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Specialization: Transport Engineering and Logistics

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Title: **Cost reduction of Ship-To-Shore container gantry cranes for the Asia-Pacific market**

Author: A.D. Oudshoorn

Title (in Dutch) Kostenreductie van containerkadekranen voor de Aziatische markt

Assignment: Master's thesis

Confidential: yes (until October 2014)

Initiator (university): prof. dr. ir. G. Lodewijks

Initiator (company): ir. R. Kleiss (Cargotec Netherlands BV.)

Supervisor: ir. W. van den Bos (TUDelft), ir. W. de Jong (Cargotec Netherlands BV.)

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Student:	A.D. Oudshoorn	Assignment type:	Graduation Project
Supervisors (TUD):	Prof. dr. ir. G. Lodewijks	Credit points (EC):	35
	Ir. W. van den Bos	Specialization:	TEL
Supervisors (Cargotec):	Ir. R. Kleiss	Report number:	2013.TEL.7771
	Ir. W. de Jong, IWE	Confidential:	Yes

Subject:
Cost reduction of Ship-To-Shore container gantry cranes for the Asia-Pacific market

Company:
The project comes forth from Cargotec Kalmar (The Netherlands) which design, among others, Ship-To-Shore container gantry cranes. The company has formed a joint venture with Nantong Rainbow Heavy Industries (steel structures and products, P.R. China), named Rainbow Cargotec Industries (P.R. China), which does the manufacturing, assembly and sales of the cranes that come from Cargotec Kalmar.

General introduction, background and context:
The project comes forth from a number of sessions within the company on how to reduce the cost in Ship-To-Shore container gantry cranes. A number of results from these sessions have been placed together into a project. The reason for reducing the cost is to increase the container crane volume sold.

Problem definition and questions to be answered:
Cost reduction is necessary due to the current price level of the competition. Furthermore production, assembly and sales is done in P.R. China, however no cranes are sold in the Asia-Pacific market. Based on this the following research question has been formulated:

What is the possible cost reduction that can be attained by redesigning the portal frame (replace bolted flange plate connections by welded flange plate connections and the use of a lower steel quality grade) and part of the machinery works (application of an open gearing for the crane travelling gear) of Panamax and Post Panamax Ship-To-Shore container gantry cranes for the Asia-Pacific market?

The following points will be addressed:
- Asia-Pacific market (standard, requirements, demands, size, and developments)
- Technical quality (steel quality)
- Portal frame (replacement of bolted flange plates by welded flange plate connections and its influences on design, production, assembly, and transport)
- Machinery work (application of an open gearing in the bogie set)

The report should comply with the guidelines of the section. Details can be found on the website.

Supervisor,

Prof. dr. ir. G. Lodewijks

Preface

This report is the conclusion of my Master's thesis as a master student Transportation Engineering and Logistics at the faculty of Mechanical, Maritime and Material Science Engineering of the Technical University Delft, the Netherlands.

The structure of this report is such that a number of topics are discussed that fall within the main context of my Master's thesis, namely the reduction of the cost of Ship-To-Shore container gantry cranes. The topics discussed have been noted below.

Part I: Market overview and demands of the Asia-Pacific market for Ship-To-Shore container gantry cranes.

Part II: Steel quality application for Ship-To-Shore container gantry cranes.

Part III: Application of an open gearing transmission for the crane travelling gear of Ship-To-Shore container gantry cranes.

Part IV: Replacement of bolted flange connections by welded connections in the portal frame of Ship-To-Shore container gantry cranes.

The paper can be reviewed in Appendix A.

Before proceeding I would like to direct a word of praise to those people who have stood by me during this period of time.

Firstly I would like to thank ir. W. de Jong and ir. R. Kleiss from Cargotec Netherlands BV and ir. W. van den Bos and Prof. dr. ir. G. Lodewijks from the Technical University Delft for their supervision, discussion and comments on my work.

I would also like to express my gratitude to the people at Rainbow Cargotec Industries Co., Ltd. for providing me with the support I needed for my Master's thesis, especially MSc. J. Cheng for his support and discussion.

Furthermore, I would like to thank my external supervisors, assoc. Prof. X. Shi and assoc. Prof. Z.C. Du, at the Shanghai Jiao Tong University for their involvement and comments on my work.

Lastly I would like to thank my family and friends in the Netherlands and China for their support and company during this intensive period.

Anton David Oudshoorn 安东大卫

September 26th, 2013 二零一三年九月二十六日

ANTON

Summary (English)

Cargotec Netherlands BV is a global manufacturer of Ship-To-Shore container gantry cranes and other types of cranes. However, the company has noticed that the cost price (cost made during production and assembly, excluding transport and cost at the client's site) of its Ship-To-Shore container gantry cranes is 5 to 10 % higher than that of competitors. Therefore the company wants to reduce the cost of its cranes. To achieve a cost reduction, several measures have been thought of (by the company) by comparing with competitors and from practice. A number of these topics have been found suitable to form a Master's thesis. These measures are the application of a different steel quality in the steel structure, the application of an open gearing transmission for the crane travelling gear, and the replacement of bolted flange connections by welded connections in the portal frame.

The goal of this study is to provide a solution for the implementation of those measures that result in a cost reduction of Ship-To-Shore container gantry cranes and to give an indication of that cost reduction. For the application of the steel quality the goal is to provide a guideline for selecting the appropriate steel quality and what the cost reduction will be. For the application of an open gearing transmission the goal is to compare an open gearing with a standard gantry travelling gear and to indicate the cost reduction that can be achieved. For the replacement of bolted flange plate connections by welded connections, the goal is to determine which connection in the portal frame should be replaced and what the consequences are for production, assembly and transport, next to indicating the cost reduction. Beside these measures an overview of the Asia-Pacific market and the demands from this market has been provided with regards to the previously mentioned measures.

For the evaluation of the steel quality a number of methods can be applied, however, for this thesis only the selection procedure as stated in standards has been evaluated. The importance of selecting the right steel quality is to prevent brittle fracture. Brittle fracture is a type of fracture, which is preceded with little or no plastic deformation. This is opposed to what can be observed with a ductile fracture, whereby the material shows a large degree of plastic deformation before fracture. Brittle fracture occurs when three conditions are in place, namely high tensile stresses, low temperatures and large plate thicknesses. The standard takes these three conditions into account in order to come to the correct steel quality, which is expressed as B, C or D-quality steel. B-quality steel has a low resistance against brittle fracture and D-quality steel has a high resistance against brittle fracture. Based on an evaluation of the steel construction of an existing Ship-To-Shore container gantry crane, through the steel quality selection procedure defined in the European standard FEM 1.001, the conclusion has been drawn that the steel structure can be made from a combination of steel plates consisting of B, C and D-quality, as opposed to the current practice of only applying D-quality steel. This leads to a cost reduction of 22,500 Euro per crane.

With the use of an open gearing in the gantry travelling gear of Ship-To-Shore container gantry cranes a comparison has been made between an existing gantry travelling gear (a single engine with closed gearing powers a single crane wheel) and a number of open gearing models (a single engine powers two or more crane wheels through an combination of an open and closed gearing). Based on this comparison a number of conclusions have been drawn regarding the design of an open gearing and the possible cost reduction that can be attained. When designing an open gearing for the gantry travelling gear it should firstly be noted that the efficiency of this type of transmission will be lower compared to the closed gearing. Secondly, in order to limit this reduction in efficiency, the guideline should be to apply a minimal amount of gearwheels. Thirdly, if the overall transmission is a combination of open and closed gearing, the transmission ratio of the open gearing should be made as large as possible in order to reduce the size of the closed gearing (thereby decreasing the cost). Due to the application of an open gearing, the number of engines, closed gearboxes, engine couplings, etcetera can be reduced drastically (even though the open gearing brings with it a number of additional components and assembly time) and with it the cost of the gantry travelling gear. For the application of an open gearing, whereby the engine powers two crane wheels, the cost reduction amounts to 61,900 Euro compared to an existing gantry travelling gear. The situation where the engine powers four crane wheels will lead to an decrease of 61,000 Euro. In case the travelling gear is shortened in length the cost reduction will amount to 87,500 Euro.

A bolted flange plate connection is a type of connection applied in the steel construction to attach components. A bolted flange plate connection is a type of connection which offers a high degree of flexibility during assembly for the placement and attachment of components, though comes with high production cost. For the replacement of bolted flange plate connections by welded connections, the cost reduction that can be attained is dependent on the location of assembly, the type of sea transport and (un-)loading, and the assembly capacity (assembly area and available hoisting equipment). The choice for the type of connection is thus not only based on an economical evaluation, but also by taking these factors into account. In case assembly takes place at Taicang Port the conclusion is that if fewer welded connections are used, the cost reduction will be higher. Replacing almost all bolted flange plate connections will result in a cost increase instead of a decrease. Depending on the concept the difference in cost ranges from -20,600 Euro (cost increase) to 48,600 Euro (cost decrease) from a conservative point of view. In case assembly takes place at RCI assembly site the conclusion is that using more welded connections will lead to a higher cost reduction. Also in this situation depending on the concept the cost reduction ranges from 38,300 Euro to 67,300 Euro from a conservative point of view. The difference results from a balance between the cost removed by replacing the bolted flange plate connections and the cost that return by a welded connection, with the increase in assembly time.

For the Asia-Pacific market an overview of the size, competitors, environmental conditions, standards used and demands concerning the previously mentioned topics is constructed with the help of tender documents.

Summary (Dutch)

Cargotec Netherlands BV is een producent van, onder andere containerkadekranen, welke verkocht worden aan klanten over de hele wereld. Echter, Cargotec Netherlands BV heeft de laatste jaren ervaren dat de kostprijs (van productie en assemblage) van de door hen gelevered containerkadekranen 5 tot 10 % hoger ligt dan die van de concurrentie. Om deze reden wil Cargotec Netherlands BV de kostprijs verlagen door middel van een aantal maatregelen die zijn voortgekomen door de huidige werkwijze van Cargotec Netherlands BV te vergelijken met die van concurrenten en uit de praktijk. Een aantal van deze maatregelen zijn geschikt bevonden voor een Masters thesis. Deze maatregelen betreffen het volgende: de toepassing van een andere staalkwaliteit voor de staalstructuur van de kraan, de toepassing van een open vertraging voor het rijwerk van de kraan, en de vervanging van boutverbindingen door gelaste verbindingen in het portaalframe van de kraan.

Het doel van deze studie is om een praktisch advies naar voren te brengen voor de onderwerpen die worden behandeld; welke moet leiden tot een vermindering van de kostprijs van container kadekranen en om een indicatie te geven van de grootte van deze kostenbesparing. Voor de toepassing van een andere staalkwaliteit is het doel om een richtlijn te geven welke staalkwaliteit kan worden toegepast in de staalconstructie van de kraan, en wat de kostenbesparing zal zijn. Voor de toepassing van een open vertraging is het doel om een vergelijking te maken tussen een open vertragingstoepassing en een gesloten vertragingstoepassing voor het rijwerk van de kraan en om aan te geven wat de kostenbesparing zal zijn. Voor de vervanging van boutverbindingen door gelaste verbindingen is het doel om te bepalen welke boutverbinding in het portaalframe vervangen moeten worden en wat de gevolgen van deze vervanging zijn voor productie, assemblage en transport, naast een indicatie van de kostenbesparing. Verder wordt een overzicht van de Aziatische markt en de eisen die voortkomen uit deze markt naar voren gebracht in dit rapport.

Voor de evaluatie van de staalkwaliteit zijn er een aantal methodieken die kunnen worden toegepast, echter wordt de focus gericht op de staalkwaliteitsselectieprocedure zoals deze is definieert in normen. Het selecteren van de juiste staalkwaliteit is van belang voor het voorkomen van een brosse breuk. Een brosse breuk is een type breuk, waarbij weinig of geen plastische vervorming optreedt voor de daadwerkelijke breuk. Dit in tegenstelling tot een taaibreuk, waarbij een grote hoeveelheid plastische vervorming kan worden waargenomen voor de daadwerkelijke breuk zelf. Brosse breuk treedt op wanneer drie condities aanwezig zijn, namelijk een hoge trekspanning, lage temperatuur en een grote plaatdikte. De norm neemt deze drie factor in rekening bij het bepalen van de juiste staalkwaliteit, welke wordt uitgedrukt in B,C en D-kwaliteit staal. B-kwaliteit staal is een staalkwaliteit met een lage weerstand tegen brosse breuk; D-kwaliteit staal heeft een hoge weerstand tegen brosse breuk. Gebaseerd op een evaluatie van een bestaande staalconstructie van een container kadekraan,

door middel van de Europese norm FEM 1.001, kan de conclusie getrokken worden dat de staalstructuur kan worden opgebouwd uit een combinatie van B, C en D-kwaliteit staal. Dit in tegenstelling tot de huidige praktijk waarbij het bedrijf standaard D-kwaliteit staal toepast. Op basis van de evaluatie kan er geconcludeerd worden dat een kostenbesparing behaald kan worden van 22.500 Euro.

Als het gaat om de toepassing van een open vertraging voor het rijwerk van containerkadekranen is er een vergelijking gemaakt tussen het bestaande rijwerk van een containerkadekraan (waarbij een enkele motor met gesloten vertragingskast een enkel kraanwiel aandrijft) en een aantal concepten van open vertragingen (waarbij een enkele motor twee of meer kraanwielen aandrijft met een combinatie van een open en gesloten vertraging). Gebaseerd op deze vergelijkingen kunnen er een aantal conclusies getrokken worden voor het ontwerp van een open vertraging en voor de mogelijke kostenbesparing die behaald kan worden. Voor het ontwerp van een open vertraging zou het doel moeten zijn om het aantal tandwielen te beperken tot een minimum, omdat de efficiëntie van de overbrenging lager is dan voor het bestaande rijwerk. Om deze vermindering in efficiëntie zo klein mogelijk te houden moet het aantal tandwielen van de open vertraging zo klein mogelijk gehouden worden. Verder moet ernaar worden gestreefd om de overbrengingsverhouding van de open vertraging zo groot mogelijk te maken, indien de totale overbrenging een combinatie is van een gesloten vertragingskast en een open vertraging (dit vermindert de kosten). Vanwege de toepassing van een open vertraging zal het aantal motoren, gesloten vertragingskasten en dergelijke drastisch verlaagd kunnen worden en daarmee de kosten voor het rijwerk (ook al brengt een de toepassing van een open vertraging een aantal additionele componenten, tijd en daarmee kosten met zich mee). Voor de toepassing van een open vertraging, waarbij de motor twee kraanwielen aandrijft, is de kostenbesparing bepaald op 61.900 Euro in vergelijking met het bestaande rijwerk van een containerkadekraan. In het geval dat de motor vier kraanwielen aandrijft neemt de kostenbesparing af tot 61.000 Euro. Voor het geval van een verkort rijwerk zal de kostenbesparing oplopen tot 87.500 Euro.

Een boutverbinding is een type verbinding die wordt toegepast in de staalconstructie om componenten te verbinden. Een boutverbinding is een type verbinding die veel flexibility toelaat tijdens de assemblage, echter dit type verbinding gaat gepaard met hoge productiekosten. Vanwege deze hoge productiekosten is het toepassen van een gelaste verbinding interessant. Voor de vervanging van boutverbindingen door gelaste verbindingen is de kostenbesparing die kan worden behaald afhankelijk van de locatie van de assemblage, het type zeetransport en de manier van laden en lossen van de kraan, en de assemblage capaciteit (grootte van de assemblage site en hijscapaciteit). De keuze voor het type verbinding wordt niet alleen bepaald door de kosten, maar ook door de hiervoor aangegeven factoren. In het geval de assemblage plaatsvind in Taicang Port kan de conclusie getrokken worden dat hoe minder gelaste verbindingen hoe hoger de kostenbesparing zal zijn. In het geval bijna alle boutverbindingen worden vervangen, treedt een kostentoename op in plaats van een kostenbesparing. Afhankelijk van het concept zal de kostenbesparing oplopen van -20.600 Euro (kostentoename) tot 48.600 Euro (kostenbesparing) vanuit een conservatief oogpunt. In het geval de assemblage plaatvind op de RCI assemblage site kan de conclusie getrokken worden dat hoe meer gelaste verbindingen er worden toegepast hoe hoger de kostenbesparing zal zijn. Afhankelijk van welk concept bekeken wordt zal de kostenbesparing oplopen van 38.300 Euro tot 67.300 Euro vanuit een conservatief oogpunt. Het verschil in kostenreductie treedt op door een afweging van de kosten die verwijderd worden (bijvoorbeeld de productiekosten van de flensplaten voor een boutverbinding) en de kosten die daar in de plaats voor komen.

Met betrekking tot de Aziatische markt is er een overzicht gemaakt van de grootte van de markt, de spelers op deze markt, de omgevingscondities waarin de kraan moet opereren, normen die worden toegepast en de eisen die klanten hebben voor wat betreft de voorgaande onderwerpen.

List of abbreviations

STS	Ship-To-Shore
ZPMC	Zhenhua Heavy Industries Co., Ltd.
RTG	Rubber Tire Gantry crane
APAC	Asia-Pacific
RMG	Rail Mounted Gantry crane
ASC	Automated Stacking Crane
TEU	Twenty foot Equivalent Unit
PX	Panamax
PPX	Post-Panamax
MT	Metric Ton
LS	Landside
WS	Waterside
PS	Portside
SB	Starboard
FCB	Floating Crane Barge
NEN	NEderlandse Norm
FEM	Federation Europeenne de la Manutention
NEN-EN	NEderlandse Norm Europaïsche Norme
BS	British Standard
DIN	Deutsche Institut für Normung
CODT	Crack Opening Displacement Test

List of symbols

Half of the crack length a_0 [m]

Critical fracture toughness value K_{IC} [N/mm$^{3/2}$]

Shape factor depending on the location of the crack Y [-]

Tensile stress σ [N/mm^2]

Crack length c_0 [m]

J-integral value J [N/m]

Fracture toughness value K [N/mm$^{3/2}$]

Poisson constant v [-]

Modulus of elasticity E [N/mm^2]

CODT-value δ [m]

Critical J-integral value J_{IC} [N/mm]

Yield stress CODT-value σ_Y [N/mm^2]

Influence coefficient FEM 1.001 Z_i [-]

Residual tensile stress assessment coefficient FEM 1.001 Z_A [-]

Tensile stresses from the dead load σ_G N/mm^2]

Permissible tensile stress with respect to the elastic limit of load case 1 σ_a [N/mm^2]

Yield stress f_y [N/mm^2]

Temperature assessment coefficient FEM 1.001 Z_B [-]

Plate thickness t [mm]

Plate thickness assessment coefficient FEM 1.001 Z_C [-]

Temperature T [°C]

Influence coefficient NEN-EN 13001 Q_i [-]

Temperature assessment coefficient NEN-EN 13001 Q_1 [-]

Yield stress assessment coefficient NEN-EN 13001 Q_2 [-]

Material thickness assessment coefficient NEN-EN 13001 Q_3 [-]

Characteristic value of stress range assessment coefficient NEN-EN 13001 Q_4 [-]

Characteristic value of stress range $\Delta\sigma_C$ [N/mm2]

Utilization of static strength assessment coefficient NEN-EN 13001 Q_5 [-]

Design limit stress NEN-EN 13001 σ_{Sd} [N/mm^2]

Yield limit stress NEN-EN 13001 $f_{Rd\sigma}$ [N/mm^2]

Calculated fracture toughness value $K_{CALCULATED}$ [N/mm$^{3/2}$]

Fracture toughness value Q345-B K_{Q345B} [N/mm$^{3/2}$]

Fracture toughness value Q345-C K_{Q345C} [N/mm$^{3/2}$]

Fracture toughness value Q345-D K_{Q345D} [N/mm$^{3/2}$]

Fracture toughness value Q390-B K_{Q390B} [N/mm$^{3/2}$]

Fracture toughness value Q390-C K_{Q390C} [N/mm$^{3/2}$]

Fracture toughness value Q390-D K_{Q390D} [N/mm$^{3/2}$]

Power requirement due to nominal travelling resistance P_f [kW]

Power requirement due to the wind P_W [kW]

Power requirement due to the acceleration of rotating masses P_R [kW]

Power requirement due to the acceleration of linear moving masses P_L [kW]

Total nominal power $P_{nominal}$ [kW]

Total acceleration power $P_{acceleration}$ [kW]

Gearing efficiency η_G [-]

Overload factor of the engine f_A [-]

Number of driven wheels n_{wheel} [-]

Nominal power per driven wheel P_{wheel} [kW]

Number of driven bogies n_{bogie} [-]

Nominal power per driven bogieP_{bogie} [kW]

Nominal power per driven bogie pair $P_{multiple\ bogie}$ [kW]
Torque requirement due to nominal crane travelling M_f [kNm]
Torque requirement due to the wind M_W [kNm]
Torque requirement due to the acceleration of rotating masses M_R [kNm]
Torque requirement due to the acceleration of linear moving masses M_L [kNm]
Total nominal torque $M_{nominal}$ [kNm]
Total acceleration torque $M_{acceleration}$ [kNm]
Nominal torque per wheel M_{wheel} [kNm]
Nominal torque per bogie M_{bogie} [kNm]
Nominal torque per bogie pair $M_{multiple\ bogie}$ [kNm]
Maximum braking speed $n_{brake\ allowable}$ [rpm]
Braking torque $M_{brake\ total}$ [kNm]
Braking distance $s_{c\ braking}$ [m]
Wheelslip safety V [-]
Heat absorption limit of the brake $E_{allowable\ per\ brake}$ [J]
Energy requirement due to the rolling resistance E_f [kJ]
Energy requirement due to the wind E_W [kJ]
Energy requirement due to the deceleration of linear moving masses E_L [kJ]
Energy requirement due to the deceleration of rotational moving masses E_R [kJ]
Number of brakes n_{brake} [-]
Overall transmission ratio i [-]
Motor speed n_M [rpm]
Crane wheel diameter D_W [m]
Crane speed v_C [m/s]
Transmission ratio of the open gearing $i_{open\ gearing}$ [-]
Transmission ratio of the closed gearbox $i_{closed\ gearbox}$ [-]
Number of teeth of the gear wheel Z_i [-]
Diameter of gear wheel D_i [mm]
Diameter of intermediate gear wheel D_2 [mm]
Nominal engine torque required $M_{nom\ engine}$ [Nm]
Maximum engine torque required $M_{acc\ engine}$ [Nm]
Maximum coupling torque $M_{max\ coupling}$ [Nm]
Service factor coupling $S_{coupling}$ [-]
Minimum service factor S_{min} [-]
Weight of the load W_{Load} [MT]
Calculated braking speed $n_{c\ brake}$ [rpm]
Crane deceleration during braking $a_{c\ brake}$ [m/s^2]
Braking time $t_{braking}$ [s]
Total energy available E_{total} [kJ]
Energy absorbed per brake $E_{absorbed\ per\ brake}$ [kJ]
Input power P_{input} [kW]
Output power P_{output} [kW]
Input torque T_{input} [kNm]
Input speed n_{input} [rpm]
Output torque T_{output} [kNm]
Output speed n_{output} [rpm]
Maximum engine speed n_{max} [rpm]
Maximum engine torque M_{max}
Maximum engine torque and maximum engine speed $M_{max,\ nmax}$
Dynamic braking torque M_B [Nm]
Brake inertia J [kgm^2]
Maximum brake speed n_B [rpm]
Service factor closed gearbox $S_{gearbox}$ [-]
Allowable output torque closed gearbox $T_{gearbox}$ [kNm]
Weight of the crane W_{Crane} [MT]
Total weight W_{Total} [MT]
Rolling resistance f [kN/MT]
Acceleration time t_a [s]
Acceleration a_C [m/s^2]

Wind pressure q [N/m^2]

Projected surface area A [m^2]

Shape coefficient C_f [-]

Engine speed n_m [rpm]

Crane wheel diameter D_w [m]

Reduction between engine and crane wheel i [-]

Inertia of rotating parts J [kgm^2]

Crane wheel radius R_{wheel} [m]

Rotational velocity ω [rad/s]

Friction force $F_{friction}$ [kN]

Torque requirement due to nominal crane travelling per wheel $M_{f/wheel}$ [Nm]

Torque requirement due to nominal crane travelling per bogie $M_{f/bogie}$ [Nm]

Torque requirement due to nominal crane travelling per bogie pair $M_{f/multiple\ bogie}$ [Nm]

Torque requirement due to wind per wheel $M_{wind/wheel}$ [Nm]

Torque requirement due to wind per bogie $M_{wind/bogie}$ [Nm]

Torque requirement due to wind per bogie pair $M_{wind/bogie}$ [Nm]

Torque requirement due to the acceleration of rotating masses per wheel $M_{R/wheel}$ [Nm]

Torque requirement due to the acceleration of rotating masses per bogie $M_{R/bogie}$ [Nm]

Torque requirement due to the acceleration of rotating masses per bogie pair $M_{R/multiple\ bogie}$ [Nm]

Torque requirement due to the acceleration of linear moving masses per wheel $M_{lin/wheel}$ [Nm]

Torque requirement due to the acceleration of linear moving masses per bogie $M_{lin/bogie}$ [Nm]

Torque requirement due to the acceleration of linear moving masses per bogie pair $M_{lin/multiple\ bogie}$ [Nm]

Wind load on the crane F_{wind} [kN]

Corner load per corner F_{ci} [kN]

Number of wheels per corner $n_{wheels/corner}$ [-]

Inertia of drive I_{drive} [kgm^2]

Inertia of brake I_{brake} [kgm^2]

Inertia of coupling $I_{coupling}$ [kgm^2]

Inertia of gearing $I_{gearing}$ [kgm^2]

Brake torque M_{brake} [Nm]

Maximum rotation speed of the engine n_{drive} [rpm]

Brake closing time t_{brake} [s]

Brake efficiency η_{brake} [-]

Sliding friction coefficient μ [-]

Gravitational constant g [m/s^2]

Total inertia $I_{inertia}$ [kgm^2]

Crane speed after brake activation time $v_{c\ brake}$ [m/s]

Total real braking torque $M_{brake\ total\ real}$ [kNm]

Crane deceleration $a_{c\ brake}$ [$^{m/s2}$]

Friction force per wheel corner $F_{\mu i}$ [kN]

Total maximum brake force per wheel $F_{brake\ slip}$ [kN]

Maximum brake force per corner $F_{brake\ i}$ [kN]

Total brake slip force $F_{brake\ slip\ total}$ [kN]

Kinetic energy released during braking E_{kin} [kJ]

Rotational energy of the brake E_{rot} [kJ]

Friction energy released during braking $E_{friction}$ [kJ]

Friction energy due to the wind force $E_{friction\ wind}$ [kJ]

Total energy released E_{total} [kJ]

Calculated friction coefficient for wheelslip $\mu_{Calculation}$ [-]

Minimum wheel load on a driven crane wheel F_1 [kN]

Maximum driving force of the gantry travelling engine on the circumference of a driven crane wheel F_2 [kN]

Total available driving power of the engine N [kW]

Resulting wheel pressure p [N/mm^2]

Wheel pressure p_{zui} [N/mm^2]

Average wheel load R_{mean} [kN]

Width of the rail head k [mm]

Radius of curvature of the edges of the rail head r_1 [mm]

Dimensionless constants c_1, c_2, c_3 [-]

Maximum wheel load R_{max} [kN]

Minimum wheel load R_{min} [kN]

Contents

Introduction

The background of this Master's thesis comes forth from the company's desire to reduce the cost price of Ship-To-Shore (STS) container gantry cranes, thereby regaining its competitiveness. Even though the company still receives crane orders from clients, when bidding for a tender the usual response from clients is that the cost price (cost of production and assembly; excluding sea transport and cost made at the client's site) is 5 to 10% higher than that of competitors. Based on this situation the company realized that the cost has to be reduced, therefore a number of discussions have been held within the company on measures for reducing the cost price. A number of these measures have been combined into a single Master's thesis, which eventually has resulted in this report. The measures dealt with originate from a comparison with the largest crane manufacturer, Zhenhua Heavy Industries Co., Ltd., (ZPMC) and from practical experience. With regards to the largest crane manufacturer the question asked is what do they do different and can this be applied by Cargotec Netherlands BV?

From a general perspective it can be stated that ZPMC has a production and assembly capacity of approximately 300 Ship-To-Shore container gantry cranes per year. All equipment for production and assembly are owned by the company itself. Furthermore for transport of cranes to clients the company has its own fleet of transportation vessels for delivering Ship-To-Shore container gantry cranes either semi-erected or fully-erected [1]. Comparing this with Cargotec Netherlands BV it can be stated that the production is performed by a Chinese partner, Rainbow Heavy Industries Co., Ltd., Nantong; the assembly Is performed on a rented quayside at Taicang Port, Taicang. The joint venture, Rainbow Cargotec Industries Co., Ltd., handles the assembly at Taicang Port. Recently a new assembly site has been constructed (next to Taicang Port), of which the assembly halls are finished, but the quayside and jetty for final assembly has not been finished. The capacity of this assembly site amounts to an estimated 40 Ship-To-Shore container gantry cranes per year, including 100 Rubber Tire Gantry (RTG) cranes and an unspecified number of offshore cranes. For assembly at Taicang Port all equipment for assembly has to be rented (as opposed to the new assembly site). For transport of cranes to the client Cargotec Netherlands BV is dependent on the vessel available on the market. The company does not have its own fleet of transportation vessels.

Asia-Pacific market

As stated before, the production and assembly of Cargotec Netherlands BV takes place in P.R. China through its partners, though at this moment no Ship-To-Shore container gantry cranes are sold within this market (referred to as the Asia-Pacific market (APAC market), of which P.R. China is part). Reducing the cost of the crane not only means that it is more attractive for the clients Cargotec Netherlands BV has a contract with now, but also for new clients. However, in order to address new clients within this market there is a need to know to what the crane has to live up to in order to be sold. For addressing this topic the decision has been made to specify this towards the issues for the cost reduction.

Steel quality

Cargotec Netherlands BV has always applied a high quality steel without contemplating the need for doing this. Since the necessity has come forth to reduce the cost, changing from a high quality steel to a lower quality steel fits within this perspective. The point to address is what the allowable steel quality should be for the crane steel structure and not simply to apply a lower steel quality.

Open gearing

A topic that originates from practice is based on a project that Cargotec Netherlands BV did. The client was willing to accept the application of an open gearing within the steel structure of the bogie for the crane travelling gear. What was noticed with this type of transmission (whereby two wheels are driven by one engine) is that it was cheaper than the conventional solution (a single engine drives a single wheel). A structured comparison between both situations was not made. For that reason this topic is addressed within the context of the cost reduction.

Replacement of bolted flange plate connections

In the past Cargotec Netherlands BV produced and assembled cranes in Rotterdam. Due to the limited size of the assembly area the company was forced to produce the crane in components that would be bolted together during assembly. The choice for bolting came forth from the flexibility that comes with this type of connection during assembly and the amount of space needed with an assembly with bolted flange plate connections.

Due to the size of the assembly area of ZPMC, that company is able to lay out the entire crane structure horizontally and form welded sub-assemblies (or welded connection between components). Considering that the joint venture, Rainbow Cargotec Industries Co., Ltd., will have access to its own assembly area, the question comes forth if a welded connection should also be applied. The other reason behind this question is the large amount of production cost related to a bolted flange plate connection. Taking into account the need for reducing the cost of the crane this is where the interest for applying a welded connection between components comes from. ZPMC applies the welded connection between components almost throughout the entire crane steel structure. However considering that the situation between ZPMC and Cargotec Netherlands BV differs the strategy for applying a welded connection would be to determine which bolted connection should be replaced within the crane steel structure and what the consequences are of this replacement for production, assembly and transport.

As stated at the beginning of this paragraph a number of measures have been thought of for the cost reduction. Other measures that came forth are:

- Standardized loading and unloading procedures for Ship-To-Shore container gantry cranes;
- Combined inbound and outbound transport of Ship-To-Shore container gantry cranes, Rubber Tired Gantry cranes, and Automated Stacking Cranes;
- Reduction of sea-fastening components for cranes;
- Development of recyclable sea-fastening components for cranes;
- Standardized cranes for the Asia-Pacific market.

Based on the previous descriptions three research questions have been formulated, which lead to the main research question.

Research question 1:
What is the steel quality grade that can be applied for Ship-To-Shore container gantry cranes?

Research question 2:
Does the application of an open gearing lead to a cost reduction of the crane travelling gear?

Research question 3:
Which bolted flange plate connection can be replaced by a welded connection in the portal frame of a Ship-To-Shore container gantry crane?

Main research question:
What is the possible cost reduction that can be attained by redesigning the portal frame (replace bolted flange plate connections by welded connections and the use of a lower steel quality grade) and part of the machinery works (application of an open gearing for the crane travelling gear) of Panamax and Post Panamax Ship-To-Shore container gantry cranes for the Asia-Pacific market?

Methodology

Due to the character of this Master's thesis an approach has been determined in order to handle all four topics.

The focus on the Asia-Pacific market has been dealt with by reasoning from the perspective of Cargotec Netherlands BV. What would the company want to know in order to bid for a contract from this market? This means that an insight is required into the demands from clients from this market, but also into the operational circumstances in which the Ship-To-Shore container gantry cranes have to operate. For this reason the decision has been made to build up a framework for the Asia-Pacific market based on tender documentation from clients from the Asia-Pacific market. The information retrieved from the tender documentation is focused specifically on the steel quality, crane travelling gear and the portal frame, thereby also covering the aspect of which standard is applied within this market (Report part I).

Focusing on the steel quality, the issue comes forth on how to select the appropriate steel quality in order to prevent brittle fracture and what the exact background is of brittle fracture. Based on the information from tender documentation the conclusion was made that the steel quality is either specified by the client or it is based on the definition of a certain standard. This means that for determining the steel quality crane standards should be reviewed. A number of standards have been reviewed In order to provide an indication of the appropriate steel quality which can be used by the company (Report part II).

With regards to the crane travelling gear, the focus is on how to apply an open gearing and what the economic benefits are of applying an open gearing as opposed to a closed gearing. The approach to this topic has been done from a theoretical background. Based on formula's on the different requirements of the open gearing, an estimation of the different component sizes has been made, which in turn has led to an estimated cost reduction by comparing with an existing crane design. From the perspective of the Asia-Pacific market an indication has been found on whether there is a market for this type of transmission (Report part III).

For the replacement of bolted flange plate connections by welded connections within the portal frame the issue at hand is to determine which connection should be replaced and what the consequences are. By reviewing an existing crane design an overview could be made of the location of the bolted flange plate connections, which in turn has been used to develop a number of concepts of bolted flange plate connections and welded connections. These concepts have in turn been evaluated by stating the different limitations, demands and requirements. The final evaluation of the remaining concepts has been done according to the cost that are associated with having a bolted flange plate connection or a welded connection. Based on this economic evaluation an indication has been made on which bolted flange plate connection should be replaced by a welded connection (Report part IV).

Report part I Market overview and demands of the Asia-Pacific market for Ship-To-Shore container gantry cranes

1.1 Introduction

Cargotec Netherlands BV is in the position that all its production, and assembly sites are located in P.R. China, however, within the Asia-Pacific market no products are sold. In order to let Cargotec Netherlands enter this market it would be of interest to investigate the Asia-Pacific market and to determine what the differences are compared to the markets in which Cargotec Netherlands does sell cranes. Considering the topics that are discussed in this Master's thesis, the market investigation will focus on these topics. Furthermore, in this chapter an introduction to Ship-To-Shore container gantry cranes will be provided. This chapter has been divided as follows.

- **Paragraph 1.2** presents the background of Ship-To-Shore container gantry cranes.
- **Paragraph 1.3** discusses the size of the Asia-Pacific market.
- **Paragraph 1.4** discusses the demands regarding the steel quality, crane travelling gear and the portal frame.

1.2 Ship-To-Shore container gantry cranes

The Ship-To-Shore container gantry crane falls under the group of container handling equipment. Other types of container gantry cranes are mobile harbor cranes, Rubber Tire Gantry cranes, Rail Mounted Gantry cranes (RMG) and the Automated Stacking Cranes (ASC) (Figure 1.1). Container handling equipment can be found in inland harbors, deep sea harbors and inland transfer stations (for road and rail transport).

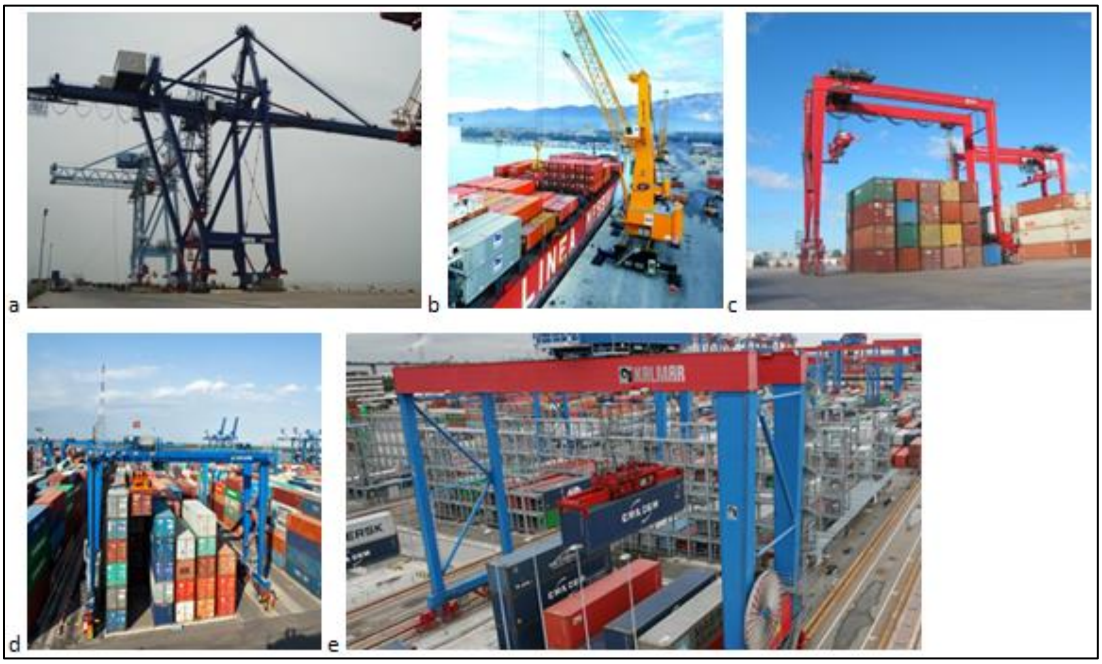


Figure 1.1 Container handling equipment a) Ship-To-Shore container gantry crane b) Mobile harbor crane c) Rubber Tire Gantry crane d) Rail Mounted Gantry crane e) Automated Stacking Crane

A ship-to-shore container crane is solely meant for container handling and can be defined as a discontinuous type of transport equipment [2-4]. From an economic point of view the purpose of this type of crane is to (un)load containers as fast as possible, thereby minimizing the time spend by a container vessel in a harbor. This in turn has multiple advantages (such as increasing the number of vessels the harbor is able to handle).

Depending on the size of the container vessel and the hoisting load on the ropes, the dimensions of the Ship-To-Shore container gantry crane (or type of crane) differs.
Distinction by container vessel size is made by the type of vessel; Panamax, Post-Panamax, etcetera. The width of the ship determines the outreach of the Ship-To-Shore container gantry crane. Besides the width the stacking height of the containers on the container vessel determine the height of the crane itself. The general idea behind matching the crane size with the vessel size is the thought that the container terminal needs to have enough capacity to deal with a certain range of ship sizes (e.g. Figure 1.2a).
Distinction by hoisting load is made by the ability of the crane to lift a certain amount of metric tons or the number of containers (expressed in twenty foot equivalent unit (TEU)). Lifting capacities range from 1 TEU, 2 TEU, 4 TEU, 6 TEU up to 8 TEU (single hoist, tandem lift, single hoist tandem lift, dual hoist tandem lift) [5]. This determines the spacing between the legs portside and starboard of the crane (e.g. Figure 1.2b).
Other aspects of the crane have been influenced by the landside transportation system (e.g. automated guided vehicles, trucks, see Figure 1.2c), which has to pass underneath the cross girders and between the landside and seaside legs (to allow long travel and cross travel).

Figure 1.2 a) Panamax container vessels b) Lifting capacity c) Landside transportation system

For Cargotec Netherlands BV the most commonly sold Ship-To-Shore container gantry cranes are Panamax (PX) and Post-Panamax (PPX) Ship-To-Shore container gantry cranes. Panamax and Post-Panamax Ship-To-Shore container gantry cranes are cranes used to load and discharge containers from Panamax (13 bays wide) and Post-Panamax (14 to 20 bays wide) container vessels. This means that, based on the beam of a Panamax vessel the outreach of the crane is larger than 32.3 m.

However, the dimensions of the outreach are influenced by not only the vessels but also by the quay. The distance from the waterside rail to the quay wall may vary depending on the port. Lifting height (above apron) is considered to be larger than 25 m [6]. Besides a distinction based on vessel size the crane can also be distinguished based on the boom design (lattice girder, mono box boom girder or double box boom girder, e.g. Figure 1.3).

Figure 1.3 a) Lattice girder boom b) Mono box boom girder c) Double box boom girder

For a general lay out of a Ship-To-shore container gantry crane and its components Figure 1.4 is referred to, with an explanation of the function of the different components [7].

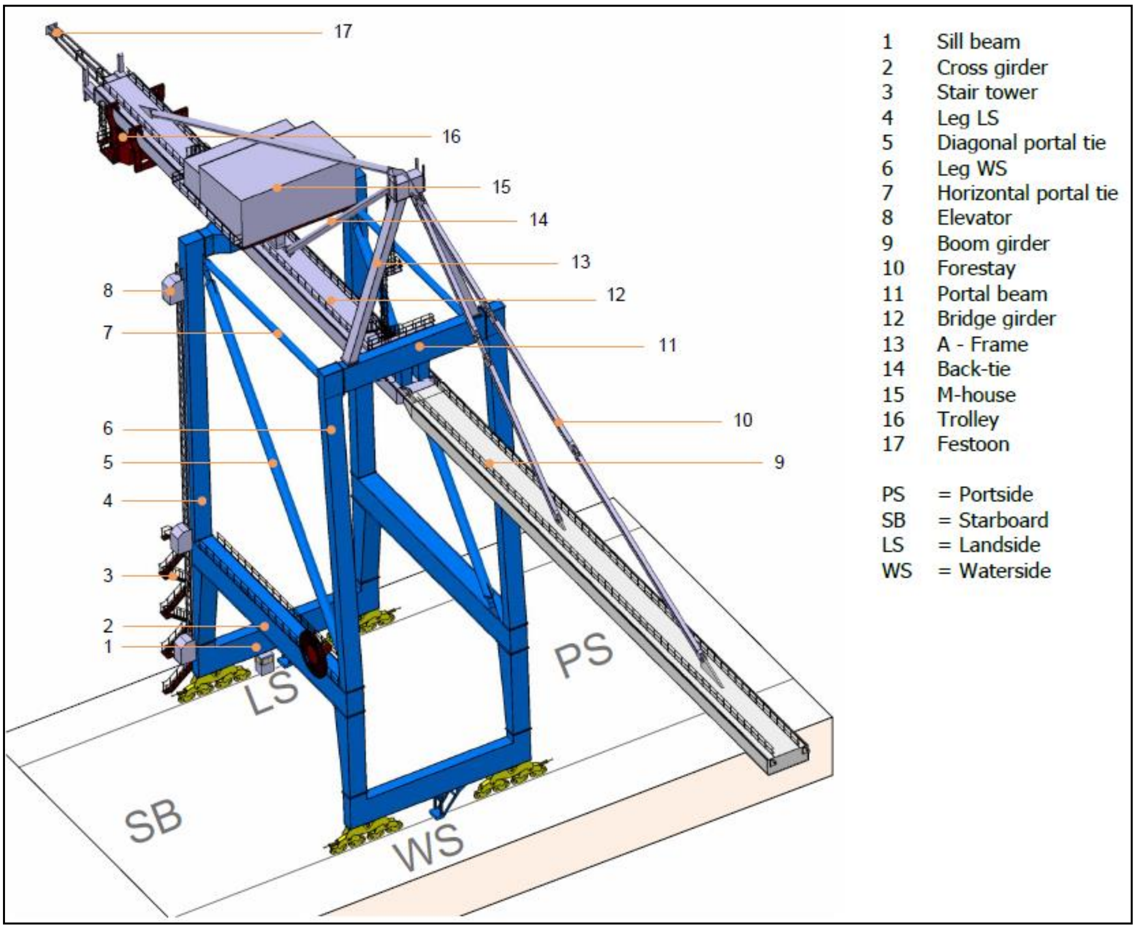


Figure 1.4 Ship-To-Shore container gantry crane

A-frame The A-frame connects the back-ties and forestays with the main structure, thus introducing the loads into the portals. The boom hoisting ropes run via the boom hoisting sheaves on the A-frame to the machinery house.

Back-tie The back-tie transfers loads from the boom to the bridge girder. When a long back reach is present two back-ties are used.

Boom girder The boom girder allows the trolley to travel on rails above the water. When a ship arrives the boom will be hoisted to allow the ship to moor.

Bridge girder The bridge girder allows the trolley to travel on rails above land. It also stiffens the portals through the portal beams.

