requirements are necessary to define. First of all, the maximum width of the crane should be 27 meters. This constraint is chosen because this width is generally accepted in industry as the maximum width per crane to ensure enough cranes can serve a ship to have a decent wharf productivity. In case the crane would have a larger width, the increased productivity by the crane would be (partly) annihilated due to the influence on the wharf productivity.

Another dimension directly following from the surrounding terminal is the rail span of the crane. As long as the crane can drive on existing rails, the constraint regarding the rail span is met. The rail span can be any existing rail span.

Furthermore, the concept should be able to serve ULCVs. In case the concept encompasses a whole new crane this means the lifting height and outreach should be sufficient to cope with the ship dimensions. In case the concept encompasses an adjusted existing crane, the requirement is that the concept can at least be applied to existing cranes that are large enough to serve these ULCVs.

Finally, the crane dimensions should not obstruct the terminal process in a disturbing way. The terminal process should be able to continue, despite the fact that the new concept is implemented in the terminal. For instance, ground vehicles should be able to drive underneath the gantry and at the LS of the LS legs there should be enough space to let the wharf process continue. Also the ship should be able to berth as usual without being obstructed by the crane.

5.2. Objectives

Objectives are desirable characteristics. In contrast to constraints, objectives do not necessarily have to be met for a concept to be a potential solution for the design problem. However, the more an objective is met, the better. Therefore the objectives will tremendously influence the concept selection. The concept that best suits the objectives (while meeting the constraints) will eventually be selected. The objectives all describe properties the concepts should have to be more valuable for the terminal operator and/or the manufacturer of the crane. The objectives were formed in such a way to prevent overlap between multiple criteria as much as possible. The objectives are listed below. In the subsequent subsections these objectives will be explained.

- Productivity
- Existing crane adjustability
- Terminal compatibility
- Initial costs
- Operation reliability
- Operating costs
- Commercial opportunities

Productivity

The most important objective is the productivity of the STS crane concept. The more container moves per hour can be realised, the better.

Existing crane adjustability

The ability to adjust an existing crane would be a major advantage, and therefore the existing crane adjustability is one of the objectives. With this is meant that a concept can be realised on an existing crane by partly adjusting it, while reusing a (large) portion of the existing crane. This ability has several advantages. First of all, it is not necessary to manufacture a whole new crane. Instead, the existing crane can be reused to a large extend which reduces costs. On top of that, adjusting an existing crane reduces the risk a terminal operator takes when applying the concept. Building a new crane would be a large capital investment without having guaranteed success. An adjusted crane would be a lower investment, and in case the concept turns out to be unsuccessful there is a higher change that the crane could be restored to the original condition. A crane that is slightly adjusted to apply a concept would thus be a relatively small risk for a terminal operator. The more an existing crane should be adjusted to implement a concept, the larger risk the terminal operator has. As a result, terminal operators are reluctant to apply concepts that require to build a completely new crane. A crane adjustment is a smaller step for terminal operators, and thus a larger change of getting the job as an engineering firm.

Terminal compatibility

As described in the constraints, a concept should at least be compatible with one existing container terminal, regardless of which specific type of terminal it is. However, the extend to which a concept is able to work on (various types of) terminals also influences the applicability in practice. It is an enormous advantage if the concept can successfully harmonize with all existing terminals. Therefore one of the objectives is the terminal compatibility.

This compatibility depends to a large extent on the corner loads of the crane. A crane that is heavy and has a large wind area cannot be easily implemented on all terminals due to the limited load capacity of the quay. Second, this objective also depends on the wharf process compatibility. For example, it could be that a certain concept requires the load to be unloaded at a specific location on the quay, which is not practical on every terminal.

Initial costs

For a concept to be successful, the initial costs should be acceptable. Implementing a new concept into the terminal is a huge risk for a terminal operator. Although high initial costs can be worth it, there is no guaranteed success. Therefore, one of the objectives is to minimize the the initial costs. Without this objective the chosen concept could become unrealistically expensive.

Operation reliability

For a successful implementation, the concept should have as little inconvenience as possible during operation. For this reason, operation reliability is one of the objectives. A concept with good operation reliability operates without problems. On the other hand, a concept with many risks and complicated container handling procedures would be problematic. The operation reliability characterizes how much downtime or delay can be expected. A concept with novel working principles is more likely to be unreliable than a concept based on proven techniques. Also when a concept relies on many components it is more likely to be unreliable in practice. For example, a concept that requires a container to be moved consecutively by three different trolleys cannot operate as soon as one trolley is out of service. The operating costs are not part of this objective, as this is a separate objective. This is because a concept could have high operating costs while the operation process is robust and reliable.

Operating costs

Another objective for an STS crane concept is to have low operating costs. The operating costs consist of recurring costs like labour, maintenance and power consumption. For instance, concepts that require multiple operators or additional maintenance would have higher operating costs than conventional cranes.

Commercial opportunities

The last objective covers the commercial opportunities that Iv-Consult has for every concept. This depends on multiple aspects. First of all, it depends on the existing patents for every concept. As elaborated in chapter 4, a wide variety of concepts is already covered in patent literature. Patents that are still in force can prevent concepts from being commercially exploited. On the other hand, some ideas are described in patents that are not in force anymore. These ideas can be employed in a concept without any problems related to intellectual property. However, ideas that are already described in patents cannot be patented again. This is also the case for any other public documents. Although in this case the concept cannot be patented, this is not necessarily a problem. A concept does not necessarily have to be patented to be successfully designed and sold. This is because the engineering phase is time consuming and the design is not easily mimicked. The most lucrative scenario would be a concept that is not described anywhere in literature, and consequently is not patented.

Apart from the patents, also the engineering opportunities for Iv-Consult influence how suitable a concept is. For example, a concept that requires custom engineering for every crane would be a great commercial opportunity for Iv-Consult. As a company, specializing in custom crane adjustments or new crane designs could be of great value for customers. Customers will likely prefer a company with experience in implementing a certain STS crane concept in practice to execute the job. Based on the just mentioned aspects, for every potential concept it will be estimated how lucrative a concept would be for Iv-Consult.

6 Concept establishment

This chapter describes the process of establishing concepts. To do so, a functional decomposition (section 6.1) and a morphological chart (section 6.2) will be used. Although the aim is to come up with concepts for the simultaneous transfer of 4 TEU, concepts could also contain solutions for the simultaneous transfer of even more TEU. The possible solutions are not restricted to lifting 4 TEU in one move, but also cover the lifting of single containers once by once. All possible solutions are considered, as long as 4 TEU or more are simultaneously transferred by the crane. The concepts and working principles in this chapter are not thoroughly elaborated, as this is only the selection phase of a certain concept. Once a concept is chosen, it will be further worked out.

6.1. Functional decomposition

A convenient approach to solve complex tasks is to decompose it into smaller sub problems that are more easily managed. This is also the case for engineering design, where large design problems can be decomposed into smaller design problems. As described by Dieter et al., physical decomposition and functional decomposition are ways to break down a product for the ease of design [40, p. 216]. In this work, functional decomposition will be employed to alleviate the design task. Every function is enumerated, according to the enumeration method described by Dym and Little [41].

An overview of the functional decomposition is provided in table 6.1. As adequately described by Dieter et al., "Functional decomposition is a top-down strategy where a general description of a device is refined into more specific arrangements of functions and subfunctions", and "Functional decomposition does not initially impose a design, allowing more leeway for creativity and generates a wide variety of alternative solutions. This feature of the functional decomposition method is called solution-neutrality" [40, p. 216]. These properties of functional decomposition make it a suitable approach for the design problem in this work. Initially, another functional decomposition was formed, but this resulted in some difficulties during the concept establishment. The initial functional decomposition and the process of forming the eventual functional decomposition can be seen in Appendix C.

Table 6.1: Functional decomposition.

Transferring containers between a container vessel and a quay
Subfunctions: 1. Attach and detach the container(s) 2. Hoist and lower containers, and obtain the correct position above the ship or quay 3. Move the container between landside and waterside 4. Support handling process with secondary system below the main girder

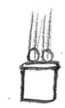
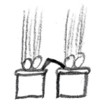
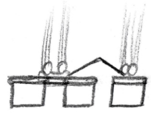
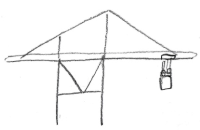
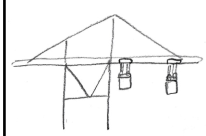
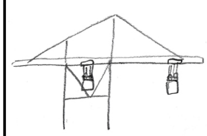
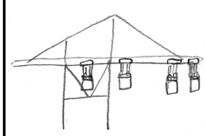
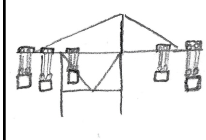
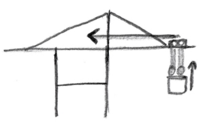
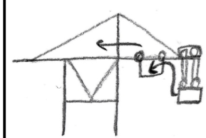
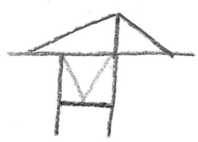
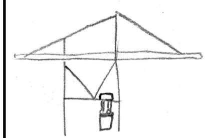
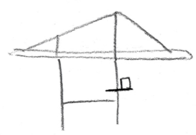
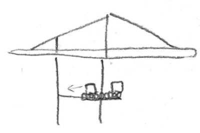
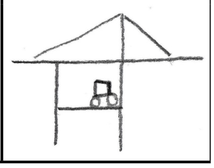
6.2. Morphological chart

A convenient method to create new concepts is a morphological chart. In this section a morphological chart will be formed to create alternative concepts for an STS crane that can simultaneously transfer 4 TEU or more. In the following block quotation, Dym and Little accurately outline the definition of a morphological chart.

> A morphological chart (aka a morph chart) is a matrix in which the leftmost column is a list of all of the principal functions that our design must perform and also some of the key features it must have. The list should be of a manageable size, and all of the entries should be at the same level of detail to help ensure consistency. Then, across from each of the functions or features, we list each of the different means of realizing the function or feature that we can think of. [41, p. 93]

In table 6.2 the morphological chart used in this work can be seen. In the starting column, the functions of table 6.1 are listed, together with multiple potential means for each function in the adjacent cells.

Table 6.2: Morphological chart

↓ Functions	Means →				
Attach and detach the container(s)	Single spreader-headblock system 	Tandem spreader-headblock system 	Triple spreader-headblock system 		
Hoist and lower containers, and obtain the correct position above the ship or quay	One trolley with hoisting means for both WS and LS 	Two trolleys with hoisting means that both operate at WS and LS 	Separate trolley for WS and LS 	Two trolleys for both WS and LS 	Other combinations of 1, 2, 3, or 4 trolleys at WS and/or LS 
Move the container(s) between landside and waterside	Same trolley(s) as used during hoisting and lowering* 	Container(s) transferred to another vehicle for horizontal transport** 			
Secondary system below the main girder (multiple options possible)	No secondary system 	Secondary trolley (somewhere below main girder, e.g. portal beam height) 	Transfer platform 	Conveyor system 	Transfer vehicle(s) 

* See table 6.3.
** See table 6.4.

The "move the container(s) between landside and waterside" function has only two options in the morphological chart. However, this function can be fulfilled by much more potential means. Therefore the means for this function are subdivided among two auxiliary sub charts. Table 6.3 shows an overview for all options by which containers can be moved between LS and WS by the same trolley(s) as used during hoisting and lowering. Table 6.4 includes all options for which the containers are transferred to another vehicle for the horizontal movement. The two sub charts are necessary because moving the container(s) between landside and waterside is a problem that can be solved in a multitude of ways. By listing all these solutions in one morphological chart, it would require too many columns. Dym and Little considered this to be a convenient approach by stating: "We might even choose to create a morph chart for some of these subsystems to help us appreciate the design choices implicit in our concepts and schemes" [41, p. 95].

In both the morphological chart and the sub charts, trolleys and transfer vehicles are regularly mentioned. Therefore, it should be clearly defined what the difference between a trolley and a transfer vehicle is. In this work, a trolley is a vehicle that guides the hoisting cables or contains the whole hoisting mechanism, while being able to drive in the horizontal direction. On the other hand, a transfer vehicle is a vehicle that does not include any hoisting means. A transfer vehicle is able to transfer containers between WS and LS, but cannot hoist or lower containers. The morphological chart and sub chart allows to investigate different combinations and configurations of transfer vehicles and trolleys that can simultaneously transfer 4 TEU.

Table 6.3: Trolleys sub chart

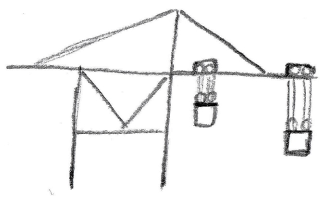
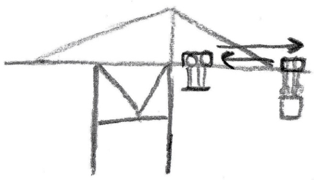
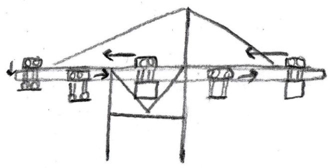
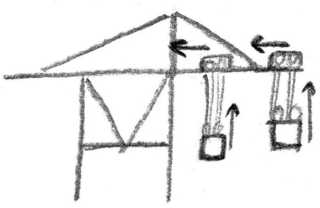
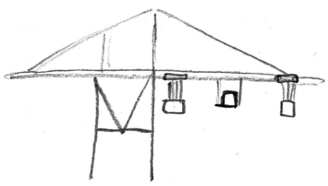
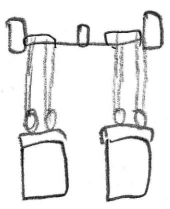
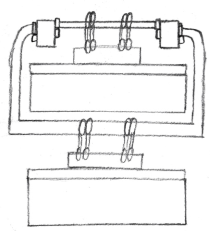
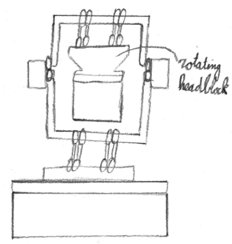
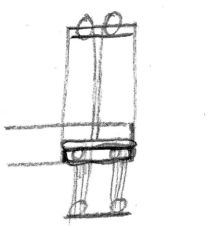
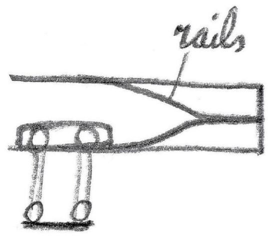
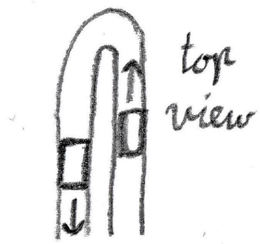
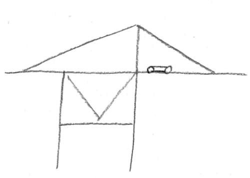
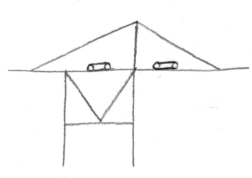
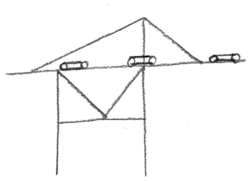
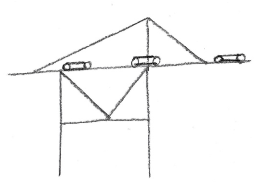
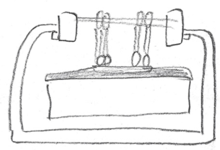
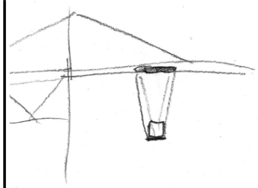
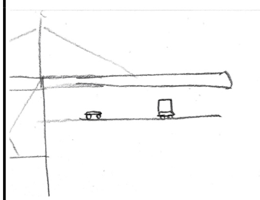
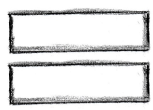
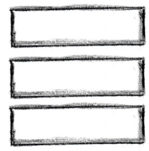
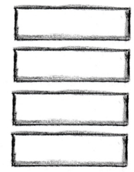
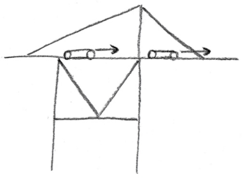
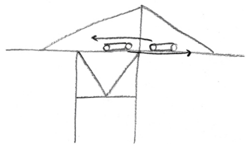
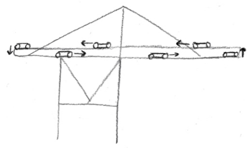
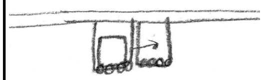
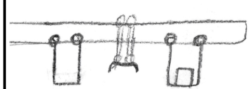
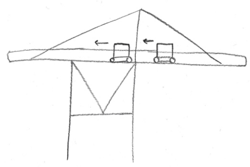
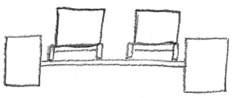
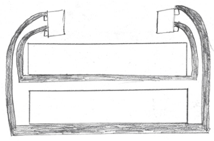
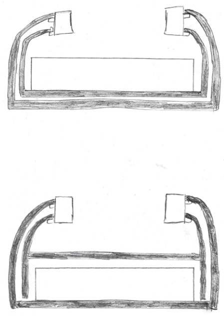
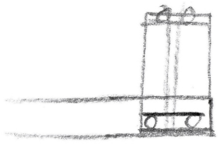
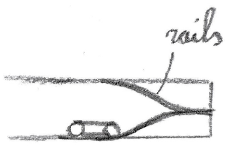
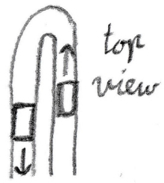
↓ Features	Means →		
Cycle method	Not passing each other 	Passing each other 	Circulating system, 2 rail systems, one for each direction 
In case of not passing	All trolleys operate like a conventional trolley 	Platform somewhere on the main girder allows transfer of container(s) between trolleys 	
In case of passing	Side by side 	Upper/inner and lower/outer trolley. Both can pass with container 	Upper/inner and lower/outer trolley, upper container rotated. Both can pass with container 
In case of circulating	Elevator at both boom ends 	Switches at both boom ends 	Curve at both boom ends 

Table 6.4: Transfer vehicles sub chart

↓ Features	Means →			
Number of transfer vehicles	1 	2 	3 	3+ 
Transfer vehicle type	Transfer vehicle installed on main girder. The vehicle is low enough for a trolley to load and unload it 	Transfer trolley with hoisting means connected to a suspended platform that can be hoisted and lowered 	Transfer vehicle(s) driving on track below the main girder 	
Number of containers on one transfer vehicle	2 TEU 	4 TEU 	6 TEU 	8 TEU 
Cycle pattern	Not passing each other 	Passing each other 	Circulating 	
In case of not passing	Transfer of container to other vehicle by means of conveyor system on transfer vehicles 	Spreader somewhere on the main girder transfers the container from one vehicle to another 	Containers are not transferred between vehicles 	

Continued on next page

Table 6.4 – continued from previous page

↓ Features	Means →			
In case of passing	Side by side 	Upper/inner and lower/outer transfer vehicles that fit into each other which allows them to pass each other 	Upper and lower transfer vehicle. Upper vehicle has movable bottom that allows the lower/outer vehicle to pass with container(s) 	
In case of circulating	Elevator at both boom ends 	Switches at both boom ends 	Curve at both boom ends 	

As explained in the beginning of this section, the morphological chart should be of manageable size, while all entries should have the same level of detail. For this reason, the morphological chart does not cover details like exact headblock and spreader types, trolley types (RTT or MOT), and single or dual hoist configurations in case of tandem lifting. Also twistlock removal, movement parallel to the quay, and other subsidiary aspects of an STS crane were not covered in the morphological chart. The morph chart is only a tool to create new concepts. It is a tool to support the creative process. It is not a tool to take all aspects of a certain concept into account. In the concept generation phase these details are not important yet.

Nonetheless, it can of course happen that a concept that is formed with the morphological chart comes with additional requirements and problems. It might be that a certain concept requires additional features that were not covered in the morphological chart to be a valid solution. In case a concept formed in the morph chart comes with additional requirements and/or problems, they will be taken into account even though they are not part of the morph chart. For instance, in case an STS crane concept requires the boom to be a twin girder, this will be taken into account even though the boom type is not part of the morphological chart.

6.3. Composed concepts

The morphological overview together with the auxiliary sub charts were used to form concept by combining different means. In Appendix C it can be seen how the combination of different means led to 12 potential concepts. Out of these 12 concepts, 7 concepts were chosen to further elaborate before choosing a final concept. This process is further elaborated in Appendix C. The 7 concepts that will be further examined in chapter 7 are shown in this section. Throughout the text, numbers between brackets will be used to refer to the images of the respective concept. All concepts are assumed to be remote controlled.

6.3.1. Concept 1: Two trolleys, not passing

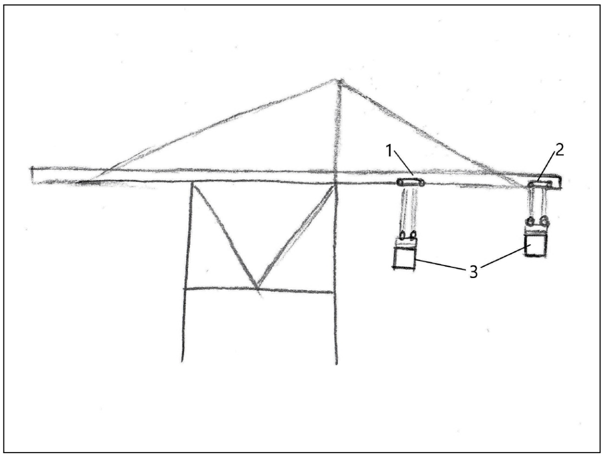


Figure 6.1: Concept 1. Simplified side view drawing. 1: first trolley. 2: second trolley. 3: container.

An STS crane equipped with two trolleys, that both operate like a conventional trolley. Figure 6.1 shows the general arrangement. The trolleys drive on the same rails. Both the first trolley (1) and second trolley (2) transfer containers (3) between the ship and the quay. The trolleys cannot pass each other. They will simultaneously move towards the waterside or landside, because otherwise they will block each others way. This means that the LS trolley cannot reach every container row on the ship. Both trolleys are connected to a conventional spreader, that is able to perform single lifting and/or twin lifting.

6.3.2. Concept 2: Two trolleys, passing

An STS crane with two trolleys that can pass each other. Trolley 1 in figure 6.2 and figure 6.3 is a conventional trolley, while trolley 2 is modified to enable a position below trolley 1. The figures show simplified drawings of this concept in case of a twin girder boom. A second rail system (5) is installed at the outer sides of the girders. Trolley 2 drives on this rail system, as can be seen in figure 6.3. The design of the lower trolley allows the upper trolley to pass while carrying a container. However, trolley 1 can only pass trolley 2 when the container carried by trolley 1 is hoisted to the highest position. The configuration of trolley 1 could be problematic when serving large container vessels. In this case the lower trolley cannot be used, unless the crane is high enough.

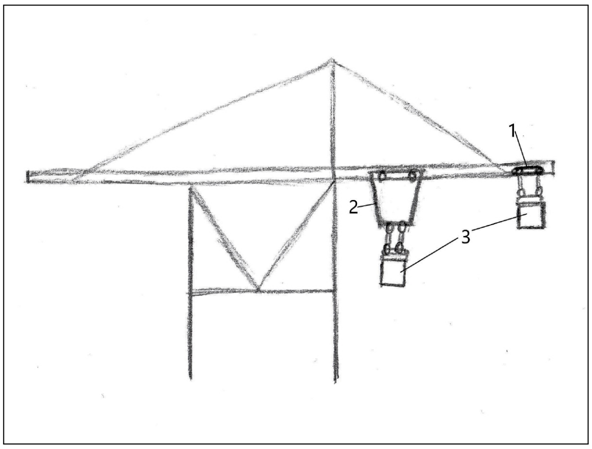


Figure 6.2: Concept 2. Simplified side view drawing. 1: upper trolley. 2: lower trolley. 3: container. 4: rails for upper trolley. 5: rails for lower trolley.

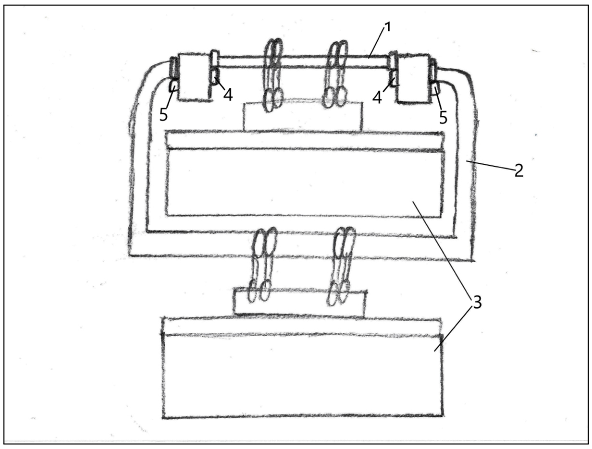


Figure 6.3: Concept 2. Simplified cross section drawing. 1: upper trolley. 2: lower trolley. 3: container. 4: rails for upper trolley. 5: rails for lower trolley

6.3.3. Concept 3: Two trolleys, passing with rotating headblock

This concept is simular to concept 2, but with rotating headblock

An STS crane with two trolleys that can pass each other. Figure 6.4 and 6.5 show simplified drawings of this concept. The concept consists of an upper (1) and lower trolley (2). The upper trolley carries a container that is rotated with 90 degrees, enabling to lift the headblock, spreader, and container partly in between the girders (see figure 6.5). By doing so, there is more space underneath the upper trolley to pass underneath. This rotation is performed by a rotating headblock (4). After the container is lifted from the ship or quay, the container is hoisted to the highest position while the headblock rotates. In this way, the upper trolley can pass the lower trolley. After passing, the headblock rotates again. Also when the upper trolley does not move a container, the headblock should rotate with 90 degrees before passing the lower trolley, because otherwise the spreader would not fit through. Although in the proposed configuration the rotational movement is performed by the headblock, the headblock does not necessarily have to be the rotating component. A rotating spreader or trolley is also possible. The two trolleys drive on separate rails. The upper trolley drives on upper rails (5), while the lower trolley drives on lower rails (6). The configuration of trolley 1 could be problematic when serving large container vessels. In this case the lower trolley cannot be used, unless the crane is high enough.

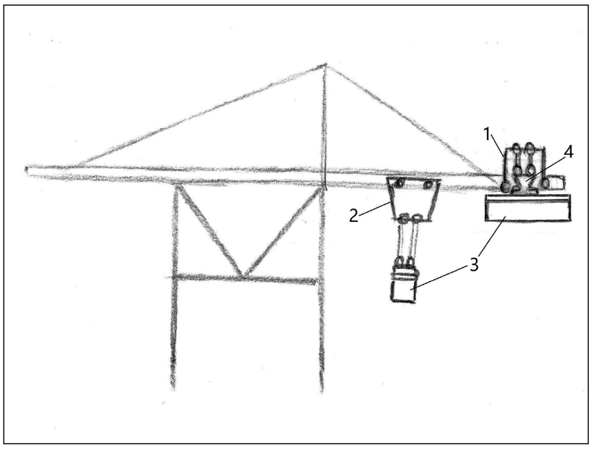


Figure 6.4: Concept 3. Simplified side view drawing. 1: upper trolley. 2: lower trolley. 3: container. 4: rotating headblock.

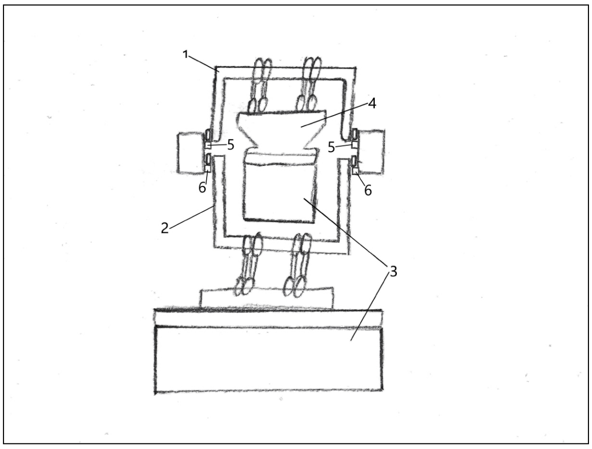


Figure 6.5: Concept 3. Simplified cross section drawing. 1: upper trolley. 2: lower trolley. 3: container. 4: rotating headblock. 5: rails for upper trolley. 6: rails for lower trolley.

6.3.4. Concept 4: WS and LS trolley with 1 transfer vehicle

An STS crane with a separate waterside trolley (1) and landside trolley (2), and one transfer vehicle (3) that transfers containers between WS and LS. Figure 6.6 and 6.7 show simplified drawings of this concept. Both trolley 1 and trolley 2 are conventional trolleys. The transfer vehicle is installed on the boom, and can drive underneath a trolley to be loaded or unloaded. In figure 6.7 a cross section of the transfer vehicle with a trolley can be seen. The transfer vehicle drives on rails on the outer sides of the girders (6). The transfer vehicle only has to be able to move horizontally, which allows a relatively simple design. One of the trolleys loads the transfer vehicle, after which the transfer vehicle drives to the other trolley to be unloaded. The trolleys cannot pass each other, and during normal operation they will stay at either the landside or waterside. In this way, containers will be given through between the trolleys while loading or unloading a ship.

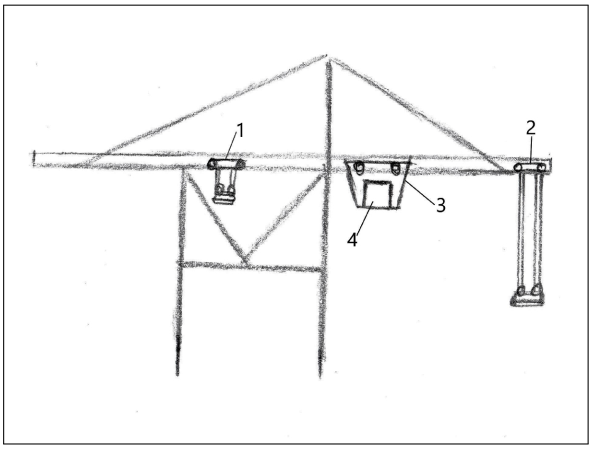


Figure 6.6: Concept 4. Simplified side view drawing. 1: first trolley. 2: second trolley. 3: transfer vehicle. 4: container.

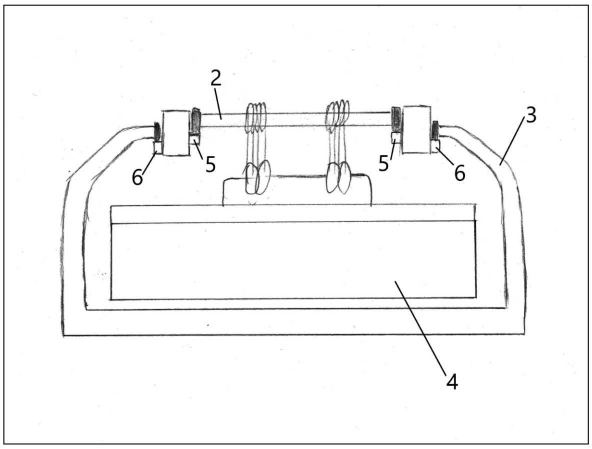


Figure 6.7: Concept 4. Simplified cross section drawing. 2: conventional trolley. 3: transfer vehicle. 4: container. 5: rails for conventional trolleys. 6: rails for transfer vehicle.

6.3.5. Concept 5: WS and LS trolley with 2 transfer vehicles and movable bottom

This concept is similar to concept 4, but now with an extra transfer vehicle.

An STS crane with a separate waterside trolley (2) and landside trolley (1), and two transfer vehicles (3 and 4) that transfer containers between WS and LS. Figure 6.8, 6.9, and 6.10 show simplified drawings of this concept. Both trolleys are conventional trolleys. One of the trolley lifts a container from the ship or quay, after which a transfer vehicle drives underneath the trolley. Subsequently, the container is unloaded on the transfer vehicle. The transfer vehicle drives to the other side, to be unloaded by the other trolley. Both transfer vehicles drive on rails on the outer sides of the girders (7 and 8), as can be seen in figure 6.9. The transfer vehicles consist of a lower (3) and upper vehicle (4). As can be seen in figure 6.9, the transfer vehicles can easily pass when a container is carried by the upper vehicle. However, when the lower vehicle carries a container, the lower vehicle would be in the way when they have to pass. To solve this, the upper transfer vehicle (4) is equipped with a movable bottom (5). This bottom can be moved upwards when the vehicles pass each other. In figure 6.10 the bottom of the upper transfer vehicle is moved upwards, to allow the transfer vehicles to pass each other.

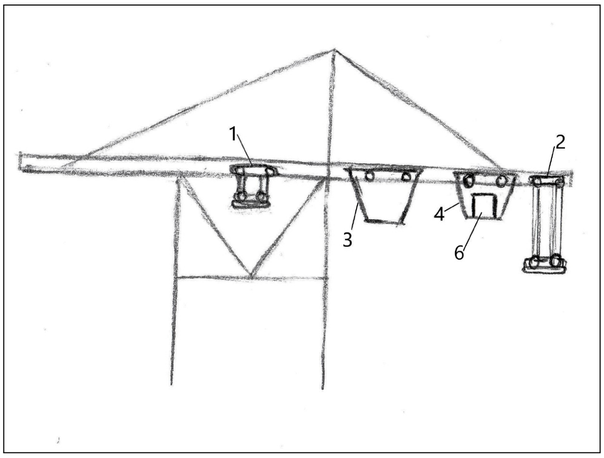


Figure 6.8: Concept 5. Simplified side view drawing. 1: LS trolley. 2: WS trolley. 3: Lower transfer vehicle. 4: upper transfer vehicle. 6: container.

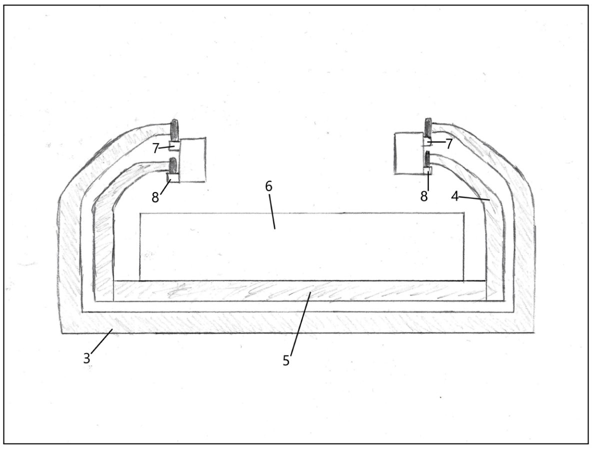


Figure 6.9: Concept 5. Simplified cross section drawing. The bottom of the upper transfer vehicle is moved down. 3: lower trolley. 4: upper trolley. 5: movable bottom of upper trolley. 6: container. 7: rails for upper transfer vehicle. 8: rails for lower transfer vehicle.

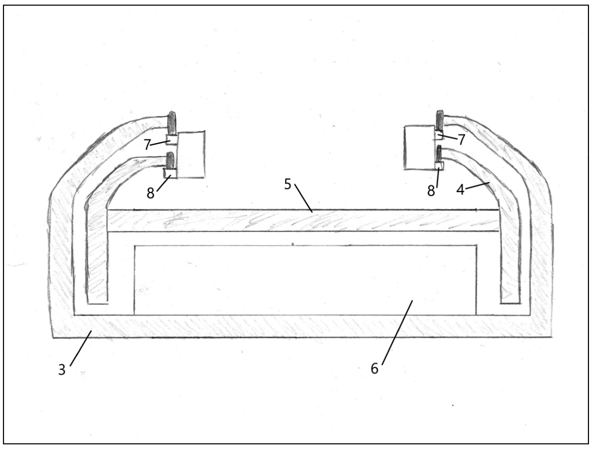


Figure 6.10: Concept 5. Simplified cross section drawing. The bottom of the upper transfer vehicle is moved up. 3: lower trolley. 4: upper trolley. 5: movable bottom of upper trolley. 6: container. 7: rails for upper transfer vehicle. 8: rails for lower transfer vehicle.

6.3.6. Concept 6: WS and LS trolley and 2 transfer vehicles above each other

This concept is similar to concept 4, but now with an extra transfer vehicle.

An STS crane with a separate waterside trolley (2) and landside trolley (1), and two transfer vehicles (3 and 4) that transfer containers between WS and LS. Figure 6.11, and 6.12 show simplified drawings of this concept. Both trolleys are conventional trolleys. One of the trolley lifts a container from the ship or quay, after which a transfer vehicle drives underneath the trolley. Subsequently, the container is unloaded on the transfer vehicle. The transfer vehicle drives to the other side, to be unloaded by the other trolley. Both transfer vehicles drive on rails on the outer sides of the girders (6 and 7), as can be seen in figure 6.12. The transfer vehicles consist of a lower (3) and upper vehicle (4). The lower transfer vehicle (3) is low enough to pass the upper vehicle, even when it carries a container (see figure 6.12).

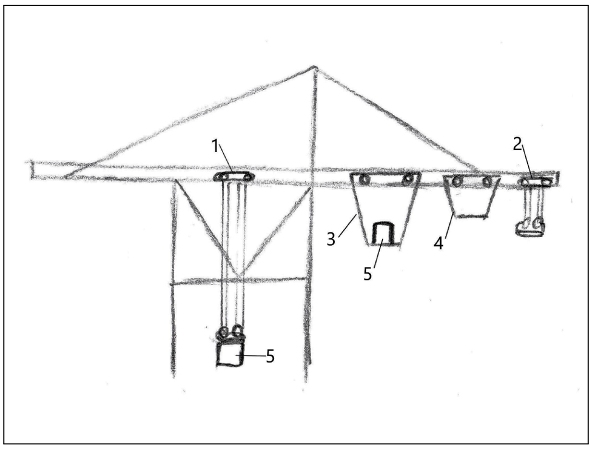


Figure 6.11: Concept 6. Simplified side view drawing. 1: LS trolley. 2: WS trolley. 3: lower transfer vehicle. 4: upper transfer vehicle. 5: container.

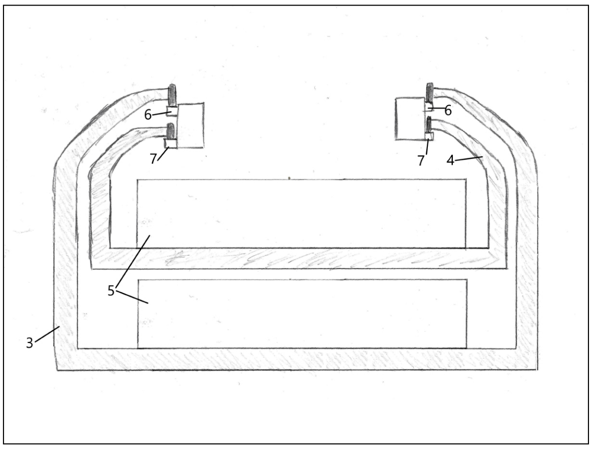


Figure 6.12: Concept 6. Simplified cross section drawing. 3: lower transfer vehicle. 4: upper transfer vehicle. 5: container. 6: rails for lower transfer vehicle. 7: rails for upper transfer vehicle.

6.3.7. Concept 7: One trolley with multiple transfer vehicles

The transfer vehicles are comparable to the transfer vehicles of concept 5, but now without moving bottom.

An STS crane that has one conventional trolley (1) that serves both the ship and the quay. Multiple transfer vehicles drive between LS and WS. The example shown here contains two transfer vehicles, but the amount of transfer vehicles can be adjusted in a later stage. The transfer vehicles are positioned above each other, as can be seen in figure 6.14. In this way the transfer vehicles can pass each other. However, when a transfer vehicle is loaded with a container, it can only pass lower, empty transfer vehicles.

In case of unloading a ship, first the trolley (1) lifts a container (4) from the ship and unloads it on the upper transfer vehicle (2). This transfer vehicle subsequently drives towards the quay, and waits there. Then the next transfer vehicle (3) is loaded by the trolley, which also drives to the quay and waits there. Every time a transfer vehicle is loaded, it drives towards the landside. When all transfer vehicles are loaded, the trolley picks up another container from the ship, and drives towards the LS to unload it on the quay. Subsequently, the trolley will unload all transfer vehicles on the quay.

In case of loading a ship, the process is slightly changed. First the trolley will load all transfer vehicles, which are all located above the quay. The loaded transfer vehicles will wait above the quay, instead of already driving towards the ship. After all transfer vehicles are loaded, the trolley picks up another container from the quay, and moves to the ship to unload it there. Now the lower trolley (3) moves towards the WS, to be unloaded by the trolley (1). After being unloaded, the lower trolley drives back to the quay. Simultaneously, the upper transfer vehicle (or second lowest trolley in case of more than 2 transfer vehicles) drives towards the WS. Also this vehicle is unloaded by the trolley. Now all vehicles, including the trolley, drive back towards the quay. If all loaded transfer vehicles would wait above the ship, a large moment would be exerted on the boom. To prevent this, the process of loading a ship differs from the unloading case.

In case of more transfer vehicles, the working principle will remain the same. Also the number of containers per transfer vehicle could be adjusted. This also does not influence the working principles described above.

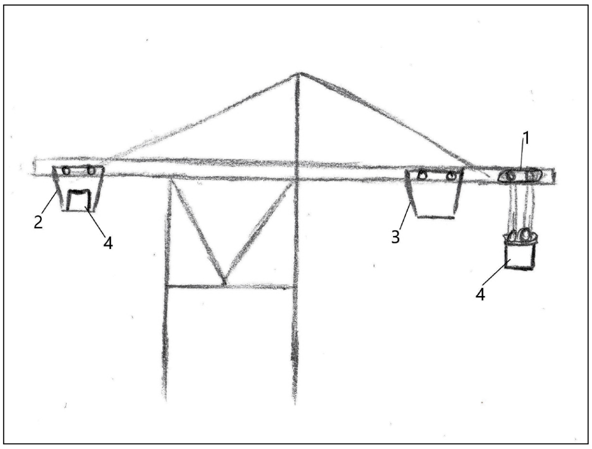


Figure 6.13: Concept 7. Simplified side view drawing. 1: trolley. 2: upper transfer vehicle. 3: lower transfer vehicle. 4: container.

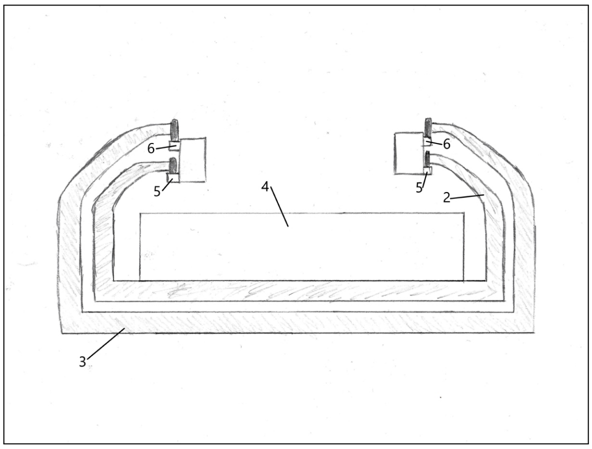


Figure 6.14: Concept 7. Simplified cross section drawing. 2: upper transfer vehicle. 3: lower transfer vehicle. 4: container. 5: rails for upper transfer vehicle. 6: rails for lower transfer vehicle.

7
Concept selection

In this chapter, one concept is chosen after a comparison between the concepts is performed. The most important objective is the productivity, for which section 7.1 explicates the calculation method for the cycle times. Besides the productivity, also the weight, load moment, and costs are compared. These aspects are documented in appendix D, and a summary of the properties of all concepts is given in section 7.2. Finally, section 7.3 shows the definitive concept choice.

7.1. Cycle calculations

This section shows the theoretical productivity of all concepts. First, the cycle calculations for a conventional crane are elaborated. Subsequently, the differences in cycle calculations for the concepts are explained. In the cycle time calculations all containers are assumed to be 40 foot containers.

7.1.1. Conventional crane

Figure 7.1 and table 7.1 show the distances that are of importance in the cycle calculations. In Appendix D the travel distances are described for every container position on the ship.

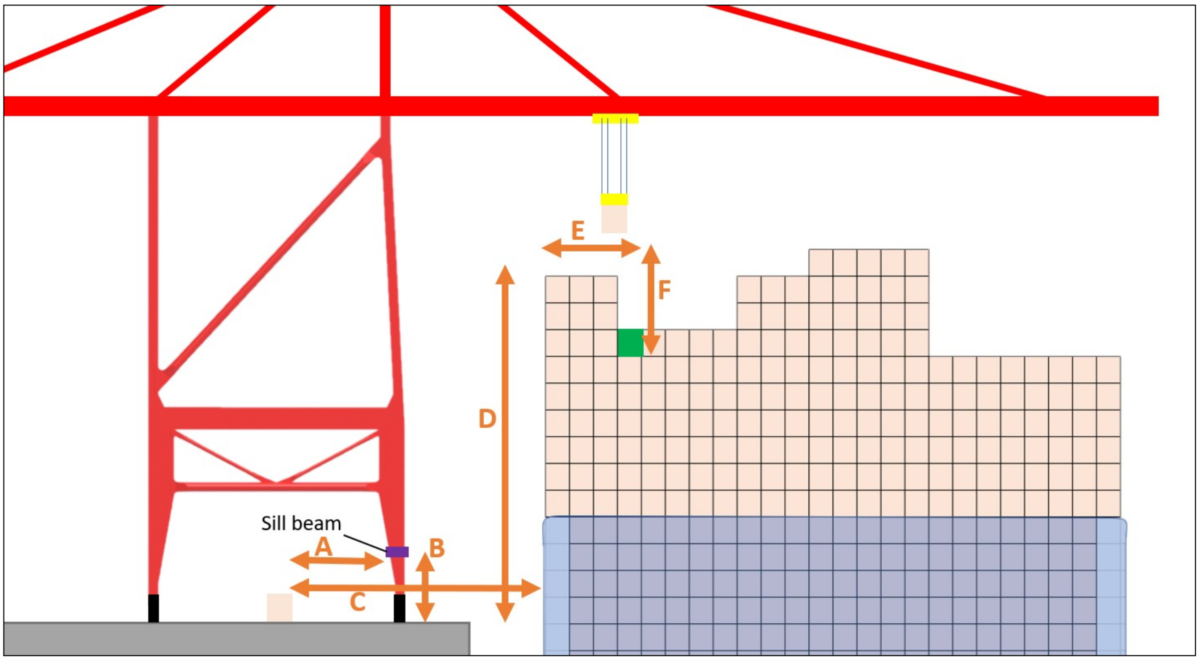


Figure 7.1: Distances for cycle time calculations. The distances are drawn for the green container. The explanation of all distances can be seen in table 7.1

Table 7.1: Travel distances as depicted in figure 7.1 and figure 7.2. In Appendix D the values of these distances are described for every container position on the ship.

	Description
A	Horizontal distance from position on quay to sill beams
B	Vertical distance from position on quay to sill beams
C	Horizontal distance from position on quay to side of ship
D	Vertical distance from position on quay to the height necessary to pass obstructing containers
E	Horizontal distance from side of ship to container position on ship
F	Vertical distance from hoisting height to position on ship. In case of below deck containers, F is the distance from the hoisting height to the cell guides.
G	Vertical distance from begin cellguides to container position on ship.

In table 7.2 the symbols for the travelling times for hoisting, lowering, and trolley travelling are listed. These will be used in the calculations.

Table 7.2: Times that are part of the loading and unloading cycle of the crane. In Appendix D the travel time calculation method is elaborated.

Symbol	**Description**
$H^F_{X,1}$	Time it takes to hoist distance X with full load without accelerating or decelerating
$H^F_{X,2}$	Time it takes to hoist distance X with full load with either acceleration or deceleration
$H^F_{X,3}$	Time it takes to hoist distance X with full load with accelerating and decelerating
$H^E_{X,1}$	Time it takes to hoist distance X with empty container or spreader without accelerating or decelerating
$H^E_{X,2}$	Time it takes to hoist distance X with empty container or spreader with either acceleration or deceleration
$H^E_{X,3}$	Time it takes to hoist distance X with empty container or spreader with accelerating and decelerating
$L^F_{X,1}$	Time it takes to lower distance X with full load without accelerating or decelerating
$L^F_{X,2}$	Time it takes to lower distance X with full load with either acceleration or deceleration
$L^F_{X,3}$	Time it takes to lower distance X with full load with accelerating and decelerating
$L^E_{X,1}$	Time it takes to lower distance X with empty container or spreader without accelerating or decelerating
$L^E_{X,2}$	Time it takes to lower distance X with empty container or spreader with either acceleration or deceleration
$L^E_{X,3}$	Time it takes to lower distance X with empty container or spreader with accelerating and decelerating
$T^F_{X,1}$	Time it takes to trolley travel distance X with full load without accelerating or decelerating
$T^F_{X,2}$	Time it takes to trolley travel distance X with full load with either acceleration or deceleration
$T^F_{X,3}$	Time it takes to trolley travel distance X with full load with accelerating and decelerating
$T^E_{X,1}$	Time it takes to trolley travel distance X with empty container or spreader without accelerating or decelerating
$T^E_{X,2}$	Time it takes to trolley travel distance X with empty container or spreader with either acceleration or deceleration
$T^E_{X,3}$	Time it takes to trolley travel distance X with empty container or spreader with accelerating and decelerating
t_{tl}	Time it takes to turn the twistlocks of the spreader
t_{tc}	Time it takes to tension the cables
t_{odtl}	Time it takes to remove the twistlocks in case of on-deck containers
t_p	Time it takes to position the spreader or container on its location. Also applicable when entering the cellguides.

In table 7.3 all steps in the cycle calculation for loading on deck containers is performed. In case of unloading, the extensions F (for full containers) and E (for empty spreader) are interchanged. The cycle starts at the moment that the the spreader is positioned on a container on the quay.

Table 7.3: Cycle calculation for loading on deck containers.

Step	Time
Turning spreader twistlocks	t_{tl}
Tensioning cables	t_{tc}
Placing twistlocks in the container	t_{odtl}
Moving container above container position on ship	if $H^F_{D,3} > T^F_{C,3} + T^F_{E,3} \rightarrow$ $H^F_{D,3} + T^F_{E,2}$ else $T^F_{C,2} + T^F_{E,2} + MAX(MAX(H^E_{B,3} - T^F_{A,2}; H^F_{D,3} - T^F_{C,2}); 0)$
Lowering container towards container position	$L^F_{F,3}$
Position container	t_p
Turning spreader twistlocks	t_{tl}
Tensioning cables	t_{tc}
Hoisting empty spreader above adjacent containers	$H^E_{F,3}$
Moving spreader to next container on the quay	if $L^E_{D,3} > T^E_{C,3} + T^E_{E,3} \rightarrow$ $L^E_{D,3} + T^E_{E,2}$ else $T^E_{C,2} + T^E_{E,2} + MAX(L^E_{D,3} - T^E_{C,2}; 0)$
Positioning spreader on container	t_p

In case of below deck containers some extra steps are necessary. The extra time steps in case of loading a container ship are listed in table 7.4. If the sum of time steps in table 7.4 is added to the time steps in table 7.3, the cycle times for below deck containers are determined. In figure 7.2 it can be seen that F is the distance to the cellguides, while G is the vertical distance from the cellguides to the container position below deck. In case of unloading a ship, the extensions E and F should be interchanged.

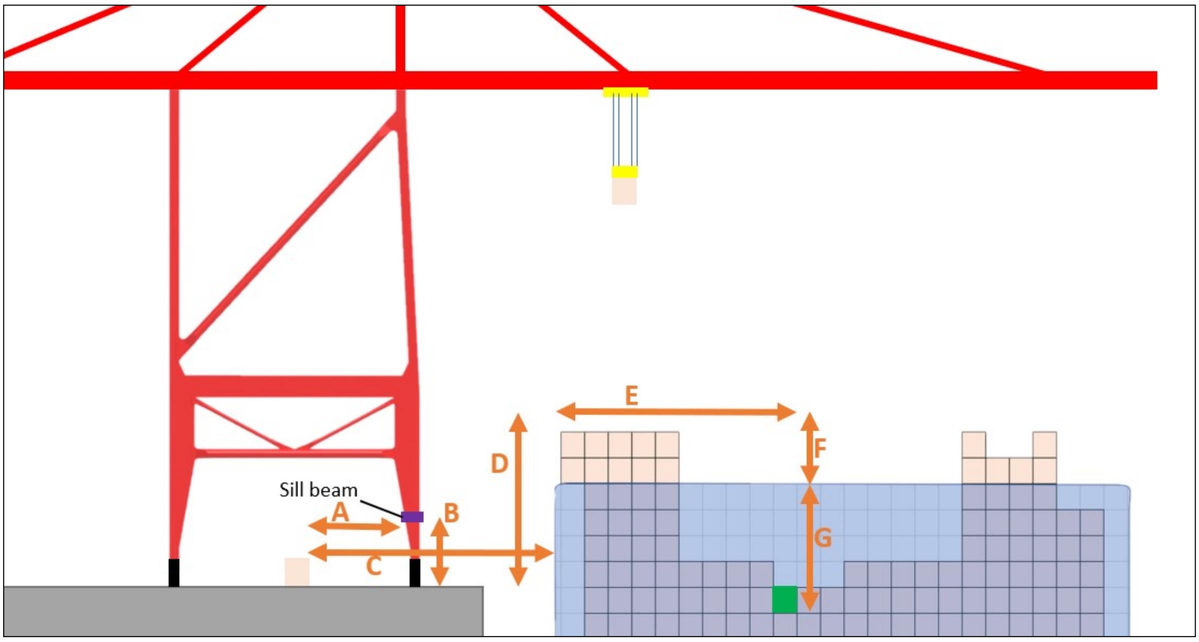


Figure 7.2: Distances for cycle time calculations for below deck containers. The distances are drawn for the green container. The explanation of all distances can be seen in table 7.1.

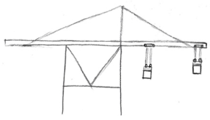
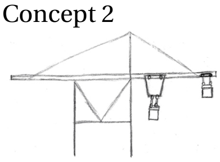
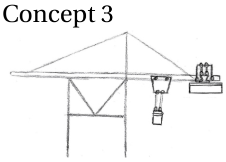
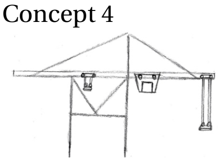
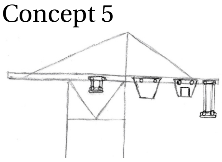
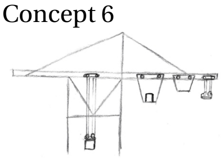
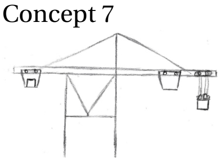
Table 7.4: Extra steps in cycle calculation for below deck containers. For below deck containers, the times listed in this table should be added to the times listed in table 7.3.

Step	Time
Lowering container from cellguides to container position	$L^F_{G,3}$
Positioning container	t_p
Hoisting spreader to the cellguides	$H^E_{G,1}$
No on-deck twistlocks are necessary, so they should be substracted	$-t_{odtl}$

7.1.2. Adjustments for concepts

The cycle calculations for the 7 concepts (and the dual hoist crane) are somewhat different compared to a conventional crane. In table 7.5 the cycle time assumptions compared to a conventional crane for all concepts are listed. Only 40 ft containers are considered. The dual hoist crane is included in the comparison as this puts the other concepts in more perspective.

Table 7.5: Cycle time calculations for different concepts. For each concept, the differences compared to the cycle calculations of a conventional crane are explained.

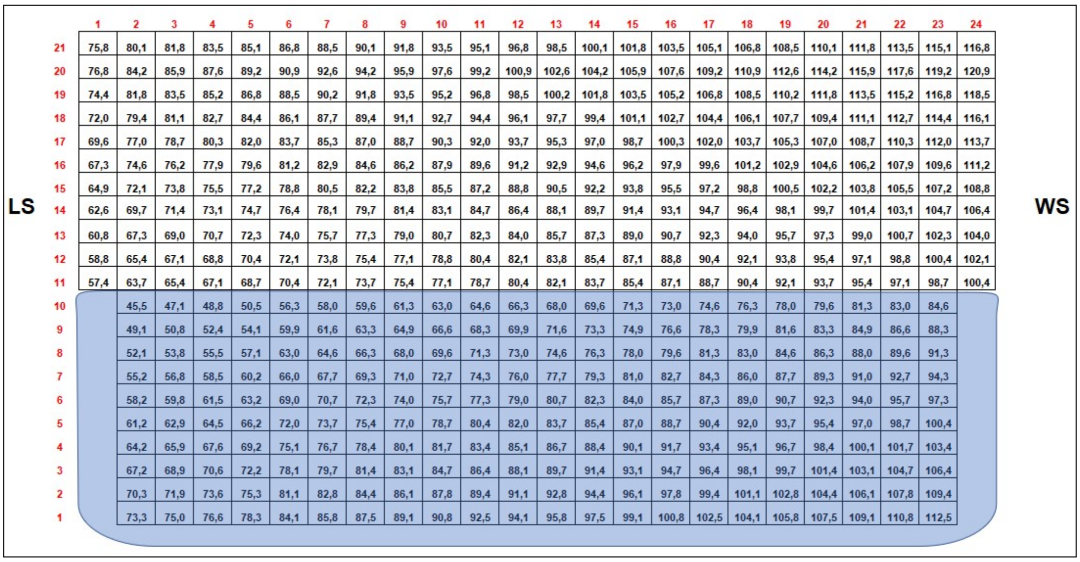
Concept	**Cycle time calculation approach**
Dual hoist crane	All cycle times are divided by 2, but for every container a 10 second penalty is added to imitate the more complex operator control and heavier trolley.
Concept 1 	One trolley serves the first half of the ship, while the other trolley serves the other half of the ship. As the LS trolley should wait for the WS trolley, the cycle times for the left half of the ship are considered the same as for the right half of the ship. However, per cycle an extra 20 seconds is added (so 10 seconds per container) to mimic the extra time necessary for the coordination between the trolleys.
Concept 2 	Before the trolleys can pass each other, one of the trolleys should hoist the load (or empty spreader) to the highest position. The trolleys pass each other above the quay side of the ship. For each container position the cycle time of the slowest trolley is taken, because every cycle one trolley has to wait until the other trolley is finished.
Concept 3 	The same as for concept 2, because rotating the container can be done during hoisting.
Concept 4 	The cycle is divided into three steps: the WS trolley, transfer vehicle and WS trolley. The slowest step is taken for each container position. To transfer containers to or from the transfer vehicle, the spreader should be in the highest position. The transfer vehicle has the same travelling speed as a normal trolley.
Concept 5 	The same as for concept 4, but now the capacity of the transfer vehicles is almost twice as high.
Concept 6 	The same as for concept 4, but now the capacity of the transfer vehicles is twice as high. Also, for the upper transfer vehicle the spreader should be hoisted higher before containers can be transferred to or from the transfer vehicle.
Concept 7 	First the trolley picks up two containers from the ship and hoists to the highest position to transfer the container to a transfer cart. Subsequently, a third container is picked up by the trolley which drives to the quay to drop off the container. Next, the transfer vehicles are unloaded by the trolley. To do so, the spreader is hoisted to the highest position, and back to the quay.