Cross girder The cross girder connects the waterside and landside legs to create stiffness in the trolley travelling direction.

Diagonal tie The diagonal portal tie connects the cross girder and upper legs, thus creating stiff triangles.

Elevator The elevator is used to get at several crane levels, including the cross girder, trolley and bridge girder.

Festoon	The trolley is powered by cables hanging on small trolleys behind it. The cable needs to cover the entire length of the crane when the trolley is at the maximum outreach. However when the trolley is located at the maximum back reach the cable trolleys still need a significant amount of space. The festoon station is used to provide this space and maintenance activities on the cable or cable trolleys can also be executed at the festoon.
Forestays	The forestays induce loads from the boom girder to the A-frame. When the boom is hoisted the forestay must be able to fold, so it consists of several parts. A container crane has got one or two forestays depending on the outreach.
Horizontal tie	The horizontal portal tie is used to stiffen the portal in the trolley travelling direction.
Leg WS/LS	The landside and waterside legs support the upper structure and provide the correct hoisting height.
M-house	The machinery house consists of the boom hoist, trolley travelling winch and spreader hoist. Along with the electric house, located at the back of the machinery house, it is the heart of the crane. The spreader hoist enables vertical positioning of the container.
Portal beam	The portal beams connect the legs to the bridge girder.
Sill beam	The sill beams consist of the crane travelling gear, checkers cabin and storm anchor. The crane travelling gear moves the entire crane along the rails, thus enable container movements parallel to the quay. The checkers cabin is used to check the container's condition and control the crane movements from the ground. The storm anchor is used to transfer the horizontal storm loads on the crane to the ground when a storm occurs.
Stair tower	The stairs are used for an emergency situation, when the elevator is not operational or for inspection. The stairs on the upper leg can be located inside the leg.
Trolley	The trolley handles the containers, with a spreader, and travels over the rails on the girders. It enables horizontal movement of the container perpendicular to the quay. The trolley is able to move from the maximum outreach up to the maximum back reach.

1.3 Asia-Pacific market

For the Asia-Pacific market many countries can be listed, however they may not be of interest. The focus in the Asia-Pacific market should be on those countries which can be pointed out as being a potential offset region for Ship-To-Shore container gantry cranes. In order to have an insight two approaches are used. Firstly the yearly overview of World Cargo News will be used and secondly the yearly container throughput for the countries in the Asia-pacific market will be examined. The definition of the Asia-Pacific region will be restricted to those countries listed in the yearly overview of World Cargo News, where both clients and suppliers are listed for the world market. The Asia-Pacific market thus comprises of the following countries [8-16]:

- Bangladesh
- Cambodia
- P.R. China
- India
- Indonesia
- Japan
- Korea
- Malaysia
- Myanmar
- Pakistan
- Philippines
- Singapore
- Sri Lanka
- Taiwan
- Thailand
- Vietnam

For the number of crane orders the following results have been listed in Table 1.1 for the period July 2004 to June 2012 (Appendix B displays the complete table) [9-16].

Table 1.1 Ship-To-Shore container gantry crane order overview

Country	Orders	Country	Orders
Bangladesh	2	Myanmar	2
Cambodia	2	Pakistan	7
P.R. China	514	Philippines	18
India	60	Singapore	59
Indonesia	15	Sri Lanka	23
Japan	46	Taiwan	29
Korea	67	Thailand	23
Malaysia	73	Vietnam	27

A comment to be made with the information used is that these numbers are the result of information provided by manufacturers. Also noted is that not all manufacturers have provided an order overview. Therefore these numbers can be pointed out to be incomplete or to some degree inaccurate.

What can be noted in Table 1.1 is firstly that the largest number of Ship-To-Shore container crane orders originates from P.R. China and are also manufactured by a Chinese manufacturer. Secondly, the Japanese crane orders are all handled by Japanese suppliers. Thirdly, except for P.R. China and

Japan all other countries in the Asia-Pacific market are supplied by manufacturers originating from either Asia or Europe[1]. A general remark is that the order overview only focuses on those orders originating from major seaports. The entire market for smaller ports is left out of the scope. Therefore it would be likely that the entire market for Ship-To-Shore container gantry cranes is much larger. Besides the overview in Table 1.1 it would also be useful to look at the container throughput of these countries, in order to have an insight in the growth of this region regarding container handling (and thus indirectly in the growth of required container handling capacity) [17, 18]. In Appendix B the yearly container throughput has been listed for the period 2004 to 2010. Assuming a standard yearly handling capacity for Ship-To-Shore container gantry cranes an estimation can be made on the amount of orders that should come forward for the Asia-Pacific market to accommodate the increase in container throughput, Table 1.2.

Table 1.2 Ship-To-Shore container gantry crane order overview

Country	Orders	Estimated number of orders	Country	Orders	Estimated number of orders
Bangladesh	2	6	Myanmar	2	2
Cambodia	2	2	Pakistan	7	7
P.R. China	514	436	Philippines	18	11
India	60	44	Singapore	59	63
Indonesia	15	24	Sri Lanka	23	15
Japan	46	13	Taiwan[2]	29	-
Korea	67	34	Thailand	23	15
Malaysia	73	54	Vietnam	27	30

A number of comments can be made with the outcome of Table 1.2:

1. The outcome is highly subjective to the assumed yearly handling capacity for Ship-To-Shore container gantry cranes.
2. Even though some countries display a decrease in container throughput this does not imply that some ports are not expanding and thus would require additional handling equipment.
3. An increase in handling capacity does necessarily imply new crane orders. Existing cranes can be modified and the existing container handling capacity may be sufficient to handle an increase in container throughput.
4. New orders do not lead to an increase in the total number of container cranes; existing cranes may also need to be replaced. Furthermore, this overview concentrates on Ship-To-Shore container gantry cranes, leaving out other types of container handling equipment.

[1] The European manufacturers list both Barge-To-Shore and Ship-To-Shore container gantry cranes. A distinction between these types of cranes has not been made in Table 1.1.

[2] The estimated number of orders based on the container throughput for Taiwan have not been determined. The container throughput is normally summed with the total throughput of Chinese ports.

Comparing the equivalent handling capacity for Ship-To-Shore container gantry cranes from Table 1.2 with the summed order overview from Table 1.1 it can be stated that Table 1.1 gives a rough indication of the number of orders from the Asia-Pacific market.

With regards to the competitors operating within the Asia-Pacific market the following crane manufacturers can be listed with the associated market shares in Table 1.3 [9-16].

Table 1.3 Crane manufacturer overview

Manufacturer	8 year average market share [%]	Average absolute deviation [%]
Zhenhua Heavy Industries Co., Ltd. (including SPMP)	80.29	4.75
Doosan Heavy Industries (including PT Doosan Heavy Industries, and Doosan Vina)	2.92	2.92
Mitsubishi	1.19	1.17
Paceco licensees (Mitsui Zosen, Hyundai Samho, Mitsui Engineering & Shipbuilding)	9.48	1.96
JFE Engineering	0.37	0.47
Liebherr CC	0.85	1.00
Impsa PS	1.57	1.96
K. Eberswalde	0.40	0.70
Dalian HI-DCW	0.65	1.14
Noell China (Fantuzzi Group and Terex)	0.99	1.48
Kocks Ardelt	0.63	1.10
Anupam MHI	0.38	0.66
Konecranes	0.27	0.48

Table 1.3 displays the average market share over an 8 year period; however, this may be deceiving because most crane manufacturers operating in the Asia-Pacific market experience years in which 0 cranes are ordered from this market. Besides this some crane manufacturers only operate in one country while others operate within the entire Asia-Pacific market (such as is the case with the Japanese market).

1.4 Demands Asia-Pacific market

Now that the size of the Asia-Pacific market has be indicated it can be questioned which countries are of interest. The largest markets (e.g. P.R. China, South Korea, Singapore, Malaysia) are of course of interest, but smaller countries could provide orders that are more suitable to the current and desired future production capacity of Cargotec Netherlands BV (moving from approximately 10 Ship-To-Shore container gantry cranes per year to 40 Ship-To-Shore container gantry cranes per year). Besides this, countries from where very few orders come from may be interesting in the future. In order to determine whether a selection has to be made the decision has been taken to look at several tender documents originating from the Asia-Pacific region. In this way it can be seen to which standards a Ship-To-Shore container gantry crane has to comply to and what kind of requirements, demands, and others, for the targeted countries. This will result into having a framework that allows for the development of a Ship-To-Shore container gantry crane that covers most of the Asia-Pacific market without having to make a selection on which countries to focus on. The demands from the Asia-Pacific market have been specified towards those topics that are dealt with in this report.

1.4.1 Demands Asia-Pacific market steel quality

With regards to the Asia-Pacific market the interest would be in what the temperatures are that are experienced at ports in the Asia-Pacific market (for the steel quality topic the temperature is one of the important parameters) and what the allowable standards are with regards to the steel structure, thereby also covering the steel quality selection procedure. The reason for investigating this topic is due to the current steel quality applied by Cargotec Netherlands BV. From a historic perspective D-quality steel has been applied, however, the application of D-quality steel is only limited to very thick plate thicknesses or in case of very low temperatures (conclusion from Chapter 2). This indicates that in warmer areas the use of D quality steel is only necessary for those very thick plates within the crane steel structure. By evaluating the temperature range and the standard applicable in the Asia-Pacific market the appropriate steel quality for this market can be pointed out [19-28].

In Table 1.4 the temperature range of several ports has been defined. As can be seen in Table 1.4 only countries located in the northern part of the Asia-Pacific market experience temperatures below 0°C.

In Table 1.5 the standard regarding the calculation of the steel structure has been listed. The listed standard is the standard that is allowable according to the tender document from this country. This does not mean that other standards are not allowable. Furthermore for countries in the periphery of P.R. China, the standard GB/T 3811 is a commonly allowed standard. A demand that is always stated

in each tender document is that yielding should occur before brittle fracture. This is done to ensure that brittle fracture will not occur (to prevent any catastrophic failure of the crane steel structure).
Due to the limited number of tender documents that have been retrieved a conclusion with regards to Table 1.5 is difficult. The allowable standard is dependent on the location of the client, the preferences of this client and of the external consultants writing the tender document for the client.

Based on Table 1.5 it could be concluded that the Asia-Pacific market can be divided into a number of areas:

- Most of South-East Asia can be covered by European standard FEM 1.001, though Malaysia will be covered by the British standard BS 2573;
- P.R. China is covered by its own national standard GB/T 3811;
- Japan is covered by its own national standard JIS;
- South Korea does have its own standard, KS, though from the tender document FEM 1.001 would be allowable.

In Chapter 2 the standards FEM 1.001, BS 2573 and GB/T 3811, among others, are discussed.

Table 1.4 Temperature range at different ports with the Asia-Pacific market

Country Asia-Pacific market	Port	Temperature range [°C]
Bangladesh	-	-
Cambodia	-	-
P.R. China	Jinzhou	-25 – +40
	Xiamen	-25 to +50
India	Mundra	+10 to +45
Indonesia	Jakarta	+24 to +32
Japan	-	-
South-Korea	Busan	-20 to +50
Malaysia	Bintulu	+10 to +40
Myanmar	Yangon	+15 to +50
Pakistan	-	-
Philippines	Manila	+18 to +40
Singapore	-	-
Sri Lanka	Sri Lanka	0 to +45
Taiwan	-	-
Thailand	Laem Chabang	+5 to +50
Vietnam	Ho Chi Minh	0 to +40

Table 1.5 Allowable standard regarding the crane steel structure

Country Asia-Pacific market	Standard steel structure
Bangladesh	-
Cambodia	-
P.R. China	GB/T 3811
India	FEM 1.001
Indonesia	FEM 1.001
Japan	JIS
South-Korea	FEM 1.001
Malaysia	BS 2573
Myanmar	FEM 1.001
Pakistan	-
Philippines	FEM 1.001
Singapore	-
Sri Lanka	-
Taiwan	-
Thailand	FEM 1.001
Vietnam	FEM 1.001

1.4.2 Demands Asia-Pacific market crane travelling gear

With regards to the crane travelling gear the interest is if clients from the Asia-Pacific market are willing to accept an open gearing for the crane travelling gear as opposed to a closed gearbox transmission between the engine and the wheels. The desire for having an open gearing transmission is due to the reduced cost of this type of gearing regarding the initial purchase price of the crane.
The open gearing is meant for the situation of powering both wheels (and more) with a single engine as opposed to the situation of having a single engine driving a single wheel (Chapter 3).

When reviewing the demands from the tender documentation the following points can be listed [19-28]:

- In general a closed gearbox is preferred due to the lower maintenance cost during the operational phase of the crane travelling gear as opposed to the open gearing transmission;
- Open gearing transmission is allowable according to a number of tender documents, though the open gearing should be housed in the bogie steel structure;
- In general tender documents state that preferably each wheel will have its own engine with closed gearbox as opposed to having an open gearing transmission.

Based on the demands listed above it has been concluded that an open gearing is in some cases allowable.

1.4.3 Demands Asia-Pacific market portal frame

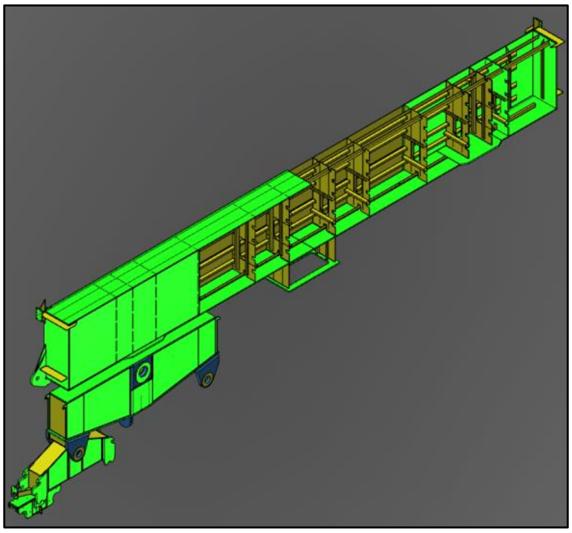
For the assembly of the portal frame Cargotec Netherlands BV has always connected the components of the crane via a bolted flange plate connection, with in some cases a welded connection between certain components. Instead of having a bolted flange plate connection between all components of the portal frame it could be possible to have the connections welded. This would mean that the flange plates needed for the bolted flange plate connection are less necessary, thereby removing a significant cost post with the production of the components.

When reviewing the tender documentation from the Asia-Pacific market the following statements can be found [19-28]:

- Field connections between components shall be made by high strength bolting or field welding;
- The sill beam, legs, and portal beams shall form a continuous rigid frame. The connection between these components shall be welded (and in some case it states bolted and/or welded).

These statements indicate that there is flexibility regarding the application of either a bolted flange plate connection or a welded connection. The reason why a welded connection is preferred by the client is due to the regular inspection needed in case of bolted flange plate connections as opposed to a welded connection.

Report part II Steel quality application for Ship-To-Shore container gantry cranes



2.1 Introduction

From a historic perspective Cargotec Netherlands BV has always applied D-quality steel (and in some cases E-quality steel) for the steel structure of Ship-To-Shore container gantry cranes. However, the question with regards to brittle fracture is what the appropriate steel quality should be, thereby pointing out whether the current practice of Cargotec Netherlands BV is necessary or not.

The purpose of this study is to indicate whether Cargotec Netherlands BV can apply a lower steel quality for the steel structure of its Ship-To-Shore container gantry cranes and what the possible cost reduction could be.

This chapter has been structured as follows.

- **Paragraph 2.2** discusses the background and provides a theoretical description of brittle fracture and its causes.
- **Paragraph 2.3** presents the discussion of standards with regards to the prevention of brittle fracture and thus the application of the correct steel quality.
- **Paragraph 2.4** presents a generalized outcome whereby based on the plate thickness and ambient temperature the correct steel quality can be determined.
- **Paragraph 2.5** discusses the application of the European standard on an existing crane structure, thereby also pointing out what the possible cost reduction could be.
- **Paragraph 2.6** is focused on the steel quality required for the Asia-Pacific market.
- **Paragraph 2.7** presents an alternative to the selection procedure as defined in the European standard.
- **Paragraph 2.8** presents the conclusion and recommendation regarding the steel quality application for Ship-To-Shore container gantry cranes and its potential cost saving.

2.2 Brittle fracture

Fracture is a type of failure mode, for which two different fractures can be distinguished: ductile fracture and brittle fracture. With a brittle fracture a smaller amount of energy is absorbed compared to a ductile fracture. Brittle fractures are associated with very little noticeable plastic deformations.

Brittle fracture is the occurrence of a rapidly growing crack that could lead to a structural failure. This type of fracture is very sudden compared to a ductile fracture[3]. With regards to a brittle fracture it can be noted that this type of fracture is only experienced with tensile stresses.

[3] The occurrence of a brittle fracture can be explained, from the back ground of fracture mechanics, by the critical crack size, whereby failure occurs when the free energy attains a peak value at a critical crack length, beyond which the free energy decreases by increasing the crack length [29].

Brittle fracture occurs along a cleavage plane and is related to the normal stress acting on this plane. Fracture occurs when the normal stress reaches a critical value. For tensile stress one can distinguish crack propagation along the cleavage plane (the crystallographic planes) leading to failure. For shear stress one can distinguish slip along the cleavage plane (though slip is less likely to occur).

From a macroscopic point of view, a ductile fracture exhibits the following characteristics [30]:

- A large amount of plastic deformation precedes the fracture;
- Shear lips[4] may be present;
- The fracture may appear to be fibrous or have a matte or silky texture;
- The cross section at the fracture may be reduced by necking, and crack growth will be slow.

From a macroscopic point of view, brittle fractures are characterized by the following [30]:

- Little or no plastic deformation precedes the fracture;
- The fracture is generally flat and perpendicular to the surface of the component;
- The fracture may appear granular or crystalline and is often highly reflective to light. Facets may also be observed, especially in coarse-grained steels;
- Herringbone or chevron patterns[5] may be present and cracks propagate rapidly.

2.2.1 Conditions for brittle fracture

Now that the general characteristics have been listed the conditions that lead to brittle fracture are of importance. A brittle fracture occurs when the following conditions are present [31]:

1. Sufficiently high nominal stresses (tensile stresses);
2. Sufficiently low operating temperature;
3. Sufficiently high degree of tri-axial state of stress;
4. Sufficiently high strain rate;
5. Large plate thickness.

These conditions are explained below.

[4] A shear lip is a characteristic surface feature where the fracture surface is at a 45° angle to the normal stress, indicating that slip has occurred.

[5] When a fatigue fracture occurs the fracture surface shows a number of lines, which show the graduation growth of the fatigue crack. For a brittle fracture similar lines can be distinguished on the fracture surface, in a chevron or herringbone pattern.

Nominal stresses

The nominal stresses are not only stresses from loads, but also stresses due to production and from the dead weight of the structure, referred to as residual stresses. Residual stresses from production arise from most mechanical or thermal operations performed in processing engineering materials. For welding, residual stresses are caused by the thermal cycle that occurs when hot weld metal is laid on a much cooler base metal or previous weld passes. Subsequent cooling causes thermal, plastic, and transformation strains to set up in the materials. These strains give rise to residual stresses [31]. Residual stresses lead to a higher probability on crack formation.

Operating temperature

Metals show ductile-to-brittle transition behavior when subjected to decreasing temperature, resulting from a strong yield stress dependency on the temperature. This is due to the availability of slip systems within the material (a slip system is defined as the ability of crystals to move relative to one another). A limited number of slip systems are available at low temperature, minimizing the plastic deformation during the fracture process. Increasing temperature allows more slip systems to operate, resulting in plastic deformation prior to failure.

The criterion for a material to change its fracture behavior from ductile to brittle mode is when the yield stress at an observed temperature is larger than the stress necessary for the growth of micro cracks [32-34].
Brittle fracture is formed by an abrupt crack growth or propagation. Crack propagation occurs when the released elastic strain energy is at least equal to the energy required to generate new crack surfaces. Metals are not ideally brittle and normally fail with a certain amount of plastic deformation; the fracture stress is increased due to blunting of the crack tip. The nucleation of the crack occurs when the shear stress created by the pile up of dislocations at a grain boundary reaches a certain value. Imperfections in the material must also be taken into account (inclusions, porosity and second phase particles or precipitates are preferential sites for cleavage initiation).

Tri-axial state of stress, strain rate and plate thickness

A notch or a sharp crack increases the tendency for brittle fracture in four important ways [32-34]:

- Producing high local stresses;
- Introducing a tri-axial stress state;
- Producing high local strain hardening and cracking;
- Producing a local magnification to the strain rate.

Concerning these four points the following can be said with regards to stresses and strains. In a thin plate the stress in the thickness direction is absent. It can be seen as a two-dimensional stress state similar to the stress state at the surface of a plate, the so-called plane stress condition. Deeper inside a thick plate, a three-dimensional stress state develops because of the restrained contraction in the thickness direction. This state is called plane strain. Under this condition, the critical resistance of a material to fracture is the lowest. This is a material property called fracture toughness which depends on the material, temperature and, to some extent, the rate of loading. In testing materials for the fracture toughness value, a minimum wall thickness of the specimens must be present to ensure the plane strain state [35].

From the view point of tri-axial stress states the following can be said (though similar to the plane strain). In a thicker plate the stress in tensile direction is constrained due to the reaction stresses in x and z direction, leading to a tri-axial stress state. Tri-axial stresses limit plastic deformation ahead of the crack tip, raising the general yield, making the material prone to brittle fracture [32-34].

2.2.2 Toughness of the material

Commonly referred to in standards, the notch toughness value is used as a guideline for the steel quality on the prevention of brittle fracture. The notch toughness is defined as the ability to absorb energy when placed under a tensile stress (the amount of energy is defined as the amount required for fracture). The tensile stress is the stress type that causes crack growth and thus could lead to brittle fracture [32].

With a lowering operating temperature (temperature of the surroundings in which the crane operates), the ability of steel to absorb energy lowers (the lower the temperature, the lower the notch toughness). This increases the risk of a brittle fracture in the situation of a high loading [33].

The notch toughness is determined with a Charpy-V test, in which a steel sample is subjected to an impact load at a certain ambient temperature. The steel sample is subjected to this test in two orientations due to the prevailing direction of the crystallite structure of the steel. The use of a Charpy-V test is of importance to demonstrate the degree of resistance to low temperature failure, especially if the steel undergoes a ductile-brittle transition as the temperature decreases [35].

Even though brittle fracture is usual thought of being related to the notch toughness as measured by the Charpy-V test, there are a number of remarks to be made with the use of this test. The Charpy-V test has the following disadvantages when the results are applied to a practical design [30]:

- The Charpy-V notch impact test does not reproduce the tri-axiality that occurs in thicknesses greater than 10 mm;
- The notch of the test specimen is blunt by comparison with natural cracks. The plasticity makes a large contribution to the energy absorbed in crack propagation because plastic deformation at the crack tip blunts the tip (lowers stress concentration) and substantially increases the amount of work required per unit crack advance;

- It is an impact test, and the majority of brittle failures in service occurs under static conditions;
- The material tested is usually taken from a test sample that is not always entirely representative for the material as a whole.

For this reasons it would be useful to look at a different type of toughness which is better representative for calculation purposes and for pointing out in a correct way which steel quality is appropriate. This toughness can by indicated by the fracture toughness value, J-integral value or the Crack Opening Displacement Test (CODT) value.

For fracture the basic assumption is that crack propagation will occur when the stress intensity at the crack tip reaches a critical value. There are three modes of fracture, mode I being identified as the opening mode, in which the crack surfaces move opposite and perpendicular to each other; modes II and III involve sliding and lateral tearing.

In linear elastic fracture mechanics the fracture resistance of a material is defined in terms of the elastic stress field intensity near the tip of a crack. In fact, the fracture toughness value is only valid when determined under conditions which prevent significant yielding at the crack tip. Such conditions are difficult to achieve in practice for lower strength steels, though with low temperature this value can be used.

The theory on crack formation states that there is a critical crack size to be defined at which fracture will occur. The crack size is defined as follows (Eq. 2.1):

$$a_c = \frac{1}{\pi} \bullet \left(\frac{K_{IC}}{Y \bullet \sigma} \right)^2 \ [\mathrm{m}] \tag{2.1}$$

Whereby a_c [m] is defined as being half the critical crack length, K_{IC} [N/mm$^{1.5}$] as the critical fracture toughness value, Y [-] as a dimensionless shape factor depending on the location of the crack, and σ [N/mm^2] as the occurring tensile stress. K_{IC} is defined as the ability to withstand a given stress field intensity at the tip of a crack and to resist progressive tensile crack extension. There are a number of metallurgical factors that affect the fracture toughness value. For a given structure, higher toughness is associated with lower strength levels. The microstructure itself influences the toughness to a considerable degree. Differences in toughness strength relationships are evident when quenched steels are compared with those in the normalized and tempered condition. Increasing the tempering temperature, which lowers the strength, has the effect of increasing the K_{IC} value. From a metallurgical point of view decreasing the sulphur content increases the fracture toughness.

Increasing sulphur and phosphorus together has the effect of lowering the fracture toughness[6] (see also Appendix G for the metallurgical composition of different steel types used).

The shape factor of the crack is dependent on the type and location of the crack, besides the crack dimensions. Listed below are the most basic forms of the shape factor for different types of cracks (see also Figure 2.1).

For a centrally cracked plate, Eq. 2.2:

$$K_{IC} = \sigma Y \sqrt{\pi a_c} \text{ [N/mm}^2\text{]} \quad Y = 1 \text{ [-]} \tag{2.2}$$

For a single edge cracked plate, Eq. 2.3:

$$K_{IC} = \sigma Y \sqrt{\pi a_c} \text{ [N/mm}^2\text{]} \quad Y = 1.12 \text{ [-]} \tag{2.3}$$

For a double edge cracked plate, Eq. 2.4:

$$K_{IC} = \sigma Y \sqrt{\pi a_c} \text{ [N/mm}^2\text{]} \quad Y = 1.12 \text{ [-]} \tag{2.4}$$

For an imbedded circular crack, Eq. 2.5:

$$K_{IC} = \sigma Y \sqrt{\pi a_c} \text{ [N/mm}^2\text{]} \quad Y = \frac{2}{\pi} \text{ [-]} \tag{2.5}$$

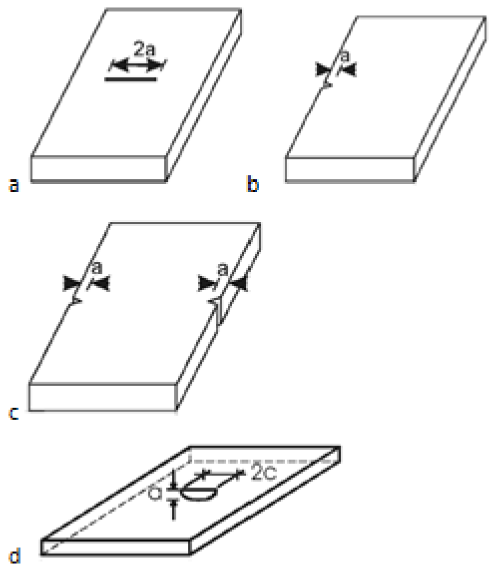


Figure 2.1 Crack locations a) centrally cracked plate b) single edge cracked plate c) double edge cracked plate d) imbedded circular crack

For each situation the following condition must count whereby a_C is much smaller than the width of the plate. In case the crack length is not very small compared to the plate width the shape factor differs, whereby the ratio between the crack length (in this case defined as c_0 [m]) and the crack depth (in this case defined as a_0 [m]) is of importance.

As stated before, certain conditions are difficult to attain, therefore with the formation of a crack which exhibits yielding at a crack tip before fracture occurs, a reference can be given to yield fracture mechanics. A method for dealing with yield fracture mechanics is the J-integral value, which is the

[6] The purity of the material can be improved by desulphurization of the steel (lowering the sulphur content of the steel). By desulphurization of the steel the number of sulphur enclosures will be limited, reducing the number of locations within the material where stress peaks may occur [36].

average measure of the elastic-plastic stress/strain field ahead of a crack. For elastic behavior, the J-integral value is expressed as the energy release rate per unit crack extension, Eq. 2.6.

$$J = \frac{(1-\nu^2)\cdot K^2}{E} \text{ [N/m]} \tag{2.6}$$

Whereby v [-] is defined as the Poisson constant, E [N/mm^2] as the modulus of elasticity and K [N/mm$^{3/2}$] as the fracture toughness value.

Furthermore, the relation between the J-integral value and the crack opening displacement test (CODT) is defined according to Eq. 2.7.

$$CODT = \delta = \frac{J_{IC}}{\sigma_Y} \text{ [m]} \tag{2.7}$$

Whereby J_{IC} [N/mm] is defined as the critical J-integral value and σ_Y [N/mm2] is defined the yield stress

What can be noticed is that both the J-integral value and the CODT value can be expressed with the fracture toughness value. With the use of each value there is a remark to be made. Within a steel structure there are a number of additional factors to be taken into account that influences the likeliness of brittle fracture (e.g. residual tensile stresses due to production, purity of the steel, and others). For proper use of the theory on fracture mechanics the correction factors presented in EUR 23510 EN should be applied and a reference check should be made with NEN-EN 1993-1-10.

2.3 Standards

For the selection of the steel quality a number of factors have to be taken into account for determining the appropriate steel quality. These factors are dealt with differently depending on which standard is looked at. The selection of the steel quality will be discussed for the following standards:

- Dutch standard NEN 2019, *Cranes; The metal structure*
- European standard FEM 1.001, *Rules for the design of hoisting appliances, booklet 3, Calculating the stresses in structures*
- European standard NEN-EN 13001: *Cranes general design, part 3-1, Limit states and proof competence of steel structure*
- Chinese standard GB/T 3811, *Design rules for cranes*
- British standard BS 2573, *Permissible stresses in cranes, part 1, Structures*

The objective of the selection procedure in these standards is to determine the required minimum steel quality in order to prevent brittle fracture. The standard FEM 1.001 is the currently used standard in Europe and the standard NEN-EN 13001 is the intended standard to be used in time. The Chinese and British standard are evaluated due to the Asia-Pacific market context in which this thesis has been placed (paragraph 1.4.1).

2.3.1 Dutch standard NEN 2019

The Dutch standard NEN 2019 provides an insight into the factors leading to brittle fracture, however, in contrast to the current standard a selection procedure is not provided [37].

The standard specifies 8 steel qualities, namely 0, A, B, C, D, DD, 1 and 2, of which 0, 1, and 2 are not suitable for steel constructions and B is considered to be a minimum for the load carrying steel structure according to EURONORM 25-72.

The distinction between the steel qualities (Table 2.1) is based on the notch toughness and can be considered as the degree of quenching of the steel and the grain size.

Table 2.1 Steel quality

Quality according to EURONORM 25-72	Minimum Energy value Charpy-V test value [J]	Temperature [°C]
A	-	-
B	28	20
C	28	0
D	28	-20
DD (Fe510)	40	-20

The standard states that brittle fracture occurs when:

- The strain rate is large and the capacity to use the plastic deformation is small (the difference between the ultimate strength and the yield strength is small);

- The load on fatigue is large (fatigue cracks and cracks that occur due to brittleness are closely related to each other; a fatigue crack can become the starting point for a brittle fracture);
- The fabrication conditions are not favorable;
- The material quality is lesser than expected;
- The thickness of the material is large;
- Cold deformation is applied after welding;
- The operating temperature is low.

The notch toughness of the material increases with the capacity for plastic deformation before fracture. The prescription of a lower allowable stress as a safety against brittle fracture is of no use if the notch toughness remains the same.

2.3.2 European standard FEM 1.001

The European standard FEM 1.001 states three influences on the sensitivity to brittle fracture in steel structures, which are assessed with the influence coefficient Z_i [38].

The first coefficient is defined based on the combined effect of the longitudinal tensile stresses with the tensile stresses from the dead load, Z_A. This coefficient has been subdivided into three categories:

In case the steel structure has no welds or only transverse welds the coefficient is defined as (Eq. 2.8):

$$Z_A = \frac{\sigma_G}{0.5 \bullet \sigma_a} - 1 \text{ [-]} \quad (2.8)$$

With the condition that $\sigma_G \geq 0.5\sigma_a$ and σ_a being defined as the permissible tensile stress with respect to the elastic limit of load case 1 (f_y / 1.5). σ_G is defined as the residual tensile stress due to its own weight. The influence of the residual tensile stresses due to welding have been taken into account by the type of weld.

In case the steel structure contains longitudinal welds the coefficient is defined as (Eq. 2.9):

$$Z_A = \frac{\sigma_G}{0.5 \bullet \sigma_a} \text{ [-]} \quad (2.9)$$

The last category is that in case the steel structure contains accumulations of welds the coefficient is defined as (Eq. 2.10):

$$Z_A = \frac{\sigma_G}{0.5 \bullet \sigma_a} + 1 \text{ [-]} \quad (2.10)$$

The outcome of these equations has been presented in Figure. 2.2.

The influence of the residual tensile stresses has been taken into account due to the situation that if all stresses that the crane structure experiences come from residual stresses, this will result in an unfavorable situation. If the steel structure in this case experiences a dynamical load there will be very little resistance against a brittle fracture.

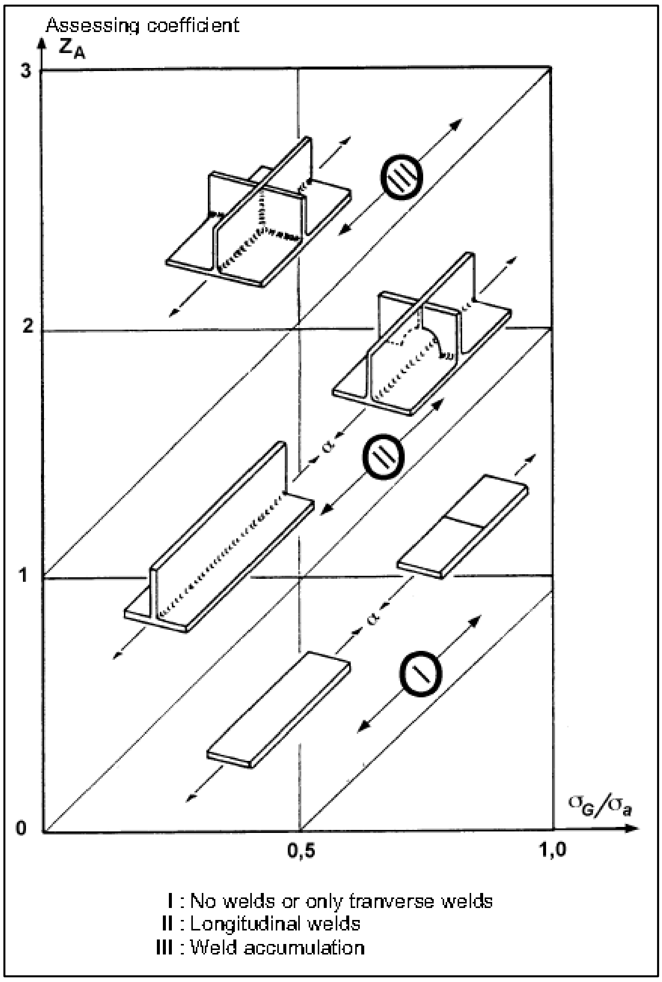


Figure 2.2 Influence coefficient of the residual stresses from welded and stresses from dead weight

The second coefficient is the influence of the thickness of the member or plate, Z_B. As stated before, large plate thicknesses experience tri-axial stresses, which can lead to brittle fracture. The influence of this coefficient has been listed in Table 2.2.

Table 2.2 Influence of material thickness

t [mm]	Z_B [-]	t [mm]	Z_B [-]	t [mm]	Z_B [-]	t [mm]	Z_B [-]	t [mm]	Z_B [-]
		10	0.40	30	2.5	60	4.3	90	5.6
5	0.10	12	0.50	35	2.9	65	4.55	95	5.8
6	0.15	15	0.80	40	3.2	70	4.8	100	6.0
7	0.20	16	0.9	45	3.5	75	5.0		
8	0.25	20	1.45	50	3.8	80	5.2		
9	0.30	25	2.0	55	4.0	85	5.4		

The third coefficient is the influence of the ambient temperature on the steel structure, Z_C. With decreasing temperature the steel behaves in a brittle manner, due to the smaller amount of slip systems within the steel to allow plastic deformation. The influence of this coefficient has been listed in Table 2.3[7].

Table 2.3 Influence of cold

T [°C]	Z_C [-]	T [°C]	Z_C [-]
0	0.0	-30	3.4
-5	0.1	-35	4.5
-10	0.4	-40	5.6
-15	0.8	-45	6.7
-20	1.5	-50	7.9
-25	2.3	-55	9.0

The summation of the influence coefficients leads to a combined value, with which the required steel quality group can be determined (Table 2.4). With the steel quality group the designated steel can be found (Table 2.5: listed as steel qualities A, B, C and D according to Euronorm 25).

Table 2.4 Steel quality group

$\sum Z = Z_A + Z_B + Z_C$ [-]	Quality group
≤ 2	1
≤ 4	2
≤ 8	3
≤ 16[8]	4

Table 2.5 Steel

Quality group	Notch toughness measured in ISO sharp notch test ISO-R 148 in Nm/cm^2	Test temperature T [°C]	Designation of steels
1	-	-	Fe 360 – A Fe 430 – A
2	35	+20	Fe 360 – B Fe 430 – B Fe 510 – B
3	35	0	Fe 360 – C Fe 430 – C Fe 510 – C
4	35	-20	Fe 360 – D Fe 430 – D Fe 510 – D

[7] The temperature in Table 2.3 is defined from 0 °C and lower. The reason for this is most likely due to the characteristic brittle-ductile transition that steel experiences at this temperature. If the temperature is below 0 °C steel will act brittle; thus having the possibility of a brittle fracture.

[8] If the value of Z is higher than 16, it will be assumed that E-quality is applicable.

2.3.3 European standard NEN-EN 13001

The European standard NEN-EN 13001 has a similar approach compared to FEM 1.001, however, five influences have been defined which are assessed with influence coefficient Q_i [39]. The first coefficient concerns the operating temperature, Q_1. The influence has been listed in Table 2.6.

Table 2.6 Operating temperature

Operating temperature T $[°C]$	Influence coefficient Q_1
$0 \leq T$	0
$-10 \leq T < 0$	1
$-20 \leq T < -10$	2
$-30 \leq T < -20$	3
$-40 \leq T < -30$	4
$-50 \leq T < -40$	6

The second coefficient concerns the influence of the yield stress f_y, Q_2. With increasing plate thickness the yield strength decreases, thus leading to lower allowable stresses and higher strength steels have a reduced toughness, thus requiring a higher steel quality. Table 2.7 lists the influence of this coefficient.

Table 2.7 Yield stress

Yield stress f_y $[N/mm^2]$	Influence coefficient Q_2
$f_y \leq 300$	0
$300 < f_y \leq 460$	1
$460 < f_y \leq 700$	2
$700 < f_y \leq 1000$	3
$1000 < f_y \leq 1300$	4

The third coefficient concerns the material thickness (and thus the occurrence of tri-axial stress states in the steel structure), Q_3. Table 2.8 lists the influence of this coefficient.

Table 2.8 Material thickness

Material thickness t $[mm]$	Influence coefficient Q_3
$t \leq 10$	0
$10 < t \leq 20$	1
$20 < t \leq 40$	2
$40 < t \leq 60$	3
$60 < t \leq 80$	4
$80 < t \leq 100$	5
$100 < t \leq 125$	6
$125 < t \leq 125$	7

The fourth coefficient concerns the influence of the characteristics value of the stress range $\Delta\sigma_C$, Q_4. This value concerns the allowable tensile stresses range with regards to the shape and type of weld applied. The influence of this coefficient has been listed in Table 2.9.

Table 2.9 Characteristic value of stress range

Characteristic value of stress range $\Delta\sigma_C$ $[N/mm^2]$	Influence coefficient Q_4
$\Delta\sigma_C > 125$	0
$80 < \Delta\sigma_C \leq 125$	1
$56 < \Delta\sigma_C \leq 80$	2
$40 < \Delta\sigma_C \leq 56$	3
$30 < \Delta\sigma_C \leq 40$	4
$\Delta\sigma_C \leq 30$	5

The fifth coefficient is the utilization of static strength (design stresses and limit design stresses or the Von Mises equivalent stresses) σ_{Sd}, Q_5. The influence of this coefficient has been listed in Table 2.10.

Table 2.10 Utilization of static strength

Design limit stress σ_{Sd} [N/mm^2] Yield limit stress $f_{Rd\sigma}$[N/mm^2]	Utilization of static strength σ_{Sd} $[N/mm^2]$	Influence coefficient Q_5
	$\sigma_{Sd} > 0.75f_{Rd\sigma}$	0
	$0.5f_{Rd\sigma} < \sigma_{Sd} \leq 0.75f_{Rd\sigma}$	-1
	$0.25f_{Rd\sigma} < \sigma_{Sd} \leq 0.5f_{Rd\sigma}$	-2
	$\sigma_{Sd} \leq 0.25f_{Rd\sigma}$	-3

The effects of each influence is determined with a dimensionless factor Q_i that leads to a combined value. With the combined value the steel quality can be found (Table 2.11).

Table 2.11 Impact toughness requirement and corresponding steel quality NEN-EN 13001

	$Q_i \leq 5$	$6 \leq Q_i \leq 8$	$9 \leq Q_i \leq 11$	$12 \leq Q_i \leq 14$
Impact energy/ test temperature requirement	27 J/ +20 °C	27 J/ 0 °C	27 J/ -20 °C	27 J/ -40 °C
EN 10025-2[9]	JR	J0	J2	a)
a) May be used if the impact toughness is at least 27 J at -40 °C, tested in accordance with EN 10045-1 and specified.				

[9] In EN 10025-2 the notch toughness of a structural steel is listed as J, K or L. The letter designates the energy value from the Charpy-V impact test. J equals min. 27 J as average, K equals min. 40 J as average, L equals min. 60 J as average. The testing temperature of the Charpy-V impact test is listed as R = +20 [°C], 0 = 0 [°C], 2 = -20 [°C], 4 = -40 [°C]. Based on this definition different steel qualities have been defined; E.g. S355JR, S355J0, S355J2, and others.

2.3.4 Chinese standard GB/T 3811

The standard used in P.R. China is the GB/T 3811 with regards to the loads on the crane structure, fatigue, and, among others, the steel quality selection [40]. Comparing GB/T 3811 with FEM 1.001 the steel quality selection only differs with regards to the influence of the residual tensile stresses. All other factors (influence of the plate thickness and ambient temperature) are evaluated similarly.

With regards to the combined effect of the longitudinal tensile stresses with the tensile stresses from the dead load, Z_A, the following formulas can be stated. In case the steel structure has no welds or only transverse welds the coefficient is defined as (Eq. 2.11):

$$Z_A = \frac{\sigma_G}{0.3 \bullet \sigma_a} - 1 \text{ [-]} \tag{2.11}$$

With the condition that $\sigma_G \geq 0.3\sigma_a$ and σ_a being defined as the permissible tensile stress with respect to the elastic limit of load case 1. σ_G is defined as the residual tensile stress due to its own weight. The influence of the residual tensile stresses due to welding have been taken into account by the type of welding.

In case the steel structure contains longitudinal welds the coefficient is defined as (Eq. 2.12):

$$Z_A = \frac{\sigma_G}{0.3 \bullet \sigma_a} \text{ [-]} \tag{2.12}$$

The last category is that in case the steel structure contains accumulations of welds the coefficient is defined as (Eq. 2.13):

$$Z_A = \frac{\sigma_G}{0.3 \bullet \sigma_a} + 1 \text{ [-]} \tag{2.13}$$

As can be noted when comparing the formulas the Chinese standard will lead to a higher steel quality than the European standard due to the more severe influence accounted to the influence of the residual tensile stresses.

2.3.5 British standard BS 2573

The standard used in Malaysia (former British protectorate) with regards to the crane structure is BS 2573. The standard states, with regards to the selection of steel, the following [41]:

Steel shall be selected from either:

(a) Standard structural steels according to BS 4360;

(b) Other steels, provided that the crane manufacturer shows that they have comparable properties to steels defined in BS 4360 and that they have been subjected to equivalent tests.

Where thicknesses of steel are specified that exceed the maximum values given in BS 4360 for Charpy V- notch impact tests, the impact test requirements on standard specimens shall not be less than the value given in BS 4360 for the type of steel under consideration on the standard specimen.

Where cranes are to be used at low temperatures such that brittle fracture might occur, the material used for load bearing members shall have specified low temperature impact properties, adequate to meet the service conditions inherent in the design. For temperate or tropical conditions, steels having no guaranteed impact test values are acceptable, with the exception of the following, which shall not be used unless impact or other test show that the material is suitable for service:

(a) Plates and sections above 30 mm thickness where brittle fracture might occur under tension loads;
(b) Plates and sections above 25 mm thickness where brittle fracture under tension loads would result in major structural collapse.

For the steel quality selection procedure a different standard is needed (has been separated from BS 2573), however, the British Standard does state an interesting point. It states that for temperate or tropical conditions, steels having no guaranteed impact test values are acceptable, which is applicable for plate thicknesses equal to or lower than 25 mm. It could be assumed, taking NEN 2019 into account, this implies that for plate thicknesses equal to or lower than 25 mm B-quality steel could be applied. For larger plate thicknesses a Charpy-V impact test is required.

2.4 Steel quality tables

For FEM 1.001, NEN-EN 13001 and GB/T 3811 it is possible to tabularize the results of the selection procedure, which has been presented in this paragraph.

2.4.1 Steel quality tables European standard FEM 1.001

When reviewing the factors listed in FEM 1.001 it would be desirable to have an overview whereby based on a certain temperature the steel quality can be determined within a range for the plate thicknesses. The factors FEM 1.001 evaluates are:

1. Combined effect of longitudinal residual tensile stresses with tensile stresses from the dead load, Z_A;

   For the effect of the tensile stresses the ratio between the allowable tensile stresses for load case 1 and the residual tensile stresses from the dead load has been determined by evaluating a number of existing crane designs. Based on this the following assumption has been made: $\frac{\sigma_G}{\sigma_a} \approx 0.5$ [-].

   The types of weld in the sill beam steel structure are longitudinal welds and weld accumulations, which results in Z_A = 1 [-] for longitudinal welds and Z_A = 2 [-] for weld accumulations.

2. Thickness of the member, Z_B;
3. Influence of cold (or the operating temperature), Z_C.

Taking into account the plate thicknesses and the temperature range as specified in FEM 1.001, the following resulting tables can be formed (Table 2.12, 2.13, and 2.14). The complete tables have been listed in Appendix C.

Table 2.12 Steel quality

$\sum Z = Z_A + Z_B + Z_C$ [−]	Group	Quality
$\sum Z \leq 2$	1	A
$2 < \sum Z \leq 4$	2	B
$4 < \sum Z \leq 8$	3	C
$8 < \sum Z \leq 16$	4	D

Table 2.13 Resulting steel qualities based on temperature and plate thickness, FEM 1.001

$\sum Z = Z_a + Z_B + Z_C \ [-]$ $\rightarrow Z_a = 1$	Temperature $T\ [°C]$					
Plate thickness $t\ [mm]$	0	-5	-10	-15	-20	-25
5	1.1	1.2	1.5	1.9	2.6	3.4
6	1.15	1.25	1.55	1.95	2.65	3.45
7	1.2	1.3	1.6	2	2.7	3.5
8	1.25	1.35	1.65	2.05	2.75	3.55
9	1.3	1.4	1.7	2.1	2.8	3.6
10	1.4	1.5	1.8	2.2	2.9	3.7
12	1.5	1.6	1.9	2.3	3	3.8
15	1.8	1.9	2.2	2.6	3.3	4.1
16	1.9	2	2.3	2.7	3.4	4.2
20	2.45	2.55	2.85	3.25	3.95	4.75
25	3	3.1	3.4	3.8	4.5	5.3
30	3.5	3.6	3.9	4.3	5	5.8
35	3.9	4	4.3	4.7	5.4	6.2
40	4.2	4.3	4.6	5	5.7	6.5
45	4.5	4.6	4.9	5.3	6	6.8
50	4.8	4.9	5.2	5.6	6.3	7.1
55	5	5.1	5.4	5.8	6.5	7.3
60	5.3	5.4	5.7	6.1	6.8	7.6
65	5.55	5.65	5.95	6.35	7.05	7.85
70	5.8	5.9	6.2	6.6	7.3	8.1
75	6	6.1	6.4	6.8	7.5	8.3
80	6.2	6.3	6.6	7	7.7	8.5
85	6.4	6.5	6.8	7.2	7.9	8.7
90	6.6	6.7	7	7.4	8.1	8.9
95	6.8	6.9	7.2	7.6	8.3	9.1
100	7	7.1	7.4	7.8	8.5	9.3

Table 2.14 Resulting steel qualities based on temperature and plate thickness, FEM 1.001

$\sum Z = Z_a + Z_B + Z_C \ [-]$ $\rightarrow Z_a = 2$	Temperature $T\ [°C]$					
Plate thickness $t\ [mm]$	0	-5	-10	-15	-20	-25
5	2.1	2.2	2.5	2.9	3.6	4.4
6	2.15	2.25	2.55	2.95	3.65	4.45
7	2.2	2.3	2.6	3	3.7	4.5
8	2.25	2.35	2.65	3.05	3.75	4.55
9	2.3	2.4	2.7	3.1	3.8	4.6
10	2.4	2.5	2.8	3.2	3.9	4.7
12	2.5	2.6	2.9	3.3	4	4.8
15	2.8	2.9	3.2	3.6	4.3	5.1
16	2.9	3	3.3	3.7	4.4	5.2
20	3.45	3.55	3.85	4.25	4.95	5.75
25	4	4.1	4.4	4.8	5.5	6.3
30	4.5	4.6	4.9	5.3	6	6.8
35	4.9	5	5.3	5.7	6.4	7.2
40	5.2	5.3	5.6	6	6.7	7.5
45	5.5	5.6	5.9	6.3	7	7.8
50	5.8	5.9	6.2	6.6	7.3	8.1
55	6	6.1	6.4	6.8	7.5	8.3
60	6.3	6.4	6.7	7.1	7.8	8.6
65	6.55	6.65	6.95	7.35	8.05	8.85
70	6.8	6.9	7.2	7.6	8.3	9.1
75	7	7.1	7.4	7.8	8.5	9.3
80	7.2	7.3	7.6	8	8.7	9.5
85	7.4	7.5	7.8	8.2	8.9	9.7
90	7.6	7.7	8	8.4	9.1	9.9
95	7.8	7.9	8.2	8.6	9.3	10.1
100	8	8.1	8.4	8.8	9.5	10.3

2.4.2 Steel quality tables European standard NEN-EN 13001

When reviewing the factors stated in NEN-EN 13001 the following assumptions have been made with regards to these factors:

1. Operating temperature;

   The temperature range shall be taken as the same temperature range for FEM 1.001, though defined with the influence coefficient Q_1.

2. Yield stress;

   The yields stress is dependent on the material properties. Currently the steels used for the Ship-To-Shore container crane of Cargotec Netherlands BV are Q345-D (with a yield stress of 345 N/mm^2) and Q390-D (with a yield stress of 390 N/mm^2). Taking into account that the yield stress lowers with increasing plate thickness (Table 2.15) both steel types have been evaluated separately[10].

   Table 2.15 Yield stress based on plate thickness

Yield stress [N/mm^2]	Steel type	
Material thickness [mm]	Q345	Q390
t ≤ 16	345	390
16 < t ≤ 35	325	370
35 < t ≤ 50	295	350
50 < t ≤ 100	275	330

   For Q345-D Q_2 = 1 [-] (for t ≤ 35mm)

   For Q345-D Q_2 = 0 [-] (for t ≥ 35mm)

   For Q390-D Q_2 = 1 [-]

3. Material thickness;

   For the material thickness only the correct value within the standard has to be selected and the associated influence coefficient Q_3.

4. Characteristics value of the stress range;

   For the determination of the characteristic value the type of weld and the weld shape has to be taken into account. Furthermore, the quality will have to be selected. Without making a distinction between butt welds and angular welds the

[10] The yield strength decreases with increasing material thickness. This takes into account the effect that with the increase in material thickness, the addition of alloying elements needs to be higher to achieve constant yield strength over the thickness. However, with the addition of alloying elements, the carbon equivalent value rises and welding becomes problematic. Welding is substantial to the application of structural steel. Thus, the normative rules have considered this fact by lowering the yield stress for thicker plates to account for weldability [42].

inconsistencies in a welded connection are qualified into three levels: low (D), average (C), and high (B). The required quality is dependent on whether it is a dynamically loaded structure or not (among others) [14]. With regards to a Ship-To-Shore container gantry crane the weld quality is standard B and sometimes (for secondary components) C. The tables in NEN-EN 13001 show a characteristic value of the stress range at $80 < \Delta\sigma_C \leq 125$ N/mm^2 and $56 < \Delta\sigma_C \leq 80$ N/mm^2, respectively. Therefore the coefficient can be set as $Q_4 = 1$ [-] for $80 < \Delta\sigma_C \leq 125$ N/mm^2 and $Q_4 = 2$ [-] for $56 < \Delta\sigma_C \leq 80$ N/mm^2.

5. Utilization of static strength (design stresses and limit design stresses or the Von Mises equivalent stresses).

   For a Ship-To-Shore container gantry crane it may be assumed that the stress ranges are fully utilized, resulting in $Q_5 = 0$ [-].

Taking into account the plate thicknesses and the temperature range as specified in NEN-EN 13001, the following resulting tables can be formed (Table 2.16, 2.17, 2.18, 2.19 and 2.20). The complete tables have been listed in Appendix C. From a conservative point of view only the tables with $Q_4 = 2$ [-] could be looked at with NEN-EN 13001, thereby covering all situations from the most conservative point of view.

Table 2.16 Steel quality

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$	Quality	Corresponding quality
$\sum Q_i \leq 5$	JR	B
$6 \leq \sum Q_i \leq 8$	J0	C
$9 \leq \sum Q_i \leq 11$	J2	D
$12 \leq \sum Q_i \leq 14$	J4	E

What can be noted is that NEN-EN 13001 does not define A-quality steel as a suitable steel type, which is why it has not been defined in Table 2.16.

Table 2.17 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 1$	Steel type Q345					
	Temperature T [°C]					
Plate thickness t [mm]	0	-5	-10	-15	-20	-25
5	2.0	3.0	3.0	4.0	4.0	5.0
6	2	3	3	4	4	5
7	2	3	3	4	4	5
8	2	3	3	4	4	5
9	2	3	3	4	4	5
10	2	3	3	4	4	5
12	3	4	4	5	5	6
15	3	4	4	5	5	6
16	3	4	4	5	5	6
20	3	4	4	5	5	6
25	4	5	5	6	6	7
30	4	5	5	6	6	7
35	4	5	5	6	6	7
40	3	4	4	5	5	6
45	4	5	5	6	6	7
50	4	5	5	6	6	7
55	4	5	5	6	6	7
60	4	5	5	6	6	7
65	5	6	6	7	7	8
70	5	6	6	7	7	8
75	5	6	6	7	7	8
80	5	6	6	7	7	8
85	6	7	7	8	8	9
90	6	7	7	8	8	9
95	6	7	7	8	8	9
100	6	7	7	8	8	9

Table 2.18 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 2$	Steel type Q345					
	Temperature T [°C]					
Plate thickness t [mm]	0	-5	-10	-15	-20	-25
5	3.0	4.0	4.0	5.0	5.0	6.0
6	3	4	4	5	5	6
7	3	4	4	5	5	6
8	3	4	4	5	5	6
9	3	4	4	5	5	6
10	3	4	4	5	5	6
12	4	5	5	6	6	7
15	4	5	5	6	6	7
16	4	5	5	6	6	7
20	4	5	5	6	6	7
25	5	6	6	7	7	8
30	5	6	6	7	7	8
35	5	6	6	7	7	8
40	4	5	5	6	6	7
45	5	6	6	7	7	8
50	5	6	6	7	7	8
55	5	6	6	7	7	8
60	5	6	6	7	7	8
65	6	7	7	8	8	9
70	6	7	7	8	8	9
75	6	7	7	8	8	9
80	6	7	7	8	8	9
85	7	8	8	9	9	10
90	7	8	8	9	9	10
95	7	8	8	9	9	10
100	7	8	8	9	9	10

Table 2.19 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 1$	Steel type Q390					
	Temperature T $[°C]$					
Plate thickness t $[mm]$	0	-5	-10	-15	-20	-25
5	2.0	3.0	3.0	4.0	4.0	5.0
6	2	3	3	4	4	5
7	2	3	3	4	4	5
8	2	3	3	4	4	5
9	2	3	3	4	4	5
10	2	3	3	4	4	5
12	3	4	4	5	5	6
15	3	4	4	5	5	6
16	3	4	4	5	5	6
20	3	4	4	5	5	6
25	4	5	5	6	6	7
30	4	5	5	6	6	7
35	4	5	5	6	6	7
40	4	5	5	6	6	7
45	5	6	6	7	7	8
50	5	6	6	7	7	8
55	5	6	6	7	7	8
60	5	6	6	7	7	8
65	6	7	7	8	8	9
70	6	7	7	8	8	9
75	6	7	7	8	8	9
80	6	7	7	8	8	9
85	7	8	8	9	9	10
90	7	8	8	9	9	10
95	7	8	8	9	9	10
100	7	8	8	9	9	10

Table 2.20 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 2$	Steel type Q390					
	Temperature T $[°C]$					
Plate thickness t $[mm]$	0	-5	-10	-15	-20	-25
5	3.0	4.0	4.0	5.0	5.0	6.0
6	3	4	4	5	5	6
7	3	4	4	5	5	6
8	3	4	4	5	5	6
9	3	4	4	5	5	6
10	3	4	4	5	5	6
12	4	5	5	6	6	7
15	4	5	5	6	6	7
16	4	5	5	6	6	7
20	4	5	5	6	6	7
25	5	6	6	7	7	8
30	5	6	6	7	7	8
35	5	6	6	7	7	8
40	5	6	6	7	7	8
45	6	7	7	8	8	9
50	6	7	7	8	8	9
55	6	7	7	8	8	9
60	6	7	7	8	8	9
65	7	8	8	9	9	10
70	7	8	8	9	9	10
75	7	8	8	9	9	10
80	7	8	8	9	9	10
85	8	9	9	10	10	11
90	8	9	9	10	10	11
95	8	9	9	10	10	11
100	8	9	9	10	10	11

2.4.3 Steel quality tables Chinese standard GB/T 3811

When reviewing the factors listed in GB/T 3811 it can be noted that the same procedure as with FEM 1.001 is applied. Only the outcome for the tensile stress assessment coefficient differs. For longitudinal welds Z_A = 1.6 [-], for weld accumulations Z_A = 2.6 [-]. The reason for this difference with FEM 1.001 is unclear. The steel quality tables have been listed in Tables 2.21 and 2.22. The complete steel quality tables have been listed in Appendix C.

Table 2.21 Resulting steel qualities based on temperature and plate thickness, GB/T 3811

$\sum Z = Z_a + Z_B + Z_C\ [-]$ $\rightarrow Z_a = 1.6$	Temperature $T\ [°C]$					
Plate thickness $t\ [mm]$	0	-5	-10	-15	-20	-25
5	1,7	1,8	2,1	2,5	3,2	4.0
6	1,75	1,85	2,15	2,55	3,25	4.05
7	1,8	1,9	2,2	2,6	3,3	4.1
8	1,85	1,95	2,25	2,65	3,35	4.15
9	1,9	2	2,3	2,7	3,4	4.2
10	2	2,1	2,4	2,8	3,5	4.3
12	2,1	2,2	2,5	2,9	3,6	4.4
15	2,4	2,5	2,8	3,2	3,9	4.7
16	2,5	2,6	2,9	3,3	4	4.8
20	3,05	3,15	3,45	3,85	4,55	5.35
25	3,6	3,7	4	4,4	5,1	5.9
30	4,1	4,2	4,5	4,9	5,6	6.4
35	4,5	4,6	4,9	5,3	6	6.8
40	4,8	4,9	5,2	5,6	6,3	7.1
45	5,1	5,2	5,5	5,9	6,6	7.4
50	5,4	5,5	5,8	6,2	6,9	7.7
55	5,6	5,7	6	6,4	7,1	7.9
60	5,9	6	6,3	6,7	7,4	8.2
65	6,15	6,25	6,55	6,95	7,65	8.45
70	6,4	6,5	6,8	7,2	7,9	8.7
75	6,6	6,7	7	7,4	8,1	8.9
80	6,8	6,9	7,2	7,6	8,3	9.1
85	7	7,1	7,4	7,8	8,5	9.3
90	7,2	7,3	7,6	8	8,7	9.5
95	7,4	7,5	7,8	8,2	8,9	9.7
100	7,6	7,7	8	8,4	9,1	9.9

Table 2.22 Resulting steel qualities based on temperature and plate thickness, GB/T 3811

$\sum Z = Z_a + Z_B + Z_C\ [-]$ $\rightarrow Z_a = 2.6$	Temperature $T\ [°C]$					
Plate thickness $t\ [mm]$	0	-5	-10	-15	-20	-25
5	2,7	2,8	3,1	3,5	4,2	5.0
6	2,75	2,85	3,15	3,55	4,25	5.05
7	2,8	2,9	3,2	3,6	4,3	5.1
8	2,85	2,95	3,25	3,65	4,35	5.15
9	2,9	3	3,3	3,7	4,4	5.2
10	3	3,1	3,4	3,8	4,5	5.3
12	3,1	3,2	3,5	3,9	4,6	5.4
15	3,4	3,5	3,8	4,2	4,9	5.7
16	3,5	3,6	3,9	4,3	5	5.8
20	4,05	4,15	4,45	4,85	5,55	6.35
25	4,6	4,7	5	5,4	6,1	6.9
30	5,1	5,2	5,5	5,9	6,6	7.4
35	5,5	5,6	5,9	6,3	7	7.8
40	5,8	5,9	6,2	6,6	7,3	8.1
45	6,1	6,2	6,5	6,9	7,6	8.4
50	6,4	6,5	6,8	7,2	7,9	8.7
55	6,6	6,7	7	7,4	8,1	8.9
60	6,9	7	7,3	7,7	8,4	9.2
65	7,15	7,25	7,55	7,95	8,65	9.45
70	7,4	7,5	7,8	8,2	8,9	9.7
75	7,6	7,7	8	8,4	9,1	9.9
80	7,8	7,9	8,2	8,6	9,3	10.1
85	8	8,1	8,4	8,8	9,5	10.3
90	8,2	8,3	8,6	9	9,7	10.5
95	8,4	8,5	8,8	9,2	9,9	10.7
100	8,6	8,7	9	9,4	10,1	10.9

2.4.4 Comparison and remarks

When reviewing the resulting tables for the steel quality the following can be noted. As can be seen, FEM 1.001 and GB/T 3811 both have the option for A-quality steel. However, both NEN 2019 and NEN-EN 13001 do not have this steel quality. NEN 2019 even states that steel quality A is not suitable for the main structural steel components. For this reason the A-quality steel that comes forth with the use of FEM 1.001 or GB/T 3811 will be taken a B-quality steel as a minimum.

When comparing the resulting tables of FEM 1.001 and NEN-EN 13001 it can be seen that for some plate thicknesses the steel quality differs, though for the largest part there is an overlap in the appropriate steel quality. Even though FEM 1.001 uses fewer factors for the evaluation, the factors themselves are more accurate. NEN-EN 13001 has more factors taken into account, though the factors themselves are divided into larger groups compared to FEM 1.001. Another point to address is the fact that FEM 1.001 (and in this case also GB/T 3811) does not mention the application of E-quality steel. This does raise the question of the validity of FEM 1.001 with regards to very low temperatures.

When comparing FEM 1.001 with GB/T 3811 it can be said that the Chinese standard leads to a more conservative result with regards to the selected steel quality. Therefore this will most likely lead to a higher degree of D-quality steel within the steel structure.

After having provided a theoretical background to brittle fracture (paragraph 2.2) and having discussed the standards (paragraph 2.3 and 2.4) a number of remarks can be made.

- When reviewing Table 2.7 of NEN-EN 13001, it can be noted that a reduction of the yield stress is taken into account. The reason for this reduction is due to high strength materials being less tough than low strength materials. A characteristic of high strength steel is that it has a reduced toughness compared to a lower strength steel, which can be expressed with the ultimate tensile stress / yield stress ratio. This ratio is an indication of the degree of plastic deformation of the steel that can occur before fracture. For a low strength steel, e.g. S355, this ratio varies between 1.4 (510 MPa / 355 MPa) and 1.9. This value depends, among others, on the quality of the steel. For high strength steel, e.g. S690, this ratio varies between 1.1 (770 MPa / 690 MPa) and 1.3. Due to the lower ratio, high strength steel has a limited capacity for plastic deformation, which decreases when the ambient temperature is lowered. This limited capacity is an indication for a reduced toughness of the material, thereby being more sensitive to brittle fracture, because brittle fracture is preceded with little or no plastic deformation.

- It can be thought of that lowering the allowable tensile stresses is a way to avoid brittle fracture. However, this measure should not to be taken. It is not the allowable tensile stresses that are of importance, but the occurring tensile stresses. The occurring tensile stress can be magnified at a location within the material where an impurity is to be found. This increased tensile stress can be higher than the yield stress of the material. If the material allows little plastic deformation this will lead to a crack growth or a fracture. These impurities are always present in the material in the form of sulphur particles and others (which is the reason why the fracture toughness value of apparently similar materials may not be compared if the metallurgical compositions of these materials differs). Lowering the allowable tensile stresses is, from this point of view, not helpful, unless the allowable tensile stresses are very low. This can be noted with NEN-EN 13001, Table 2.10, where the coefficient Q_5 is given a negative value with decreasing utilization of the static strength of the material. What also must be noted is that with lowering the allowable tensile stresses, the plate thickness will increase (under the assumption of having the same loads), which will result in tri-axial stress states in the material[11].

[11] There is an interesting point to mention with lowering the utilization stresses in case it concerns high strength steels. High strength steels have a smaller capacity for plastic deformation, making the material prone for brittle fracture in case of high stresses beyond the yield stress. In steel structures that experience a large number of load cycles (such as the steel structure of Ship-To-Shore container gantry cranes), the tensile and compression fatigue stresses are limiting. In case the fatigue factor is taken as $\chi = 0.0$ with a notch factor of K2 (with the number of load cycles larger than 1,000,000) the difference in allowable fatigue stress for a low strength steel and a high strength steel, e.g. S355 and S690, is almost non-existent. This means that for a high strength steel the static strength is only partially used and in case a high peak stress is sometimes experienced, this peak stress may be below the yield stress, thus not leading to a brittle fracture. This might be an indication that the steel quality for a high strength steel may be more favorable than with the use of a low strength steel. Whether from a cost perspective this is more favorable is dependent on the steel type, e.g. S460, S690, and the consequences of the use of high strength steel in a steel structure.

2.5 Cost reduction

Based on the resulting steel quality tables it can be seen that, regardless of which standard is reviewed, the need for D-quality steel is restricted to low temperatures in combination with large plate thicknesses. Of interest is what the actual steel quality division is of the steel structure of a Ship-To-Shore container gantry crane and what the possible cost reduction is.

2.5.1 Case study

For the application of FEM 1.001 the approach has been structured such that first a component will be evaluated, followed by a sub-assembly, concluding with an evaluation of the entire steel structure of the crane. This is done to indicate how the procedure works and to point out if there are any conflicting points. For the component evaluation FEM 1.001, NEN-EN 13001 and GB/T 3811 will be applied. For the sub-assembly and the crane structure only FEM 1.001 will be applied.

The component evaluation focusses on the sill beam WS of an existing Ship-To-Shore container gantry crane from Cargotec Netherlands BV (see Appendix Y for general arrangement drawing of the sill beam WS). The following crane specifications have been listed which are necessary for the case study [28, 43]:

- The tender documentation states that the ambient temperature is within the range of 15 °C to 35 °C. The ambient temperature according to the technical specification of Cargotec Netherlands BV is rated from 19 °C to 45 °C;
- Mass of the sill beam WS is listed as 43.7 Metric Tonnes (MT);
- Main structural steel elements are Q345-D and Q390-D;
- Applicable standard is FEM 1.001.

Based on the minimum temperature, the material list and the component's drawing, all factors can be evaluated according to the procedure in FEM 1.001. However, for the temperature there is some caution necessary. Even though the operating temperature is above 0°C, the production and assembly sites are in an area where far lower temperatures are experienced. The following situations need to be considered.

- The temperature at the production and assembly site;
- The temperature experienced during transport;
- The operating temperature at the client.

The determination of the minimum temperature is also dependent on the time of year when the crane is produced, assembled, transported and delivered, which increases the difficulty of selecting the appropriate temperature.

Besides the temperature brittle fracture can occur under severe loadings. It can be questioned when the crane structure experiences these kind of severe loadings. During transport the crane structure experiences high loads due to, for example, high waves, though transport ships tend to execute a transport during favorable weather conditions. It can also be questioned when the crane experiences the worst combination of temperature and stresses that lead to brittle fracture.

However, a distinction between these situations is not provided in the standards regarding the selection of the appropriate steel quality and the influence of this consideration. The standard mentions only that the temperature is based on the temperature at the place of erection (or the use of the hoisting appliance).

If one looks at the specified ambient conditions the assessment coefficients in FEM 1.001 (indicated by Z_C) and NEN-EN 13001 (indicated by Q_1) can be rated as 0, even though when evaluating the temperature conditions in Nantong and Taicang, Jiangsu Province, P.R. China (minimum temperature of approximately -10 °C), the value of the assessment coefficients can be rated to be equal to Z_C = 0.4 [-] and Q_1 = 1.0 [-]. The temperatures experienced during transport are entirely dependent on the shipping route, the season in which the transport takes place, etcetera. The minimum temperature of -10°C has been taken as a guideline for further proceedings.

In Appendix E the resulting steel qualities according to FEM 1.001, NEN-EN 13001 and GB/T 3811 have been listed. Figure 2.3 displays the evaluated component and indicates the differences between FEM 1.001 and NEN-EN 13001. As can be seen in Appendix E there are some resulting steel qualities according to FEM 1.001 which differ with NEN-EN 13001 and GB/T 3811. The reason for this is due to the different factors taken into account. Besides that, NEN-EN 13001 also takes into account the reduction in yield stress due to increasing plate thickness. This has its effect on the total score. GB/T 3811 in some situations results in a more conservative result than FEM 1.001, though for this situation the difference is negligible. When comparing GB/T 3811 with NEN-EN 13001 the same comments as with FEM 1.001 can be made.

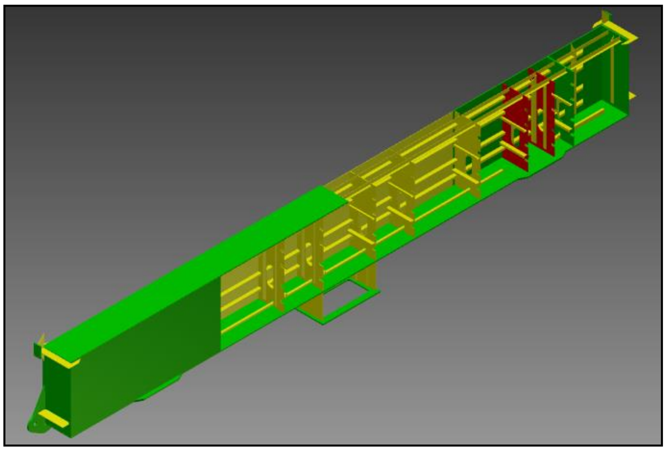


Figure 2.3 Sill beam waterside, indication of steel quality. The difference in result between FEM 1.001 and NEN-EN 13001 has been indicated with red.

As stated in the introduction, from an historic perspective Cargotec has always applied D-quality steel. Based on the case study the steel quality for all plates can be reduced to C and B-quality. This has its reflection on the cost for the sill beam WS. Based on data provided by Rainbow Cargotec Industries Co., Ltd. (partner company of Cargotec Netherlands BV), on the price difference between D and C, B-quality steel the following cost reduction could be attained. The A-quality steel that comes forth from FEM 1.001 will be taken as B-quality. The price difference between D and C-quality steel is set equal to 12.5 Euro/MT. The price difference between D and B-quality steel is set equal to 37.5 Euro/MT. From the evaluation it can be concluded that 13.98 MT can be B-quality steel and 29.73 MT can be C-quality steel. The total cost reduction amounts to 895.83 Euro.

The important point to conclude with the component case study is the issue with selecting the appropriate temperature. Taking this into account the interest would now be to indicate what the cost reduction would be for the entire portal frame based on the same crane specifications as defined before (Table 2.23 and 2.24). In this case only FEM 1.001 is evaluated since this concerns the standard currently used. It must be stated though that the result of the cost reduction is entirely dependent on the factors stated in FEM 1.001. If the temperature factor is defined to be lower there will be a shift from B to C and from C to D-quality steel.

Table 2.23 Steel quality division for case study

Portal frame Ship-To-Shore container gantry crane, steel quality division, T = -10 °C					Existing situation
Component	Total mass [MT]	% B-quality steel	% C-quality	% D-quality	% D-quality
Bogie WS steel structure	8.9	10.2	89.8	0.0	100.0
Balance WS steel structure	12.7	37.7	62.3	0.0	100.0
Main balance WS steel structure	26.7	8.0	64.4	27.6	100.0
Bogie LS steel structure	9.7	11.8	88.2	0.0	100.0
Balance LS steel structure	9.7	49.0	51.0	0.0	100.0
Main balance LS steel structure	21.5	31.9	65,5	2.6	100.0
Sill beam WS	43.7	32.0	68.0	0.0	100.0
Sill beam LS	40.1	63.0	37.0	0.0	100.0
Lower leg PS WS (SB WS)	20.7 (sum)	51.7	48.3	0.0	100.0
Lower leg PS LS (SB LS)	8.0 (7.4)	67.8	32.2	0.0	100.0
Cross girder PS (SB)	81.8 (sum)	74.6	25.4	0.0	100.0
Long leg PS WS (SB WS)	56.4 (sum)	80.3	19.7	0.0	100.0
Long leg PS LS (SB LS)	24.4 (24448)	91.4	8.6	0.0	100.0
Upper leg PS WS (SB WS)	35.0 (sum)	75.3	24.7	0.0	100.0
Upper leg PS LS (SB LS)	20.9 (20112)	76.7	23.3	0.0	100.0
Portal beam WS	36.0	57.4	42.6	0.0	100.0
Portal beam LS	39.5	40.8	59.2	0.0	100.0
A frame	14.7	89.5	10.5	0.0	100.0
Diagonal tie PS (SB)	20.5 (sum)	90.9	9.1	0.0	100.0
Tie portal frame WS	5.6 (sum)	75.4	24.6	0.0	100.0
That the total mass may differ from the summation of the individual components. There is a certain degree of revision present when estimating the weight and the total weight.					

Table 2.24 Steel quality cost reduction

	Total mass [MT]	% B-quality steel	% C-quality steel	% D-quality steel
Portal frame Ship-To-shore container gantry crane	586.0	61.8	36.9	1.3
Cost reduction [Euro]	16,300			
The total mass listed in Table 2.23 is a mass that has been revised and therefore differs from the mass of each plate or others of these components.				

Of interest is what the cost reduction would be when the operational temperature is lower than the assumed lowest temperature at the production and assembly site. Any temperature above the assumed lowest temperature at the production and assembly site is not of concern. Furthermore, the entire crane structure should be evaluated to determine if the crane steel structure still contains D-quality steel (Table 2.25, 2.26, Appendix D, and Appendix Y for the general drawing of the crane). Figure 2.4 shows an example of the development of the changing steel quality with lowering temperature of the bogie set WS.

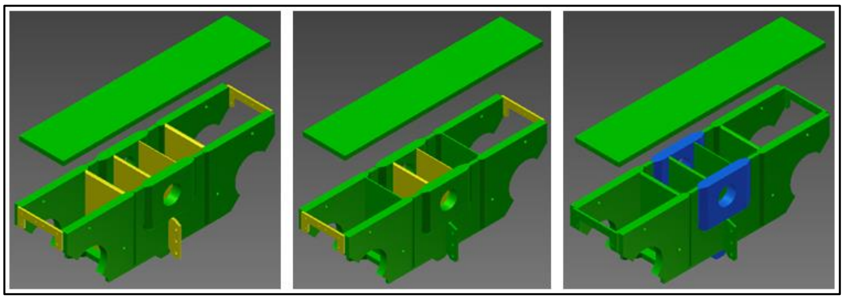


Figure 2.4 Example of the steel quality division for a temperate of T = -10°C (l), -15°C (m), and -20°C (r) for the bogie set WS

Table 2.25 Steel quality cost reduction according to varying temperatures

		T = -10 °C			T = -15 °C			T = -20 °C			T = -25 °C		
	Total mass [MT]	%B	%C	% D	%B	%C	% D	%B	%C	% D	% B	% C	% D
Portal frame	586.0	61.8	36.9	1.3	52.1	46.5	1.3	38.8	58.1	3.2	10.5	76.3	13.2
Upper structure	376.5	65.8	26.4	7.8	53.0	39.1	7.9	46.3	44.6	9.0	5.6	85.2	9.2
Machinery house	29.5	58.4	41.6	0.0	58.2	41.8	0.0	52.2	46.9	0.9	0.0	97.6	2.4
Trolley	14.9	75.5	19.7	4.9	68.3	26.8	4.9	53.4	41.7	4.9	0.0	94.1	5.9

Table 2.26 Steel quality division and cost reduction

Temp. [°C]	B [%]	C [%]	D [%]	Cost reduction [Euro]
-10	63.4	32.8	3.8	28,100
-15	52.9	43.3	3.8	25,400
-20	42.2	52.5	5.3	22,500
-25	8.2	80.5	11.3	13,200

What can be noted is that even after evaluating the main structural steel components, the percentage of D-quality steel components in the steel structure is very small compared to B and C-quality steel. Based on the minimum temperature experienced during all phases (production, assembly, transport, operation) an indication of the cost saving can be found in Table 2.26.

There are a number of remarks to be made. The plate thickness range for FEM 1.001 has been defined until 100 mm thickness. There are a number of components which contain a plate thickness larger than 100 mm. Because the value of the assessment coefficient for plate thicknesses above 100 mm has not been defined, the assessment coefficient has been taken equal to the same value as for a plate thickness of 100 mm. The critical point with this is that it may be possible that according to FEM 1.001 plate thicknesses larger than 100 mm should be made of E-quality steel instead of D-quality steel. Furthermore, secondary parts in the crane structure have not been taken into account. The actually possible saving by applying FEM 1.001 will be higher. Lastly the evaluation is performed on a global level. If a specific steel plate is observed the ratio between the tensile stresses may be lower and the steel quality could be lower. This is of interest for the thick plates within the steel structure that remain D-quality (see paragraph 2.5.2 for further explanation and Appendix F).

2.5.2 Practical application of the European standard FEM 1.001

As can be noted in paragraph 2.5.1, it is arduous to determine the steel quality by evaluating each individual plate in a steel construction. The question is now how to adjust the outcome of the application of FEM 1.001 to a practical solution for Cargotec Netherlands BV.

In order to apply the methodology in FEM 1.001 it would be preferable to present a number of guidelines with which the steel quality could be determined easily. These have been listed below:

1. Determine for the crane if the ratio between the residual tensile stresses from dead weight and elastic limit stress from load case 1 is smaller than or equal to 0.5 (σ_G / σ_a ≤ 0.5 [-]). If not, FEM 1.001 has to be reviewed to determine the appropriate tensile stress assessment coefficient in combination with step 2.
2. If the ratio is smaller than or equal to 0.5, assume that the most conservative welding situation occurs; tensile stress assessment coefficient equals to 2 (Z_A = 2 [-]).
3. Determine the minimum temperature based on the tender specifications and compare with the minimum temperature experienced in Nantong and Taicang (Jiangsu Province, P.R. China) and during sea transport. Select the lowest temperature.
4. Use the tables in Appendix C to determine the plate thickness range for each steel quality.
5. Based on the material list determine the steel quality.

If nesting is to be taking into account it would be convenient to have certain plate thicknesses in the range of B, C or D-quality based on a conservative temperature specification. This is done to prevent the situation where different steel qualities have to be used for the same plate thickness. In table 2.27 the result of table 2.14 has been modified. This table covers all plate thicknesses and indicates the appropriate steel quality. This table has only been listed up to a temperature of – 20 °C. This covers most of the existing cranes that Cargotec Netherlands BV has delivered.

Table 2.27 Resulting steel qualities based on temperature and plate thickness, FEM 1.001, taking nesting into account

FEM 1.001	Temperature T $[°C]$				
Plate thickness t $[mm]$	0	-5	-10	-15	-20
5	2.1	2.2	2.5	2.9	3.6
6	2.15	2.25	2.55	2.95	3.65
7	2.2	2.3	2.6	3	3.7
8	2.25	2.35	2.65	3.05	3.75
9	2.3	2.4	2.7	3.1	3.8
10	2.4	2.5	2.8	3.2	3.9
12	2.5	2.6	2.9	3.3	4
15	2.8	2.9	3.2	3.6	4.3
16	2.9	3	3.3	3.7	4.4
20	3.45	3.55	3.85	4.25	4.95
25	4	4.1	4.4	4.8	5.5
30	4.5	4.6	4.9	5.3	6
35	4.9	5	5.3	5.7	6.4
40	5.2	5.3	5.6	6	6.7
45	5.5	5.6	5.9	6.3	7
50	5.8	5.9	6.2	6.6	7.3
55	6	6.1	6.4	6.8	7.5
60	6.3	6.4	6.7	7.1	7.8
65	6.55	6.65	6.95	7.35	8.05
70	6.8	6.9	7.2	7.6	8.3
75	7	7.1	7.4	7.8	8.5
80	7.2	7.3	7.6	8	8.7
85	7.4	7.5	7.8	8.2	8.9
90	7.6	7.7	8	8.4	9.1
95	7.8	7.9	8.2	8.6	9.3
100	8	8.1	8.4	8.8	9.5

Based on Table 2.27 the following range can be specified.

- For a plate thickness range of 5 – 12 mm B-quality steel can be applied;
- For a plate thickness range of 15 – 60 mm C-quality steel can be applied;
- For a plate thickness range of 65 – 100 mm D-quality steel can be applied.

However, as noted earlier, the entire analysis is based on the assumption that σ_G / $\sigma_a \leq 0.5$ [-]. If this is not valid it would be of interest to know what the plate thickness range for each steel quality would be. This result has been listed in Table 2.28. What can be concluded from Table 2.28 is that with decreasing influence of the residual tensile stresses the plate thickness range for B and C-quality steel increases, while for D-quality steel it decreases.

Table 2.28 Steel quality plate thickness range at a minimum temperature of T = -20 °C, FEM 1.001

$\frac{\sigma_G}{\sigma_a}$	Steel quality plate thickness range at T = -20 °C [mm]		
	B	C	D
0.0	5 – 20	25 – 85	90 – 100
0.1	5 – 16	20 – 80	85 – 100
0.2	5 – 16	20 – 75	80 – 100
0.3	5 – 16	20 – 70	75 – 100
0.4	5 – 12	15 – 65	70 – 100
0.5	5 – 12	15 – 60	65 – 100
0.6	5 – 8	9 – 60	65 – 100
0.7	5	6 – 55	60 – 100
0.8	-	5 – 50	55 – 100
0.9	-	5 – 45	50 – 100
1.0	-	5 – 45	50 – 100

Furthermore, in the crane structure the influence of the residual tensile stresses varies, therefore the ratio will also vary throughout the steel structure. In order to determine the sensitivity of this assumption and to indicate the possible cost reduction difference that can be achieved if this ratio would be determined on a detailed level, the results of Table 2.28 have been used. For the crane steel structure the following division can be given on the plate thickness of an existing Ship-To-Shore container gantry crane (Table 2.29). A comment with this table is that only the plates in the steel structure have been evaluated (882.6 MT of 1006.9 MT). The neglected mass consists of tube and bar elements.

Table 2.29 Plate thickness division

Plate thickness [mm]	Mass [MT]	Mass percentage [%]	Plate thickness [mm]	Mass [MT]	Mass percentage [%]
4	0.0	0.0	50	30.1	3.4
5	0.0	0.0	55	3.9	0.4
6	3.1	0.4	60	24.0	2.7
7	24.9	2.8	65	0.0	0.0
8	120.3	14.0	70	0.6	0.1
9	0.0	0.0	75	5.3	0.6
10	97.7	11.1	80	9.3	1.1
12	80.8	9.2	85	0.0	0.0
15	0.1	0.0	90	0.4	0.0
16	108.0	12.2	95	0.0	0.0
20	100.6	11.0	100	15.7	1.8
25	102.6	11.6	110	1.1	0.1
30	28.8	3.3	120	3.0	0.3
35	6.1	6.9	130	0.3	0.0
40	36.0	4.1	150	2.5	0.3
45	22.3	2.5	Total mass	882.6	100.0

Using Table 2.28 the following result can be given regarding the cost reduction difference (Table 2.30). The cost reduction difference is only determined at a temperature of -20 °C. The price difference between D and C-quality steel is taken equal to 12.5 Euro/MT; the price difference between D and B-quality steel amounts to 37.5 Euro/MT.

Table 2.30 Cost reduction depending on the influence of residual stresses

Ratio	Plate thickness range B-quality steel [mm]	Plate thickness range C-quality steel [mm]	Plate thickness range D-quality steel [mm]	Cost reduction [Euro]	Difference compared to $\frac{\sigma_G}{\sigma_a} = 0.5$ [-] in Euro
0.0	5 – 20	25 – 85	90 – 100	24,100	5,400
	535.6 MT	324.2 MT	22.9 MT		
0.1	5 – 16	20 – 80	85 – 100	21,600	2,900
	435.0 MT	424.7 MT	22.9 MT		
0.2	5 – 16	20 – 75	80 – 100	21,500	2,800
	435.0 MT	415.4 MT	32.2 MT		
0.3	5 – 16	20 – 70	75 – 100	21,400	2,700
	435.0 MT	410.1 MT	37.5 MT		
0.4	5 – 12	15 – 65	70 – 100	18,700	0
	326.8 MT	517.7 MT	38.1 MT		
0.5	5 – 12	15 – 60	65 – 100	18,700	-
	326.8 MT	517.7 MT	38.1 MT		

For the ratio in the steel structure it can be said that this ratio will be minimally equal to 0.1 (each component will always experience some stresses due to its own weight). Comparing from that range the increase in cost reduction (assuming that all components are determined on the ratio of 0.1) will be at most 2,900 Euro.

If individual plates are separately evaluated with the rest of the structure according to $\sigma_G / \sigma_a \leq 0.5$ [-], it can be noted that the cost reduction difference will be even smaller. If a different temperature would be defined the same analysis could be performed. The outcome is entirely dependent on the plate thickness range for the different steel qualities and in which plate thickness range the largest mass falls.

A further remark can be made with the assumption of the ratio of the residual stresses. When reviewing Figure 2.5 it can be noted that the residual stress varies in the entire steel structure. For the analysis in this report the decision is made to base the ratio of the residual stress on the highest occurring ratio. However, this is for some parts of the crane a conservative assumption. It would be possible to divide the steel structure into several ratio classes and thereby come to a more favorable result than currently determined. But the question can be asked whether this is a practical result when taking both Table 2.27 and 2.28 into account. By varying the ratio classes the situation will occur in the production plant of having several steel qualities of the same plate thickness. As explained before this is an unfavorable situation. In case the production would concern a single project at a time the ratio classes can be applied, however if it concerns multiple projects at the same time (which is the case with Cargotec Netherlands BV) this cannot be done.

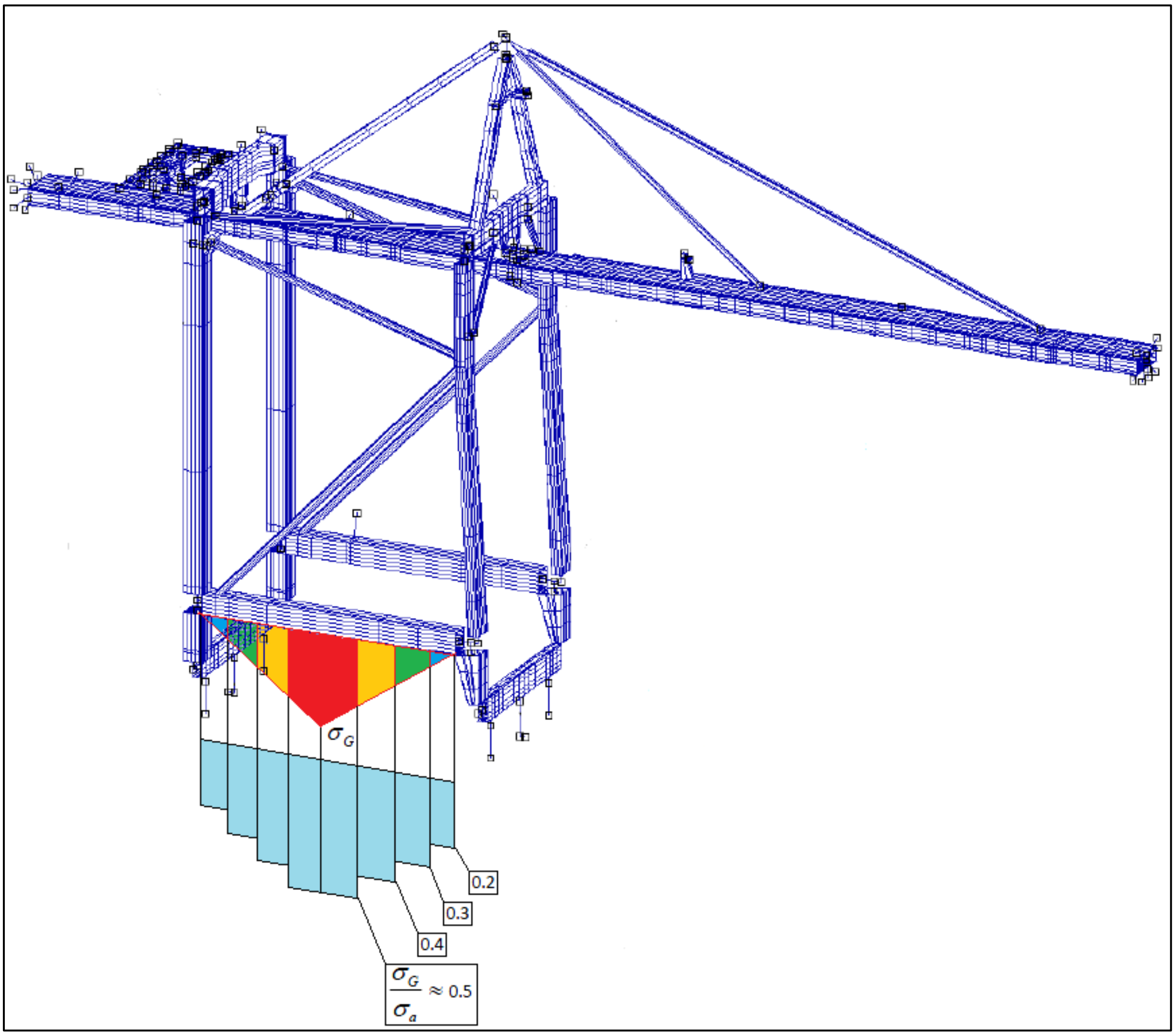


Figure 2.5 Residual stress classification

Although there could be a reason for applying different residual stress classifications if there is a need for removing D-quality steel for the steel structure as much as possible. When purchasing D-quality steel it will have to be ordered from the steel mill as opposed to C and B-quality steel, which are readily available.