7.1.3. Productivity

The maximum speeds and accelerations as listed table 7.6 are used. These speeds and accelerations, in combination with the approach listed in table 7.5, result in cycle times for every container position on the ship. In figure 7.3 an example of cycle times for each container position can be seen. These cycle times are the average of loading full containers, unloading full containers, loading empty containers, and unloading empty containers. For the productivity calculation, the average cycle time of all container position containers on the ship is taken.
Table 7.7 shows the productivity of all concepts. All containers are assumed to be 40 foot containers.

Table 7.6: Speeds and accelerations used in the cycle time calculations.

Description	Speed		Acceleration	
Hoisting empty spreader or empty container	3	m/s	0.8	m/s^2
Hoisting full load spreader	1.5	m/s	0.6	m/s^2
Lowering empty spreader or empty container	3	m/s	1.5	m/s^2
Lowering full load spreader	1.5	m/s	1.125	m/s^2
Hoisting empty spreader or empty container in cellguide	2.4	m/s	0.64	m/s^2
Lowering empty spreader or empty container in cellguide	2.4	m/s	1.2	m/s^2
Hoisting full load spreader in cellguide	1.2	m/s	0.48	m/s^2
Lowering full load spreader in cellguide	1.2	m/s	0.9	m/s^2
Trolley travelling	3	m/s	0.8	m/s^2
Transfer vehicle travelling	3	m/s	0.8	m/s^2



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
21	75,8	80,1	81,8	83,5	85,1	86,8	88,5	90,1	91,8	93,5	95,1	96,8	98,5	100,1	101,8	103,5	105,1	106,8	108,5	110,1	111,8	113,5	115,1	116,8
20	76,8	84,2	85,9	87,6	89,2	90,9	92,6	94,2	95,9	97,6	99,2	100,9	102,6	104,2	105,9	107,6	109,2	110,9	112,6	114,2	115,9	117,6	119,2	120,9
19	74,4	81,8	83,5	85,2	86,8	88,5	90,2	91,8	93,5	95,2	96,8	98,5	100,2	101,8	103,5	105,2	106,8	108,5	110,2	111,8	113,5	115,2	116,8	118,5
18	72,0	79,4	81,1	82,7	84,4	86,1	87,7	89,4	91,1	92,7	94,4	96,1	97,7	99,4	101,1	102,7	104,4	106,1	107,7	109,4	111,1	112,7	114,4	116,1
17	69,6	77,0	78,7	80,3	82,0	83,7	85,3	87,0	88,7	90,3	92,0	93,7	95,3	97,0	98,7	100,3	102,0	103,7	105,3	107,0	108,7	110,3	112,0	113,7
16	67,3	74,6	76,2	77,9	79,6	81,2	82,9	84,6	86,2	87,9	89,6	91,2	92,9	94,6	96,2	97,9	99,6	101,2	102,9	104,6	106,2	107,9	109,6	111,2
15	64,9	72,1	73,8	75,5	77,2	78,8	80,5	82,2	83,8	85,5	87,2	88,8	90,5	92,2	93,8	95,5	97,2	98,8	100,5	102,2	103,8	105,5	107,2	108,8
14	62,6	69,7	71,4	73,1	74,7	76,4	78,1	79,7	81,4	83,1	84,7	86,4	88,1	89,7	91,4	93,1	94,7	96,4	98,1	99,7	101,4	103,1	104,7	106,4
13	60,8	67,3	69,0	70,7	72,3	74,0	75,7	77,3	79,0	80,7	82,3	84,0	85,7	87,3	89,0	90,7	92,3	94,0	95,7	97,3	99,0	100,7	102,3	104,0
12	58,8	65,4	67,1	68,8	70,4	72,1	73,8	75,4	77,1	78,8	80,4	82,1	83,8	85,4	87,1	88,8	90,4	92,1	93,8	95,4	97,1	98,8	100,4	102,1
11	57,4	63,7	65,4	67,1	68,7	70,4	72,1	73,7	75,4	77,1	78,7	80,4	82,1	83,7	85,4	87,1	88,7	90,4	92,1	93,7	95,4	97,1	98,7	100,4
10		45,5	47,1	48,8	50,5	56,3	58,0	59,6	61,3	63,0	64,6	66,3	68,0	69,6	71,3	73,0	74,6	76,3	78,0	79,6	81,3	83,0	84,6	
9		49,1	50,8	52,4	54,1	59,9	61,6	63,3	64,9	66,6	68,3	69,9	71,6	73,3	74,9	76,6	78,3	79,9	81,6	83,3	84,9	86,6	88,3	
8		52,1	53,8	55,5	57,1	63,0	64,6	66,3	68,0	69,6	71,3	73,0	74,6	76,3	78,0	79,6	81,3	83,0	84,6	86,3	88,0	89,6	91,3	
7		55,2	56,8	58,5	60,2	66,0	67,7	69,3	71,0	72,7	74,3	76,0	77,7	79,3	81,0	82,7	84,3	86,0	87,7	89,3	91,0	92,7	94,3	
6		58,2	59,8	61,5	63,2	69,0	70,7	72,3	74,0	75,7	77,3	79,0	80,7	82,3	84,0	85,7	87,3	89,0	90,7	92,3	94,0	95,7	97,3	
5		61,2	62,9	64,5	66,2	72,0	73,7	75,4	77,0	78,7	80,4	82,0	83,7	85,4	87,0	88,7	90,4	92,0	93,7	95,4	97,0	98,7	100,4	
4		64,2	65,9	67,6	69,2	75,1	76,7	78,4	80,1	81,7	83,4	85,1	86,7	88,4	90,1	91,7	93,4	95,1	96,7	98,4	100,1	101,7	103,4	
3		67,2	68,9	70,6	72,2	78,1	79,7	81,4	83,1	84,7	86,4	88,1	89,7	91,4	93,1	94,7	96,4	98,1	99,7	101,4	103,1	104,7	106,4	
2		70,3	71,9	73,6	75,3	81,1	82,8	84,4	86,1	87,8	89,4	91,1	92,8	94,4	96,1	97,8	99,4	101,1	102,8	104,4	106,1	107,8	109,4	
1		73,3	75,0	76,6	78,3	84,1	85,8	87,5	89,1	90,8	92,5	94,1	95,8	97,5	99,1	100,8	102,5	104,1	105,8	107,5	109,1	110,8	112,5	

Figure 7.3: Cycle times for each position on a container ship. In the figure, the average cycle times for loading full containers, loading empty containers, unloading full containers, and unloading empty containers of a conventional STS crane are shown. The red numbers indicate the container position on the ship.

Table 7.7: Productivity of each concept, based on the cycle calculations.

Concept	Productivity	
Conventional crane	41.6	Containers per hour
Dual hoist	67.0	Containers per hour
Concept 1	61.5	Containers per hour
Concept 2	60.7	Containers per hour
Concept 3	60.7	Containers per hour
Concept 4	47.6	Containers per hour
Concept 5	47.5	Containers per hour
Concept 6	46.4	Containers per hour
Concept 7	32.2	Containers per hour

Although the dual hoist crane has a theoretical high productivity, in practice this productivity is barely achieved. Often, the percentage of tandem lift operations is below 20% [2] [1]. This is due to the dependency on for instance the ship model and stacking plan of the ship.

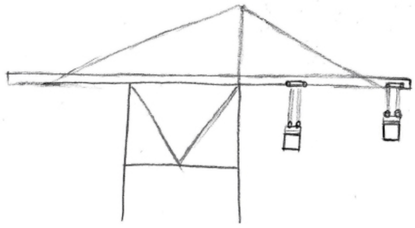
7.2. Concept properties summary

Besides the cycle time calculations, also the weight, load moment and initial costs were compared between all concepts. These comparisons can be seen in appendix D. In this section, for each concept the properties are summarized. In this comparison, all concepts are considered to be built on a new crane. The additional weight and costs compared to a conventional standard crane structure are roughly estimated. A standard crane structure is assumed to be the crane structure of a conventional crane, without any machinery for hoisting or trolley travelling. In other words: all components that can differ per concept are not present on the standard crane structure. Also the conventional crane and the dual hoist crane are part of the comparison, so that the extra components of each concept can be put into perspective. Although the concepts are considered to be built on a new crane in this comparison, "existing crane adjustability" is still one of the objectives.

Characteristic	**Conventional crane**	**Dual hoist crane**
Productivity	41.1 containers per hour	67.0 containers per hour
Additional weight on top of conventional crane structure	95 tons	300 tons
Load moment	83 MNm	159 MNm
Additional costs on top of conventional crane structure	€1,650,000.-	€3,285,000.-

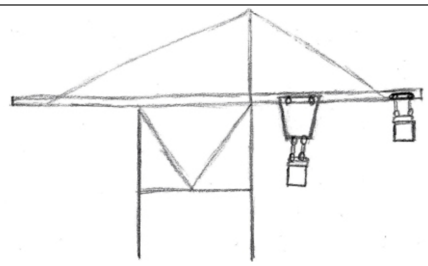
Table 7.8: Summary of the most important properties of conventional and dual hoist cranes.

Table 7.9: Concept 1 properties



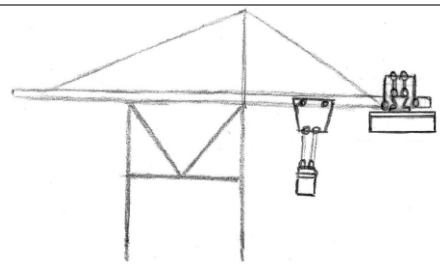
Objective	Properties
Productivity	61.5 containers per hour
Existing crane adjustability	• Additional trolley required. • Additional drives (and wire ropes) for hoisting via the additional trolley, and for travelling of the additional trolley, should be installed. • The wire rope reeving running to the two trolleys can obstruct each other. This must be solved by redesigning (one of) the trolleys, or redesigning the wire rope reeving. • Power supply to the additional trolley needs to be installed.
Terminal process compatibility	• Additional weight to crane structure of 325 tons • Maximum load moment of 128 MNm (instead of 83 MNm for conventional crane). In case the LS may only lift 40 ft containers, this can be decreased to 114 MNm. If necessary, this can be further decreased by using only one trolley in case of exceptional high loads. • Unloads up to 4 TEU simultaneously on the quay. Wharf capacity needs to cope with this. Also, the terminal process must be able to deliver 2 container simultaneously when loading a ship.
Additional costs on top of conventional crane structure	€3,705,000.-
Operation reliability	Has 1 more trolley that can fail. However, the crane can still operate with only one trolley.
Operating costs	One more operator is required. One operator is also possible in case of remote control, but this decreases the productivity. More maintenance due to extra trolley.
Commercial opportunities	This concept does not exist in practice, and needs an engineering firm to fit the second trolley on the same rails, including all cable reeving and drives. Some patents that are not in force are found. This means this concept can be used, but not patented.

Table 7.10: Concept 2 properties



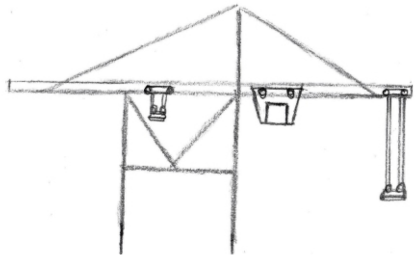
Objective	**Properties**
Productivity	60.7 containers per hour . This concept can simultaneously load and unload containers.
Existing crane adjustability	• Additional specialized trolley is required. This trolley is installed below the conventional trolley. Therefore its shape should allow the upper trolley to pass while carrying a container. • Additional rails should be installed on the outside of the boom girders, on which the lower trolley can drive. • The crane should be elevated with approximately 7.5 meters, to allow the lower trolley to serve high container rows on the ship. As an alternative, the lower trolley cannot serve the highest container layers on the ship. In this case, it will not be necessary to adjust the height of the crane. • Additional drives for hoisting via the lower trolley and for trolley travelling should be installed. • Wire rope reeving of the lower trolley should be installed in such way that obstructing the upper trolley is prevented. • Power supply to the additional trolley needs to be installed.
Terminal process compatibility	• Additional weight to crane structure of 405 tons • Maximum load moment of 100 MNm (instead of 83MNm for conventional crane). • Wharf capacity needs to cope with increased productivity.
Additional costs on top of conventional crane structure	€4,285,000.-
Operation reliability	Has 1 more trolley that can fail. However, the crane can still operate with only one trolley.
Operating costs	One more operator is required. One operator is also possible in case of remote control, but this decreases the productivity. More maintenance due to extra trolley. Remote control will be beneficial, as cabins are hard to fit in the design.
Commercial opportunities	Patents of this working principle are found, but these are older than 20 years. This means the concept can be applied by Iv-Consult. An engineering firm will be required to successfully design and install the extra rails and lower trolley, including the hoisting and travel mechanism.

Table 7.11: Concept 3 properties



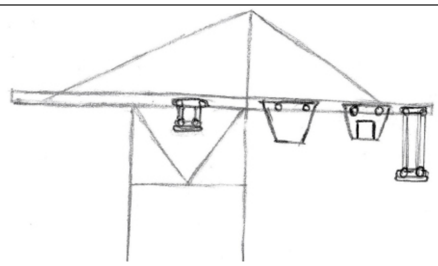
Objective	Properties
Productivity	60.7 containers per hour . This concept can be used to simultaneously load and unload containers.
Existing crane adjustability	• Two trolleys need to be designed. The upper trolley should be able to (partly) hoist a container in between the girders of a twin girder boom. The lower trolley should be adjusted in such way that allows the upper trolley to pass while carrying a container. • Rotating headblock or spreader is necessary. • Wire rope reeving of the lower trolley should be adjusted to prevent obstructing the upper trolley while hoisting or lowering. • Additional rails should be installed on the inside of the boom. • The crane should be elevated with approximately 4 meters, to allow the lower trolley to serve high container rows on the ship. As an alternative, the lower trolley cannot serve the highest container layers on the ship. In this case, it will not be necessary to adjust the height of the crane. This concept needs less extra height than concept 2. • Additional drives for hoisting via the lower trolley and trolley travelling should be installed. • Power supply to the additional trolley needs to be installed. • Stiffener beams between the girders of the twin girder boom can prevent a successful implementation of this concept. • This concept can only be implemented on a twin girder boom crane.
Terminal process compatibility	• Additional weight to crane structure of 410 tons • Maximum load moment of 103 MNm • Wharf capacity needs to cope with increased productivity.
Additional costs on top of conventional crane structure	€4,420,000.-
Operation reliability	Has 1 more trolley and a rotating headblock that can fail. However, the crane can still operate with only one trolley.
Operating costs	One more operator is required. One operator is also possible in case of remote control, but this decreases the productivity. More maintenance due to extra trolley and rotating headblock. Remote control will be beneficial, as cabins are hard to fit in the design.
Commercial opportunities	Patents of this working principle are found, but these are older than 20 years. This means the concept can be applied by Iv-Consult. An engineering firm will be required to successfully design and install the trolleys and extra rails.

Table 7.12: Concept 4 properties



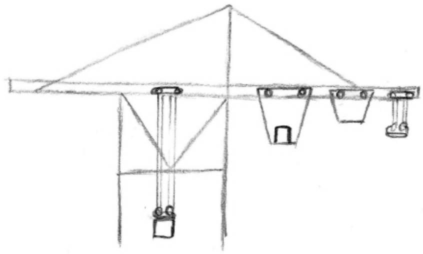
Objective	Properties
Productivity	47.6 containers per hour
Existing crane adjustability	• Additional trolley needs to be installed. This additional trolley should be adjusted to prevent obstructing the wire ropes running to the other trolley. • Transfer vehicle should be designed and installed. • Additional rails at the outside of the boom should be installed on which the transfer vehicle can drive. • Drives for hoisting and travelling of additional trolley, and for travelling of transfer vehicle need to be installed. • Power supply to the additional trolley and transfer vehicle should be installed.
Terminal process compatibility	• Additional weight to crane structure of 385 tons • Maximum load moment of 114 MNm • Wharf capacity needs to cope with increased productivity
Additional costs on top of conventional crane structure	€4,570,000.-
Operation reliability	Extra trolley and transfer vehicle can fail. However, the crane can also operate with just 1 trolley, or 1 trolley and transfer vehicle.
Operating costs	Extra operator needed for extra trolley. One operator is also possible, but this decreases the productivity. More maintenance due to extra trolley and transfer vehicle. Transfer vehicle should be automated.
Commercial opportunities	Patents of this working principle are found, but these are older than 20 years. This means the concept can be applied by Iv-Consult. An engineering firm will be required to successfully design and install the extra trolley and transfer vehicle.

Table 7.13: Concept 5 properties



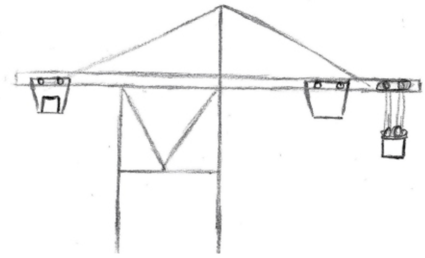
Objective	**Properties**
Productivity gain	47.5 containers per hour
Existing crane adjustability	• Additional trolley needs to be installed. This additional trolley should be adjusted to prevent obstructing the wire ropes running to the other trolley. • Two transfer vehicles should be designed and installed. The upper transfer vehicle has a movable bottom. • Two sets of additional rails at the outside of the boom should be installed on which the transfer vehicles can drive. • Drives for hoisting and travelling of additional trolley, and for travelling of transfer vehicles and the hoisting of the movable bottom need to be installed. • Power supply to the additional trolley and transfer vehicles should be installed.
Terminal process compatibility	• Additional weight to crane structure of 445 tons • Maximum load moment of 119 MNm • Wharf capacity needs to cope with the increased productivity
Additional costs on top of conventional crane structure	€5,495,000.-
Operation reliability	Extra trolley and 2 extra transfer vehicles that can fail. However, the crane can also operate with only 1 trolley.
Operating costs	Extra operator needed for extra trolley. One operator is also possible, but this decreases the productivity. The transfer vehicles should be automated. There will be more maintenance due to the extra trolley and transfer vehicles.
Commercial opportunities	No patents of a transfer vehicle with a movable bottom have been found. Patents of normal transfer vehicles are found, but these are older than 20 years. This means the concept can be applied by Iv-Consult. An engineering firm will be required to successfully design and install the extra trolley and transfer vehicles.

Table 7.14: Concept 6 properties



Objective	Properties
Productivity gain	46.4 containers per hour . This concept can be used to simultaneously load and unload containers.
Existing crane adjustability	• Additional trolley needs to be installed. This additional trolley should be adjusted to prevent obstructing the wire ropes running to the other trolley. • Two transfer vehicles should be designed and installed. The lower transfer vehicle is positioned underneath the other, in such way that the upper transfer vehicle can pass while the lower trolley is carrying a container. • Two sets of additional rails at the outside of the boom should be installed on which the transfer vehicles can drive. • Drives for hoisting and travelling of additional trolley, and for travelling of transfer vehicles need to be installed. • Power supply to the additional trolley should be installed. • The crane should be elevated with approximately 5 meters, to allow the lower transfer cart to drive above high container layers on the ship. As an alternative, the lower transfer vehicle cannot be used when serving the highest container layers on the ship. In this case, it will not be necessary to adjust the height of the crane.
Terminal process compatibility	• Additional weight to crane structure of 500 tons • Maximum load moment of 121 MNm • Wharf capacity needs to cope with the increased productivity
Additional costs on top of conventional crane structure	€5,720,000.-
Operation reliability	Extra trolley, and 2 extra transfer vehicles that can fail. However, the crane can operate with only 1 trolley.
Operating costs	Extra operator needed for extra trolley. One operator is also possible, but this decreases the productivity. The transfer vehicles should be automated. There will be more maintenance due to the extra trolley and transfer vehicles.
Commercial opportunities	Patents of this working principle are found, but these are older than 20 years. This means the concept can be applied by Iv-Consult. An engineering firm will be required to successfully design and install the extra trolley and transfer vehicles.

Table 7.15: Concept 7 properties



Objective	Properties
Productivity gain	32.2 containers per hour .
Existing crane adjustability	• Two transfer vehicles should be installed, of which one is located below the other in such way that they can pass when the lower vehicle does not carry a container. • Two additional pairs of rails should be installed at the outside of the boom on which the transfer vehicles can drive. • Drives for the transfer vehicle travelling should be installed.
Terminal process compatibility	• Additional weight to crane structure of 335 tons • Maximum load moment of 133 MNm • The container throughput is not constant. Multiple containers are loaded or unloaded consecutively. While on other moments there is no container unloaded at all. The wharf process needs to cope with this.
Additional costs on top of conventional crane structure	€3,740,000.-
Operation reliability	Two extra transfer vehicles that can fail. However, the crane only needs the trolley to be able to operate.
Operating costs	Just one operator necessary. The transfer vehicles should be automated. There will be more maintenance due to the extra transfer vehicles.
Commercial opportunities	The transfer vehicles are seen in other patents. However, the operation method of this concept is not found in any patents. An engineering firm will be required to successfully design and install the transfer vehicles.

7.3. Concept selection

A concept assessment form is formed to judge every concept based on the objectives (see Appendix D). Based on the cycle calculations (see section 7.1), concept 5, 6 and 7 are excluded. Concept 7 has a lower productivity than a conventional crane. Concept 5 and 6 have the same productivity as concept 4, even though they are more complicated. For this reason, the concept assessment form includes only the first 4 concepts. Each participant had to give a score from 0 to 10 for each objective. Also, each participant had to score the importance of each objective. The concept assessment form is filled in by the author and mechanical engineer J.C. Rietveld of Iv-Consult. Table 7.16 shows the averaged scores of the assessment form. Concept 1 received the highest score of all concepts. In consultation with Iv-Consult, concept 1 is chosen. In Appendix D.5, all existing patents related to the chosen concept are addressed.

Table 7.16: Concept selection. Average scores of the assessment form.

Objective	Concept 1	Concept 2	Concept 3	Concept 4	Factor
Productivity	9.0	8.5	8.5	4.5	8.5
Existing crane adjustability	8.5	6.0	4.25	6.5	4.5
Terminal compatibility	7.0	8.0	7.0	6.0	5.5
Initial costs	9.0	5.75	5	6.9	6.0
Operation reliability	7.5	7.5	5.5	6.25	8.0
Operating costs	7.5	6.4	5.5	5.5	5.0
Commercial opportunities	6.75	7.75	7.0	7.5	4.0
Total score	**332**	**301**	**259**	**249**	

7.4. Concept 1 (dis)advantages

Now that concept 1 is chosen, for convenience the advantages and disadvantages compared to the existing solutions and other concepts are emphasized in the lists below.

Advantages:

- The productivity of concept 1 is 47% compared to a conventional crane. Although the theoretical maximum productivity of a dual hoist crane is still 9% higher, on average the productivity of concept 1 will turn out to be higher, assuming that both trolleys are employed for the majority of the operations.
- The ability to simultaneously transfer 4 TEU is less dependent on the stacking plan of the ship. As long as the LS trolley can serve containers on the LS half of the ship, while the WS trolley can serve containers on the WS half of the ship, 4 TEU can simultaneously be transferred.
- When only one trolley is used, the crane is still as efficient as a conventional crane.
- There is no need to switch between spreader configurations. Instead, either one or two trolleys are employed.
- In contrast to other concepts, concept 1 requires a relatively small adjustment compared to a conventional crane. This results in relatively low costs. Due to the analogy to a conventional crane, terminal operators will be less reluctant to implement the concept.
- When one trolley is out of service, the other trolley can still operate.

Disadvantages:

- The operation of concept 1 might be more complicated, as two trolleys need to be simultaneously operated. This could result in the necessity of a second operator. However, as a result of the increasing automation of STS container cranes, it is realistic to assume that only one operator is required in the future.
- Having two trolleys on the same rails could result in dangerous operations. To ensure safe operations, the trolleys should stay sufficiently apart from each other.
- Often the LS trolley needs to wait for the WS trolley, as the WS trolley needs to travel longer distances.

8
Concept design

Concept 1 will be further elaborated. In theory, this concept can be implemented on an existing crane. However, this comes with additional constraints. In consultation with Iv-Consult it is decided that during the design the crane structure can be considered a custom made crane structure. This means that the exact boom and trolley dimensions can be chosen freely. In figure 8.1 an impression of the end result of the concept design can be seen. The LS trolley (in red) is called trolley A. WS LS trolley (in blue) is called trolley B.

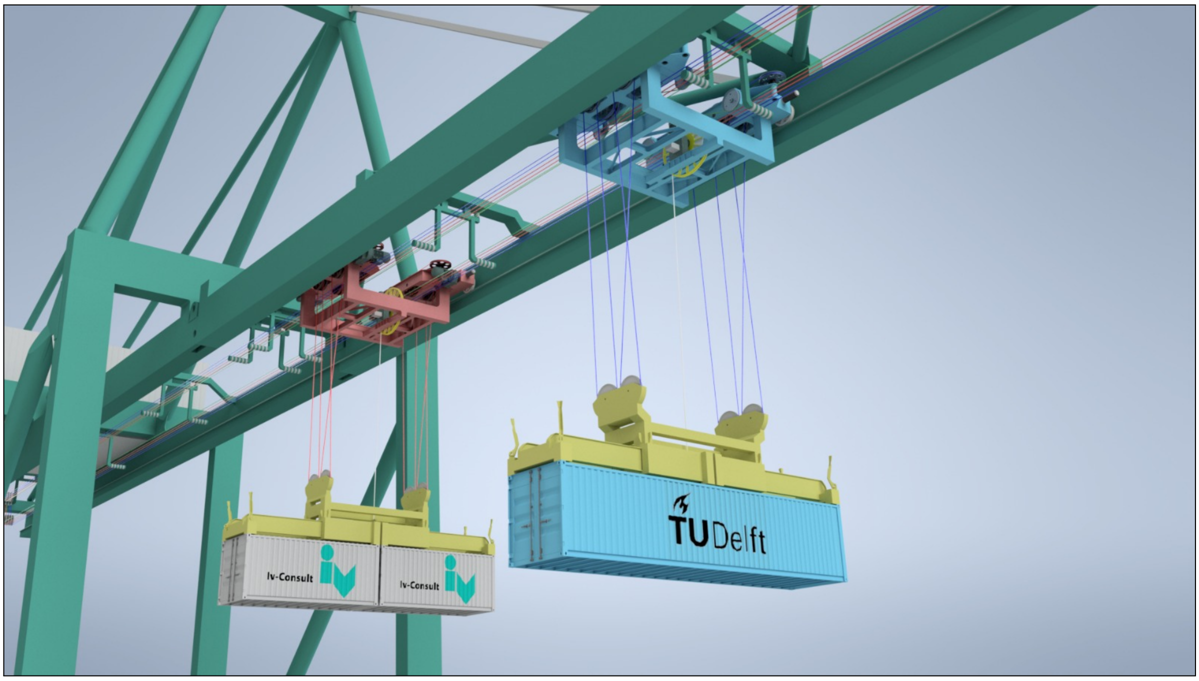


Figure 8.1: STS crane with two main trolleys. The left (red) trolley is trolley A. On the right is trolley B (in blue).

Both trolleys are based on an existing trolley. Although there are plenty of differences, it can clearly be seen that figure 8.2, 8.3, and 8.4 are alike. In table 8.1 the most important differences between the original trolley, trolley A, and trolley B are listed.

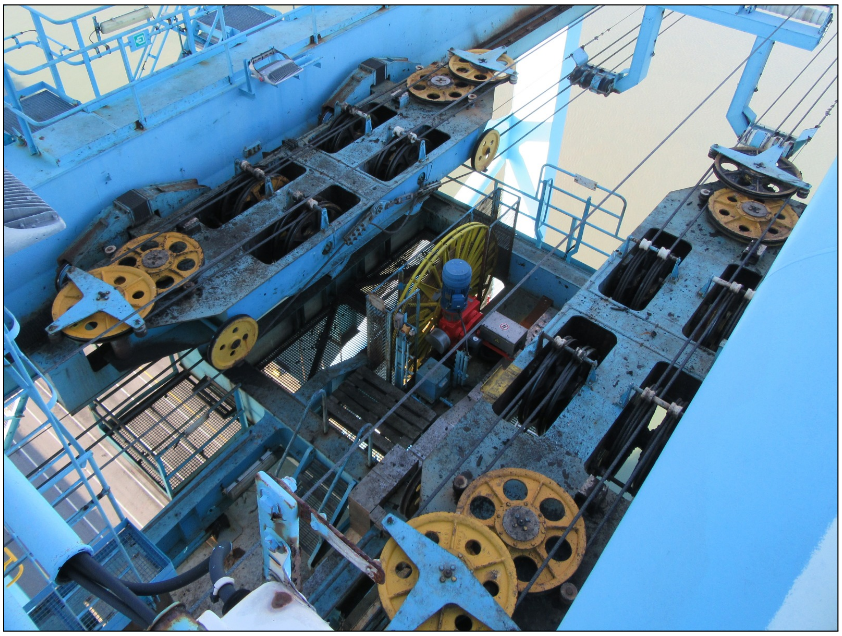


Figure 8.2: Photo of trolley with continuous rope support. Photo is made by the author.

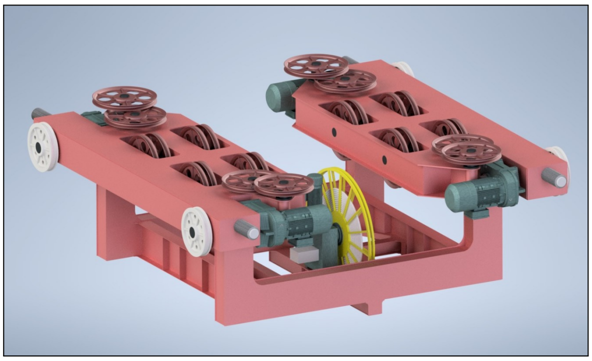


Figure 8.3: Trolley A

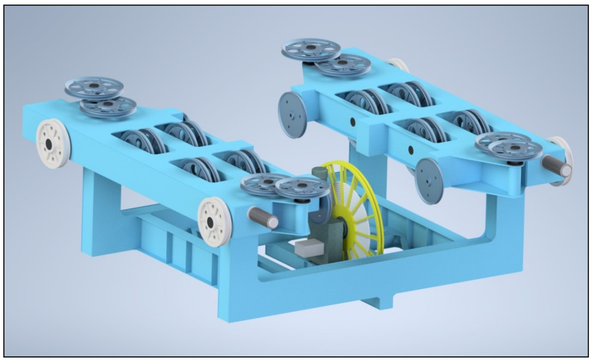


Figure 8.4: Trolley B

Table 8.1: Differences between the original, existing trolley and trolley A and Trolley B.

Original trolley	**Trolley A**	**Trolley B**
8 wheels	4 wheels	4 wheels
Rope towed	Directly driven	Rope towed
Cabin	No cabin	No cabin
"Normal" turning sheaves	Slightly larger sheaves*	Slightly smaller sheaves*
"Normal" sheave position	Sheaves positioned more compact*	Sheaves positioned more outwards*
Buffers on both sides	Buffers on both sides	Buffers on WS
37 tons	38 tons	33 tons

*See figure 8.7

During the concept design, various design decisions were made. In the following sections, the reasoning behind these decisions will be elaborated.

8.1. Trolley types

First of all, the trolley types for the new concept should be chosen. As explained in section 2.1, there are three types of trolleys: rope towed trolley (RTT), Machinery trolley (MOT), and semi rope trolley. The simplest way to have two trolleys on the same rails is by installing two machinery trolleys. Besides the power supply, this does not require any ropes to run to the trolleys. However, a machinery trolley is very heavy. As adding an extra trolley to the crane already has an impact on the crane structure, it is not beneficial to have machinery trolleys. Therefore a RTT or semi rope trolley is more desirable.

Having two rope towed trolleys can also be problematic. This would mean that two trolley travel mechanisms and two hoisting mechanisms should be placed in the machinery house. This would require a large machinery house. However, by having one rope towed trolley and one semi rope trolley, only one trolley travel mechanism and two hoisting mechanisms should be placed in the machinery house. This is exactly the same configuration as is the case for dual hoist cranes (see section 2.3). The disadvantage of semi rope trolleys is that the acceleration is limited by wheel slip. However, in this concept trolley A can be somewhat slower than trolley B. If both trolleys have the same maximum acceleration and speed, trolley A would have to wait for trolley B. For the reasons mentioned above, one rope towed trolley and one semi rope trolley is chosen. Trolley A (LS trolley) will be semi rope trolley, while trolley B (WS trolley) will be a rope towed trolley.

Another choice regarding the trolleys is whether a cabin will be installed for the operator. In this case, there will be no cabin on the trolleys. The concept will be remote controlled. First if all, this makes the trolleys lighter, which is beneficial for the crane structure. Second, by remotely controlling the crane both trolleys could potentially be operated by a single (experienced) operator. In case two operators are required, it is beneficial to sit in the same office, instead of separate cabins.

8.2. Rope support system

As explained in section 2.1.6, the wire ropes can either be supported by catenary trolleys or a continuous rope support system. When designing an STS crane with two trolleys, the continuous rope support would be a more logical option. In case of a conventional crane with catenary trolleys, the cables are supported on both sides of the main trolley by a catenary trolley. In the new concept, this would mean that three catenary trolleys are required. As a result, the rope support system will become more complicated. A conventional crane with a continuous rope support system does not require any additional components when it is extended by adding another main trolley. The support rollers of a system with two trolleys require only a slight adjustment compared to a conventional crane. For this reason, a continuous wire rope support system will be chosen for the new concept. This rope support system requires the boom and trolley girder to be of the twin box type.

In figure 8.5 the cable support as implemented in the concept can clearly be seen. The wire ropes in the figure are the hoisting wire ropes of both trolleys, and the trolley travel wire ropes wire ropes of trolley B. Despite these extra wire ropes, the continuous rope support system is still easily applicable.

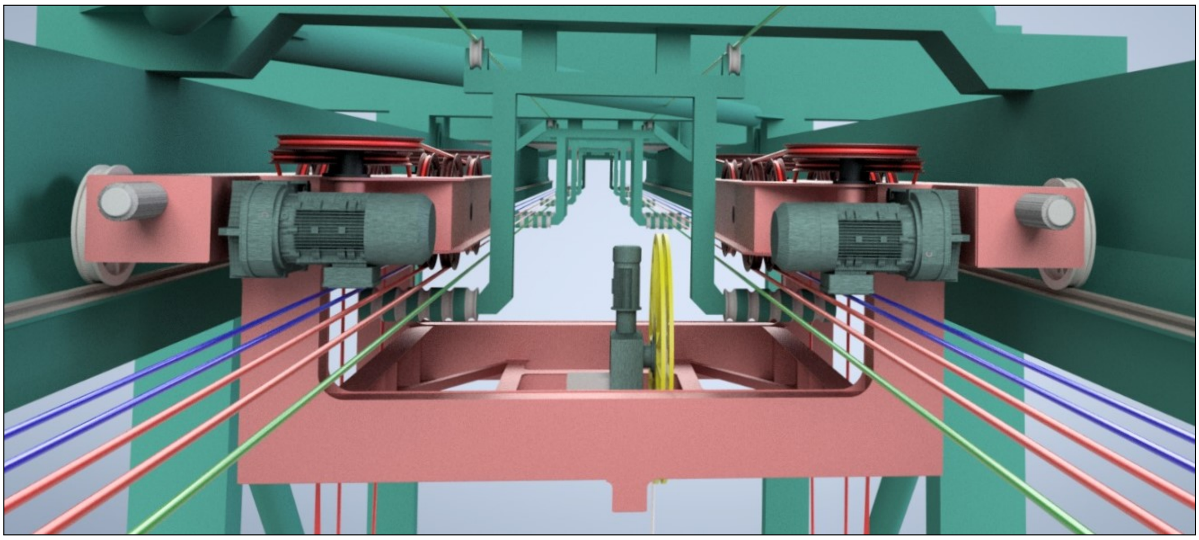


Figure 8.5: Rope support system. Trolley A is shown in the figure. In reality, the wire ropes would hang on the cable supports.

8.3. Reeving system

The wire rope reeving becomes more complicated by having an extra trolley on the crane. The cables of both trolleys are not allowed to interfere with one another. For the combination of a rope towed trolley and a semi rope trolley, this results in two sets of hoisting cables and 1 set of towing cables. To fit these all together, the cable reeving becomes more complex compared to a conventional crane. This is shown in figure 8.6, where the frames of both trolleys are not visible.

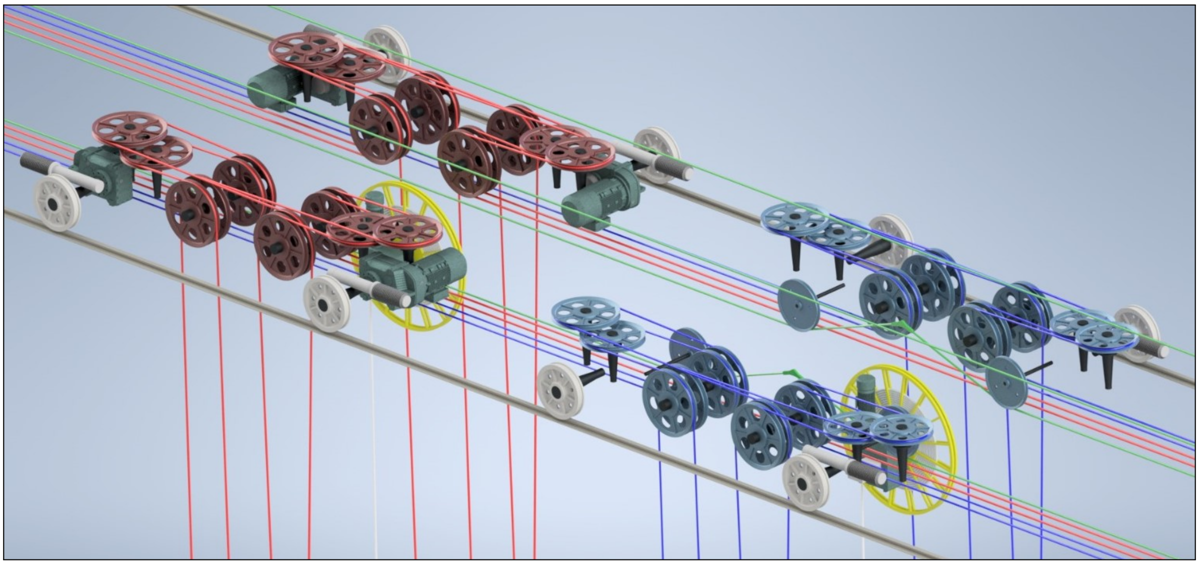


Figure 8.6: Both trolleys without trolley frame. Trolley A is left, trolley B is right. The red cables are the hoisting cables of trolley A. The blue cables are the hoisting cables of trolley B. The green cables are the towing cables of trolley B.

In figure 8.7 a top view of the two trolleys is given. The red and blue cables are the hoisting wire ropes of the crane. All red cables run to trolley A (also in red), while all blue cables run to trolley B (also in blue). The green cables are the trolley towing ropes of trolley B. In the figure it can be seen that many wire ropes are located in the same area. For the cables to be positioned adjacently on the wire rope support, they all need to be connected to the trolley at a different position. This is clearly depicted in figure 8.7, where the sheaves of trolley A are positioned more compact than the sheaves of trolley B. Also the size of the horizontally positioned sheaves on both trolleys influence the position of the hoisting cables. The horizontal sheaves of trolley A are somewhat larger in diameter compared to the horizontal sheaves of trolley B.

The wire ropes are located in such way that they run approximately vertically towards the headblock sheaves, see figure 8.8. In the figure it is evident that the distance between the headblock sheaves differs for both trolleys. Trolley B is connected to a headblock with the maximum distance between the headblock sheaves, while trolley A is connected to a headblock with a smaller distance between the headblock sheaves. The difference in headblock sheave distance is beneficial for the positioning of the cables. Figure 8.9 shows how the cables run from the trolleys towards the headblocks.

The reeving system as explicated above influences the diameters of the sheaves. In figure 8.10 all trolley sheaves are numbered. In table 8.2 all diameters are listed for both trolleys.

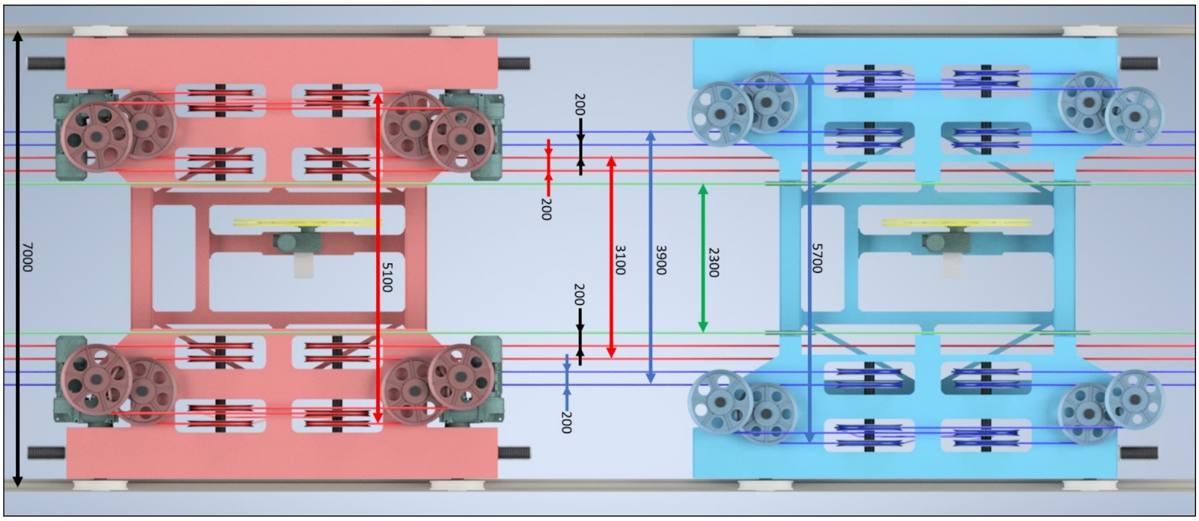


Figure 8.7: Top view of both trolleys. Trolley A has the red wire ropes. Trolley B has the blue wire ropes. The green wire rope is the trolley travel cable of trolley B. The LS is left in the figure, the WS is right in the figure. All dimensions are in mm.

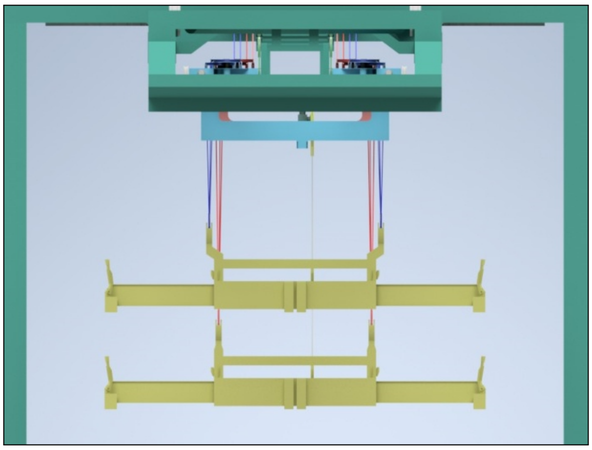


Figure 8.8: Front view of the trolleys, headblocks and spreaders.

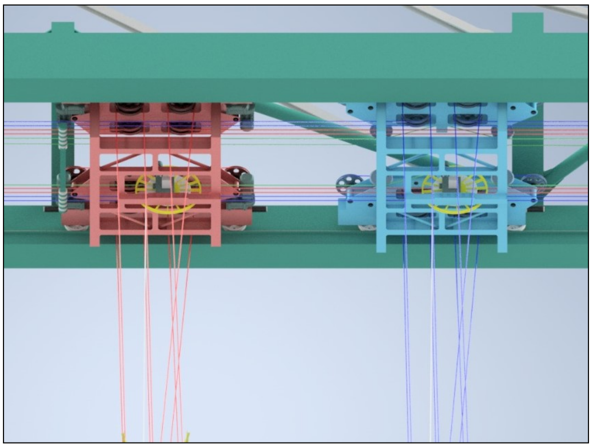


Figure 8.9: Hoisting cables running from the trolleys towards the headblocks.

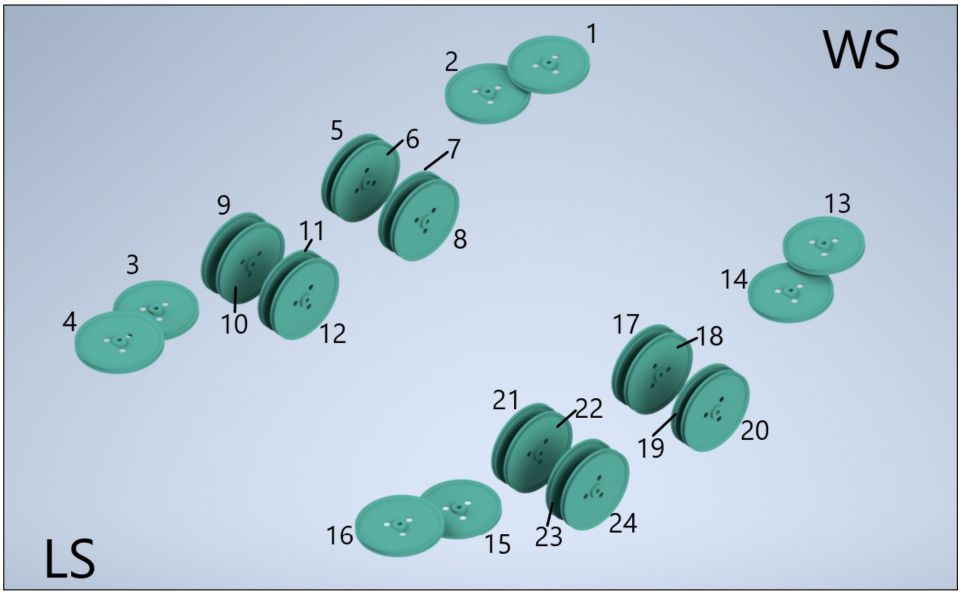


Figure 8.10: Overview of trolley sheaves of hoisting reeving system. Both trolleys have the same configuration of sheaves, although the size and position can differ.

Table 8.2: Heart to heart diameters of sheaves. The sheave numbers refer to figure 8.10

Sheave number	**Trolley A**	**Trolley B**
1	960 mm	860 mm
2, 3	1000 mm	900 mm
4	1040 mm	940 mm
5, 6, 7, 8, 9, 10, 11, 12, 17, 18, 19, 20, 21, 22, 23, 24	960 mm	960 mm
13	960 mm	860 mm
14, 15	1000 mm	900 mm
16	1040 mm	940 mm

In table 8.3 the wire ropes for both trolley A and B are listed. Figure 8.11 and 8.12 show the wire rope types of trolley A and B, respectively. The proof of static and fatigue strength of the hoisting cables according to the EN 13001-3-2 standard is documented in appendix E. In practice, trolley B will probably be used more often, because most likely the LS trolley will not be used in cases when only 1 trolley is used. On top of that, trolley A has larger sheaves than trolley B. As a result, the wire ropes of trolley A would normally last longer than the wire ropes of trolley B (see Appendix E for details). To compensate this, trolley A has a cheaper wire rope (that comes with a larger diameter).

Table 8.3: Wire rope characteristics.

Description	**Type**	**Diameter**	**Grade**	**Minimum breaking force**
Hoisting wire ropes trolley A	Steel Wire Rope 6x36WS-IWRC [42]	36 mm	1960 N/mm^2	904.0 kN
Hoisting wire ropes trolley B	Steel wire rope veropro 8 [42]	32 mm	1960 N/mm^2	922.9 kN
Trolley travel wire rope trolley B	Steel Wire Rope 6x36WS-IWRC	28 mm	1960 N/mm^2	547 kN

8.4. Motors, gearbox & brakes

Trolley A is directly driven. The motors and gearboxes should therefore be installed on the trolley itself. Before the exact configuration on the trolley can be determined, the required motor characteristics should be calculated. The motor power calculations are elaborated in Appendix G. All four wheels of trolley A of the trolley are directly driven by a gearmotor. The details are listed in table 8.4. The gearmotor is equipped with a DC-operated electromagnetic disk brake that is released electrically and applied using spring force. The trolley travel motor of trolley B is addressed in Appendix H.

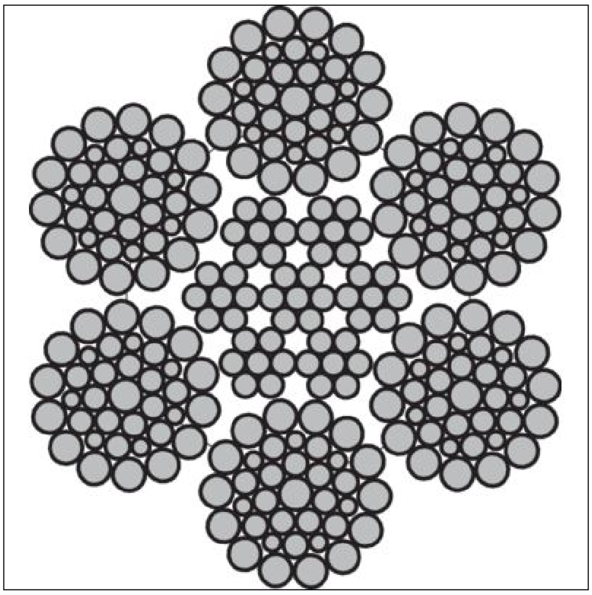


Figure 8.11: 6x36WS-IWRC wire rope. From [42]

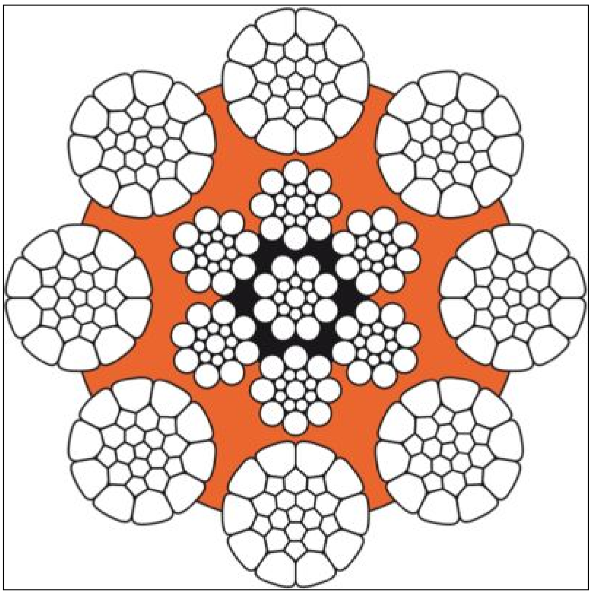


Figure 8.12: Veropro 8 wire rope. From [42]

Table 8.4: Gearmotor characteristics trolley A. From [43]

Name	FHZ157DRN280S4
Gearbox configuration	Parallel shaft
Motor power	75 kW
Rated motor speed	1482 rev/min
Overall gear ratio	22.16
Service factor	1.85
Hollow shaft	125 mm
Weight	1210 kg
Efficiency class	IE3
Built-in type	B14 flange-mounted design
Shaft connection	Hollow shaft with shrink disc
Surface protection	OS3
Brake type	BE brake
Brake torque	1000 Nm

Figure 8.13: FHZ157DRN280S4 gearmotor. From [43]

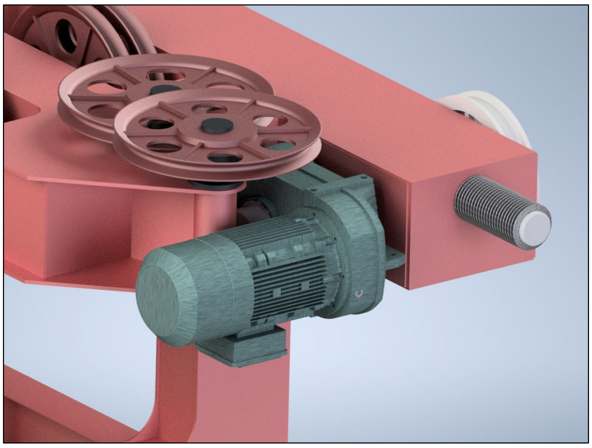


Figure 8.14: Gearmotor implemented in the trolley A frame. In all four corners of trolley A, a gearmotor is installed.

8.5. Rails and wheels

Trolley A has four wheels, as that is the simplest way to directly drive the wheels (result of a semi rope trolley). For convenience in terms of maintenance and design, also trolley B has four wheels. In table 8.5 the rails and wheels of both trolleys are specified. Figure 8.15 shows the dimensions of the rails. Figure 8.16, figure 8.17, and 8.6 show the wheels and their dimensions. In appendix F the calculations according to the EN 13001-3-3 standard are performed.

Table 8.5: Rail and wheels type and material.

Description	**Type**	**Material**	**Surface hardening**
Rails on boom and girder	A75 rails, according to DIN 536-1 [44]	R260Mn	No
Wheels trolley A	Crane wheel S 800 × 85 × 180 H7 DIN 15093 [45]	42CrMo4	Hardness of 285 N/mm^2 at 10.4 mm depth.
Wheels trolley B	Crane wheel S 800 × 85 × 180 H7 DIN 15093 [45]	42CrMo4	Hardness of 275 N/mm^2 at 10.2 mm depth.

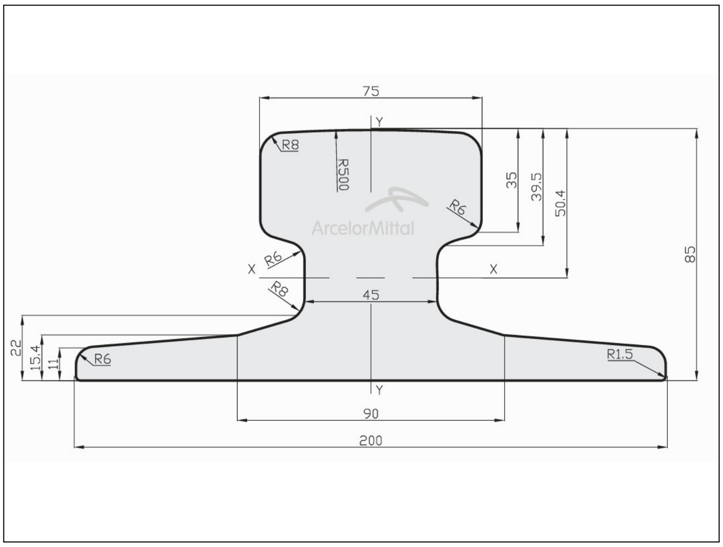


Figure 8.15: Drawing of A75 rails. From [44]

Figure 8.16: Narrow crane wheel according to DIN 15093. From [45]

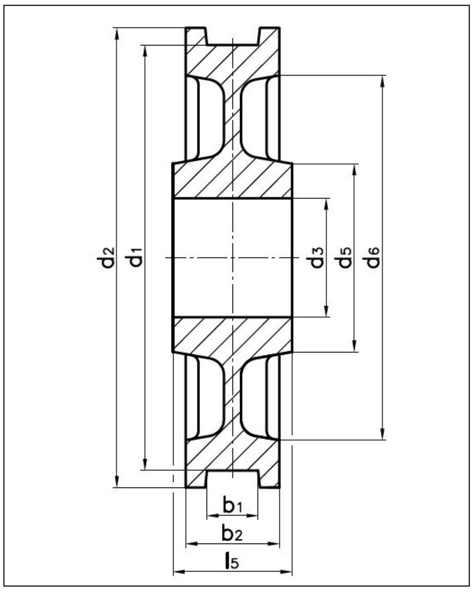


Figure 8.17: Narrow crane wheel drawing according to DIN 15093. From [45]

Table 8.6: Dimensions in figure 8.17 of trolley wheels of both trolley A and B.

d_1	800 mm
d_2	850 mm
d_3	180 mm
d_5	285 mm
d_6	710 mm
b_1	85 mm
b_2	140 mm
I_5	180 mm

8.6. Buffers

Both trolleys are equipped with gas-hydraulic buffers to limit the impact force when a collision occurs. Trolley A has buffers on both the LS and WS, while trolley B solely has buffers on the WS. Table 8.7 and figure 8.18 show the buffer specifications.

Table 8.7: Buffer specifications. From [46]

Name	Buffer PB 125
Stroke (see fig. 8.18)	500 mm
Energy/stroke	300 kJ
Max. buffer force	660 kN
Weight	148 kg
A (see fig. 8.18)	1550 mm
L (see fig. 8.18)	651 mm

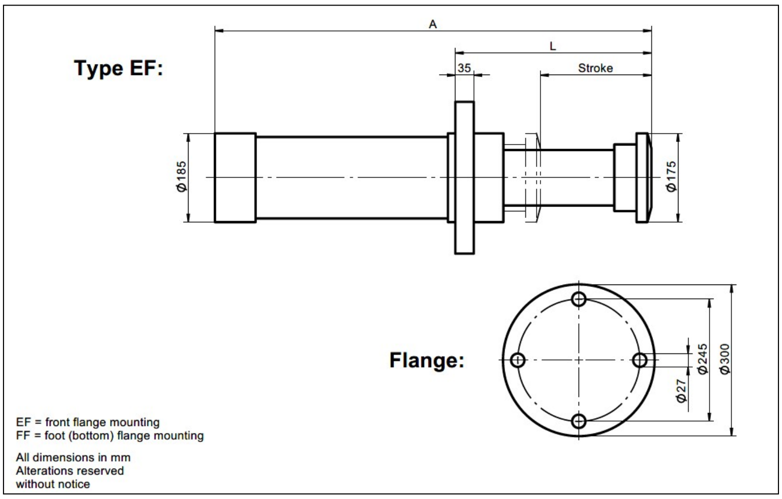


Figure 8.18: Buffer drawing. From [46]

8.7. Power supply

On both girders of the boom and trolley girder an energy chain is installed. Both trolleys have their own energy chain, which makes installing the energy chains identical to a conventional crane with an energy chain. Energy chains are already used frequently on STS cranes [47]. Trolley A needs a larger power supply than trolley B, as the trolley travel motors of trolley A need to be driven. As the energy chains are identical to the energy chain of a conventional crane, this is not further elaborated.

9

Trolley Frames FEA

As elaborated in chapter 8, the trolleys are based on an existing trolley. This is mainly due to the cable support system, that requires the trolley to have a shape that allows passing this support system. As a consequence, the trolley frames will be similar to the existing frame. Despite the similar shape, the trolleys of the new design have some differences compared to the existing trolley frame. For this reason, it should be proven that the adjusted trolleys can still deal with the forces that are exerted on them. Accordingly, the frame of both trolley A and B is verified by means of a finite element analysis. Ansys Mechanical 2021 R2 is used for the analysis. Both a proof of static strength and fatigue strength are performed, according to the EN13001 standard.

9.1. Plate model

A plate model of both trolleys is composed. Figure 9.1 and 9.2 show the frames of trolley A and B, respectively.

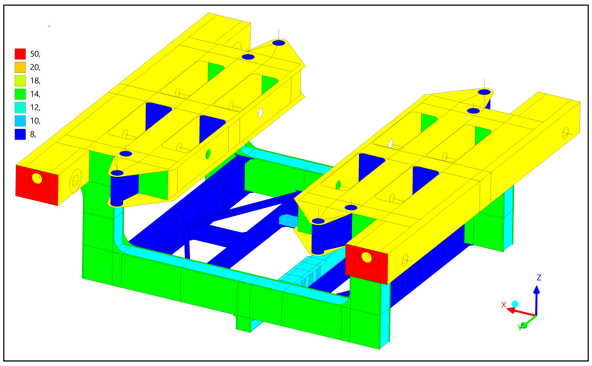


Figure 9.1: Plate model of trolley A. The colours indicate the plate thickness in mm.

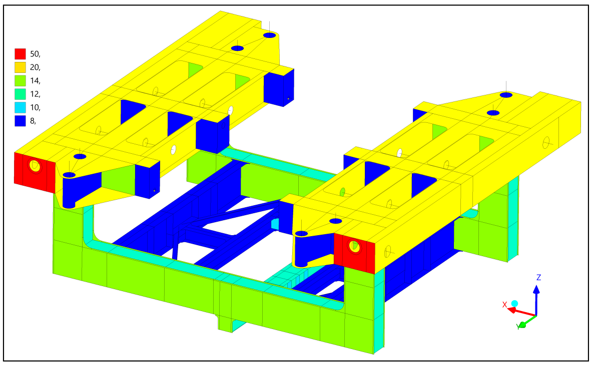


Figure 9.2: Plate model of trolley B. The colours indicate the plate thickness in mm.

9.2. Load combinations

In table 9.1 all relevant loads and load combinations for the proof of static strength are listed. The other loads and load combinations described in the EN13001-2 standard are not of interest for a trolley frame. For instance, wind forces are important when examining a crane structure, but will have a minor impact on the trolley frame. In appendix I the factors ϕ_i of table 9.1 will be derived.

Table 9.1: Relevant loads and load combinations for the proof of static strength the trolley frames. This table is an adjusted version of Table 13 in the EN13001-2 standard [48]. The values of γ_p for loads resulting from (part of) the mass of the crane are adopted from EN13001-2: Table 9, given that the trolley mass is unfavourable for the proof of static strength.

Loads f_i		Load combinations A			Load combinations B		Load combinations C				
		γ_p	A1	A3	γ_p	B5	γ_p	C1	C3	C4	C6
Gravitation acceleration and impact actions	Mass of the crane	1.22	ϕ_1	1	1.16	-	1.10	ϕ_1	ϕ_1	1	1
	Mass of the hoist load	1.34	ϕ_2	1	1.22	-	1.1	$\phi_{2,c}$	-	1	1
Acceleration actions from drives	Hoisting movements excluded	1.34	-	ϕ_5	1.22	ϕ_5	1.1	-	ϕ_5	-	-
	All movements	1.34	-	ϕ_5	1.22	-	1.1	-	-	-	-
Skewing		-	-	-	1.16	1	-	-	-	-	-
Test loads		-	-	-	-	-	1.1	-	ϕ_6	-	-
Buffer forces		-	-	-	-	-	1.1	-	-	ϕ_7	-
Drive forces due to E-stop		-	-	-	-	-	1.1	-	-	-	ϕ_5

All loads shown in table 9.1 have been implemented in Ansys Mechanical. The loads that are implemented in Ansys Mechanical are described below:

- **Mass of the crane.** A gravitational acceleration is applied on all bodies.
- **Mass of the hoist load.** The force in the wire ropes is determined from the hoist load. For every sheave, the resulting force is calculated and applied in Ansys Mechanical. These forces are applied on the shafts. These shafts are connected to the frame.
- **Acceleration actions from drives.**
  - Trolley A: A remote force is applied on the wheel shafts. This remote force is located at the wheel/rail contact point. To compensate these forces, an opposing force is applied on all bodies, to represent the inertia of the frame.
  - Trolley B: A force is applied on the locations on the frame where the trolley travel wire rope is connected. To compensate these forces, an opposing force is applied on all bodies, to represent the inertia of the frame.
- **Skewing.** A rotational acceleration is applied on all bodies, while constraining the wheel axes in the X-direction. This rotational acceleration is adjusted until the desired reaction forces are obtained.
- **Test loads.** The hoist load is increased with 10%.
- **Buffer forces.** At the buffer locations, a constant displacement in Y-direction is applied. An acceleration on all bodies is added and iterated until the correct reaction forces are obtained.
- **Drive forces due to E-stop.** The emergency stop forces are applied to the sheaves.

In figure 9.3 an impression is given of the forces applied on the frame. All shafts are modelled as rigid beams. Subsequently, on every shaft all forces and joints are applied on the right locations. The motors and cable reel are implemented in the model as a point mass. These point masses are connected to the plates on which they are installed.

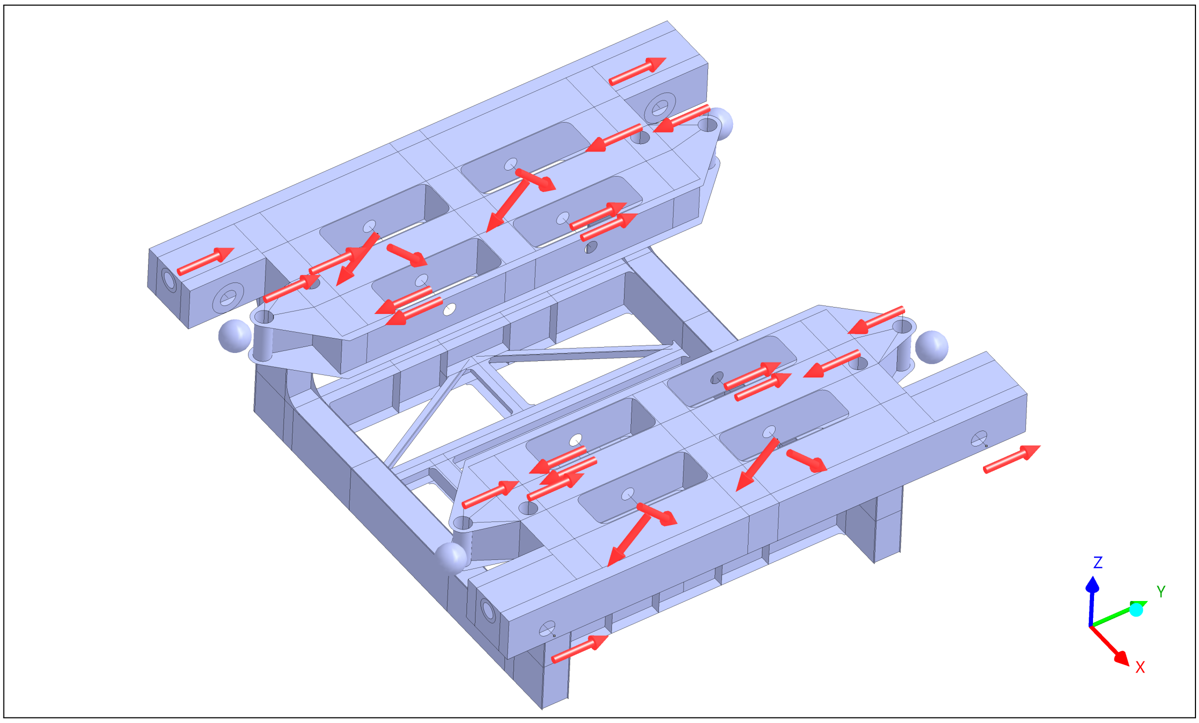


Figure 9.3: Hoisting and trolley acceleration forces on the frame of trolley A. The forces hoisting forces are applied on the sheave locations. The sheave shafts are modelled as rigid axes. The motors and cable reel are represented by a point mass. In case of trolley B, the point masses of the motors are missing and the acceleration forces are applied on the frame instead of the wheels.

As described in the EN 13001-2 standard, "The proof of competence for fatigue strength shall be done by applying the Load Combinations A, with all partial safety factors γ_p set to 1,0 but applying the ϕ-factors in accordance with this document" [48, p. 41]. The loads and load combinations for the proof of fatigue strength can be seen in table 9.2

Table 9.2: Relevant loads and load combinations for the proof of fatigue strength of the trolley frames. This table is an adjusted version of Table 13 in the EN13001-2 standard [48].

Loads f_i		Load combinations A		
		γ_p	A1	A3
Gravitation acceleration and impact actions	Mass of the crane	1	ϕ_1	1
	Mass of the hoist load	1	ϕ_2	1
Acceleration actions from drives	All movements	1	-	ϕ_5

9.3. Constraints

The constraints are described in the following list:

- In all situations, the ends of the wheel shafts are constrained in z-direction.
- In all situations except load combination C4, two wheel shaft ends (that are located above the same rail) are constrained in x-direction.
- In load combination B5 all wheel shaft ends are constrained in x-direction.
- In load combination C4, the buffer locations are constrained in y-direction. One wheel shaft end is constrained in x-direction.

9.4. Mesh

Figure 9.4 and 9.5 show the mesh for trolley A and B, respectively. Both trolleys are meshed in an identical way. After the global element size was reduced to 30 mm, the mesh quality was adequate in most locations.

In some critical locations the mesh required some more refinement. These refinements can be seen in figure 9.6. This included the impact area of the buffers, and the plates where most stress took place during hoisting. The lowest element quality is 0.2, but these elements were not at locations with large stress variation. In table 9.3 some details regarding the mesh of both trolleys can be seen.

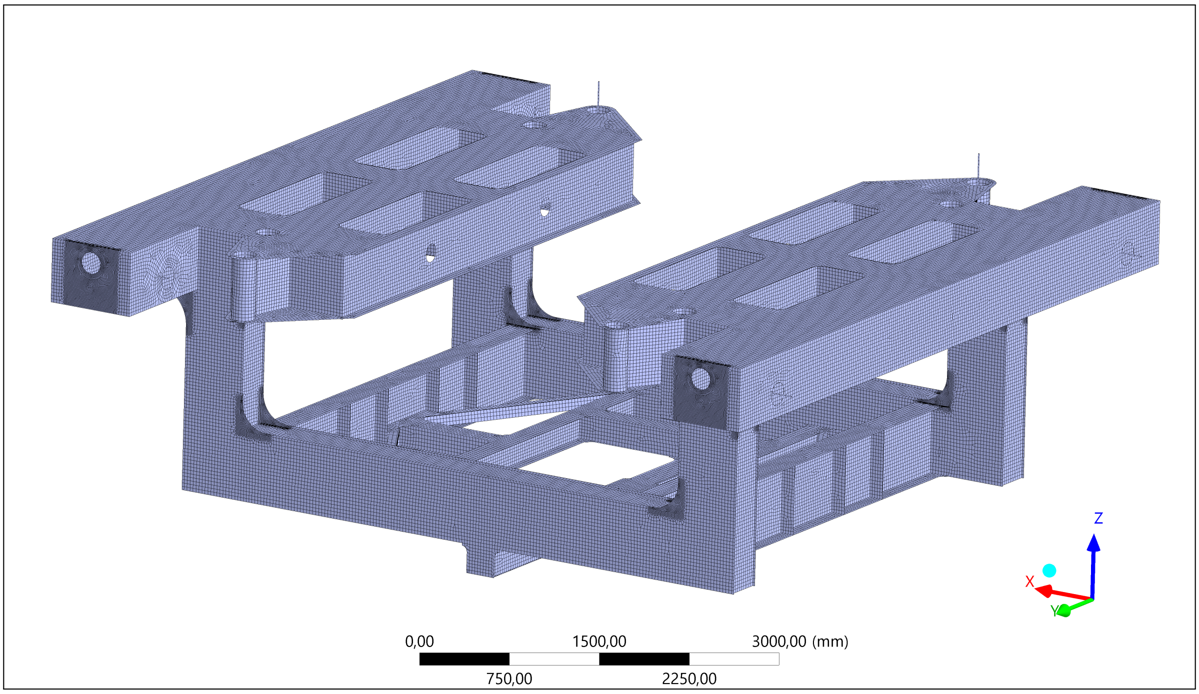


Figure 9.4: Mesh of trolley A.

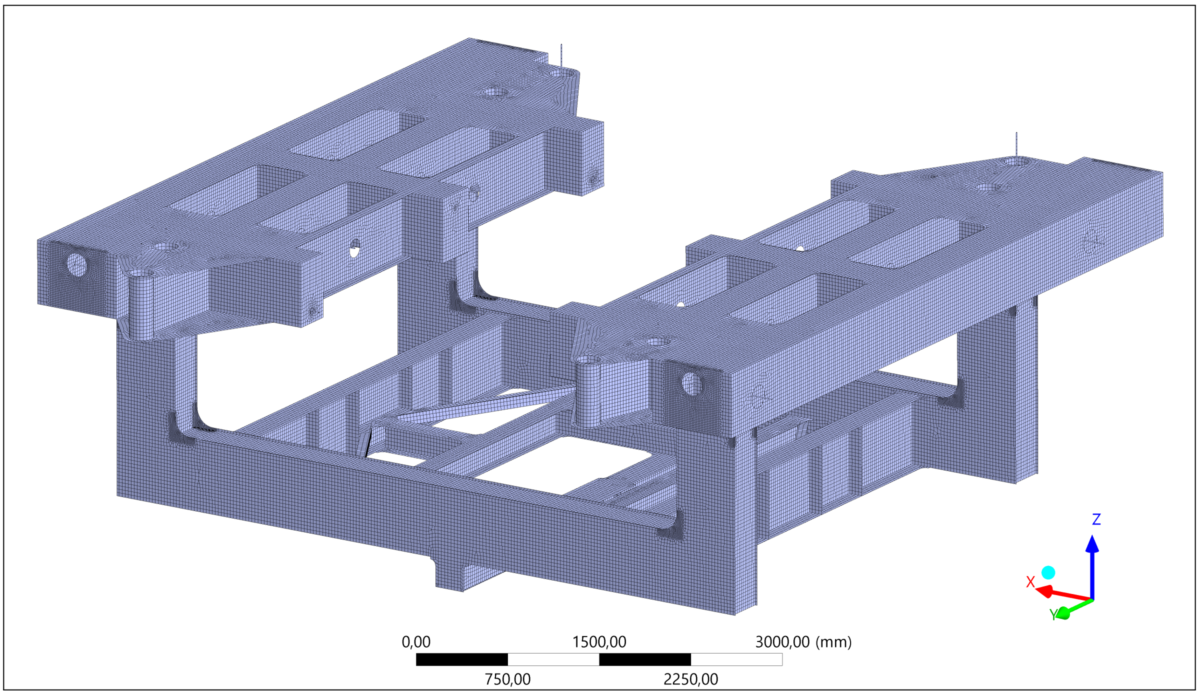


Figure 9.5: Mesh of trolley B.

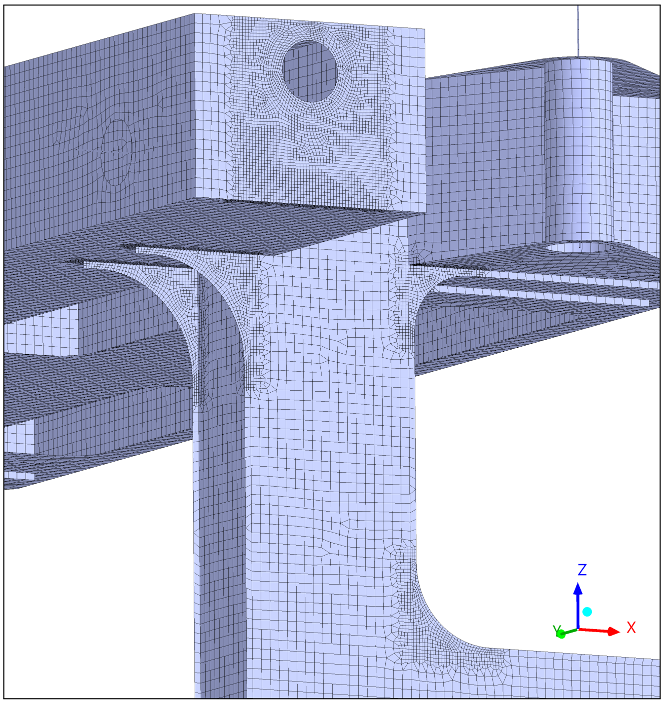


Figure 9.6: Mesh refinements on trolley A. The refinements on trolley B are almost identical. The refinements shown are present in all four corners of the trolleys.

Table 9.3: Mesh specifications of both trolleys.

Number of elements trolley A	221601
Number of nodes trolley A	218541
Global element size trolley A	30 mm
Number of elements trolley B	197865
Number of nodes trolley B	195097
Global element size trolley B	30 mm

9.5. Proof of static strength

As described in the EN 13001-3-1 standard, the proof of static strength for structural members can be written as:

$$\sigma_{Sd} \leq f_{Rd\sigma} \tag{9.1}$$

Where σ_{Sd} is the design stress, and $f_{Rd\sigma}$ is the limit design stress. In this proof the von Mises equivalent stresses are used. According to the same standard, the limit design stress is calculated as follows:

$$f_{Rd\sigma} = \frac{f_y}{\gamma_{Rm}} \tag{9.2}$$

$$\gamma_{Rm} = \gamma_m \cdot \gamma_{sm} \tag{9.3}$$

For plates made out of S355 steel, with a thickness of 63 mm or less, the yield strength is [49]:

$$f_y = 335\ \mathrm{N/mm^2} \tag{9.4}$$

$\gamma_{sm} = 0.95$ for stresses in the plane of rolling [49]. The value for γ_m is 1.1 [48].

$$f_{Rd\sigma} = \frac{335\ \mathrm{N/mm^2}}{0.95 \cdot 1.1} = 321\ \mathrm{N/mm^2} \tag{9.5}$$

Although for most plates in the frame, $f_y = 345\ \mathrm{N/mm^2}$ (thickness less than 40 mm) or $f_y = 355\ \mathrm{N/mm^2}$ (thickness less than 16 mm) [49], for simplicity $f_y = 335\ \mathrm{N/mm^2}$ and $f_{Rd\sigma} = 321\ \mathrm{N/mm^2}$ are chosen for the whole frame.

9.5.1. Most critical load combination

Figure 9.7 and figure 9.8 show equivalent Von Mises stress for the most critical load combination for trolley A and B, respectively. For both trolleys, load combination A1 turned out to be most critical. The results of the load combinations are documented in appendix I.

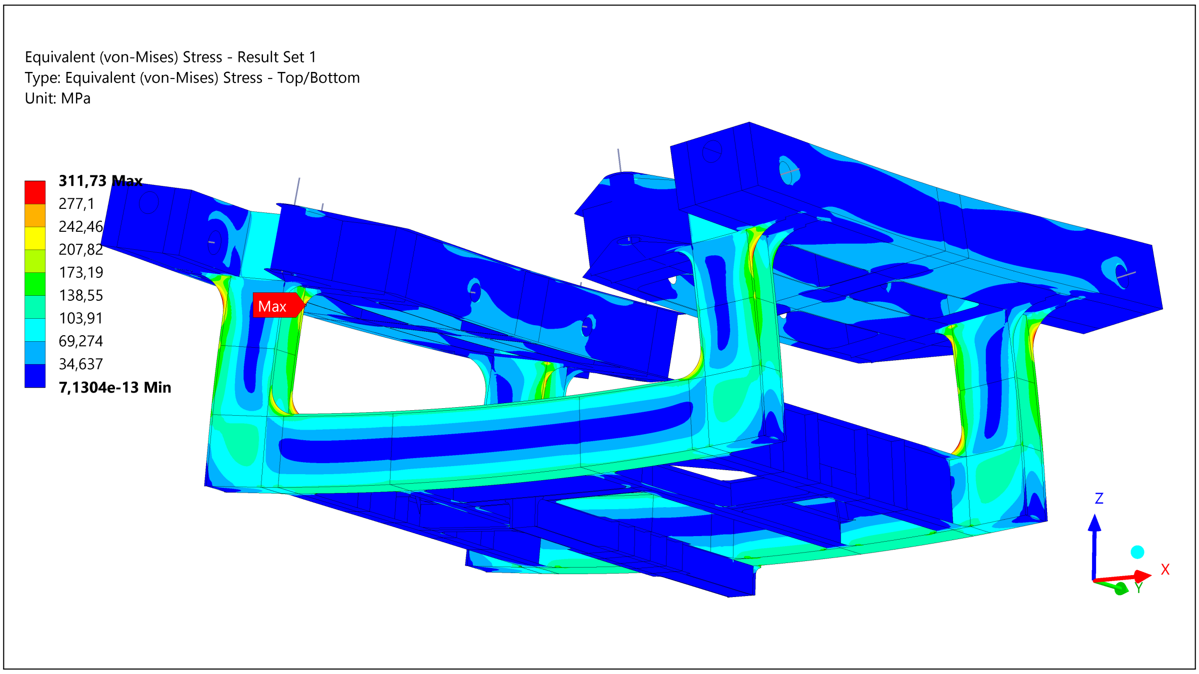


Figure 9.7: Proof of static strength for trolley A. Load combination A1. The deformation is scaled with a factor of 21.

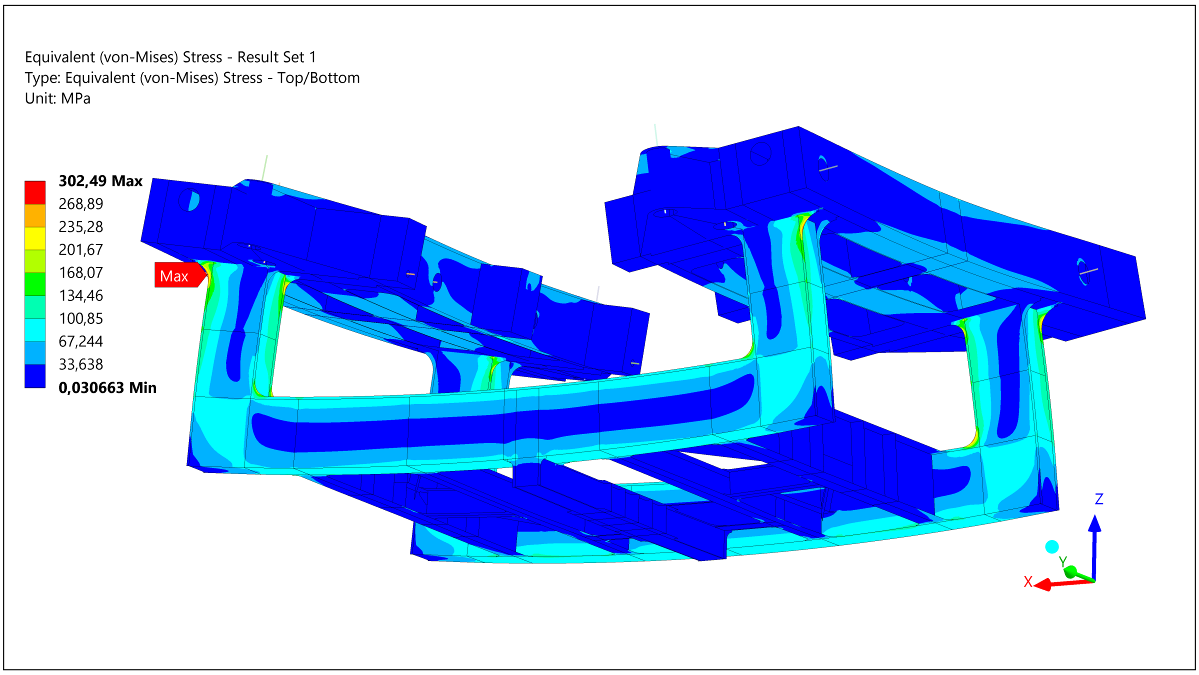


Figure 9.8: Proof of static strength for trolley B. Load combination A1. The deformation is scaled with a factor of 26

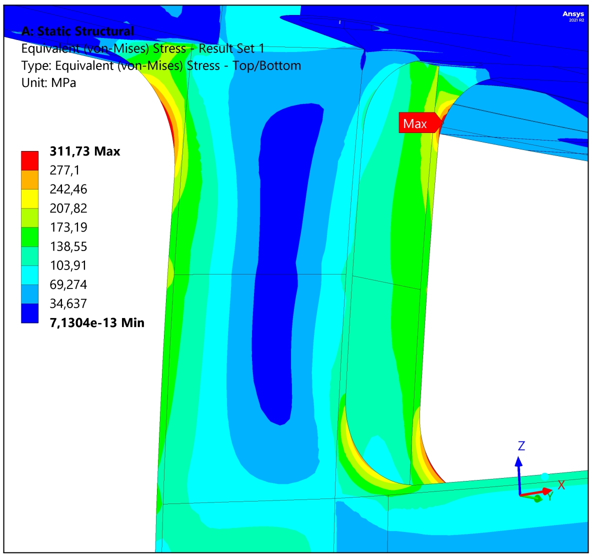


Figure 9.9: Proof of static strength for trolley A. Load combination A1. The deformation is scaled with a factor of 21.

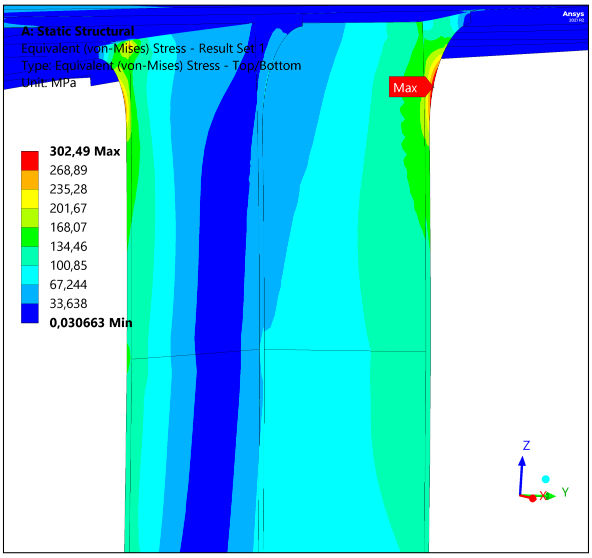


Figure 9.10: Proof of static strength for trolley B. Load combination A1. The deformation is scaled with a factor of 26

Trolley A:

$$\sigma_{Sd} = 312 \text{ N/mm}^2 \leq f_{Rd\sigma} \tag{9.6}$$

Trolley B:

$$\sigma_{Sd} = 302 \text{ N/mm}^2 \leq f_{Rd\sigma} \tag{9.7}$$

Static strength is proven for both trolleys.

9.6. Proof of fatigue strength

The maximum principal stress is used for the proof of fatigue strength. The EN13001-3-1 standard provides the following equations:

$$\Delta\sigma_{Sd} \leq \Delta\sigma_{Rd} \tag{9.8}$$

$$\Delta\sigma_{Rd} = \frac{\Delta\sigma_c}{\gamma_{mf} \cdot \sqrt[m]{s_m}} \tag{9.9}$$

Where $\Delta\sigma_{Sd}$ is the maximum range of design stresses, $\Delta\sigma_{Rd}$ is the limit design stress range, $\Delta\sigma_c$ is the characteristic fatigue strength, γ_{mf} is the fatigue strength resistance factor, and m is the slope constant of the $\log\Delta\sigma$-$\log N$ curve [49]. The stress history parameter s_m can be determined as follows:

$$s_m = \nu \cdot k_m \tag{9.10}$$

$$k_m = \sum_i \left[\frac{\Delta\sigma_i}{\Delta\hat{\sigma}}\right]^m \cdot \frac{n_i}{N_t} \tag{9.11}$$

$$\nu = \frac{N_t}{N_{ref}} \tag{9.12}$$

Where ν is the relative total number of occurences of stress ranges, k_m is the stress spectrum factor dependant on m, $\Delta\sigma_i$ is the stresss range i, $\Delta\hat{\sigma}$ is the maximum stress range, n_i is the number of occurences of stress range i, and N_t is the total number of stress ranges during the design life of the crane. From the same standard follows that:

$$N_{ref} = 2 \cdot 10^6 \tag{9.13}$$

The proof of fatigue strength performed in this work focuses on the quality of the details (welds) that are necessary. Therefore the value $m = 3$ is chosen [49]. $\gamma_{mf} = 1.25$ for non-accessible details with hazards for persons [49]. Although this value is somewhat conservative for some details in the frame, this value is chosen for all details in the frame. In this work we take $N_t = 4 \cdot 10^6$ as the total number of stress cycles, which results in $v = 2$. Based on data provided bij Iv-Consult, the following value for k_3 is obtained:

$$k_3 = 0.106 \tag{9.14}$$

Now s_m and can be obtained.

$$s_m = 0.106 \cdot 2 = 0.212 \tag{9.15}$$

It turns out that the maximum range of design stress and the characteristic fatigue strength have the following relation:

$$\Delta\sigma_{Sd} \leq \frac{\Delta\sigma_c}{1.25 \cdot \sqrt[3]{0.212}} \tag{9.16}$$

$$\Delta\sigma_c \geq 0.75\Delta\sigma_{Sd} \tag{9.17}$$

9.6.1. Most critical load combination

In figure 9.11 and 9.12 the maximum principal stress for trolley A and B is shown, respectively. Figure 9.13 and 9.14 give a closer view to the most stressed areas. For both trolleys load combination A1 turns out to be most critical.

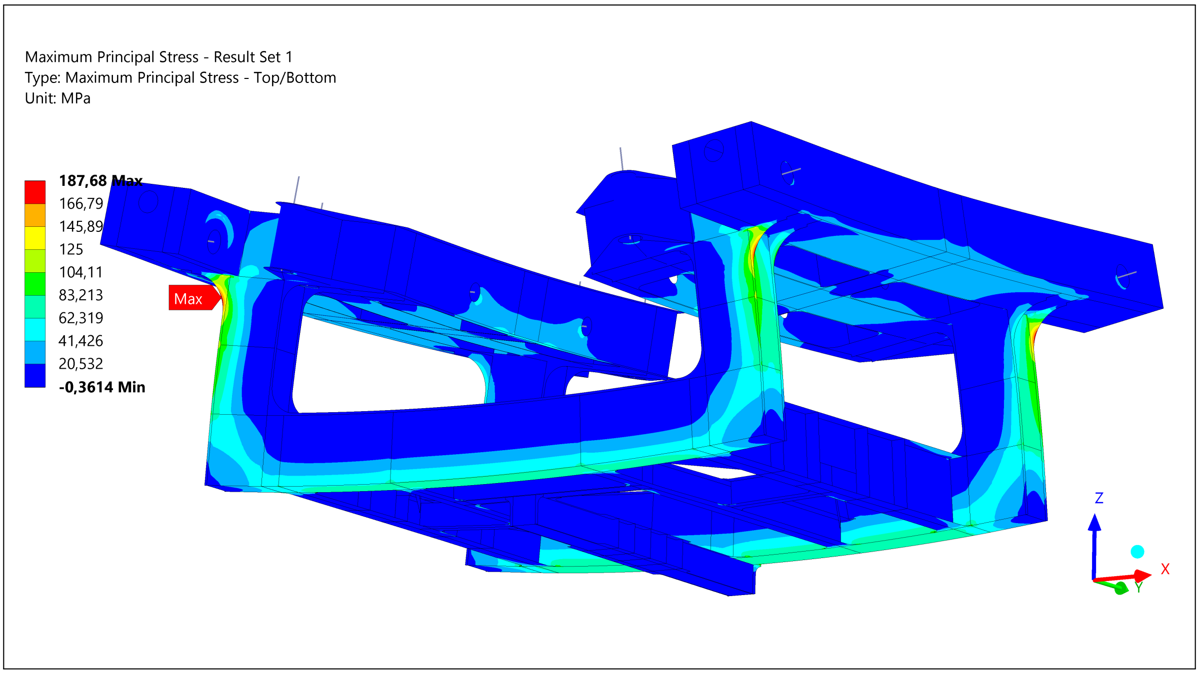


Figure 9.11: Proof of fatigue strength for trolley A. Load combination A1. The deformation is scaled with a factor of 45.

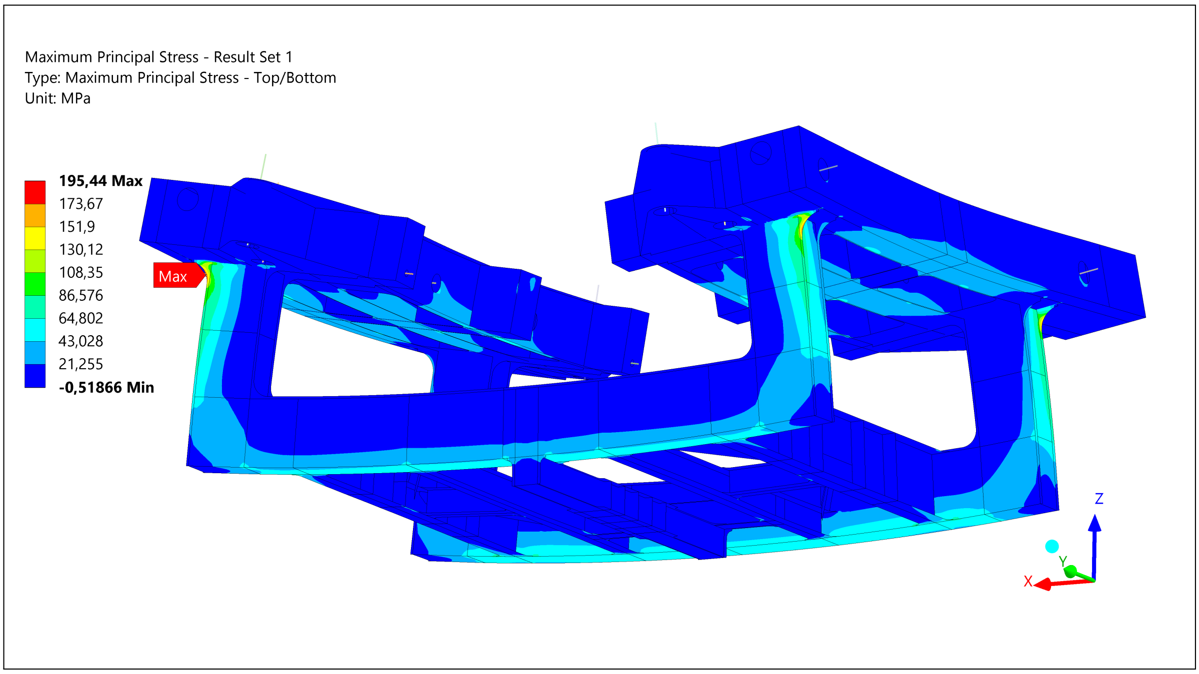


Figure 9.12: Proof of fatigue strength for trolley B. Load combination A1. The deformation is scaled with a factor of 45.

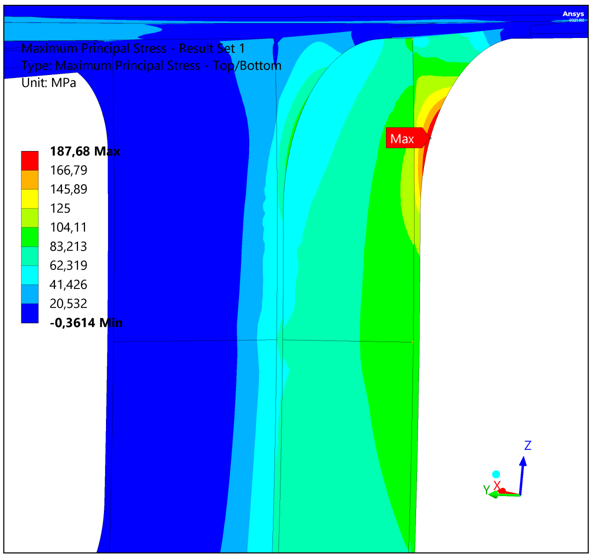


Figure 9.13: Proof of fatigue strength for trolley A. Load combination A1. The deformation is scaled with a factor of 45.

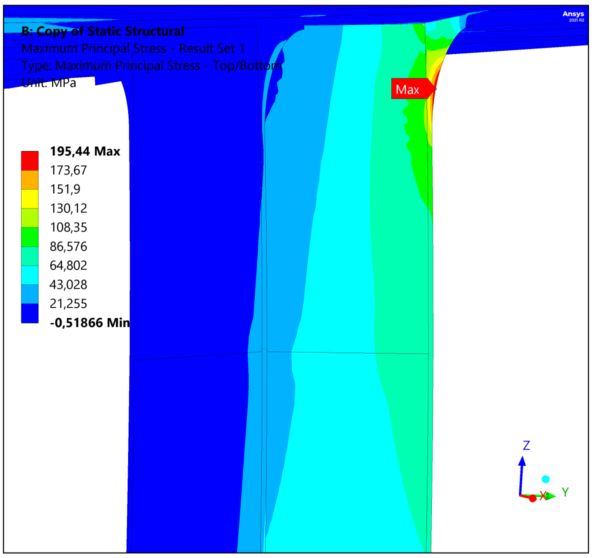


Figure 9.14: Proof of fatigue strength for trolley B. Load combination A1. The deformation is scaled with a factor of 45.

9.6.2. Weld quality

As both trolleys have comparable results, weld quality requirements will be described for both trolleys simultaneously. The largest principal stress is 195 N/mm^2. However, there are no welds on the location of largest principal stress. For welds in the vicinity of the critical spot, the maximum principal stress is 125 N/mm^2. For these welds, the characteristic fatigue strength should adhere to:

$$\Delta\sigma_c \geq 0.75 \cdot 125\ N/mm^2 = 94\ N/mm^2 \tag{9.18}$$

In Annex E of standard EN 13001-3-1 it can be seen that a notch class of $\Delta\sigma_c$ = 100 N/mm^2 is sufficient for these areas. In every corner of both trolleys there is a region in which the welds need to adhere to this quality. When moving away from this spot, the welds can be of a lower notch class. In figure 9.15 the requirements for the welds are depicted. The red line in the figure represents the welds that should adhere to notch class $\Delta\sigma_c = 100$ N/mm^2, while the orange lines represent the welds that should be of notch class $\Delta\sigma_c = 71$ N/mm^2. All other welds can be of notch class $\Delta\sigma_c = 63$ N/mm^2. Of course various welds can have an even lower notch class, but a detailed description of every individual weld is not included in this work. The welds shown in figure 9.15 apply to all four corners of both trolleys. Although both trolleys are somewhat different, the welds drawn for trolley A in figure 9.15 can also be drawn for trolley B in the same way.

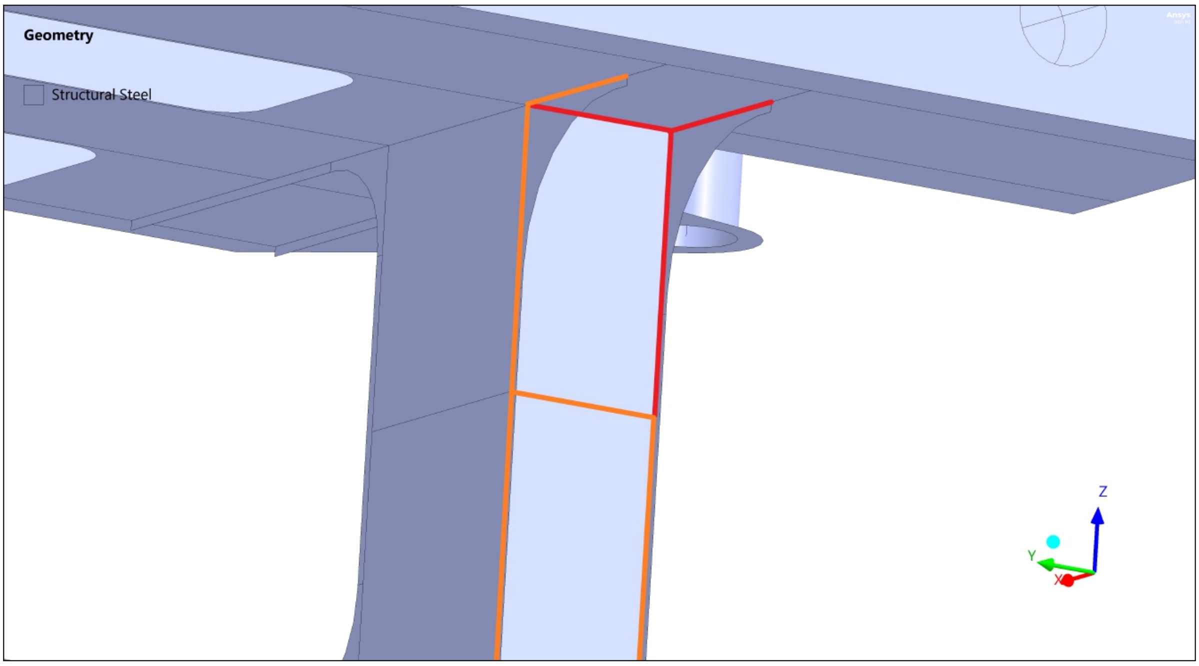


Figure 9.15: Weld positions that require a certain quality. The red area requires a notch class of at least $\Delta\sigma_c = 100$ N/mm^2. The orange area requires a notch class of at least $\Delta\sigma_c = 71$ N/mm^2. All other welds can be notch class $\Delta\sigma_c = 63$ N/mm^2. In the figure a part of trolley A is shown, but the same scheme can be made for trolley B. The specified welds apply in all four corners of the trolleys.

10

Crane structure considerations

Having two trolleys on one crane structure can have detrimental consequences in terms of stability, required structure, quay loads, and safety. The crane structure design is not part of this work. However, it is important to specify whether a standard crane structure is capable of carrying the double trolley system. This chapter provides some simple reasoning to demonstrate that concept 1 can be built on a standard crane structure without major problems. To do so, concept 1 is compared to a dual hoist crane, for which it is known that the crane structure is strong enough.

10.1. Weight and load moment

The trolley of a dual hoist crane weighs approximately 50 tons [2]. The trolleys of concept 1 weigh 38 tons and 33 tons, respectively. Both cranes can simultaneously move the same number and weight of containers. Consequently, the difference in weight is 21 tons. This could results in 21 tons $\cdot$ 9.81 m/s^2 = 206 kN extra load on componetns of the crane. Although the total mass of concept 1 is heavier, the load moment of the dual hoist crane is larger, as can be seen in table 10.1. Trolley A only needs to serve the first half of the ship, while trolley B must also reach the furthest container row on the ship. Based on a ship with 24 rows, in the worst case scenario trolley A needs to travel 35 meters from the WS legs, while trolley B needs to travel 65 meters (see figure 10.1). While calculating the load moment, a dynamic factor of 1.3 is used.

Table 10.1: Load moment in worst case scenario for every concept.

Concept	**Description**	**Weight**	**Arm**	**Dynamic factor**	**Total load moment**
Dual hoist	Trolley	50 tons	65 m	1.3	171 MNm
	Headblock + spreader + max. load	156 tons	65 m	1.3	
Concept 1	Trolley B	33 tons	65 m	1.3	144 MNm
	Headblock + spreader + max. load	78 tons	65 m	1.3	
	Trolley A	38 tons	35 m	1.3	
	Headblock + spreader + max. load	78 tons	35 m	1.3	

As the load moment of concept 1 is smaller than the load moment of the dual hoist crane, there is no danger in terms of stability. The next section looks into the consequences of this moment for the forestays and the WS apex leg.

10.2. Forestay forces

The tension force in the forestays, and the resulting forces on the WS apex legs are discussed in this section. An STS crane with two forestays is assumed. Figure 10.1 and 10.2 show the most critical situation for concept 1 and the dual hoist crane, respectively. Besides the situation in figure 10.2, for the dual hoist crane also the situation where the trolley is at 25 meters from the WS legs is analysed. The dimensions shown in figure 10.1

and 10.2 are roughly estimated based on existing cranes. In this comparison, the weight of the boom itself is neglected.

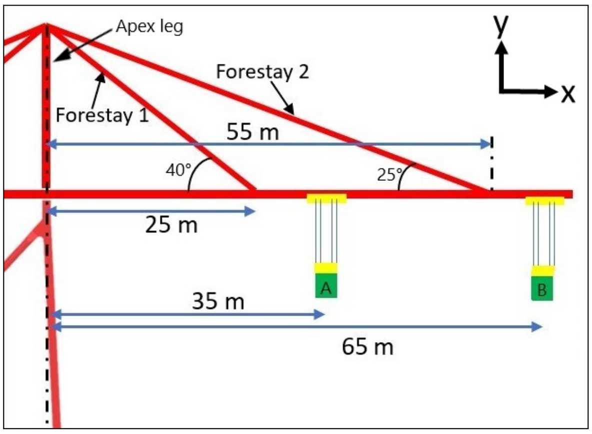


Figure 10.1: Concept 1 most critical trolley positions.

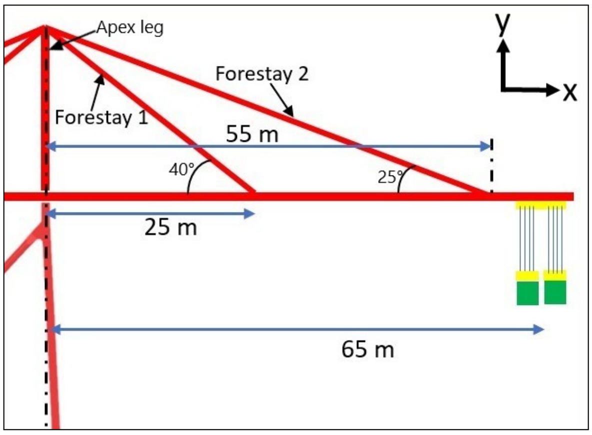


Figure 10.2: Dual hoist crane most critical trolley position.

When trolley A is at its furthest position (35 m), the distance between forestay 1 and forestay 2 is covered for one third. For this reason, it is assumed that trolley A is supported for $\frac{2}{3}$ by forestay 1 and for $\frac{1}{3}$ by forestay 2. Trolley B has passed forestay 2, so it will be assumed that the moment caused by trolley B is completely supported by forestay 2. For concept 1, the tension force $F_{p1,c1}$ of forestay 1 and tension force $F_{p2,c1}$ of forestay 2 are calculated as follows:

$$F_{p1,c1} = \frac{\frac{2}{3} \cdot 116 \text{ tons} \cdot 35 \text{ m} \cdot 1.3 \cdot 9.81 \text{ m/s}^2}{25 \text{ m} \cdot \sin 40°} = 2148 \text{ kN} \tag{10.1}$$

$$F_{p2,c1} = \frac{\frac{1}{3} \cdot 116 \text{ tons} \cdot 35 \text{ m} \cdot 1.3 \cdot 9.81 \text{ m/s}^2 + 111 \text{ tons} \cdot 65 \text{ m} \cdot 1.3 \cdot 9.81 \text{m/s}^2}{55 \text{ m} \cdot \sin 25°} = 4701 \text{ kN} \tag{10.2}$$

For the dual hoist crane, the tension force $F_{p1,d}$ of forestay 1 is $F_{p1,d} = 0$ in the situation shown in figure 10.2. The value for the tension force $F_{p2,d}$ of forestay 2 in this situation is:

$$F_{p2,d} = \frac{206 \text{ tons} \cdot 65 \text{ m} \cdot 1.3 \cdot 9.81 \text{m/s}^2}{55 \text{ m} \cdot \sin 25°} = 7347 \text{ kN} \tag{10.3}$$

However, when the dual hoist trolley is located underneath forestay 1 (at 25 m), the tension force $F_{p1,d}$ is:

$$F_{p1,d} = \frac{206 \text{ tons} \cdot 25 \text{ m} \cdot 1.3 \cdot 9.81 \text{ m/s}^2}{25 \text{ m} \cdot \sin 40°} = 4087 \text{ kN} \tag{10.4}$$

The combined tension forces in the forestays are applied on the WS apex legs. The force exerted on the top of the waterside apex leg is listed in table 10.2 for both concept 1 and the dual hoist crane.

Table 10.2: Force exerted on top of the apex leg as a result of the the load moment of both concept 1 and a dual hoist crane.

Force component	**Concept 1**	**Dual hoist trolley at 65 m**	**Dual hoist trolley at 35 m**
$F_{al,x}$	5906 kN	6659 kN	3131 kN
$F_{al,y}$	-3367 kN	-3105 kN	-2627 kN

The maximum absolute value of the force in y-direction $F_{al,y}$ is 262 kN larger for concept 1 compared to the dual hoist crane. This means that the WS (apex) legs might need some reinforcements to implement this concept. The tension forces in the forestays and the force in x-direction $F_{al,x}$ are lower for concept 1 compared to the dual hoist crane. Consequently, it is realistic to assume that a standard crane structure that is strong enough can be built to implement concept 1.

10.3. Wind area

The largest corner loads exerted on the quay are caused by storm loads. These storm loads increase with increasing wind area of the crane. One additional trolley causes an extra wind area of no more than 20 m^2. As a complete crane has a surface area of more than 1500 m^2 [39], this is only a minor increase, and thus this will not be problematic for the corner loads on the quay.

11 Conclusions

11.1. Conclusions

In this work, the following main research question is answered:

"In which way can a new concept to simultaneously transfer 4 TEU during the loading and unloading of a container ship be designed on a standard ship-to-shore crane structure?"

This main research question is subdivided among five sub-questions, for which the conclusions are stated below.

What are the existing solutions for the simultaneous transfer of 4 TEU by an STS container crane?
Currently, 4 TEU is simultaneously transferred by means of tandem lifting. In this configuration a crane with two adjacently positioned spreaders can load and unload two adjacent rows of a ship. Tandem lifting can be performed in either a single hoist or dual hoist configuration. Single hoist tandem lifting includes only one hoisting mechanism, while dual hoist tandem lifting makes use of two separate hoisting mechanisms. In practice, tandem lifting comes with some disadvantages. During single hoist tandem lifting, the spreader configuration of the crane needs to be changed when switching between single lifting and tandem lifting. Dual hoist tandem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley. Triple lifting is a combination of single hoist and dual hoist tandem lifting, and allows to transfer 6 TEU simultaneously. However, triple lifting is barely used in practice. Occasionally, 4 TEU is lifted in a vertical tandem configuration, where containers vertically connected by twistlocks. However, this is considered an unsafe practice. Various modern cranes have a secondary trolley on the lower portal beams. This secondary trolley transfers the load between the quay and a platform installed on the crane, while the main trolley transfers containers between the platform and the ship.

Which new concepts can be applied for the simultaneous transfer of 4 TEU on a standard ship-to-shore crane structure?
The simultaneous transfer of 4 TEU can alternatively be achieved by different combinations of trolleys and transfer vehicles. In (patent) literature, the cycle is often divided between a vertical and horizontal transfer part. In this case, the horizontal part is performed by some type of transfer vehicle(s). This transfer vehicle cannot hoist or lower the load. On both the ship and quay side, one or more hoisting means load and unload the transfer vehicle(s). In case of multiple transfer vehicles, they can often either pass each other, or circulate via multiple tracks on the crane. Another option is to have multiple trolleys installed on the crane. These trolleys can either pass each other or not, while each trolley fulfills the (un)loading cycle independently. In total, 7 concepts are composed in this work that are all a variation of trolleys and transfer vehicles.

What are the objectives and constraints of an STS crane with a standard STS crane structure?
Multiple constraints are important for an STS crane. First of all, it should adhere to a renowned crane standard (e.g. the European EN 13001 standard) in terms of static strength, fatigue strength, and stability. The weight and size of an STS crane should be limited to prevent large loads on the quay. In this work, a 10% increase in weight and a 5% increase in wind surface area compared to a standard crane structure are taken as

the maximum values. An STS crane should also be compatible with a terminal process, and the dimensions crane dimensions should provide enough space for adjacent cranes to serve the same ship. Lastly, in this work the crane dimensions should be sufficiently large enough to serve ultra large container vessels.

Besides the constraints, multiple objectives are important for an STS crane. To start off, the productivity of an STS crane is the most important objective. The productivity determines to a large extent whether a crane concept is worth the investments. Furthermore, the ability to adjust an existing crane to implement a crane concept is of importance, as this tremendously decreases the reluctance of terminal operators. Moreover, terminal compatibility in terms of both corner loads and terminal process compatibility is an objective. Other objectives are the initial costs, operation reliability, operating costs, and commercial opportunities.

Which concept is most suitable and feasible for the simultaneous transfer of 4 TEU on a standard crane structure, taking into account the constraints and objectives of an STS crane?
Out of the 7 composed concepts, concept 1 turned out the be the most suitable concept for the simultaneous transfer of 4 TEU on a standard STS crane structure. Concept 1 is a crane with two trolleys on the same rails that cannot pass each other. Both trolleys operate independently, but they must remain sufficiently apart to prevent collisions. The productivity of concept 1 is 47% higher compared to a conventional crane. Although the theoretical maximum productivity of a dual hoist crane is still 9% higher, on average the productivity of concept 1 will turn out to be higher, assuming that both trolleys are employed for the majority of the operations. In contrast to tandem lifting, the ability to simultaneously transfer 4 TEU with concept 1 is less dependent on the stacking plan of the ship. As long as the landside trolley can serve containers on the landside half of the ship, while the waterside trolley can serve containers on the waterside half of the ship, 4 TEU can simultaneously be transferred. When only one trolley is used, the crane is still as efficient as a conventional crane. There is no need to switch between spreader configurations. Instead, either one or two trolleys are employed. In contrast to other concepts, concept 1 requires relatively small adjustments compared to a conventional crane. This results in relatively low costs. Due to the analogy to a conventional crane, terminal operators will be less reluctant to implement the concept. When one trolley is out of service, the other trolley can still operate.

Despite being the most suitable concept overall, concept 1 comes with some disadvantages. The operation of concept 1 might be more complicated, as two trolleys need to be simultaneously operated. This could result in the necessity of a second operator. However, as a result of the increasing automation of STS container cranes, it is realistic to assume that only one operator is required in the future. Having two trolleys on the same rails could result in dangerous operations. To ensure safe operations, the trolleys should stay sufficiently apart from each other. Often the landside trolley needs to wait for the waterside trolley, as the waterside trolley needs to travel a longer distance.

How can a design to simultaneously transport 4 TEU on a standard STS crane structure be realized by applying this concept?
Installing two trolleys on the same rails requires some ingenuity. To prevent a large load moment on the crane structure, the hoisting mechanisms of both trolleys are located in the machinery house on the trolley girder. The landside trolley is a semi rope trolley, while the waterside trolley is a rope towed trolley. In this way, only one of the trolley travel mechanisms needs to be located in the machinery house. This results in a machinery house configuration identical to a dual hoist crane. As the semi rope trolley has directly driven wheels, the trolley acceleration is limited by wheel slip. However, this is not problematic as the landside trolley needs to travel smaller distances than the waterside trolley. The wire ropes are supported by a continuous rope support system. This configuration requires only slight adjustments compared to a conventional crane with a continuous rope support system. All wire ropes should run adjacently on top of the rope support rollers, with sufficient space in between. To accomplish this, the sheave positions and diameters of both trolleys differ. Also the headblock sheave distance of both trolleys is different. The changes in the wire rope reeving slightly decreases the wire rope lifetime. To allow the different sheave positions, the frames of both trolleys need to be adjusted compared to a conventional trolley. Also the installation of the motors and gearbox on the semi rope trolley requires some adjustments. The trolley frame adjustments are validated by means of a finite element analysis. The addition of an extra trolley has no major disadvantageous consequences for the crane structure, assuming a crane structure of a dual hoist crane is used.

11.2. Recommendations

In this project, a concept design of an STS crane with two trolleys on the same rails is elaborated. Although the focus of this work laid on the most important and critical aspects of this design, multiple secondary aspects are not worked out yet. To start off, the equipment required for the remote control of the trolleys is not taken into account yet. To account for this, plenty of space on both trolleys is preserved. Moreover, the service platforms on both trolleys that provide access for maintenance personnel are not included in the design yet. Also the exact sizes of all axes need to be defined according to the EN 13001 standard. In this work, the trolley frames are worked out in terms of dimensions and plate thicknesses. Some plate thicknesses are somewhat overdimensioned in certain locations. Before implementing this concept these thicknesses should be adjusted to spare out weight. Also, the welds in the frames need to be specified individually, instead of the rough description provided in this work.

The crane structure design is not part of this project. In this work, only a simple comparison between the concept and a dual hoist crane is made to demonstrate that it is possible to successfully build a standard STS crane structure to implement the concept. In future work, the crane structure for this concept should be designed. Moreover, this work assumed the crane structure to be custom made for this concept. However, this concept has the potential to be built on an existing crane. Depending on the respective existing crane, the concept could be adjusted to fit on that crane structure. Preferably, this existing crane would already have a continuous rope support system. This is an opportunity for future projects.