A remark with the use of FEM 1.001 is that the standard does not specific E-quality steel as opposed to NEN-EN 13001. This does question the validity of FEM 1.001 regarding very low temperatures, since in practice E-quality is indeed applied for very low temperatures. Table 2.31 indicates at which temperature E-quality steel is of importance according to NEN-EN 13001.

Table 2.31 Steel quality plate thickness range at a minimum temperature, NEN-EN 13001

	Steel quality plate thickness range at T = -40 °C [mm]		
	C	D	E
Q390	5 – 20	25 – 80	85 – 100

Until a temperature of -40 °C the outcome of FEM 1.001 and NEN-EN 13001 are comparable, however, with a temperature of -40 °C and lower NEN-EN 13001 indicates that there is a need for applying E-quality steel.

Furthermore, in the crane structure there are larger plate thicknesses than 100 mm, therefore with higher temperatures E-quality steel may appear sooner in the steel structure. In this case, when it concerns a client with a terminal in an area with a very low ambient temperature, the client will specify that E-quality steel is necessary, without referring to the standard.

2.6 Steel quality Asia-Pacific market

In Chapter 1 the Asia-Pacific market has been discussed, whereby the temperature range from several tender documents has been specified. In this chapter the steel quality based on the temperature range of -10 °C to -25 °C has been specified. Comparing both the temperature range from tender documents and the steel quality according to the temperature range it has been concluded that most of South-East Asia can be covered with the steel quality division at a temperature of -10 °C. Other parts of Asia, such as the northern part, require the steel quality division at a temperature of -20 °C or lower (Table 2.32 and Table 2.33).

Table 2.32 Steel quality division for the Asia-Pacific market, FEM 1.001

Country Asia-Pacific market	Port	Temperature range [°C]	FEM 1.001, steel quality division according to minimum temperature, plate thickness range [mm]		
P.R. China	Jinzhou	-25 to +40	-	5 – 45	50 – 100
	Xiamen	-25 to +50	-	5 – 45	50 – 100
India	Mundra	+10 to +45	5 – 20	25 – 90	90 – 100
Indonesia	Jakarta	+24 to +32	5 – 20	25 – 90	90 – 100
South-Korea	Busan	-20 to +50	5 – 12	15 – 60	65 – 100
Malaysia	Bintulu	+10 to +40	5 – 20	25 – 90	90 – 100
Myanmar	Yangon	+15 to +50	5 – 20	25 – 90	90 – 100
Philippines	Manila	+18 to +40	5 – 20	25 – 90	90 – 100
Sri Lanka	Sri Lanka	0 to +45	5 – 20	25 – 90	90 – 100
Thailand	Laem Chabang	+5 to +50	5 – 20	25 – 90	90 – 100
Vietnam	Ho Chi Minh	0 to +40	5 – 20	25 – 90	90 – 100

Table 2.33 Steel quality division for the Asia-Pacific market, GB/T 3811

Country Asia-Pacific market	Port	Temperature range [°C]	GB/T 3811, steel quality division according to minimum temperature, plate thickness range [mm]		
P.R. China	Jinzhou	-25 to +40	-	5 – 35	40 – 100
	Xiamen	-25 to +50	-	5 – 35	40 – 100
India	Mundra	+10 to +45	5 – 16	20 – 75	80 – 100
Indonesia	Jakarta	+24 to +32	5 – 16	20 – 75	80 – 100
South-Korea	Busan	-20 to +50	-	5 – 50	55 – 100
Malaysia	Bintulu	+10 to +40	5 – 16	20 – 75	80 – 100
Myanmar	Yangon	+15 to +50	5 – 16	20 – 75	80 – 100
Philippines	Manila	+18 to +40	5 – 16	20 – 75	80 – 100
Sri Lanka	Sri Lanka	0 to +45	5 – 16	20 – 75	80 – 100
Thailand	Laem Chabang	+5 to +50	5 – 16	20 – 75	80 – 100
Vietnam	Ho Chi Minh	0 to +40	5 – 16	20 – 75	80 – 100

Table 2.32 and 2.33 have been constructed because both FEM 1.001 and GB/T 3811 are allowable standards within the Asia-Pacific market (omitting the preference of clients). The standardized table (Table 2.27) has not been applied, but the more detailed tables have been used (Table 2.14 and 2.22)

to give a detailed insight. Countries that have not been specified (Bangladesh, Cambodia, Japan, Pakistan, Singapore and Taiwan) have been left out of both tables.

2.7 Fracture toughness

As brought forward at the discussion of the case study, the determination of the temperature assessment coefficient requires an insight into the location of production, assembly, route of transport, and of the client. Further, it can be questioned when the severest load, leading to brittle fracture, will occur.

Since brittle fracture occurs at low temperatures, severe loadings, or a combination it would be of interest to know at which temperature in combination with a certain tensile stress value brittle fracture is most likely to occur.

The intention is to determine the minimum fracture toughness values that lead to brittle fracture and compare these with the fracture toughness values of the steel types themselves. In this way the appropriate steel quality can be determined. However, for the determination of the minimum fracture toughness the stresses and the crack sizes need to be known. A suitable methodology has been explained and applied in EUR 23510 EN and forms the background of NEN-EN 1993-1-10.

With regards to the fracture toughness value, the only manner in which this value for Q345 and Q390, for B, C and D-quality steel can be retrieved is by having the materials tested, because the fracture toughness value is dependent on the chemical composition and will therefore differ for different steel types even if the yield strength of the steels are similar (Appendix G). In this case the materials have not been tested, therefore the discussion in this paragraph is limited to the general structure of the calculation of the steel quality and does not provide any results.

For the calculation it is important to select a number of variables of which the critical crack size as brought forward in paragraph 2.1 is the most difficult one. What must be noted is that any crack size present in the material can lead to brittle fracture. With regards to the crack size, there are two ways of defining this value.

1. Depending on the allowable size of the crack as determined by the engineer, a starting point for the crack size is to take the minimum detectable crack size by the inspection methods used.
2. Assuming that the critical crack size can be calculated. A certain crack size does not automatically lead to brittle fracture; therefore the critical crack size can be determined by the engineer himself. Considering the large number of different crack shapes that can develop a certain boundary has be chosen, which logically should not be larger than the plate thickness or the root length of the weld for a random plate. This however does not mean that if a larger crack size is present this will lead to brittle fracture. This will only happen if the circumstances are right for brittle fracture to occur.

The calculation of the fracture toughness value is expressed by reformulating Equation 2.1. In order to calculate the fracture toughness the following data has to be retrieved:

- With regards to the production, assembly, transport and operational phase the largest tensile stress in each phase should be determined.
- The critical crack size can be determined as stated previously.
- With regards to the production, assembly, transport and operational phase the fracture toughness value of the material itself should be tested, also taking into account the temperature dependency of this value.

According to EUR 23510 EN there are a number of factors to be taken into account. These are the shape of the crack, the location of the crack (besides the Y value as stated in the equation for the fracture toughness value), the presence of residual stresses, and etcetera.

In order to determine the appropriate steel quality the following conditions need to be checked for both Q345 and Q390. For steel type Q345 these are:

- $K_{CALCULATED} \leq K_{Q345B}$ [N/mm$^{3/2}$] results in B-quality steel
- $K_{Q345B} < K_{CALCULATED} \leq K_{Q345C}$ [N/mm$^{3/2}$] results in C-quality steel
- $K_{Q345C} < K_{CALCULATED} \leq K_{Q345D}$ [N/mm$^{3/2}$] results in D-quality steel

For steel type Q390 these are:

- $K_{CALCULATED} \leq K_{Q390B}$ [N/mm$^{3/2}$] results in B-quality steel
- $K_{Q390B} < K_{CALCULATED} \leq K_{Q390C}$ [N/mm$^{3/2}$] results in C-quality steel
- $K_{Q390C} < K_{CALCULATED} \leq K_{Q390D}$ [N/mm$^{3/2}$] results in D-quality steel

Based on these conditions for each phase (thus with the maximum tensile stress that occurs within that phase) a fracture toughness value can be calculated for various crack shapes, locations, and etcetera, in the steel structure. The calculated fracture toughness value can then be compared with the fracture toughness value of the steel at different temperatures (due to the temperature dependency of the fracture toughness value). By using these conditions the correct steel quality can be selected.

Similar to the steel quality tables from FEM 1.001, also in this case steel quality tables can be constructed on a plate thickness-temperature range, if for the stress the yield stress is taken as limiting stress. The use of the yield stress is not an unlikely decision since tender documents state that yielding should occur before brittle fracture.
The yield stress has a dependency on both the plate thickness and the temperature; therefore in this case also Q345 and Q390 need to be tested to retrieve this data (the influence of the quality group is negligible with regards to the yield stress).

2.8 Conclusion and recommendation

Based on the evaluation of the steel quality selection procedure as defined in FEM 1.001 it has been concluded that the current practice of Cargotec Netherlands BV is unnecessary. The application of B and C-quality steel is allowable depending on the type of weld, the temperature experienced and the plate thickness. From a minimum temperature of -20 °C and higher the minimum cost reduction will amount to around 22,500 Euro based on the evaluation of the main structural steel components of a representative Ship-To-Shore container gantry crane from Cargotec Netherlands BV. With a cost price of the evaluated crane of 3,600,000 Euro, this leads to a 0.6 % reduction of the total cost price (excluding transport cost and cost made at the client’s location).

The steel quality selection procedure, as defined in FEM 1.001, only focusses on the temperature and stresses occurring in the operational phase. For this reason the minimum temperature has been taken as the minimum temperature occurring after evaluating the temperature at the production and assembly site, and the temperature at the client’s site. Brittle fracture is most likely to occur when the steel structure experiences high tensile stresses, low temperatures and large plate thicknesses, therefore the focus on the operational phase only can be seen as a conflicting situation, since the environmental circumstances can vary. What further must be noted is that the temperature experienced during transport has not been evaluated. Climatic data from sea transport will have to be reviewed in order to determine the temperature experienced during transport, however, in this case this type of information has not been found. Besides this, there is doubt on which minimum temperature should be taken. The absolute minimum temperature experienced during a period of time or the average minimum temperature experienced during a period of time, and how long this time frame should be taken (although the absolute minimum temperature is perhaps the most likely choice). The same can be said with regards to the specified temperature range in tender documents. Having said this, by having a uniform rule on the steel quality division based on a temperature of -20 °C, this uncertainty in the area of the production, assembly site and initial loading of the crane (thus the first phase of sea transport) is covered.

In order to overcome the use of the standards a suggestion has been made for the calculation of the appropriate steel quality, thereby taking into account the tensile stress, temperature and plate thickness. This allows for determining the correct steel quality necessary during each phase of the crane (because during the assembly and transport phase the steel structure also experiences high tensile stresses in combination with low temperatures).

Other conclusions are:

- Regarding the outcome of FEM 1.001 for very low temperatures, the standard does not specify the use of E-quality steel, even though from practice E-quality steel is applied in regions with very low environmental temperatures. This raises the question of the validity of the results of FEM 1.001 for very low temperatures. NEN-EN 13001 does specify the use of E-quality steel and seems therefore more in line with what is to be expected in case of very low temperatures, even though for lesser low temperatures the results between both standards are more in line with each other.
- Regarding the Asia-Pacific region; most of the Asia-Pacific market can be covered by the selection procedure stated in FEM 1.001, otherwise the Chinese standard GB/T 3811 can be used. Results in that case will be more conservative compared to FEM 1.001.
- The results from FEM 1.001 are not limited to only Ship-To-Shore container gantry cranes. The results can also be applied to other crane types on which FEM 1.001 is also applicable.

As a recommendation it is suggested that in order to evaluate the outcome of FEM 1.001 and the applicability of FEM 1.001 on the required steel quality for the production, assembly and transportation phase it would be desirable to calculate the steel quality based on the fracture toughness value. This requires testing the steel types of the main and secondary structural steel components for B, C and D-quality based on varying temperatures.

Report Part III Application of an open gearing transmission for the crane travelling gear of Ship-To-Shore container gantry cranes

3.1 Introduction

The application of an open gearing for the crane travelling gear was a common practice, however, this type of transmission became unfavorable to clients. There are still clients who are willing to accept this type of transmission and its disadvantages with regards to the maintenance issues due to its lower initial purchase cost compared to applying a closed gearbox.

The goal, with regards to the application of an open gearing for the crane travelling gear of a Ship-To-Shore container gantry crane, is to indicate what the design could be of the open gearing for an existing Ship-To-Shore container gantry crane within certain constraints and the possible cost reduction.

This chapter has been divided as follows.

- **Paragraph 3.2** provides an introduction to the crane travelling gear, including the working principles of the crane travelling gear, its general design, and others.
- **Paragraph 3.3** will contain a description of the different open gearing designs that will be evaluated for the cost comparison.
- **Paragraph 3.4, 3.5 and 3.6** will provide the power, torque and brake calculation for selecting the motor, brake and gearbox.
- **Paragraph 3.7** will discuss the combination of a closed gearbox with open gearing for the different open gearing designs.
- **Paragraph 3.8** presents the cost calculation based on the different types, number of, and size of motor, brake, gearing, and other components.
- **Paragraph 3.9** provides a conclusion and recommendation regarding the application of an open gearing for the crane travelling gear.

As a remark related to the removal of bolted flange plates in the crane steel structure (see Report part IV), the influence of this removal on the power consumption and the wheel pressure for the crane travelling gear (thereby also on the wheel size (Appendix M)) has been presented in Appendix K.

3.2 Crane travelling gear

The function of the crane travelling gear is to facilitate the crane travelling motion along the quayside, to allow the crane to position itself along the vessel for loading and unloading of containers. Limitation to the size of the machinery work and the number of wheels is the maximum width of the crane (27 m from the buffer positions on both ends with the buffers not compressed) and the allowable rail line load or the maximum wheel load.

The crane travelling gear consists of a number of components, of which the bogie assembly is of main interest (Figure 3.1 and Table 3.1). The entire travelling gear consists of both the steel housing of the main balance, balances and bogies, and of the components for realizing the gantry travelling motion.

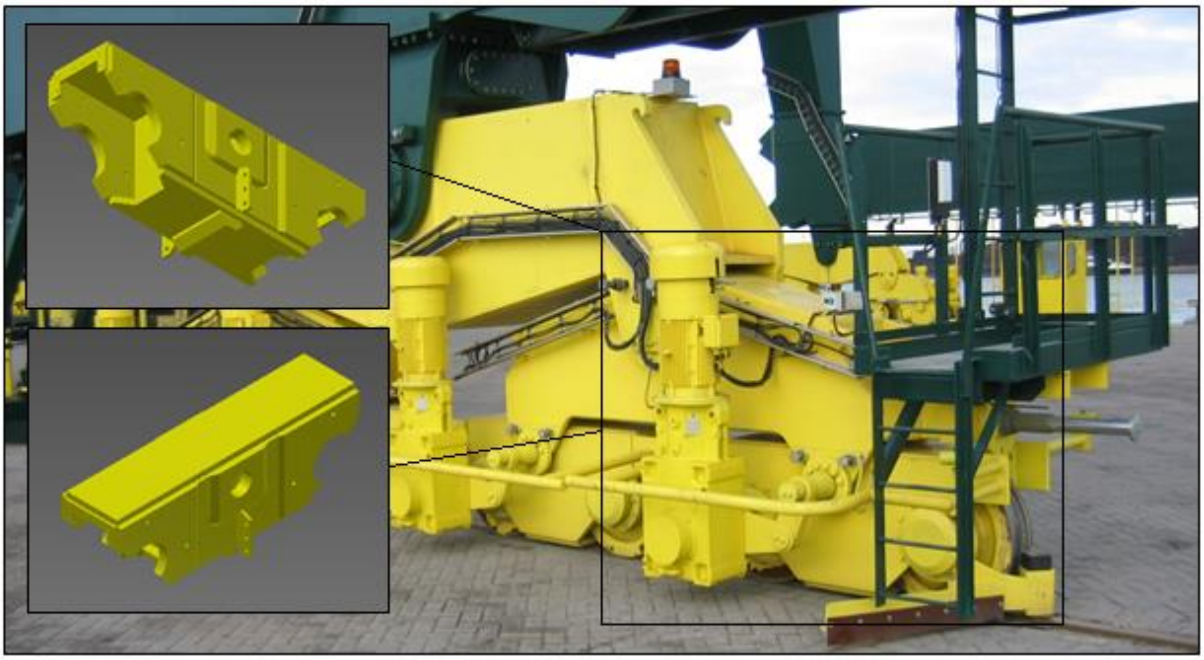


Figure 3.1 Gantry travelling gear or crane travelling gear of a Ship-To-Shore container gantry crane with separately the bogie steel structure

The calculations presented in this chapter are based on an existing crane from Cargotec Netherlands BV. General information of the existing crane has been listed here. For the crane provided by Cargotec Netherlands BV the following general information can be listed [44] (see Appendix Y for the production drawing of the bogie steel structure (part of the gantry travelling gear)):

- Weight of the crane with spreader 1,355 MT
- Crane speed 0.83 m/s
- Gantry acceleration time, empty spreader 6.0 s
- Gantry acceleration time, rated load 10.0 s
- Hoisting capacity, twin lift 65 MT
- Wind load conditions, in service 20 m/s or 25 m/s in case of a gust
- Wind load conditions, stowed 40 m/s (maintenance)
  56 m/s (stowed)

The crane has in total 32 crane wheels on which 24 crane wheels are mounted with a travelling gear. The non-powered crane wheels will be equipped with a wheel brake. All wheels on the waterside will be powered; on the landside only 8 wheels are powered. The reason for this unequal division of engines is due to the high wheel load experienced on the waterside, thereby reducing the risk of wheel slip. However, with this unequal distribution of engines the crane will experiences skewing forces[12]. This will increase the wear of the wheels and rail head.

The crane travel gear consists of a number of components, which have been listed in Table 3.1. This overview is of importance because it will provide the basis on which the cost comparison will be based.

Table 3.1 Component overview original crane model

Component	Amount	Description
Crane wheel	32	-
Driven crane wheel	24	-
Wheel shaft	32	-
Bearing crane wheel	64	SKF 24130 CC/W33
Bearing housing crane wheel	64	-
Engine	24	Wölfer DRKO-160L-4
Gearbox	24	ZPMC TNR 440
Engine coupling	24	CNTR ML7
Operational brake (build on engine)	24	Pintsch Bubenzer KFB25
Wheel brake	8	Bubenzer RWB7

In Table 3.1 the steel structure of the bogie has been left out. It will be assumed that any changes to the bogie steel structure with regards to the open gearing models will be negligible from a cost perspective.

Cargotec Netherlands BV has produced cranes with an open gearing, however there are some disadvantages with this type of transmission:

1. The open gearing, even if housed within the bogie steel structure, will be prone to the accumulation of dirt from the environment (even if covers are present);
2. The lubrication of the open gearing is problematic. The open gearing could lead to spillage of lubrication oil onto the quayside;
3. The lubrication of the gears has to be done manually;

[12] In case the engine power is equal for each wheel and the engines are unequally distributed over waterside and landside, this will lead to skewing forces on the rails. The traction forces of the engine torque onto the crane wheels and thereby on the rail head is unequally distributed. Assuming that the center distance of the traction forces is equal, this will lead to a resulting torque around the center between the waterside and landside rail, which in turn results in a horizontal force against the side of the rail head and the flange of the crane wheels.

4. The application of an open gearing will increase the number of components necessary for the transmission;
5. Another reason may be the need for redundancy in case of engine failure. Normally the crane will have a large number of wheels powered, each with its own engine with closed gearbox. When one engine fails, there will be enough power left to drive the crane forward in heavy wind conditions. In case an open gearing transmission is applied the engine drives two wheels at least. If engine failure occurs there may not be enough power left to drive the crane forward in heavy wind conditions. This problem will be more acute when the engine powers more wheels (up to four crane wheels maximum, if each bogie houses two crane wheels). Next to powering the crane to move it also concerns the braking distance, because with an open gearing the number of engine-mounted brakes is reduced (a suggestion for overcoming the redundancy issue is presented in Appendix N).

Considering that the open gearing is still used today there are some advantages that make it interesting for clients to accept this type of open transmission:

1. With the application of an open gearing the number of engines and closed gearboxes can be reduced;
2. Due to the use of an open gearing the transmission ratio of the closed gearbox will also be smaller, thereby reaching a reduction in both size and number (in case the entire transmission ratio cannot be achieved via the open gearing alone);
3. Each driven wheel of the crane travelling gear has its own engine with brake mounted on the engine. The wheels that are not powered will be equipped with a wheel brake. In case of an open gearing all wheels will be powered, thereby eliminating the use of a wheel brake;
4. By having an engine powering more than one wheel the risk of wheelslip is reduced (Appendix L). In case of unequal wear of the wheels, this may be reversed.

Concluding the application of an open gearing will result in a reduction of the number of engines, closed gearboxes and brakes, thereby reducing the initial purchase price. The reduction of the initial purchase price is the point of interest for clients.

3.3 Open gearing models

For the design of the open gearing, an existing crane structure will be taken for determining the constraints of the open gearing. Based on tender documentation the following point can be stated which is of importance for the constraints of the open gearing: open gears shall be housed inside the bogie frame. This means that the open gearing transmission has to fit within the bogie steel structure.

Taking into account that a reduction is necessary between the engine speed and the wheel speed it could be possible that the open gearing will have to be combined with a closed gearbox to realize the necessary transmission ratio. When reviewing the size of the gears, the number of gears that will fit within the bogie steel structure and the necessary transmission ratio it can be stated that this combination is unavoidable.

To summarize the following conditions or constraints can be stated for the open gearing models:

- The open gearing is placed within the bogie steel structure;
- The outer dimensions of the bogie steel structure are taken as limitations for the open gearing;
- The open gearing is connected to a closed gearbox, which in turn is connected to the engine (with a coupling in between).

With regards to the application of an open gearing within an existing crane structure, there are a number of situations that can be evaluated. Of interest for this thesis are the open gearing models as described on the next page. In Figure 3.2 existing applications have been displayed.

Figure 3.2 Application of an open gearing for the crane travelling gear 1) RTG open gearing 2) Open gearing whereby the engine powers two bogies 3) Open gearing whereby the engine powers two wheels (gearing on the outside of the housing)

The interest with these models is to determine the size and the number of components and its effect on the total cost with regards to the components for the crane travelling motion.

1. Application of an open gearing consisting of 5 gears, whereby the engine drives both wheels. In this case the engine is connected to a closed gearbox, which in turn is connected to the open gearing placed within the bogie steel structure. The open gears transfer the power onto the wheels. The open gearing consists of 5 gears: 1 pinion wheel gear, 2 crane wheel gears, and 2 intermediate gears (Figure 3.3, Appendix Y).
2. Application of an open gearing consisting of 5 gears, where the engine drives the wheels of two bogies (Figure 3.4, Appendix Y). In this concept the engine is connected to two closed gearbox, each closed gearbox mounted on a bogie. The closed gearboxes are in turn connected to the open gearing within the bogie steel structure. The engine is placed between both bogies.
3. Application of an open gearing consisting of 3 gears, whereby the engine drives both wheel. In this case it is assumed that the length of the bogie steel structure is shortened and that other dimensions are fixed (Figure 3.5, Appendix Y). In this situation the engine is connected to a closed gearbox, which in turn is connected to the open gearing placed within the bogie steel structure. The open gears transfer the power onto the wheels. The open gearing does, in this case, not have any intermediate gears (1 pinion wheel gear, 2 crane wheel gears).

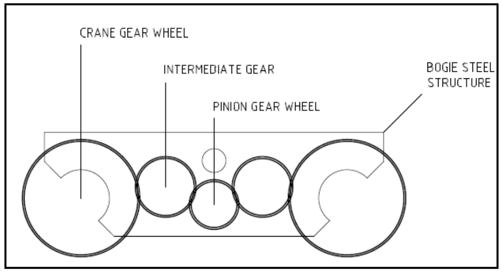


Figure 2.3 Open gearing model 1

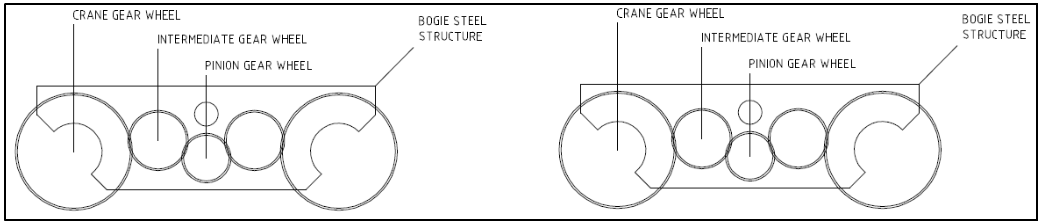


Figure 3.4 Open gearing model 2

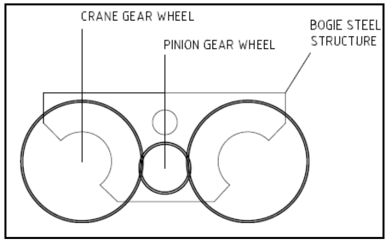


Figure 3.5 Open gearing model 3

3.4 Power calculation

With regards to the power necessary for the crane travelling motion, it can be stated that the forces on the crane structure do not change, however, the individual engine power is raised due to the smaller number of engines that will be applied. Also, the efficiency of the complete gearing (open gearing in combination with a closed gearbox) will be lower, thereby raising the required engine power even more [44, 45].

For the power calculation the following factors are taken into account:

- The power requirement due to nominal crane travelling (rolling resistance), P_f [kW];
- The power requirement due to the wind (wind resistance), P_W [kW];
- The power requirement due to the acceleration of rotating masses (rotational acceleration resistance), P_R [kW];
- The power requirement due to the acceleration of linear moving masses (linear acceleration resistance), P_L [kW].

The total nominal power is calculated by Eq. 3.1.

$$P_{\text{nominal}} = \frac{1}{\eta_G}\left(P_f + P_W\right) \text{ [kW]} \tag{3.1}$$

And the total acceleration power is calculated by Eq. 3.2.

$$P_{\text{acceleration}} = \frac{1}{\eta_G}\left(P_f + P_W + P_L\right) + P_R \text{ [kW]} \tag{3.2}$$

The efficiency of the gearing is defined as η_G [-]. For the formulas the efficiency has been taken out to show the influence of this variable on the nominal and acceleration power.

For the engine power the following condition must hold, Eq. 3.3:

$$P_{\text{acceleration}} \leq f_A \bullet P_{\text{nominal}} \tag{3.3}$$

f_A [-] is defined as the overload factor of the engine.

Of interest is how the power will scale according to which open gearing model is looked at, compared to the existing gantry travelling gear. What can be noted is that with the use of an open gearing the efficiency of the gearing will be lower, due to the increased amount of components in the gearing where a friction loss is experienced. The increase in total nominal power equals to, Eq. 3.4:

$$\frac{\eta_{G\_1}}{\eta_{G\_2}} \bullet 100\% \text{ [-]} \tag{3.4}$$

The efficiency in case each engine drives a single wheel is defined as η_{G_1} [-].

The efficiency in case of the application of an open gearing is defined as η_{G_2} [-].

With regards to the amount of power needed per engine, this is dependent on the number of wheels that needs to be driven. In case each engine powers one wheel, the power per wheel is dependent on the number of driven wheels (n_{wheel} [-]) and the total nominal power, Eq. 3.5:

$$P_{wheel} = \frac{P_{\text{nominal}}}{n_{wheel}} \text{ [kW]} \tag{3.5}$$

If the engine drives both wheels of a bogie then the engine power is dependent on the number of driven bogies (n_{bogie} [-]) and the nominal power, Eq. 3.6:

$$P_{bogie} = \frac{P_{\text{nominal}}}{n_{bogie}} \text{ [kW]} \tag{3.6}$$

If the engine powers the wheels of two bogies the engine power is defined as Eq. 3.7:

$$P_{multiple\_bogies} = \frac{P_{\text{nominal}}}{\left(\frac{n_{bogie}}{2}\right)} \text{ [kW]} \tag{3.7}$$

Comparing these situations the power increase per engine in case of powering the wheels of a single bogie amounts to, Eq. 3.8:

$$\frac{\eta_{G\_1}}{\eta_{G\_2}} \bullet \frac{n_{wheel}}{n_{bogie}} \bullet 100\% \text{ [-]} \tag{3.8}$$

In case the engine powers the wheels of two bogies the power increase per engine compared to the situation that an engine drives a single wheel is, Eq. 3.9:

$$\frac{\eta_{G\_1}}{\left(\eta_{G\_2}\right)^2} \bullet \frac{2 \bullet n_{wheel}}{n_{bogie}} \bullet 100\% \text{ [-]} \tag{3.9}$$

The complete calculation can be reviewed in Appendix H.

3.5 Torque calculation

Similar to the approach for the power calculation, due to the larger number of wheels that have to be driven, the engine needs to be able to deliver a larger torque. This has its reflection on the torque that has to be transferred via the closed gearbox. The torque calculation shows the same relations concerning the increase in torque as with the power calculation when the different open gearing models are compared with the existing gantry travelling gear [44, 45]. For the torque calculation the following factors are taken into account:

- The torque requirement due to nominal crane travelling (rolling resistance), M_f [kNm];
- The torque requirement due to the wind (wind resistance), M_W [kNm];
- The torque requirement due to the acceleration of rotating masses (rotational acceleration resistance),M_R [kNm];
- The torque requirement due to the acceleration of linear moving masses (linear acceleration resistance), M_L [kNm].

The total nominal torque is calculated by Eq. 3.10.

$$M_{\text{nominal}} = \frac{1}{\eta_G}\left(M_f + M_W\right) \text{ [kNm]} \tag{3.10}$$

And the total acceleration torque is calculated by Eq. 3.11.

$$M_{\text{acceleration}} = \frac{1}{\eta_G}\left(M_f + M_W + M_L + M_R\right) \text{ [kNm]} \tag{3.11}$$

Of interest is how the torque will scale according to which open gearing model is looked at, compared to the existing gantry travelling gear. What can be noted is that with the use of an open gearing the efficiency of the gearing will be lower, due to the increased amount of components in the gearing where a friction loss is experienced. The increase in total nominal torque equals to, Eq. 3.12:

$$\frac{\eta_{G\_1}}{\eta_{G\_2}} \bullet 100\% \text{ [-]} \tag{3.12}$$

The efficiency in case each engine drives a single wheel is defined as η_{G_1} [-].
The efficiency in case of the application of an open gearing is defined as η_{G_2} [-].

In relation to the amount of torque needed per engine, this is dependent on the number of wheels that needs to be driven. In case each engine powers one wheel, the torque per wheel is dependent on the number of driven wheels (n_{wheel} [-]) and the total nominal torque, Eq. 3.13:

$$M_{wheel} = \frac{M_{\text{nominal}}}{n_{wheel}} \text{ [kW]} \tag{3.13}$$

If the engine drives both wheels of a bogie then the engine torque is dependent on the number of driven bogies (n_{bogie} [-]) and the nominal torque, Eq. 3.14:

$$M_{bogie} = \frac{M_{\text{nominal}}}{n_{bogie}} \text{ [kW]} \tag{3.14}$$

If the engine powers the wheels of two bogies the engine torque is defined as Eq. 3.15:

$$M_{multiple\_bogies} = \frac{M_{\text{nominal}}}{\left(\frac{n_{bogie}}{2}\right)} \text{ [kW]} \tag{3.15}$$

Comparing these situations the torque increase per engine in case of powering the wheels of a single bogie amounts to, Eq. 3.16:

$$\frac{\eta_{G\_1}}{\eta_{G\_2}} \bullet \frac{n_{wheel}}{n_{bogie}} \bullet 100\% \text{ [-]} \tag{3.16}$$

In case the engine powers the wheels of two bogies the torque increase per engine compared to the situation that an engine drives a single wheel is, Eq. 3.17:

$$\frac{\eta_{G\_1}}{\left(\eta_{G\_2}\right)^2} \bullet \frac{2 \bullet n_{wheel}}{n_{bogie}} \bullet 100\% \text{ [-]} \tag{3.17}$$

The complete calculation can be reviewed in Appendix I.

3.6 Brake calculation

With regards to the brake calculation, what first must be noted is that in case the engine powers all bogies and thereby all wheels of the crane the use of wheel brakes is no longer necessary. The only operational brakes that remain are those mounted on the engine.
For the calculation of the appropriate brake size the following situations must be checked:

1. Maximum braking speed, $n_{brake\ allowable}$ [rpm];
2. The required braking torque and braking distance, $M_{brake\ total}$ [kNm] and $s_{c\ braking}$ [m];
3. Wheelslip safety, V[m];
4. The heat absorption limit of the brake, $E_{allowable\ per\ brake}$ [kJ]

Due to the increase in torque (paragraph 3.5) the size of the brake has to be increased. The reason for the increase is not necessarily because of the increase in torque requirement (because the brake applied in case of having each engine power a single wheel may still have sufficient braking torque) or the energy absorption limit, but is due to the increase in braking distance or braking time [44, 45]. The entire calculation background has been presented in Appendix J. As opposed to power and torque calculation, for the brake calculation the factors that can be derived between different situations are difficult and not straight forward. In this case the general conditions will be stated.

The calculation of braking speed, braking torque and braking distance can be derived from the moment equilibrium condition (Eq. 3.18).

$$M_f + M_{\text{brake total}} \geq M_W + M_L + M_R \quad (3.18)$$

Whereby M_f [kNm] is defined as the torque due to the rolling resistance, $M_{brake\ total}$ [kNm] is the summed braking torque, M_W [kNm] is the torque due to the wind, M_L [kNm] is the torque due to the deceleration of linear moving masses, M_R is the torque due to the deceleration of rotating masses.
Both the torque due to the deceleration of linear moving masses and rotating masses contains an element of time, which allows for the calculation of the braking speed and braking distance.

The wheelslip safety is based on the corner load, the total braking torque and the allowable braking torque according to the allowable friction force before wheelslip between the crane wheel and the rail head.

The heat absorption limit is based on an energy equilibrium (Eq. 3.19).

$$\frac{E_f + E_W + E_L + E_R}{n_{brake}} \leq E_{\text{allowable per brake}} \quad (3.19)$$

Whereby E_f [kJ] is defined as the energy due to the rolling resistance, E_W [kJ] is the energy due to the wind, E_L [kJ] is the energy due to the deceleration of linear moving masses, E_R [kJ] is the deceleration of rotational moving masses and n_{brake} [-] is defined as the number of active brakes.

In this case it is not the decrease in efficiency that poses a problem, but the decrease in the number of brakes. Due to the decrease in the number of brakes, the energy that has to be absorbed per brake increases. Not only the decrease in the number of brakes, but also the changes in inertia of the brake disk and the rotational speed of the brake disk have to be taken into account.

3.7 Gear design

For the design of the open gearing, the goal is to implement a gearing system within the bogie steel structure.

An initial step into the design of the open gearing is to first determine the overall transmission ratio, Eq. 3.20 [44-46].

$$i = \frac{n_m \bullet \pi \bullet D_{wheel}}{v_c} \text{ [-]} \tag{3.20}$$

The overall transmission ratio is determined by the maximum motor speed (n_m [rpm]), the diameter of the crane wheel (D_{wheel} [m]) and the speed of the crane (v_c [m/s]).

The ratio of the open gearing is defined by the ratio between the overall transmission ratio and the transmission ratio of the closed gearbox ($i_{closed\ gearbox}$ [-]), Eq. 3.21.

$$i_{\text{open gearing}} = \frac{i}{i_{\text{closed gearbox}}} \text{ [-]} \tag{3.21}$$

The ratio of the open gearing is dependent on the size of the gear wheels that fit within the housing of the bogie steel structure. The goal however should be to keep the number of gear wheels as small as possible, otherwise the efficiency lowers drastically, and to make the open gearing ratio as large as possible in order to reduce the size of the closed gearbox.

The efficiency of the open gearing can be defined according to the number of gears placed within the open gearing, Eq. 3.22.

$$\eta_{G\_2} = \sum_{1}^{x} \eta_G^x \tag{3.22}$$

For a 5 gear transmission x = 3, for a 3 gear transmission x = 2 with η_G = 0.96 [-].

The open gearing transmission ratio is dependent on the size (or number of teeth) of the gear wheels and can be defined as follows, Eq. 3.23, whereby Z_i is defined as the number of teeth of the gear wheel (the number of teeth is related to the diameter of the gear wheel, D_i [mm]; the dimensions of the gear wheels have been derived based on the specified dimensions of the crane gear wheel according to DIN 15082 and reference literature [47-50]).

$$i_{open\ gearing} = \sum_{i=1}^{i} \frac{Z_2}{Z_1} \bullet \frac{Z_3}{Z_2} \bullet \ldots \bullet \frac{Z_i}{Z_{i-1}} = \frac{Z_i}{Z_1} \text{ [-]} \tag{3.23}$$

For the determination of the size and dimensions of the gear wheels it can be stated that the crane gear wheel is selected by DIN15082 and equals in size to Z_3 =62 [-].

The smallest allowable gear size for the pinion wheel equals to 17 teeth [46]. However, it can be questioned whether it is desirable to apply the smallest allowable gear size, even if this will lead to the smallest size of the closed gearbox (and thus a greater cost reduction). From a conservative point of view the preference is to have a gear size that is somewhere in between the maximum gear size that fits within the bogie steel structure and the minimum gear size (to prevent the failure of the gear teeth). For this reason the pinion wheel has been set to Z_1 = 25 [-]. An important notification with the open gearing transmission ratio is that the ratio does not depend on the size or number of intermediate gears, but solely on the ratio between the input or pinion gear wheel and the output or crane gear wheel. In order to determine the size of the intermediate gear and to check Equation 3.51, the size has been determined by focusing on the size of the gear that fits within the bogie steel structure (Table 3.2 and Figure 3.6; this table and figure are representative for open gearing model 1 and 2).

Table 3.2 Intermediate gear size and related open gearing transmission ratio

Pinion wheel size $Z_1 = 25$ [-], Crane gear wheel size $Z_3 = 62$ [-]				
D_2 [mm]	Z_2 [-]	$i_{1,2} = \frac{Z_2}{Z_1}$ [-]	$i_{2,3} = \frac{Z_3}{Z_2}$ [-]	$i_{open\ gearing} = i_{1,2} \bullet i_{2,3}$ [-]
380	38	1.52	1.63	2.48
340	34	1.36	1.82	2.48
310	**31**	**1.24**	**2.00**	**2.48**
300	30	1.2	2.06	2.48
300	30	1.2	2.06	2.48
290	29	1.16	2.13	2.48

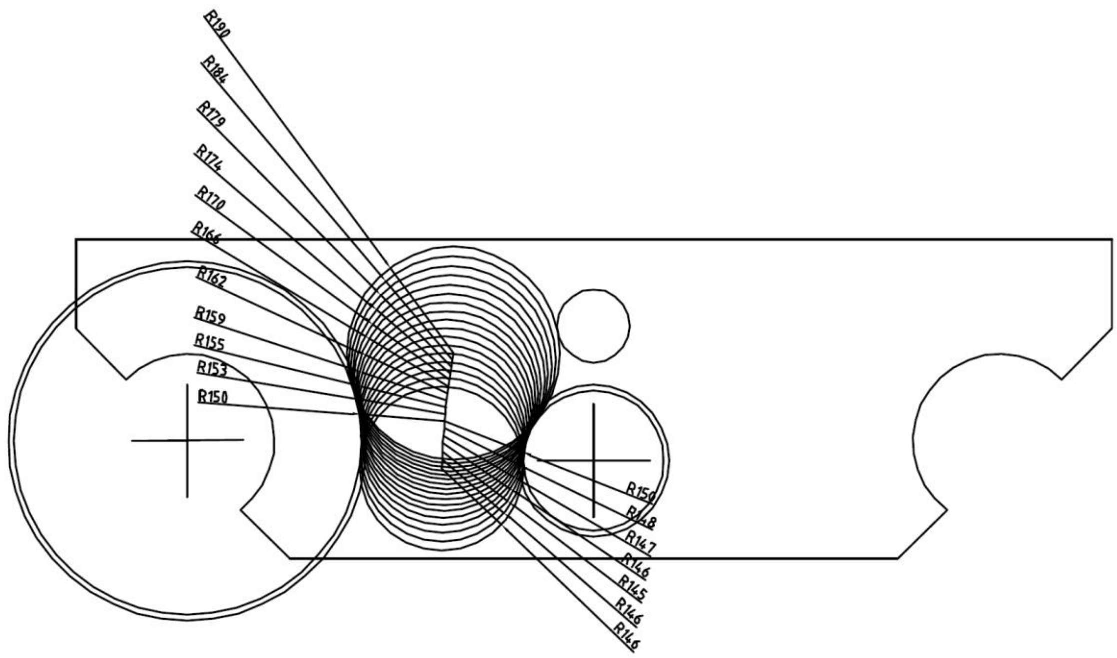


Figure 3.6 Intermediate gear wheel sizes

3.8 Calculation results

This paragraph displays the calculation results of the original situation and the open gearing models. Firstly, the results of the original situation will be provided followed by the calculation results of the open gearing models. Appendices H, I, J and K can be reviewed for the complete tabulated calculation results.

3.8.1 Calculation situations; load cases

Considering that the crane will operate in different environmental conditions, a number of load cases have to be checked for the determination of the correct power, torque, brake size, etcetera. The load cases are (these are different for the brake calculation, but this will be discussed in paragraph 3.8.4):

1. Boom down, trolley at the maximum outreach of the boom, with a wind load of 250 N/mm^2, with and without a load under the spreader;
2. Boom down, trolley at the maximum outreach of the boom, with a wind load of 125 N/mm^2, with and without a load under the spreader;
3. Boom down, trolley at the maximum back reach of the boom, with a wind load of 250 N/mm^2, with a load under the spreader;
4. Boom down, trolley at the maximum outreach of the boom, with a wind load of 390 N/mm^2, with and without a load under the spreader;
5. Boom up, trolley at parking position, a wind load of 250 N/mm^2 without a load under the spreader. In this case the crane is in parking position.

These load cases are considered to be the critical ones for the calculation. Loading situation 1 is the general situation. The other loading situations are situation that needs to be checked if the engine power is sufficient or not (though temporary overloading the engine can be done and there is a redundancy margin, meaning that the actual engine power will be slightly higher, but this has not been taken into account in the calculation).

3.8.2 Calculated engine power

For presenting the results of the calculation each situation has been summarized. For the power calculation only the nominal power has been listed. For the existing crane example the calculated nominal power has been presented in Table 3.3.

Table 3.3 Nominal power calculation existing crane

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm^2]	250		125		250	390		250	
P_f [kW]	62	59	62	59	62	62	59	59	59
P_W [kW]	346	346	173	173	346	540	540	344	536
$P_{\text{nominal}} = P_f + P_W$ [kW]	408	405	235	232	408	602	599	402	595
n_{wheel} [-] (powered)	24	24	24	24	24	24	24	24	24
$\text{P}_{wheel} = \frac{P_{\text{nominal}}}{n_{wheel}}$ [kW]	17	17	10	10	17	26	25	17	25

The nominal power calculation for open gearing model 1 has been listed in Table 3.4.

Table 3.4 Nominal power calculation open gearing model 1

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm^2]	250		125		250	390		250	
P_f [kW]	67	64	67	64	67	67	64	64	64
P_W [kW]	375	375	188	188	375	585	585	372	580
$P_{\text{nominal}} = P_f + P_W$ [kW]	442	439	255	255	442	652	649	436	644
n_{bogie} [-] (powered)	16	16	16	16	16	16	16	16	16
$\text{P}_{bogie} = \frac{P_{\text{nominal}}}{n_{bogie}}$ [kW]	28	28	16	16	28	41	41	28	41

The nominal power calculation for open gearing model 2 has been listed in Table 3.5.

Table 3.5 Nominal power calculation open gearing model 2

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm²]	250		125		250	390		250	
P_f [kW]	76	72	76	72	76	76	72	72	72
P_W [kW]	423	423	212	212	423	660	660	420	655
$P_{nominal} = P_f + P_W$ [kW]	499	495	287	284	499	736	732	492	727
n_{bogie} [-] (powered)	16	16	16	16	16	16	16	16	16
$P_{bogie} = \frac{P_{nominal}}{\left(\frac{n_{bogie}}{2}\right)}$ [kW]	63	62	36	36	63	92	92	62	91

The nominal power calculation for open gearing model 3 has been listed in Table 3.6.

Table 3.6 Nominal power calculation open gearing model 3

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm²]	250		125		250	390		250	
P_f [kW]	65	62	65	62	65	65	62	62	62
P_W [kW]	361	361	181	181	361	562	562	358	558
$P_{nominal} = P_f + P_W$ [kW]	425	422	245	242	425	627	624	419	619
n_{bogie} [-] (powered)	16	16	16	16	16	16	16	16	16
$P_{bogie} = \frac{P_{nominal}}{n_{bogie}}$ [kW]	27	27	16	16	27	40	39	27	39

As explained in paragraph 3.4 the efficiency of the gearing and the number of wheels the engine powers determines the required engine power.

3.8.3 Calculated engine torque

For presenting the results of the calculation each situation has been summarized. For the torque calculation only the nominal and maximum engine torque has been listed. These values are of importance for selecting the closed gearbox. For the existing crane example the calculated nominal and maximum torque has been presented in Table 3.7.

Table 3.7 Torque calculation existing crane

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm²]	250		125		250	390		250	
M_{nominal} [kNm]	148	147	86	85	148	219	218	147	216
$M_{\text{acceleration}}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{\text{nominal}}}{n_{wheel} \cdot i \cdot \eta_{G\_i}}$ [Nm]	88	88	51	51	88	130	130	88	129
$M_{acc\_engine} = \frac{M_{\text{acceleration}}}{n_{wheel} \cdot i \cdot \eta_{G\_i}}$ [Nm]	111	123	73	86	111	158	156	109	155

The nominal and acceleration torque calculation for open gearing model 1 has been listed in Table 3.8.

Table 3.8 Torque calculation open gearing model 1

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm²]	250		125		250	390		250	
M_{nominal} [kNm]	148	147	86	85	148	219	218	147	216
$M_{\text{acceleration}}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{\text{nominal}}}{n_{bogie} \cdot i \cdot \eta_{G\_i}}$ [Nm]	143	142	82	81	143	211	210	142	208
$M_{acc\_engine} = \frac{M_{\text{acceleration}}}{n_{bogie} \cdot i \cdot \eta_{G\_i}}$ [Nm]	184	208	124	148	184	262	259	182	257

The nominal and acceleration torque calculation for open gearing model 2 has been listed in Table 3.9.

Table 3.9 Torque calculation open gearing model 2

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm^2]	250		125		250	390		250	
M_{nominal} [kNm]	148	147	86	85	148	219	218	147	216
$M_{\text{acceleration}}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{\text{nominal}}}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	322	320	186	183	322	475	472	320	469
$M_{acc\_engine} = \frac{M_{\text{acceleration}}}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	408	457	272	321	408	581	574	402	571

The nominal and acceleration torque calculation for open gearing model 3 has been listed in Table 3.10.

Table 3.10 Torque calculation open gearing model 3

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm^2]	250		125		250	390		250	
M_{nominal} [kNm]	148	147	86	85	148	219	218	147	216
$M_{\text{acceleration}}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{\text{nominal}}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	137	136	79	78	137	202	202	137	200
$M_{acc\_engine} = \frac{M_{\text{acceleration}}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	174	195	116	137	174	248	245	172	243

As an extension of the engine torque, the engine coupling can be determined based on the torque requirement. The purpose of a engine coupling is to transfer the rotational energy between two axles or between an axle and an attached component. It can also be used to compensate radial, axial or angular deviations between axles and act as a damping element due to impact. Besides this, the coupling can act as a switch between transferring and not transferring a torque.

For the calculation of the appropriate engine coupling, the torque input and output can be calculated from both frictional resistance, rotational masses, wind resistance and linear moving masses. However, the current engine coupling of the example gantry travelling gear can also be evaluated and determined whether or not this components is suitable for the open gearing models. What needs to be checked is whether the torque that the engine coupling is able to transfer is higher than the required torque. This is expressed by a service factor, $S_{coupling}$ [-], of the engine coupling that has to be checked with the minimum service factor, S_{min} [-], to ensure that the coupling will suffice for the number of hours the travelling gear has been specified to (Table 3.11, 3.12, 3.13). The minimum factor compared to is sometimes taken larger than the actual minimum, due to uncertainty on the quality from the Chinese supplier for this product.

Table 3.11 Open gearing model 1

Type	CNTR ML 7		Service factor $S_{coupling}$	$S_{min} = 4$ [-]
M_{nom_engine} [Nm]	143	$S_{coupling} = \frac{M_{max\_coupling}}{M_{nom\_engine}}$ [-]	7.8	$S_{coupling} \geq S_{min}$
M_{acc_engine} [Nm]	184			
		$S_{coupling} = \frac{M_{max\_coupling}}{M_{acc\_engine}}$ [-]	6.1	$S_{coupling} \geq S_{min}$
$M_{max\_coupling}$ [Nm]	1120			

Table 3.12 Open gearing model 2

Type	CNTR ML 7		Service factor $S_{coupling}$	$S_{min} = 4$ [-]
M_{nom_engine} [Nm]	322	$S_{coupling} = \frac{M_{max\_coupling}}{M_{nom\_engine}}$ [-]	7.1	$S_{coupling} \geq S_{min}$
M_{acc_engine} [Nm]	408			
		$S_{coupling} = \frac{M_{max\_coupling}}{M_{acc\_engine}}$ [-]	5.6	$S_{coupling} \geq S_{min}$
$M_{max\_coupling}$ [Nm]	1120			
Engine torque is divided over two bogies. The engine coupling will experience half of the engine torque.				

Table 3.13 Open gearing model 3

Type	CNTR ML 7		Service factor $S_{coupling}$	$S_{min} = 4$ [-]
M_{nom_engine} [Nm]	137	$S_{coupling} = \frac{M_{max\_coupling}}{M_{nom\_engine}}$ [-]	8.1	$S_{coupling} \geq S_{min}$
M_{acc_engine} [Nm]	174			
		$S_{coupling} = \frac{M_{max\_coupling}}{M_{acc\_engine}}$ [-]	6.5	$S_{coupling} \geq S_{min}$
$M_{max\_coupling}$ [Nm]	1120			

It has been concluded that the engine coupling from the example gantry travelling gear is sufficient for the open gearing models.

3.8.4 Calculated braking device

For the brake calculation the loading situations differ. The loading situations have been defined as follow. After defining the situations the calculation results for the braking device will be summarized.

1. Boom down, trolley at the maximum outreach of the boom, with a wind load of 390 N/mm^2, with full load under the spreader;
2. Boom down, trolley at the maximum outreach of the boom, with a wind load of 390 N/mm^2, with full load under the spreader;
3. Boom down, trolley at the maximum back reach of the boom, with a wind load of 390 N/mm^2, with a load under the spreader;
4. Boom down, trolley at the maximum outreach of the boom, with a wind load of 390 N/mm^2, with and without a load under the spreader;
5. Boom up, trolley at parking position, a wind load of 250 N/mm^2 without a load under the spreader. In this case the crane is in parking position.
6. Boom up, trolley at parking position, a wind load of 390 N/mm^2, without a load under the spreader. In this case the crane is in parking position.

These load cases are considered to be the most critical ones for the calculation.

For the calculation results see Table 3.14, 3.15, 3.16 and 3.17 for the summarized results. The entire calculation can be reviewed in Appendix J, with an explanation of each variable. For this paragraph only the calculation results for the open gearing models have been listed. The input variables for the type of brake come from the component selection in paragraph 3.8.6.2.

Table 3.14 General torque calculation for the crane

	Boom down				Boom up	
	Trolley at outreach	Trolley at back reach	Trolley at outreach	Trolley at back reach	parked	parked
W_{Load} [MT]	84	84	19	19	19	19
Wind load [N/mm^2]	390	390	390	390	250	390
M_f [kNm]	8.95	8.95	8.54	9.14	8.54	8.54
M_{wind} [kNm]	193	193	193	193	124	193
Open gearing model 1 M_{brake_total} [kNm]	657	657	657	657	657	657
Open gearing model 2 M_{brake_total} [kNm]	731	731	731	731	731	731
Open gearing model 3 M_{brake_total} [kNm]	679	679	679	679	679	679

Table 3.15 Open gearing model 1

	Boom down				Boom up	
	Trolley at outreach	Trolley at back reach	Trolley at outreach	Trolley at back reach	parked	parked
W_{Load} [MT]	84	84	19	19	19	19
Wind load [N/mm^2]	390	390	390	390	250	390
Maximum brake speed check						
$n_{c\ brake}$ [rpm]	2,027	2,027	2,033	2,032	1,964	2,032
Check condition	< 4,700	< 4,700	< 4,700	< 4,700	< 4,700	< 4,700
Braking torque and braking distance						
$a_{c\ brake}$ [m/s^2]	-0.64	-0.64	-0.66	-0.66	-0.76	-0.66
$t_{braking}$ [s]	1.43	1.43	1.40	1.39	1.16	1.39
$s_{c\ braking}$ [m]	1.96	1.96	1.91	1.91	1.55	1.91
Check condition	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
Wheelslip check						
V [-]	48	48	46	49	72	46
Check condition	> 1	> 1	> 1	> 1	> 1	> 1
Heat absorption limit						
E_{total} [kJ]	2,337	2,337	2,284	2,281	1,587	2,280
Number of brakes	16	16	16	16	16	16
$E_{absorbed\ per\ brake}$ [kJ]	146	146	143	143	99	142
Check condition	< 169[13]	< 169	< 169	< 169	< 169	< 169

Table 3.16 Open gearing model 2

	Boom down				Boom up	
	Trolley at outreach	Trolley at back reach	Trolley at outreach	Trolley at back reach	parked	parked
W_{Load} [MT]	84	84	19	19	19	19
Wind load [N/mm^2]	390	390	390	390	250	390
Maximum brake speed check						
$n_{c\ brake}$ [rpm]	2,024	2,024	2,030	2,029	1,962	2,030
Check condition	< 3,600	< 3,600	< 3,600	< 3,600	< 3,600	< 3,600
Braking torque and braking distance						
$a_{c\ brake}$ [m/s^2]	-0.73	-0.73	-0.75	-0.75	-0.85	-0.75
$t_{braking}$ [s]	1.25	1.25	1.22	1.22	1.04	1.22
$s_{c\ braking}$ [m]	1.71	1.71	1.67	1.67	1.38	1.67
Check condition	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
Wheelslip check						
V [-]	48	48	46	49	72	46
Check condition	> 1	> 1	> 1	> 1	> 1	> 1
Heat absorption limit						
E_{total} [kJ]	2,187	2,187	2,138	2,135	1,527	2,134
Number of brakes	8	8	8	8	8	8
$E_{absorbed\ per\ brake}$ [kJ]	137	137	134	133	95	133
Check condition	< 169	< 169	< 169	< 169	< 169	< 169

[13] Energy value from the original crane model brake, used as a reference point.

Table 3.17 Open gearing model 3

	Boom down				Boom up	
	Trolley at outreach	Trolley at back reach	Trolley at outreach	Trolley at back reach	parked	parked
W_{Load} [MT]	84	84	19	19	19	19
Wind load [N/mm^2]	390	390	390	390	250	390
Maximum brake speed check						
$n_{c\ brake}$ [rpm]	2,027	2,027	2,033	2,033	1,964	2,033
Check condition	< 4,700	< 4,700	< 4,700	< 4,700	< 4,700	< 4,700
Braking torque and braking distance						
$a_{c\ brake}$ [m/s^2]	-0.67	-0.67	-0.69	-0.69	-0.79	-0.69
$t_{braking}$ [s]	1.37	1.37	1.33	1.33	1.12	1.33
$s_{c\ braking}$ [m]	1.87	1.87	1.83	1.83	1.48	1.83
Check condition	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0
Wheelslip check						
V [-]	48	48	46	48	72	46
Check condition	> 1	> 1	> 1	> 1	> 1	> 1
Heat absorption limit						
E_{total} [kJ]	2,280	2,280	2,228	2,225	1,562	2,224
Number of brakes	16	16	16	16	16	16
$E_{absorbed\ per\ brake}$ [kJ]	142	142	139	139	98	139
Check condition	< 169	< 169	< 169	< 169	< 169	< 169

3.8.5 Calculated closed gearbox

As a general approach Table 3.18, 3.19, and 3.20 have been constructed to provide the general outlines of the closed gearbox.

Table 3.18 Open gearing model 1

Torque from engine (input transmission)		Transmission	Torque from two wheels (output transmission)	
Nominal torque [Nm]	143	Overall ratio:	Nominal torque [kNm]	9.25
Nominal engine speed [rpm]	1500	i = 73.23	-	-
Acceleration torque [Nm]	184	Ratio closed gearbox:	Acceleration torque [kNm]	11.58
Maximum engine speed [rpm]	1850	$i_{closed\ gearbox}$ = 29.53	Maximum wheel speed [rpm]	26
Data in this table represents the situation of boom down, trolley at maximum outreach, full load at normal wind conditions.				

Table 3.19 Open gearing model 2

Torque from engine (input transmission)		Transmission	Torque from four wheels (output transmission)	
Nominal torque [Nm]	322	Overall ratio:	Nominal torque [kNm]	18.50
Nominal engine speed [rpm]	1500	i = 73.23	-	-
Acceleration torque [Nm]	408	Ratio closed gearbox:	Acceleration torque [kNm]	23.16
Maximum engine speed [rpm]	1850	$i_{closed\ gearbox}$ = 29.53	Maximum wheel speed [rpm]	26
Data in this table represents the situation of boom down, trolley at maximum outreach, full load at normal wind conditions.				

Table 3.20 Open gearing model 3

Torque from engine (input transmission)		Transmission	Torque from two wheels (output transmission)	
Nominal torque [Nm]	137	Overall ratio:	Nominal torque [kNm]	9.25
Nominal engine speed [rpm]	1500	i = 73.23	-	-
Acceleration torque [Nm]	174	Ratio closed gearbox:	Acceleration torque [kNm]	11.58
Maximum engine speed [rpm]	1850	$i_{closed\ gearbox}$ = 29.53	Maximum wheel speed [rpm]	26
Data in this table represents the situation of boom down, trolley at maximum outreach, full load at normal wind conditions.				

The results in Table 3.18, 3.19 and 3.20 have been used to select the appropriate gearbox based on tabulated data from gearbox manufacturers. However, the output torque of the closed gearbox needs to be known, which can be calculated by applying Equation 3.24, whereby the input torque is selected as the maximum engine torque ($M_{acc\ engine}$ [Nm]).

$$P_{input} = P_{output} \rightarrow T_{input} \bullet n_{input} = T_{output} \bullet n_{output} \quad (3.24)$$

P_{input}, T_{input} and n_{input} are, respectively the input power, torque and speed of the closed gearbox. P_{output}, T_{output} and n_{output} are the output power, torque and speed of the closed gearbox.

Table 3.8, 3.9 and 3.10 have been used for the input data for equation 3.52. The output rotational speed can be determined by the ratio of the closed gearbox. The output rotational speed has been used to determine the output torque (the reason for the focus on the output torque is because this is the largest torque experienced by the closed gearbox). This output torque is used to select the correct closed gearbox. One has to keep in mind that with open gearing model 2 the engine torque is divided over two bogies.

3.8.6 Component selection

Based on the calculation results the components have been selected. This focuses on the engine, closed gearbox, and (engine) brake. Table 3.27, 3.28 and 3.29 summarize the component selection.

3.8.6.1 Engine

For the engine selection the following results have been listed. The data regarding the selected engine for the existing crane example has been listed in Table 3.21. The engine manufacturer is Franz Wölfer Elektromaschinenfabrik Osnabrück GmbH [51].

Table 3.21 Engine data existing crane example

Engine classification		Wölfer DRKO-160L-4	
Nominal torque		Maximum torque	
P_{nom} [kW]	16	$n_{\max}$ [rpm]	1850
n_{nom} [rpm]	1500	$M_{\max} = M_{nom} \bullet f_a$ [Nm]	184
$M_{nom} = \frac{9550 \bullet P_{nom}}{n_{nom}}$ [Nm]	102	Maximum torque at maximum engine speed	
		$M_{\max,n_{\max}} = \min\left(M_{\max}, M_{\max} \bullet \frac{n_{nom}^2}{n_{\max}^2}\right)$ [Nm]	121

The data regarding the selected engine for the open gearing model 1 has been listed in Table 3.22. The nominal and maximum torque exceed both the calculated nominal and maximum torque, therefore the engine is sufficient.

Table 3.22 Engine data open gearing model 1

Engine classification		Wölfer DRKO-180L-4bb	
Nominal torque		Maximum torque	
P_{nom} [kW]	30	$n_{\max}$ [rpm]	1850
n_{nom} [rpm]	1500	$M_{\max} = M_{nom} \bullet f_a$ [Nm]	344
$M_{nom} = \frac{9550 \bullet P_{nom}}{n_{nom}}$ [Nm]	191	Maximum torque at maximum engine speed	
		$M_{\max,n_{\max}} = \min\left(M_{\max}, M_{\max} \bullet \frac{n_{nom}^2}{n_{\max}^2}\right)$ [Nm]	227

The data regarding the selected engine for the open gearing model 2 has been listed in Table 3.23. The nominal and maximum torque exceed both the calculated nominal and maximum torque, therefore the engine is sufficient.

Table 3.23 Engine data open gearing model 2

Engine classification		Wölfer DRKO-250M-4	
Nominal torque		Maximum torque	
P_{nom} [kW]	64	$n_{\max}$ [rpm]	1850
n_{nom} [rpm]	1500	$M_{\max} = M_{nom} \bullet f_a$ [Nm]	734
$M_{nom} = \frac{9550 \bullet P_{nom}}{n_{nom}}$ [Nm]	408	Maximum torque at maximum engine speed	
		$M_{\max,n_{\max}} = \min\left(M_{\max}, M_{\max} \bullet \frac{n_{nom}^2}{n_{\max}^2}\right)$ [Nm]	483

The data regarding the selected engine for the open gearing model 3 has been listed in Table 3.24. The nominal and maximum torque exceed both the calculated nominal and maximum torque, therefore the engine is sufficient.

Table 3.24 Engine data open gearing model 3

Engine classification		Wölfer DRKO-180L-4b	
Nominal torque		Maximum torque	
P_{nom} [kW]	26	n_{max} [rpm]	1850
n_{nom} [rpm]	1500	$M_{max} = M_{nom} \bullet f_a$ [Nm]	298
$M_{nom} = \frac{9550 \bullet P_{nom}}{n_{nom}}$ [Nm]	166	Maximum torque at maximum engine speed	
		$M_{max,n_{max}} = \min\left(M_{max}, M_{max} \bullet \frac{n_{nom}^2}{n_{max}^2}\right)$ [Nm]	196

3.8.6.2 *Braking device*

For the braking device selection the following results have been listed (Table 3.25). The brake manufacturer is Pintsch Bubenzer GmbH [52].

Table 3.25 Engine mounted braking device

Model	Braking device classification	Specifications	
Original situation	KFB 25	Dynamic braking torque M_B [Nm]	250
		Inertia J [kgm^2]	0.0048
		Maximum brake speed n_B [min^{-1}]	6,000
Open gearing model 1	KFB 63	Dynamic braking torque M_B [Nm]	630
		Inertia J [kgm^2]	0.0175
		Maximum brake speed n_B [min^{-1}]	4,700
Open gearing model 2	KFB 160	Dynamic braking torque M_B [Nm]	1,600
		Inertia J [kgm^2]	0.050
		Maximum brake speed n_B [min^{-1}]	3,600
Open gearing model 3	KFB 63	Dynamic braking torque M_B [Nm]	630
		Inertia J [kgm^2]	0.0175
		Maximum brake speed n_B [min^{-1}]	4,700

3.8.6.3 *Closed gearbox*

For the closed gearbox selection the following results have been listed. The closed gearbox manufacturer is Zhenhua Heavy Industries Co., Ltd. Nantong Heavy Gear Reducer [53] (Table 3.26).

For the original situation the selected closed gearbox is a custom build closed gearbox. The closed gearboxes for the open gearing models have been selected from a catalogue of the aforementioned closed gearbox manufacturer. The specifications for the closed gearbox for both the existing situation and the open gearing models have been listed in Table 3.28. It must be noted that there is a required service factor of 1.4 ($S_{gearbox}$ [-]).

Table 3.26 Selected closed gearbox

Three stages Reducer Sizes						
Model	Classification of closed gearbox	Transmission ratio of closed gearbox [-]	Mass [kg]	Allowable output torque closed gearbox $T_{gearbox}$ [kNm]	T_{output} [kNm] (see Eq. 3.24)	$T_{gearbox} \geq T_{output} \bullet S_{gearbox}$
Original situation	TNR 440.74	73.61	535	10.0	3.3	Ok
Open gearing model 1	TNR 315.32	31.5	350	9.8	5.5	Ok
Open gearing model 2	TNR 315.32	31.5	350	9.8	6.0	Ok
Open gearing model 3	TNR 315.32	31.5	350	9.8	5.2	Ok

3.8.6.4 Gear selection

The gear selection has already been specified in paragraph 3.7. In this paragraph only a notification will be made. The application of an open gearing will lead to additional components for securing and protecting the gears during use (such as covers, shafts, bearings, etcetera) and additional assembly time. For the cost comparison this means that there will be additional cost and assembly time from these components and actions.

Table 3.27 Open gearing model 1, component data

Engine data; Wölfer DRKO-180L-4bb			
Nominal power per engine [kW]	30		
Nominal engine speed [rpm]	1500	Maximum engine speed [rpm]	1850
Nominal torque [Nm]	191	Maximum torque [Nm]	344
		Maximum torque at maximum engine speed [Nm]	227

Braking device data; Bubenzer KFB 63	
Dynamic braking torque [Nm]	630
Inertia [kgm2]	0.0175
Maximum braking speed [rpm]	4,700

Closed gearbox data; TNR 315.32	
Transmission ratio [-]	31.5
Mass [kg]	535
Nominal output torque [kNm]	9.8

Engine coupling data; CNTR ML 7	
Maximum coupling torque [Nm]	1120

Open gearing data	
Transmission ratio [-]	2.48
Pinion gear wheel Z [-]	25
Intermediate gear wheel Z [-]	31
Crane gear wheel Z [-]	62

Table 3.28 Open gearing model 2, component data

Engine data; Wölfer DRKO-250M-4			
Nominal power per engine [kW]	64		
Nominal engine speed [rpm]	1500	Maximum engine speed [rpm]	1850
Nominal torque [Nm]	408	Maximum torque [Nm]	734
		Maximum torque at maximum engine speed [Nm]	483

Braking device data; Bubenzer KFB 160	
Dynamic braking torque [Nm]	1,600
Inertia [kgm2]	0.050
Maximum braking speed [rpm]	3,600

Closed gearbox data; TNR 315.32	
Transmission ratio [-]	31.5
Mass [kg]	535
Nominal output torque [kNm]	9.8

Engine coupling data; CNTR ML 7	
Maximum coupling torque [Nm]	1120

Open gearing data	
Transmission ratio [-]	2.48
Pinion gear wheel Z [-]	25
Intermediate gear wheel Z [-]	31
Crane gear wheel Z [-]	62

Table 3.29 Open gearing model 3, component data

Engine data; Wölfer DRKO-180L-4b			
Nominal power per engine [kW]	26		
Nominal engine speed [rpm]	1500	Maximum engine speed [rpm]	1850
Nominal torque [Nm]	166	Maximum torque [Nm]	298
		Maximum torque at maximum engine speed [Nm]	196

Braking device data; Bubenzer KFB 63	
Dynamic braking torque [Nm]	630
Inertia [kgm2]	0.0175
Maximum braking speed [rpm]	4,700

Closed gearbox data; TNR 315.32	
Transmission ratio [-]	31.5
Mass [kg]	535
Nominal output torque [kNm]	9.8

Engine coupling data; CNTR ML 7	
Maximum coupling torque [Nm]	1120

Open gearing data	
Transmission ratio [-]	2.48
Pinion gear wheel Z [-]	25
Crane gear wheel Z [-]	62

3.9 Cost calculation

At the beginning of this chapter it was stated that the calculation focuses on the components of the crane travelling gear. For the cost calculation a comparison has been made based on the cost of the components for the original crane travelling gear and the open gearing models. For the estimation of the cost, existing tender documentation has been reviewed and the costing sheet of the original crane. The cost of the original crane's main travelling gear has been listed in Table 3.30.

Table 3.30 Cost overview main components gantry travelling gear

Component	Amount	Description	Cost [Euro]	Total cost [Euro]
Driven crane wheel	24	-	1,770	42,480
Non driven crane wheel	8	-	1,770	14,160
Wheel shaft	32	-	300	9,600
Bearing crane wheel	64	SKF 24130 CC/W33	320	20,480
Bearing housing crane wheel	64	-	250	16,000
Engine	24	Wölfer DRKO-160L-4	2,450	58,800
Operational brake	24	Pintsch Bubenzer KFB25		
Gearbox	24	ZPMC TNR 440.74	2,590.50	62,172
Engine coupling	24	CNTR ML7	250	6,000
Wheel brake	8	Bubenzer RWB7	6,550	52,400
Reaction plate	24	-	75	1,800
Miscellaneous	-	-	-	10,860
			Total cost	294,800

For the steel structure of the bogies WS and LS the cost contains not only the material cost, but also the material processing cost for manufacturing the steel structure and the assembly. The cost for the steel structure has not been taken into account, because for the open gearing models these cost will be of the same order. Other components have been summed and placed under the heading of 'Miscellaneous' (such as smaller bearings, rings, strips, bolts/nuts, steel plates, and so on). In this case the buffer has been left out of the overview. This component is only of significance for the outer bogies WS SB/PS and LS SB/PS.

Table 3.31, 3.32, and 3.33 list the cost for the open gearing models.

Table 3.31 Cost overview main components open gearing model 1

Component	Amount, cost per component	Total cost [Euro]
Driven crane wheel	32; 1,770 Euro	56,640
Wheel shaft	32; 300 Euro	9,600
Bearing crane wheel	64; 320 Euro	20,480
Bearing housing crane wheel	64; 250 Euro	16,000
Engine and operational brake	16; 3,400 Euro	54,400
Gearbox	16; 1,179 Euro	18,864
Pinion gear wheel	16; 120 Euro	1,920
Intermediate gear wheel	32; 130 Euro	4,160
Intermediate gear wheel shaft	32; 100 Euro	3,200
Intermediate gear wheel bearing	32; 150 Euro	4,800
Crane wheel gear	32; 300 Euro	9,600
Open gear covers	32; 200 Euro	6,400
Engine coupling	16; 250 Euro	4,000
Reaction plate	16; 75 Euro	1,200
Miscellaneous	-	12,000
Additional assembly time	16; 10 Euro/hr 2 men per bogie, 30 hr	9,600
Total cost		232,900

Table 3.32 Cost overview main components open gearing model 2

Component	Amount, cost per component	Total cost [Euro]
Driven crane wheel	32; 1,770 Euro	56,640
Wheel shaft	32; 300 Euro	9,600
Bearing crane wheel	64; 320 Euro	20,480
Bearing housing crane wheel	64; 250 Euro	16,000
Engine and operational brake	8; 7,000 Euro	56,000
Gearbox	16; 1,179 Euro	9,431
Pinion gear wheel	16; 120 Euro	1,920
Intermediate gear wheel	32; 130 Euro	4,160
Intermediate gear wheel shaft	32; 100 Euro	3,200
Intermediate gear wheel bearing	32; 150 Euro	4,800
Crane wheel gear	32; 300 Euro	9,600
Open gear covers	32; 200 Euro	6,400
Engine coupling	16; 250 Euro	4,000
Reaction plate	8; 75 Euro	600
Miscellaneous	-	12,000
Additional assembly time	16; 10 Euro/hr 2 men per bogie, 30 hr	9,600
Total cost		233,800

Table 3.33 Cost overview main components open gearing model 3

Component	Amount, cost per component	Total cost [Euro]
Driven crane wheel	32; 1,770 Euro	56,640
Wheel shaft	32; 300 Euro	9,600
Bearing crane wheel	64; 320 Euro	20,480
Bearing housing crane wheel	64; 250 Euro	16,000
Engine and operational brake	16; 3200 Euro	51,200
Gearbox	16; 1,179 Euro	18,864
Pinion gear wheel	16; 120 Euro	1,920
Intermediate gear wheel	-	-
Intermediate gear wheel shaft	-	-
Intermediate gear wheel bearing	-	-
Crane wheel gear	32; 300 Euro	9,600
Open gear covers	-	-
Engine coupling	16; 250 Euro	4,000
Reaction plate	16; 75 Euro	1,200
Miscellaneous	-	12,000
Additional assembly time	16; 10 Euro/hr 2 men per bogie, 18 hr	5,760
Total cost		207,300

Comparing the original situation with the open gearing models it can be stated that the open gearing models lead to a cost reduction. In general the following effects can be noted:

- A decrease in the number of engines results in a higher price per engine. In this case there will be a decrease in cost, because the increase in cost due to the increased power requirement per engine is lower than the decrease in cost due to the fewer number of engines.
- With regards to the closed gearbox, there will be a significant cost reduction, though dependent on the size of the open gearing transmission ratio, due to the smaller closed gearbox transmission ratio and the fewer number required.
- Concerning the operational brakes, the cost for this type of component will increase. A larger brake will be necessary to keep the braking time or distance acceptable.
- With the application of an open gearing there will be many additional cost that come from the gear wheels, shafts, gear covers, gear wheel bearings, additional assembly time, etcetera. This does indicate that with increasing number of gears the application of an open gearing will influence the cost reduction negatively.

Table 3.34 summarizes the results and compares with the total cost price of the original crane.

Table 3.34 Cost results gantry travelling gear

Model	Cost of gantry travelling gear [Euro]	Cost reduction compared to the original situation [Euro (%)]	Cost reduction compared to the total cost price of the original crane (3,600,000 Euro) [%]
Original situation	294,800	-	-
Open gearing model 1	232,900	61,900 (21.0)	1.7
Open gearing model 2	233,800	61,000 (20.7)	1.7
Open gearing model 3	207,300	87,500 (29.7)	2.4

3.10 Conclusion and recommendation

The conclusion has been drawn that the application of an open gearing will result in a cost reduction, even though there are some disadvantages to be noted with this type of transmission, that will come forth during the operational phase. Furthermore, it can be noted that the smaller the number of gears used for the open gearing, the larger the cost reduction will be. Therefore, it can be said that for cranes with short travelling gears the use of an open gearing will be even more favorable from the viewpoint of a cost reduction.

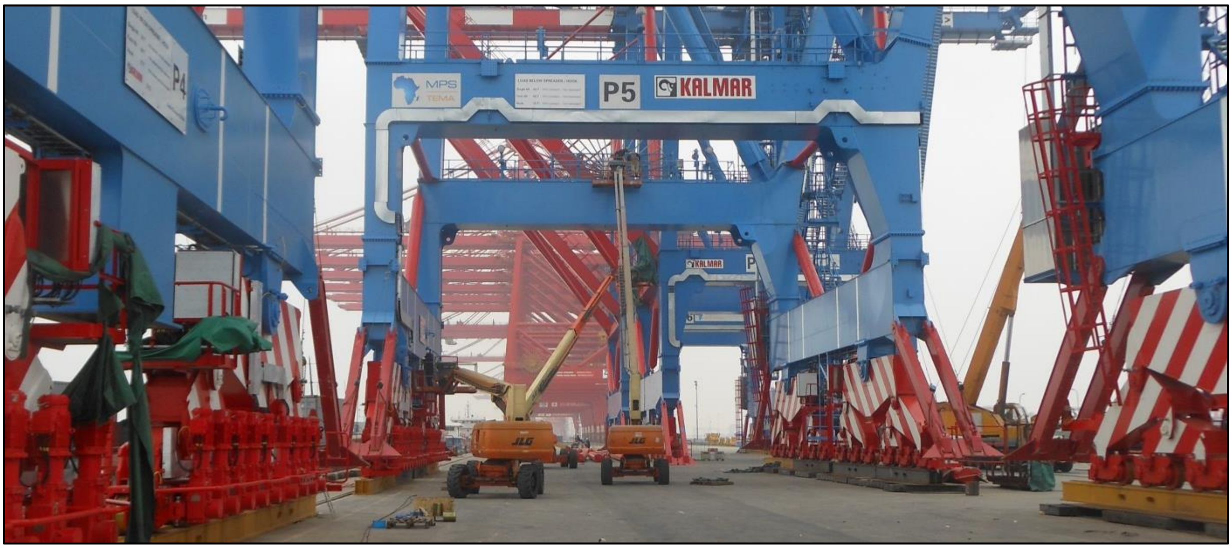
In case the engine powers both wheels of the bogie with 5 gears per bogie, the cost reduction amounts to 1.7 % of the total cost price of the Ship-To-Shore container gantry crane. If the engine powers the wheels of two bogies, the cost reduction will amount to 1.7 % of the total cost price. In case the engine powers both wheels of the bogie with 3 gears per bogie, the cost reduction amounts to 2.4 % of the total cost price.

With the application of an open gearing the goal should be to keep the number of gears as small as possible, and the transmission ratio of the open gearing as large as possible. This will reduce the size of the closed gearbox.

The cost during the maintenance phase has not been taken into account. The reason for this is because this cost post is highly dependent on the number of times maintenance needs to occur, the number of people involved, the location of the crane (which in turn influences the number of times maintenance needs to occur), local conditions, and other factors.

As a recommendation for the determination of the engine power and brake torque it can be stated that the selection of these components should be such that in case of engine failure (and thereby rendering the engine-mounted brake useless), there is still enough engine power available for crane travelling and enough braking torque available for stopping the crane within a certain braking distance. This means that the selected components should be larger than necessary and this decreases the cost reduction. This has not been taken into account in the presented results.

Report Part IV Replacement of bolted flange plate connections by welded connections in the portal frame of Ship-To-Shore container gantry cranes



4.1 Introduction

Current practice of Cargotec Netherlands BV for the assembly of the portal frame of Ship-To-Shore container gantry cranes is to attach the components for a large extent using a bolted flange plate connection. However, with this connection there is a large amount of cost associated that, from the viewpoint of cost reduction, are unwanted. For this reason, the focus is on removing bolted flange plate connections by welded flange plate connections, on the assumption that this will be cheaper. The question, with regards to the replacement of bolted flange connections by welded flange plate connections, is to indicate which connections within the portal frame steel structure should be replaced and what the possible cost reduction could be.

The main point with the replacement of bolted flange plate connections by welded flange plate connections is that if the bolted flange plate is removed the production and assembly cost associated with this bolted flange plate are removed as well, though this will be compensated by cost that come forth due to the use of a welded flange plate connection. The question which connection should be replaced within the portal frame is therefore an economic one, though with influences from external factors and preferences from both the side of the manufacturer and the client.

This chapter has been structured as follows.

- **Paragraph 4.2** will present a general introduction of the portal frame, followed by an introduction of the bolted flange plate connection.
- **Paragraph 4.3** will discuss the general build-up of the portal frame in case of bolted flange plate connections.
- **Paragraph 4.4** describes the production and assembly site and the transport in between.
- **Paragraph 4.5** presents the estimated cost of a bolted flange plate connection.
- **Paragraph 4.6** presents the cost estimation of a welded flange plate connection.
- **Paragraph 4.7** discusses the two main influences on the type of connection, namely sea transport and the assembly capacity.
- **Paragraph 4.8** gives an overview of the different concepts that will be reviewed and the build-up of each concept.
- **Paragraph 4.9** provides a cost calculation in order to compare the different concepts with the situation of a portal frame with only bolted flange plate connections.
- **Paragraph 4.10** provides a conclusion and recommendation.

4.2 Introduction to the portal frame

The portal frame consists of a number of components, which have been listed below [54]:

Sill beams

- Sill beam waterside
- Sill beam landside

Portal portside

- Lower legs
- Cross girder
- Long legs
- Upper legs
- Diagonal tie
- Horizontal tie

Bogie sets

- Bogie sets waterside
- Bogie sets landside

Portal starboard

- Lower legs
- Cross girder
- Long legs
- Upper legs
- Stairs
- Elevator
- Diagonal tie
- Horizontal tie

Additional components are the portal beam (both waterside and landside), the A-frame, and the ties supporting the connection between the portal beams with the upper legs on the waterside. Cargotec has always applied bolted flange plate connections in its Ship-To-Shore container gantry cranes. Sometimes a welded flange plate connection is applied between the lower legs and the sill beams. In the portal frame the following flange plate connections can be identified (Figure 4.1, Appendix O and Z (general drawing of the crane)):

Connection no.	Description
1	Connection between the sill beam and the lower legs
2	Connection between the lower legs and the cross girders
3	Connection between the cross girders and the long legs
4	Connection between the long legs and the upper legs
5	Connection between the diagonal tie and the cross girders
6	Connection between the diagonal tie and the long legs
7	Connection between the upper legs and the portal beams
8	Connection between the upper legs WS and the horizontal tie
9	Connection between the upper legs LS and the horizontal tie
10	Connection between the sill beams and the main balance connections
11	Connection between the portal beam and the A-frame
12	Connection between the sill beams and the storm brakes
13	Connecting tie WS between the upper legs and portal beam

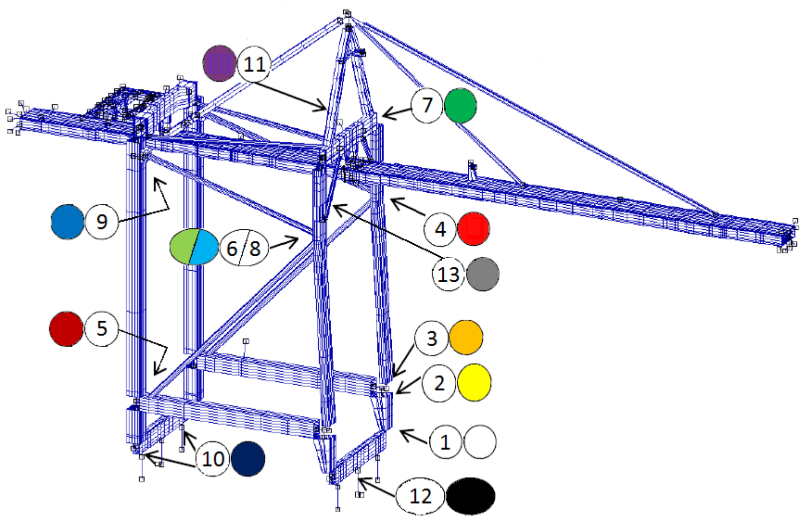


Figure 4.1 Overview of bolted connections

The orientation of the flanges can depend on a number of factors of which the assembly of the crane and the method of transport form two of them (see Figure 4.2 for a typical bolted flange plate). In general the flanges will be orientated horizontally with the exception of the connection between the upper legs and the portal beams (omitting the connections of the ties).

- If the top structure can be placed on top of the upper legs, the flanges of the upper legs will be orientated horizontally (can be the case for component transport and in case of final assembly at the client's site, semi-erected transport where the top structure is not placed in the portal frame, and fully-erected transport but normally only in case of a small crane). The different types of transport and assembly will be explained in paragraph 4.7).
- If the top structure is to be lifted up between the legs the flanges of the upper legs will be orientated vertically (which is the case for strand jacking, see Figure 4.11b).

The reason for applying a bolted flange plate connection is due to the past situation of Cargotec Netherlands BV, whereby limited assembly capacity and transport capacity was available.
However, if the assembly and transport capacities are available the bolted flange plate connection could be replaced by a welded flange plate connection. It must be stated that with the use of bolted flange plate connections there is a degree of flexibility present, which welded flange plate connections do not offer. This can be the case if, for example, a crane cannot be transported fully-erected due to restrictions during voyage.

Figure 4.2 Bolted flange plate

4.3 Assembly of the portal frame of a Ship-To-Shore container gantry crane

Since the crane is composed of a number of components the assembly of these components forms an important aspect. The components have to be erected and fastened in order to have an operational structure that complies with the client's specification.

The crane is fully assembled in order to test the product before it is handed to the client. It may be the case that the crane runs its final tests at the client's quayside instead of at the manufacturer's site. The need for assembling the crane to a certain degree depends on, among others, the type of transport available for transport to the client, but also on the capacity of the manufacturer. The following reasons can be listed:

- Client wishes to have a fully erected crane on delivery;
- The possibility to assemble the crane at assembly site/ client site;
- Restrictions during voyage;
- Hoisting capacity and area capacity available for assembling the crane;
- Transport capacity available for transporting a heavy load;
- Others.

The general procedure for the built up of the portal frame is as follows in case it concerns bolted flange plate connections between the components (Figure 4.3) [55]:

- Lay out the reel plates with the welded block reel;
- Place the reel plates on the adjusted railway gauge and water level it with (there could be a height difference between the waterside rail and the landside rail);
- Placing the assembled travelling gear (wheels/bogies/balances/main balances are in line);
- Erect the sill beams;
- Erect the lower legs waterside and landside (temporary bracings are used for holding the assembly in position; for safety and security);
- Erect the cross girders (bolt holes for connecting the diagonal tie have not been drilled) (cross girders totally assembled including cable trays, railing, etcetera) (removal of temporary bracings);
- Erect the long legs waterside (line up the long legs, lower legs, sill beams, gantry);
- Erect the diagonal ties (bolted connection on cross girder has now been drilled, bolted connection on long legs has already been drilled);
- Erect long legs landside;
- Erect upper legs waterside and landside;
- Erect the horizontal ties;

- Further complete the portal with stairways, walkways, storm anchors, collision security for the gantry, main cable reel, cable locks, etcetera);

This general procedure will be used for the cost comparison between different concepts (paragraph 4.9), but this procedure can differ slightly depending on the crane.

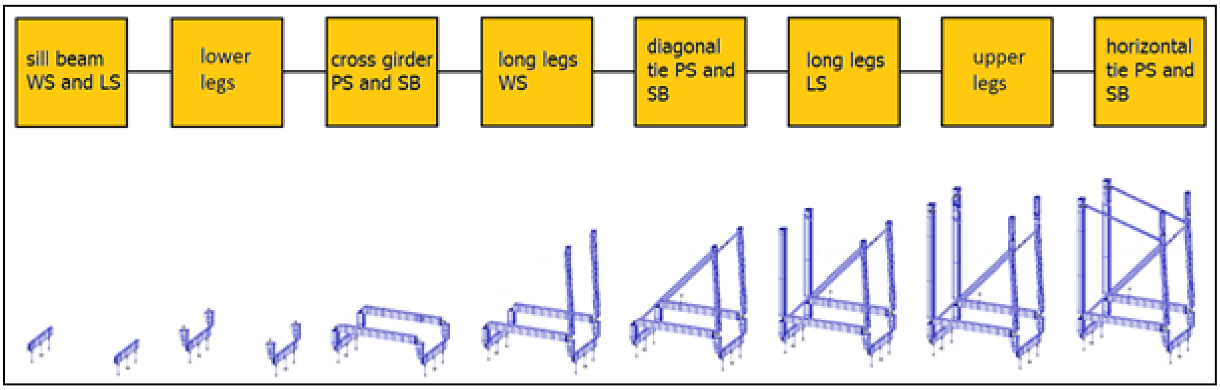


Figure 4.3 Assembly sequence bolted portal frame

The sequence in which the crane is assembled has its reflection on the way of transport; component transport, semi-erected transport and fully erected transport (this will become of importance when discussing the influence of sea transport on the connection between the portal frame and the upper structure, paragraph 4.7). The following assembly methods can be distinguished if it concerns semi-erected transport.

Four methods can be discussed for the assembly sequence in case of semi-erected transport:

1. The first method consists of placing the bogie sets with the sill beams. The next step is to place the top structure onto the sill beams, after which the portal SB and portal PS will be placed. In this way the top structure is between the legs of the crane. When placing the top structure in the right position for final assembly, strand jacking (a method where winches are placed upon the upper legs; the top structure is hoisted upwards and then fastened) is used. The top structure can be placed on the sill beams with a floating crane barge or with self-propelled modular vehicles (Figure 4.4a).
2. The second method consists of placing the bogie sets with the sill beams on which then the portal SB is placed (Figure 4.4b). Then next step is the placement of the upper structure on the sill beams, after which the portal PS is placed in position. Also in this case strand jacking is used for placing the top structure in the right position at the client's site.
3. The third method consists of the placement of the bogie sets with the sill beams, after which the portal SB and portal PS will be placed. The top structure is then positioned in between the

legs of the crane, by using a floating crane barge. Also in this case strand jacking is used for placing the top structure in the right position at the client's site.

4. The fourth method is to transport the lower and top structure separately. In this case the top structure will be placed onto the upper legs by using a floating crane barge (Figure 4.4c).

If it concerns fully erected transport the crane is fully assembled at the assembly site. This means that the use of strand jacking is not there. A floating crane barge can be used to place the top structure onto the upper legs.