To ensure safe operations, a control system should be designed to prevent any collisions between the trolleys or the loads. Inputs like the trolley speeds, relative position, load mass, and load height could be used to set a minimum distance that should be maintained between the trolleys. In case of any any potential hazardous situations, the control system can limit the speed of the trolleys. Besides the safety aspects, also the operational aspects of the control of this concept will determine whether it can be successfully implemented in practice. Both trolleys will be remotely controlled. Although remote control of STS container cranes is already successfully implemented in practice, these cranes have only one trolley. The number of operators that are necessary to operate the double trolley crane could be decisive for the success of this concept. Having only 1 operator to remote control both trolleys could result in a delay. This can easily be tested without the necessity to build a crane with two trolleys. To test this, an operator can try to operate two conventional remote controlled cranes simultaneously, while acting like the trolleys are installed on the same crane. In case the control by one operator turns out to be problematic, it will be a matter of time before the process can be successfully automated. Automation would be a perfect solution for this concept to perform effectively.

The problem definition in this work focuses on STS container crane concept that could be applied to a standard crane structure. However, this limits the solution space. Allowing alternative structure designs allows more concepts to be formed. In future research, more STS crane concepts can be addressed by allowing all types of crane structures.

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A
Research paper

A study into new concepts to simultaneously transport 4 TEU with a ship-to-shore container crane

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Abstract—As a result of the need for higher productivity ship-to-shore container cranes, seven concepts are composed that can simultaneously transfer 4 Twenty Foot Equivalent Unit containers. All concept can be built on a standard ship-to-shore crane structure. These concepts are based on working principles found in (patent) literature. The concepts are compared based on multiple objectives, after which one concept is chosen to realize a concept design. A ship-to-shore crane with two trolleys turns out to be the most suitable concept. The two trolleys consist of a rope towed trolley and a semi rope trolley, which are combined with a continuous rope support system. The design of the trolleys is based on an existing trolley. For all wire ropes to run adjacently, the sheave diameters and positions on both trolleys deviate from the existing trolley. The sheave positions have consequences for the trolley frame design. To validate the adjusted trolley frames, a finite element analysis is performed.

Keywords— Ship-to-shore container crane, concepts, design

I. Introduction

Container ships are increasingly growing in size. Due to these larger ships, the productivity of ship-to-shore (STS) container cranes drops, as the travel distances to the containers on the ship increase. For this reason, there is a need for STS cranes with higher productivity. Increasing the hoisting and trolley travel speeds to improve the productivity has its limitations. To significantly increase the productivity of STS cranes, new concepts with alternative working principles should be implemented. In general, terminal operators are reluctant to implement new STS crane concepts due to the high risks and investment costs, especially when the concepts deviate substantially from a conventional crane design. This is the reason that multiple high productivity crane concepts were never implemented in practice. To decrease this reluctance, high productivity crane concepts should be closely related to the conventional solution.

In practice, some solutions to increase the productivity of STS cranes already exist. These cranes apply tandem lifting to transfer more containers per movement. During tandem lifting, containers are lifted side by side by using a double spreader configuration. In this way, 4 Twenty Foot Equivalent Unit (TEU) containers can be loaded or unloaded, instead of 2 TEU for a conventional crane. To apply tandem lifting, the containers should be positioned in two adjacent rows on the ship. Tandem lifting can both be performed by cranes with a single lifting system (single hoist tandem) and a double lifting system (dual hoist tandem). Both designs can switch to a single spreader configuration when necessary. Whether tandem lifting will be applied depends on multiple factors, like the ship model, stacking plan, and crane operator. Although the theoretical productivity of tandem lifting is high, in practice the percentage of tandem lift operations is often below 20% [1]. Dual hoist tandem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley. Single hoist tandem cranes need to swap spreaders every time there is a switch between single lifting and tandem lifting. On top of that, terminal operators willing to transport 4 TEU simultaneously with a ship-to-shore container crane are limited in their choice. They are often restricted to a single crane manufacturer, which results in high costs. For this reason, alternative concepts for the simultaneous transfer of 4 TEU with a STS crane should be designed.

II. Literature research

a. Existing solutions

Single hoist tandem cranes have only one hoisting mechanism, just like a conventional crane. The difference to conventional cranes is the headblock-spreader system. As can be seen in figure 1, a single headblock connects two spreaders that can both hold a container. When switching between single lifting and tandem lifting, the spreader configuration of the crane needs to be changed. Manufacturers of a tandem lift headblock are Stinis [2], Bromma [3], and RAM [4].

Dual hoist tandem lifting makes use of two separate hoisting mechanisms. In figure 2 a dual hoist tandem configuration is shown. In the figure, two sets of hoisting cables can be seen. Both spreaders of a dual hoist crane can be operated independently from each other [6]. As a result, a dual hoist crane can also perform single lifting by leaving one trolley

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Fig. 1: Single hoist tandem lifting. From [5]

Fig. 2: Dual hoist tandem lifting. From [7]

and headblock in the stowed position. Dual hoist tandem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley.

Triple lifting is a combination of single hoist and dual hoist tandem lifting, and allows to transfer 6 TEU simultaneously [8]. However, triple lifting is barely used in practice. Occasionally, 4 TEU is lifted in a vertical tandem configuration, where containers vertically connected by twistlocks, but this is considered an unsafe practice. Various modern cranes have a secondary trolley on the lower portal beams. This secondary trolley transfers the load between the quay and a platform installed on the crane, while the main trolley transfers containers between the platform and the ship [5].

b. Non-applied solutions

The simultaneous transfer of 4 TEU can alternatively be achieved by different combinations of trolleys and transfer vehicles. In (patent) literature, the cycle is often divided between a vertical and horizontal transfer part. In this case, the horizontal part is performed by some type of transfer vehicle(s). This transfer vehicle cannot hoist or lower the load. On both the waterside (WS) and landside (LS) one or more hoisting means load and unload the transfer vehicle(s). In case of multiple transfer vehicles, they can often either pass each other, or circulate via multiple tracks on the crane. Another option is to have multiple trolleys installed on the crane. These trolleys can either pass each other or not, while each trolley fulfills the (un)loading cycle independently.

III. Concept generation

Seven concepts are generated by means of functional decomposition and a morphological chart.

a. Functional decomposition

A functional decomposition as described by Dieter et al. [9] and Dym and Little [10] is performed. Initially, listing all functions resulted in an unpractical overview. Consequently, a more concise version is composed and listed below.

- Attach and detach the container(s)
- Hoist and lower containers, and obtain the correct position above the ship or quay
- Move the container(s) between landside and waterside
- Support handling process with secondary system below the main girder

b. Concepts

By means of a morphological chart, seven concepts are formed. All concepts are a variation of a combination of trolleys and transfer vehicles.

- **Concept 1** (figure 3)
  Two trolleys that cannot pass each other. Both serve one half of the ship.
- **Concept 2** (figure 4)
  Two trolleys that can pass each other. One trolley is positioned underneath the other trolley. The upper trolley needs to hoist the headblock to the highest position before it can pass the other trolley.
- **Concept 3** (figure 5)
  Same as concept 2, but now the upper trolley has a rotating headblock. In this way, the lower trolley can be more compact.
- **Concept 4** (figure 6)
  The WS and LS have a separate trolley. A transfer vehicle transfers containers between the WS and LS trolley.
- **Concept 5** (figure 7)
  Same as concept 4, but now the concept has 2 transfer vehicles that can pass each other. The upper transfer vehicle has a movable bottom, which moves upwards when the lower trolley needs to pass with a container.
- **Concept 6** (figure 8)
  Same as concept 4, but now the concept has 2 transfer vehicles that can pass each other. The lower transfer vehicle is located low enough for the upper transfer vehicle to pass with a container.
- **Concept 7** (figure 9)
  One trolley with two transfer vehicles. First, the trolley loads both transfer vehicles. Subsequently, the transfer vehicles travel to the other side where they are unloaded by the trolley.

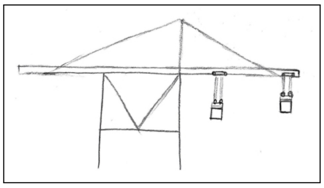

Fig. 3: Concept 1

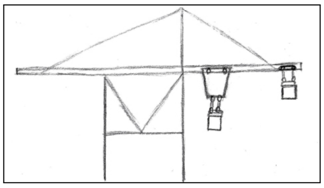

Fig. 4: Concept 2

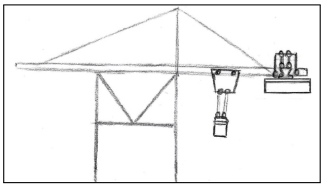

Fig. 5: Concept 3

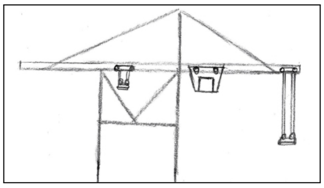

Fig. 6: Concept 4

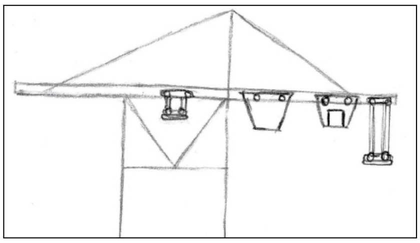

Fig. 7: Concept 5

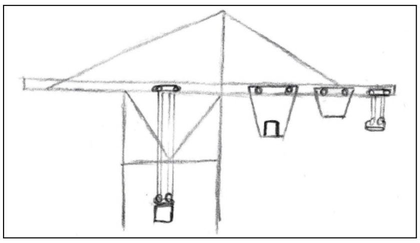

Fig. 8: Concept 6

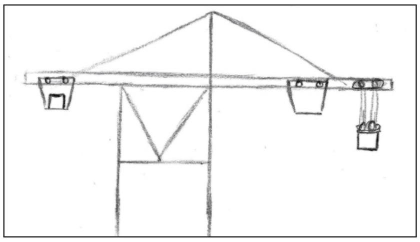

Fig. 9: Concept 7

IV. Concept selection

The concepts are compared in terms of productivity, the ability to adjust an existing crane, terminal compatibility, initial costs, operation reliability, and commercial opportunities. In table 1 the estimated productivity of all concepts is listed, which is the most important objective.

Table 1: Productivity of each concept, based on the cycle calculations.

Concept	Productivity	
Conventional crane	41.6	Containers per hour
Concept 1	61.5	Containers per hour
Concept 2	60.7	Containers per hour
Concept 3	60.7	Containers per hour
Concept 4	47.6	Containers per hour
Concept 5	47.5	Containers per hour
Concept 6	46.4	Containers per hour
Concept 7	32.2	Containers per hour

Out of the 7 composed concepts, concept 1 turned out the be the most suitable concept for the simultaneous transfer of 4 TEU on a standard STS crane structure. The productivity of concept 1 is 47% higher compared to a conventional crane. Although concept 2 and concept 3 have an almost identical productivity, these concepts scored worse on the other objectives. Concept 1 is chosen to realize a concept design.

V. Concept design

The crane has a LS and WS trolley. Figure 10 gives an impression. The LS trolley (in red) is called trolley A, while the WS trolley (in blue) is called trolley B. Both trolleys are assumed to be remote controlled.

a. Trolley types

Trolley A is a semi rope trolley, while trolley B is a rope towed trolley. The weight of the trolleys is limited as the hoisting mechanisms are located in the machinery house on the crane structure. This prevents the trolleys from applying a large load moment on the crane. The wheels of trolley A are directly driven. This spares out space in the machinery house, while the weight of trolley A is only slightly increased. Directly driven wheels can result in limited accelerations due to wheel slip. However, this is not problematic for trolley A as it should travel less distance than trolley B.

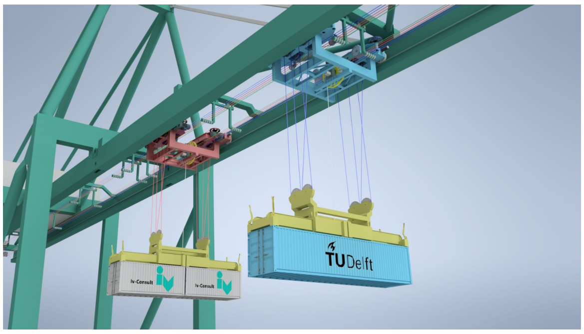

Fig. 10: Concept 1 design. Left: Trolley A. Right: Trolley B

Both trolleys are based on an existing trolley. Figure 11 shows a photo of an existing trolley, while figure 12 and 13 give an impression of trolley A and trolley B, respectively. The shape of the trolleys is a result of the wire rope support system (see next section). In table 2 the differences between the trolleys are summarized.

Fig. 11: Trolley with continuous rope support system

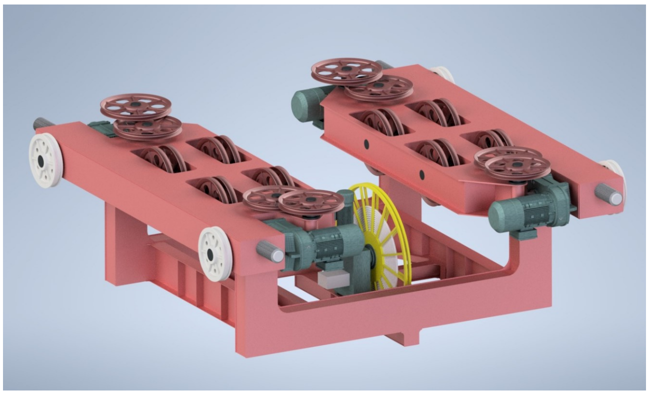

Fig. 12: Trolley A

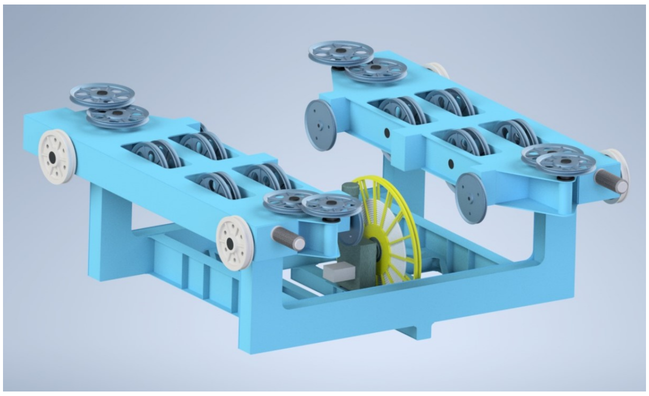

Fig. 13: Trolley B

TABLE 2: DIFFERENCES BETWEEN THE ORIGINAL, EXISTING TROLLEY AND TROLLEY A AND TROLLEY B.

Original trolley	**Trolley A**	**Trolley B**
8 wheels	4 wheels	4 wheels
Rope towed	Directly driven	Rope towed
Cabin	No cabin	No cabin
"Normal" turning sheaves	Slightly larger sheaves*	Slightly smaller sheaves*
"Normal" sheave position	Sheaves positioned more compact*	Sheaves positioned more outwards*
Buffers on both sides	Buffers on both sides	Buffers on WS
37 tons	38 tons	33 tons

*See figure 15

b. Rope support system

Large STS cranes with a rope towed trolley or semi rope trolley need the wire ropes to be supported to prevent wire rope sag. In general, two types of rope support systems exist. The first option is by installing catenary trolleys on the crane. Catenary trolleys are smaller trolleys that drive with the main trolley to support the wire ropes. Normally, on either side of the main trolley of a conventional crane a catenary trolley drives at half the speed. The other option to support the cables is a continuous rope support system. In a continuous rope support system, fixed cable supports on the crane structure can be passed by the trolley. For this design, a continuous rope support system is chosen, as this system requires only minor adjustments compared to a conventional crane. This is in contrast to the system with catenary trolleys, which would require an additional catenary trolley. In figure 14 the cable support in combination with trolley A can be seen. The cable support is fixed to the crane structure, while the trolley shape allows it to pass the cable supports.

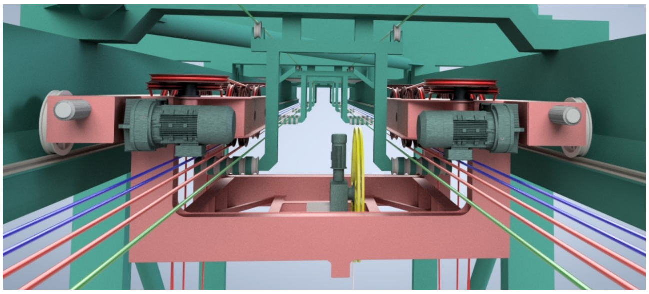

Fig. 14: Continuous rope support system with trolley A

c. Reeving system

All wire ropes should run adjacently on top of the rope support rollers, with sufficient space in between. To accomplish this, the sheave positions and diameters of both trolleys differ. This has some minor detrimental consequences for the lifetime of the wire ropes, which are calculated according to the EN 13001-3-2 standard [11]. In figure 15 the relative positions of the cables of both trolleys are depicted. The red cables are the hoisting cables of trolley A, the blue cables are the hoisting cables of trolley B, and the green cables are the trolley travel cables of trolley B. In the figure the difference in sheave size and position of both trolleys can be seen.

d. Finite Element Analysis

Due to the adjusted cable reeving, the sheave positions of both trolley A and trolley B are adjusted compared to a conventional crane. As a result, also the trolley frames need to be adjusted. A finite element analysis in Ansys Mechanical 2021 R2 is performed for both the proof of static and fatigue strength according to the EN 13001-3-1 standard [12]. The EN 13001-2 standard [13] is used to choose the relevant loads and load combinations. Load combinations A1, A3, B5, C1, C3, C4, and C6 are relevant for a trolley frame. As described in the EN 13001-3-1 standard, the proof of static strength for structural members can be written as:

$$\sigma_{Sd} \leq f_{Rd\sigma} \tag{1}$$

Where σ_{Sd} is the design stress and $f_{Rd\sigma}$ is the limit design stress. In this proof the von Mises equivalent stresses are used. For the trolley frames, turns out that:

$$f_{Rd\sigma} = 321 \text{ N/mm}^2 \tag{2}$$

In figure 16 it can be seen that for trolley A the maximum value is $\sigma_{Sd} = 312$ N/mm^2. For trolley B the value of σ_{Sd} is lower. Therefore, static strength is proven. For the proof of fatigue strength the maximum principle stresses are analysed for the weld locations. For both frames, the following relation can be derived from the standard:

$$\Delta\sigma_c \geq 0.75\Delta\sigma_{Sd} \tag{3}$$

Where σ_c is the characteristic fatigue strength, and σ_{Sd} is the maximum range of design stresses. In figure 17 the

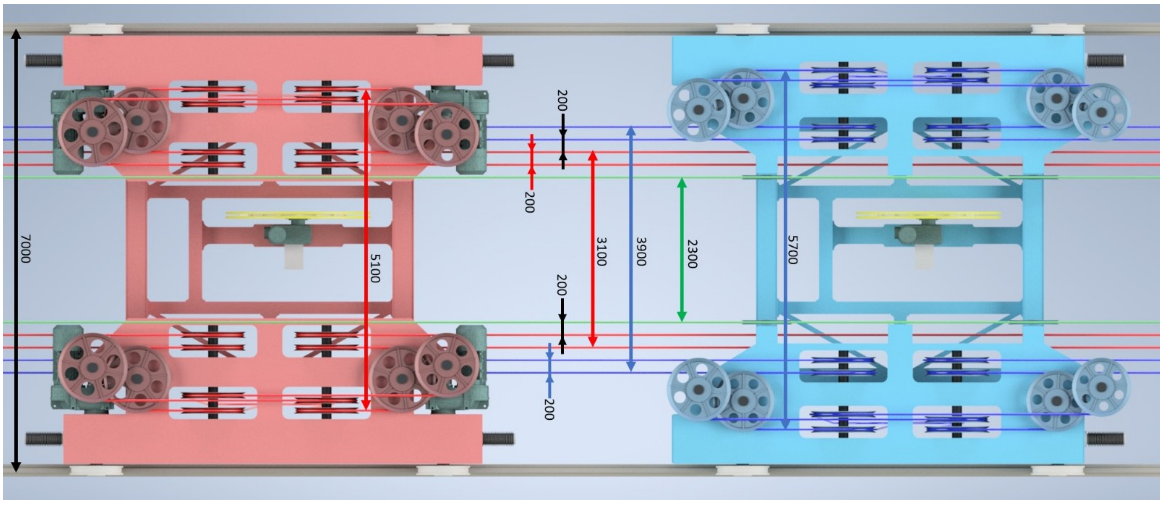

Fig. 15: Top view of both trolleys. Trolley A has the red wire ropes. Trolley B has the blue wire ropes. The green wire rope is the trolley travel cable of trolley B. The LS is left in the figure, the WS is right in the figure. All dimensions are in mm.

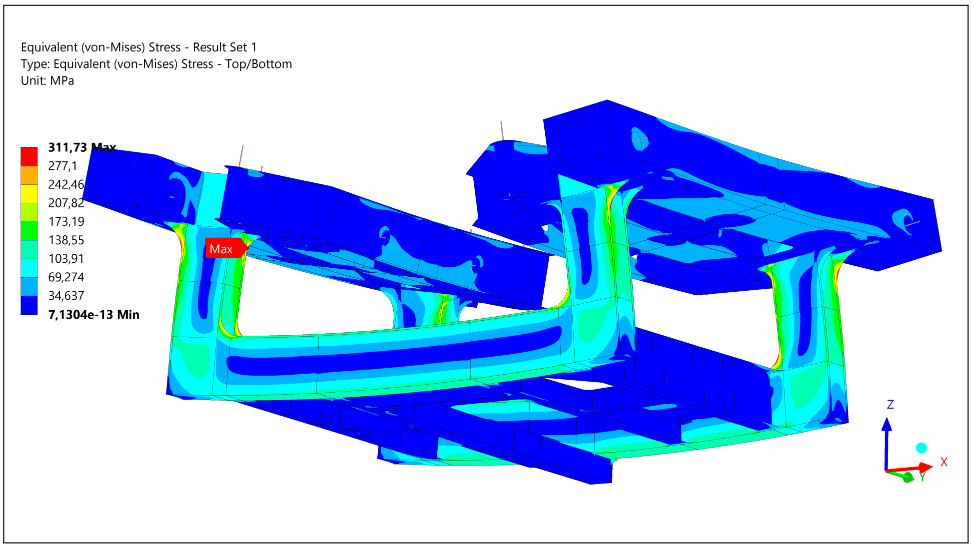

Fig. 16: Proof of static strength of trolley A. Load combination A1. The maximum Von Mises stress is shown.

maximum value of σ_{Sd} is 195 N/mm^2. However, this stress is not on any weld location. The welds in the vicinity of the peak stress have a maximum principal stress of no more than 125 N/mm^2. In figure 18 it is specified which quality the most critical welds need to adhere to. Some welds in all corners of the trolley require a notch class of at least $\Delta\sigma_c =$ 100 N/mm^2 or $\Delta\sigma_c = 71$ N/mm^2, while all other welds in the frame can be of notch class $\Delta\sigma_c = 63$ N/mm^2 or lower. These requirements are the same for both trolleys, as the value of σ_{Sd} for trolley A is only slightly lower.

VI. Conclusions & Discussion

a. Conclusions

Currently, 4 TEU is simultaneously transferred by means of tandem lifting. In this configuration a crane with two adjacently positioned spreaders can load and unload two adjacent rows of a ship. Tandem lifting can be performed in either a single hoist or dual hoist configuration. Single hoist tandem lifting includes only one hoisting mechanism, while dual hoist tandem lifting makes use of two separate hoisting mechanisms. During single hoist tandem lifting, the spreader

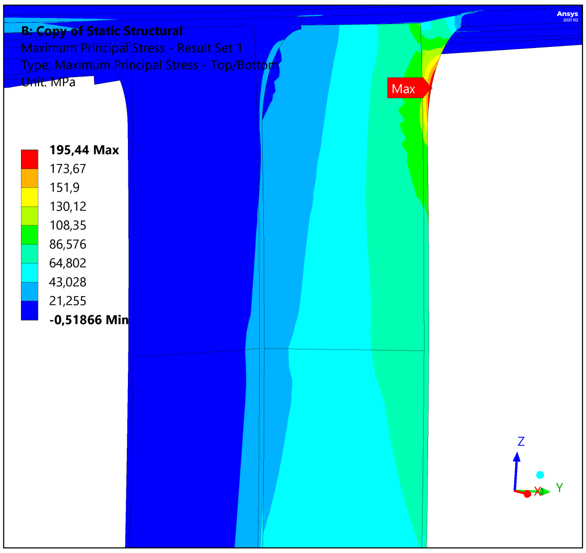

Fig. 17: Proof of fatigue strength of trolley B. Load combination A1. The maximum principal stress is shown.

configuration of the crane needs to be changed when switching between single lifting and tandem lifting. Dual hoist tan-

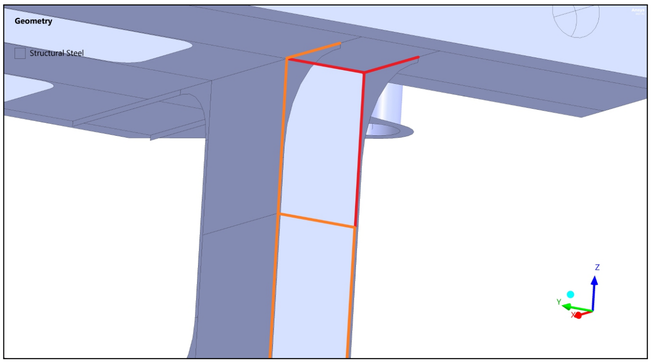

Fig. 18: Weld positions that require a certain quality. The red area requires a notch class of at least $\Delta\sigma_c = 100$ N/mm^2. The orange area requires a notch class of at least $\Delta\sigma_c = 71$ N/mm^2. All other welds can be notch class $\Delta\sigma_c = 63$ N/mm^2. In the figure a part of trolley A is shown, but the same scheme can be made for trolley B. The specified welds apply in all four corners of the trolleys.

dem cranes operate less efficiently when operating in single hoist mode, due to the larger trolley. The simultaneous transfer of 4 TEU can alternatively be achieved by different combinations of trolleys and transfer vehicles.

In total, 7 concepts are composed in this work that are all a variation of trolleys and transfer vehicles. The concepts are compared in terms of productivity, the ability to adjust an existing crane, terminal compatibility, initial costs, operation reliability, and commercial opportunities. Out of the 7 composed concepts, concept 1 turned out the be the most suitable concept for the simultaneous transfer of 4 TEU on a standard STS crane structure. The productivity of concept 1 is 47% higher compared to a conventional crane.

To prevent a large load moment on the crane structure, the hoisting mechanisms of both trolleys are located in the machinery house on the trolley girder. The landside trolley is a semi rope trolley, while the waterside trolley is a rope towed trolley. In this way, only one of the trolley travel mechanisms needs to be located in the machinery house. As the semi rope trolley has directly driven wheels, the trolley acceleration is limited by wheel slip. However, this is not problematic as the landside trolley needs to travel smaller distances than the waterside trolley. The wire ropes are supported by a continuous rope support system. All wire ropes should run adjacently on top of the rope support rollers, with sufficient space in between. To accomplish this, the sheave positions and diameters of both trolleys differ. The changes in the wire rope reeving slightly decreases the wire rope lifetime. To allow the different sheave positions, the frames of both trolleys need to be adjusted compared to a conventional trolley. The trolley frame adjustments are validated by means of a finite element analysis.

b. Discussion

The focus of this work laid on the most important and critical aspects of this design. However, multiple secondary aspects are not worked out yet. Future work needs to focus on the detailed design of the trolleys. Also, the crane structure of the concept needs to be designed.

To ensure safe operations, a control system should be designed to prevent any collisions between the trolleys or the loads. Besides the safety aspects, also the operational aspects of the control of this concept will determine whether it can be successfully implemented in practice. Both trolleys will be remotely controlled. Although remote control of STS container cranes is already successfully implemented in practice, these cranes have only one trolley. The number of operators that are necessary to operate the double trolley crane could be decisive for the success of this concept. In case the control by one operator turns out to be problematic, it will be a matter of time before the process can be successfully automated. Automation would be a perfect solution for this concept to perform effectively.

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[12] European Committee for Standardization, “En 13001-3-1 cranes - general design - part 3-1: Limit states and proof of competence of steel structure,” 2018.

[13] European Committee for Standardization, “En 13001-2 cranes - general design - part 2: Load actions,” 2021.

B

Patent study

This appendix documents all patents (and utility models) that were found, while taking into account the requisites described in chapter 4. For every category, a table of the patents is shown, followed by a sequence of figures. The figures shown are the cover figures of the patents. To position the figures effectively on the pages, some images will be rotated with 90 degrees. Often, multiple patents are related to the same invention. In this case, they are placed in one row in the table, and represented by a single figure. If possible, the main patent is listed first, followed by all related patents or utility models.

B.1. Transfer vehicle(s)

Table B.1: Patents of STS cranes with transfer vehicles.

Patent number	**Applicant(s)**	**Brief description**	**Priority year, month**	**Fig.**
WO03099700A2	UNIV DELFT TECH [NL]; LUTTEKES EVERT [NL]; RIJSENBRIJ JOANNES CORNELIS [NL]	TU Delft carrier crane. see section 3.1 for explanation.	2002, 05	B.1
ES2860848A1	BARBERA MAYOR JUAN CARLOS [ES]	Separate WS and LS hoists. A horizontal transport trolley driving between WS and LS.	2020, 04	B.2
WO0125131A1	UNIV DELFT TECH [NL]; LUTTEKES EVERT [NL]; RIJSENBRIJ JOANNES CORNELIS [NL]	STS crane with an auxiliary frame. Trolleys drive on the auxiliary frame to transfer containers between LS and WS hoist(s) on the main girder.	1999, 09	B.3
US5931625A	TAX INGENIEWIGESELLSCHAFT M B [DE]	STS crane with a LS and WS trolley with hoisting means. A transfer unit drives between LS and WS. The transfer unit is loaded and unloaded by the hoists. The trolleys are able to pass the transfer unit, but they cannot pass each other.	1993, 03	B.4
DE1906212A1	TAX HANS	STS crane with two transfer vehicles between LS and WS hoists. The transfer vehicles can pass each other.	1969, 02	B.5
US5048703A US5152408A DE8916221U1	TAX INGENIEURGESELLSCHAFT MBH [DE]	STS crane with a transfer vehicle that drives between a LS and WS trolley.	1988, 05	B.6
EP0759885A1	TAX INGENIEURGESELLSCHAFT MBH [DE]	STS crane with a transfer vehicle that drives between a LS and WS trolley. The transfer vehicle consists of one ore more vertical layers.	1994, 05	B.7
WO9914151A1	TAX INGENIEURGESELLSCHAFT MBH [DE]; TAX HANS [DE]; BAUER DIETER [DE]; HOESLER KLAUS [DE]	STS crane with at least two rail tracks on which multiple trolleys and transfer vehicles can drive.	1997, 09	B.8
CN103303805A CN203359820U	HUADIAN HEAVY IND CO LTD	An STS crane with double-layered boom. The higher layer is for a hoisting trolley that unloads or loads a vessel. Lower layer is for transfer vehicle that transfers container between WS and LS.	2013, 06	B.9
CN103523680A CN203529777U	HUADIAN HEAVY IND CO LTD	STS crane with double layer girder and three trolleys. The middle trolley is a transfer trolley. Other trolleys have hoisting means and spreaders	2013, 10	B.10

Continued on next page

Table B.1 – continued from previous page

Patent number	Applicant(s)	Brief description	Priority year, month	Fig.
CN203359821U	HUADIAN HEAVY IND CO LTD	Double layer crane. Rails for transfer trolley(s) are positioned below the main traveling girders.	2013, 06	B.11
CN103818832A CN203699710U	HUADIAN HEAVY IND CO LTD	STS crane with truss crossbeam and three trolleys. On an upper track drive two trolleys, both with hoisting means and a spreader, while the middle trolleys transfers container between WS and LS.	2014, 02	B.12
JPH0768036B2 JPH1121071A JPH09175781A JPH09301674A JPH09315758A JPH0958973A JP2006327735A	ISHIKAWAJIMA HARIMA HEAVY IND	Multiple variations of an STS crane with WS and LS trolley and a transfer vehicle. The transfer vehicle transfers containers between the WS and LS trolley.	1986, 07	B.13
JPH11278790A JP2000143154A	ISHIKAWAJIMA HARIMA HEAVY IND	STS crane with WS and LS trolley and two transfer vehicles that transfer containers between LS and WS. The transfer vehicles can pass each other, even in loaded configuration.	1998, 03	B.14
JPH10330078A	ISHIKAWAJIMA HARIMA HEAVY IND	STS crane with WS and LS trolley and two transfer vehicles that transfer containers between LS and WS. The transfer vehicles cannot pass each other, but have to transfer the container to one another.	1997, 06	B.15
JP3329844B2	ISHIKAWAJIMA HARIMA HEAVY IND	A WS trolley with hoisting means picks up a container and sets it on a primary horizontal carrying device that drives towards the LS. The container is transferred to a secondary horizontal carrying device which hands it over to a yard crane.	1991, 10	B.16
JPH09301681A	ISHIKAWAJIMA HARIMA HEAVY IND	Transfer vehicles that drive on a girder below the main girder transfer containers between WS and LS. Both a WS and LS trolley are positioned on the main girder.	1996, 05	B.17
EP0879785A2 JPH11157777A WO9940019A1 JP2000211743A WO9940020A1 JP3298488B2 JPH11255472A	HITACHI LTD [JP]	Crane with three trolleys on main girder. LS and WS trolley have lifting means and are capable of picking up and setting down containers, while the middle trolley only has lifting means to hoist and lower a container. Middle trolley serves as carrier to transfer container between WS and LS trolley. LS and WS trolleys can load and unload the middle trolley.	1997, 05	B.18
JPH10226492A JPH1111871A JPH10226493A JPH09315759A JPH10120366A	ISHIKAWAJIMA HARIMA HEAVY IND	Multiple patents related to traversers that serve as transfer vehicle.	1996, 05	B.19
JPH01317995A	SUMITOMO HEAVY INDUSTRIES	STS crane with three trolleys. The WS and LS trolley have hoisting means and a spreader, while the middle trolley serves as transfer vehicle.	1988, 06	B.20

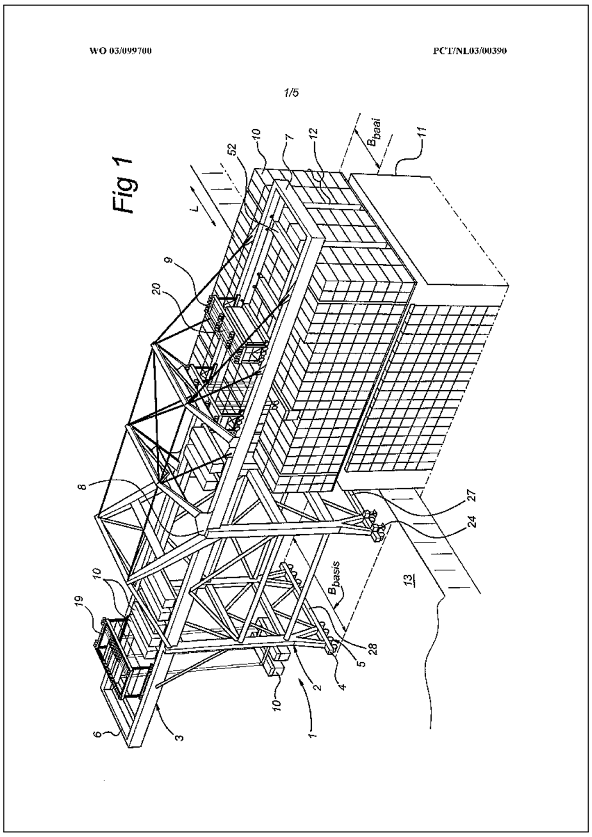


Figure B.1: WO03099700A2

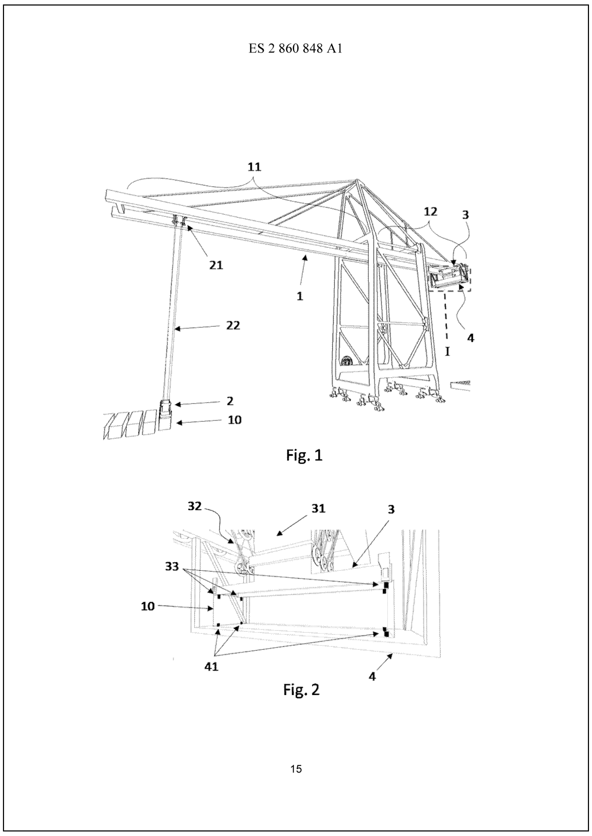


Figure B.2: ES2860848A1

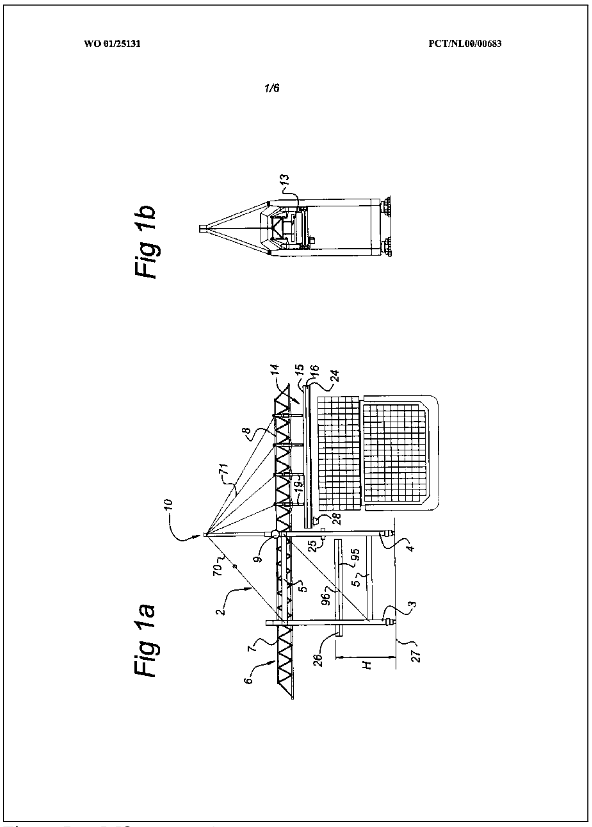


Figure B.3: WO0125131A1

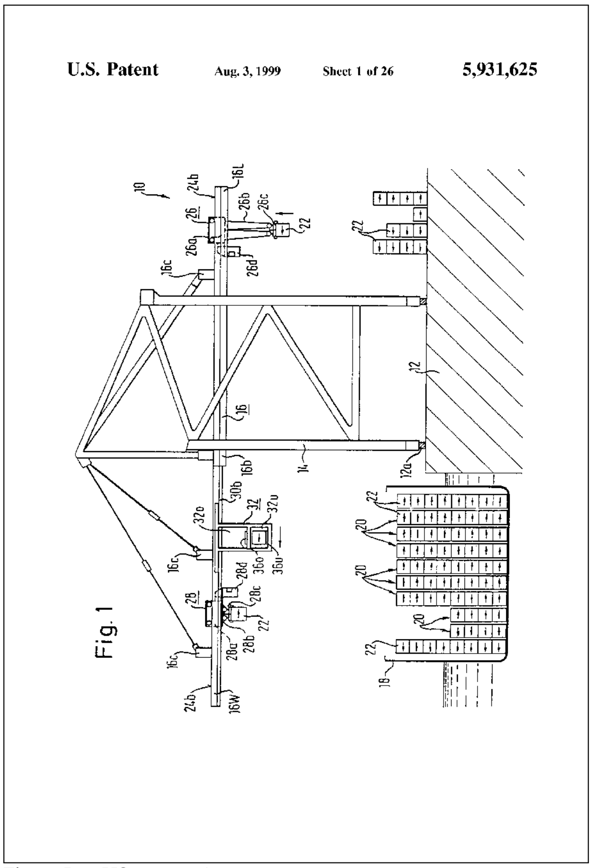


Figure B.4: US5931625A

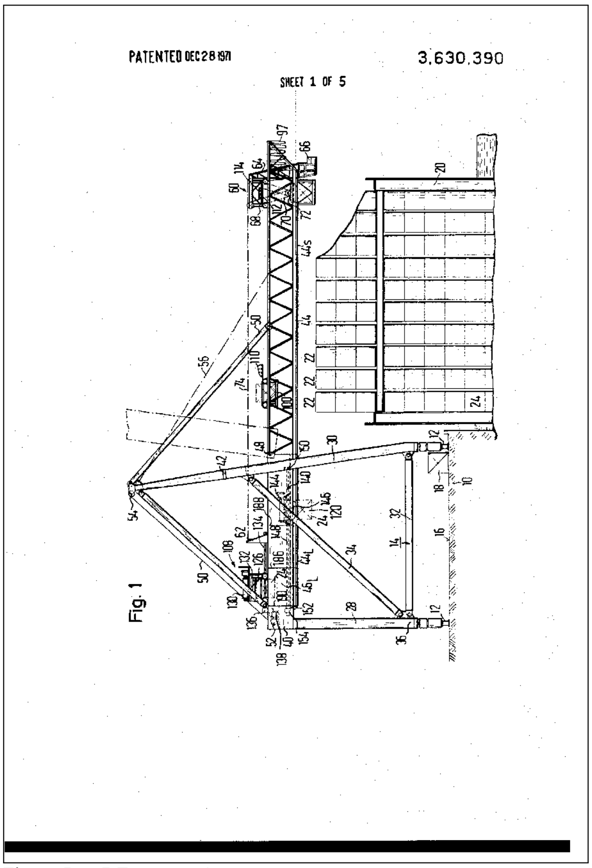


Figure B.5: DE1906212A1

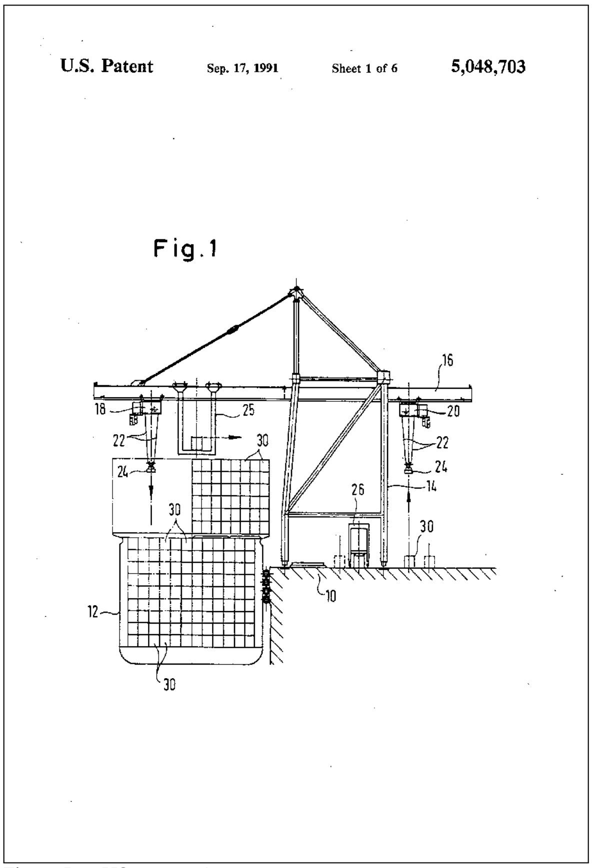


Figure B.6: US5048703A

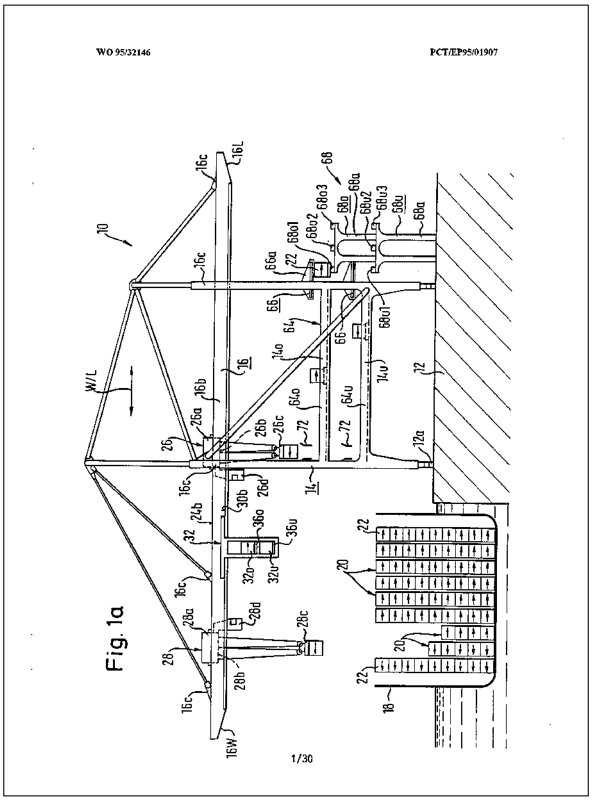


Figure B.7: EP0759885A1

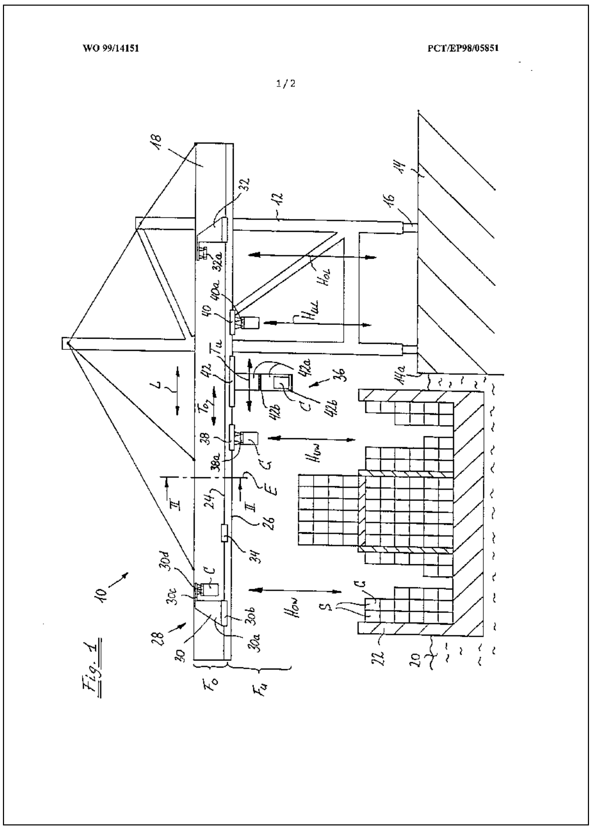


Figure B.8: WO9914151A1

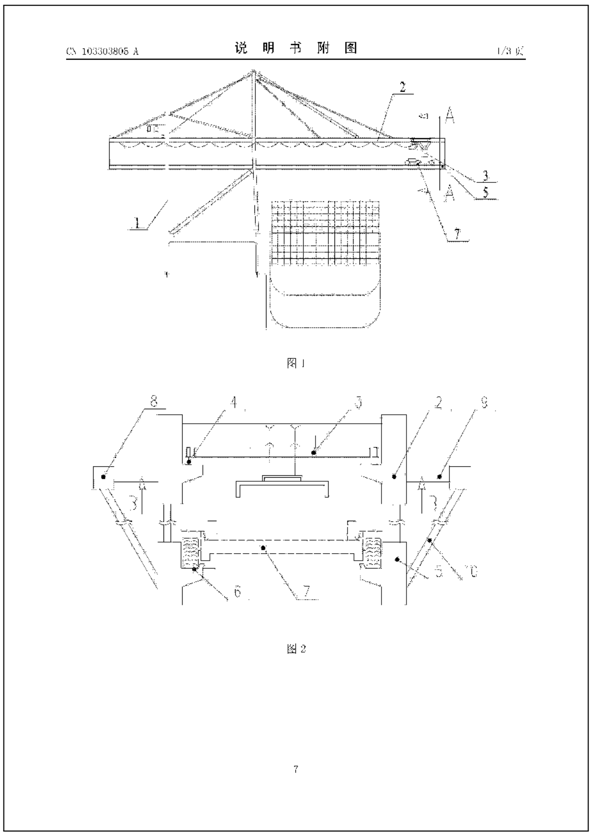


Figure B.9: CN103303805A

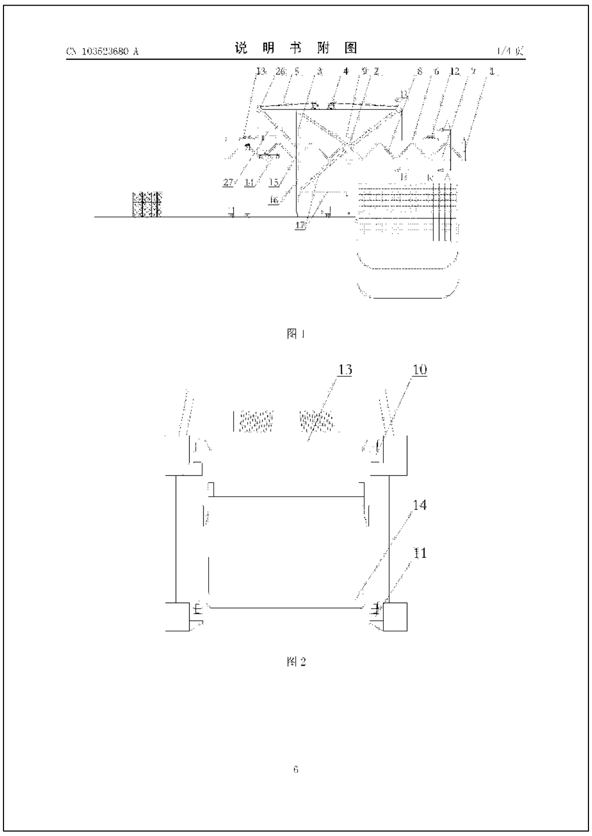


Figure B.10: CN103523680A

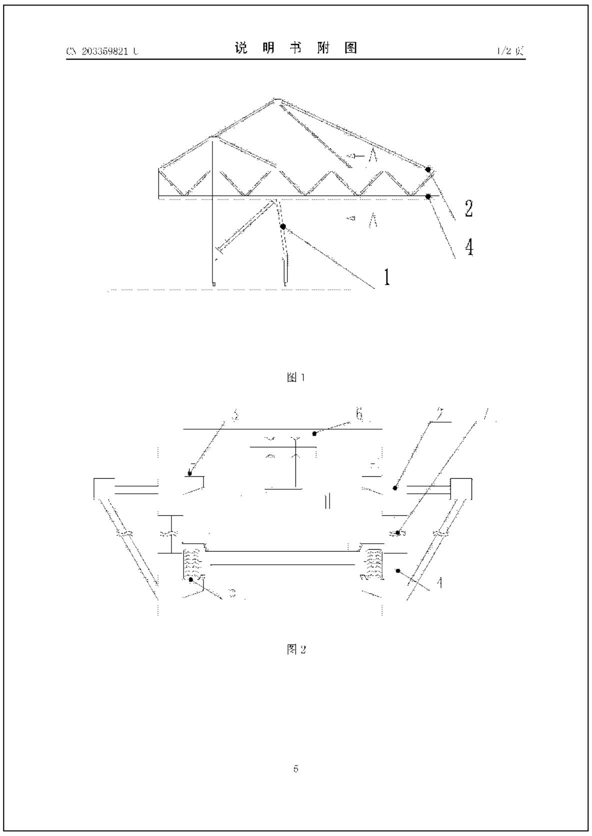
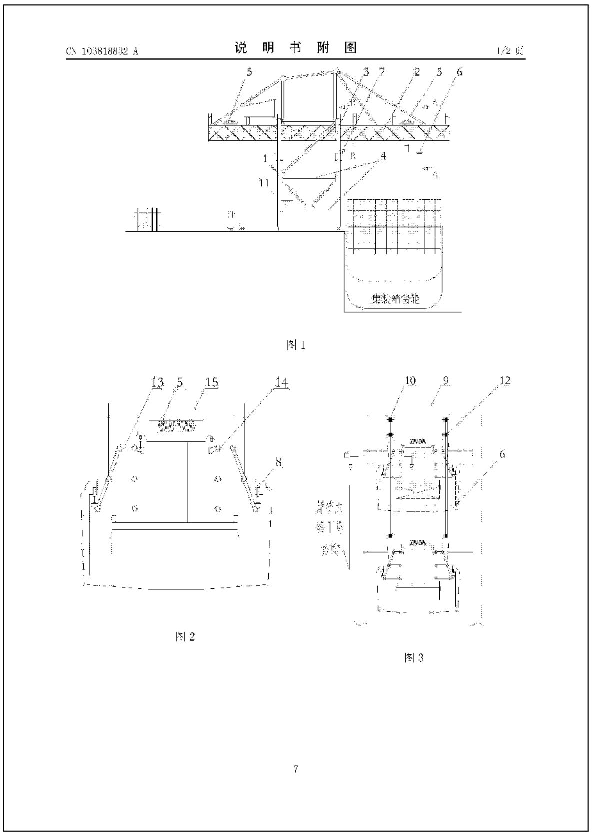


Figure B.11: CN203359821U



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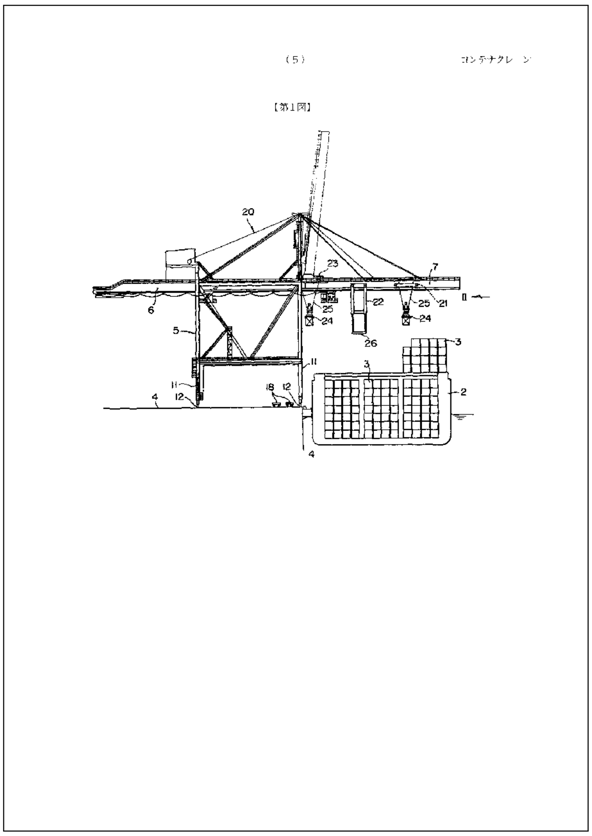