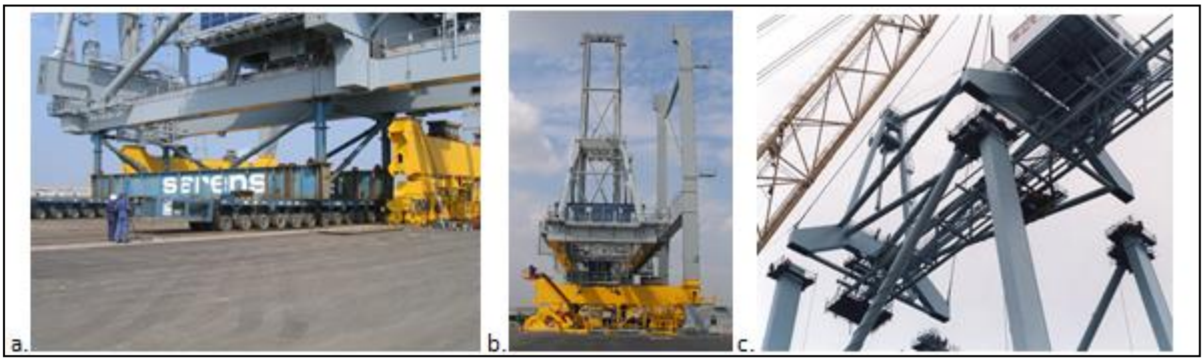


Figure 4.4 a) Placement of the upper structure on top of the sill beams b) semi-erected crane, whereby the side portal starboard is placed c) Placement of the upper structure onto the portal frame

4.4 Production site and assembly site

With regards to the production and assembly cost it must be pointed out where the production and assembly site are located (to state this clearly they are separated), and how the transport of components in between is arranged (Appendix S provides an overview of the hoisting capacity of the sites, Appendix Y can be reviewed for the site maps of both the production and assembly sites). Figure 4.5 gives a flow diagram of the different phases.

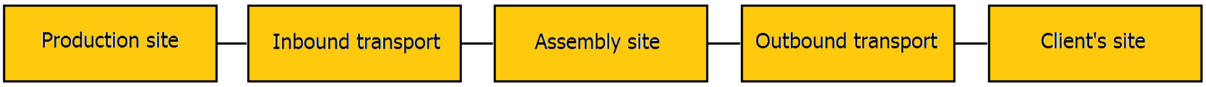


Figure 4.5 Phases for production, assembly and transport

Production site

The production site is located in Nantong (Jiangsu province, P.R. China), which entails the fabrication of components, painting, and packaging before shipment to the assembly site. The production site is separate from the assembly site, which is why the components are loaded onto barges for shipment to the assembly site. The production site does not only focus on the production of Ship-To-Shore container gantry cranes, but also offshore cranes and others.

Shipment (inbound transport)

Shipment of components is done with the use of barges, where components are placed (separately) onto the barges. For the barges there are not capacity limitations (both mass and dimensional aspects of the components, 650 – 841 m^2 deck surface area and 600 MT loading capacity, respectively), however, for the transport between the production and assembly sites there is a height restriction (5.3 m). Furthermore, due to the width of the barge[14] (which is limited to the dimensions of the waterway), sub-assemblies cannot be formed unless the sub-assembly forms an elongation along one axis of a number of components (e.g. the formation of the sub-assembly long leg – upper leg) or small sub-assemblies (e.g. the formation of the sub-assembly sill beam – gantry travelling gear connection). Once the barge arrives at the assembly site the barge will be unloaded and the components will be transported to either the yard area of Taicang Port or the assembly halls (in case of the RCI assembly site) for storage and preparation. It must be said that for smaller components transport may take place using heavy load trucks.

[14] Two types of barges are used. Dimensions of the deck surface area of the barges are:

1. 58 m length, 14.5 m width
2. 52 m length, 12.5 m width

Assembly site

For the assembly site two locations can be distinguished, which have been listed below.

Assembly site

Taicang Port	RCI assembly site
All hoisting equipment needed for the assembly of the crane is rented	All hoisting equipment is property of the company, with the exception of auxiliary hoisting equipment and floating crane barges
Assembly area consists of a quayside and a yard area. For the assembly of the crane at the quayside a limited amount of space is present. Assembly area is rented.	The assembly area consists of assembly halls and a assembly area with quayside. For the assembly of the crane it can be assumed that there are no space limitations. Assembly site is company property.

Currently Cargotec Netherlands BV is using the assembly site at Taicang Port, but in the future the RCI assembly site will be used.

Outbound transport and the client's site

After assembly of the crane (to either full erection or semi-erection) the sea fastenings will be mounted on the crane, preparing the crane for sea transport (or outbound transport). For sea transport a vessel is rented. In this case there is a dependency on the available vessels on the market. After sea transport the crane is delivered at the client's site.

4.5 Cost of a bolted flange plate connection

As brought forward in the introduction, the choice for a bolted or welded flange plate connection is (besides external factors) an economic evaluation. With the removal of the bolted flange plates, production and assembly cost are removed. The size of the assembly cost will depend on the manner of assembly, which will come forth at the comparison between different assembly concepts, however, the production cost (Appendix P) can be determined and form the motivation behind the desire to remove the bolted flange plates (see Appendix Y '*drawing of the sill beam WS*' for an example of a bolted flange plate in a steel construction).

For the production of the bolted flange plates a number of production steps can be distinguished. These steps have been used to determine the production cost for each individual bolted flange plate in the portal frame. The production steps entail a number of general items which have been stated below [56, 57].

- Needed work shop area
- Hoisting equipment for components and assemblies within the production site
- Transport equipment for components and assemblies within the production site
- Mounting equipment
- Production methodology
    - Material preparation
    - Primary shaping of the material
    - Secondary shaping of the material
    - Material treatments
    - Material surface treatments
    - Assembly
- Personnel

The production steps are all related to these general items. The cost of the bolted flange plates have been determined based on evaluation of the cost related to the flange plates of other projects and from the cost calculations provided by the production plant.

With regards to the production of a flange, there are a number of steps in the production process to be distinguished. For the production steps a line precedence diagram can be used as presented in Table 4.1.

Table 4.1 Precedence table of the production steps

Handling procedure no.	Handling procedure	Must be proceeded by handling procedure no.
1	Material preparation	-
2	Plate cutting	1
3	Fabrication of the girder	-
4	Bolt holes in the flange plate	1, 2
5	Welding of the flange plate to the girder	1, 2, 3, 4
6	Machining of the flange plate surface	1, 2, 3, 4, 5
7	Pre-assembly	1, 2, 3, 4, 5, 6
8	Blasting and painting	1, 2, 3, 4, 5, 6, 7

The other steps that can be distinguished have a relation to the transport and assembly phases. In general each phase contains a certain degree of measurement and inspection to ensure that the right component is used and attached accordingly to the right girder, etcetera. Furthermore, each phase contains a number of moves which in turn requires personnel and equipment.

With the application of a welded flange plate connection it must be noted that the cost with the production steps in Table 4.1 are not present in the same degree (this will be discussed in paragraph 4.6). From the viewpoint of a cost reduction it would therefore be of interest to determine the production cost associated with a bolted flange plate. Besides the cost during production, the cost during assembly also differ, due to the difference in assembly time and equipment needed.

The resulting flange plate production cost have been listed in Table 4.2 (see Figure 4.6 for an explanation of the notation for the flange plate). A remark with Table 4.2 is that the cost of components on starboard are the same as those on portside (it is a symmetrical steel structure regarding the main structural steel components).

Table 4.2 Flange plate cost production phase

Flange plate	Total production cost bolted flange plate connection [Euro]
Sill beam connection storm brake WS	2,800
Sill beam connection main balance WS	1,900
Sill beam connection storm brake LS	2,800
Sill beam connection main balance LS	1,900
Lower leg connection sill beam WS	2,500
Lower leg connection sill beam LS	2,300
Lower leg connection cross girder WS	3,300
Lower leg connection cross girder LS	2,900
Cross girder connection long leg WS	2,600
Cross girder connection long leg LS	2,700
Cross girder connection lower leg WS	3,800
Cross girder connection lower leg LS	2,900

Cross girder connection diagonal tie PS	1,400
Long leg connection cross girder WS	2,100
Long leg connection upper leg WS	2,300
Long leg connection diagonal tie PS	900
Upper leg connection long leg WS	2,300
Upper leg connection portal beam WS	2,400
Upper leg connection tie portal frame	500
Long leg connection cross girder LS	2,000
Long leg connection upper leg LS	1,900
Upper leg connection portal beam LS	2,600
Upper leg connection long leg LS	1,800
Portal beam connection Upper leg WS	4,000
Portal beam connection tie portal frame	700
Portal beam connection upper leg LS	4,200
Tie portal frame connection upper leg	700
Tie portal frame connection portal beam	500
Diagonal tie connection cross girder PS	1,000
Diagonal tie connection long leg PS	1,000
A frame connection	1,500

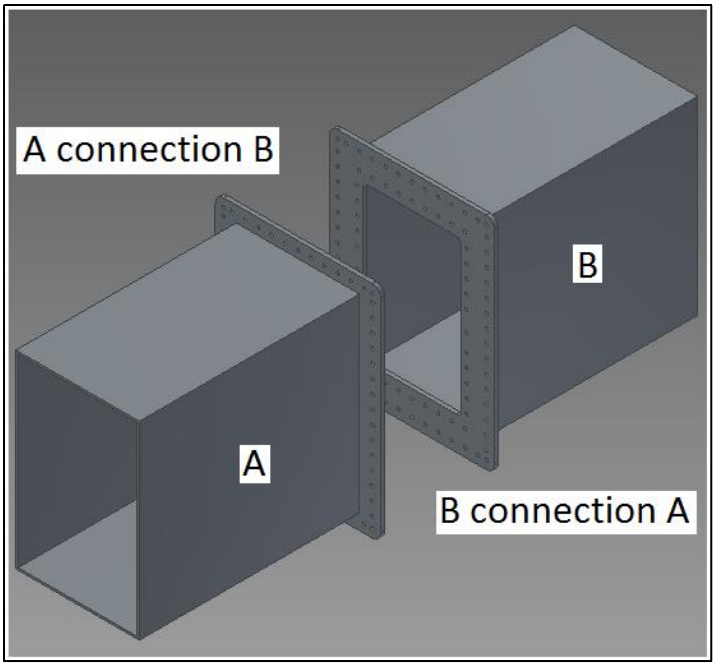


Figure 4.6 Bolted flange plate connection

4.6 Cost of the welded flange plate connection

Even though the production cost of the bolted flange plates have been determined the assembly cost of the bolted flange plates will have to be determined depending on the assembly sequence and the equipment and personnel involved. For the welded connection, however, the cost involved for the production phase will dependent on the design of the welded connection.

There are a number of factors to take into account when realizing a welded connection between two girders:

- From the perspective of the assembly site, reducing the size of the weld and the number of welds that will have to be made at the assembly site will influence the assembly cost;
- From the perspective of assembly, the connection should facilitate the alignment of the girders.

Assembly site perspective

In Figure 4.7a a sectional view of the bolted connection is displayed. When removing the bolted flange plates the connection could be realized as in Figure 4.7b and 4.7c, however, it has to be kept in mind that the assembly of the components requires open field welding. With the bolted flange plate connection the welding of the flange plates is performed on the production site, where the cost that are allocated to welding are very low. If the welded connection as in Figure 4.7b and 4.7c is to be performed this will lead to a very long assembly times and large cost (see also Table 4.4 '*Welding time [hr]*'). A method of reducing this welding time is to increase the number of welders working on the connection (has already been assumed to be a maximum of two welders per connection) or to have the welding time divided over the production phase and the assembly phase. From this perspective the connection as displayed in Figure 4.7d is an option. By having the welded flange plate attached to one of the girders at the production phase, the welding time at the assembly site will be reduced by half. This will significantly influence the cost in case all hoisting equipment is rented.

Assembly perspective

One of the characteristics of a bolted flange plate connection is the flexibility this type of connection gives during vertical assembly for the alignment of the girders. With the removal of the bolted flange plate connection this flexibility is lost. In order to compensate this loss and thereby ensure the alignment of the girders, (temporary) guiding structures have to be in place. Figure 4.7c displays the lengthening of the length stiffeners to act as guiding rails, Figure 4.7d displays plate elements on the flange plate. In this case it would be best to have these guiding structures restricted to temporary plate elements, such as in Figure 4.7d, in order to prevent any damage during assembly to any component of the girder.

A remark is to be placed with the flange plate connection. The flange plate is not considered to be a cross stiffener. Therefore it does not act as a component that transfers a force to all sides of the girder or to provide torsional stiffness (even though it can function as such). For a vertical connection between two girder this is the case, but if the connection is to be realized between a vertically standing girder and a horizontally lying girder this is not the case. In that situation the flange plate for a welded connection will function as a point where the stresses from one components have to flow to the other components. For the vertical connection this is also the case, but in this case the stresses have to flow from a vertically standing girder into a horizontally lying girder (see Appendix Y). The flange plate can act as a component to realize this. If, however, the connection would be modeled as in Figure 4.7b (one end of the girder welded to the side of another girder), this would lead to a very unfavorable connection. Having stated this, the welded connection will be assumed to be a welded flange plate connection.

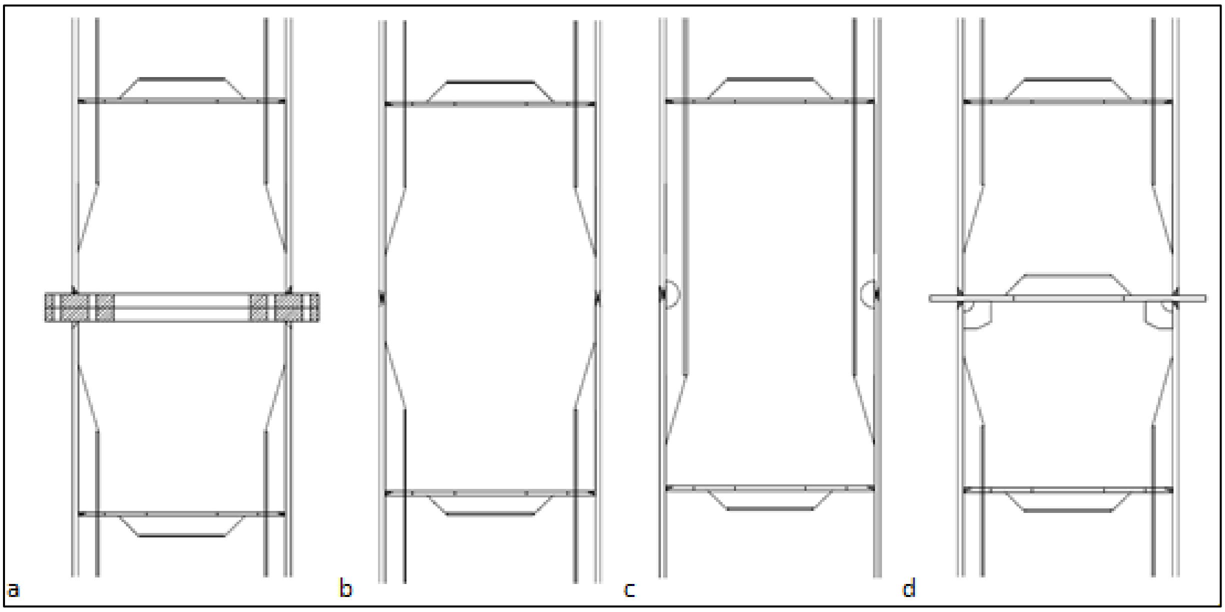


Figure 4.7 Sectional view a) Bolted flange plate connection b) Welded connection without flange plate (no lengthening of length stiffeners) c) Welded connection without flange plate (lengthened length stiffeners) d) Welded flange plate connection

With regards to the cost of a welded flange plate connection it can be said that even though the removal of the bolted flange plates will lead to a reduction of the production cost, the replacement by a welded flange plate will bring with it other production cost. In order to estimate these cost it has been assumed to have these cost set at 20, 30 or 40% of the production cost of the bolted flange plate connection (Table 4.3, Appendix Q). When reviewing the cost of the bolted flange plates (Appendix P), it can be noted that the largest part of the cost comes from the purchase of bolts and the milling of the flange plate surface. In case of a welded flange plate the requirement will be less stringent. A further advantage of this assumption is that the welding times for realizing the connection do not have to be changed (Table 4.4) [61].

Table 4.3 Welded flange plate production cost

Flange plate component	Total production cost bolted flange plate connection [Euro]	Production cost welded flange plate connection 20% [Euro]	Production cost welded flange plate connection 30% [Euro]	Production cost welded flange plate connection 40% [Euro]
Sill beam connection storm brake WS	2,800	600	800	1,100
Sill beam connection main balance WS	1,900	400	600	800
Sill beam connection storm brake LS	2,800	600	800	1,100
Sill beam connection main balance LS	1,900	400	600	800
Lower leg connection sill beam WS	2,500	500	800	1,000
Lower leg connection sill beam LS	2,300	500	700	900
Lower leg connection cross girder WS	3,300	700	1,000	1,300
Lower leg connection cross girder LS	2,900	600	900	1,100
Cross girder connection long leg WS	2,600	500	800	1,000
Cross girder connection long leg LS	2,700	500	800	1,100
Cross girder connection lower leg WS	3,800	800	1,100	1,500
Cross girder connection lower leg LS	2,900	600	900	1,200
Cross girder connection diagonal tie PS	1,400	300	400	500
Long leg connection cross girder WS	2,100	400	600	800
Long leg connection upper leg WS	2,300	500	700	900
Long leg connection diagonal tie PS	900	200	300	300
Upper leg connection long leg WS	2,300	500	700	900
Upper leg connection portal beam WS	2,400	500	700	1,000
Upper leg connection tie portal frame	500	100	200	200
Long leg connection cross girder LS	2,000	400	600	800
Long leg connection upper leg LS	1,900	400	600	800
Upper leg connection portal beam LS	2,600	500	800	1,100
Upper leg connection long leg LS	1,800	400	500	700
Portal beam connection Upper leg WS	4,000	800	1,200	1,600
Portal beam connection tie portal frame	700	200	200	300
Portal beam connection upper leg LS	4,200	800	1,200	1,700
Tie portal frame connection upper leg	700	100	200	300
Tie portal frame connection portal beam	500	100	200	200
Diagonal tie connection cross girder PS	1,000	200	300	400
Diagonal tie connection long leg PS	1,000	200	300	400
A frame connection	1,500	300	500	600

Table 4.4 Welding time

Flange plate connection	Welding time [hr.]	Assembly time horizontal assembly[hr.]
Storm brake connection sill beam WS	31	20
Main balance connection sill beam WS	77	43
Storm brake connection sill beam LS	31	20
Main balance connection sill beam LS	77	43
Lower leg connection sill beam WS	72	40
Lower leg connection sill beam LS	51	30
Lower leg connection cross girder WS	104	56
Lower leg connection cross girder LS	104	56
Cross girder connection long leg WS	62	35
Cross girder connection long leg LS	40	24
Cross girder connection lower leg WS	102	55
Cross girder connection lower leg LS	40	24
Long leg connection cross girder WS	39	24
Long leg connection upper leg WS	42	25
Upper leg connection long leg WS	62	35
Upper leg connection portal beam WS	42	25
Long leg connection cross girder LS	18	13
Long leg connection upper leg LS	26	17
Upper leg connection portal beam LS PS	88	47
Upper leg connection long leg LS PS	26	17
Upper leg connection portal beam LS SB	45	27
Upper leg connection long leg LS SB	36	22
Portal beam connection upper leg WS	168	87
Portal beam connection upper leg LS	37	23
Tie portal WS	40	24
Diagonal tie	61	35
Horizontal tie	50	29
A-frame	41	24

For the assembly time for horizontal assembly an additional time of 4 hours is assumed in case of horizontal or vertical placement of components. This contains placement, preparation and inspection. The connection is realized by using two welders.

In this case the assumption has been made to let the components remain as they are and only to focus on the bolted flange plates. If this assumption is led loose that the components are not to be changed, a different design can be proposed with regards to the components. In this case the lower leg, attachment for the cross girder, long leg and upper leg can be seen as one component.

The welding times have been determined by reviewing existing projects of which certain connections have been welded. Of these connections the welding volume has been used, in combination with the know welding time, in order to determine a welding capacity (expressed in mm^3/hr). By reviewing the case study crane the welding volume for each flange plate – girder connection has been determined, thereby leading to the welding time. For the welding time additional time has been factored in for installing and others based on reviewing existing projects.

4.7 Connection considerations

The replacement of bolted flange plate connections will have an influence on the production, assembly and transport, but this can also be said the other way around. For the way the crane is assembled there are two key factors to be distinguished, which are the assembly capacity (expressed in the area and available hoisting capacity) and the limitations from sea transport. The connection overview in Figure 4.2 can thus be divided into two main groups whereby certain connections are reviewed from the perspective of sea transport (whether they should be bolted or welded) and certain connections are reviewed from the perspective of the assembly capacity (Table 4.5, Figure 4.8).

Table 4.5 Connection from the perspective of sea transport or assembly capacity

Group	Connection no.
Sea transport	7, 10, 11, 12, 13
Assembly capacity	1, 2, 3, 4, 5, 6, 8, 9

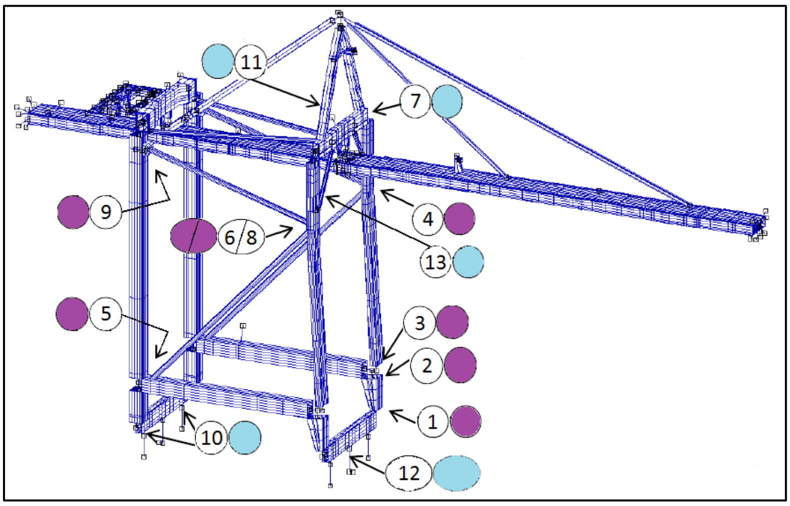


Figure 4.8 Sea transport influence (light blue), assembly capacity influence (purple)

4.7.1 Sea transport

Sea transport consists of the transport of a number of cranes from the assembly site to the client's site. In the case of Cargotec Netherlands BV the company is dependent on the availability on the market of a vessel for the transport of its Ship-To-Shore container gantry cranes. This vessel will depend on the number of cranes to be transported, the location of the client, the availability of equipment at the client's site and others, which in turn determines whether a crane is transported in components, semi-erected or fully erected and its manner of (un-)loading. Having said this, sea transport will have an influence on the following connections (Figure 4.9):

- The connection between the portal frame and the upper structure (also referred to as the connection between the upper legs and the portal beams, connection no. 7);
- The connection between the sill beam and the main balance (connection no. 10);
- The connection between the sill beam and the storm brake (connection no. 12);
- The connection of the A-frame (connection no. 11);
- The connection between the ties on WS with the upper legs and portal beam (connection no. 13).

Each will be discussed separately from a cost perspective or by stating the restrictions or situations which determine whether it should remain bolted or become welded.

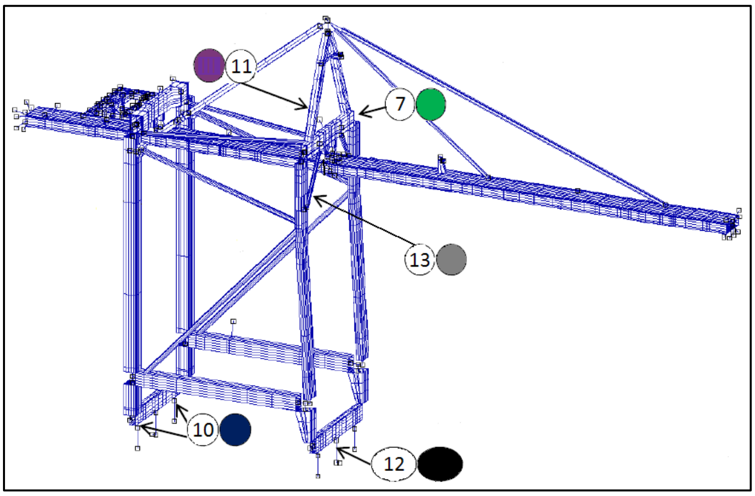


Figure 4.9 Connection overview influenced by sea transport

4.7.1.1 The influence of sea transport on the connection between the portal frame and the upper structure

The interest is to point out the influence of sea transport on the connection between the upper structure and the portal frame (Figure 4.10), thereby also taking into account the different methods for (un-)loading. This is done to determine whether or not to have the connection between the portal frame and upper structure bolted or welded. The determination is based on a cost calculation on which the (un-)loading method has an influence.

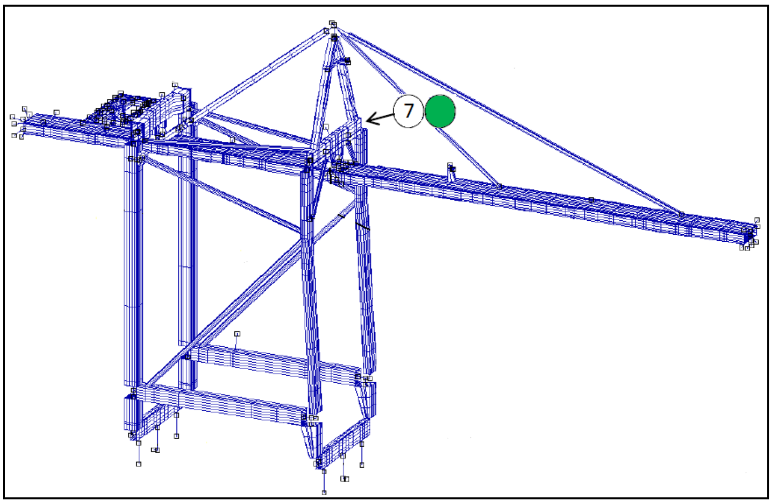


Figure 4.10 Connection between the portal frame and upper structure

For the calculation an existing crane example is used concerning the transport of four (4) Ship-To-Shore container gantry cranes from Taicang (P.R. China) to a client in Mexico. Any restrictions experienced, which would limit the comparison between different loading methods, will be left out. Although it will be assumed that if a certain loading method is applied, this same loading method will also be applied for unloading[15]. In this case the company has the preference for the roll on, roll off method using SPMTs[16]; the (un-)loading method will be specified towards this and towards the use of a Floating Crane Barge (FCB). For semi-erected and fully erected transport the following aspects can be considered [54].

Semi-erected transport

1. Semi-erection
2. Sea transport to the client
3. Placing in rail
4. (self) Erection
5. Final assembly
6. Commissioning

Fully erected transport

1. Erection
2. Final assembly
3. Pre-commissioning
4. Sea transport to the client
5. Placing on rails
6. Commissioning

[15] The assumption is not valid in each situation, depending on the availability it is possible to have one method for loading and another method for unloading.

[16] Skidding shoes have been used by Cargotec Netherlands BV for the last three projects, but have not been taken into account for the cost calculation. The assumption has been made that the use of SPMTs or a FCB is standard, which has been the case in the past.

For the calculation only the erection, assembly and transport phases are of interest. The commissioning aspect will be left out of the overview and is assumed to be the same for each situation.

It must be stated though that the focus before shipment is only on the connection between the upper structure and the portal frame. For the manner in which the connection is realized a number of situations have to be taken into account:

1. Connection between the upper structure and the portal frame is bolted. The crane is fully assembled before shipment. The cost with the assembly between the upper structure and the portal frame are taken into account (use of a FCB, Figure 4.11a). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs or FCB, whereby the cost is determined for this type of fully erected transport[17].
2. Connection between the upper structure and the portal frame is welded. The crane is fully assembled before shipment. The cost with the assembly between the upper structure and the portal frame are taken into account (use of a floating barge crane, removal of flange plate production cost).). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs or FCB, whereby the cost is determined for this type of fully erected transport.
3. Connection between the upper structure and the portal frame is bolted. The crane is fully assembled at the client's site. The cost with the assembly between the upper structure and the portal frame are taken into account (use of a floating barge crane). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs or FCB, whereby the cost is determined for this type of semi-erected transport.
4. Connection between the upper structure and the portal frame is bolted. The crane is fully assembled at the client's site. The cost with the assembly between the upper structure and the portal frame are taken into account (use of strand jacking, Figure 4.11b). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs whereby the cost is determined for this type of semi-erected transport.
5. Connection between the upper structure and the portal frame is welded. The crane is fully assembled at the client's site. The cost with the assembly between the upper structure and the portal frame are taken into account (use of a floating barge crane). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs or FCB, whereby the cost is determined for this type of semi-erected transport.

[17] If a floating crane barge is used for the assembly it would be logical to also use this floating crane barge for (un-)loading the crane onto (off) the vessel.

6. Connection between the upper structure and the portal frame is welded. The crane is fully assembled at the client's site. The cost with the assembly between the upper structure and the portal frame are taken into account (use of strand jacking[18]). The different (un-)loading methods will be specified towards roll on, roll off using SPMTs whereby the cost is determined for this type of semi-erected transport.

Beside the distinctions made above, the different assembly locations also have to be taken into account. This concerns either assembly at Taicang Port (where all hoisting equipment for assembly has to be rented) or assembly at the RCI assembly site (where all main hoisting equipment for assembly is company property).

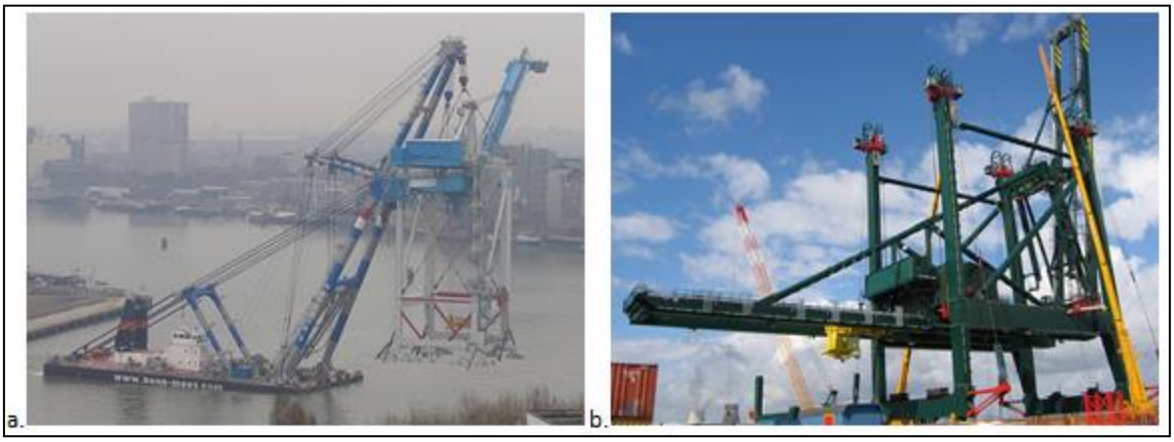


Figure 4.11 a) Placement of crane on rail using a floating crane barge b) Erection of crane on site using strand jacking

The way the portal frame is assembled or produced has its influence on the way the crane is transported and the cost involved. In general the following options can be distinguished (not taking into account the type of flange connection):

- If the side portal is partially or completely assembled apart from the sill beam assembly (with the crane travelling gear) all options for transport (except component transport) are available;
- If the portal frame with or without the crane travelling gear is fully erected at the manufacturer's site, semi-erected transport and fully erected transport are the options available.

The type of self-propelled vessel (as opposed to a barge which is a non-self-propelled vessel) is left out of the overview and a fixed cost is assumed for the use of this vessel. In this case the cost of the

[18] With strand jacking the connection between the portal beam and the upper legs is difficult to reach in case of welding, unless the portal beam can be secured. This would allow the removal of the strand jacking equipment (or part of it) so that the welded connection can be realized.

vessel depends on the number of cranes to be transported, the size of the vessel, the length of the voyage and the type of vessel used (among others). There are three types of vessels to be distinguished of which one is related to component transport. The remaining two are either dock ships or semi-submersible ships. Dock ships are the type of vessel focused on for the transport of cranes, though in some cases semi-submersible vessels can also be used.

For the type of (un-)loading a number of methods can be distinguished (which also involves the placement of the crane onto the rails at the client's site) [62-66]:

- Floating crane barge; a floating crane barge is used for either assembling the upper structure with the portal frame or for lifting the entire crane and place it onto the rails or vessel (Figure 4.12a);
- Roll on, Roll off with self-propelled modular transporters (SPMTs): self-propelled vehicles are used (in combination with a support frame) to drive the crane on and of the vessel and place it onto the rails or vessel (Figure 4.12b);
- Roll on, Roll off bogies: similar to the use of SPMTs, separate bogies can be used with a winch. The crane is jacked up to fit the travelling bogies (or to turn the crane's own bogies) and then lowered onto a temporary rail to roll on or off the vessel (Figure 4.12c);
- Skidding: skidding involves sliding the crane on or off the vessel using low friction plates located in a channel-shaped slide beam (Figure 4.12d);
- Forklift: the crane is lifted completely by support structured attached to the side of the crane (outer riggers). Once the crane is lifted using the outer riggers the crane is skidded further onto the vessel (Figure 4.12e);
- Heavy lift ship: by using the mast cranes onboard of a heavy lift ship the entire crane can be placed on deck of the heavy lift ship without the use of additional auxiliary equipment.

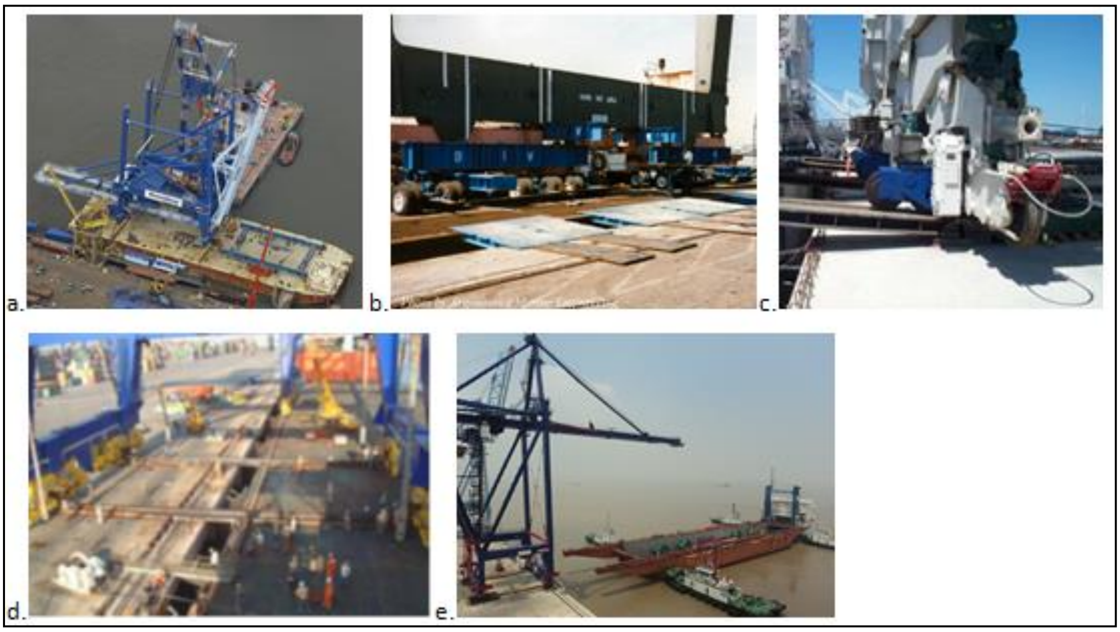


Figure 4.12 a) Loading with a floating crane barge b) Loading with Self-Propelled Modular Vehicles c) Loading with bogies d) Loading via skidding e) Loading via a ship using the forklift method

The positioning of the crane (and thereby the decision to place the crane semi-erected or fully erected on the vessel) depends on the shipping route (loads experienced and thereby influencing the direction of placement on the vessel (taking into account the vessel stability) and restrictions experienced along the shipping routes such as height limitations), available berthing space, availability of vessels, and the number of cranes to be transported. The amount of sea fastenings on the crane will also be influenced. For the comparison this aspect will be assumed to be equal for each situation. Concerning the general orientation of the crane on the vessel the following options can be distinguished [62-66]:

- Longitudinal shipment; if a vessel is moored with either its bow or its stern towards the quay, the container crane is arranged longitudinally (Figure 4.13a);
- Transverse shipment; when the transport vessel is moored to the quayside with its side, the crane is arranged transversely on board (Figure 4.13b);

Besides the general orientation the boom position can also be changed depending on the number of cranes to be transported and the available deck space of the vessel [62-66]:

- Lowered completely (fixed to the deck of the vessel, Figure 4.14a).
- Lowered (working condition)
- Raised to the APEX of the crane (Figure 4.14 b);

Figure 4.13 a) Longitudinal loading b) Transverse loading

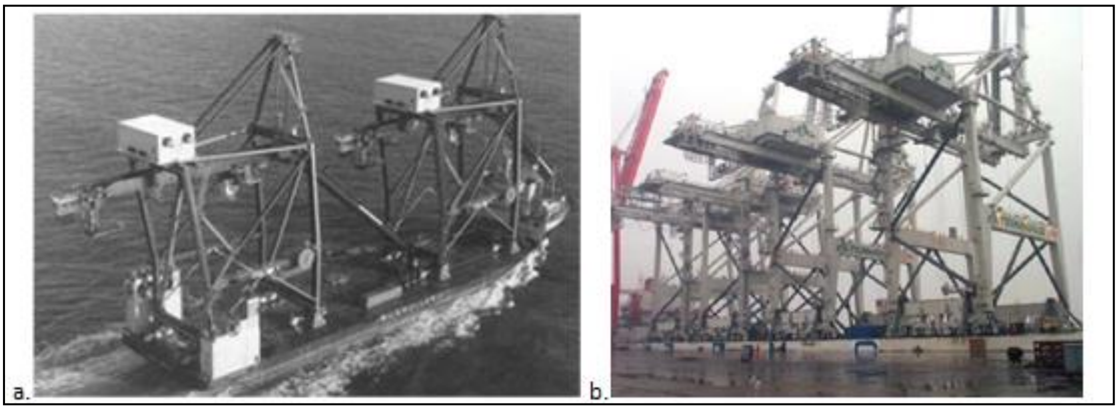


Figure 4.14 a) Boom lowered to the deck of the ship b) Boom raised to the APEX of the crane

Stowing multiple cranes onto a vessel with a limited free deck space, often results in transverse stowage. The width of a crane is typically limited to a maximum distance between the gantry bumpers (which can be removed, if the total width is too large) of 27 m to permit two cranes to work side-by-side on alternate hatches. Even with its boom up, this length is much greater, given the crane's back reach. Unless the cranes can be nested (with their superstructures temporary secured at different elevations), a transport of 3 cranes typically shows the cranes stowed transversely. These days, the typical crane rail spacing is 30m, which fits transversely on a Panamax size ship with a beam of 32.2m. When a project cargo ship is used and the crane is lifted on and off using the ship's own hoisting gear, the container crane is typically stowed transversely, as rotating it with the ship's cranes is difficult if not impossible.

A transverse stowage is often more favorable for the crane structure as the largest forces are acting in the stiffest direction of the crane. The crane structure is designed to lift heavy containers at the tip of its boom, from where the trolley travels towards the quayside with the load, resulting in a bracing in each of its side planes to ensure stiffness in the trolley travel direction. To allow for the container to pass through, the water and landside portals however are open, which makes the crane less rigid in the crane travel direction. Smaller reinforcements are required in the water and landside portals if they are subjected to lesser pitch motions.

Stowing a crane with the boom up allows for securing of the boom to the APEX. With the boom down, securing the boom is more complicated as this may require pipe bracings or tension rods back to the portal beam. With 2 cranes stowed longitudinally, the boom of the aft crane may have to be slightly raised to clear the crane in front. Occasionally, a crane is transported with its boom rotated all the way down, with its boom tip resting on the deck, on a special support. This option requires an additional set of (lower) boom hinges and longer boom hoisting wires, or a separate lowering winch. The forestays need to be disconnected from the boom and secured.

With a crane stowed on deck with its boom horizontal (working condition), the stability will be greater and the ship will be stiffer (shorter natural roll period), resulting in higher lateral accelerations. But, because the crane's center of gravity is lower, the net increase may be small. The total inertia force on the horizontal boom is likely smaller as its center of gravity is much lower compared to the boom up situation. Also the total wind area is smaller (if it concerns transverse stowage of the vessel), which combined with the increased stability results in a smaller wind angle of roll. The angle of roll is defined as the angle of heel to either starboard or portside due to the ship being unstable when upright. Stated otherwise it is the resulting angle that the ship makes at the moment when the center of buoyancy is directly below the center of gravity.

When looking at the general cost of the transport of cranes the following items can be listed [62]:

1. Cargo insurance premium for transportation;
2. Day rate;
3. Speed of the ship can partly offset its day rate;
4. The transport schedule affects the fabrication and delivery schedule. A faster transport can result in a later departure, leaving more time for commissioning;
5. Mobilization and demobilization cost for the marine equipment and all specialized loading and offloading equipment;
6. Material, fabrication, installation, and removal of the sea fastening and crane reinforcement are largely dependent on the design accelerations;
7. Rental cost of the auxiliary equipment for loading and offloading, such as mobile cranes, forklifts, man lifts, welding machines, including all consumables, qualified operators;
8. Operational marine cost for tug boats, pilots, line handlers, long shore labor, dock fees, agents;
9. Travel expenses and board and lodging for supervisors, representatives, surveyors;
10. Shipment of equipment back to the manufacturer.

Of these items only the day rate (2), the mobilization and demobilization cost for marine equipment and all specialized (un-)loading equipment (4), rental cost of auxiliary equipment for (un-)loading (7) and the shipment of equipment back to the company (10) are taken into account. The cost involved for sea-fastening (6) are taken as equal regardless of the type of transport. Other items have been allocated to the transportation cost. It must be stated though that the cost for transport are not completely allocated to the company only.
Part of the transportation cost are sometimes carried by the client (such as the insurance for the transport).

The day rate has been fixed to the distance travelled from the assembly site in Nantong to the client in Mexico. The cost for transport of semi and fully erected can be divided according to the distance travelled, but the focus is in this case only on this route. The reason for this is because the production cost of the bolted flange plates connections and the welded equivalents have been based on this project.

The possibility of component transport is excluded, because the focus of the removal of the bolted flange plates is that the portal frame will be erected completely. The only option that remain in the case that the portal frame is completely erected are semi-erected and fully erected transport.

With regards to semi-erected transport a number of remarks are to be made prior to the cost calculation.

- Semi-erection on site

  Use of a floating barge crane or overhead crane (with personnel) for placing the upper structure on the sill beams or the decision is made to place the upper structure separately. The alternative is to place the upper structure on the strand jacking structure (which is placed on the sill beams). This does mean that the erection on site is either performed by floating crane barge or by strand jacking. Furthermore due to the placement between the legs of the portal frame only (un-)loading methods that lift the crane from the bottom up can be used. Cargotec Netherlands BV has the preference to use the roll on, roll off method using SPMTs. A distinction has to be made here between semi-erection on the assembly site in Taicang Port or at the RCI assembly site.
- Transport to the client

  Transport consists of both the loading and unloading method as well as the transport itself, including the addition and removal of sea fastening. With unloading the placement of the crane on to the rails at the client's site is included.
- Erection at the client's site

This is performed either by strand jacking or by a floating crane barge. Auxiliary equipment in the form of mobile cranes is necessary for securing the connection between the upper structure and the portal frame. This also covers part of the final assembly of the crane.

Other phases such as (the remaining part of the) final assembly and commissioning can be considered the same for each situation.

With regards to fully erected transport also a number of remarks are to be made prior to the cost calculation.

- Erection on site

  Erection on site includes the final assembly, similar to the semi-erection transport with the erection at the client's site. Erection on site involves either the use of a floating crane barge (Taicang Port) or the use of an overhead crane (RCI assembly site).

- Transport to the client

  Transport consists of both the loading and unloading method as well as the transport itself, including the addition and removal of sea fastening. With unloading the placement of the crane onto the rails at the client's site is included. In this case the method of (un-)loading can be specified towards either the use of SPMTs or the use of a floating crane barge.

Other phases such as pre-commissioning and commissioning can be considered the same for each situation.

Based on the initially stated situations and the previously mentioned remarks the following tables have been constructed (Table 4.6 and 4.7, Figure 4.15 and Figure 4.16).