Figure B.13: JPH0768036B2

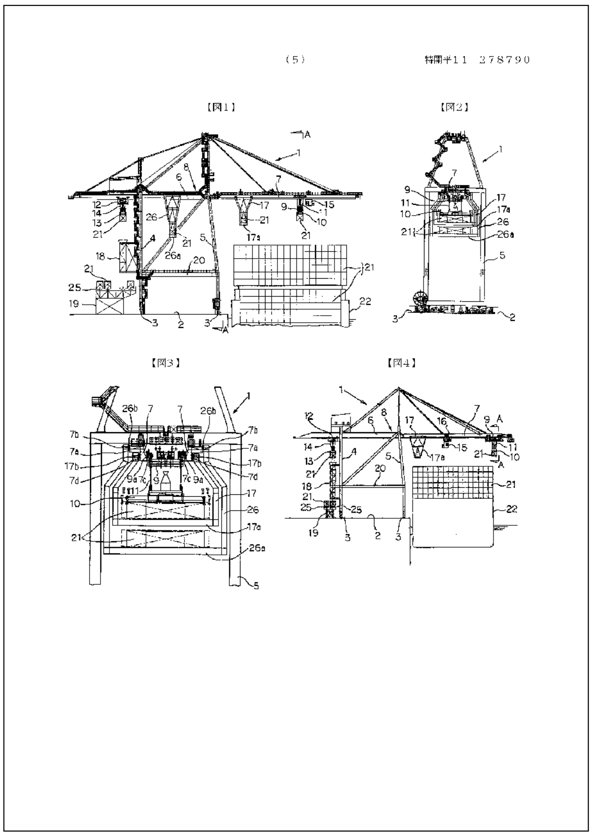


Figure B.14: JPH11278790A

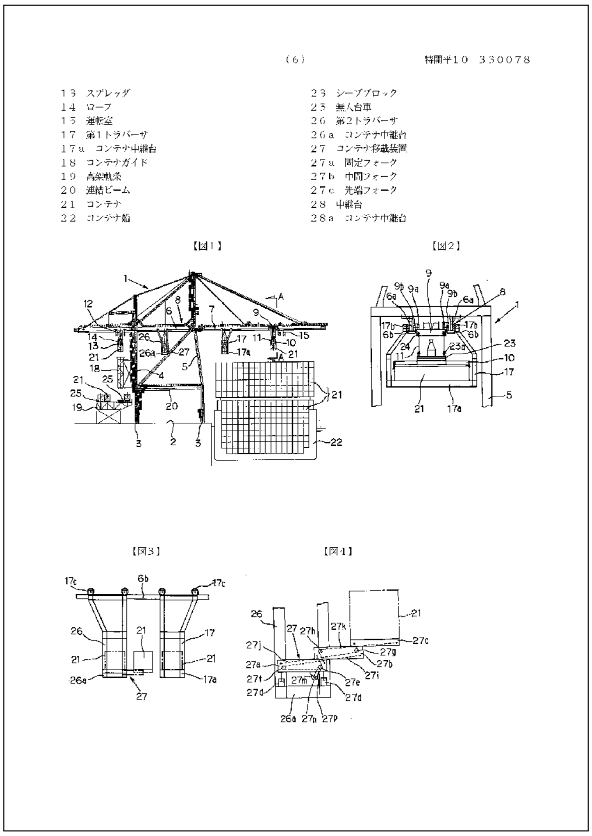


Figure B.15: JPH10330078A

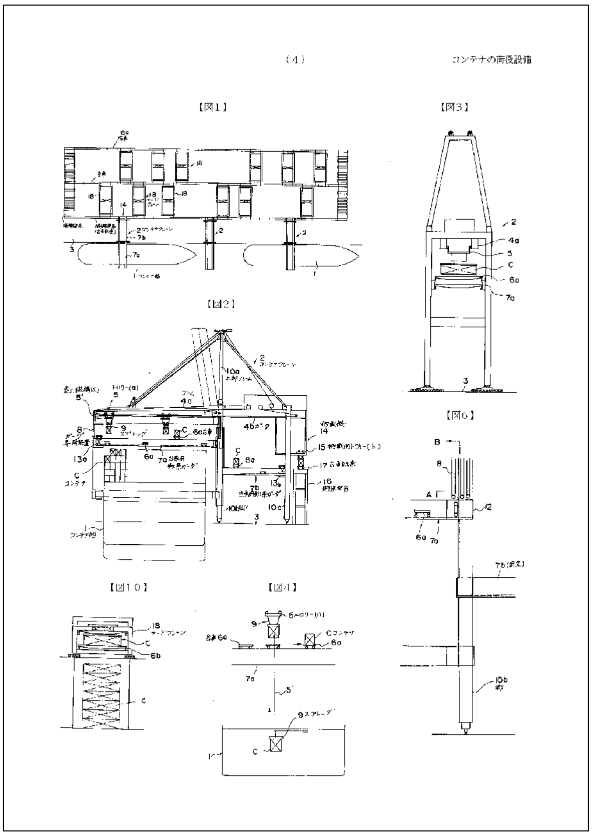


Figure B.16: JP3329844B2

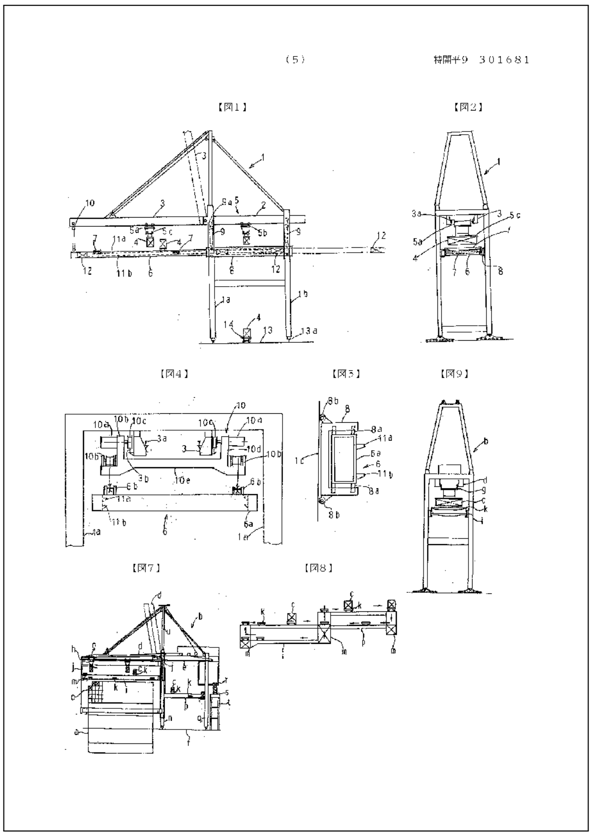


Figure B.17: JPH09301681A

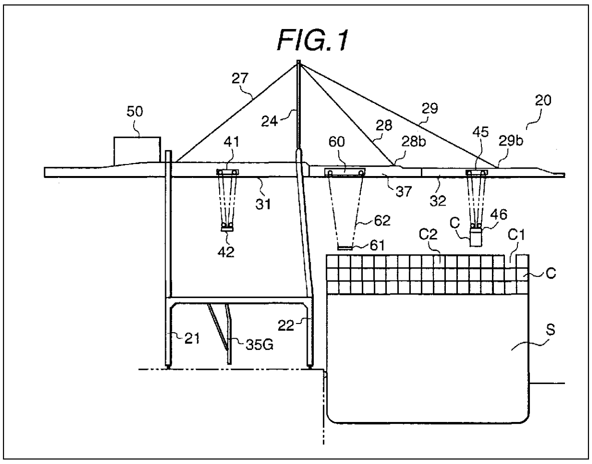


Figure B.18: EP0879785A2

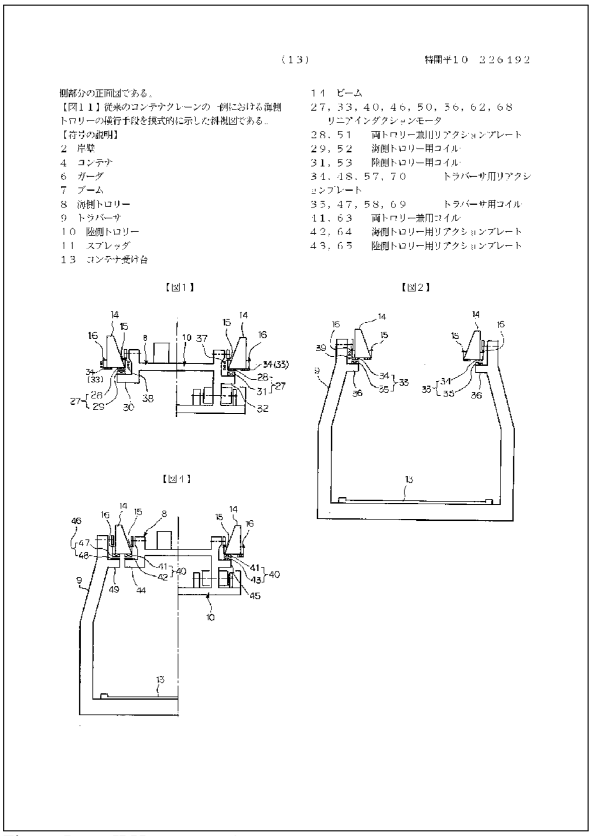


Figure B.19: JPH10226492A

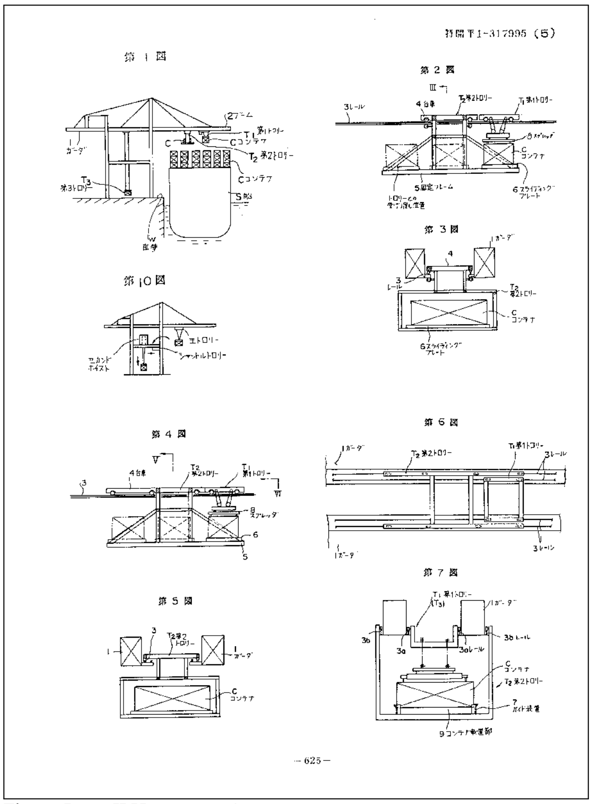


Figure B.20: JP01317995A

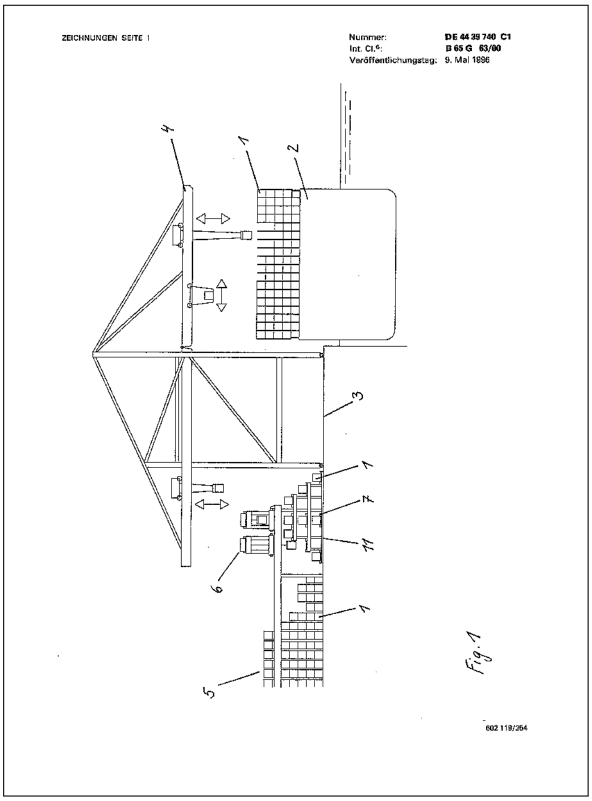


Figure B.21: DE4439740C1

B.2. Trolleys passing each other

Table B.2: Patents of STS cranes with trolleys that can pass each other.

Patent number	Applicant(s)	Brief description	Priority year, month	Fig.
US6530492B2	NOELL CRANE SYS GMBH [DE]	STS crane with at least two trolleys on main girder, which can pass each other. Both trolleys drive on different running tracks.	1997, 02	B.22
US3881608A	CONRAD STARKE B V	STS crane with two trolleys driving on vertically spaced apart tracks. When the upper trolley has a suspended load, the trolleys can pass each other. The upper trolley can be provided with rotational means, to enable a 90 degree rotation of the container.	1972, 08	B.23
CN104261267A CN104340863A CN204111203U CN204198282U CN104310231A CN204588520U CN104261268A CN211895744U CN113003431A CN112744716A CN211895771U CN211444775U CN112573384A CN211895768U CN211444750U CN112744717A	HUADIAN HEAVY IND CO LTD	Crossing type crane with double trolleys. The trolleys can pass each other, by fitting inside one another.	2014, 10	B.24
WO2020224050A1 CN109969937A CN110002347A CN209853575U CN210340128U CN209853595U CN209853593U CN209853587U CN110002344A	HUADIAN HEAVY IND CO LTD [CN]	Upgrade of a traditional crane to a crossing type crane with double trolleys. The trolleys can pass each other, by fitting inside one another.	2019, 05	B.27
CN101323415A	MOAYONG FAN [CN]	STS crane with two trolleys that can pass each other. The centrally located trolley can rotate which allows it to pass the other trolley while carrying a container.	2008, 07	B.26
WO2020224050A1	HUADIAN HEAVY IND CO LTD [CN]	STS crane with two trolleys that are able to pass each other. The trolleys drive on different tracks. One trolley is positioned above the other.	2019, 05	B.27

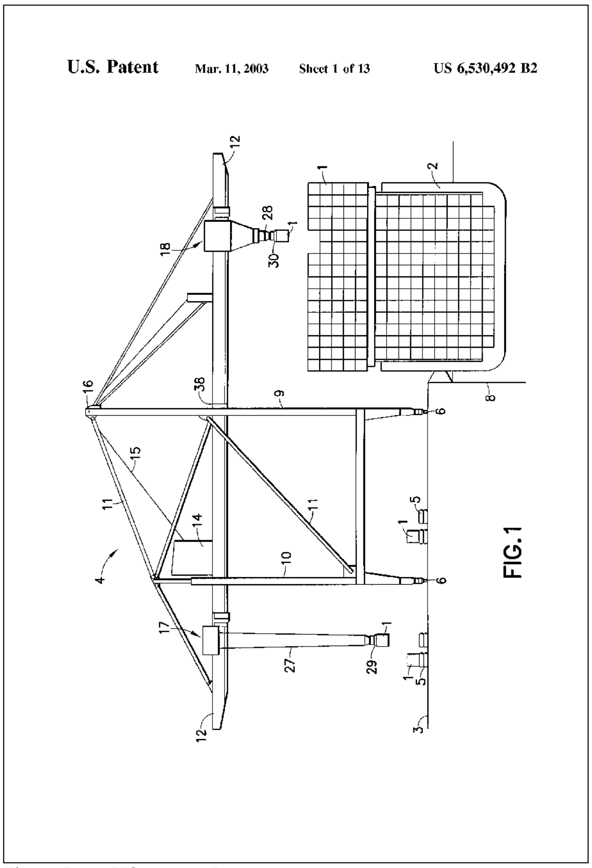


Figure B.22: US6530492B2

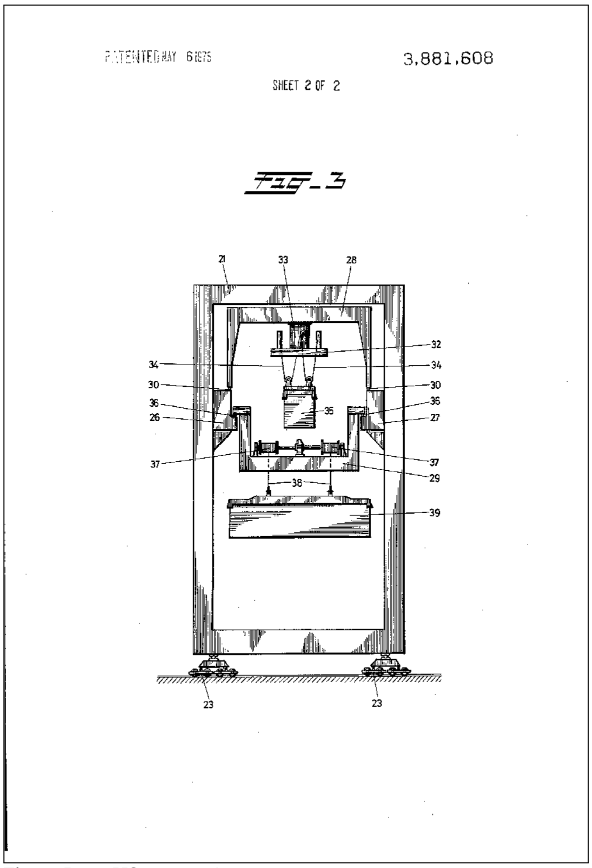


Figure B.23: US3881608A

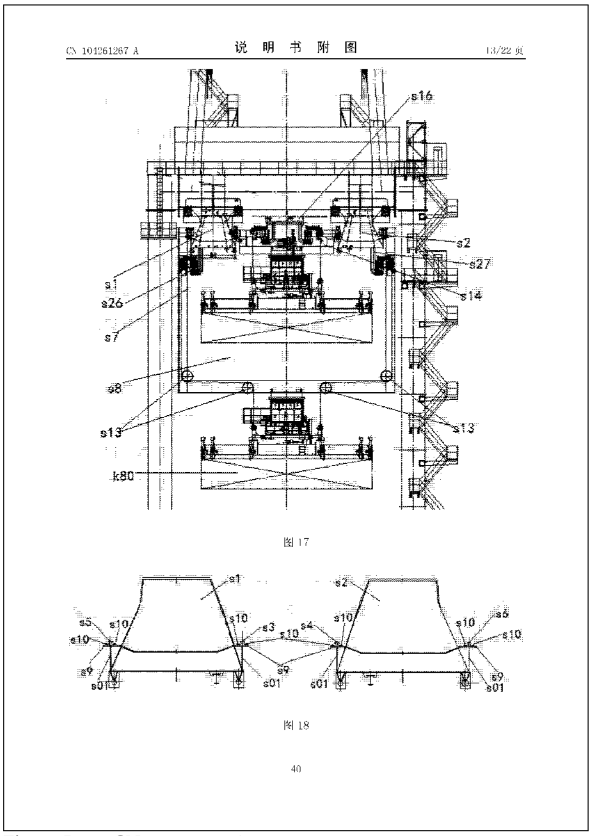


Figure B.24: CN104261267A

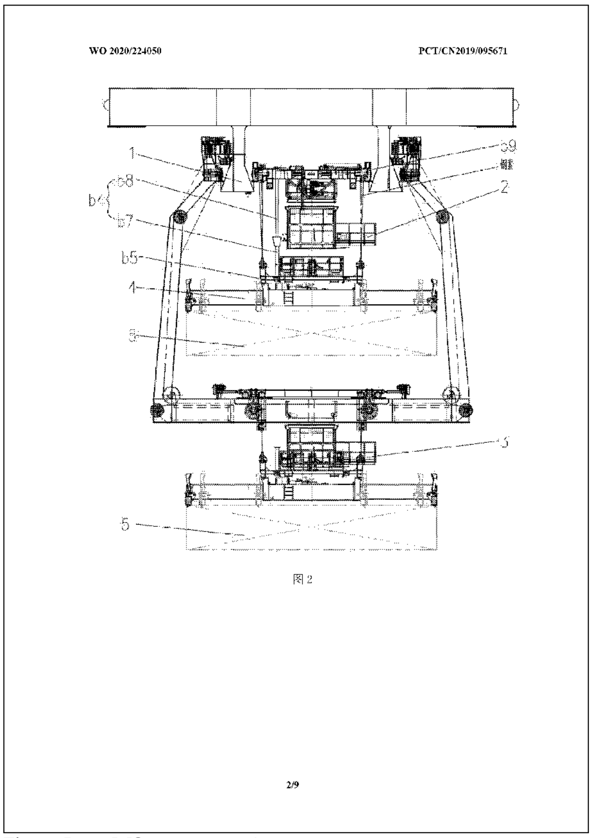


Figure B.25: WO2020224050A1

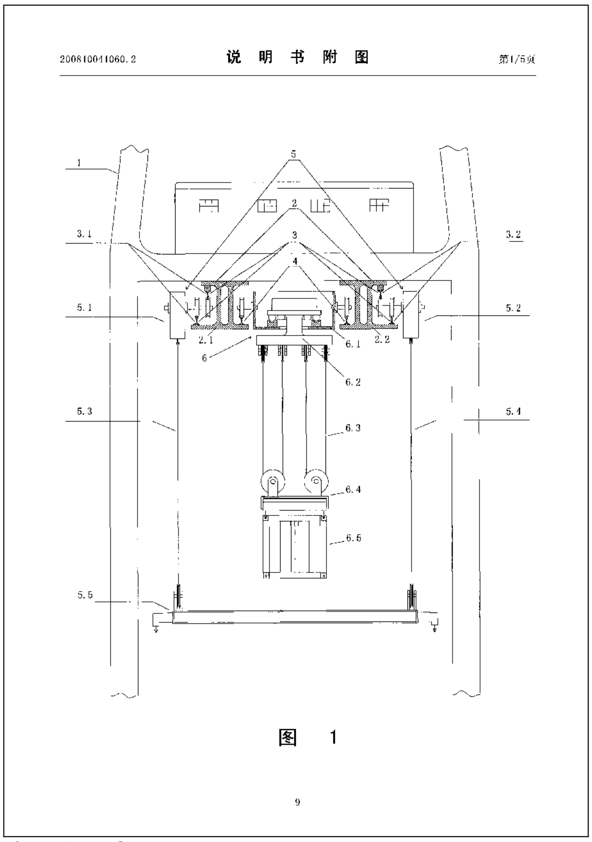


Figure B.26: CN101323415A

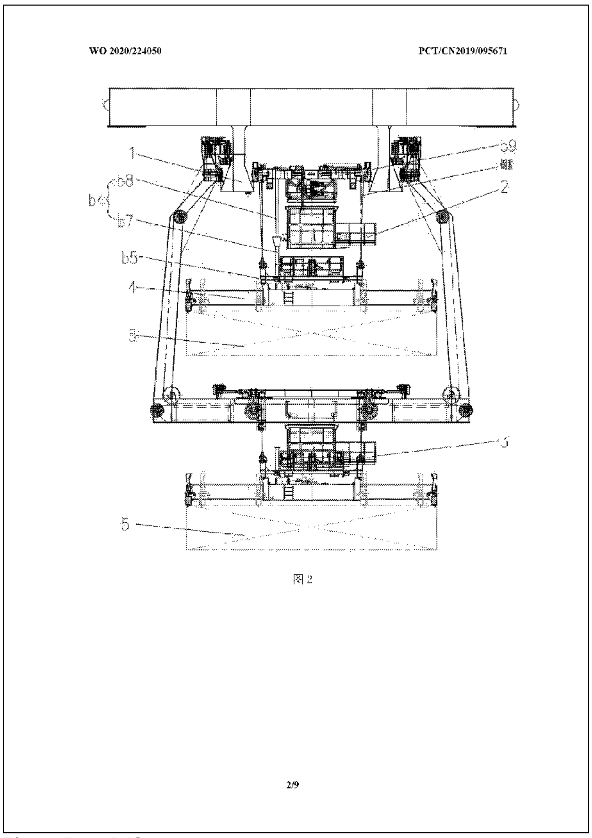


Figure B.27: WO2020224050A1

B.3. Trolleys not passing

Table B.3: Patents of STS cranes with multiple trolleys that cannot pass each other.

Patent number	**Applicant(s)**	**Brief description**	**Priority year, month**	**Fig.**
CN107285208A	SHANGHAI ZHENHUA HEAVY IND CO	STS crane with two trolleys on main girder. The trolleys can be either connected to enable tandem lifting, or used separately.	2017, 08	B.28
CN105000480A CN204778506U	RAINBOW CARGOTEC IND CO LTD	STS crane with two independent trolleys.	2015, 07	B.29
CN102548889A	PACECO CORP	Wire rope reeving system for two trolleys that can operate either co-ordinately or independently.	2009, 07	B.30
US7559429B1	PACECO CORP [US]	Wire rope reeving system for two trolleys that can operate either co-ordinately or independently.	2008, 06	B.31

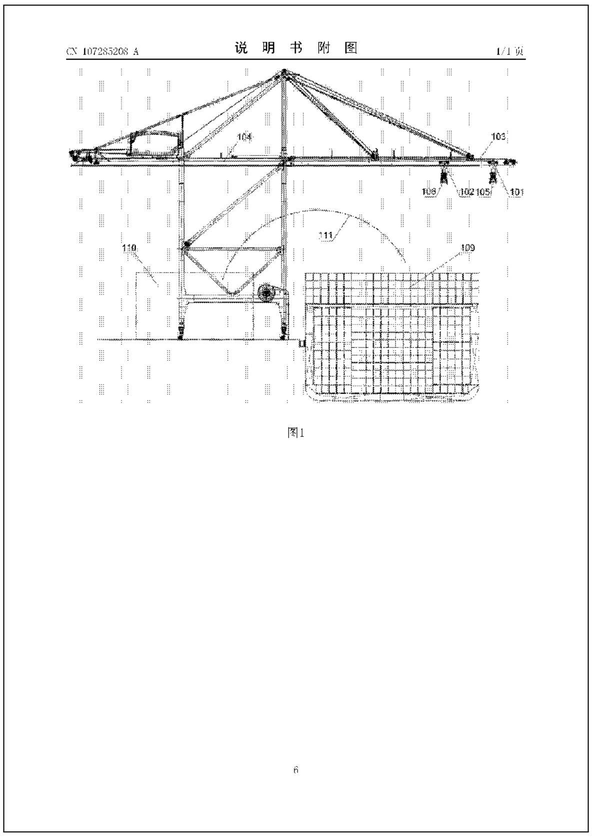


Figure B.28: CN107285208A

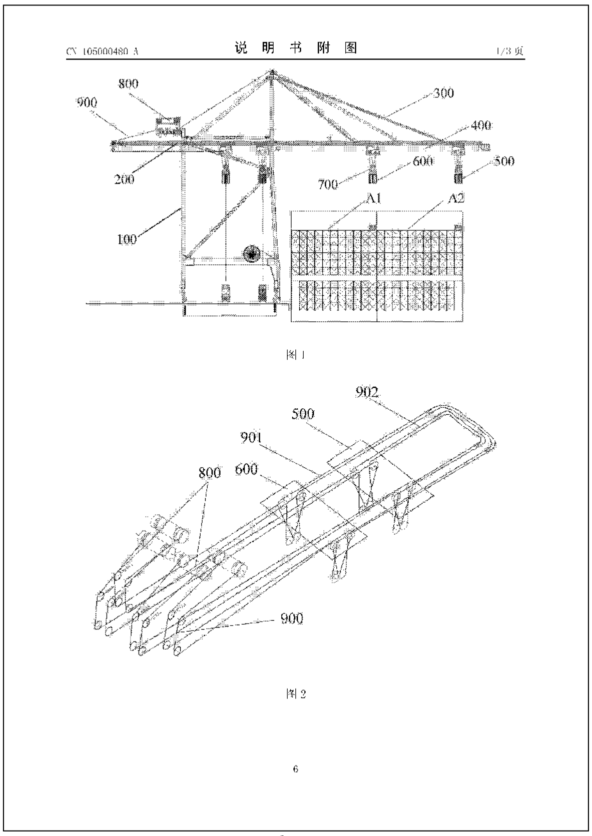


Figure B.29: CN105000480A and CN204778506U

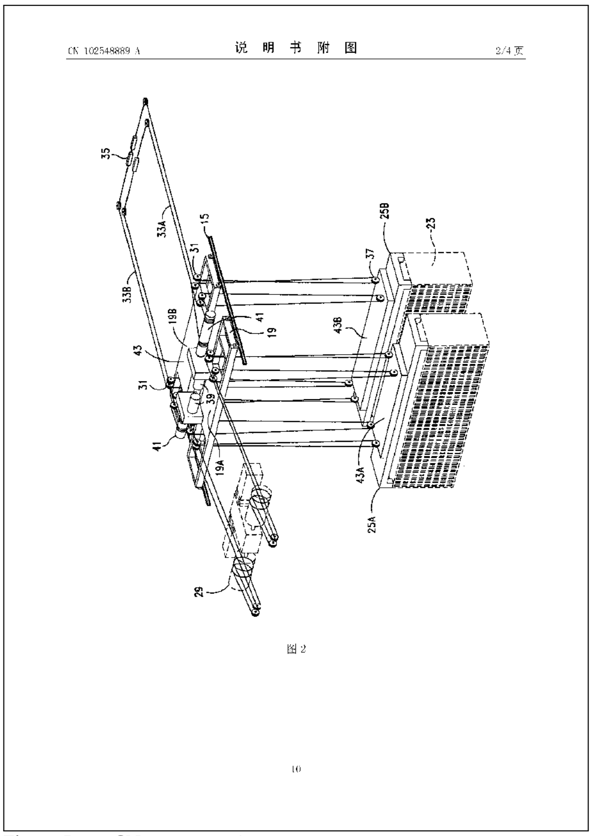


Figure B.30: CN102548889A

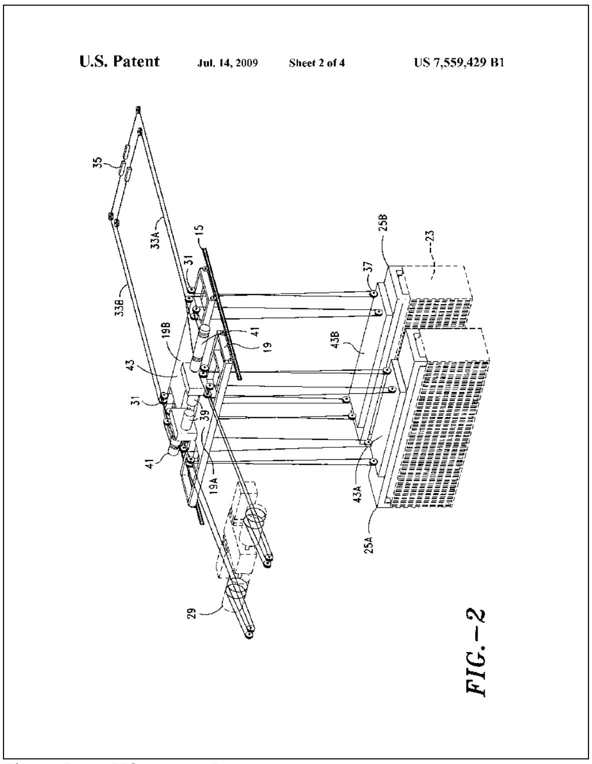


Figure B.31: US7559429B1

B.4. Dual hoist

Table B.4: Patents of STS cranes with the dual hoist working principle.

Patent number	**Applicant(s)**	**Brief description**	**Priority year, month**	**Fig.**
EP1927569A1	KALMAR IND B V [NL]	STS container crane with trolley with 2 hoisting mechanisms. A cabin is positioned in between the hoists. The hoists can be operated independently.	2006, 12	B.32
JPS53138164A JPS546267A JPS5447264A	ISHIKAWAJIMA HARIMA HEAVY IND	Dual hoist principle. Multiple hoisting systems, one trolley.	1977, 05	B.33
JPS61267690A	ISHIKAWAJIMA HARIMA HEAVY IND	STS crane with a WS and LS trolley. A relay frame in between the trolleys serves as a transfer platform.	1985, 05	B.34
JP2007261770A	MITSUI SHIPBUILDING ENG	Dual hoist principle. One trolley, two hoisting mechanisms.	2006, 03	B.35

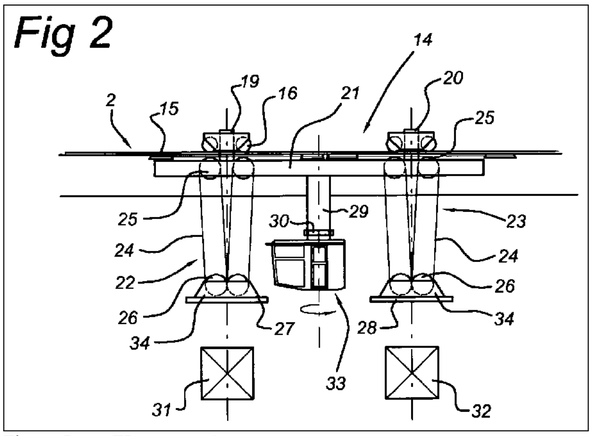


Figure B.32: EP1927569A1

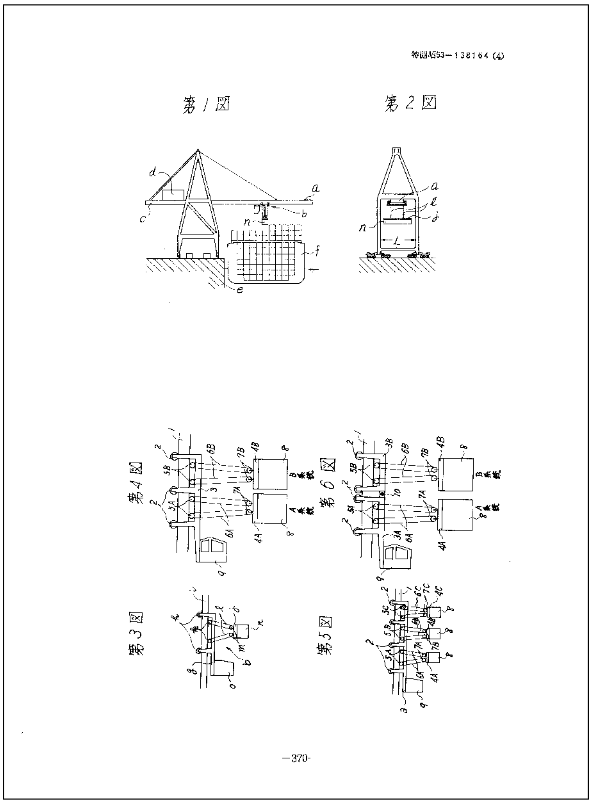


Figure B.33: JPS53138164A

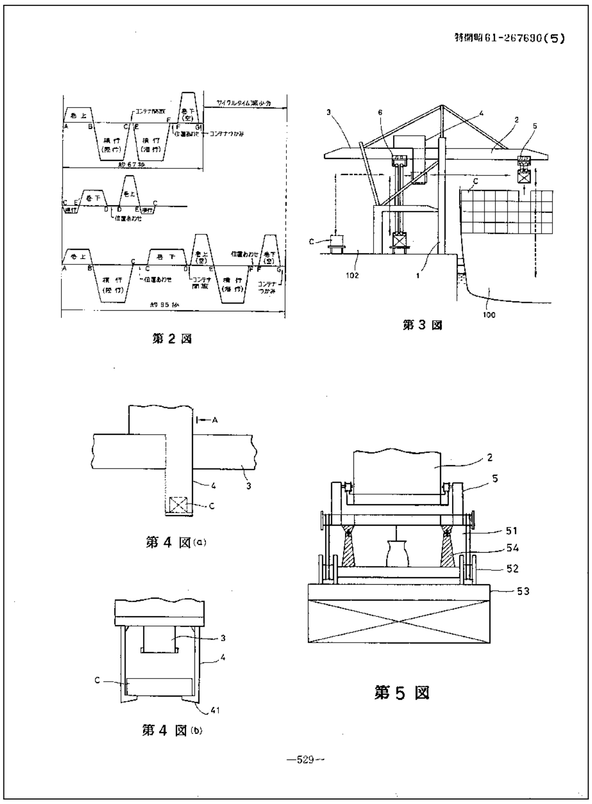


Figure B.34: JPS61267690A

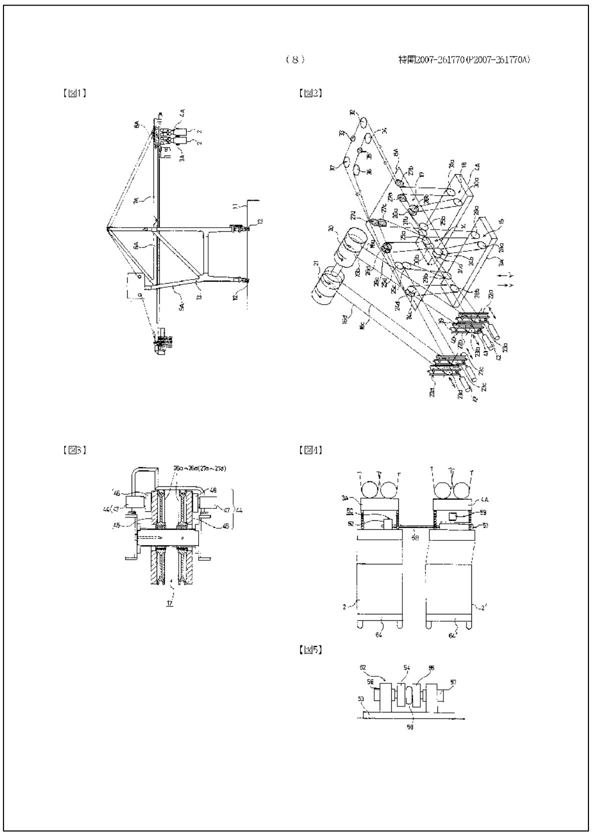


Figure B.35: JP2007261770A

B.5. Circulating systems

Table B.5: Patents of STS cranes with a circulating system.

Patent number	Applicant(s)	Brief description	Priority year, month	Fig.
CN103395699A	HUADIAN HEAVY IND CO LTD	Double-layered quay crane with elevators. Trolleys can drive on a lower and upper track. Elevators lift and lower the trolleys at the WS and LS of the girder. In this way the trolleys can circulate.	2013, 07	B.36
KR20030006012A	HAN MAN YOP [KR]	The CreaTech Technotainer (see section 3.3 for explanation).	2001, 07	B.37
KR0143699B1	HAN MAN YEUP [KR]	An STS crane with two booms positioned above each other, with trolleys that circulate between the booms. Each trolley has lifting means with a spreader to pick up and set down containers.	1995, 09	B.38
WO0048937A1 WO0069767A1	CREATECH CO INC [KR]; HAN MAN YOP [KR]; SON SEUNG YO [KR]	STS crane with a circulating boom that is located at a single height. Trolleys can circulate on the boom. A spreader is attached to a trolley when travelling, and detached when a container is hoisted or lowered. Two hoists are located on the boom to enable lifting.	1999, 02	B.39
CN110877865A	UNIV WUHAN TECH	STS crane capable of circularly loading and unloading. The crane consists of two booms positioned side by side. Trolleys can turn at the WS and LS, to drive back on the other boom.	2019, 11	B.40
NL1001548C2	IV CONSULT B V [NL]	Container crane with elongated closed loop rail track on the girder, which allows trolleys to circulate.	1996, 11	B.41

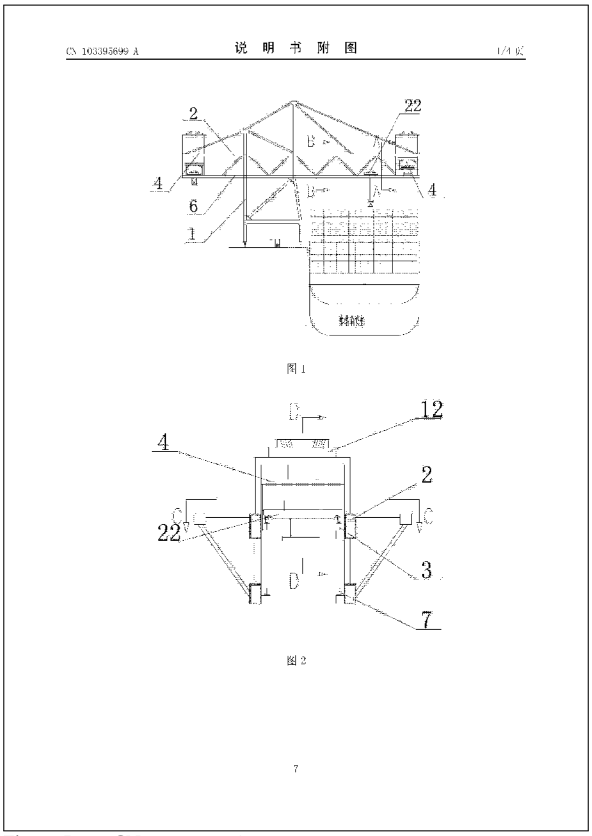


Figure B.36: CN103395699A

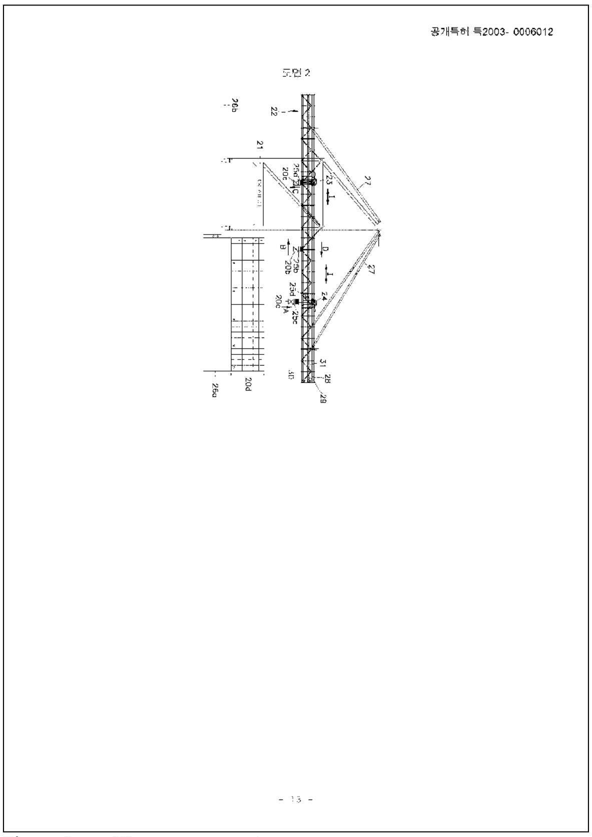


Figure B.37: KR20030006012A

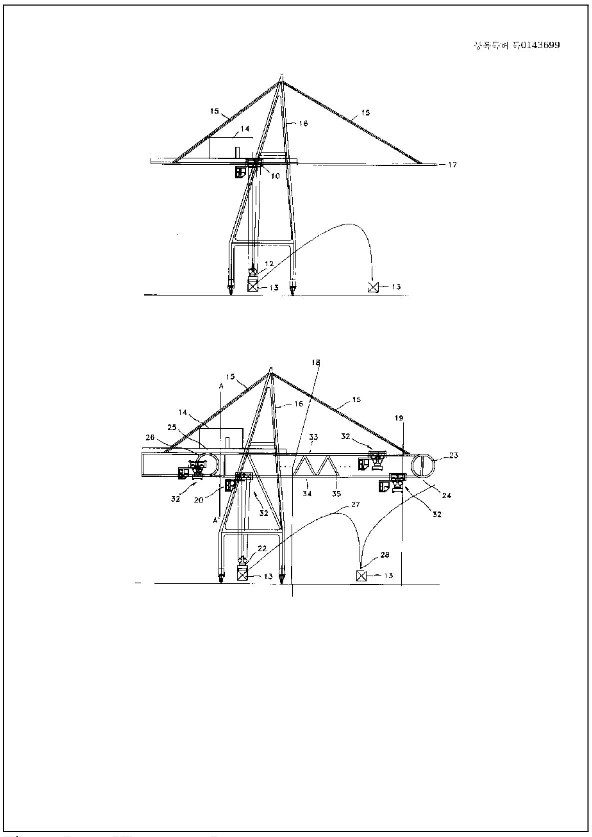


Figure B.38: KR0143699B1

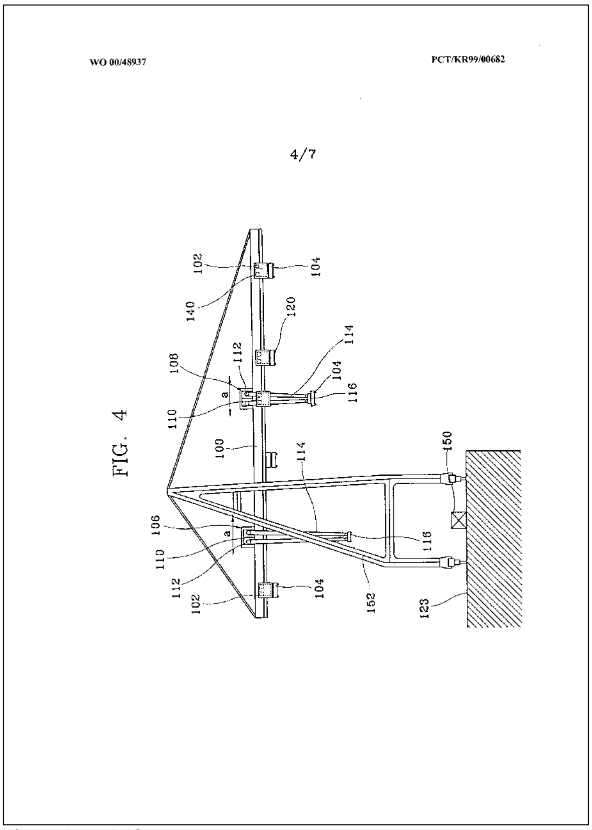


Figure B.39: WO0048937A1

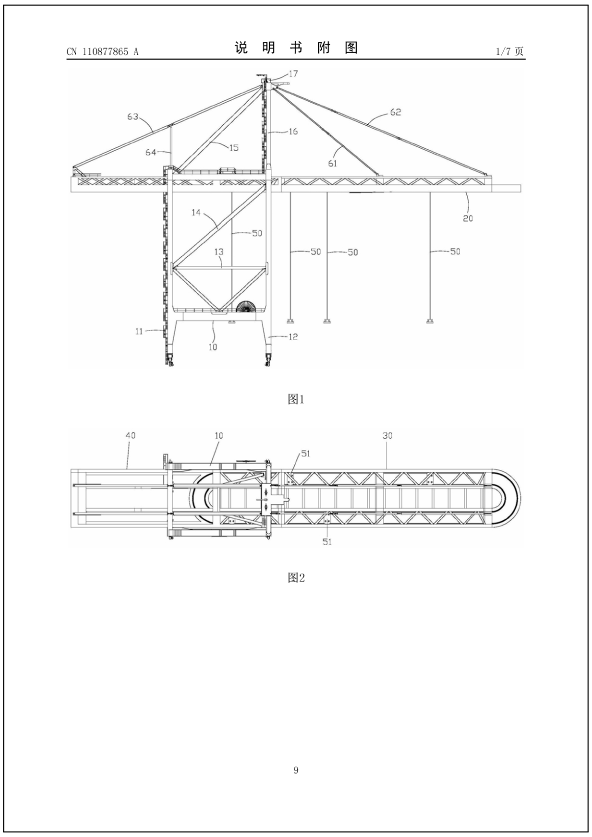


Figure B.40: CN110877865A

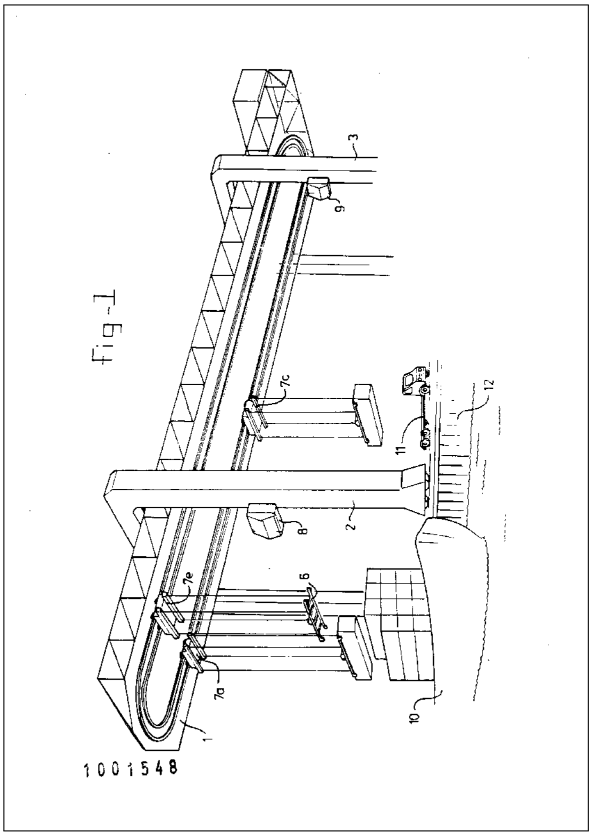


Figure B.41: NL1001548C2

C
Concept generation

C.1. Functional decomposition

In table 6.1, all functions of an STS container crane are listed.

Table C.1: Functional decomposition. Extensive version.

Transferring containers between a container vessel and a quay
Subfunctions: 1. Obtain the correct position above the ship 2. Lower container attachment device (with or without container) towards the ship 3. Hoist container attachment device (with or without container) from the ship 4. Attach and detach the container 5. Move the container between WS and LS 6. Obtain the correct position above the quay 7. Lower the container attachment device (with or without container) to the quay 8. Hoist the container attachment device (with or without container) from the quay 9. Enable twistlock removal* 10. Support the containers' and its own weight** 11. Move parallel to the quay 12. Enable wharf vehicles do drive underneath the crane 13. Remove, store, and put back hatch covers*** 14. Distribute loads on the quay

* The crane itself does not have to remove twistlocks. However, there should be a possibility to let them removed (manually).

**This function is fulfilled by the structure of the crane, including the main girder.

***The hatch covers do not have to be stored on the crane, as long as there is some place underneath the crane where they can be temporarily stored.

The functions described in table C.1 are all necessary to successfully transfer containers between a container vessel and quay. Decomposed functions can be used in a morphological chart, in which multiple solutions for every function will be listed. Like Dieter et al. described it, "The decompositions are useful for understanding the design task and allocating resources to it" [40, p. 216].

However, the function list in table C.1 is too elaborated to be useful in a morphological chart. This function list would make the design space impractically large. After an attempt to use the functions of table C.1 in a morphological chart, it was concluded that the design space was too large to be effective in generating new designs. In this situation, it is necessary to contract the design space [41, p. 101]. For this reason, several functions listed in table C.1 were removed from the list or combined with other functions. Eventually this led to the concise function list as shown in table 6.1. Although this list does not cover all subfunctions an STS crane should fulfill, it will be an appropriate foundation for the morphological chart. The reasoning behind the removing, merging, or adding functions is elaborated below.

- Functions 9 till 14 from table C.1 are removed.
  These functions were removed in case they were not likely to influence the eventual concept. First of all, it should be realised that the purpose of this work is to find alternative solutions for the simultaneous transfer of 4 TEU with an STS container crane. This purpose does not require details that will not influence this ability. Therefore any function in the function list that does probably not influence the ability to simultaneously transfer 4 TEU will not be taken into account in the morphological chart. On top of that, it is important to remark that not a whole STS crane will be designed in this work. The emphasis in this work lays on working principles to enable the simultaneous transfer of 4 TEU, without going into details about the crane structure and other accompanying components that are not directly involved in the container handling process. This is another reason to exclude these functions. Although these aspects might be important as well, they will not be taken into account in this work as long as there is no reason to assume these aspects will be a bottleneck in the design. Accordingly, function 9 till 14 in table C.1 will most likely not influence the working principles of a new concept, and were therefore removed from the list.

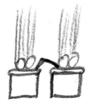
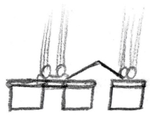
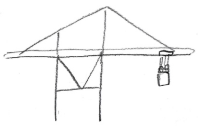
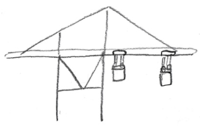
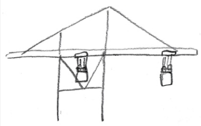
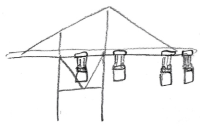
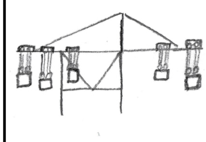
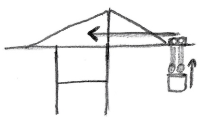
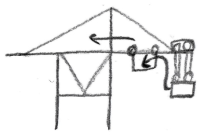
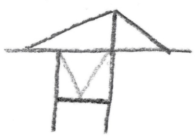
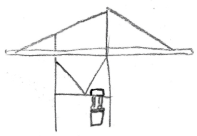
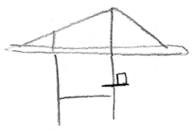
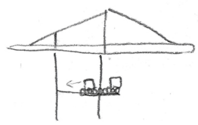
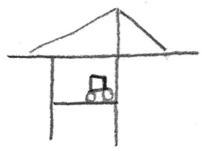
- Functions 1, 2, 3, 6, 7 and 8 from table C.1 are merged into a single function.
  The hoisting and lowering functions are combined to a single function, as in practice there is no difference between the means that fulfill these function. In theory the hoisting from the quay, lowering to the quay, hoisting from the ship and lowering to the ship could all be performed by other means. However, this is very unrealistic as they will be almost certainly be performed by a single (type of) mean. On top of that, obtaining the correct position above the ship and the quay is done by the same (type of) means in a realistic STS crane concept. To further simplify the function list, the hoisting/lowering function and the correct positioning function can be seen as a single function, because in practice this will always be performed by a trolley-like mean (with hoisting equipment). This is because it is hard to think of a concept that positions the hoisting equipment without accommodating the hoisting cables itself. For the just mentioned reasons, functions 1, 2, 3, 6, 7, and 8 in table C.1 were combined into a single function.

- An extra function is added to the list of table C.1: Support handling process with secondary system below the main girder.
  The last adjustment in the function list was an addition of a feature. As shown in section 2.4, STS cranes can be equipped with a secondary system positioned somewhere below the main girder. This system can consist of multiple means. A trolley (with hoisting means) and a platform on portal beam height are frequently used in existing cranes. Examples of alternative means are conveyor systems and transfer vehicles. A secondary system can substantially influence the container handling process, and thus it can influence the ability to simultaneously transfer 4 TEU between a ship and quay. For this reason, it is important to add the ability to add a secondary system to the morphological chart. However, to improve STS crane productivity, the handling system on the main girder should (also) be improved. By only adding a secondary system on which containers can be unloaded, the productivity is not or barely improved when the system on the main girder is remained as usual, even though the crane is strictly moving 4 TEU (or more) simultaneously. For this reason the emphasis in this work does not lay on the secondary system. Nevertheless the secondary system will be part of the morphological chart, as the combination with a system on the main girder might allow relevant new concepts.

C.2. Morphological chart

In this section, several combinations of means will be chosen from the morphological overview of table 6.2 (and table 6.3 and 6.4). To do so, these charts are reproduced in this chapter (see table C.2, C.3 and C.4). The charts in this Appendix are provided with numbers indicated in red, which represent the different concepts that are formed out of the charts. In total, 12 concepts were formed. The combinations of means were chosen based on common sense. Combinations that would result in an inappropriate solution were not selected.

Table C.2: Morphological chart. Every number indicates a concept and is represented with an unique color. For each concept the combination of means is shown.

↓ Functions	Means →				
Attach and detach the container(s)	Single spreader-headblock system  1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12	Tandem spreader-headblock system  8	Triple spreader-headblock system 		
Hoist and lower containers, and obtain the correct position above the ship or quay	One trolley with hoisting means for both WS and LS  7	Two trolleys with hoisting means that both operate at WS and LS  1, 2, 3	Separate trolley for WS and LS  4, 5, 6, 8, 9, 10, 11, 12	Two trolleys for both WS and LS 	Other combinations of 1, 2, 3, or 4 trolleys at WS and/or LS 
Move the container(s) between landside and waterside	Same trolley(s) as used during hoisting and lowering*  1, 2, 3, 8	Container(s) transferred to another vehicle for horizontal transport**  4, 5, 6, 7, 9, 10, 11, 12			
Secondary system below the main girder (multiple options possible)	No secondary system  1, 2, 3, 4, 5, 6, 7, 8, 9, 10	Secondary trolley (somewhere below main girder, e.g. portal beam height)  11, 12	Transfer platform 	Conveyor system 	Transfer vehicle(s) 

* See table 6.3.
** See table 6.4.

Table C.3: Trolleys sub chart. This chart complements the morphological chart in table C.2. Every number indicates a concept and is represented with an unique color. For each concept the combination of means is shown.

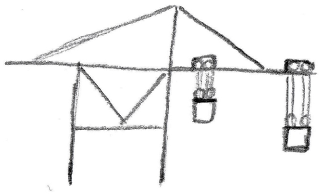
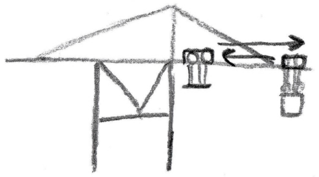
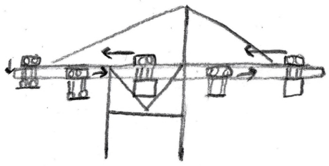
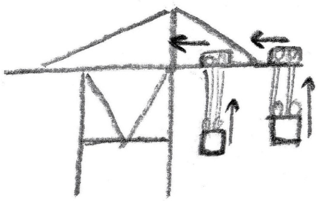
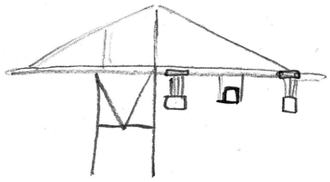
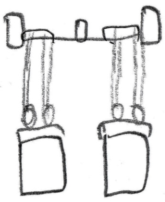
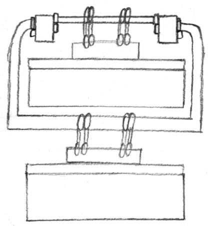
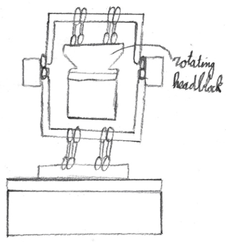
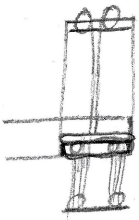
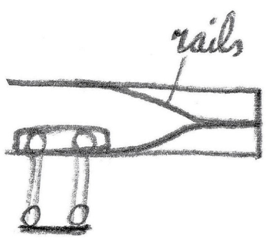
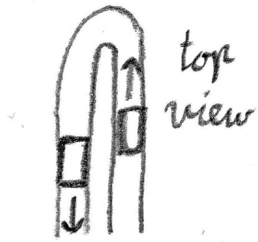
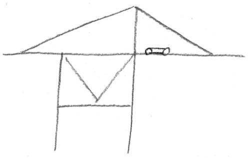
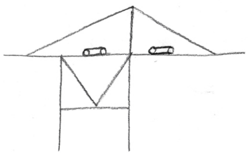
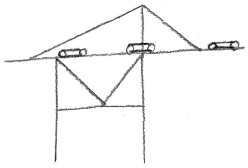
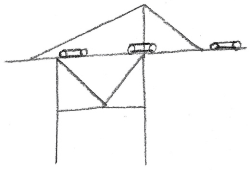
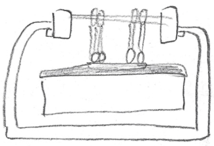
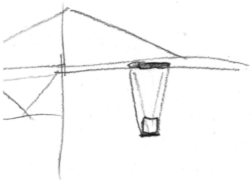
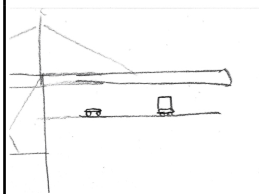
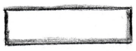
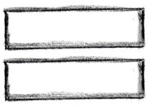
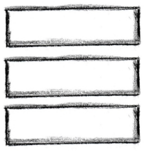
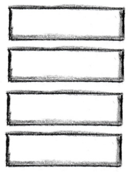
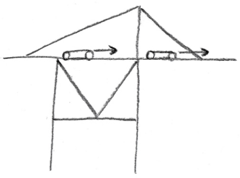
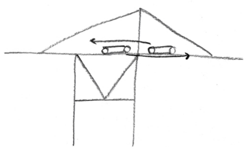
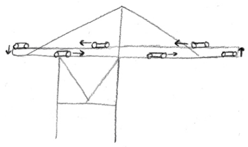
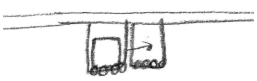
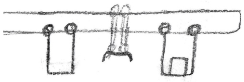
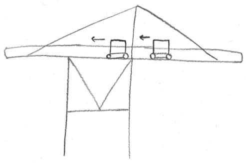
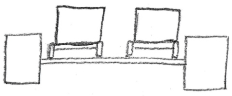
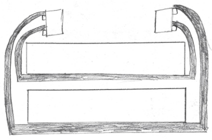
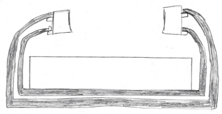
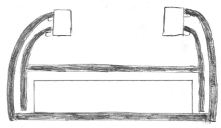
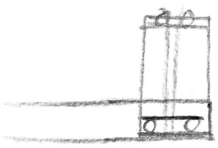
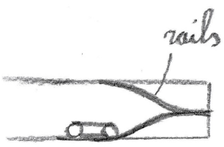
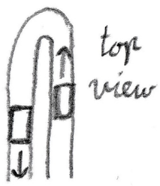
↓ Features	Means →		
Cycle method	Not passing each other  1, 8	Passing each other  2, 3	Circulating system, 2 rail systems, one for each direction 
In case of not passing	All trolleys operate like a conventional trolley  1	Platform somewhere on the main girder allows transfer of container(s) between trolleys  8	
In case of passing	Side by side 	Upper/inner and lower/outer trolley. Both can pass with container  2	Upper/inner and lower/outer trolley, upper container rotated. Both can pass with container  3
In case of circulating	Elevator at both boom ends 	Switches at both boom ends 	Curve at both boom ends 

Table C.4: Transfer vehicles sub chart. This chart complements the morphological chart in table C.2. Every number indicates a concept and is represented with an unique color. For each concept the combination of means is shown.

↓ Features	Means →			
Number of transfer vehicles	1  4, 11	2  5, 6, 10, 12	3  7	3+  9
Transfer vehicle type	Transfer vehicle installed on main girder. The vehicle is low enough for a trolley to load and unload it  4, 5, 6, 7, 10	Transfer trolley with hoisting means connected to a suspended platform that can be hoisted and lowered  11, 12	Transfer cart(s) driving on track below the main girder  9	
Number of containers on one transfer vehicle	2 TEU  4, 5, 6, 7, 9, 10, 11, 12	4 TEU 	6 TEU 	8 TEU 
Cycle pattern	Not passing each other  4, 10, 11	Passing each other  5, 6, 7, 12	Circulating  9	

Continued on next page

Table C.4 – continued from previous page

↓ Features	Means →			
In case of not passing	Transfer of container to other vehicle by means of conveyor system on transfer vehicles  10	Spreader somewhere on the main girder transfers the container from one vehicle to another 	Containers are not transferred between vehicles  4, 11	
In case of passing	Side by side 	Upper/inner and lower/outer transfer vehicles that fit into each other which allows them to pass each other  6, 7, 12	Upper and lower transfer vehicle. Upper vehicle has movable bottom that allows the lower/outer vehicle to pass with container(s)   5	
In case of circulating	Elevator at both boom ends  9	Switches at both boom ends 	Curve at both boom ends 	

Below, all concept formed out of the morphological chart are listed. The enumeration of the concepts in this Appendix are not random. The concepts that were selected to be further elaborated are listed first. This is to ensure that the number of each concept agrees with the numbers in chapter 6. The enumeration in this text was adjusted after the concepts to further elaborate were chosen. Concept 8 till 12 did not make it to the concept selection. Concept 1 till 7 are described in chapter 6.

1. **Two trolleys, without passing each other. Operate like conventional trolleys.**
   - Single spreader-headblock
   - Two trolleys with hoisting means that oth operate at both WS and LS
   - Same trolleys as used during hoisting and lowering
     - Not passing each other
     - Both trolleys operate like a conventional trolley
   - No secondary system
2. **Two trolleys that can pass each other. One trolley is lower than the other.**
   - Single spreader-headblock system
   - Two trolleys with hoisting means that both operate at both WS and LS

- Same trolleys as used during hoisting and lowering
  - Passing each other
  - Upper and lower trolley. Both can pass with container
- No secondary system

3. **Two trolleys that can pass each other. Upper and lower trolley, the upper trolley carries a rotated container.**
   - Single spreader-headblock system
   - Two trolleys with hoisting means that both operate at both WS and LS
   - Same trolleys as used during hoisting and lowering
     - Passing each other
     - Upper and lower trolley. Upper container rotated. Both can pass with container
   - No secondary system
4. **One transfer vehicle driving between WS and LS.**
   - Single spreader-headblock system
   - Separate trolley for WS and LS
   - Container(s) transferred to another vehicle
     - 1 vehicle
     - Platform installed on main girder that can be driven underneath trolley
     - 1 container on vehicle
     - Not passing
     - Containers are not given through
   - No secondary system
5. **Two transfer vehicles driving between WS and LS. They can pass. Upper and lower vehicle, with the upper vehicle able to lift the bottom. In this way they can pass.**
   - Single spreader-headblock system
   - Separate trolley for WS and LS.
   - Container(s) transferred to another vehicle
     - 2 vehicles
     - Platform installed on main girder that can be driven underneath trolley
     - 1 container on vehicle
     - Passing each other
     - Upper and lower transfer vehicle. Upper vehicle has movable bottom
6. **Two transfer vehicles driving between WS and LS. One vehicle is way lower than the other, which allows them to pass.**
   - Single spreader-headblock system
   - Separate trolley for WS and LS
   - Container(s) are transferred to another vehicle
     - 2 vehicles
     - Platform installed on main girder that can be driven underneath trolley
     - 1 container on vehicle
     - Passing each other
     - Upper/middle and lower/outer transfer vehicles that fit into each other
   - No secondary system

7. **One trolley, multiple transfer vehicles.**
    - Single spreader-headblock system
    - One trolley with hoisting means for both WS and LS
    - Container(s) transferred to another vehicle for horizontal transport
        - 2 or more vehicles
        - Platform installed on main girder that can be driven underneath trolley
        - 1 or 2 containers on vehicle
        - Passing each other
        - Upper/middle and lower/outer trolley transfer vehicle(s) that fit into each other
8. **Two trolleys, with tandem spreaders and a platform on the main girder.**
    - Tandem spreader-headblock system
    - Separate trolley for WS and LS
    - Same trolleys as used during hoisting and lowering
        - Not passing each other
        - Platform halfway the main girder which allows transfer between trolleys
    - No secondary system
9. **Circulating transfer carts.**
    - Single spreader-headblock system
    - Separate trolley for WS and LS
    - Container(s) transferred to another vehicle
        - More than 3
        - Transfer cart driving on lower tracks below the main girder
        - 1
        - Circulating
        - Elevators
    - No secondary system
10. **Two transfer vehicles driving between WS and LS, container is given through**
    - Single-spreader headblock system
    - Separate trolley for WS and LS
    - Container(s) transferred to another vehicle
        - 2 vehicles
        - Platform installed on main girder that can be driven underneath trolley
        - 1 container on vehicle
        - Not passing each other
        - Giving container through with conveyor system on transfer vehicles
    - No secondary system
11. **Transfer trolley with hanging platform**
    - Single spreader-headblock system
    - Separate trolley for WS and LS
    - Container(s) transferred to another vehicle
        - 1 vehicle
        - Transfer trolley with hanging platform that can be hoisted and lowered
        - 1 container on vehicle

    - Not passing
    - Containers are not given through
  - Lower secondary trolley to lift container from the hanging platform. The secondary trolley serves as LS trolley

12. **Two transfer trolleys with hanging platform**
  - Single spreader-headblock system
  - Separate trolley for WS and LS
  - Container(s) transferred to another vehicle
    - 2 vehicles
    - Transfer trolley with hanging platform that can be hoisted and lowered
    - 1 container on vehicle
    - Passing each other
    - Upper/middle and lower/outer transfer vehicle(s) that fit into each other
  - Lower secondary trolley to lift container from the hanging platforms. The secondary trolley serves as LS trolley

D
Concept comparison

D.1. Cycle time calculation

In chapter 7 the method for determining the productivity of all seven concepts is elaborated. This appendix provides some additional information to complement the description of chapter 7. Every container on the ship has an x- and y-position, as can be seen in figure D.1. This position on the ship determines the travel distances to the container.

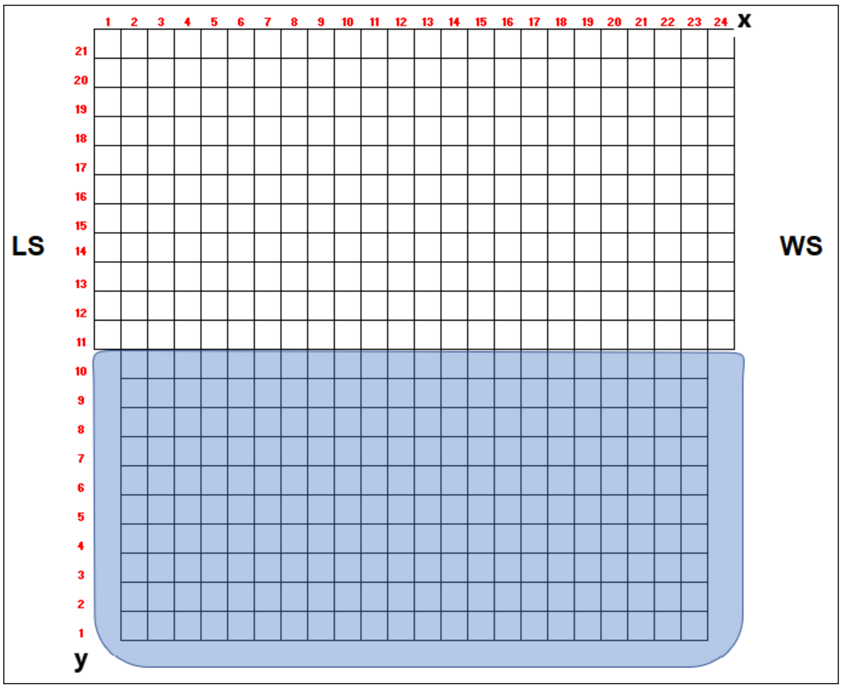


Figure D.1: Container positions on a container ship. Each container has a horizontal position x and a vertical position y.

In the calculations, it is assumed that there are always 2 obstructing containers to overcome. 1 obstructing container means that there is at least 1 container on the same y-position between the target container and the quay. 2 obstructing containers mean that there is at least 1 container at one y-position above the target container. Table D.1 gives a description of the travel distances as depicted in figure 7.1 and 7.2.

Table D.1: Travel distances as depicted in figure 7.1 and figure 7.2. Some distances depend on the container position on the ship. There is also a difference between the situation with a container, and the situation without a container (empty spreader). All values are in meters. For every container with horizontal position x and vertical position y (see figure D.1).

	With container. On deck [m]	**With container. Below deck [m]**	**Empty spreader. On deck [m]**	**Empty spreader. Below deck [m]**
A	13.75	13.75	13.75	13.75
B	7	7	4.1	4.1
C	19.75	19.75	19.75	19.75
D	if $y = 21 \rightarrow 11.5 + (y - 10) \cdot 2.9$ if $y = 20 \rightarrow 11.5 + (y - 9) \cdot 2.9$ else $\rightarrow 11.5 + (y - 8) \cdot 2.9$	17.3	if $y = 21 \rightarrow 11.5 + (y - 11) \cdot 2.9$ if $y = 20 \rightarrow 11.5 + (y - 10) \cdot 2.9$ else $\rightarrow 11.5 + (y - 9) \cdot 2.9$	14.4
E	$x \cdot 2.5$	$x \cdot 2.5$	$x \cdot 2.5$	$x \cdot 2.5$
F	6.8	6.8	3.9	6.8
G	-	$1.5 + (11 - y) \cdot 2.9$	-	$1.5 + (10 - y) \cdot 2.9$

In table D.2 the calculation of travel time t for distance d is given, with maximum speed v and acceleration a. These calculations are used to determine the parts of the cycle time as described in table 7.2. The acceleration time t_a and acceleration distance d_a are calculated as follows:

$$t_a = \frac{v}{a} \tag{D.1}$$

$$d_a = \frac{0.5 \cdot v^2}{a} \tag{D.2}$$

Table D.2: Time t necessary to travel distance d, with acceleration a and speed v. In tis way, the travel times in table 7.2 are calculated.

Situation	**Travel time** t
No acceleration and deceleration	$t = \frac{d}{v}$
Only acceleration or deceleration	if $d > d_a \rightarrow t = t_a + (d - d_a)/v$ else $\rightarrow t = \sqrt{2 \cdot \frac{d}{a}}$
Both acceleration and deceleration	if $d > 2 \cdot d_a \rightarrow t = 2 \cdot t_a + (d - 2 \cdot d_a)/v$ else $\rightarrow t = 2 \cdot \sqrt{\frac{d}{a}}$

D.2. Weight increase & load moment

To be able to judge each concept in terms of terminal compatibility, it is useful to make a rough estimation of the weight increase, and the load moment created by the trolley(s), transfer vehicle(s), and loads. For all concepts, the additional weight to the standard crane structure is roughly estimated. A standard crane structure is assumed to be the crane structure of a conventional crane, without any machinery for hoisting or trolley travelling. In other words: all concepts that can differ per concept are not present on the standard crane structure. Also the conventional crane and the dual hoist crane are part of the comparison, so that the extra components of each concept can be put into perspective. In this comparison, all concepts are considered to be built on a new crane. The weight estimations of some standard components are listed below.

Component	Estimated weight
Normal trolley	30 tons
Transfer vehicle	30 tons
Hoisting mechanism	35 tons
Travel mechanism	15 tons
Headblock + spreader pair	15 tons

When components deviate from the standard components in the table, their weight will be adjusted. For each concept, the increase of crane structure weight will be estimated, based on the differences in structure weight between a conventional crane and a dual hoist crane. Concepts 2, 3 and 6 have a larger increase in crane structure weight, as these concepts require a higher crane to serve ULCVs.

Table D.3: Additional weight to crane structure

Concept	Component	Expected weight	Total weight increase
Conventional	Trolley Headblock + spreader Hoisting mechanism Travel mechanism Crane structure	30 tons 15 tons 35 tons 15 tons -	95 tons
Dual hoist	Trolley Headblocks + spreaders Hoisting mechanisms Travel mechanism Crane structure	50 tons 30 tons 70 tons 15 tons 135 tons	300 tons
Concept 1	Trolley 1 Trolley 2 Headblocks + spreaders Hoisting mechanisms Travel mechanism Crane structure	30 tons 30 tons 30 tons 70 tons 30 tons 135 tons	325 tons
Concept 2	Upper trolley Lower trolley Headblocks + spreaders Hoisting mechanisms Travel mechanisms Crane structure	30 tons 50 tons 30 tons 70 tons 30 tons 195 tons	405 tons
Concept 3	Upper trolley Lower trolley Headblocks + spreaders Hoisting mechanisms Travel mechanisms Crane structure	45 tons 45 tons 30 tons 70 tons 30 tons 190 tons	410 tons
Concept 4	Trolley 1 Trolley 2 Headblocks + spreaders Hoisting mechanisms Travel mechanisms Transfer vehicle Crane structure	30 tons 30 tons 30 tons 70 tons 45 tons 30 tons 150 tons	385 tons
Concept 5	Trolley 1 Trolley 2 Headblocks + spreaders Hoisting mechanisms Travel mechanisms Upper transfer vehicle Lower transfer vehicle Crane structure	30 tons 30 tons 30 tons 70 tons 60 tons 35 tons 30 tons 160 tons	445 tons
Concept 6	Trolley 1 Trolley 2 Headblocks + spreaders Hoisting mechanisms Travel mechanisms Upper transfer vehicle Lower transfer vehicle Crane structure	30 tons 30 tons 30 tons 70 tons 60 tons 30 tons 40 tons 210 tons	500 tons
Concept 7	Trolley Headblock + spreader Transfer vehicle 1 Transfer vehicle 2 Hoisting mechanism Travel mechanisms Crane structure	30 tons 15 tons 30 tons 30 tons 35 tons 45 tons 150 tons	335 tons

Table D.4: Load moment in worst case scenario for every concept. g=10m/s^2

Concept	Description	Weight	Arm	Dynamic factor	Total load moment
Conventional	Trolley Headblock + spreader + max. load	30 tons 75 tons	65 m 65 m	- 1.3	83 MNm
Dual hoist	Trolley Headblock + spreader + max. load	50 tons 150 tons	65 m 65 m	- 1.3	159 MNm
Concept 1	Trolley Headblock + spreader + max. load Trolley Headblock + spreader + max. load	30 tons 75 tons 30 tons 75 tons	65 m 65 m 35 m 35 m	- 1.3 - 1.3	128 MNm
Concept 2	Trolley Headblock + spreader + max. load Trolley + headblock + spreader	50 tons 75 tons 45 tons	65 m 65 m 10 m	- 1.3 -	100 MNm
Concept 3	Trolley Headblock + rotating spreader + max. load Trolley + headblock + spreader	45 tons 80 tons 60 tons	65 m 65 m 10 m	- 1.3 -	103 MNm
Concept 4	Trolley Headblock + spreader + max. load Transfer vehicle + max. load	30 tons 75 tons 90 tons	65 m 65 m 35 m	- 1.3 -	114 MNm
Concept 5	Trolley Headblock + spreader + max. load Upper transfer vehicle + max. load Lower transfer vehicle	30 tons 75 tons 95 tons 30 tons	65 m 65 m 35 m 10 m	- 1.3 - -	119 MNm
Concept 6	Trolley Headblock + spreader + max. load Lower transfer vehicle + max. load Upper transfer vehicle	30 tons 75 tons 100 tons 30 tons	65 m 65 m 35 m 10 m	- 1.3 - -	121 MNm
Concept 7	Trolley Headblock + spreader + max. load Transfer vehicle + max. load Transfer vehicle	30 tons 75 tons 90 tons 30 tons	65 m 65 m 35 m 61 m	- 1.3 - -	133 MNm

- **Conventional**
  Trolley is hoisting full load at the WS end of the boom.
- **Concept 1**
  One trolley is hoisting full load at the WS end of the boom, while the other trolley is hoisting full load halfway above the ship.
- **Concept 2**
  Lower trolley is hoisting full load at the WS end of the boom, while (empty) upper trolley is driving towards the ship.
- **Concept 3**
  Upper trolley is hoisting full load at the WS end of the boom, while (empty) lower trolley is driving towards the ship.
- **Concept 4**
  WS trolley is hoisting full load at the WS end of the boom, while fully loaded transfer vehicle is driving towards the quay.
- **Concept 5**
  WS trolley is hoisting full load at the WS end of the boom, while fully loaded upper transfer vehicle is driving towards the quay. The lower (empty) transfer vehicle is already driving towards the ship.
- **Concept 6**
  WS trolley is hoisting full load at the WS end of the boom, while fully loaded lower transfer vehicle is driving towards the quay. The upper (empty) transfer vehicle is already driving towards the ship.

- **Concept 7**
  Trolley is hoisting full load at the WS end of the boom, while fully loaded upper transfer vehicle is driving towards the quay. The lower (empty) transfer vehicle is waiting next to the trolley to be loaded.

D.3. Initial costs

Also the initial costs are important when judging the concepts. For each type of component, an estimation is made of the total costs per kilogram. Although the estimations are not accurate, they can still serve as an useful comparison between the concepts.

Table D.5: Additional initial costs on top of a standard crane structure

Concept	Component	Expected weight	Costs	Total additional costs
Conventional	Trolley	30 tons	€15/kg	€1,650,000.-
	Headblock + spreader	15 tons	€20/kg	
	Hoisting mechanism	35 tons	€18/kg	
	Travel mechanism	15 tons	€18/kg	
	Crane structure	-		
Dual hoist	Trolley	50 tons	€15/kg	€3,285,000.-
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanism	15 tons	€18/kg	
	Crane structure	135 tons	€3/kg	
Concept 1	Trolley 1	30 tons	€15/kg	€3,705,000.-
	Trolley 2	30 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanism	30 tons	€18/kg	
	Crane structure	135 tons	€3/kg	
Concept 2	Upper trolley	30 tons	€15/kg	€4,285,000.-
	Lower trolley	50 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanisms	30 tons	€18/kg	
	Crane structure	195 tons	€3/kg	
	Extra set of rails	-	€100.000	
Concept 3	Upper trolley	45 tons	€15/kg	€4,420,000.-
	Lower trolley	45 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanisms	30 tons	€18/kg	
	Crane structure	190 tons	€3/kg	
	Extra set of rails	-	€100.000	
Concept 4	Trolley 1	30 tons	€15/kg	€4,570,000.-
	Trolley 2	30 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanisms	45 tons	€18/kg	
	Transfer vehicle	30 tons	€15/kg	
	Crane structure	150 tons	€3/kg	
	Extra set of rails	-	€100.000	
Concept 5	Trolley 1	30 tons	€15/kg	€5,495,000.-
	Trolley 2	30 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanisms	60 tons	€18/kg	
	Upper transfer vehicle	35 tons	€15/kg	
	Lower transfer vehicle	30 tons	€15/kg	
	Crane structure	160 tons	€3/kg	
	Two extra sets of rails	-	€200.000	
Concept 6	Trolley 1	30 tons	€15/kg	€5,720,000.-
	Trolley 2	30 tons	€15/kg	
	Headblocks + spreaders	30 tons	€20/kg	
	Hoisting mechanisms	70 tons	€18/kg	
	Travel mechanisms	60 tons	€18/kg	
	Upper transfer vehicle	30 tons	€15/kg	
	Lower transfer vehicle	40 tons	€15/kg	
	Crane structure	210 tons	€3/kg	
	Two extra sets of rails	-	€200.000	
Concept 7	Trolley	30 tons	€15/kg	€3,740,000.-
	Headblock + spreader	15 tons	€20/kg	
	Transfer vehicle 1	30 tons	€15/kg	
	Transfer vehicle 2	30 tons	€15/kg	
	Hoisting mechanism	35 tons	€18/kg	
	Travel mechanisms	45 tons	€18/kg	
	Crane structure	150 tons	€3/kg	
	Two extra sets of rails	-	€200.000	

D.4. Concept assessment form

Only the first four concepts are present on the assessment form, as concept 5, 6 and 7 did not deliver the desired productivity. Below, the exact content that was shown on the assessment form is shown.

Please give a score (0-10) for each concept and objective.

Concepts → ↓Objectives	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Productivity				
Existing crane adjustability				
Terminal compatibility				
Initial costs				
Operation reliability				
Operating costs				
Commercial opportunities				

How important (0-10) do you think each objective is?

Objective	**Score**
Productivity	
Existing crane adjustability	
Terminal compatibility	
Initial costs	
Operation reliability	
Operating costs	
Commercial opportunities	

D.5. Potential patent problems

Now that a concept is chosen, it important to analyse to which extent existing patents can be problematic. Due to existing patents or other literature it might be impossible to patent a concept. Several patents that are related to the chosen concept have been found. These can be seen in table D.6.

Table D.6: Patents related to concept 1. Although only one patent number is shown, the whole patent family is meant.

Patent number	**Applicant**	**Description**	**Status**	**fig-ure**
CN105000480A	RAINBOW CARGOTEC IND CO LTD	STS crane with two independent trolleys.	Patent application rejected in China. No applications in other countries [50] [51].	B.29
CN204778506U	RAINBOW CARGOTEC IND CO LTD	STS crane with two independent trolleys.	Utility model granted at 2015-11-18 in China. No applications in other countries [50].	B.29
CN107285208A	SHANGHAI ZHENHUA HEAVY IND CO	STS crane with two trolleys that can be connected to operate like a dual hoist crane. They can also be disconnected, in which case only 1 trolley operates while the other waits.	Patent application rejected in China. No applications in other countries [50] [51] [52].	B.28
CN102548889A	PACECO CORP	Wire rope reeving system for two trolleys that can operate either coordinately or independently.	Application deemed to be withdrawn in the designated states [50] [52] [51].	B.30
US7559429B1	PACECO CORP [US]	Wire rope reeving system for two trolleys that can operate either coordinately or independently.	Lapsed due to failure to pay maintenance fee [50].	B.31

As described by the European Patent Office, to be certain about the legal status of a patent in a country, the national patent office should be consulted [53]. The most important markets of Iv-Consult are the Netherlands and Belgium, which makes it necessary to check the national patent offices of these countries for any patents that can be problematic. Of all patents in table D.6, only CN102548889A is also filed in European countries (with publication number EP2454184). To check the legal status of this patent, the national patent offices of the Netherlands [54] and Belgium [55] were consulted. Searching the patent number did not result in any patents that are in force. On top of that, all patents with an applicant that contained the term "Paceco" were searched in both national patent registers. This did not result in finding any conflicting patents. As a consequence, to the best of the authors knowledge, there are no patents that are problematic for Iv-Consult to commercially exploit concept 1. Also in other countries no problematic patents are found, except for the utility model with publication number CN204778506U. In case the concept will be employed or manufactured in China, it should be checked in the chinese patent register whether this utility model is still in force and whether this could be problematic. Also, to be certain about the freedom to operate, it should be verified in the Chinese national patent register that patent CN105000480A is rejected and that patents CN107285208A and CN102548889A are rejected and withdrawn, respectively.

E

Wire ropes and sheaves

The wire ropes of the crane are listed in table 8.3. This chapter elaborates the proof of static and fatigue strength of the hoisting wire ropes according to the EN13001-3-2 standard. The trolley travel wire ropes of trolley B are not calculated in this appendix, as the exact size and type of this cable is not critical for the design. Instead, this cable is reverse engineered based on a rope towed trolley of an existing crane.

E.1. Hoisting wire ropes

The cables of both trolleys are examined simultaneously. It is clearly stated when (part of) the calculations are different for both trolleys. In case nothing is stated, the calculation is valid for both trolleys. In table E.1 the dimensions required for the wire rope calculations are listed.

Table E.1: Dimensions of hoisting wire ropes required for EN13001-3-2 calculations.

Description	Symbol	Value	Unit
Diameter hoisting cables trolley A	D_{wrA}	36	mm
Diameter hoisting cables trolley B	D_{wrB}	32	mm
Smallest sheave diameter trolley A	D_A	960	mm
Smallest sheave diameter trolley B	D_B	860	mm

E.1.1. Proof of static strength

Static strength according to EN13001-3-2

Proof of static strength equation

$F_{Sd,s} \leq F_{Rd,s}$	$F_{Sd,s}$ is the design rope force $F_{Rd,s}$ is the limit design rope force	[EN13001-3-2 eq. 1]

Design rope force equation

$F_{Sd,s} = \frac{m_{Hr} \cdot g}{n_m} \cdot \phi \times f_{S1} \times f_{S2} \times f_{S3} \times \gamma_p \times \gamma_n$	m_{Hr} is the mass of the hoist load or that part of the mass of the hoist load that is acting on the rope falls under consideration. g is the acceleration due to gravity. n_m is the mechanical advantage of falls carrying m_{Hr}. ϕ is the dynamic factor for inertial and gravity effects. f_{S1} to f_{S3} are the rope force increasing factors. γ_p is the partial safety factor. γ_n is the risk coefficient.	[EN13001-3-2 eq. 2]

$n_m = 2$	See hoisting wire rope reeving	[EN13001-3-2 figure 2]
$\gamma_p = 1.34$ for LC A $\gamma_p = 1.22$ for LC B $\gamma_p = 1.10$ for LC C		[EN13001-3-2 eq. 1]
Risk class 0 $\gamma_n = 1.0$	An STS container crane has risk class 0.	[EN13001-2 Annex D]

Calculating m_{Hr}
In figure E.1 an example for an eccentric hoist mass can be seen. According to the formula shown in this figure, the maximum part of the hoist mass acting on one sheave (m_{Hr}) is calculated. As an intermediate step, the maximum part of the hoist mass acting on two sheaves (m_{Hr1}) is calculated.

$m_{Hr1} = m_H \cdot (0.5 \cdot L_{H1} + Ec \cdot L_c)/L_{H1}$	m_H is the hoist mass. L_c is the container length. L_{H1} is the headblock sheaves distance long side. E_c is the maximum eccentricity of the container mass.
$m_H = 78$ tons $L_{H1} = 4.9$ m for trolley A $L_{H1} = 5.5$ m for trolley B $L_c = 12.2$ m $E_c = 10\% = 0.1$	
Trolley A: $m_{Hr1} = 78 \text{ tons} \cdot (0.5 \cdot 4.9 \text{ m} + 0.1 \cdot 12.2 \text{ m})/4.9 \text{ m} = 58.4 \text{ tons}$	
Trolley B: $m_{Hr1} = 78 \text{ tons} \cdot (0.5 \cdot 5.5 \text{ m} + 0.1 \cdot 12.2 \text{ m})/5.5 \text{ m} = 56.3 \text{ tons}$	
$m_{Hr} = m_{Hr1} \cdot (0.5 \cdot L_{H2} + Ec \cdot W_c)/L_{H2}$	W_c is the container width. L_{H2} is the headblock sheaves distance short side.
$L_{H2} = 1.186$ m $W_c = 2.4$ m	
Trolley A: $m_{Hr} = 58.4 \text{ tons} \cdot (0.5 \cdot 1.186 \text{ m} + 0.1 \cdot 2.4 \text{ m})/1.186 \text{ m} = 41.0 \text{ tons}$	
Trolley B: $m_{Hr} = 56.3 \text{ tons} \cdot (0.5 \cdot 1.186 \text{ m} + 0.1 \cdot 2.4 \text{ m})/1.186 \text{ m} = 39.5 \text{ tons}$	

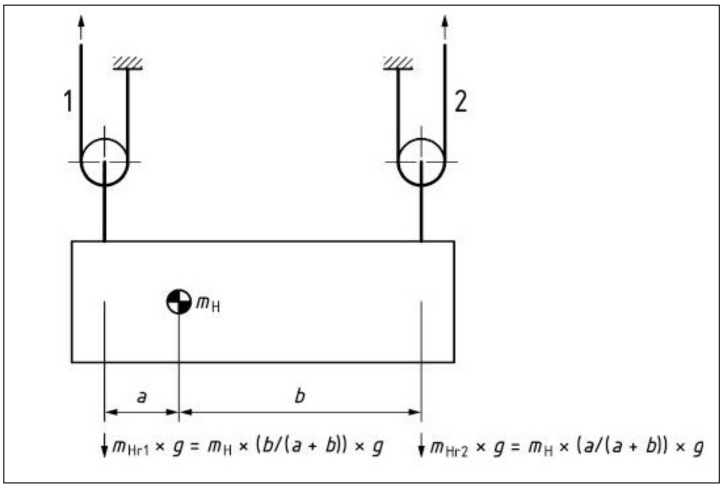


Figure E.1: Example for the acting parts of hoist mass. From EN13001-3-2 [48]

Determining dynamic factor ϕ
Hoisting an unrestrained grounded load:

$\phi = \phi_2$	ϕ_2 is the dynamic factor for inertial and gravity effects when hoisting an unrestrained grounded load	[EN13001-3-2 eq. 3]
$\phi_2 = \phi_{2,min} + \beta_2 \times v_h$	β_2 is the factor dependent upon the stiffness class of the crane v_h is the characteristic hoisting speed of the load in [m/s]	[EN13001-2 eq. 3]
Stiffness class is HC2 $\rightarrow \beta_2 = 0.34$	Stiffness class HC2 is chosen based on existing cranes with comparable dimensions and hoisting capacity.	[EN13001-2 Table 2]
Hoisting drive class HD4 $v_h = 0.5 \cdot v_{h,max}$ for LC A and LC B $v_h = v_{h,max}$ for LC C $v_{h,max} = 1.5$ m/s $v_h = 0.75$ m/s (LC A), $v_h = 1.5 m/s$ (LC C)	HD4: Step-less hoist drive control, which performs with continuously increasing speed. $v_{h,max}$ is the hoisting speed when fully loaded, based on existing cranes with comparable dimensions and hoisting capacity.	[EN13001-2 Table 3]
$\phi_{2,min} = 1.1$	$\phi_{2,min}$ is based on HC2 and HD4	[EN13001-2 Table 4]
$\phi = \phi_2 = 1.1 + 0.34$ s/m $\times$ 0.75 m/s $=$ 1.36 (LC A and B) $\phi = \phi_{2C} = 1.1 + 0.34$ s/m $\times$ 1.5 m/s $= 1.61$ (LC C)		[EN13001-2 eq. 3]

Acceleration or deceleration of the suspended load:

$\phi = 1 + \phi_5 \times \frac{a}{g}$	ϕ_5 is the dynamic factor for loads caused by acceleration a is the vertical acceleration or deceleration g is the acceleration due to gravity	[EN13001-3-2 eq. 4]
$\phi_5 = 1.5$	$1 \leq \phi_5 \leq 1.5$ for drives with no backlash or in cases where existing backlash does not affect the dynamic forces (e.g. typical for gear boxes) and with smooth change of forces.	[EN13001-2: 4.2.2.5]
$a = 0.6 m/s^2$ $g = 9.81 m/s^2$	a is the hoisting acceleration when fully loaded, based on existing cranes with comparable dimensions and hoisting capacity.	

$\phi = 1 + 1.5 \times \frac{0.6}{9.81} = 1.09$		[EN13001-2 eq. 4]

Test load:

$\phi = \phi_6$	ϕ_6 is the dynamic factor for test load.	[EN13001-3-2 eq. 5]
$\phi_6 = \phi_2$ (Dynamic test load)		[EN13001-2 eq. 16]
$\phi_6 = 1.36$		[EN13001-2 eq. 16]

Maximum dynamic factor:

LC A and B: $\phi = \max(1.36, 1.09, 1.36) = 1.36$
LC C: $\phi = \max(1.61, 1.09, 1.36) = 1.61$

Determining force increasing factors f_{S1} to f_{S3}
Rope reeving efficiency:

$f_{S1} = \frac{1}{\eta_{tot}}$	η_{tot} is the total rope reeving efficiency of the rope drive	[EN13001-3-2 eq. 6]
$\eta_{tot} = \frac{(\eta_S)^{n_s}}{n_m} \times \frac{1-(\eta_S)^{n_m}}{1-\eta_S}$	η_S is the efficiency of a single sheave. n_m is the mechanical advantage. n_s is the number of fixed sheaves between drum and moving part.	[EN13001-3-2 eq. 7]
$\eta_S = 0.985$	For sheave with roller bearing.	[EN13001-3-2: 5.2.3]
$n_m = 2$ $n_s = 5$	See wire rope reeving system	
$\eta_{tot} = \frac{(0.985)^5}{2} \times \frac{1-(0.985)^2}{1-0.985} = 0.92$		[EN13001-3-2 eq. 7]
$f_{S1} = \frac{1}{0.92} = 1.09$		[EN13001-3-2 eq. 6]

Non parallel falls:

$f_{S2} = \frac{1}{\cos\beta_{max}}$	β_{max} is the maximum angle between the falls and the direction of load.	[EN13001-3-2 eq. 8]
$\beta_{max} = 20°$	Based on the hoisting reeving system with the headblock in highest position.	
$f_{S2} = \frac{1}{\cos 20°} = 1.06$		[EN13001-3-2 eq. 8]

Horizontal forces on the hoist load:

$f_{S3} = 1.009$	Value for f_{S3} is provided by Iv-Consult.	[EN13001-3-2 eq. 9]

Design rope force calculation:
Load combination A:

Trolley A: $F_{Sd,s} = \frac{41.0\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.36 \times 1.09 \times 1.06 \times 1.009 \times 1.34 \times 1.0 = 427.3 kN$	[EN13001-3-2 eq. 2]
Trolley B: $F_{Sd,s} = \frac{39.5\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.36 \times 1.09 \times 1.06 \times 1.009 \times 1.34 \times 1.0 = 411.6 kN$	[EN13001-3-2 eq. 2]

Load combination B:

Trolley A: $F_{Sd,s} = \frac{41.0\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.36 \times 1.09 \times 1.06 \times 1.009 \times 1.22 \times 1.0 = 389.0\text{ kN}$	[EN13001-3-2 eq. 2]
Trolley B: $F_{Sd,s} = \frac{39.5\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.36 \times 1.09 \times 1.06 \times 1.009 \times 1.22 \times 1.0 = 374.8\text{ kN}$	[EN13001-3-2 eq. 2]

Load combination C:

Trolley A: $F_{Sd,s} = \frac{41.0\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.61 \times 1.09 \times 1.06 \times 1.009 \times 1.10 \times 1.0 = 415.2\text{ kN}$	[EN13001-3-2 eq. 2]
Trolley B: $F_{Sd,s} = \frac{39.5\text{ tons}\cdot 9.81\text{ m/s}^2}{2} \cdot 1.61 \times 1.09 \times 1.06 \times 1.009 \times 1.10 \times 1.0 = 400.0\text{ kN}$	[EN13001-3-2 eq. 2]

Maximum value of $F_{Sd,s}$:

Trolley A: $F_{Sd,s} = \max(427.3\text{ kN}; 389.0\text{ kN}; 415.2\text{ kN}) = 427.3\text{ kN}$
Trolley B: $F_{Sd,s} = \max(411.6\text{ kN}; 374.8\text{ kN}; 400.0\text{ kN}) = 411.6\text{ kN}$

Limit design rope force equation:

$F_{Rd,s} = \frac{F_u}{\gamma_{rb}}$	F_u is the specified minimum breaking force of the rope. γ_{rb} is the minimum rope resistance factor.	[EN13001-3-2 eq. 13]
$\gamma_{rb} = 1.35 + \frac{5.0}{(\frac{D}{d})^{0.8} - 4} \geq 2.07$	D is the minimum relevant diameter. d is the rope diameter	[EN13001-3-2 eq. 14]
$D = min(D_{sheave}, 1.125 \times D_{drum}, 1.125 \times D_{comp})$		

$D = 960$ mm for trolley A $D = 860$ mm for trolley B $d = 36$ mm for trolley A $d = 32$ mm for trolley B		
$\frac{D}{d} = \frac{960}{36} \geq 20.0$ for trolley A $\frac{D}{d} = \frac{860}{32} \geq 20.0$ for trolley B $\gamma_{rb} = 2.07$ for both trolleys		[EN13001-3-2 Table 3]
$F_u = 904.0$ kN for trolley A $F_u = 922.9$ kN for trolley B	Property of chosen wire ropes.	
Trolley A: $F_{Rd,s} = \frac{904.0kN}{2.07} = 436.7kN$		[EN13001-3-2 eq. 13]
Trolley B: $F_{Rd,s} = \frac{922.9kN}{2.07} = 445.8kN$		[EN13001-3-2 eq. 13]

Proof of static strength calculation

$F_{Sd,s} \leq F_{Rd,s}$		[EN13001-3-2 eq. 1]
Trolley A: 427.3 kN ≤ 436.7 kN	Sufficient static strength is proven.	
Trolley B: 411.6 kN ≤ 445.8 kN	Sufficient static strength is proven.	

E.1.2. Proof of fatigue strength

Proof of fatigue strength equation

$F_{Sd,f} \leq F_{RD,f}$	$F_{Sd,f}$ is the design rope force for fatigue. $F_{Rd,f}$ is the limit design rope force for fatigue.	[EN13001-3-2 eq. 16]

Design rope force equation

As stated in EN13001-3-2, "the design rope force $F_{Sd,f}$ shall be calculated for regular loads (load combinations A, see EN 13001-2) only, with partial safety factors γ_p and rope reeving efficiency η_{tot} set to 1" [56, p. 18].

$F_{Sd,f} = \frac{m_{Hr} \times g}{n_m} \times \phi^* \times f^*_{S2} \times f^*_{S3} \times \gamma n$	m_{Hr} is the mass of the hoist load or that part of the mass of the hoist load that is acting on the rope. g is the acceleration due to gravity. n_m is the mechanical advantage of falls carrying m_{Hr} ϕ^* is the dynamic factor for inertial and gravity effects. f^*_{S2}, f^*_{S3} are the rope force increasing factors.	[EN13001-3-2 eq. 17]
$m_{Hr} = 41.0$ tons for trolley A $m_{Hr} = 39.5$ tons for trolley B		See E.1.1

$n_m = 2$	Mechanical advantage for 1 sheave.	
$\gamma_n = 1$		

Inertial effects

$\phi^* = \sqrt[3]{\frac{(w-1)+\phi^3}{w}}$	w is the relevant number of bendings per movement. ϕ is the dynamic factor.	[EN13001-3-2 eq. 19]
$w = 18$	Only the bendings on the trolley and headblock are relevant.	[EN13001-3-2 Annex A]
$\phi = 1.36$		See E.1.1
$\phi^* = \sqrt[3]{\frac{(18-1)+1.36^3}{18}} = 1.02$		

Non parallel falls

$f^*_{S2} = 1 + \left[\frac{1}{cos\beta(z_2)} - 1\right] \times \left(\frac{z_{ref}-z_2}{z_{ref}-z_1}\right)^{0.9}$		[EN13001-3-2 eq. 21]
$z_{ref} = 61.5$ m $z_1 = 29$ m $z_2 = 58$ m	The most frequent working range is chosen in a conservative way.	
$\beta(z_2) = \beta(58\text{ m}) = 14.2°$		
$f^*_{S2} = 1 + \left[\frac{1}{cos14.2°} - 1\right] \times \left(\frac{61.5\text{ m}-58\text{ m}}{61.5\text{ m}-29\text{ m}}\right)^{0.9} = 1.004$		

Horizontal forces in vertical hoisting

$f^*_{S3} = f_{S3}$		[EN13001-3-2 eq. 24]
$f^*_{S3} = 1.009$		

Design rope force calculation

Trolley A: $F_{Sd,f} = \frac{41.0\text{ tons}\times 9.81\text{ m/s}^2}{2} \times 1.02 \times 1.004 \times 1.009 \times 1 = 207.8$ kN		[EN13001-3-2 eq. 17]
Trolley B: $F_{Sd,f} = \frac{39.5\text{ tons}\times 9.81\text{ m/s}^2}{2} \times 1.02 \times 1.004 \times 1.009 \times 1 = 200.2$ kN		[EN13001-3-2 eq. 17]

Limit design rope force equation

$F_{Rd,f} = \frac{F_u}{\gamma_{rf} \times \sqrt[3]{s_r}} \times f_f$		[EN13001-3-2 eq. 25]
$\gamma_{rf} = 7$		[EN13001-3-2 eq. 25]

$F_u = 904.0$ kN for trolley A $F_u = 922.9$ kN for trolley B	Property of wire ropes.	

Rope history parameter

$s_r = k_r \times v_r$	k_r is the rope force spectrum factor. v_r is the relative total number of bendings.	[EN13001-3-2 eq. 26]
$k_r = \sum_{i=1}^{i_{max}} \left(\frac{F_{Sd,f,i}}{F_{Sd,f}}\right)^3 \times \frac{w_i}{w_{tot}}$	i is the index of one movement with $F_{Sd,f,i}$. i_{max} is the total number of movements per rope. $F_{Sd,f,i}$ is the design rope force in movement i. $F_{Sd,f}$ is the maximum design rope force. w_i is the relevant number of bendings in one movement i. w_{tot} is the total number of bendings during the design life of a rope.	[EN13001-3-2 eq. 27]
$k_r = \frac{0.5}{i_{tot}} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{Cm_i + m_{sh}}{4 \cdot n_m \cdot F_{Sd,f}}\right)^3 + 0.5 \cdot \left(\frac{m_{sh}}{4 \cdot n_m \cdot F_{Sd,f}}\right)^3$	Cm_i is the mass of container i m_{sh} is the combined mass of the spreader and headblock.	
Trolley A: $k_r = 0.5 \cdot 0.0197 + 0.5 \cdot 0.0010 = 0.0104$	The value of k_r is based on data provided by Iv-Consult.	
Trolley B: $k_r = 0.5 \cdot 0.0220 + 0.5 \cdot 0.0011 = 0.0116$	The value of k_r is based on data provided by Iv-Consult.	
$v_r = \frac{w_{tot}}{w_D}$	w_D is the number of bendings at reference point.	[EN13001-3-2 eq. 29]
$w_D = 5 \cdot 10^5$		[EN13001-3-2 eq. 29]
$w_{tot} = L_r \cdot Ch \cdot 2 \cdot w$	L_r is the lifetime of 1 wire rope. Ch is the number of cycles per hour. Factor 2 because each cycle has two movements.	
$L_r = 4800$ hours for trolley A $L_r = 5900$ hours for trolley B		
$Ch = 30$ Cycles per hour		
$w = 18$		
Trolley A: $w_{tot} = 4800 \cdot 30 \cdot 2 \cdot 18 = 5184000$		
Trolley B: $w_{tot} = 5900 \cdot 30 \cdot 2 \cdot 18 = 6372000$		
Trolley A: $v_r = \frac{5184000}{5 \cdot 10^5} = 10.37$		[EN13001-3-2 eq. 29]
Trolley B: $v_r = \frac{6372000}{5 \cdot 10^5} = 12.74$		[EN13001-3-2 eq. 29]
Trolley A: $s_r = 0.0104 \cdot 10.37 = 0.108$		[EN13001-3-2 eq. 26]

Trolley B: $s_r = 0.0116 \cdot 12.74 = 0.148$	[EN13001-3-2 eq. 26]

Further influences on the limit design rope force
Diameters of drum and sheaves:

$f_{f1} = \frac{D/d}{R_{Dd}}$	[EN13001-3-2 eq. 33]
$d = 36$ mm for trolley A $d = 32$ mm for trolley B $D = 960$ mm for trolley A $D = 860$ mm for trolley B	See table E.1
$R_{Dd} = 10 \times 1.125^{\log_2\left(\frac{w_{tot}}{8000}\right)}$	[EN13001-3-2 eq. 32]
Trolley A: $R_{Dd} = 10 \times 1.125^{\log_2\left(\frac{5184000}{8000}\right)} = 30.04$	
Trolley B: $R_{Dd} = 10 \times 1.125^{\log_2\left(\frac{6372000}{8000}\right)} = 31.12$	
Trolley A: $f_{f1} = \frac{960\ \text{mm}/36\ \text{mm}}{30.04} = 0.89$	
Trolley B: $f_{f1} = \frac{860\ \text{mm}/32\ \text{mm}}{31.12} = 0.86$	

Tensile strength of wire:

$f_{f2} = \left(\frac{1770}{R_r}\right)^{0.6}$	R_r is the rope grade.	[EN13001-3-2 eq. 34]
$R_r = 1960\ \text{N/mm}^2$		See table 8.3
$f_{f2} = \left(\frac{1770}{1960}\right)^{0.6} = 0.94$		

Fleet angle:

$\delta = \sqrt[3]{\frac{\sum_{j=1}^{n} \delta_j^3}{n}}$	δ is the design fleet angle. δ_j is the fleet angle at the tangential contact point j of rope at drum or sheave. n is the number of contact points passed by the most bent part of the rope.	[EN13001-3-2 eq. 35]
$n = 14$	See figure E.2	
δ_1 till δ_{14} are listed in table E.2		

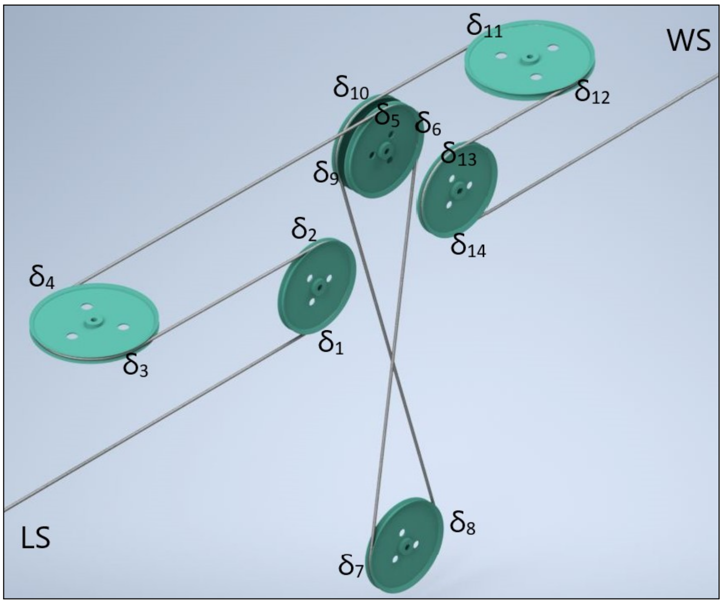


Figure E.2: Fleet angles of the hoisting reeving system.

Table E.2: Table of fleet angles trolley A and trolley B

	A	**B**
δ_1	0°	0°
δ_2	0°	0°
δ_3	2.49°	1.75°
δ_4	1.18°	0.98°
δ_5	0°	0°
δ_6	0.80°	0.80°
δ_7	0.80°	0.80°
δ_8	0.57°	0.57°
δ_9	0.57°	0.57°
δ_{10}	0°	0°
δ_{11}	1.91°	1.08°
δ_{12}	1.91°	1.08°
δ_{13}	0°	0°
δ_{14}	0°	0°

Trolley A:
$$\delta = \sqrt[3]{\frac{2.49^{\circ 3}+1.18^{\circ 3}+2\cdot 0.80^{\circ 3}+2\cdot 0.57^{\circ 3}+2\cdot 1.91^{\circ 3}}{14}} = 1.32^\circ$$

Trolley B:
$$\delta = \sqrt[3]{\frac{1.75^{\circ 3}+0.98^{\circ 3}+2\cdot 0.80^{\circ 3}+2\cdot 0.57^{\circ 3}+2\cdot 1.08^{\circ 3}}{14}} = 0.90^\circ$$

Interpolating the values in Table 5 of EN13001-3-2 to obtain f_{f3}:

Trolley A: $f_{f3} = (2.0-1.32)\cdot(0.95-0.86)+0.86 = 0.92$	[EN13001-3-2 Table 5]
Trolley A: $f_{f3} = (1.0-0.90)\cdot(1.0-0.95)+0.95 = 0.96$	[EN13001-3-2 Table 5]

Rope lubrication:

$f_{f4} = 1$	Value for ropes with internal lubrication.	[EN13001-3-2: 6.4.5]

Groove:

$f_{f6} = 1$	$r_g/d < 0.53$ and $\omega < 60^\circ$	[EN13001-3-2 Table 6]

Rope types

$f_{f7} = \frac{1}{t}$		[EN13001-3-2 eq. 36]
$t = 1.00$ for trolley A $t = 0.95$ for trolley B	Trolley A hoisting cables have 6 outer strands, without plastic impregnation [42]. Trolley B hoisting cables have 8 outer strands, with plastic impregnation [42].	[EN13001-3-2 Table 7]

Trolley A: $f_{f7} = \frac{1}{1.00} = 1$	[EN13001-3-2 eq. 36]
Trolley B: $f_{f7} = \frac{1}{0.95} = 1.05$	[EN13001-3-2 eq. 36]

No multilayer drum, so $f_{f5} = 1$ [56, p. 26].

Limit design rope force calculation

Trolley A: $F_{Rd,f} = \frac{904.0 \text{ kN}}{7\times\sqrt[3]{0.108}} \times 0.89 \times 0.94 \times 0.92 \times 1 \times 1 \times 1 \times 1 = 208.7 \text{ kN}$	[EN13001-3-2 eq. 25]
Trolley B: $F_{Rd,f} = \frac{922.9 \text{ kN}}{7\times\sqrt[3]{0.148}} \times 0.89 \times 0.94 \times 0.96 \times 1 \times 1 \times 1 \times 1.05 = 210.2 \text{ kN}$	[EN13001-3-2 eq. 25]

Proof of fatigue strength calculation

$F_{Sd,f} \leq F_{Rd,f}$		[EN13001-3-2 eq. 16]
Trolley A: 207.8 kN ≤ 208.7 kN	Sufficient fatigue strength is proven.	
Trolley B: 200.2 kN ≤ 210.2 kN	Sufficient fatigue strength is proven.	

E.2. Sheave positions

As trolley A is directly driven, some space is required for the motors and gearboxes. For this reason, the horizontal sheaves on trolley A should not be too far apart. This would result in a long trolley, which can be problematic when both trolleys operate close to each other. As a consequence, it should be determined what the minimum distance between the LS and WS horizontal sheaves is. In figure E.3 the distances between the sheaves are depicted. In figure E.4 and figure E.5 S_2 and S_4 are varied for trolley A, to find the minimal distance for S_2 and the optimal distance for S_4. The maximum fleet angle should not exceed 2.5 degrees [8, p. 43]. Also the design fleet angle (see appendix E) should not become too large, because this is detrimental for the fatigue life of the wire rope. Table E.3 and E.4 show the values for the sheave distances of trolley A and B, respectively.

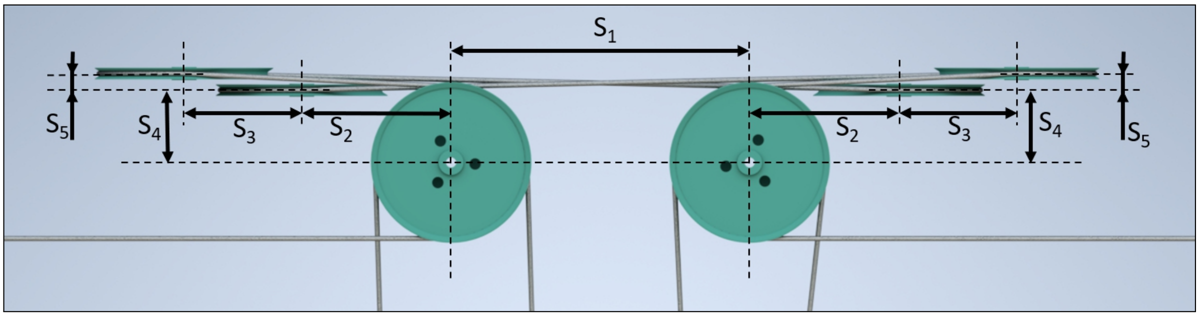


Figure E.3: Trolley sheave distances.

Table E.3: Values for the distances depicted in figure E.3 for trolley A.

S_{1A}	1800 mm
S_{2A}	900 mm
S_{3A}	710 mm
S_{4A}	438 mm
S_{5A}	100 mm

Table E.4: Values for the distances depicted in figure E.3 for trolley B.

S_{1B}	1800 mm
S_{2B}	1585 mm
S_{3B}	710 mm
S_{4B}	438 mm
S_{5B}	100 mm

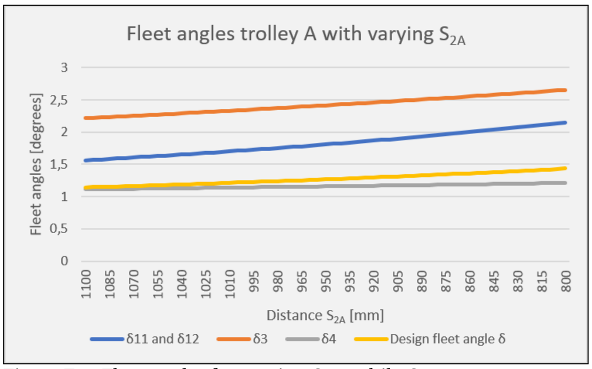


Figure E.4: Fleet angles for varying S_{2A}, while S_{4A} = 438 mm.

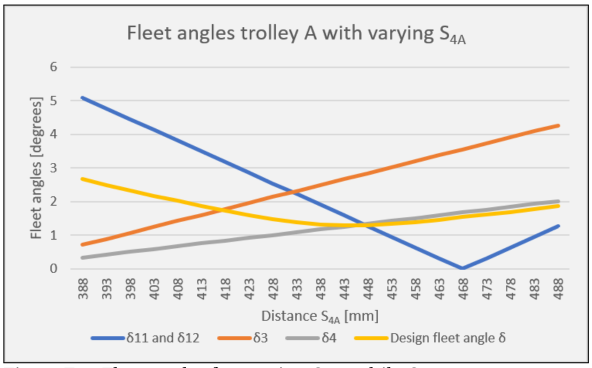


Figure E.5: Fleet angles for varying S_{4A}, while S_{2A} = 900 mm.

F
Rails and wheels

The trolley wheel and rail types are listed in table 8.5. In figure 8.15 the cross section drawing of the rails is depicted. Figure 8.16 and 8.17 show the crane wheels of both trolley A and trolley B. Table 8.6 lists the dimensions of the wheels, according to figure 8.17. This chapter elaborates both the proof of static strength and fatigue strength of the rails and wheels, according to the EN13001-3-3 standard. The masses of trolley A and B are chosen conservatively, as the exact masses are not known yet.

F.1. Rails calculation

In table F.1 all necessary parameters for the rail calculations are listed.

Table F.1: Dimensions of girder rails and trolley wheels required for EN13001-3-3 rail calculations.

Description	**Symbol**	**Value**	**Unit**
Contact width of rail	b_r	59	mm
Crown radius of rail	r_k	500	mm
Width of rail head	w_r	75	mm
Diameter of wheels trolley A	D_{wA}	800	mm
Effective contact width wheels trolley A	b_{wA}	85	mm
Number of wheels trolley A	w_A	4	Wheels
Wheel base trolley A	w_{bA}	6000	mm
Mass of trolley A	m_{TA}	50	tons
Diameter of wheels trolley B	D_{wB}	800	mm
Effective contact width wheels trolley B	b_{wB}	85	mm
Number of wheels trolley B	w_B	4	Wheels
Wheel base trolley B	w_{bB}	5500	mm
Mass of trolley B	m_{TB}	40	tons
Bogie separation trolley B	b_b	4200	mm
Distance between rails	R_d	7000	mm

F.1.1. Proof of static strength

Proof of static strength equation

$F_{Sd,s} \leq F_{Rd,s}$	$F_{Sd,s}$ is the design contact force $F_{Rd,s}$ is the limit design contact force	[EN13001-3-3 eq. 5]

Determining design contact force $F_{Sd,s}$

As described in EN 13001-3-3, "The design contact force $F_{Sd,s}$ of wheel/rail contacts shall be calculated for all relevant load combinations of EN 13001-2, taking into account the respective dynamic factors ϕ_i, partial safety factors γ_p and where required the risk coefficient γ_n. The most unfavourable load effects from possible positions of the mass of the hoist load and crane configurations shall be taken into account" [57, p.

10]. For this reason, the wheel contact force for all relevant load combinations will be calculated. The risk coefficient γ_n is not required, as STS container cranes have risk class 0 [48]. The maximum contact force will be the value of $F_{Sd,s}$.