Table 4.6 Semi-erected transport concepts

Semi-erected transport			
Concept	Semi-erection on site	Transport	Erection at client's site
1	Separate handling of the portal frame and upper structure, Taicang Port	(un-)Loading with FCB	FCB, bolted connection
2	Separate handling of the portal frame and upper structure, Taicang Port	(un-)Loading with FCB	FCB, welded connection
3	FCB for placement of upper structure on sill beams for strand jacking, Taicang Port	(un-)Loading with SPMTs	Strand jacking, bolted connection
4	FCB for placement of upper structure on sill beams for strand jacking, Taicang Port	(un-)Loading with SPMTs	Strand jacking, welded connection
5	Separate handling of the portal frame and upper structure, RCI assembly site	(un-)Loading with FCB	FCB, bolted connection
6	Separate handling of the portal frame and upper structure, RCI assembly site	(un-)Loading with FCB	FCB, welded connection
7	Overhead crane for placement on sill beams for strand jacking, RCI assembly site	(un-)Loading with SPMTs	Strand jacking, bolted connection
8	Overhead crane for placement on sill beams for strand jacking, RCI assembly site	(un-)Loading with SPMTs	Strand jacking, welded connection

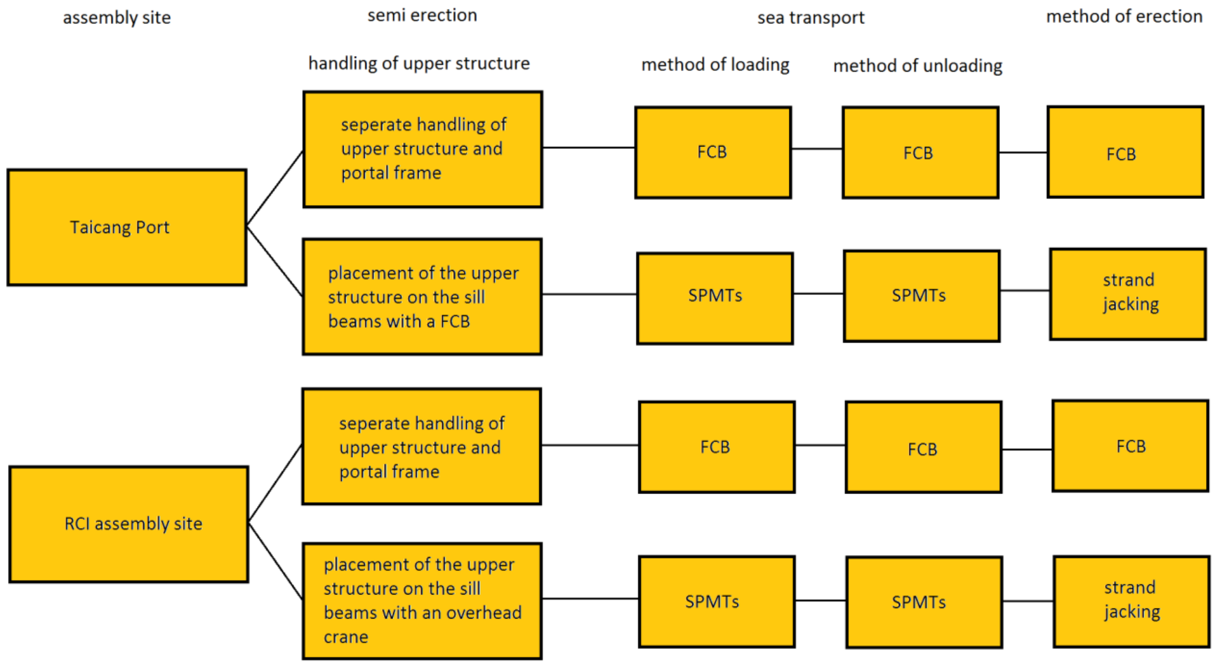


Figure 4.15 Semi-erected options

Table 4.7 Fully erected transport concepts

Fully erected transport		
Concept	Erection on site	Transport
9	FCB, Taicang Port, bolted connection	(un-)Loading with FCB
10	FCB, Taicang Port, welded connection	(un-)Loading with FCB
11	Overhead crane, RCI assembly site, bolted connection	(un-)Loading with FCB
12	Overhead crane, RCI assembly site, welded connection	(un-)Loading with FCB
13	Overhead crane, RCI assembly site, bolted connection	(un-)Loading with SPMTs
14	Overhead crane, RCI assembly site, welded connection	(un-)Loading with SPMTs

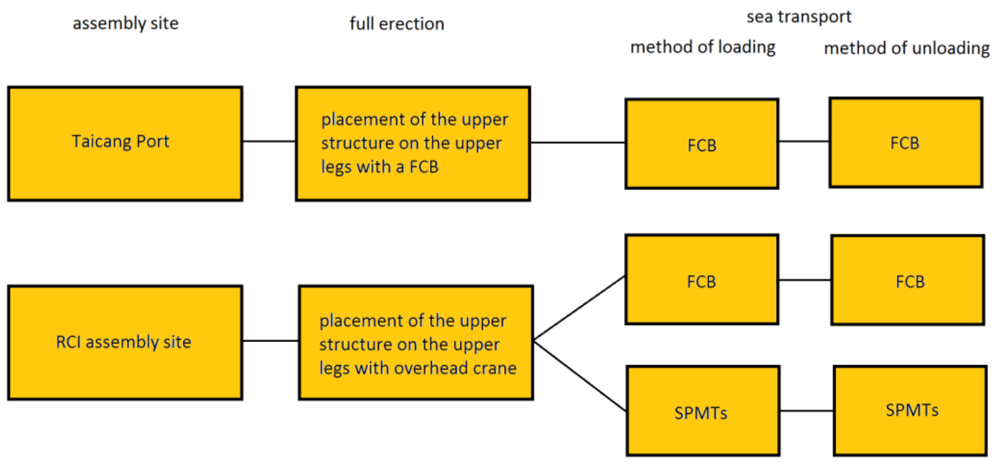


Figure 4.16 Fully erected options

It must be pointed out with Table 4.6 that in case the upper structure is loaded separately from the portal frame the (un-)loading cost have to be allocated twice.

Now that the different concepts have been brought forward the cost calculation can be made. An overview of the different cost has been listed in Appendix V for a bolted connection and a welded connection including an overview of the cost for the different concepts, of which in Table 4.8 a summary is presented.

Table 4.8 Cost overview per crane for the connection between the portal frame and upper structure

Concept	Type of transport	(un-)loading method	Bolted or welded connection	Location before shipment	Cost [Euro]
1	Semi-erected	FCB	Bolted	Taicang Port	731,000
2	Semi-erected	FCB	Welded	Taicang Port	811,000
3	Semi-erected	SPMTs	Bolted	Taicang Port	823,000
4	Semi-erected	SPMTs	Welded	Taicang Port	830,000
5	Semi-erected	FCB	Bolted	RCI assembly site	731,000
6	Semi-erected	FCB	Welded	RCI assembly site	811,000
7	Semi-erected	SPMTs	Bolted	RCI assembly site	949,000
8	Semi-erected	SPMTs	Welded	RCI assembly site	956,000
9	Fully erected	FCB	Bolted	Taicang Port	676,000
10	Fully erected	FCB	Welded	Taicang Port	751,000
11	Fully erected	FCB	Bolted	RCI assembly site	651,000
12	Fully erected	FCB	Welded	RCI assembly site	648,000
13	Fully erected	SPMTs	Bolted	RCI assembly site	731,000
14	Fully erected	SPMTs	Welded	RCI assembly site	748,000

As a conclusion it can be stated that, if it concerns semi-erected transport, the use of a bolted connection is always cheaper. The cost difference between assembly at Taicang Port and RCI assembly site can be appointed to the rental cost of the cranes for assembly that are taken into account or not. Furthermore, it can be stated that the cost difference in case of strand jacking between a bolted and welded connection is small. It can be assumed that in some circumstances the welded connection can also be done, though it will be dependent on a number of factors, such as client willingness to allow welding on site, environmental conditions, and so on. When reviewing the fully erected transport the conclusion can actually be drawn that in case it concerns assembly at the RCI assembly site a welded flange plate connection between the portal frame and the upper structure could be cheaper if erection loading is done with the use of a FCB. The reason for this is due to the removal of the bolted flange plate production cost and not having to allocate any rental cost to the cranes. In case it concerns erection at Taicang Port, the bolted flange plate connection is cheaper compared to its welded counterpart, due to the increased assembly time and the increased rental cost of the crane[19]. Even though in some situations it can be pointed out that the welded connection would be cheaper, in this case the assumption to have the connection between the portal frame and upper structure bolted is still maintained. The reason for this is because this cost calculation only concerns one project to a certain customer, other restrictions experienced during voyage have not been taken into account and the availability of a vessel to transport an unknown number of cranes is uncertain. Furthermore, for the assembly of the crane with the use of strand jacking is dependent on the weather conditions which is more critical with a welded flange plate connection. Therefore a bolted connection will be maintained in order to have flexibility to cope with these uncertainties.

4.7.1.2 The influence of sea transport on the connection between the sill beam and the main balance connection

With regards to the connection between the sill beam and the main balance connection (Figure 4.17) it can be said that this connection depends on the type of vessel for sea transport (in this case a dock ship, see Figure 4.12e or 4.13b). In case it concerns a dock ship using the forklift method the following can be said. The sidewalls of the dock ship are of importance with regards to this connection. The sidewalls run over the full length of the cargo space, protruding over the stern of the vessel. These outriggers are used for loading and unloading cargo, by applying the so-called forklift method. However for doing this the gantry travelling gear has to be turned 90°. For this reason the connection between the sill beam and the main balance connection was always bolted. However, this type of vessel is only suitable for the transport of a single large crane (knowing that crane orders from clients normally consist of orders larger than one (1) crane unit); nowadays the cranes are loaded and unloaded over the sides of the vessel, no longer requiring the gantry travelling gear to be rotated (with the exception when the crane is rolled onto the vessel via its own bogies). This means that the connection between the sill beam and the main balance connection can, in most cases, be welded.

[19] A factor that has not been taken into account is the type of contract that Cargotec Netherlands BV has with the client. In this contract it may be specified that the customer is responsible for all cost experienced during transport. This means that, depending on the type of contract that is agreed upon, the connection between the upper structure and portal frame could be bolted or welded depending on what is beneficial from the viewpoint of Cargotec Netherlands BV. Having stated this, it is clear that a single comprehensive solution for all cranes is not possible.

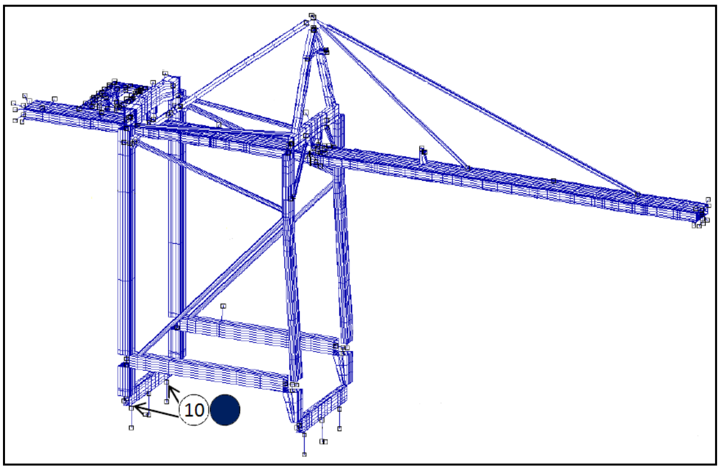


Figure 4.17 Connection between the sill beam and the main balances

Because of the size of the component that realizes the connection it is suggested to make this connection at the production site. This brings the advantage that any welding on the assembly site does not have to occur and also does not experience any restrictions for the inbound transport of components.

4.7.1.3 The influence of sea transport on the connection between the sill beam and the storm brake connection

For the connection between the sill beam and the storm brake (Figure 4.18) a restriction comes forth from use of the vessel for sea transport. If the storm brake would be welded before sea transport the storm brake would be in the way for loading the crane onto the vessel in case the crane is loaded via skidding or roll on, roll off via bogies. If a roll on, roll off via SPMTs would be applied the storm brake could not be applied anyway, because the support structure for the application of SPMTs below the sill beams could not be placed. In case of an FCB or the use of a dock ship with the fork lift method the storm brake could be welded to the sill beam, however not fully equipped.

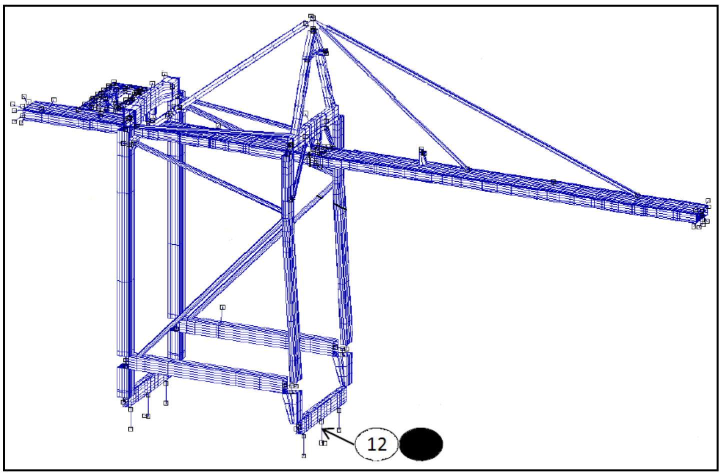


Figure 4.18 Connection between the sill beam and the storm brake

Therefore the connection between the sill beam and the storm brake is always bolted. The only option for reducing the cost of the bolted flange plate for this connection is by lowering the location of the connection as far as possible, to ensure that loading can still occur (but not in case of the preferred loading method of the company; SPMTs). The storm brake is in general a tapered construction; therefore lowering the location of the connection reduces the size of the bolted flange plate.

4.7.1.4 Influence of the sea transport on the A-frame and ties waterside

The remaining connections are the connection of the A-frame in the upper structure and the connection of the ties on the waterside, connection the upper legs with the portal beam (Figure 4.19). The connection of the A-frame is evaluated separately because this section is assembled separately from the portal frame. It belongs to the upper structure assembly.

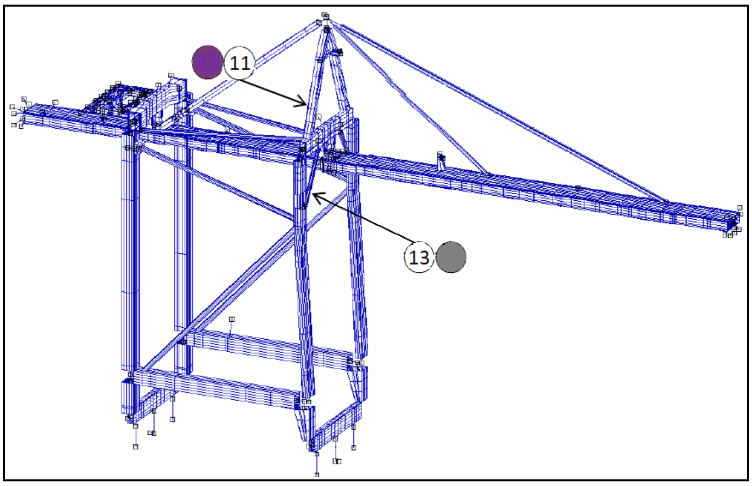


Figure 4.19 Connection of the A-frame (no. 11) and of the ties on the waterside (no. 13)

The reason why the connection of the A-frame with the rest of the upper structure is bolted is due to the height restrictions sometimes experienced during sea transport (Figure 4.20) or when it concerns component transport (where the volume of the components and sub-assemblies determines the transport cost). Depending on the type of transport this connection can either be bolted or welded.

Figure 4.20 A-frame positioned horizontally due to height restrictions experienced during sea transport

The cost that can be saved in case of welding instead of bolting is listed in Table 4.9a and 4.9b. It must be noted that the A-frame is pre-assembled with the cable block, before lifting.

Table 4.9a Bolted connection

Bolted connection

Equipment or otherwise	Description	Cost [Euro]
Mobile crane	One (1) 70 MT; 75 Euro/hr, 8 hr	600
	Two (2) dedicated workers; 15 Euro/hr	240
	One (1) building site manager; 55 Euro/hr	440
Lifting platform	Two (2); 55 Euro/hr; 8 hr	800
	Four (4) dedicated workers; 15 Euro/hr	480
	Two (2) building site managers; 55 Euro/hr	880
		3,440

Table 4.9b Welded connection

Welded connection

Equipment or otherwise	Description	Cost [Euro]
Mobile crane	One (1) 70 MT, 75 Euro/hr; 24 hr	1,800
	Two (2) dedicated workers; 15 Euro/hr	720
	One (1) building site manager; 55 Euro/hr	1,320
Lifting platform	Two (2); 55 Euro/hr; 24 hr	
	Four (4) dedicated workers; 15 Euro/hr	1,440
	Two (2) building site managers; 55 Euro/hr	2,640
Welding	Addition of welded flange plate cost (20%)	1,200
	Removal of production cost bolted flange plate	-6,000
		3,120

The connection of the ties with the upper legs and the portal beam (connection no. 13) is a connection that can only be reviewed after the upper structure has been mated with the portal frame. If the original use of the upper legs would have been there the components could have been placed during assembly of the portal frame (and could have been welded), however, since in practice this is not done this option is omitted (see paragraph 4.7.2.2). Furthermore, if the ties would have been placed during the assembly of the portal frame the option of self erection via strand jacking would not have been possible. The only (un-)loading and erection option remaining would be the use of a FCB, which does not provide enough flexibility in case of limited resources at the client's site.

The point is where the crane will be fully assembled (or where the upper structure will be mated with the portal frame). If this is at the client's site the connection can be welded or bolted, but the preference will be to have this bolted to limit the time spend on the client's site.

If the connection is realized at the assembly site of the company, there may still be an issue with welding this connection because of the sea fastenings that have to be placed in the portal frame, which in turn depends on the orientation of the crane on the vessel for sea transport (longitudinal or transverse). In order to have as much flexibility as possible the connection is assumed to be bolted.

4.7.2 Assembly capacity

A number of connections are identified as mainly being influenced by the assembly capacity available (Figure 4.21). When the portal frame is build-up several sub-assemblies can be made, however in order to lift these sub-assemblies (and of course components themselves) the hoisting capacity needs to be available. Furthermore, in order to make sub-assemblies there needs to be sufficient space to lay out the sub-assemblies (the same can be said for the components individually), before final assembly. This becomes more critical if the number of cranes to be produced increases.

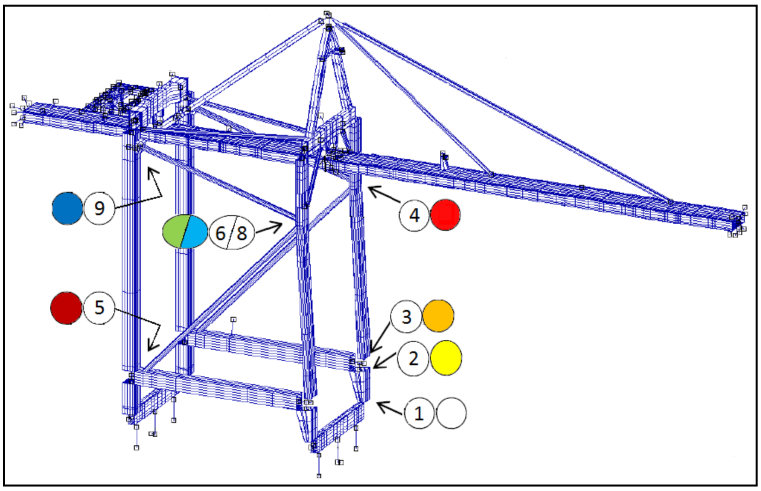


Figure 4.21 Connections influenced by the assembly capacity

For the use of space and hoisting equipment there are cost involved, which will increase in case the assembly time increases as well. Therefore a critical point can be made with regards to the outcome of the welding times in case of a welded connection, namely that the welding times are long. Normally for placing, securing and inspection of two components together a period of 8 hours is accounted for during assembly. Comparing this with the welding times (taking into account that for a welded connection 2 welders can work on a single connection, thereby reducing the total time for placement and securing to half) it can be concluded that the assembly times for each connection will be longer. Furthermore there is a distinction to be made between two situations; firstly the assembly of the crane at Taicang Port and secondly the assembly of the crane at the RCI assembly site. In the first case all equipment for hoisting the components are rented (both main and auxiliary). In the latter case the main equipment for hoisting is company property. Having stated this is must be clear that with an increase in assembly time between two components, taking into account the rental cost of hoisting equipment, the replacement of a bolted flange plate connection may not be beneficial at all.

4.7.2.1 Case study

This case study is meant to point out the influence of the increased assembly time due to welding on the overall assembly cost. The case study concerns the lifting of the side portal of a Ship-To-Shore container gantry crane with a floating crane barge for placement on the sill beams (Figure 4.22a and 4.22b). The study concerns the comparison between a bolted and a welded connection between the side portal and the sill beams, at both assembly sites. The following assumptions have been made:

- The side portal is considered as a rigid structure (the type of connections in the structure is not of concern for this case study);
- The side portal is lifted from a horizontal position and placed vertical on the lower legs waterside and landside on either starboard or portside.

Figure 4.22 a) Horizontal assembly of the side portal b) Lift of the side portal for placement

In case of assembly at Taicang Port the following cost can be accounted for (bolted flange plate connection, Table 4.10).

Table 4.10 Bolted connection

Taicang Port, bolted connection		
Equipment	Description	Cost [Euro]
FCB	One (1); 3,125 Euro/hr, 8 hr (lift, securing the bolted connection, inspection)	25,000
	Two (2) dedicated workers; 15 Euro/hr	240
	One (1) building site manager; 55 Euro/hr	440
Cherry picker	Two (2); 180 Euro/hr; 8 hr	2,880
	Four (4) dedicated workers for securing the bolted connection; 15 Euro/hr	480
Miscellaneous	Overhead FCB, 12.5 Euro/hr	100
		29,100

Additional crane is used for the initial lift of the side portal in case this is needed to prevent damage to the lower side of the side portal at the initial lift. In both situations this will be done, therefore no cost will be allocated in all situations for the use of this crane. The FCB also has additional hoisting ropes; therefore the use of an additional crane may not be necessary.

A mobile crane could also be used instead of a FCB.

In case of assembly at the RCI assembly site the following cost can be accounted for (bolted flange plate connection, Table 4.11), whereby it must be stated that instead of the rental of the main hoisting equipment (FCB) the overhead cranes of the company can be used. The rental cost for the auxiliary hoisting equipment will be taken into account.

Table 4.11 Bolted connection

RCI assembly site, bolted connection		
Equipment	Description	Cost [Euro]
Overhead crane	One (1), 25 Euro/hr; 8 hr (lift, securing the bolted connection, inspection)	200
	Two (2) dedicated workers; 15 Euro/hr	240
	One (1) building site manager; 55 Euro/hr	440
Cherry picker	Two (2); 180 Euro/hr; 8 hr	2,880
	Four (4) dedicated workers for securing the bolted connection; 15 Euro/hr	480
Miscellaneous	Overhead FCB; 12.5 Euro/hr	100
		4,340

In this case two overhead cranes are used at the initial lift (or an additional hoisting line on the overhead crane). For the actual placement and holding in place for securing the bolted flange plate connection only one crane will be used.

In case it concerns a welded connection the production cost with the removal of the bolted flange plates have to be taken into account, as well as the cost that come into view with the production of the welded flange plate as well as the additional welding time (Table 4.12a and 4.12b).

Table 4.12a Welded connection

Taicang Port, welded connection

Equipment or otherwise	Description	Cost [Euro]
FCB	One (1); 3,125 Euro/hr, 40 hr (lift, securing the welded connection, inspection)	125,000
	Two (2) dedicated workers; 15 Euro/hr	1,200
	One (1) building site manager; 55 Euro/hr	2,200
Cherry picker	Two (2); 180 Euro/hr; 40 hr (WS) and 30 hr (LS)	14,400
	Four (4) dedicated workers; 15 Euro/hr	2,400
Welding	Addition of welded flange plate cost (20%)	1,900
	Removal of production cost bolted flange plate	-9,500
Miscellaneous	Overhead FCB, 12.5 Euro/hr	500
		138,100

Table 4.12b Welded connection

RCI assembly site, welded connection

Equipment or otherwise	Description	Cost [Euro]
Overhead crane	One (1), 25 Euro/hr, 40 hr (lift, securing the welded connection, inspection)	1,000
	Two (2) dedicated workers; 15 Euro/hr	1,200
	One (1) building site manager; 55 Euro/hr	2,200
Cherry picker	Two (2); 180 Euro/hr; 40 hr (WS) and 30 hr (LS)	14,400
	Four (4) dedicated workers for securing the bolted connection; 15 Euro/hr	2,400
Welding	Addition of welded flange plate cost (20%)	1,900
	Removal of production cost bolted flange plate	-9,500
		13,600

What can be concluded after comparing the cost for placement of the side portal between a bolted and a welded connection (also between different locations) is that in case of assembly at Taicang Port the connection should remain bolted. The reason for this is not only from a cost perspective, but also due to the fact that the crane has to hold the side portal in position during securing the connection. This means that a time frame has to be present with favorable conditions to achieve this. Besides this, with welding the connection has to be welded continuously until it is finished. At the RCI assembly site it can be concluded that from a cost perspective the connection is to remain bolted.

Based on the provided case study a number of general conclusions can be drawn.

1. Vertical assembly of individual components or assemblies (in a serial sequence) with welded connections between components or assemblies should be avoided;
2. Due to the rental of hoisting equipment at Taicang Port the assembly of components will be done in a horizontal plane to limit the use of the hoisting equipment in case of welded connections between these components[20]. The following connection between this assembly and another component will be bolted if it concerns vertical assembly;

[20] Another reason for horizontal assembly is the need for ensure the accuracy of lining out the assembly in case of applying welded connections between the components. With a bolted connection the preference is to assemble in a vertical plane. With a welded connection an assembly in a vertical plane would also be possible however what must be taken into account is the increase in assembly time and thereby also the increase in assembly cost. By assembling in a horizontal plane this increase in assembly cost can be reduced.

3. As many bolted flange plate connections as possible will have to be replaced to compensate for the rental of hoisting equipment, thereby reaching the largest benefit of the removal of bolted flange plate connections in case assembly takes place at Taicang Port.

Another point to address is that the assumption is made to always have an assembly of the portside and starboard side; subassemblies of waterside and landside are not taken into account. The reason for this is because the components are assumed to remain as they are (as stated before at the design of the welded connection) and an assembly of waterside and landside assemblies is not possible in that case.

4.7.2.2 Connection between the long leg and the upper leg

The introduction of the upper leg originated from the idea to have the upper structure rest on its own legs. This would require fewer support points to be applied and it would increase the assembly efficiency, because the upper structure would already be at a certain height, making certain sections on the bottom side of the upper structure better reachable than otherwise. However, even though this component has been introduced, the use of it in practice has been very limited and the original intention behind the component is no longer there. For this reason having both the long leg and upper leg act as separate components is unnecessary (Figure 4.23). The connection between the long leg and upper leg can be welded. This not only removes the bolted flange plates, but also the inspection platforms for the bolted connection. it can be suggested to have the components joined at the production site.

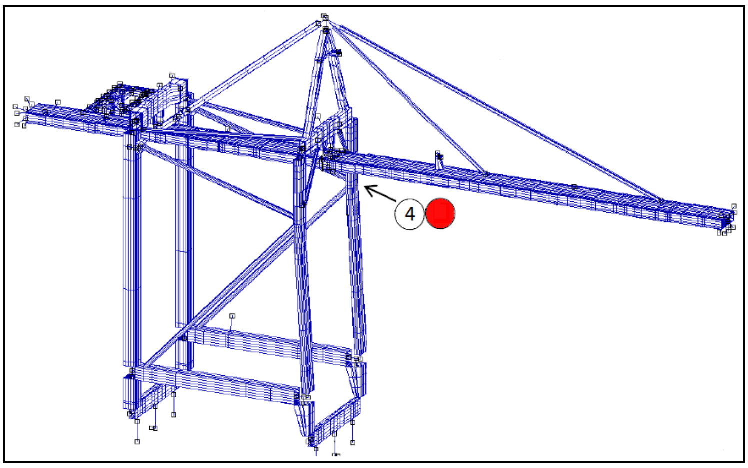


Figure 4.23 Connection between the long leg and the upper leg

A remark with assembling in a horizontal position is that if the sub-assembly is a combination of bolted flange connections and welded connections, the goal should be to have as many connections welded as possible. The reason for this is that bolted flange connections are difficult to realize with a horizontal assembly.

4.7.2.3 Connection of the diagonal and horizontal ties

With regards to the diagonal ties and horizontal ties the assumption will be made that these are always one side welded, one side bolted (connection no. 5, 6, 8, 9, Figure 4.24). The reason for this is due to the inaccuracy in the portal frame when assembling (and also when mating the portal frame with the upper structure), thereby requiring a degree of flexibility within the steel structure. For the diagonal tie and the horizontal tie, the connection with the long leg WS, upper leg WS respectively, will be welded. This will result in the removal of the inspection platforms on WS for these connections. The proposed bolted and welded connection can only be achieved if the side portals are constructed as a whole (with or without the lower legs). Otherwise all connections of the ties will have to be bolted.

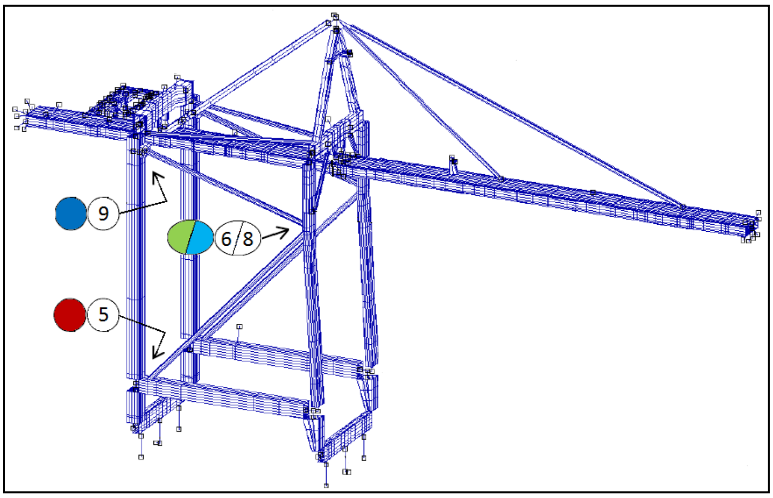


Figure 4.24 Connections of the diagonal tie and the horizontal tie

4.7.2.4 Remaining connections

The remaining connections are either to be bolted or welded (Figure 4.25). As stated with the assumption to have the welded assemblies in a horizontal plane, this means that with large sub-assemblies the connections can be welded for the most part except for those that are to be secured during vertical assembly. Another consideration with these connections is the size of the assembly areas, which will be discussed in the next section.

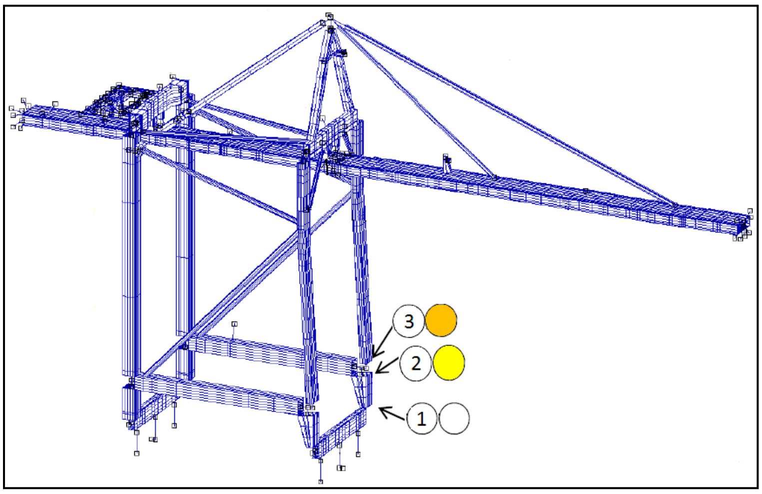


Figure 4.25 Connection between the sill beam and lower leg (no. 1); the lower leg and cross girder (no. 2); the cross girder and the long leg (no. 3)

4.7.2.5 Assembly areas

Besides the intermediate conclusions stated previously the restrictions that come forth from the production site, the assembly sites and the inbound transport between the production site and the assembly sites have to be stated.

Inbound transport and the production site

Due to the inbound transport and the restriction in height for the inbound transport it is assumed that sub-assemblies between structural steel components cannot be made at the production site unless it concerns small changes. Components are transported horizontally to ensure stability of the components during inbound transport and to reduce the shoring height of the components (and thus the amount of resources needed for fastening the components). Furthermore, it will be assumed that components are to remain as they are, though small changes can be made.

Assembly sites

As brought forward before there are two assembly sites to take into account. Firstly the assembly site at Taicang Port and secondly the assembly site of the company, referred to as the RCI assembly site.

Taicang Port

When reviewing Taicang Port there are two areas to distinguish; the yard area and the quayside. The quayside is of importance for the assembly of the Ship-To-Shore container gantry cranes. The assembly of the cranes before sea transport is done on the quayside. The reason for this is the limited dimensions of the connecting bridges between the yard area and the quayside which prevent the build-up of the crane in the yard area and the transport of the crane to the quayside. Of importance however is the available space at the quayside for the assembly of the crane, also taking into account the assumption to have the assembly laid out horizontally when welding the connection between components (Figure 4.26). This limitation not only comes forth when dealing with a very large crane, but also when dealing with a large number of cranes to be assembled. If there is not enough surface area for the assembly of large welded sub-assemblies, the assembly of the crane will be limited to smaller welded sub-assemblies and there will be more vertical assembly of components and less horizontal assembly or sub-assemblies (stated differently the number of welded connections will decrease with decreasing assembly space). When reviewing the assembly site it can be said that for a single crane (of the size the case study crane) there will not be a problem, but if the number of cranes to be assembled increases, the available surface area for the assembly of each crane will be less at the quayside. In order to deal with this situation three options have been taken into account to take this limitation of assembly area into account:

1. There is enough surface area for the assembly of large welded sub-assemblies;
2. There is a limited amount of surface area for the assembly, the welded sub-assemblies are made smaller;
3. There is not enough surface area for the assembly of large welded sub-assemblies.

This in turn determines whether connections no. 1, 2 and 3 will be bolted or welded.

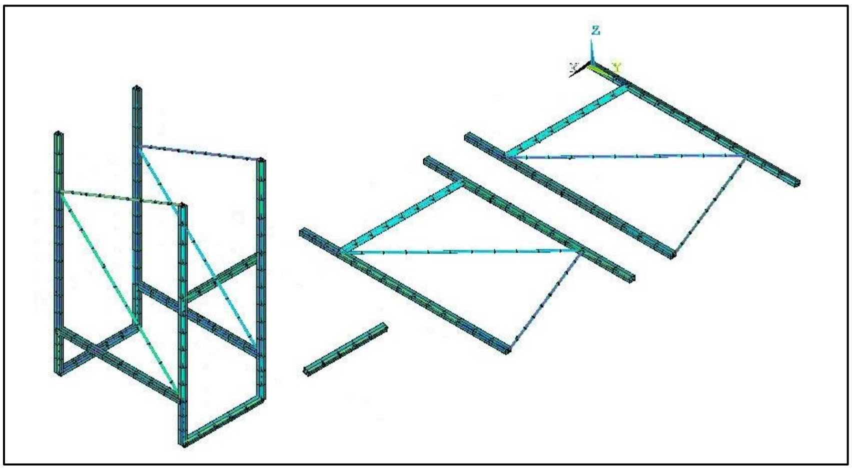


Figure 4.26 Orientation of the side portal for horizontal assembly

RCI assembly site

As opposed to the assembly site at Taicang Port the RCI assembly site does not have the previously mentioned limitations, however in order to facilitate the comparison and to point out the influence of the rental cost of hoisting equipment (main and auxiliary) as opposed to only the rental of auxiliary hoisting equipment, the same three options will be evaluated.

4.8 Connection overview and concepts

Based on the previous paragraph an overview is constructed on the different connections that are to be either bolted or welded and the different concepts that can be made with this overview (Table 4.13 , Figure 4.27; a complete overview of all possible assembly concepts with the previous assumptions has been presented in Appendix R).

Table 4.13 Overview of connection

Connection no.	Description	Bolted or welded
1	Connection between the sill beam and the lower legs	Optional
2	Connection between the lower legs and the cross girders	Optional
3	Connection between the cross girders and the long legs	Optional
4	Connection between the long legs and the upper legs	Welded
5	Connection between the diagonal tie and the cross girders	Bolted
6	Connection between the diagonal tie and the long legs	Welded
7	Connection between the upper legs and the portal beams	Bolted
8	Connection between the upper legs WS and the horizontal tie	Welded
9	Connection between the upper legs LS and the horizontal tie	Bolted
10	Connection between the sill beams and the main balance connections	Optional
11	Connection between the portal beam and the A frame	Optional
12	Connection between the sill beams and the storm brakes	Bolted
13	Connection tie waterside between the upper legs and portal beam	Bolted

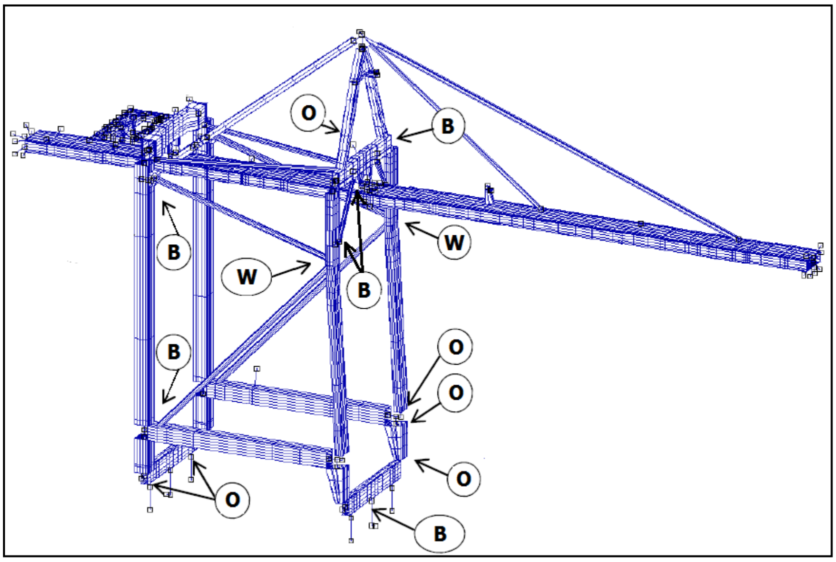


Figure 4.27 Connection overview

This overview will be specified towards a number of concepts. At this point it should be noted that the question which connection should remain bolted or could potentially be welded has been answered. The remaining connections that are optional are dependent on the situation. These situations are based on the following observations:

1. Does sea transport concern a single crane or a number of cranes?
2. Does sea transport concern semi or fully erected transport?
3. Does assembly before sea transport take place at Taicang Port or at the RCI assembly site?

In case it concerns a single crane, semi-erected or fully erected at the assembly site, a number of concepts can be reviewed for both the assembly at Taicang Port and RCI assembly site, which have been listed in Table 4.14. The main issue with this distinction is that if it concerns a single crane there will be enough space at the assembly site to have the side portals assembled completely in a horizontal plane. Furthermore, the concern is also whether the crane will be transported via a dock ship that requires (un-)loading via the fork lift method or not (thus requiring the connection between the sill beam and the main balance connections to be able to be rotated). If it concerns a single crane the fork lift method will be taken into account. For multiple cranes this method does not have to be taken into account.

Table 4.14 Single crane concept

Connection no.	Concept 1 Semi-erected transport Fork lift method	Concept 2 Semi-erected transport Dock ship or otherwise	Concept 3 Fully erected transport, though with height restriction along the way	Concept 4 Fully erected transport, no height restrictions
1	Bolted	Bolted	Bolted	Bolted
2	Welded	Welded	Welded	Welded
3	Welded	Welded	Welded	Welded
4	Welded	Welded	Welded	Welded
5	Bolted	Bolted	Bolted	Bolted
6	Welded	Welded	Welded	Welded
7	Bolted	Bolted	Bolted	Bolted
8	Welded	Welded	Welded	Welded
9	Bolted	Bolted	Bolted	Bolted
10	Bolted	Welded	Welded	Welded
11	Welded	Welded	Bolted	Welded
12	Bolted	Bolted	Bolted	Bolted
13	Bolted	Bolted	Bolted	Bolted

In case it concerns a number of cranes, semi-erected or fully erected, a number of concepts can be reviewed, stated in Table 4.15. As opposed to a single crane in this case the limiting conditions of the size of the assembly area has to be taken into account, meaning that smaller welded sub-assemblies are formed.

Table 4.15 Multiple crane concept

Connection no.	Concept 5 Semi-erected transport[21]	Concept 6 Semi or fully erected transport, though with height restriction along the way	Concept 7 Semi or fully erected transported, no height restrictions
1	Bolted	Bolted	Bolted
2	Bolted	Bolted	Bolted
3	Welded	Bolted	Bolted
4	Welded	Welded	Welded
5	Bolted	Bolted	Bolted
6	Welded	Bolted	Bolted
7	Bolted	Bolted	Bolted
8	Welded	Bolted	Bolted
9	Bolted	Bolted	Bolted
10	Welded	Welded	Welded
11	Welded	Bolted	Welded
12	Bolted	Bolted	Bolted
13	Bolted	Bolted	Bolted

These concepts will be compared with the situation that all connections are bolted (concept 0), with the build-up of the crane as explained in the beginning of this chapter (in this case it does not matter whether it concerns semi-erected transport or fully erected transport). Each concept will have to be evaluated from the perspective of assembly at Taicang Port (thus rental of both main and auxiliary hoisting equipment, and rental of assembly area) and assembly at the RCI assembly site (rental of auxiliary hoisting equipment). In case it concerns assembly at RCI assembly site connection no. 1 can be welded for concepts 1 to 4.

Now that the different concepts have been presented the assembly method of each concept will have to be addressed prior to the cost calculation. For each concept the upper structure is either placed on the sill beams during assembly of the portal frame or kept separately until it is placed on top of the portal frame.

4.8.1 Assembly sequence concept

For each concept the assembly sequence can be listed, that will form the basis for the inventory of the different resources needed during the assembly phase (see also Appendix U).

[21] There are vessels which use the forklift method that are capable of transporting two (2) cranes. In that case concept 1 can be used.

Concept 0

For the reference concept, in which all connections are bolted, the following assembly steps can be distinguished (Figure 4.28):

1. Placement of sill beams WS and LS with the crane travelling gear
2. Placement of the lowers legs WS PS, WS SB, LS PS and LS SB
3. Placement of the cross girders PS and SB
4. Placement of the long legs WS PS and WS SB
5. Placement of the diagonal ties PS and SB
6. Placement of the long legs LS PS and LS SB
7. Placement of the upper legs WS PS, WS SB, LS PS and LS SB
8. Placement of the horizontal ties PS and SB

The A-frame is placed separately as it is part of the upper structure. The ties WS are placed after full erection; bolted.

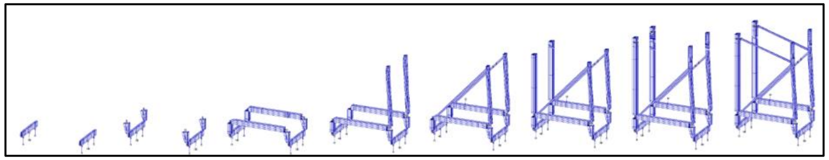


Figure 4.28 Build-up concept 0

Concept 1

For concept 1 the following assembly steps can be distinguished (Figure 4.29):

1. Placement of sill beams WS and LS with the crane travelling gear (bolted connection between the sill beam and the main balances)
2. Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS, which has been assembled horizontally)

The A-frame is placed separately as it is part of the upper structure; welded. The ties WS are placed after full erection; bolted.

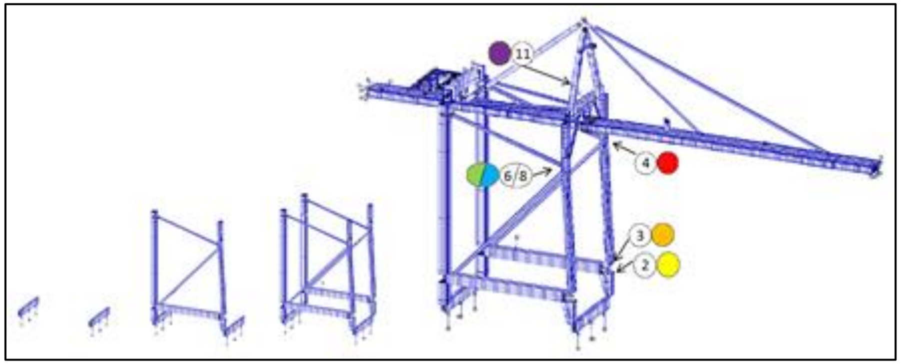


Figure 4.29 Concept 1

Concept 2

For concept 2 the following assembly steps can be distinguished (Figure 4.30):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and the main balances)
2. Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS, which has been assembled horizontally)

The A-frame is placed separately as it is part of the upper structure; welded. The ties WS are placed after full erection; bolted.