$F_{Sd,s} = max(F_{Sd,s,i})$ for $i \in$ {LC A1 ... LC C12}	$F_{Sd,s,i}$ is the maximum force exerted on one wheel in load combination i. Load combination i can be every load combination as described in EN13001-2.	EN13001-3-3: 5.2

The relevant load combinations for trolley wheel/rail contact are listed in table F.2. This table is formed by removing irrelevant loads and load combinations from the overview in EN13001-2 (table 13 in the standard). Only loads that influence the contact force between wheel and rail will be taken into account.

Table F.2: Relevant loads for trolley wheel/rail contacts. This table is an adjusted version of Table 13 in the EN13001-2 standard. The values of γ_p for loads resulting from (part of) the mass of the crane are adopted from EN13001-2: Table 9, given that the trolley mass is unfavourable for the wheel/rail contact force.

Loads f_i		Load combinations A			Load combinations B			Load combinations C			
		γ_p	A1	A3	γ_p	B1	B3	γ_p	C1	C3	C6
Gravitation acceleration and impact actions	Mass of the crane	1.22	ϕ_1	1	1.16	ϕ_1	1	1.10	ϕ_1	ϕ_1	1
	Mass of the hoist load	1.34	ϕ_2	1	1.22	ϕ_2	1	1.1	$\phi_{2,c}$	-	1
Acceleration actions from drives	All movements	1.34	-	ϕ_5	1.22	-	ϕ_5	1.1	-	-	-
Test loads		-	-	-	-	-	-	1.1	-	ϕ_6	-
Drive forces due to E-stop		-	-	-	-	-	-	1.1	-	-	ϕ_5

The contact force for the load combinations as stated in table F.2 are calculated below. Trolley A is heavier than trolley B, which results in larger wheel loads. Therefore the properties of trolley A will be used for the proof of static strength of the rails. In subsection F.3.1 the maximum wheel loads of trolley B are calculated, which confirms that the wheel loads of trolley B are lower than the wheel loads of trolley A.

Load combination A1:

$$F_{Sd,s,i} = \gamma_p \cdot \phi_1 \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot \phi_2 \cdot m_{Hr} \cdot g$$

Load combination A3:

$$F_{Sd,s,i} = \gamma_p \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot m_{Hr} \cdot g + \gamma_p \cdot \phi_5 \cdot m_{Hr} \cdot a_h$$

Load combination B1:

$$F_{Sd,s,i} = \gamma_p \cdot \phi_1 \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot \phi_2 \cdot m_{Hr} \cdot g$$

Load combination B3:

$$F_{Sd,s,i} = \gamma_p \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot m_{Hr} \cdot g + \gamma_p \cdot \phi_5 \cdot m_{Hr} \cdot a_h$$

Load combination C1:

$$F_{Sd,s,i} = \gamma_p \cdot \phi_1 \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot \phi_{2c} \cdot m_{Hr} \cdot g$$

Load combination C3:

$$F_{Sd,s,i} = \gamma_p \cdot \phi_1 \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot \phi_6 \cdot 1.1 \cdot m_{Hr} \cdot g$$

Load combination C6:

$$F_{Sd,s,i} = \gamma_p \cdot m_{TA} \cdot g / w_A + \gamma_p \cdot m_{Hr} \cdot g + \gamma_p \cdot \phi_5 \cdot m_{Hr} \cdot a_{brake}$$

γ_p is the partial safety factor. This factor can differ for each type of load and load combination (see table F.2).
m_{TA} is the mass of trolley A.
m_{Hr} is the maximum part of the hoist load that acts on one wheel.
ϕ_1 is the dynamic factor for loads caused by the mass of (parts of) the crane.
ϕ_2 is the dynamic factor for hoisting an unrestrained grounded load (LC A, LC B).
ϕ_{2c} is the dynamic factor for hoisting an unrestrained grounded load (LC C).
ϕ_5 is the dynamic factor for loads caused by acceleration of drives.
ϕ_6 is the dynamic factor for test loads.
a_h is the hoisting acceleration when fully loaded.
a_{brake} is the hoist/lower braking acceleration in case of an emergency stop.
g is the gravitational acceleration.
w_A is the number of wheels of trolley A.

The dynamic factors required in the calculations above are listed below.

$\phi_2 = 1.36$ $\phi_{2c} = 1.61$ $\phi_5 = 1.5$ $\phi_6 = 1.36$	The dynamic factors are determined in E.1.1	[EN13001-2]
$\phi_1 = 1.1$	Gravitational load effect of mass is unfavourable.	[EN13001-2: 4.2.2.1]

In the case of wheel/rail contact, m_{Hr} is the maximum part of the mass of the hoist load that acts in the wheel/rail contact, taken into account the eccentricity of the weight. In a comparable manner as in subsection E.1.1, m_{Hr} is calculated. In an intermediate step, m_{Hr1} is calculated, which is the maximum force that is carried by two wheels.

$m_{Hr1} = m_H \cdot (0.5 \cdot R_d + Ec \cdot L_c)/R_d$ $m_{Hr} = m_{Hr1} \cdot (0.5 \cdot w_{bA} + Ec \cdot W_c)/w_{bA}$	m_H is the load mass. R_d is the rail distance. Ec is the load eccentricity. L_c is the container length. W_c is the container width. w_{bA} is the distance between the WS and LS wheels of trolley A.
$m_H = 78$ tons $R_d = 7$ m $Ec = 10\% = 0.1$ $L_c = 12.2$ m $w_{bA} = 6$ m $W_c = 2.4$ m	
$m_{Hr1} = 78 \text{ tons} \cdot (0.5 \cdot 7 \text{ m} + 1.1 \cdot 12.2 \text{ m})/7 \text{ m} = 52.6 \text{ tons}$ $m_{Hr} = 52.6 \text{ tons} \cdot (0.5 \cdot 6 \text{ m} + 0.1 \cdot 2.4 \text{ m})/6 \text{ m} = 28.4 \text{ tons}$	
$w_A = 4$	

The braking acceleration in case of an emergency stop a_{brake} depends on the hoisting speed and braking time.

$a_{brake} = v_h / t_{brake}$	v_h is the hoisting/lowering speed. t_{brake} is the time in which an emergency stop is made.
$v_h = 1.5$ m/s	v_h is determined for hoisting/lowering full load.
$t_{brake} = 0.85$ s	Value for t_{brake} is provided by Iv-Consult.
$a_{brake} = \frac{1.5 \text{ m/s}}{0.85 \text{ s}} = 1.76 \text{ m/s}^2$	
$a_h = 0.6 \text{ m/s}^2$	Hoisting acceleration for fully loaded container.

Now all parameters are known. For every relevant load combination the design contact force is calculated below.

Load combination A1:

$$F_{Sd,s,i} = 1.22 \cdot 1.1 \cdot 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 1.34 \cdot 1.36 \cdot 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 = 672.3 \text{ kN}$$

Load combination A3:

$$F_{Sd,s,i} = 1.22 \cdot 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 1.34 \cdot 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 + 1.34 \cdot 1.5 \cdot 28.4 \text{ tons} \cdot 0.6 \text{ m/s}^2 = 557.2 \text{ kN}$$

Load combination B1:	
$F_{Sd,s,i} = 1.16 \cdot 1.1 \cdot 50\ \text{tons} \cdot 9.81\ \text{m/s}^2/4 + 1.22 \cdot 1.36 \cdot 28.4\ \text{tons} \cdot 9.81\ \text{m/s}^2 = 618.7\ \text{kN}$	
Load combination B3:	
$F_{Sd,s,i} = 1.16 \cdot 50\ \text{tons} \cdot 9.81\ \text{m/s}^2/4 + 1.22 \cdot 28.4\ \text{tons} \cdot 9.81\ \text{m/s}^2 + 1.22 \cdot 1.5 \cdot 28.4\ \text{tons} \cdot 0.6\ \text{m/s}^2 = 513.3\ \text{kN}$	
Load combination C1:	
$F_{Sd,s,i} = 1.1 \cdot 1.1 \cdot 50\ \text{tons} \cdot 9.81\ \text{m/s}^2/4 + 1.1 \cdot 1.61 \cdot 28.4\ \text{tons} \cdot 9.81\ \text{m/s}^2 = 641\ \text{kN}$	
Load combination C3:	
$F_{Sd,s,i} = 1.1 \cdot 1.1 \cdot 50\ \text{tons} \cdot 9.81\ \text{m/s}^2/4 + 1.1 \cdot 1.36 \cdot 1.1 \cdot 28.4\ \text{tons} \cdot 9.81\ \text{m/s}^2 = 606.8\ \text{kN}$	
Load combination C6:	
$F_{Sd,s,i} = 1.1 \cdot 50\ \text{tons} \cdot 9.81\ \text{m/s}^2/4 + 1.1 \cdot 28.4\ \text{tons} \cdot 9.81\ \text{m/s}^2 + 1.1 \cdot 1.5 \cdot 28.4\ \text{tons} \cdot 1.76\text{m/s}^2 = 523.8\ \text{kN}$	

Now the maximum design contact force is known:

$$F_{Sd,s} = max(672.3\ \text{kN}; 557.2\ \text{kN}; 618.7\ \text{kN}; 513.3\ \text{kN}; 641\ \text{kN}; 606.8\ \text{kN}; 523.8\ \text{kN}) = 672.3\ \text{kN}$$

Point or line contact
To be considered as a point contact, the crown radius r_k of the rail should adhere to the following requisite:

$5 \times min(b_r; b_w) \leq r_k \leq 200 \times min(b_r; b_w)$	[EN13001-3-3: 4.2]

As $r_k = 500$ mm, this is fulfilled:

$b_r = 59$ mm $b_w = b_{wA} = b_{wB} = 85$ mm $min(b_r; b_w) = 59$ mm
$5 \cdot 59\ \text{mm} \leq 500\ \text{mm} \leq 200 \cdot 59\ \text{mm}$
$295\ \text{mm} \leq 500\ \text{mm} \leq 11800\ \text{mm}$

The contact between rail and wheels can be considered a point contact.

Limit design force equation
As the rail material is not surface hardened, the limit design force equation for non-surface hardened materials will be used.

$F_{Rd,s} = \frac{(7 \times HB)^2}{\gamma_m} \times \frac{\pi \times D_w \times b \times (1-\nu^2)}{E_m} \times f_1 \times f_2$	E_m is the equivalent modulus of elasticity. ν is the radial strain coefficient. D_w is the wheel diameter. b is the effective load-bearing width. HB is the unit conform hardness based on the natural hardness of the material, at the depth of maximum shear. γ_m is the general resistance coefficient. f_1 is the decreasing factor for edge pressure. f_2 is the decreasing factor for non-uniform pressure distribution.	[EN13001-3-3 eq. 6]

$\gamma_m = 1.1$		[EN13001-3-3 eq. 6]
$\nu = 0.3$	Rails and wheels are made out of steel.	[EN13001-3-3 eq. 6]
$E_m = 210000\ \text{N/mm}^2$	Rails and wheels are made out of steel.	[EN13001-3-3 Table 2]
$D_w = D_{wA} = 800$ mm		
$b = min(b_r;\ b_w)$ $b = min(59\ \text{mm}; 85\ \text{mm}) = 59$ mm	b_r and b_w are the effective contact width of the rail and wheels, respectively (see figure F.1).	[EN13001-3-3 eq. 6]
$HB = 260\ \text{N/mm}^2$	Hardness of R260Mn steel.	[EN13001-3-3 Annex A]
$f_1 = 1.0$	Because of point contact.	[EN13001-3-3 eq. 6]
$f_2 = 1.0$	Because of point contact.	[EN13001-3-3 eq. 6]

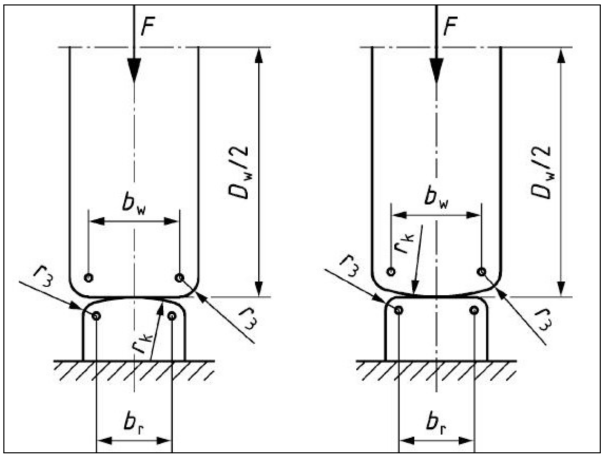


Figure F.1: Point contact between rail and wheel. From EN13001-3-3.

Limit design force calculation

$$F_{Rd,s} = \frac{(7\times260\ \text{N/mm}^2)^2}{1.1} \times \frac{\pi\times800\ \text{mm}\times59\ \text{mm}\times(1-0.3^2)}{210000\text{N/mm}^2} \times 1.0 \times 1.0 = 1934.9\ \text{kN}$$

Proof of static strength calculation

$F_{Sd,s} \le F_{Rd,s}$ 672.3 kN ≤ 1934.9 kN	Sufficient static strength is proven.	[EN13001-3-3 eq. 5]

F.1.2. Proof of fatigue strength

Proof of fatigue strength equation

$F_{Sd,f} \le F_{Rd,f}$	$F_{Sd,f}$ is the maximum design contact force force fatigue. $F_{Rd,f}$ is the limit design contact force for fatigue.	[EN13001-3-3 eq. 8]

Determining maximum design contact force
As described in EN13001-3-3, "The design contact force $F_{Sd,f}$ shall be calculated for the regular loads (load combinations A of EN 13001-2) with the risk coefficient included, and with all dynamic factors $\phi_i = 1$ and all partial safety factors $\gamma_p = 1$" [57, p. 13]. Trolley A is the heaviest of both trolleys, which results in the largest wheel loads of both trolleys. Therefore, the wheel loads of trolley A will be used in the calculation of $F_{Sd,f}$.

$F_{Sd,f} = (m_{Hr} + m_{TA}/w_A) \cdot g$	m_{Hr} is the maximum part of the hoist load that acts in a wheel/rail contact. m_{TA} is the mass of trolley A.
$F_{Sd,f} = (28.4\text{ tons} + 50\text{ tons}/4) \cdot 9.81\text{ m/s}^2 = 401.2\text{ kN}$	

Limit design contact force equation

$F_{Rd,f} = \frac{F_u}{\gamma_{cf} \times \sqrt[m]{s_c}} \times f_f$	F_u is the reference contact force. s_c is the contact force history parameter. γ_{cf} is the contact resistance factor for fatigue. f_f is the factor for further influences. m is the exponent for wheel/rail contacts.	[EN13001-3-3 eq. 9]
$\gamma_{cf} = 1.1$ $m = 10/3 = 3.33$		[EN13001-3-3 eq. 9]

Reference contact force
As the rail material is not surface hardened, the limit design force equation for non-surface hardened materials will be used.

$F_u = (3.0 \times HB)^2 \times \frac{\pi \times D_w \times b \times (1-\nu^2)}{E_m}$	E_m is the equivalent modulus of elasticity. ν is the radial strain coefficient. D_w is the wheel diameter. b is the effective load-bearing width. HB is the unit conform hardness based on the natural hardness of the material, at the depth of maximum shear.	[EN13001-3-3 eq. 10]
$\nu = 0.3$	Rails and wheels are made out of steel.	[EN13001-3-3 eq. 6]
$E_m = 210000\text{ N/mm}^2$	Rails and wheels are made out of steel.	[EN13001-3-3 Table 2]
$D_w = 800\text{ mm}$		
$b = min(b_r;\ b_w)$ $b = min(59\text{ mm}; 85\text{ mm}) = 59\text{ mm}$	b_r and b_w are the effective contact width of the rail and wheels, respectively (see figure F.1).	[EN13001-3-3 eq. 6]
$HB = 260\text{ N/mm}^2$	Hardness of R260Mn steel.	[EN13001-3-3 Annex A]
$F_u = (3.0 \times 260\text{ N/mm}^2)^2 \times \frac{\pi \times 800\text{ mm} \times 59\text{ mm} \times (1-0.3^2)}{210000\text{ N/mm}^2} = 390.9\text{ kN}$		

Contact force history parameter

$s_c = k_c \cdot \nu_c$	k_c is the force spectrum factor. ν_c is the relative total number of rolling contacts.	[EN13001-3-3 eq. 12]

$k_c = 1/i_{tot} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{F_{Sd,f,i}}{F_{Sd,f}}\right)^m$	i is the index of a rolling contact with $F_{Sd,f,i}$ i_{tot} is the total number of rolling contacts during the design life of wheel or rail. $F_{Sd,f,i}$ is the design contact force for fatigue in a contact i. $F_{Sd,f}$ is the maximum of all forces $F_{Sd,f,i}$. m is the exponent for wheel/rail contacts.	[EN13001-3-3 eq. 13]

The force spectrum factor k_c of the rails is dependent on two trolleys. The contact force in a wheel/rail contact differs per trolley (due to the difference between m_{TA} and m_{TB}). This needs to be taken into account when calculating the force spectrum factor. Furthermore, in some cases only 1 trolley is driving on the rails in a cycle. This also influences the force spectrum factor. First a separate force spectrum factor for trolley A and B is calculated, taking into account that half of the times the crane will not carry containers, but solely the headblock and spreader. Subsequently, the ratios P_1 and P_2 take into account that in part of the cycles only 1 trolley is active.

$k_c = P_2 \cdot \left(\frac{k_{cA}+k_{cB}}{2}\right) + P_1 \cdot k_{cB}$	k_{cA} is the force spectrum factor in case only trolley A would drive on the rails. k_{cB} is the force spectrum factor in case only trolley B would drive on the rails. P_1 is the ratio when only one trolley (trolley B) is active. P_2 is the ratio when both trolleys are active.
$k_{cA} = \frac{0.5}{i_{tot}} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{Cm_i+m_{sh}+m_{TA}}{w_A \cdot F_{Sd,f}}\right)^m + 0.5 \cdot \left(\frac{m_{sh}+m_{TA}}{w_A \cdot F_{Sd,f}}\right)^m$	Cm_i is the mass of container i m_{sh} is the combined mass of the spreader and headblock. m_{TA} is the mass of trolley A.
$k_{cB} = \frac{0.5}{i_{tot}} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{Cm_i+m_{sh}+m_{TB}}{w_B \cdot F_{Sd,f}}\right)^m + 0.5 \cdot \left(\frac{m_{sh}+m_{TB}}{w_B \cdot F_{Sd,f}}\right)^m$	m_{TB} is the mass of trolley B.
$k_{cA} = 0.5 \cdot 0.1548 + 0.5 \cdot 0.0510 = 0.1029$ $k_{cB} = 0.5 \cdot 0.1077 + 0.5 \cdot 0.0298 = 0.0688$	The values for k_{cA} and k_{cB} are calculated based on data provided by Iv-Consult.
$P_1 = 0.15$ $P_2 = 0.85$	In 85% of the cycles both trolleys will be active. In 15% of the cycles only trolley B is active.
$k_c = 0.85 \cdot \left(\frac{0.1029+0.0688}{2} \cdot\right) + 0.15 \cdot 0.0688 = 0.0833$	

$v_c = \frac{i_{tot}}{i_D}$	i_D is the number of rolling contacts at reference point, $i_D = 6.4 \cdot 10^6$	[EN13001-3-3 eq. 16]
$i_D = 6.4 \cdot 10^6$		[EN13001-3-3 eq. 16]
$i_{tot} = 2 \cdot n_w \cdot C$	n_w is the total number of wheels of the crane passing over the point under consideration on the particular rail. C is the total number of working cycles during the design life of the crane.	[EN13001-3-3 eq. 15]

As in some cases only 1 trolley is driving on the rails instead of 2, this should be taken into account in the calculation of i_{tot}. Again the ratios P_1 and P_2 will be used for this.

$n_w = 2$ when only trolley B is active. $n_w = 4$ when both trolleys are active.	Both trolleys have 2 wheels per side.
$C = 4 \cdot 10^6$ cycles	Value for C is provided by Iv-Consult.
$i_{tot} = P_2 \cdot 2 \cdot n_w \cdot C + P_1 \cdot 2 \cdot n_w \cdot C$	
$i_{tot} = 0.85 \cdot 2 \cdot 4 \cdot 4 \cdot 10^6 + 0.15 \cdot 2 \cdot 2 \cdot 4 \cdot 10^6 = 29.6 \cdot 10^6$	
$v_c = \frac{29.6 \cdot 10^6}{6.4 \cdot 10^6} = 4.63$	
$s_c = 0.0833 \cdot 4.63 = 0.386$	

Factors of further influences
The factors f_{f1} till f_{f4} cover any other influences.

$f_f = f_{f1} \cdot f_{f2} \cdot f_{f3} \cdot f_{f4}$	[EN13001-3-3 eq. 17]

Factor f_{f1} takes into account the edge pressure effect. For the wider party (in this case the wheel) this may be neglected. For the narrower party (in this case the rail), the following relationship applies:

$f_{f1} = f_1$		[EN13001-3-3 eq. 18]
$f_{f1} = 1$	In F.1.1 f_1 was determined to be 1.0	

The non-uniform pressure distribution is neglected for the proof of fatigue strength.

$f_{f2} = 1$	[EN13001-3-3: 6.4.3]

The skew angle α determines the factor f_{f3}. As the wheel base w_b differs for both trolleys, the skew angle will be determined for both trolleys.

$f_{f3} = 1$ for $\alpha \leq 0.005$ rad $f_{f3} = \sqrt[3]{\frac{0.005}{\alpha}}$ for $\alpha > 0.005$ rad		[EN13001-3-3 eq. 19]
$\alpha = \alpha_g + \alpha_w + \alpha_t$	α_g is skew angle due to track clearance. α_w is skew angle due to wear. α_t is skew angle due to tolerances.	[EN13001-3-3 eq. 19]
$a_g = \frac{s_{gmin}}{w_b}$ when $s_g \leq \frac{4}{3} s_{gmin}$ $a_g = 0.75 \times \frac{s_g}{w_b}$ when $s_g > \frac{4}{3} s_{gmin}$	s_g is the track clearance. s_{gmin} is the minimum track clearance. w_b is the wheel base.	[EN13001-2 Table 6]
$s_{gmin} = 4$ mm	Value for trolley traversing.	[EN13001-2 Table 6]
$s_g = b_{wA} - w_r = b_{wB} - w_r = 85$ mm $- 75$ mm $=$ 10 mm	Distance between wheel flanges minus rail head width. This distance is the same for both trolleys.	
$s_g \geq \frac{4}{3} s_{gmin}$		

$w_{bA} = 6000$ mm $w_{bB} = 5900$ mm		
Trolley A: $a_g = 0.75 \times \frac{10\text{ mm}}{6000\text{ mm}} = 0.00125$ rad Trolley B: $a_g = 0.75 \times \frac{10\text{ mm}}{5900\text{ mm}} = 0.00127$ rad		
$\alpha_t = 0.001$ rad	For both trolleys.	[EN13001-2 Table 6]
$\alpha_w = 0.1 \times \frac{b_h}{w_b}$	Equation for flanged wheels.	[EN13001-2 Table 6]
Trolley A: $\alpha_w = 0.1 \times \frac{75\text{ mm}}{6000\text{ mm}} = 0.00125$ rad Trolley B: $\alpha_w = 0.1 \times \frac{75\text{ mm}}{5900\text{ mm}} = 0.00127$ rad		
Trolley A: $\alpha = 0.00125$ rad $+ 0.001$ rad $+ 0.00125$rad $= 0.0035$ rad Trolley B: $\alpha = 0.00127$ rad $+ 0.001$ rad $+ 0.00127$rad $= 0.0035$ rad		
$\alpha \leq 0.005$ rad $\rightarrow f_{f3} = 1$	For both trolleys.	

The environment of an STS crane trolley can be considered to be without abrasive particles.

$f_{f4} = 1$		[EN13001-3-3 eq. 20]

As a result, the overall factor of further influences is:

$f_f = 1 \cdot 1 \cdot 1 \cdot 1 = 1$		[EN13001-3-3 eq. 17]

Limit design contact force calculation

$F_{Rd,f} = \frac{390.9\text{ kN}}{1.1 \times \sqrt[3.33]{0.386}} \times 1 = 473.0$ kN		[EN13001-3-3 eq. 9]

Proof of fatigue strength calculation

$F_{Sd,f} \leq F_{Rd,f}$ 401.2 kN $\leq$ 473.0 kN	Sufficient fatigue strength is proven.	[EN13001-3-3 eq. 8]

F.2. Wheels trolley A calculation

In table F.3 all necessary parameters for the wheel calculations of trolley A are listed.

Table F.3: Dimensions of girder rails and trolley A wheels required for EN13001-3-3 wheel calculations.

Description	Symbol	Value	Unit
Contact width of rail	b_r	59	mm
Crown radius of rail	r_k	500	mm
Width of rail head	w_r	75	mm
Diameter of wheels trolley A	D_{wA}	800	mm
Effective contact width wheels trolley A	b_{wA}	85	mm
Number of wheels trolley A	w_A	4	Wheels
Wheel base trolley A	w_{bA}	6000	mm
Mass of trolley A	m_{TA}	50	tons
Distance between rails	R_d	7000	mm

F.2.1. Proof of static strength

Proof of static strength equation

$F_{Sd,s} \leq F_{Rd,s}$	FSd,s is the design contact force. $F_{Rd,s}$ is the limit design contact force	[EN13001-3-3 eq. 5]

Determining design contact force

In subsection F.1.1 the design contact force is calculated. In this calculation the weight and (wheel) dimensions of trolley A were used. Therefore this value can be used for the proof of static strength for the wheels of trolley A.

$F_{Sd,s} = 672.3$ kN	F.1.1

Point or line contact

In subsection F.1.1 it is determined that the rail/wheel contact can be considered a point contact.

Limit design force equation

$F_{Rd,s} = \frac{(7 \times HB)^2}{\gamma_m} \times \frac{\pi \times D_w \times b \times (1-\nu^2)}{E_m} \times f_1 \times f_2$	E_m is the equivalent modulus of elasticity. ν is the radial strain coefficient. D_w is the wheel diameter. b is the effective load-bearing width. HB is the unit conform hardness based on the natural hardness of the material, at the depth of maximum shear. γ_m is the general resistance coefficient. f_1 is the decreasing factor for edge pressure. f_2 is the decreasing factor for non-uniform pressure distribution.	[EN13001-3-3 eq. 6]
$\gamma_m = 1.1$		[EN13001-3-3 eq. 6]
$\nu = 0.3$	Rails and wheels are made out of steel.	[EN13001-3-3 eq. 6]
$E_m = 210000$ N/mm^2	Rails and wheels are made out of steel.	[EN13001-3-3 Table 2]
$D_w = D_{wA} = 800$ mm		
$b = min(b_r;\ b_w)$ $b = min(59\text{ mm}; 85\text{ mm}) = 59$ mm	b_r and b_w are the effective contact width of the rail and wheels, respectively (see figure F.1).	[EN13001-3-3 eq. 6]
$HB = 225$ N/mm^2	Hardness of 42MrMo4 steel.	[EN13001-3-3 Annex A]

$f_1 = 1.0$	Because of point contact.	[EN13001-3-3 eq. 6]
$f_2 = 1.0$	Because of point contact.	[EN13001-3-3 eq. 6]

Limit design force calculation

The wheel material without surface hardening will be examined with respect to the proof of static strength. In the proof of fatigue strength it will be specified whether surface hardening is necessary.

$$F_{Rd,s} = \frac{(7\times225\ \mathrm{N/mm^2})^2}{1.1} \times \frac{\pi\times800\ \mathrm{mm}\times59\ \mathrm{mm}\times(1-0.3^2)}{210000\mathrm{N/mm^2}} \times 1.0 \times 1.0 = 1449.0\ \mathrm{kN}$$

Proof of static strength calculation

$F_{Sd,s} \leq F_{Rd,s}$ $672.3\ \mathrm{kN} \leq 1449.0\ \mathrm{kN}$	Sufficient static strength is proven.	[EN13001-3-3 eq. 5]

F.2.2. Proof of fatigue strength

The wheels are made out of 42CrMo4 steel with surface hardening. In this proof of fatigue strength the fatigue strength of the material without surface hardening will be calculated. Subsequently, the required surface hardening will be determined.

Proof of fatigue strength equation

$F_{Sd,f} \leq F_{Rd,f}$	$F_{Sd,f}$ is the maximum design contact force force fatigue. $F_{Rd,f}$ is the limit design contact force for fatigue.	[EN13001-3-3 eq. 8]

Determining maximum design contact force

As described in EN13001-3-3, "The design contact force $F_{Sd,f}$ shall be calculated for the regular loads (load combinations A of EN 13001-2) with the risk coefficient included, and with all dynamic factors $\phi_i = 1$ and all partial safety factors $\gamma_p = 1$" [57, p. 13].

$F_{Sd,f} = (m_{Hr} + m_{TA}/w_A) \cdot g$	m_{Hr} is the maximum part of the hoist load that acts in a wheel/rail contact. m_{Hr} is determined in subsection F.1.1. m_{TA} is the mass of trolley A.
$F_{Sd,f} = (28.4\ \mathrm{tons} + 50\ \mathrm{tons}/4) \cdot 9.81\ \mathrm{m/s^2} = 401.2\ \mathrm{kN}$	

Limit design contact force equation

$F_{Rd,f} = \frac{F_u}{\gamma_{cf} \times \sqrt[m]{s_c}} \times f_f$	F_u is the reference contact force. s_c is the contact force history parameter. γ_{cf} is the contact resistance factor for fatigue. f_f is the factor for further influences. m is the exponent for wheel/rail contacts.	[EN13001-3-3 eq. 9]
$\gamma_{cf} = 1.1$ $m = 10/3 = 3.33$		[EN13001-3-3 eq. 9]

Reference contact force

As the rail material is not surface hardened, the limit design force equation for non-surface hardened materials will be used.

$F_u = (3.0 \times HB)^2 \times \frac{\pi \times D_w \times b \times (1-\nu^2)}{E_m}$	E_m is the equivalent modulus of elasticity. ν is the radial strain coefficient. D_w is the wheel diameter. b is the effective load-bearing width. HB is the unit conform hardness based on the natural hardness of the material, at the depth of maximum shear.	[EN13001-3-3 eq. 10]
$\nu = 0.3$	Rails and wheels are made out of steel.	[EN13001-3-3 eq. 6]
$E_m = 210000\ \text{N/mm}^2$	Rails and wheels are made out of steel.	[EN13001-3-3 Table 2]
$D_w = 800\ \text{mm}$		
$b = min(b_r;\ b_w)$ $b = min(59\ \text{mm}; 85\ \text{mm}) = 59\ \text{mm}$	b_r and b_w are the effective contact width of the rail and wheels, respectively (see figure F.1).	[EN13001-3-3 eq. 6]
$HB = 225\ \text{N/mm}^2$	Hardness of 42CrMo4 steel.	[EN13001-3-3 Annex A]

$$F_u = (3.0 \times 225\ \text{N/mm}^2)^2 \times \frac{\pi \times 800\ \text{mm} \times 59\ \text{mm} \times (1-0.3^2)}{210000\ \text{N/mm}^2} = 292.8\ \text{kN}$$

Contact force history parameter

$s_c = k_c \cdot \nu_c$	k_c is the force spectrum factor. ν_c is the relative total number of rolling contacts.	[EN13001-3-3 eq. 12]
$k_c = 1/i_{tot} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{F_{Sd,f,i}}{F_{Sd,f}}\right)^m$	i is the index of a rolling contact with $F_{Sd,f,i}$ i_{tot} is the total number of rolling contacts during the design life of wheel or rail. $F_{Sd,f,i}$ is the design contact force for fatigue in a contact i. $F_{Sd,f}$ is the maximum of all forces $F_{Sd,f,i}$. m is the exponent for wheel/rail contacts.	[EN13001-3-3 eq. 13]

The force spectrum factor is calculated based on data of a real container terminal. It is assumed that half of the times the crane will not carry containers, but solely the headblock and spreader.

$k_c = \frac{0.5}{i_{tot}} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{Cm_i + m_{sh} + m_{TA}}{w_A \cdot F_{Sd,f}}\right)^m + 0.5 \cdot \left(\frac{m_{sh} + m_{TA}}{w_A \cdot F_{Sd,f}}\right)^m$	Cm_i is the mass of container i m_{sh} is the combined mass of the spreader and headblock. m_{TA} is the mass of trolley A. w_A is the number of wheels of trolley A.
$k_c = 0.5 \cdot 0.1548 + 0.5 \cdot 0.0510 = 0.1029$	The value for k_c is calculated based on data provided by Iv-Consult.

$\nu_c = \frac{i_{tot}}{i_D}$	i_D is the number of rolling contacts at reference point, $i_D = 6.4 \cdot 10^6$	[EN13001-3-3 eq. 16]
$i_D = 6.4 \cdot 10^6$		[EN13001-3-3 eq. 16]

$i_{tot} = \frac{1}{l_w} \cdot \frac{2 \cdot \bar{x} \cdot C}{\pi \cdot D_w}$	l_w is the design number of wheel sets used during the design life of the crane. $\bar{x}$ is the average displacement of the related crane motion. C is the total number of working cycles during the design life of the crane. D_w is the wheel diameter.	[EN13001-3-3 eq. 15]
$\bar{x} = 45$ m	Average displacement is determined based on data of an existing container terminal, according to EN13001-1.	
$C = 4 \cdot 10^6$ cycles	Number provided by Iv-Consult.	
Class U_8		[EN13001-1 Table 2]
$l_w = 2$	Based on class U_8	[EN13001-3-3 Table 5]
$i_{tot} = \frac{1}{2} \cdot \frac{2 \cdot 45\ \text{m} \cdot 4 \cdot 10^6}{\pi \cdot 0.8\ \text{m}} = 71.6 \cdot 10^6$ Cycles		
$v_c = \frac{71.6 \cdot 10^6}{6.4 \cdot 10^6} = 11.2$		
$s_c = 0.1029 \cdot 11.2 = 1.15$		

Factors of further influences

In subsection F.1.1 it is determined that all factors of further influences can be neglected.

$f_{f1} = f_{f2} = f_{f3} = f_{f4} = 1$	See F.1.1

Limit design contact force calculation

$F_{Rd,f} = \frac{292.8\ \text{kN}}{1.1 \times \sqrt[3.33]{1.15}} \times 1 = 255.2$ kN	[EN13001-3-3 eq. 9]

Proof of fatigue strength calculation

The wheel material needs surface hardening.

$F_{Sd,f} \le F_{Rd,f}$ 401.2 kN $\not\le$ 255.2 kN	Fatigue strength is not sufficient.	[EN13001-3-3 eq. 8]

Surface hardening

The limit design contact force is proportional to the square of the hardness of the material.

$HB_{sh} \ge \sqrt{\frac{F_{Sd,f}}{F_{Rd,f}}} \cdot HB$	HB_{sh} is the hardness of the material after surface hardening.
$HB_{sh} \ge \sqrt{\frac{401.2\ \text{kN}}{255.2\ \text{kN}}} \cdot 225\ \text{N/mm}^2 = 282.4\ \text{N/mm}^2$	
$HB_{sh} = 285\ \text{N/mm}^2$	Value of HB_{sh} adheres to the requirement stated above.

It is possible to surface harden 42CrMo4 steel to this hardness [58].

Hardness profile below contact surface
Equation of depth of maximum shear for point contact cases.

$z_{mp} = 0.68 \times \sqrt[3]{\frac{F_{Sd0,s}}{E_m} \times \frac{1-\nu^2}{\left(\frac{2}{D_w}+\frac{1}{r_k}\right)}}$	$F_{Sd0,s}$ is the maximum, non-factored design contact force within the load combinations A to C in accordance with EN13001-2.	[EN13001-3-3 eq. 3]

$F_{Sd0,s}$ can be determined by calculating the wheel load for all loads and load combinations that are relevant for wheel/rail contacts. In table F.4 these relevant loads and load combinations are listed, with all factors set to 1.

Table F.4: Relevant loads for trolley wheel/rail contacts. This table is an adjusted version of Table 13 in the EN13001-2 standard. The factors for all relevant loads are set to 1.

Loads f_i		Load combinations A			Load combinations B			Load combinations C			
		γ_p	A1	A3	γ_p	B1	B3	γ_p	C1	C3	C6
Gravitation acceleration and impact actions	Mass of the crane	1	1	1	1	1	1	1	1	1	1
	Mass of the hoist load	1	1	1	1	1	1	1	1	-	1
Acceleration actions from drives	All movements	1	-	1	1	-	1	1	-	-	-
Test loads		-	-	-	-	-	-	1	-	1	-
Drive forces due to E-stop		-	-	-	-	-	-	1	-	-	1

Load combination A1:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + m_{Hr} \cdot g$$

Load combination A3:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + m_{Hr} \cdot g + m_{Hr} \cdot a_h$$

Load combination B1:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + m_{Hr} \cdot g$$

Load combination B3:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + \cdot m_{Hr} \cdot g + m_{Hr} \cdot a_h$$

Load combination C1:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + m_{Hr} \cdot g$$

Load combination C3:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + 1.1 \cdot m_{Hr} \cdot g$$

Load combination C6:

$$F_{Sd0,s,i} = m_{TA} \cdot g / w_A + m_{Hr} \cdot g + \cdot m_{Hr} \cdot a_{brake}$$

m_{TA} is the mass of trolley A.
m_{Hr} is the maximum part of the hoist load that acts on one wheel.
a_h is the hoisting acceleration when fully loaded.
a_{brake} is the hoist/lower braking acceleration in case of an emergency stop.
g is the gravitational acceleration.
w_A is the number of wheels of trolley A.

$m_{TA} = 50$ tons
$m_{Hr} = 28.4$ tons
$w_A = 4$
$a_h = 0.6\ \mathrm{m/s^2}$
$a_{brake} = 1.76\ \mathrm{m/s^2}$
$g = 9.81\ \mathrm{m/s^2}$

See F.1.1

All parameters are known, so the non-factored design contact force for all relevant load combinations can be determined.

Load combination A1:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 = 401.2 \text{ kN}$$

Load combination A3:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 + 28.4 \text{ tons} \cdot 0.6 \text{ m/s}^2 = 418.3 \text{ kN}$$

Load combination B1:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 = 405.2 \text{ kN}$$

Load combination B3:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 + 28.4 \text{ tons} \cdot 0.6 \text{ m/s}^2 = 418.3 \text{ kN}$$

Load combination C1:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 = 401.2 \text{ kN}$$

Load combination C3:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 1.1 \cdot 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 = 429.1 \text{ kN}$$

Load combination C6:

$$F_{Sd0,s,i} = 50 \text{ tons} \cdot 9.81 \text{ m/s}^2/4 + 28.4 \text{ tons} \cdot 9.81 \text{ m/s}^2 + 28.4 \text{ tons} \cdot 1.76 \text{ m/s}^2 = 451.2 \text{ kN}$$

Now the maximum design contact force is known:

$$F_{Sd0,s} = max(401.2 \text{ kN}; 418.3 \text{ kN}; 405.2 \text{ kN}; 418.3 \text{ kN}; 401.2 \text{ kN}; 429.1 \text{ kN}; 451.2 \text{ kN} = 451.2 \text{ kN})$$

Now all parameters are known to calculate the depth of maximum shear.

$E_m = 210000 \text{ N/mm}^2$
$v = 0.3$
$D_w = 800 \text{ mm}$
$r_k = 500 \text{ mm}$

$$z_{mp} = 0.68 \times \sqrt[3]{\frac{451.2 \text{ kN}}{210000 \text{ N/mm}^2} \times \frac{1-0.3^2}{\left(\frac{2}{800 \text{ mm}} + \frac{1}{500 \text{ mm}}\right)}} = 5.2 \text{ mm}$$

As described in EN13001-3-3, "It shall be ensured that the hardness achieved extends into the material deeper than the depth of maximum shear, preferably twice this depth" [57, p. 9]. For this reason, the depth of the hardened layer should be 10.4 mm. It is possible to have the required hardness at 10.4 mm depth [58].

F.2.3. Wheel flanges

Standard EN 13135 recommends dimensions of wheel flanges. In this subsection it is proven that the wheel flanges of the chosen wheels adhere to these recommendations.

$t \geq 13.5\left(\frac{B}{100}\right)^{\frac{2}{3}} + 13.5\left(\frac{D}{500}\right)^{\frac{1}{2}} - 0.7\left(\frac{D}{500}\right) - 6.5$	t is the flange thickness. B is the effective contact width. D is the diameter of the wheel. In figure F.2 the parameters t, B, and D are visualized.	[EN13135 eq. B.1]

$h \geq 5.5 + 13.5\left(\frac{D}{500}\right)^{\frac{1}{2}}$	h is the flange height (see figure F.2).	[EN13135 eq. B.2]

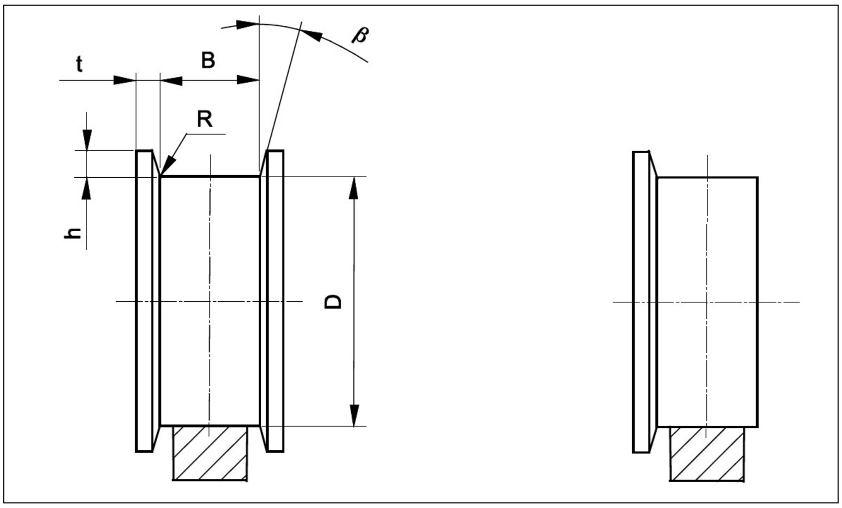


Figure F.2: Wheel dimensions. From EN13135 [59].

$t = 27.5$ mm $B = 85$ mm $D = 800$ mm $h = 25$ mm	Dimensions of the selected wheel.

The flange thickness is large enough:

$$27.5 \text{ mm} \geq 13.5\left(\frac{85 \text{ mm}}{100}\right)^{\frac{2}{3}} + 13.5\left(\frac{800 \text{ mm}}{500}\right)^{\frac{1}{2}} - 0.7\left(\frac{800 \text{ mm}}{500}\right) - 6.5 \text{ mm}$$

$27.5 \text{ mm} \geq 10.35 \text{ mm}$	The requirement is met.

The flange height is large enough:

$$25 \text{ mm} \geq 5.5 \text{ mm} + 13.5\left(\frac{800 \text{ mm}}{500}\right)^{\frac{1}{2}}$$

$25 \text{ mm} \geq 22.6 \text{ mm}$	The requirement is met.

According to EN13135, "The root radius R of the wheel flange shall be greater or equal to 1 mm ($R \geq 1$ mm) and the flange angle β shall be greater or equal to 1 degree ($\beta \geq 1°$)" [59, p. 66]. For this reason, the following values for R and β are chosen:

$R = 2$ mm

$\beta = 2°$

F.3. Wheels trolley B calculation

The wheels calculations of trolley B are almost identical to trolley A. The only differences between both trolleys for the wheel calculations are the trolley weight and wheel base. This results in (slightly) different wheel loads. As a consequence, the material needs less surface hardening. In this section the differences of the wheel calculations compared to trolley A will be highlighted, while adopting already calculated parameters from section F.2. The same process as in section F.2 is performed. In table F.5 all necessary parameters for the wheel calculations of trolley B are listed.

Table F.5: Dimensions of girder rails and trolley B wheels required for EN13001-3-3 wheel calculations.

Description	Symbol	Value	Unit
Contact width of rail	b_r	59	mm
Crown radius of rail	r_k	500	mm
Width of rail head	w_r	75	mm
Diameter of wheels trolley B	D_{wB}	800	mm
Effective contact width wheels trolley B	b_{wB}	85	mm
Number of wheels trolley B	w_B	4	Wheels
Wheel base trolley B	w_{bB}	5500	mm
Mass of trolley B	m_{TB}	40	tons
Distance between rails	R_d	7000	mm

F.3.1. Proof of static strength

Determining design contact force

The maximum part of the mass of the hoist load that acts in one wheel/rail contact, taking into account the eccentricity of the weight, is calculated as follows:

$m_{Hr1} = m_H \cdot (0.5 \cdot R_d + Ec \cdot L_c)/R_d$

$m_{Hr} = m_{Hr1} \cdot (0.5 \cdot w_{bB} + Ec \cdot W_c)/w_{bB}$

m_{Hr1} is the maximum force that is carried by two wheels.
m_H is the load mass.
R_d is the rail distance.
Ec is the load eccentricity.
L_c is the container length.
W_c is the container width.
w_{bB} is the distance between the WS and LS wheels of trolley B.

m_H = 78 tons
R_d = 7 m
Ec = 10% = 0.1
L_c = 12.2 m
w_{bB} = 5.5 m
W_c = 2.4 m

$m_{Hr1} = 78 \text{ tons} \cdot (0.5 \cdot 7 \text{ m} + 1.1 \cdot 12.2 \text{ m})/7 \text{ m} = 52.6 \text{ tons}$

$m_{Hr} = 52.6 \text{ tons} \cdot (0.5 \cdot 5.5 \text{ m} + 0.1 \cdot 2.4 \text{ m})/5.5 \text{ m} = 28.6 \text{ tons}$

Both m_{Hr} and m_{TB} are known for the calculation of $F_{Sd,s}$ for the proof of static strength of the wheels of trolley B. The same process as performed in subsection F.1.1 is repeated. However, the mass of trolley B is used instead of the mass of trolley A and the new value of m_{Hr} is used. When taking the maximum value of all load combinations as stated in table F.2, the design contact force is:

$F_{Sd,s} = 643.0$ kN

Proof of static strength calculation

The wheel material without surface hardening will be examined with respect to the proof of static strength. In the proof of fatigue strength it will be specified whether surface hardening is necessary.

$F_{Rd,s} = 1449.0$ kN — See F.2.2

$F_{Sd,s} \leq F_{Rd,s}$ 672.3 kN ≤ 1449.0 kN	Sufficient static strength is proven.	[EN13001-3-3 eq. 5]

F.3.2. Proof of fatigue strength

In this subsection, the values for $m_{Hr}, F_{Sd,f}, k_c$ and s_c are determined for trolley B. All other parameters are the same as for trolley A. The new value for m_{Hr} is known, so the maximum design contact force for fatigue can be calculated. Subsequently, the force spectrum factor, force history factor, and the limit design force can be determined.

$F_{Sd,f} = (m_{Hr} + m_{TB}/w_B) \cdot g$	m_{Hr} is the maximum part of the hoist load that acts in a wheel/rail contact. m_{TB} is the mass of trolley B.
$F_{Sd,f} = (28.6 \text{ tons} + 40 \text{ tons}/4) \cdot 9.81 \text{ m/s}^2 = 378.7 \text{ kN}$	
$k_c = \frac{0.5}{i_{tot}} \cdot \sum_{i=1}^{i_{tot}} \left(\frac{Cm_i + m_{sh} + m_{TB}}{w_B \cdot F_{Sd,f}}\right)^m + 0.5 \cdot \left(\frac{m_{sh} + m_{TB}}{w_B \cdot F_{Sd,f}}\right)^m$	Cm_i is the mass of container i m_{sh} is the combined mass of the spreader and head-block. m_{TB} is the mass of trolley B. w_B is the number of wheels of trolley B.
$k_c = 0.5 \cdot 0.1305 + 0.5 \cdot 0.0361 = 0.0833$	The value for k_c is calculated based on data provided by Iv-Consult.
$s_c = 0.0833 \cdot 11.2 = 0.93$	

$F_{Rd,f} = \frac{F_u}{\gamma_{cf} \times \sqrt[m]{s_c}} \times f_f$	F_u is the reference contact force. s_c is the contact force history parameter. γ_{cf} is the contact resistance factor for fatigue. f_f is the factor for further influences. m is the exponent for wheel/rail contacts.	[EN13001-3-3 eq. 9]
$F_{Rd,f} = \frac{292.8 \text{ kN}}{1.1 \times \sqrt[3.33]{0.93}} \times 1 = 272.0 \text{ kN}$		
$F_{Sd,f} \leq F_{Rd,f}$ $401.2 \text{ kN} \nleq 272.0 \text{ kN}$	Fatigue strength is not sufficient.	[EN13001-3-3 eq. 8]

The wheel material needs surface hardening.

Surface hardening

The limit design contact force is proportional to the square of the hardness of the material.

$HB_{sh} \geq \sqrt{\frac{F_{Sd,f}}{F_{Rd,f}}} \cdot HB$	HB_{sh} is the hardness of the material after surface hardening.
$HB_{sh} \geq \sqrt{\frac{401.2 \text{ kN}}{272.0 \text{ kN}}} \cdot 225 \text{ N/mm}^2 = 273.3 \text{ N/mm}^2$	
$HB_{sh} = 275 \text{ N/mm}^2$	Value of HB_{sh} adheres to the requirement stated above.

It is possible to surface harden 42CrMo4 steel to this hardness [58].

Hardness profile below contact surface

Trolley B is 10 tons lighter compared to trolley A. To determine $F_{Sd0,s}$ for trolley B, a force of $(m_{TA} - m_{TB}) \cdot g/4$ should be subtracted from the value of $F_{Sd0,s}$ for trolley A:

$$F_{Sd0,s} = 451.2\ \text{kN} - (50\ \text{tons} - 40\ \text{tons}) \cdot 9.81\ \text{m/s}^2/4 = 426.7\ \text{kN}$$

$$z_{mp} = 0.68 \times \sqrt[3]{\frac{426.7\ \text{kN}}{210000\ \text{N/mm}^2} \times \frac{1-0.3^2}{\left(\frac{2}{800\ \text{mm}} + \frac{1}{500\ \text{mm}}\right)}} = 5.1\ \text{mm}$$

As the depth of the hardened layer should preferably be twice the depth of the maximum shear. Therefore the depth of the hardened layer should be 10.2 mm. It is possible to have the required hardness at 10.2 mm depth [58].

F.3.3. Wheel flanges

The geometry of the wheels of trolley B are the same as for the wheels of trolley A. In subsection F.2.3 the wheel flange dimension calculations are specified.

G

Motors & brakes

G.1. Trolley A travel

Trolley A is directly driven. The trolley has 4 wheels, which are all driven by a separate motor. The trolley travel motor power calculation is performed in accordance with Verschoof [8]. The masses of trolley A and B are chosen conservatively, as the exact masses are not known yet.

Main characteristics

$v = 3$ m/s	v is the trolley travelling speed.	
$m_{TA} = 50$ tons $m_H = 78$ tons $m_{tot} = 128$ tons		
$f = 0.05$ kN/ton	f is the wheel resistance coefficient	[8, p. 67]
$\eta_t = 0.85$	η_t is the efficiency of gearings and rope sheaves.	[8, p. 67]
$F_w = \epsilon_S \times q(3) \times c_a \times A$		[EN13001-2 eq. 9]
$\epsilon_S = 0.7$		[EN13001-2 eq. 9]
Normal wind: $q(3) = 250\text{N/m}^2$ Heavy wind: $q(3) = 500\text{N/m}^2$		[EN13001-2 Table 5]
$c_a = 1$		
$A = 50\text{m}^2$		
Normal wind: $F_w = 8.8$ kN $Heavywind$: $F_w = 17.5$ kN		
Acceleration: $a = 0.8\text{m/s}^2$		

Motor speed: $n_m = 1500 rev/min$	Motor with 4 poles	
$D_{WA} = 0.8$ m	Diameter of wheels of trolley A	
$i = \frac{n_m \cdot \pi \cdot D_{WA}}{v}$		
$i = \frac{1500 \cdot \pi \cdot 0.8}{180} = 20.94$		

Resistance due to nominal travelling:

$F_1 = m_{tot} \cdot f = 128 \cdot 0.05 = 6.4$ kN	
$N_1 = \frac{F_1 \cdot v}{\eta_t} = \frac{6.4 \cdot 3}{0.85} = 22.6$ kW	

Resistance due to the energy chain:

$F_2 = 4$ kN	[8, p. 69]
$N_2 = \frac{4 \cdot 3}{0.85} = 14.1$ kW	

Resistance due to wind:

$N_3 = \frac{8.8 \cdot 3}{0.85} = 31.1$ kW or $N_3 = \frac{17.5 \cdot 3}{0.85} = 61.8$ kW	

Resistance due to the acceleration of the rotating mass:

Table G.1: Power required for the acceleration of rotating masses

Component	**Number**	**Diameter**	**Moment of inertia**	ω	$\dot{\omega}$	**Power**
Wheels	4	800 mm	32.28 kg m^2	7.50 rad/s	2.00 rad/s^2	1.94 kW
Vertical sheaves	16	960 mm	17.7 kg m^2	6.25 rad/s	1.67 rad/s^2	2.96 kW
Small ho. sheaves	2	960 mm	17.7 kg m^2	6.25 rad/s	1.67 rad/s^2	0.37 kW
Middle ho. sheaves	4	1000 mm	20.0 kg m^2	6.00 rad/s	1.60 rad/s^2	0.77 kW
Large ho. sheaves	2	1040 mm	22.5 kg m^2	5.77 rad/s	1.54 rad/s^2	0.40 kW
Spreader sheaves	2	960 mm	17.7 kg m^2	6.25 rad/s	1.67 rad/s^2	0.37 kW
Motors, gearboxes and brakes	4	-	1.5 kg m^2	157.08 rad/s	41.89 rad/s^2	39.48 kW
					Total	46.29 kW

$N_4 = 46.3$ kW

Resistance due to the acceleration of the linear mass:

$F_5 = m_{tot} \cdot a = 128 \cdot 0.8 = 102.4$ kN

$N_5 = \frac{102.4 \cdot 3}{0.85} = 361.4$ kW

$N_{tot} = 475.5$ kW

$f_a = 1.6$

$\frac{475.5}{f_a \cdot 4} = 74.3$ kW

G.2. Trolley A gearbox

The trolley wheel diameter is 800 mm. The motor speed is approximately 1500 rpm. The nominal speed of the trolley is 3 m/s.

$i = \frac{1500\ \text{rpm} \cdot \pi \cdot 0.8\ \text{m}}{180\ \text{m/min}} = 20.9$

Eventually $i = 22.16$ is chosen, because this ratio was closest to $i = 20.9$ of all suitable gearboxes when choosing the gearmotor.

G.3. Trolley A brake torque

The maximum braking torque of the brakes of trolley A depends on the wheel slip that can occur. The maximum breaking acceleration is desired, as this limits the risks of both trolleys colliding. When assuming a friction coefficient of $c_f = 0.15$ between the wheels and rail, a maximum braking acceleration can be calculated:

$m_{tot} \cdot g \cdot c_f = m_{tot} \cdot a_{brake}$

$a_{brake} = g \cdot c_f$

$a = 9.81\ \text{m/s}^2 \cdot 0.15 = 1.47\ \text{m/s}^2$

So $a_{brake} = 1.5\ \text{m/s}^2$ is assumed in the following calculations. The torque required on one wheel axis to obtain a braking acceleration of $1.5\ \text{m/s}^2$ can be calculated:

$T_{brake,wheel} = \frac{\frac{1}{2} \cdot D_w \cdot a_{brake} \cdot m_{tot}}{4}$

$T_{brake,wheel} = 19.2$ kNm

The ratio i of the gearbox is used to calculate the braking torque at the shaft of the motor:

$$T_{brake,motor} = T_{brake,wheel} / i$$

$$T_{brake,motor} = \frac{19.2\ \text{kNm}}{22.16} = 866\ \text{Nm}$$

A braking torque of 1000 Nm is chosen.

H

Machinery house equipment

The machinery house of the concept has the same configuration as the machinery house of a dual hoist crane. For convenience, the equipment and position of the equipment in the machinery house is briefly described in this chapter. In figure H.1 a top view of the machinery house equipment can be seen. Table H.1 lists the most important characteristics of the equipment. All characteristics are approximated, based on existing dual hoist cranes. As this machinery house configuration is already ubiquitous in practice, the exact design of the machinery house was not a focus point of this work.

Table H.1: Characteristics of the machinery house equipment. The equipment listed in this table can be seen in figure H.1. The data in this table is approximated, based on existing cranes.

Component	**Power, torque, ratio, or diameter**	**Quantity**	**Number in figure H.1**
Hoist motor trolley A	700 kW	2	2
Hoist motor trolley B	700 kW	2	1
Trolley travel motor trolley B	300 kW	1	3
Boom motor	400 kW	1	4
Reducer hoisting trolley A	20	1	6
Reducer hoisting trolley B	20	1	5
Reducer travel trolley B	25	1	7
Reducer boom	150	1	8
Drum hoisting trolley A	1300 mm	2	10
Drum hoisting trolley B	1300 mm	2	9
Drum travel trolley B	1100 mm	1	11
Drum boom	1300 mm	2	12
Motor brake hoisting trolley A	13000 Nm	4	14
Motor brake hoisting trolley B	13000 Nm	4	13
Motor brake travel trolley B	20000 Nm	1	15
Motor brake boom	4000 Nm	1	16
Drum brake hoisting trolley A	200 kNm	2	18
Drum brake hoisting trolley B	200 kNm	2	17
Drum brake travel trolley B	200 kNm	1	19
Drum brake boom	200 kNm	1	20

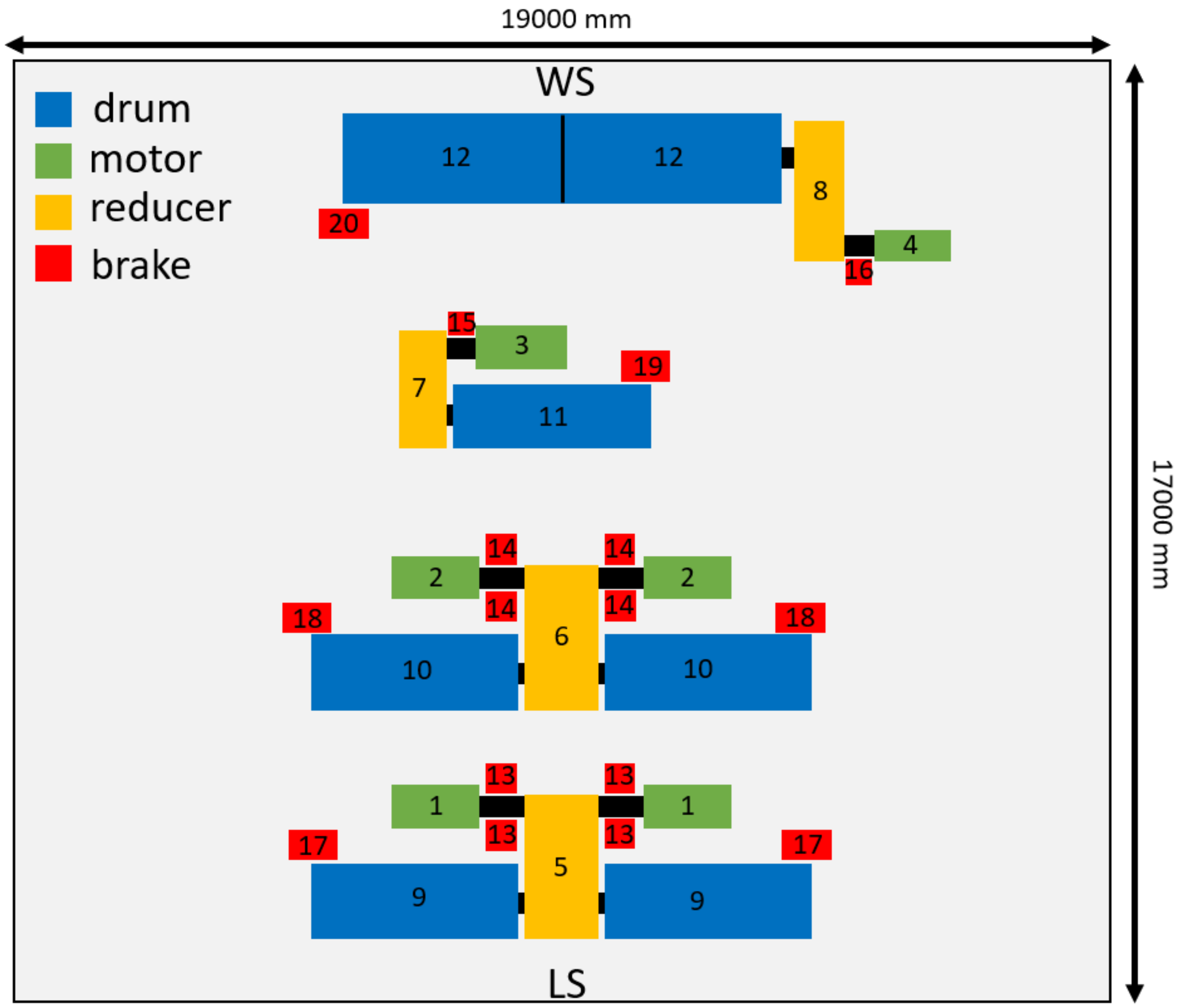


Figure H.1: Top view of machinery house configuration. The numbers refer to table H.1. The outer dimensions of the machinery house are approximated, based on existing cranes.

I

Trolley frames FEA

In this appendix, more information regarding the finite element analysis of the trolley frames is elaborated.

I.1. Loads and load combinations

In chapter 9 is stated which loads and load combinations are applied to the trolley frame. In this appendix, the values of these forces are determined.

I.1.1. Sheave forces

The rope forces (see Appendix E) are translated to forces that act on the sheaves. The cable forces are assumed to be perfectly towards the Y- or Z-direction. As every sheave changes the direction of the wire rope, the resultant force on the sheave can be calculated by adding the components in X, Y and Z direction of both rope ends that run through the sheave. In figure I.1 all sheaves are numbered, and in table I.1 the force on each sheave is listed.

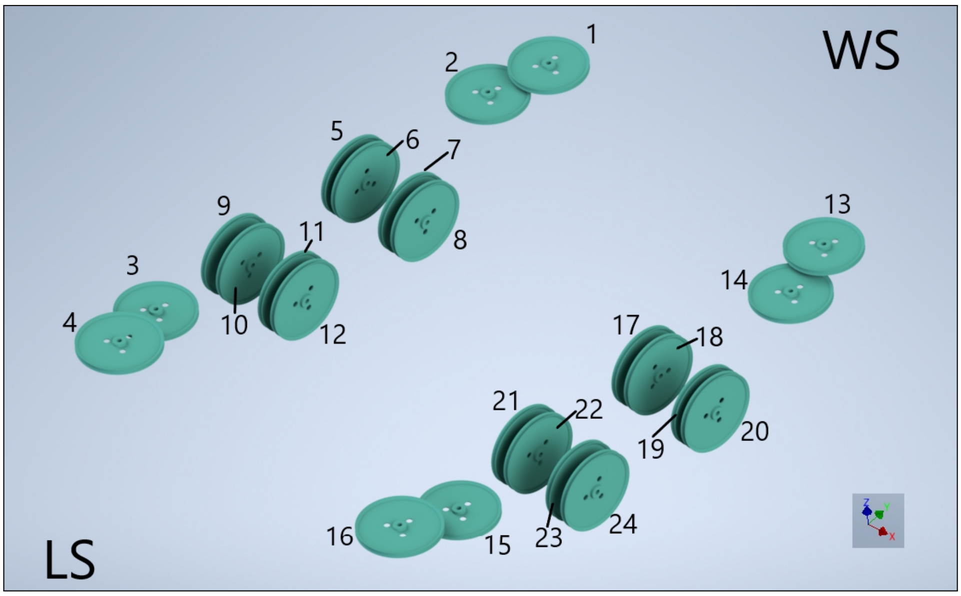


Figure I.1: Overview of trolley sheaves of hoisting reeving system. Both trolleys have the same configuration of sheaves, although the size and position can differ.

I.1.2. Acceleration forces

A trolley acceleration of $a = 0.8\ \mathrm{m/s^2}$ is assumed. In every wheel of trolley A, the acceleration force will be $F_{acc} = m_A \cdot a = 38\ \text{tons} \cdot 0.8\ \mathrm{m/s^2} = 30.4\ \mathrm{kN}$, and for trolley B $F_{acc} = m_B \cdot a = 33\ \text{tons} \cdot 0.8\ \mathrm{m/s^2} = 26.4\ \mathrm{kN}$

Table I.1: Hoisting forces on the sheaves. All values are given in Newton.

Sheave	X	Y	Z
1	0	-191295	0
2	0	-191295	0
3	0	191295	0
4	0	191295	0
5	0	95647.5	-95647.5
6	0	-95647.5	-95647.5
7	0	191295	0
8	0	191295	0
9	0	-95647.5	-95647.5
10	0	95647.5	-95647.5
11	0	-191295	0
12	0	-191295	0
13	0	-191295	0
14	0	-191295	0
15	0	191295	0
16	0	191295	0
17	0	191295	0
18	0	191295	0
19	0	-95647.5	-95647.5
20	0	95647.5	-95647.5
21	0	-191295	0
22	0	-191295	0
23	0	95647.5	-95647.5
24	0	-95647.5	-95647.5

I.1.3. Skew forces

$F_y = \upsilon \cdot f \cdot m \cdot g$		[EN13001-2 eq. 11]
$m = 50 \text{ tons} + 78 \text{ tons} = 128 \text{ tons}$		
$f = \mu_0 \cdot \left[1 - e^{-250\alpha}\right]$		
$\alpha = 0.00394\text{rad}$		
$\mu_0 = 0.2$		
$\upsilon = 1 - \frac{\sum d_i}{nh}$	For F/F	[EN13001-2]
$h = \frac{p \cdot \mu \cdot \mu' \cdot l^2 + \sum d_i^2}{\sum d_i}$		
$n = 2$ $p = 0$ $l = 7000$ $d_1 = 0$ $d_2 = 5100$ $\sum d_i = 5100$ $\sum d_i^2 = 2.6 \cdot 10^7$		

$h = \frac{0 \cdot \mu \cdot \mu' \cdot l^2 + 2.6 \cdot 10^7}{5100} = 5100\text{mm}$	
$v = 1 - \frac{5100}{2 \cdot 5100} = \frac{1}{2}$	
$f = 0.2 \cdot \left(1 - e^{-250 \cdot 0.00394}\right) = 0.125$	
$F_y = \frac{1}{2} \cdot 0.125 \cdot 128 \cdot 9.81 = 78.5\text{kN}$	

I.1.4. Buffer forces

Buffer is hydraulic, so the following relation is true:

$\frac{1}{2} \cdot m_{tot} \cdot v^2 = 2 \cdot F_{buffer} \cdot u_{buffer}$	m_{tot} is the combined mass of the trolley and load. v is the trolley speed. F_{buffer} is the force applied on the trolley by one buffer. u_{buffer} is the stroke of the buffer. Per side, a trolley has 2 buffers.
Trolley A $m_{tot,A} = 116$ tons Trolley B $m_{tot,B} = 111$ tons	
$v = 3$ m/s	
$u_{buffer} = 0.5$ m	
Trolley A: $F_{buffer} = 522$ kN Trolley B: $F_{buffer} = 500$ kN	

I.2. Values for ϕ_i

$\phi_1 = 1.1$		See appendix F
$\phi_2 = 1.36$ $\phi_{2,c} = 1.61$ $\phi_5 = 1.5$ $\phi_6 = 1.36$		See appendix E
$\phi_7 = 1.25 + 0.7(\zeta - 0.5)$	Equation for $0.5 \leq \zeta \leq 1$	[EN13001-2 eq. 17]
$\zeta = 1.0$	Value for buffers with rectangular characteristics, e.g. hydraulic buffers.	[EN13001-2:4.2.4.4]
$\phi_7 = 1.25 + 0.7(1.0 - 0.5) = 1.6$		

I.3. Proof of static strength

Below, the results of static strength for all load combinations are shown for both trolleys.

I.3.1. Trolley A

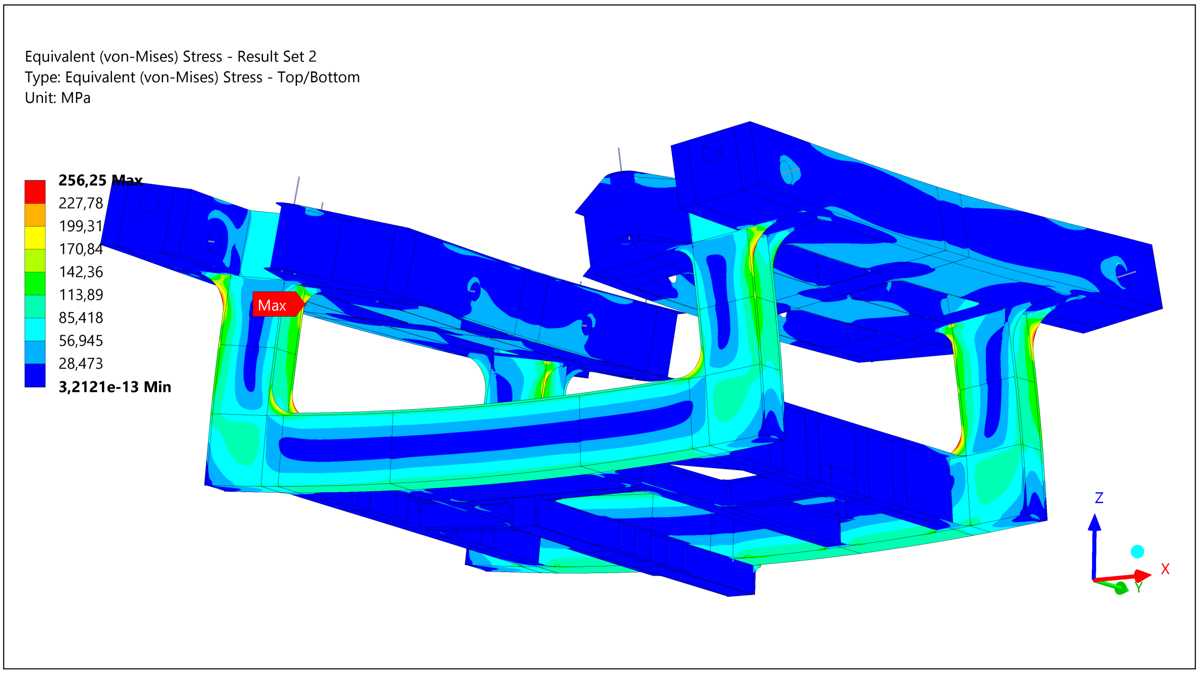


Figure I.2: Load combination A3. Proof of static strength of trolley A.

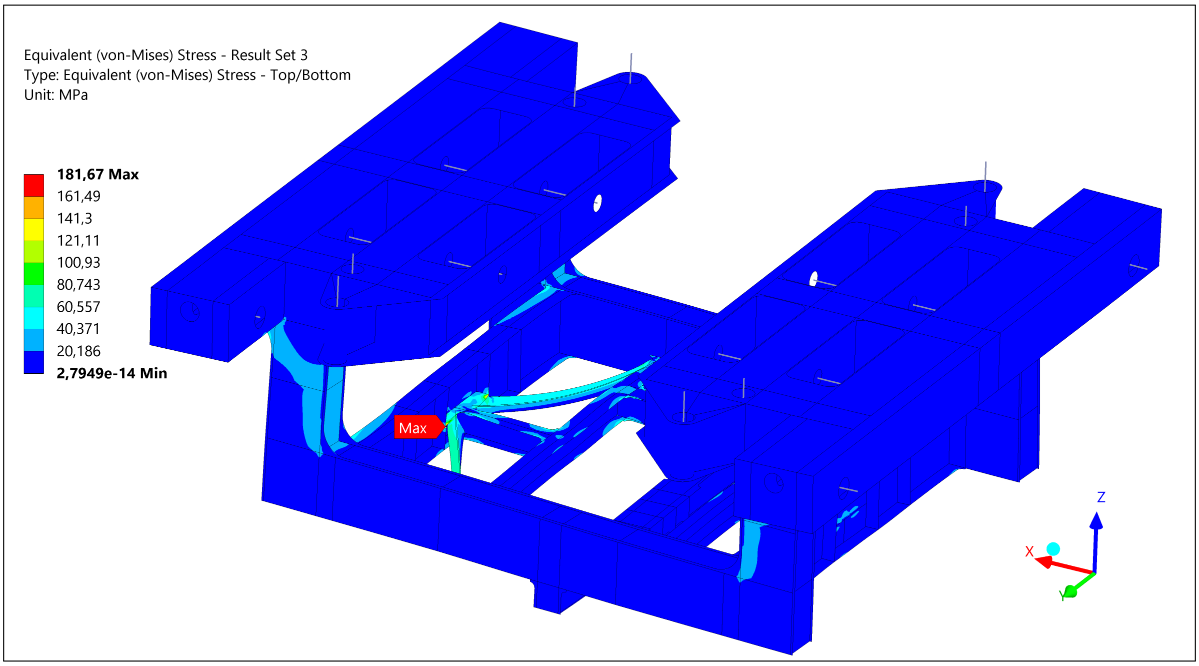


Figure I.3: Load combination B5. Proof of static strength of trolley A.

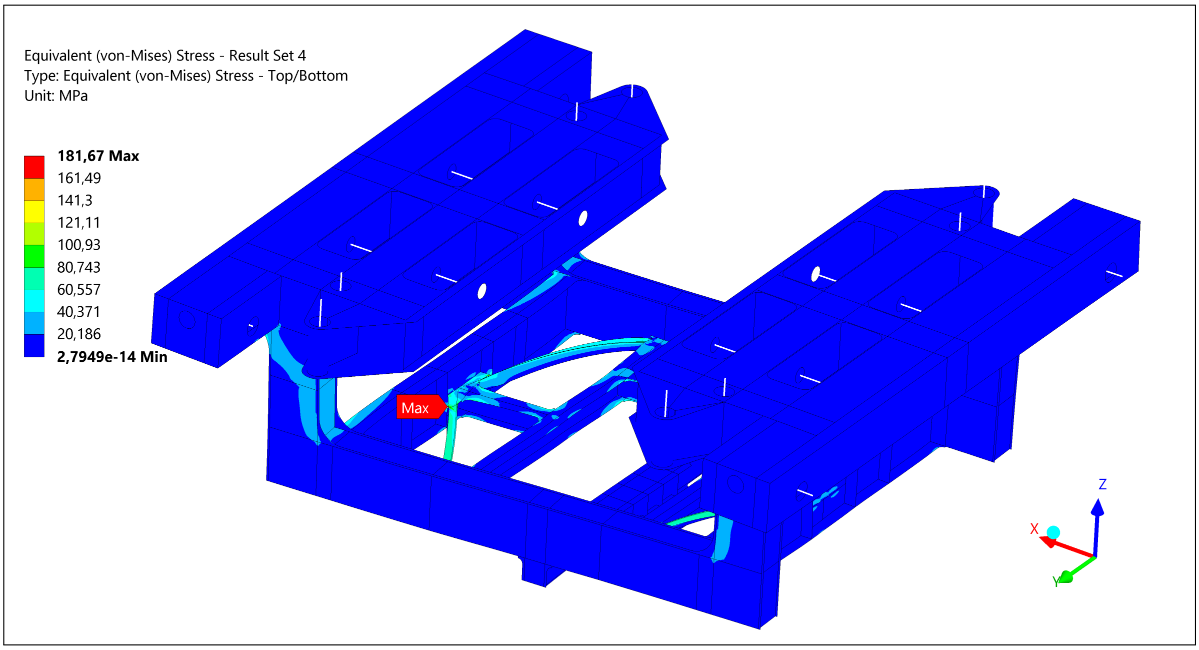


Figure I.4: Load combination B5. Proof of static strength of trolley A. Skew forces are the opposite of figure I.3

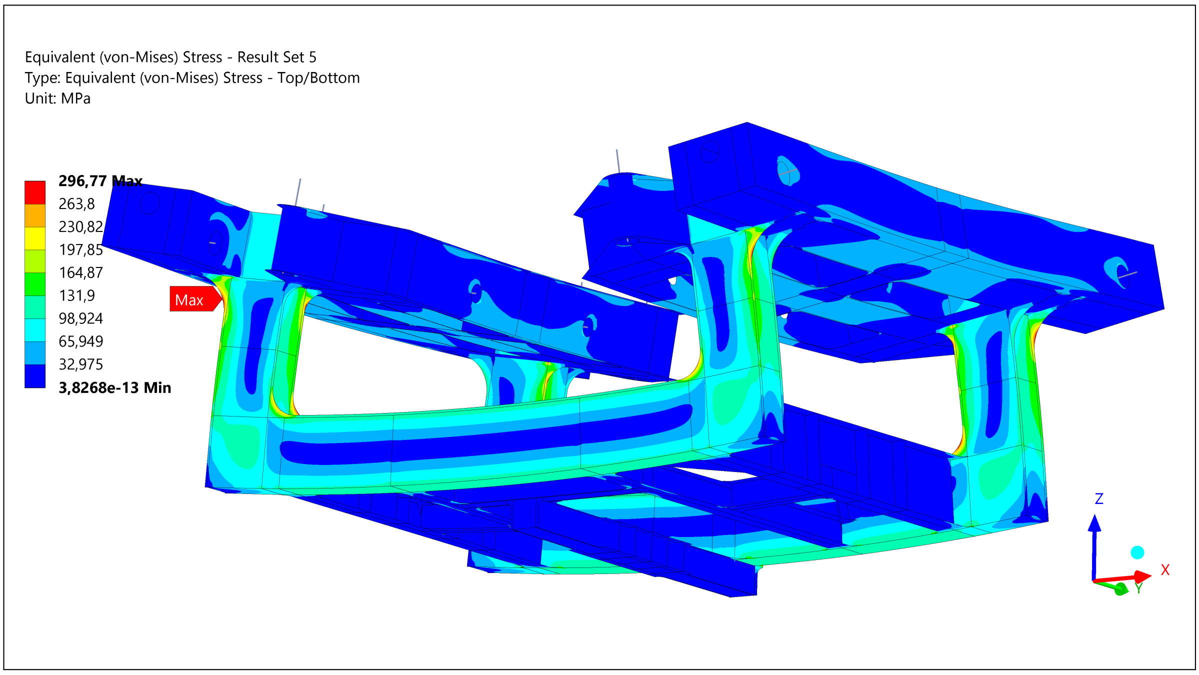


Figure I.5: Load combination C1. Proof of static strength of trolley A.

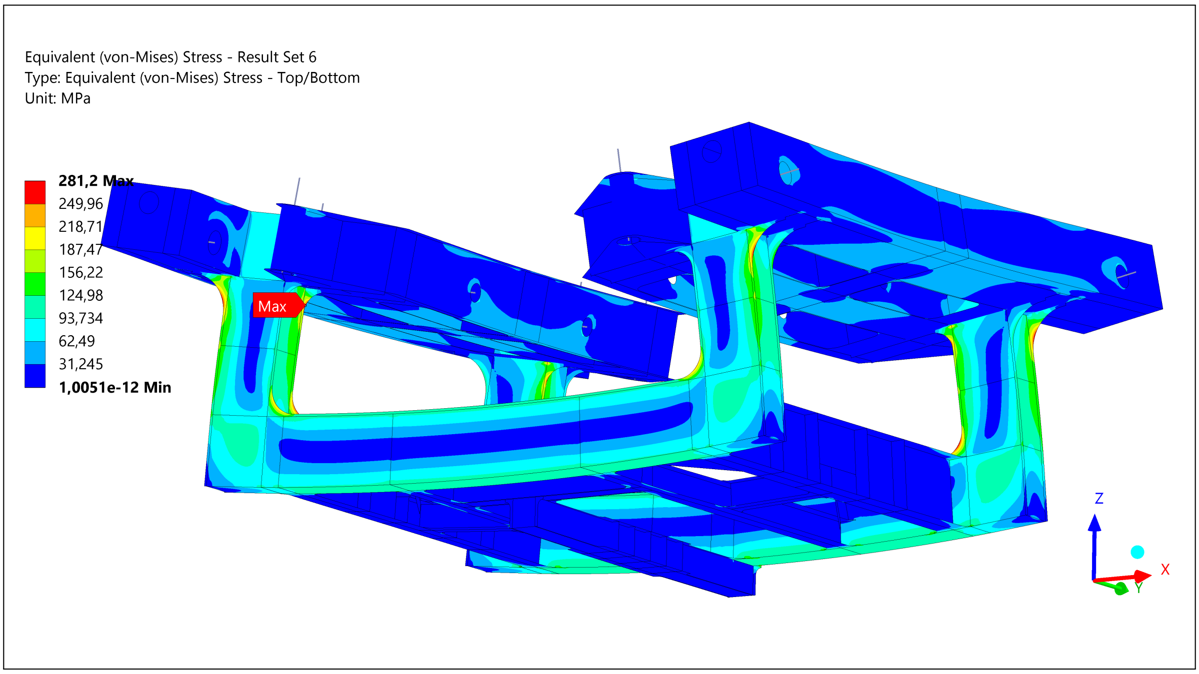


Figure I.6: Load combination C3. Proof of static strength of trolley A.

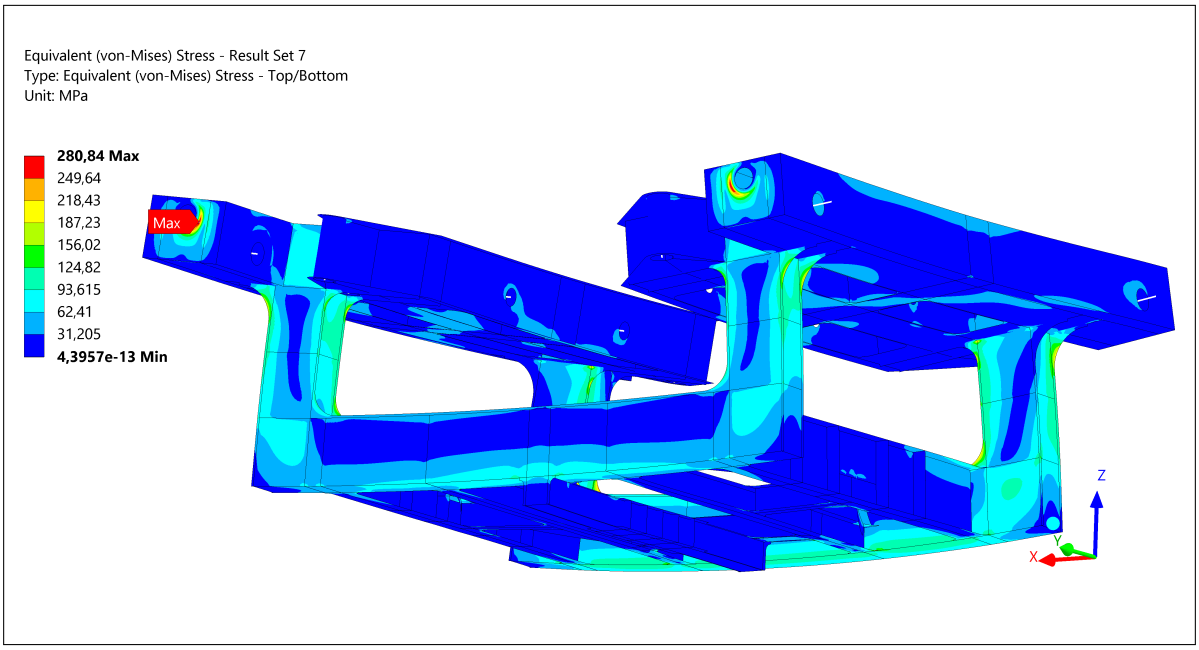


Figure I.7: Load combination C4. Proof of static strength of trolley A. Buffer forces on waterside.

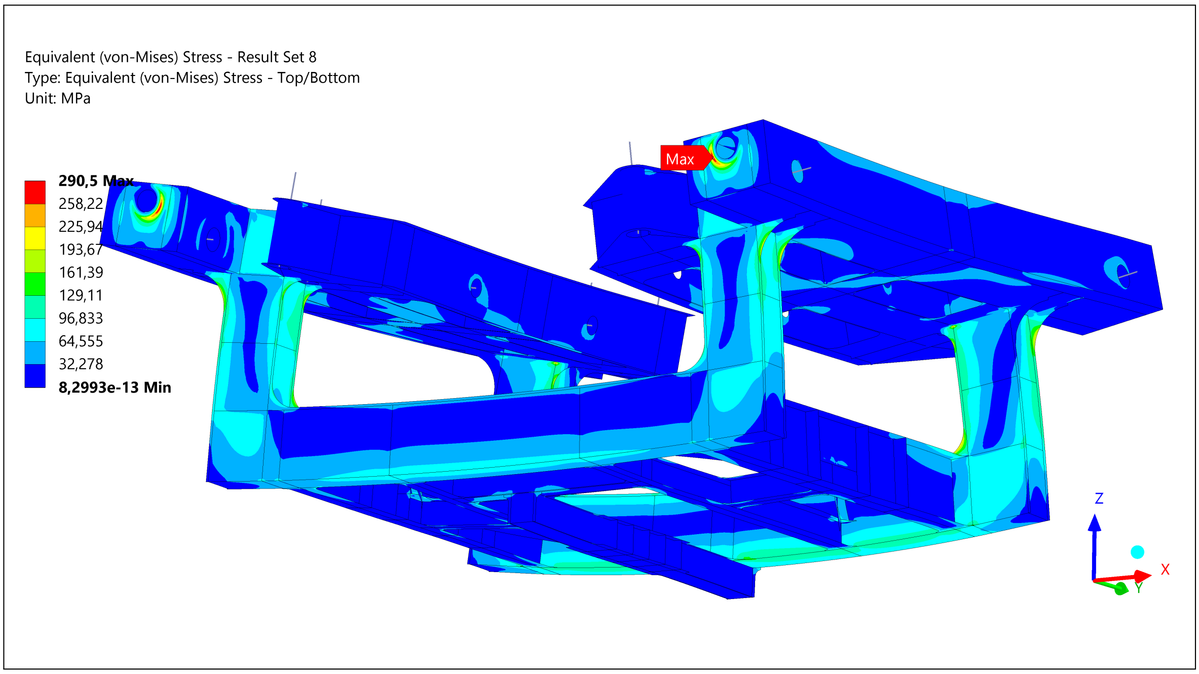


Figure I.8: Load combination C4. Proof of static strength of trolley A. Buffer forces on landside.

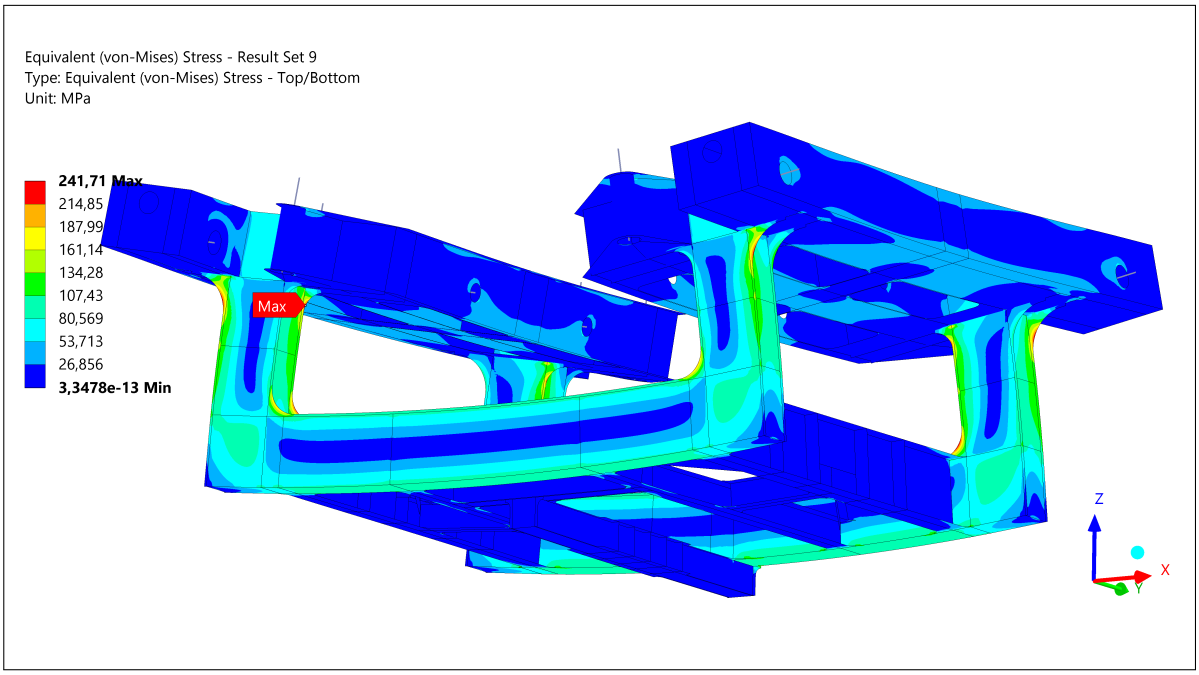


Figure I.9: Load combination C6. Proof of static strength of trolley A.

I.3.2. Trolley B

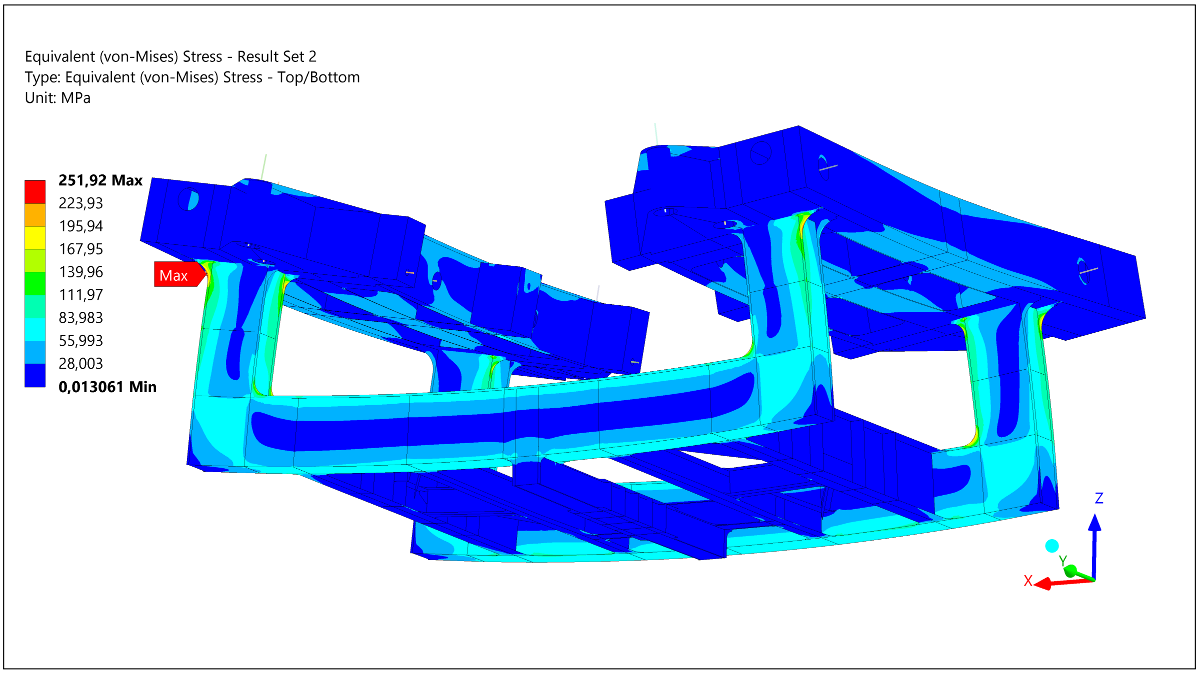


Figure I.10: Load combination A3. Proof of static strength of trolley B.

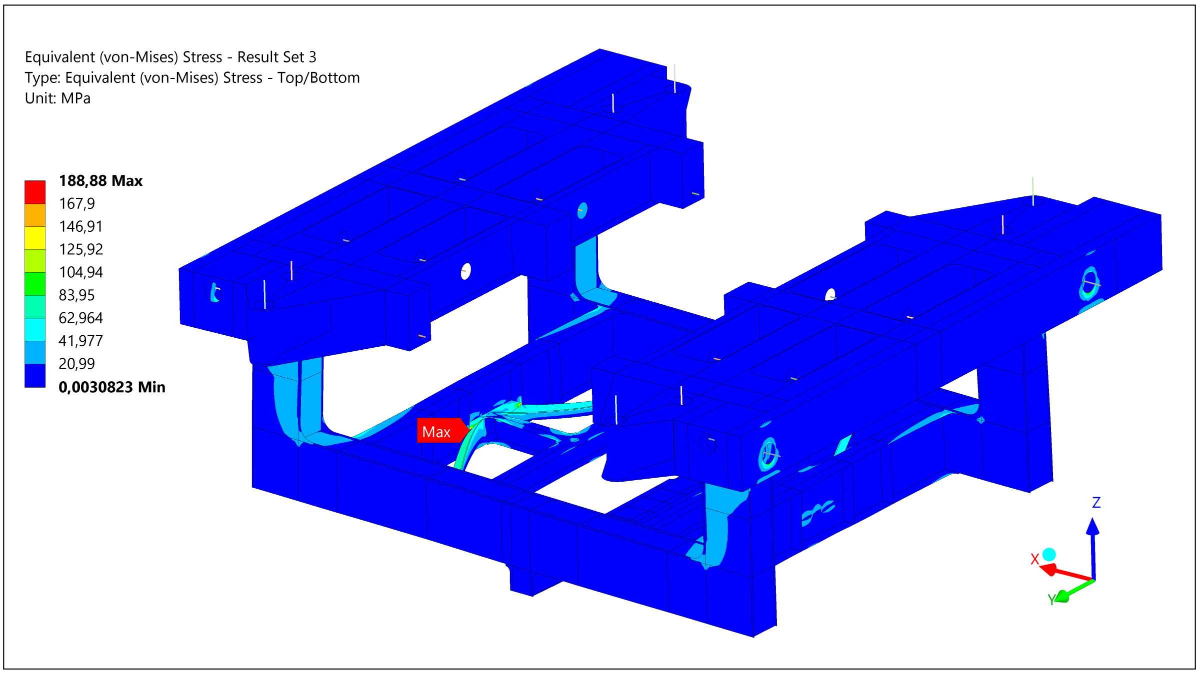


Figure I.11: Load combination B5. Proof of static strength of trolley B.

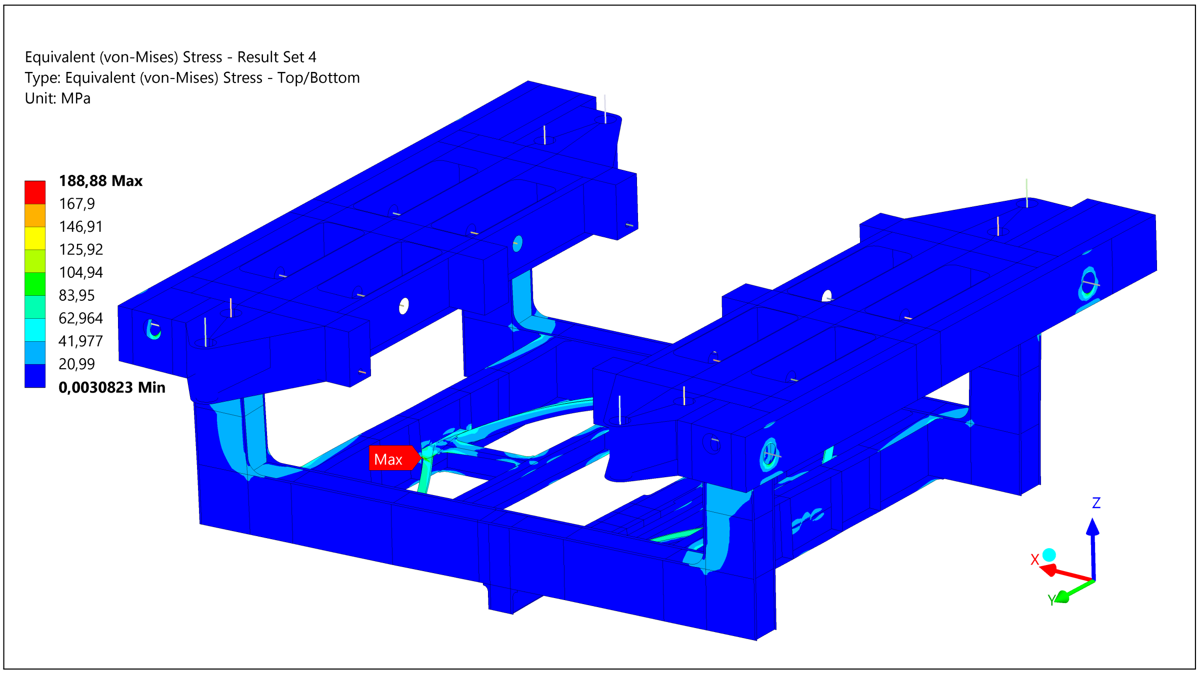


Figure I.12: Load combination B5. Proof of static strength of trolley B. Skew forces are the opposite of figure I.11

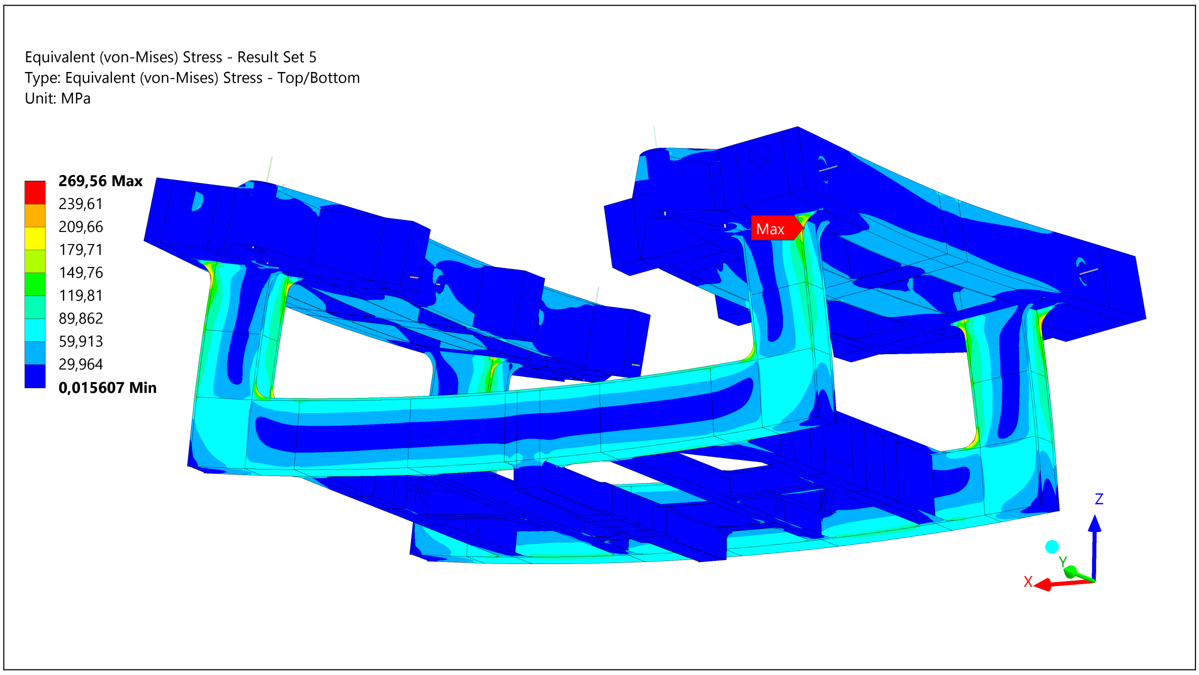


Figure I.13: Load combination C1. Proof of static strength of trolley B.

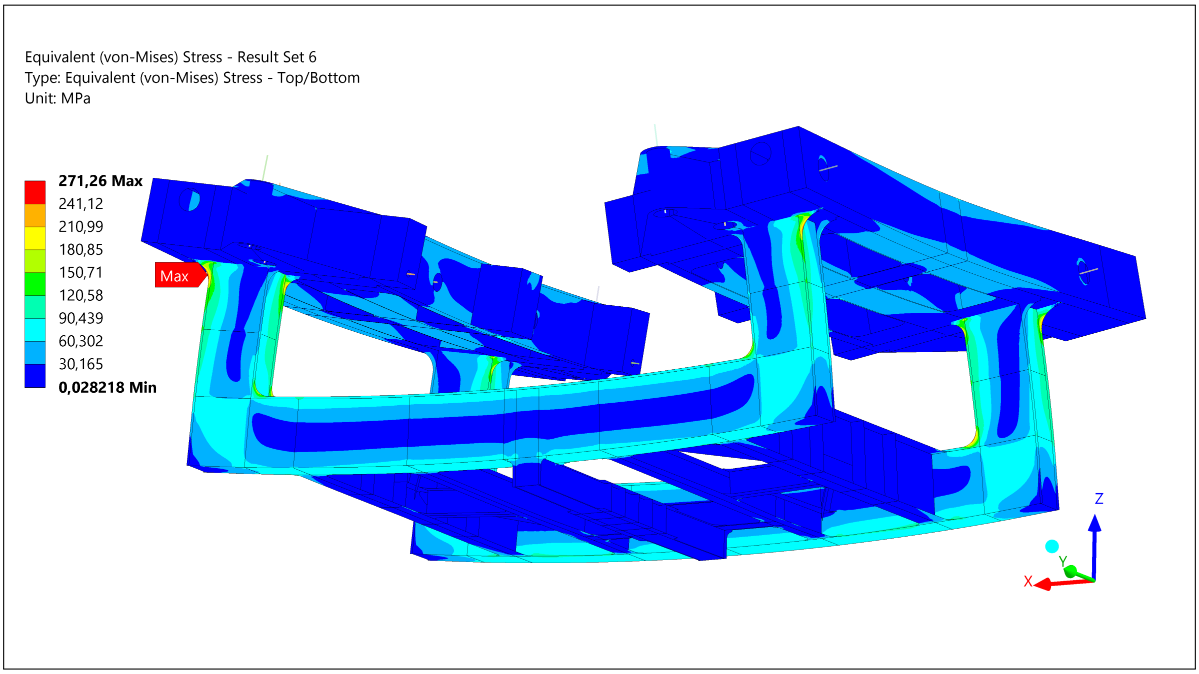


Figure I.14: Load combination C3. Proof of static strength of trolley B.

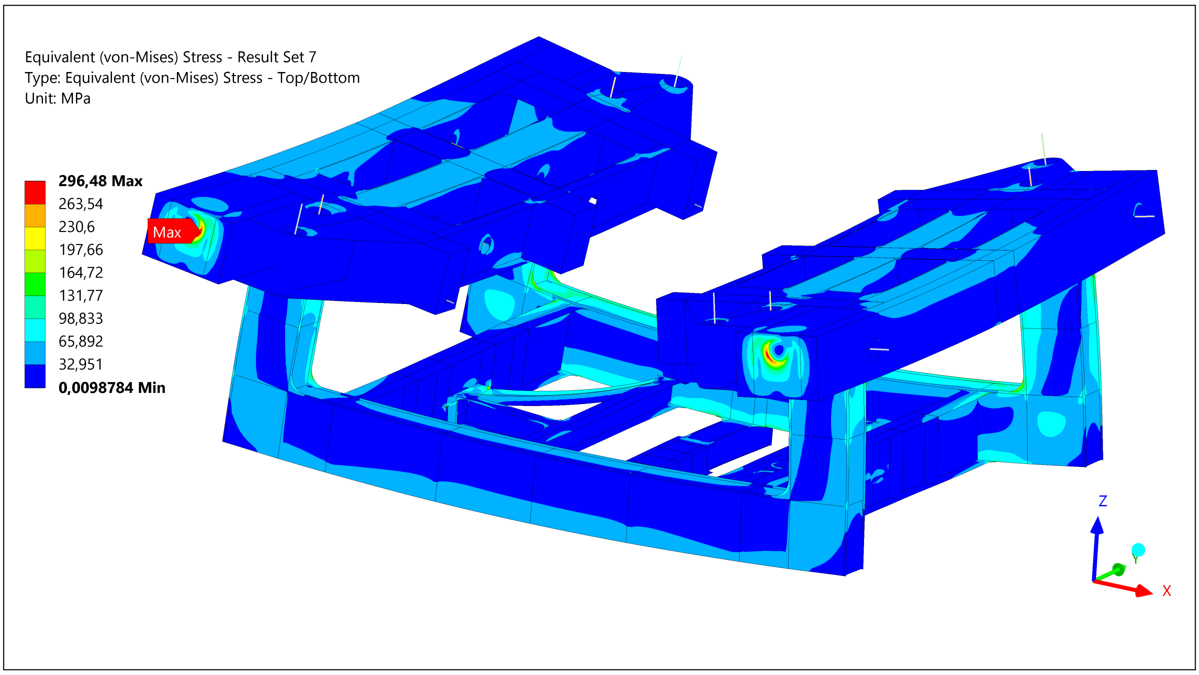


Figure I.15: Load combination C4. Proof of static strength of trolley B. Buffer forces on waterside.

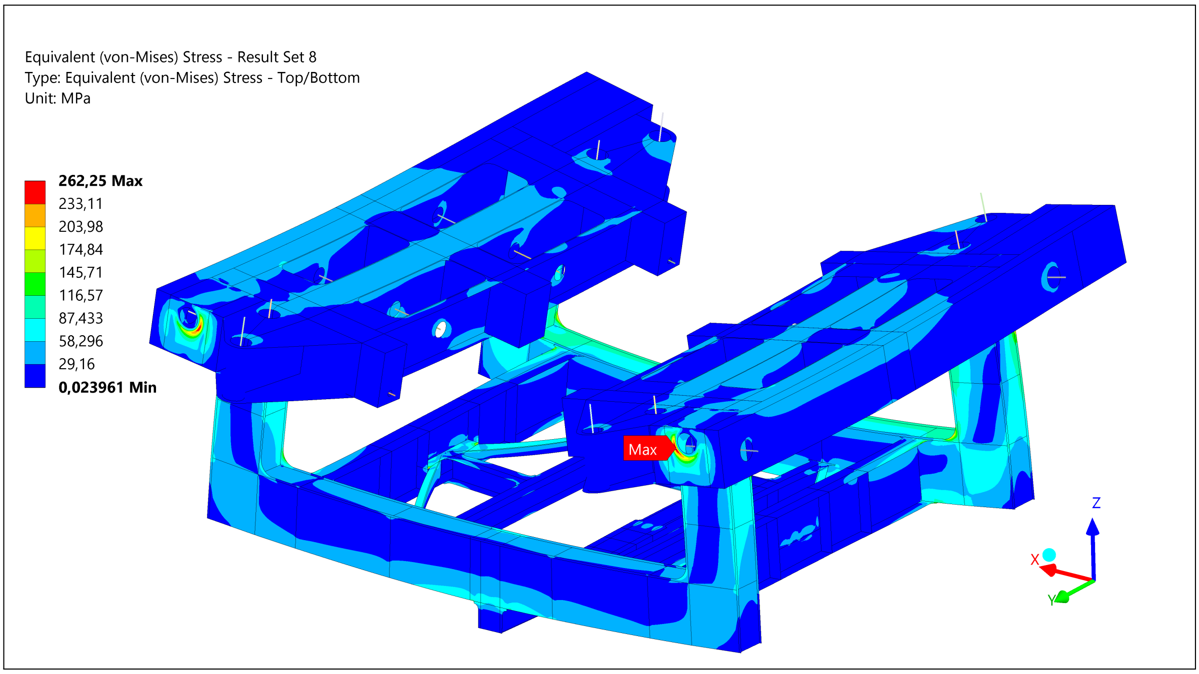


Figure I.16: Load combination C4. Proof of static strength of trolley B. Buffer forces on landside.

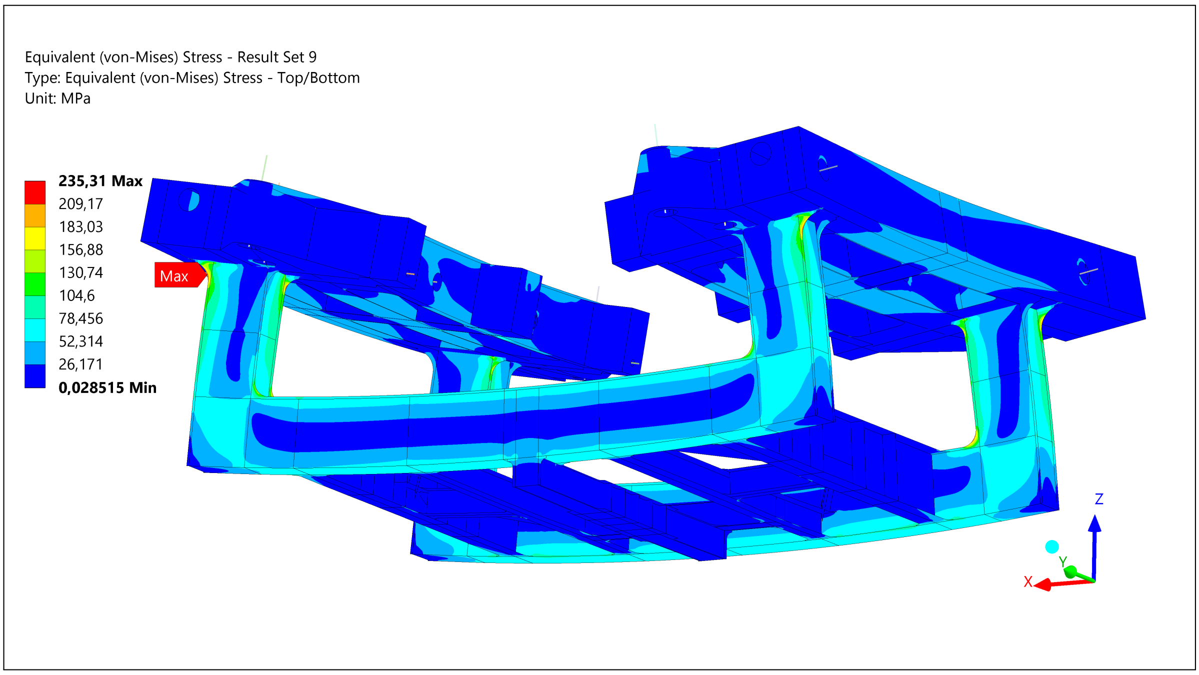


Figure I.17: Load combination C6. Proof of static strength of trolley B.

I.4. Proof of fatigue strength

Below, the results of fatigue strength for all load combinations are shown for both trolleys.

I.4.1. Trolley A

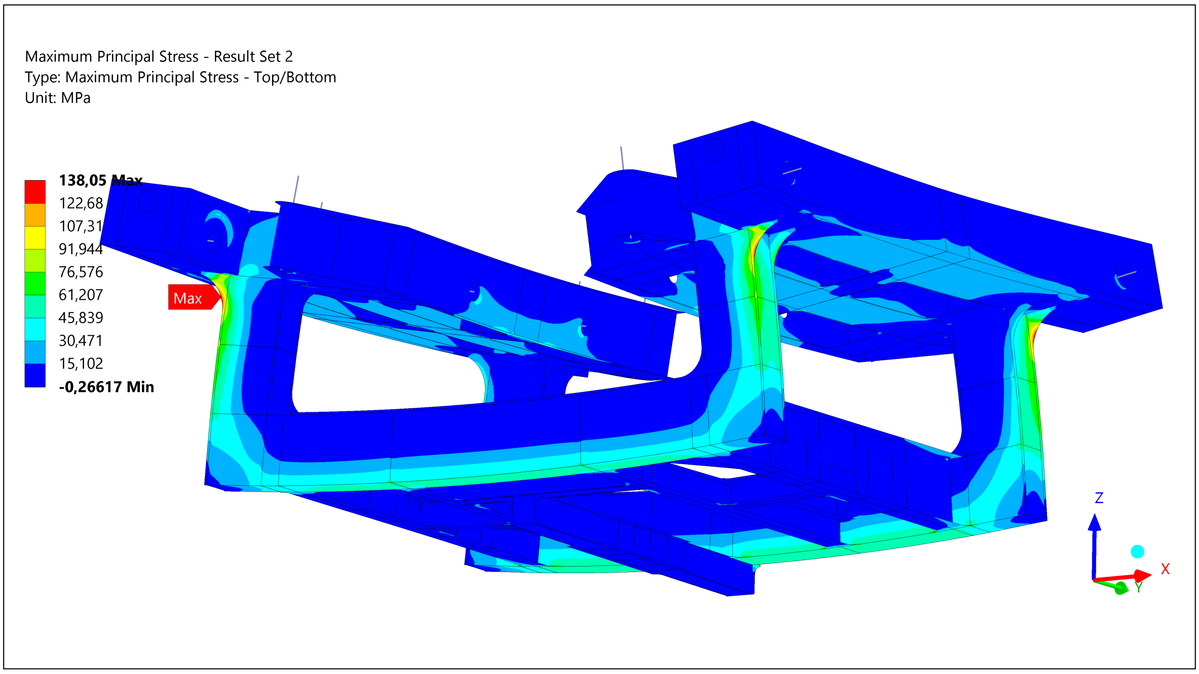


Figure I.18: Load combination A3. Proof of fatigue strength of trolley A.

I.4.2. Trolley B

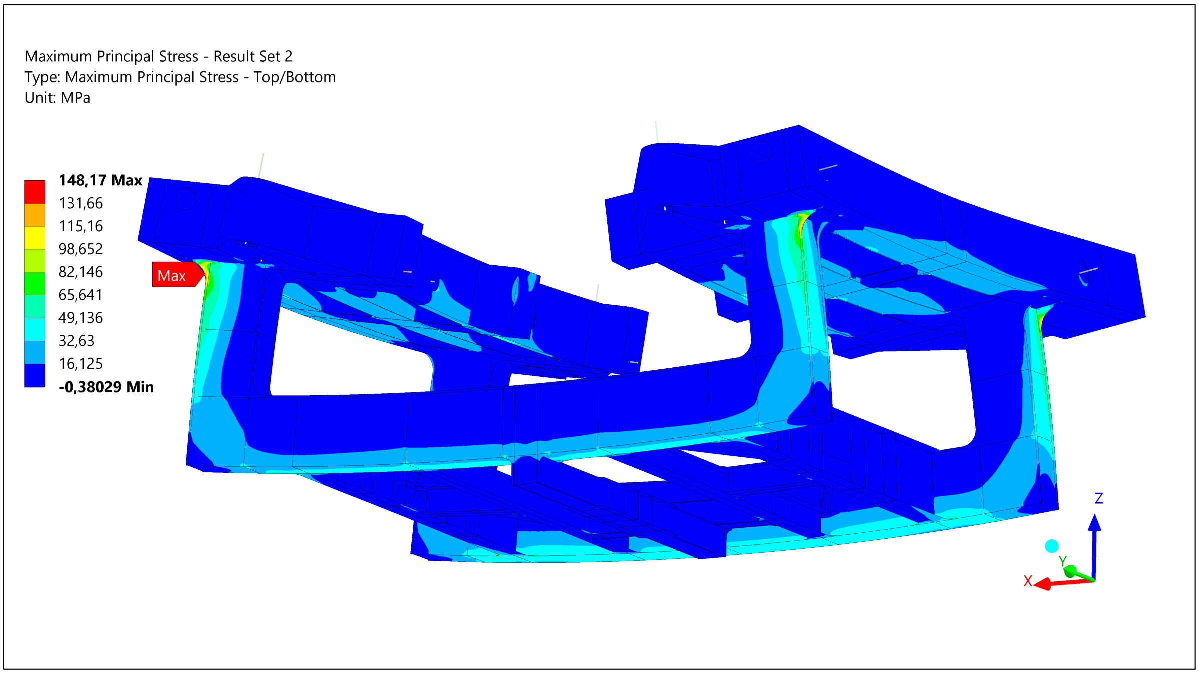


Figure I.19: Load combination A3. Proof of fatigue strength of trolley B.