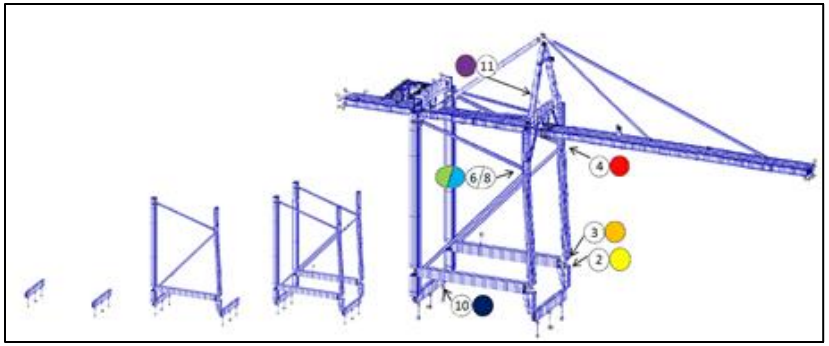


Figure 4.30 Concept 2

Concept 3

For concept 3 the following assembly steps can be distinguished (Figure 4.31):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and the main balances)
2. Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS, which has been assembled horizontally)

The A-frame is placed separately as it is part of the upper structure; bolted. The ties WS are placed after full erection; bolted.

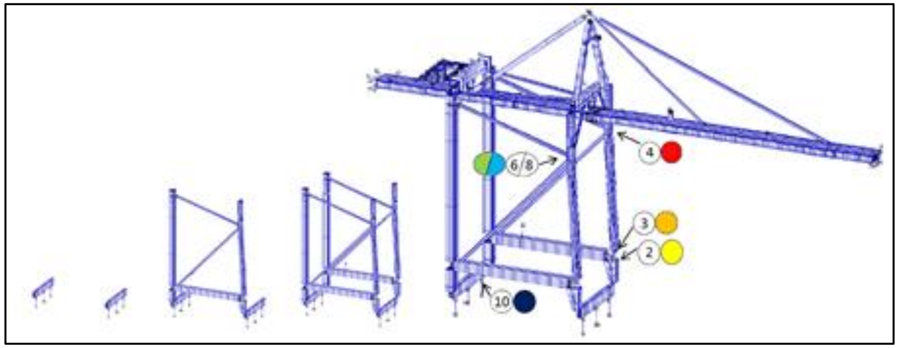


Figure 4.31 Concept 3

Concept 4

For concept 4 the following assembly steps can be distinguished (Figure 4.32):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and the main balances)
2. Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS, which has been assembled horizontally)

The A-frame is placed separately as it is part of the upper structure; welded. The ties WS are placed after full erection; bolted.

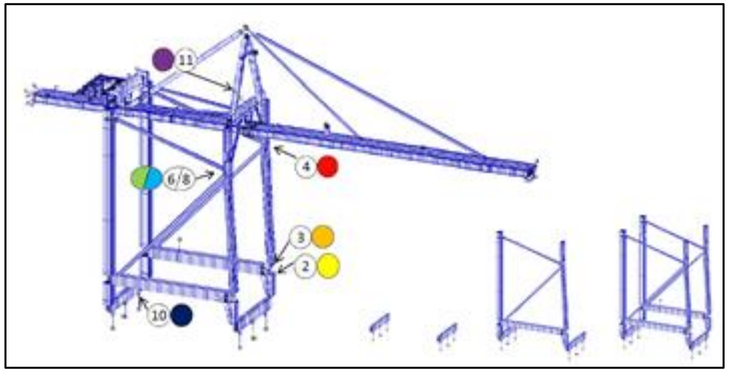


Figure 4.32 Concept 4

Concept 5

For concept 5 the following assembly steps can be distinguished (Figure 4.33):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and the main balances)
2. Placement of the lower legs WS PS, WS SB, LS PS and LS SB
3. Placement of the side portal PS and SB (the side portal PS consists of the cross girder PS, long legs WS PS and LS PS, upper legs WS PS and LS PS, diagonal tie PS and horizontal tie PS, which has been assembled horizontally)

The A-frame is placed separately as it is part of the upper structure; welded. The ties WS are placed after full erection; bolted.

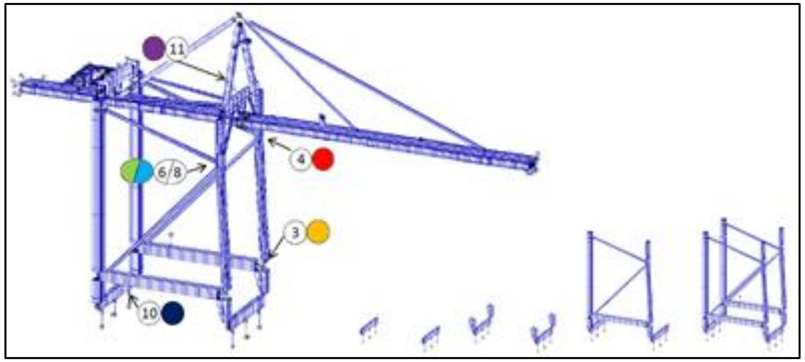


Figure 4.33 Concept 5

Concept 6

For concept 6 the following assembly steps can be distinguished (Figure 4.34):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and main balances)
2. Placement of the lower legs WS PS, WS SB, LS PS and LS SB
3. Placement of the cross girders PS and SB
4. Placement of the welded assembly of the long legs/ upper legs WS
5. Placement of the diagonal ties PS and SB
6. Placement of the welded assembly long legs/ upper legs LS
7. Placement of the horizontal ties PS and SB

The A-frame is placed separately as it is part of the upper structure; bolted. The ties WS are placed after full erection; bolted.

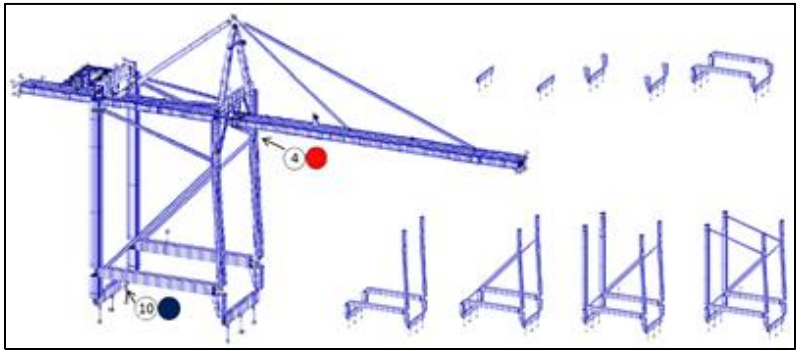


Figure 4.34 Concept 6

Concept 7

For concept 7 the following assembly steps can be distinguished (Figure 4.35):

1. Placement of sill beams WS and LS with the crane travelling gear (welded connection between the sill beam and main balances)
2. Placement of the lower legs WS PS, WS SB, LS PS and LS SB
3. Placement of the cross girders PS and SB
4. Placement of the welded assembly of the long legs/ upper legs WS
5. Placement of the diagonal ties PS and SB
6. Placement of the welded assembly long legs/ upper legs LS
7. Placement of the horizontal ties PS and SB

The A-frame is placed separately as it is part of the upper structure; welded. The ties WS are placed after full erection; bolted.

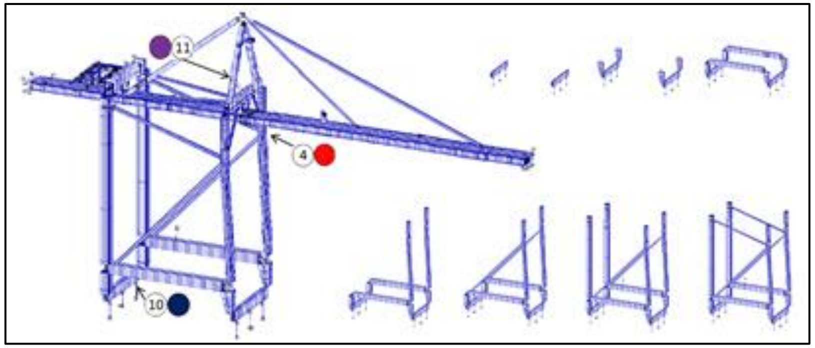


Figure 4.35 Concept 7

4.8.2 Assembly sequence side portal

For the assembly of the side portal, when it is placed in a horizontal position, the sequence of placement of the components is of importance for the total assembly time of the side portal. When placing components in a horizontal position they will have to be supported. Welding will have to be performed in a certain sequence in order to ensure the accuracy of the alignment of the components of the side portal when finished.

Complete side portal

In case it concerns the assembly of the entire side portal PS (or SB) the following sequence has been determined (see Figure 4.34, 4.35 and 4.36):

1. Horizontal placement of the cross girder PS
2. Horizontal placement of the lower leg WS and LS
3. Horizontal placement of the long leg – upper leg assembly WS (welded together before placement)
4. Horizontal placement of the diagonal tie PS
5. Horizontal placement of the long leg – upper leg assembly LS (welded together before placement)
6. Horizontal placement of the horizontal tie PS

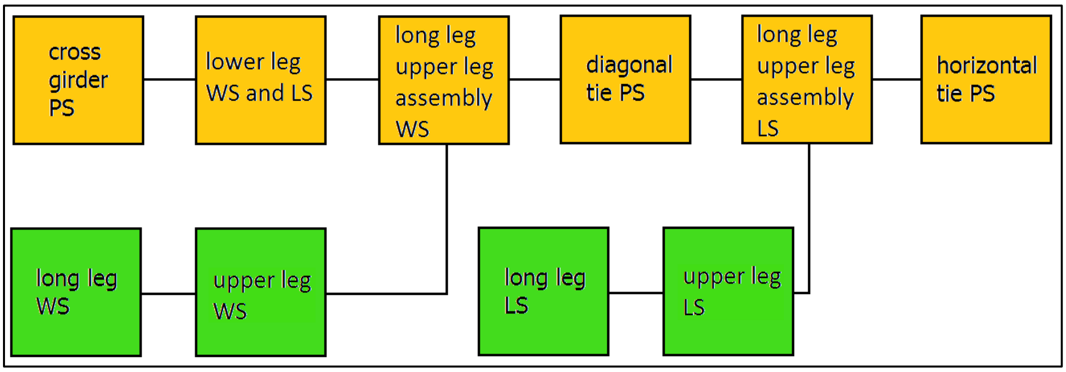


Figure 4.34 Schematic of the build-up of the side portal

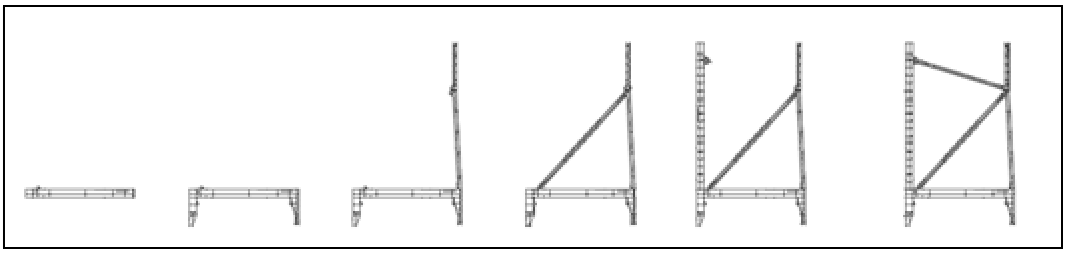


Figure 4.35 Build-up side portal

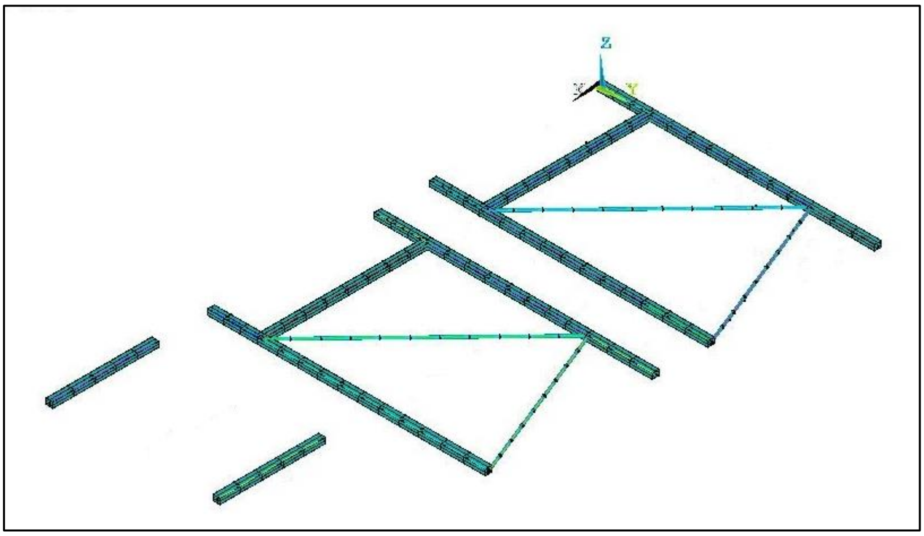


Figure 4.36 Horizontal assembly of side portals

The area requirement for the horizontal assembly of the portal frame has been based on the dimensions of the crane (Table 4.18).

- A = 1,597 m^2 (minimum)
- A = 2,517 m^2 (including safety area)

With regards to the hoisting equipment required; based on the needed surface area, the length of the components and the weight of the components and sub-assemblies, the appropriate hoisting equipment has been selected for placing the components during the horizontal assembly of the side portal and for lifting the side portal for vertical assembly (Table 4.19).

- Horizontal assembly side portal: mobile crane 160 MT, 2 cranes
- Vertical assembly side portal: FCB 1,800 MT, 1 crane

Additional auxiliary equipment will have to be taken into account, to assist with the lining out of the components.

A final important issue with this manner of assembly is the needed assembly time. This is of importance for the cost calculation; the crane rental cost (Appendix W) and the rental cost of surface area (Appendix T) at Taicang Port. The assembly time can be based on the estimated welding times, Table 4.16 (Figure 4.37).

Table 4.16 Assembly time welded side portal

Sequence	Comment	Assembly time [hr.]
Horizontal placement of the cross girder PS, t_1	Only positioning	4
Horizontal placement of the lower leg WS and LS, t_{2a} and t_{2b}	Parallel placement (max)	30 (LS, W), 40 (WS, W)
Horizontal placement of the long leg – upper leg assembly WS, t_3		24 (W)
Horizontal placement of the diagonal tie PS, t_{4a} and t_{4b}	Serial placement	8 (B), 35 (W)
Horizontal placement of the long leg – upper leg assembly LS, t_5		13 (W)
Horizontal placement of the horizontal tie PS, t_{6a} and t_{6b}	Serial placement	8 (B), 29 (W)
		161

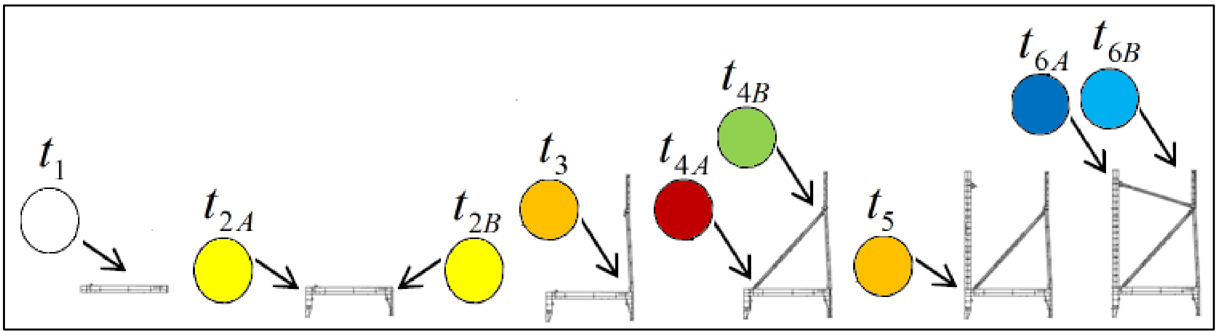


Figure 4.37 Assembly sequence side portal

For the assembly of the side portal an estimated assembly time of 161 hours has been assumed. Based on this sub-assembly the appropriate surface area requirement has also been checked (see Table 4.18 and 4.19) with the available space at Taicang Port.

Partial side portal

In case it concerns the assembly of the upper part of the side portal PS (or SB) the following sequence can be determined (Figure 4.38 and 4.39):

1. Horizontal placement of the cross girder PS
2. Horizontal placement of the long leg – upper leg assembly WS
3. Horizontal placement of the diagonal tie PS
4. Horizontal placement of the long leg – upper leg assembly LS
5. Horizontal placement of the horizontal tie PS

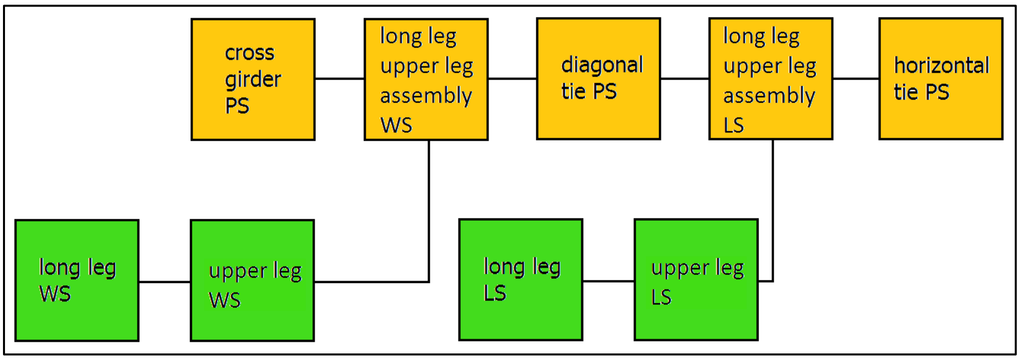


Figure 4.38 Schematic of the build-up of the side portal

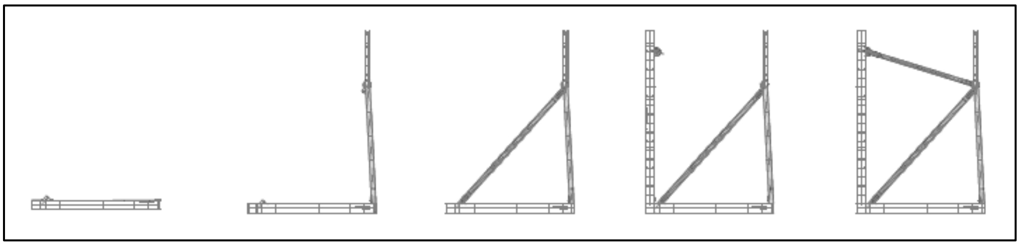


Figure 4.39 Build-up side portal

Of which in turn the appropriate surface area and hoisting equipment (Table 4.18 and 4.19) has been selected as well as the assembly time (Table 4.17 and Figure 4.40).

The area requirement for the horizontal assembly of the portal frame has been based on the dimensions of the crane (Table 4.18).

- A = 1,425 m^2 (minimum)
- A = 2,291 m^2 (including safety area)

With regards to the hoisting equipment required; based on the needed surface area, the length of the components and the weight of the components and sub-assemblies, the appropriate hoisting equipment has been selected for placing the components during the horizontal assembly of the side portal and for lifting the side portal for vertical assembly (Table 4.19).

- Horizontal assembly side portal: mobile crane 160 MT, 2 cranes
- Vertical assembly side portal: FCB 1,800 MT, 1 crane

Additional auxiliary equipment will have to be taken into account, to assist with the lining out of the components.

Table 4.17 Assembly time welded side portal

Sequence	Comment	Assembly time [hr.]
Horizontal placement of the cross girder PS, t_1	Only positioning	4
Horizontal placement of the long leg – upper leg assembly WS, t_2		24 (W)
Horizontal placement of the diagonal tie PS, t_{3a} and t^{3b}	Serial placement	8 (B), 35 (W)
Horizontal placement of the long leg – upper leg assembly LS, t_4		13 (W)
Horizontal placement of the horizontal tie PS, t_{5a} and t_{5b}	Serial placement	8 (B), 29 (W)
		121

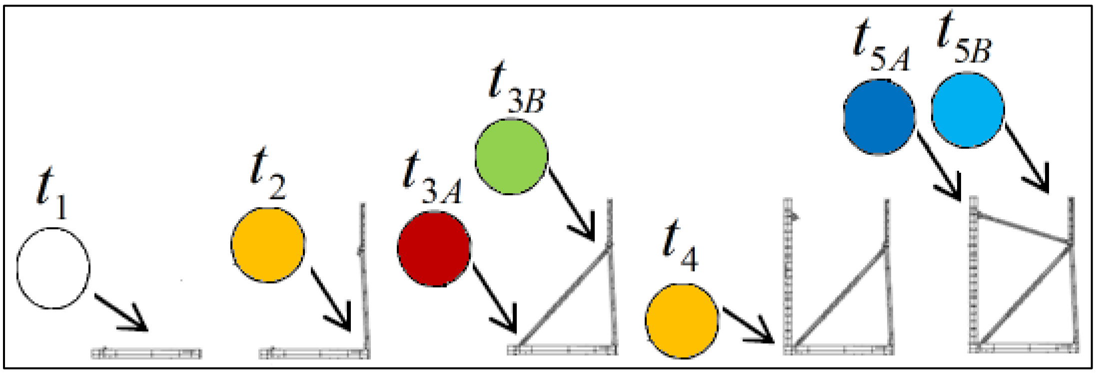


Figure 4.40 Assembly sequence side portal

For the assembly of the side portal an estimated assembly time of 121 hours has been assumed.

A remark with Table 4.16 and 4.17 is that for each welded connection only two welders can have access to the welded connection. The use of more people to reduce the assembly time is not possible. Reducing the assembly time by placing more components at the same time (as opposed to the sequence depicted in Figure 4.35 and 4.38) is to be avoided in order to ensure the accuracy of the alignment of the components.

Based on the existing crane model the mass and hoisting height, and the surface area of different sub-assemblies have been determined (Table 4.18 and Table 4.19).

Table 4.18 Hoisting mass sub-assemblies

Sub-assembly	Mass [MT]	Minimum lifting height for vertical assembly [m]
Sill Beam + Main Balance connection (WS)	59	7.1
Sill Beam + Main Balance connection (LS)	56	6.8
Sill Beam + Lower Legs (WS)	65	12.2
Sill Beam + Lower Legs (LS)	56	12.2
Lower Legs (PS LS + PS WS) + Cross Girder (PS)	60	10.2
Lower Legs (SB LS + SB WS) + Cross Girder (SB)	59	10.2
Cross Girder + Long Legs + Diagonal Tie (PS)	104	43.2
Cross Girder + Long Legs + Diagonal Tie (SB)	104	43.2
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS)	143	56.6
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB)	142	56.6
Long Leg + Upper Leg (PS, WS)	46	56.6
Long Leg + Upper Leg (PS, LS)	50	56.6
Long Leg + Upper Leg (SB, WS)	53	56.6
Long Leg + Upper Leg (SB, LS)	45	56.6
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS)	161	56.6
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB)	160	56.6

Table 4.19 Surface area sub-assemblies

Sub-assembly	Maximum surface area WS view [m2]	Maximum surface area PS view [m2]
Sill Beam + Main Balance connection (WS)	123	8
Sill Beam + Main Balance connection (LS)	120	12
Sill Beam + Lower Legs (WS)	167	21
Sill Beam + Lower Legs (LS)	172	16
Lower Legs (PS LS + PS WS) + Cross Girder (PS)	23	316
Lower Legs (SB LS + SB WS) + Cross Girder (SB)	23	316
Cross Girder + Long Legs + Diagonal Tie (PS)	72	982
Cross Girder + Long Legs + Diagonal Tie (SB)	72	982
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS)	104	1,425
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB)	104	1,425
Long Leg + Upper Leg (PS, WS)	97	128
Long Leg + Upper Leg (PS, LS)	99	97
Long Leg + Upper Leg (SB, WS)	97	128
Long Leg + Upper Leg (SB, LS)	99	97
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS)	116	1,597
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB)	116	1,597

The surface area listed in Table 4.19 is without safety area (or area for placing equipment). An minimum distance of 5 m should be present on each side. For the complete assembly sequence see Appendix V and Appendix W.

4.9 Cost calculation

For the assembly site the following items can be listed in which are of importance for the cost calculation, however only a few of these items really differ with the concept of the entire portal frame bolted (concept 0):

- Needed assembly space (storage area, preparation area, pre-assembly area, assembly area, hoisting area, office and equipment area)
- The use of special tools
- Transport equipment for components and assemblies, both main and auxiliary
- Hoisting equipment for components and assemblies, both main and auxiliary
- Personnel

For the cost calculation the interest is in those phases where a difference is expected in the cost allocated. These phases are in case of semi-erected transport the production, pre-assembly and semi-erection. For fully erected transport this is the same (production, pre-assembly and erection). The other phases are considered to be the same for a bolted portal frame, welded portal frame, or a combination.

Semi-erected transport phases

1. **Production**
2. Inbound transport
3. Unloading, storage and preparation of components
4. **Pre-assembly**
5. **Semi-erection**
6. Sea fastenings
7. Transport to the client
8. Removal of sea fastenings
9. Placing in the rail
10. (Self) Erection
11. Final assembly
12. Commissioning

Fully erected transport phases

1. **Production**
2. Inbound transport
3. Unloading, storage and preparation of components
4. **Pre-assembly**
5. **Erection**
6. Final assembly
7. Pre-commissioning
8. Sea fastenings
9. Transport to the client
10. Removal of sea fastenings
11. Placing on rails
12. Commissioning

The focus of the cost calculation is only on the needed assembly space for the pre-assembly and erection and the use of hoisting equipment and personnel. Other phases can be assumed to be similar as to the concept of having the entire portal frame bolted (concept 0). If there are other cost that come into view that do not come forth from these aspects, these will be explained and added to the cost calculation.

Based on the concepts an overview of the cost can be made for each concepts (Appendix W) based on whether assembly takes place at Taicang Port (Table 4.20) or at RCI assembly site (Table 4.21). The production cost of the bolted flange plates that are removed have been listed in Appendix X.

Table 4.20 Assembly cost Taicang Port

Taicang Port			
Concept no.	Cost estimation 20% [Euro]	Cost estimation 30% [Euro]	Cost estimation 40% [Euro]
concept 0	204,100	204,100	204,100
Concept 1	209,700	217,200	224,600
Concept 2	193,300	202,200	211,100
Concept 3	197,700	206,000	214,300
Concept 4	193,300	202,200	211,100
Concept 5	163,900	170,700	178,900
Concept 6	149,100	152,300	155,500
Concept 7	144,600	148,400	152,200

Table 4.21 Assembly cost RCI assembly site

RCI assembly site			
Concept no.	Cost estimation 20% [Euro]	Cost estimation 30% [Euro]	Cost estimation 40% [Euro]
concept 0	70,600	70,600	70,600
Concept 1	500	7,900	15,300
Concept 2	-14,600	-5,600	3,400
Concept 3	-9,100	-800	7,600
Concept 4	-14,600	-5,600	3,400
Concept 5	-5,000	1,100	8,700
Concept 6	30,300	33,500	36,700
Concept 7	24,500	28,700	32,400

Based on the assembly cost the cost reduction can be calculated. The cost reductions have been listed in Table 4.22 and 4.23.

Table 4.22 Cost reduction Taicang Port

Taicang Port			
Concept no.	Cost reduction estimation 20% [Euro]	Cost reduction estimation 30% [Euro]	Cost reduction estimation 40% [Euro]
concept 0	-	-	-
Concept 1	-5,700	-13,200	-20,600
Concept 2	10,900	1,900	-7,100
Concept 3	6,500	-2,000	-10,300
Concept 4	10,900	1,900	-7,100
Concept 5	40,200	33,400	25,200
Concept 6	55,000	51,800	48,600
Concept 7	59,500	55,700	52,000

Table 4.23 Cost reduction RCI assembly site

RCI assembly site			
Concept no.	Cost reduction estimation 20% [Euro]	Cost reduction estimation 30% [Euro]	Cost reduction estimation 40% [Euro]
concept 0	-	-	-
Concept 1	70,200	62,800	55,400
Concept 2	85,200	76,200	67,300
Concept 3	79,700	71,400	63,100
Concept 4	85,200	76,200	67,300
Concept 5	75,600	69,600	62,000
Concept 6	40,400	37,200	34,000
Concept 7	45,800	42,000	38,300

In case of the conservative estimation of the cost of a welded flange plate connection the following cost reduction percentages compared to the cost price (3,600,000 Euro, cost made during production and assembly, excluding cost made during transport and at the client's site) are achieved (Table 4.24).

Table 4.24 Cost reduction

	Taicang Port		RCI assembly site	
Concept no.	Cost reduction [Euro]	Reduction [%]	Cost reduction [Euro]	Reduction [%]
Concept 1	-20,600	0.6 (cost increase)	55,400	1.5
Concept 2	-7,100	0.2 (cost increase)	67,300	1.9
Concept 3	-10,300	0.3 (cost increase)	63,100	1.8
Concept 4	-7,100	0.2 (cost increase)	67,300	1.9
Concept 5	25,200	0.7	62,000	1.7
Concept 6	48,600	1.4	34,000	0.9
Concept 7	52,000	1.4	38,300	1.1

4.10 Conclusion and recommendation

As a general conclusion it can be said that the optimal concept is entirely dependent on internal and external factors. However, when reviewing the concepts from the perspective of the assembly site a number of trends become clear:

- When it concerns assembly of the crane at Taicang Port the concepts with the least number of welded flange plate connections leads to the largest cost reduction. The reason for this is due to the increased assembly time experienced with the other concepts and thereby the increased cost experienced from the rental of hoisting equipment and assembly area. Furthermore the concepts with the least number of welded flange plate connections, concepts 6 and 7, are assumed to have the welded connection made at the production site.
- When it concerns assembly of the crane at the RCI assembly site, the concepts with the largest number of welded flange plate connections lead to the largest cost reduction, concepts 1 to 5. This is due to the removal of the rental cost for hoisting equipment.
- Taking into account the size of the assembly area; with decreasing size of the assembly area the application of a bolted connection becomes more favorable. This means that when the number of cranes assembled within the same assembly area increases, the number of bolted flange plate connections in the portal frame increases, even if the assembly of the cranes is done one after the other.

As a recommendation the following points can be mentioned:

- For the assembly of the welded portal frame the assembly sequence is influenced by the number of cranes to be produced. For the assembly of the portal frame a certain amount of surface area is needed, within a defined assembly area. If the number of cranes to be produced within the same limited area increases the assembly of the portal frame of the Ship-To-Shore container gantry cranes changes. This has its reflection on the selection of which connection should be welded or bolted. In order to overcome this situation a test case of the existing assembly site with varying number of cranes to be produced should be made and for each situation the connection between the different components should be reviewed. In this manner the optimum concept depending on the available assembly area can be selected.
- The assembly schedule of the upper structure has not been taken into account and tuned to the assembly schedule of the portal frame. The assembly of the upper structure will have to be performed at a later moment in time to prevent extra area rental cost for this assembly (although normally this assembly is done first). Furthermore, due to the welding of the A-frame in some cases the assembly time of the upper structure will increase. The extra area rental cost for the extra time needed when welding the A-frame instead of bolting the A-frame needs to be taken into account.

- The influence on the production process has to be further clarified.
- The design of the welded connection should be slightly adjusted. There should be an element present to ensure that two components are secured to each other before welding. This can be achieved by having a temporary bolted connection at the location of the flange or by placing components in an angle instead of a horizontal position.

Report conclusion

Each part of the report presents a conclusion and recommendation for its specific topic. Of interest would now be to present a general conclusion on the thesis and to answer the main question. The main research question of the Master's thesis is:

What is the possible cost reduction that can be attained by redesigning the portal frame (e.g. replace bolt connections by welded connections, use lower grade steel quality) and part of the machinery work (e.g. bogie set) of Panamax and Post-Panamax Ship-To-Shore container gantry cranes for the Asia-Pacific market?

The topics discussed in this Master's thesis came forth from a comparison with other crane manufacturers and from practice. As a general conclusion it can be said that the application of each topic will have a positive effect on the cost price of the crane and can be applied by Cargotec Netherlands BV. If one looks at each topic separately the following main conclusion can be made (thereby answering the individual research questions).

1. Regarding the standards that are applied in the Asia-Pacific market, the European standard FEM 1.001 is a commonly applied standard. Demands from the Asia-Pacific market are largely the same as what is experienced from other markets.
2. For the application of a different steel quality the conclusion can be drawn that the current practice of applying D-quality steel is unnecessary and a combination of B, C and D-quality steel can be applied.
3. Concerning the application of an open gearing the conclusion can be drawn that an open gearing will lead to a reduction in cost even though there are some disadvantages to this type of transmission.
4. With regards to the replacement of bolted flange plate connections there are a number of connections that can be replaced by a welded connection, but which connection can be replaced will differ for each crane and depend on internal and external factors.

The goal of the cost reduction is to reduce the cost price of the production and assembly by 5 to 10%. When reviewing the possible cost reductions that can be achieved with the different topics the following can be stated based on a total cost price (excluding the cost of sea transport and the cost made at the client's site) of the crane of 3,600,000 Euro (the comparison for each topic is based on the same existing crane):

- The application of a different steel quality will result in a cost reduction of 22,500 Euro (0.6 % of the cost price of the crane);

- The application of an open gearing will result in a cost reduction of 61,900 Euro (1.7 %) in case a single engine powers two (2) crane wheels; 61,000 Euro (1.7 %) in case a single engine powers four (4) crane wheels; and 87,500 Euro (2.4 %) in case of a shortened bogie length with a single engine powering two (2) crane wheels.
- The removal of bolted flange plate connections by welded connections can result in a cost reduction, but it will depend on the assembly concept and location of assembly. From a conservative point of view either a cost increase is met of 20,600 Euro (0.6 %) or a cost decrease of 67,300 Euro (1.9 %) from a conservative point of view.

Taken all cost reductions into account it can be said that if each measure is summed it is possible to have a cost reduction of approximately 5 %.

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Appendix A Paper

Cost reduction of Ship-To-Shore container gantry cranes for the Asia-Pacific market

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Abstract

Cargotec Netherlands BV is a global manufacturer of Ship-To-Shore container gantry cranes. However the Asia-Pacific market remains to be an undisclosed area, though the production and assembly of cranes are done in this region. Furthermore the company delivers Ship-To-Shore container gantry cranes with a cost price that is too high compared to its competitors. In order to overcome this situation a number of topics will be addressed in this paper which lead to a cost reduction. These topics are: the application of a different steel quality, the application of an open gearing transmission, and the replacement of bolted flange plate connections by welded flange plate connections in the portal frame.

Keywords: *Ship-To-shore container gantry cranes, Asia-Pacific market, steel quality, open gearing, portal frame*

1. Introduction

Cargotec Netherlands BV is a global manufacturer of Ship-To-Shore container gantry cranes and other types of cranes. The company, however, has noticed that the cost price (cost during production and assembly) of its Ship-To-Shore container gantry cranes is 5 to 10 % higher than that of competitors. To overcome this problem a number of measures have been thought of by comparing with these competitors and that originate from practice. These topics are the application of a different steel quality in the steel structure of the crane; the application of an open gearing transmission for the crane travelling gear, and the replacement of bolted flange plate connections by welded connections in the portal frame of the crane. Besides these topics, an insight into the Asia-Pacific market is provided on these topics due to the situation of not delivering cranes to this market. The goal of this paper is to give an indication of the cost reduction that can be attained by addressing these topics.

2. Asia-Pacific market

The interest in the Asia-Pacific market is in the demands from clients on the main topics.

- When reviewing tender documentation [1-8] on the issue of the allowable standard for the crane structure and the steel quality it can be said that the standards in the Asia-Pacific market comprise of the European standard FEM 1.001, the Chinese standard GB/T 3811, the British standard BS 2573 and the Japanese standard. Most of South-East Asia can be covered by the European standard.
- Reviewing the crane travelling gear tender documentation from the Asia-Pacific market indicates that an open gearing would be allowed, though housed in the bogie steel structure. However, the preference is for applying a closed gearbox instead of an open gearing.
- Lastly concerning the removal of the bolted flange connections by welded connections, tender documentation states that the preference is for a rigid welded portal frame steel structure, thereby having the connection between the components of the steel structure welded as well.

3. Application of a different steel quality

Brittle fracture is a type of fracture which is experienced at low temperatures and high tensile stresses. Brittle fracture is characterized as a type of fracture whereby little or no plastic deformation precedes the moment of fracture [9, 10]. In order to prevent brittle fracture the appropriate steel quality has to be chosen. The steel quality is a reference to the resistance of the steel type against brittle fracture (referred to as A, B, C, D, and E-quality steel, whereby A-quality is the lowest steel quality and E-quality is the highest steel quality).

Brittle fracture occurs when the following conditions are present [11]:

- High tensile stresses;
- Low operating temperature;
- High degree of tri-axial state of stress;
- High strain rate;
- Large plate thickness.

The high degree of tri-axial state of stress and the high strain rate are both related to the plate thickness and tensile stresses [9].
The determination of the steel quality can be based on the guidelines from standards and on the specifications of the client. The reason for evaluating this aspect is due to the fact that Cargotec Netherlands BV always applies D-quality steel for its steel structures. The question is whether this practice is necessary according to standard and what the possible cost reduction is by changing from D-quality steel to a combination of steel qualities.

3.1 Steel quality selection

The European standard FEM 1.001 provides an evaluation procedure for the selection of the steel quality, based on three dimensionless assessment coefficients; the influence of residual tensile stresses (Z_A), the influence of the plate thickness (Z_B) and the influence of the temperature (Z_C). The influence of these three assessment coefficients is summed, leading to an accumulated Z-value (Eq. 3.1):

$$Z = Z_A + Z_B + Z_C \quad \text{Eq. 3.1}$$

With this summation the quality group is selected that leads to either A, B, C or D-quality steel [12].
The influence of tensile stresses is evaluated by the combined effect of longitudinal residual stresses from welding with tensile stresses from the dead weight, σ_G [N/mm^2], and the elastic limit for load case I, σ_a [N/mm^2]. For the determination of the influence of the residual tensile stresses the ratio between σ_G and σ_a can be defined (Eq. 3.2).

$$\text{Ratio} = \sigma_G / \sigma_a \text{ [-]} \quad \text{Eq. 3.2}$$

This ratio has been calculated to be equal to or smaller than 0.5. This value covers all cranes produced by Cargotec Netherlands BV (Figure 1). Besides this ratio the type of weld that occurs in the steel structure needs to be identified taking into account the severity of the longitudinal residual stresses. FEM 1.001 identifies three types: transverse or no weld (little or no influence of longitudinal residual stresses), longitudinal weld, and weld accumulation (large influence of longitudinal residual stresses).
The influence of the plate thickness and temperature can be evaluated by looking at the appropriate tables in FEM 1.001. This steel quality selection procedure has been applied on a representative type of crane delivered by Cargotec Netherlands BV.

There is a comment to be made with the determination of the temperature. FEM 1.001 defines the temperature based on the lowest temperature experienced at the client's site. It can be questioned whether this is an appropriate temperature if the situation occurs where the production and assembly site are at a location where lower temperatures are experienced than at the client's site. Besides the temperature high tensile stresses are experienced during the assembly and transport phase, making it possible for brittle fracture to occur. Because FEM 1.001 does not provide guidelines for this type of consideration the decision is made to select the temperature based on the lowest temperature experienced either at the production site, the assembly site, during the transportation phase, or at the client's site. Considering that the production and assembly site of Cargotec Netherlands BV (including loading for transport) are in an area with a minimum temperature of -10 °C, this temperature will be taken as a minimum for the cost calculation.
Besides the location, the minimum temperature experienced is also dependent on the time schedule of the production, assembly and transport of the crane (regarding the boundary temperature of -10 °C).

Other standards such as NEN-EN 13001 provide a similar selection procedure though with some differences. Reviewing the Asia-Pacific market, the standard allowed is FEM 1.001 or the Chinese standard GB/T 3811. The Chinese standard has the same selection procedure as FEM 1.001, however the influence of the residual tensile stresses is assumed to be more severe [17]. This leads to the situation that the Chinese standard gives a more conservative result than FEM 1.001. With these standards though, the same problem is encountered when selecting the temperature.

3.2 Steel quality table

Based on the procedure in FEM 1.001 a table is constructed in which, according to the temperature and plate thickness, the steel quality can be looked up. Figure 2 displays this table, whereby the influence of the residual tensile stresses is according to the most unfavorable welding situation (weld accumulation). As can be seen in Figure 2 D-quality steel is only used at low temperatures in combination with large plate thicknesses (In Figure 2 B-quality steel is indicated as yellow, C-quality steel as green, and D-quality steel as blue). B and C-quality steel are the prevailing steel qualities, considering that the average plate thickness range of Ship-To-Shore container gantry cranes for the steel construction equals to 7 – 60 mm plate thickness.

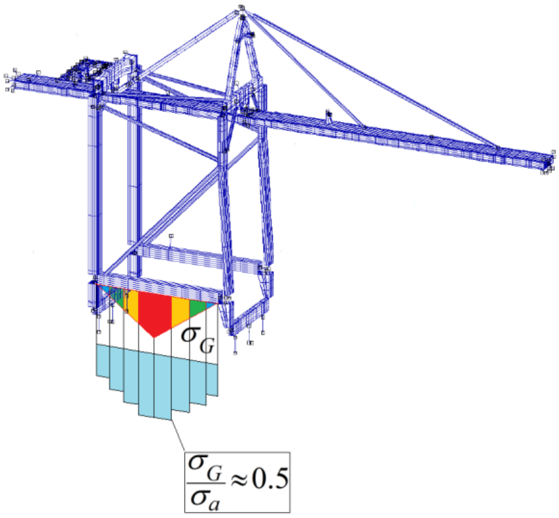

Figure 1 **Ratio for the influence of residual tensile stresses**

FEM 1.001	Temperature T [°C]				
Plate thickness t [mm]	0	-5	-10	-15	-20
5	2.1	2.2	2.5	2.9	3.6
6	2.15	2.25	2.55	2.95	3.65
7	2.2	2.3	2.6	3	3.7
8	2.25	2.35	2.65	3.05	3.75
9	2.3	2.4	2.7	3.1	3.8
10	2.4	2.5	2.8	3.2	3.9
12	2.5	2.6	2.9	3.3	4
15	2.8	2.9	3.2	3.6	4.3
16	2.9	3	3.3	3.7	4.4
20	3.45	3.55	3.85	4.25	4.95
25	4	4.1	4.4	4.8	5.5
30	4.5	4.6	4.9	5.3	6
35	4.9	5	5.3	5.7	6.4
40	5.2	5.3	5.6	6	6.7
45	5.5	5.6	5.9	6.3	7
50	5.8	5.9	6.2	6.6	7.3
55	6	6.1	6.4	6.8	7.5
60	6.3	6.4	6.7	7.1	7.8
65	6.55	6.65	6.95	7.35	8.05
70	6.8	6.9	7.2	7.6	8.3
75	7	7.1	7.4	7.8	8.5
80	7.2	7.3	7.6	8	8.7
85	7.4	7.5	7.8	8.2	8.9
90	7.6	7.7	8	8.4	9.1
95	7.8	7.9	8.2	8.6	9.3
100	8	8.1	8.4	8.8	9.5

Figure 2 **Steel quality table**

3.3 Case study and conclusion

By applying the methodology in FEM 1.001 the entire crane structure can be evaluated, based on which a conclusion can be drawn on the total cost reduction that can be achieved by changing to a different steel quality. In Table 1 the steel quality division of the crane structure has been listed according to different minimum temperatures, with the cost reduction[22]. The percentage of D- quality steel within the crane structure is small compared to the percentage B and C-quality steel. The evaluated crane has a mass of 1336 MT (without load), of which 1007 MT of structural steel components has been evaluated.

Table 1 **Cost reduction**

Temp. [°C]	B [%]	C [%]	D [%]	Cost reduction [Euro]
-10	63.4	32.8	3.8	28,100
-15	52.9	43.3	3.8	25,400
-20	42.2	52.5	5.3	22,500
-25	8.2	80.5	11.3	13,200

If the production in a factory is focused on individual cases the table in Figure 2 can be applied, but if several components will be produced from different projects at the same time there will be a problem. If these projects will come from clients situated at different places with different ambient temperatures this will lead to the situation that in the factory similar plate thicknesses of varying steel qualities will be needed. This is not a beneficial situation taking into account that from one plate several parts of different components are cut. To accommodate this situation it would be favorable to have one range in which several plate thickness ranges are defined that only fall within one steel quality. In this case a general guideline can be formulated by taking the steel quality division at -20 °C, which is a common reference temperature. Based on this division the other higher minimum temperatures are also covered. This means that:

- For a plate thickness range of 5 – 12 mm B-quality steel can be applied;
- Plate thickness range of 15 – 60 mm C-quality steel;
- Plate thickness range of 65 – 100 mm D-quality steel.

In case the minimum ambient temperature experienced during different phases of the crane is lower than -20 °C the steel quality according to the plate thickness range will shift downwards and will have to be evaluated separately.

Concluding it can be stated that Cargotec Netherlands BV can shift from using only D-quality steel to a combination of B, C and D-quality steel. Taking the temperature of -20 °C as a reference the cost reduction will amount to 22,500 Euro.

[22] Price difference for the calculation has been defined as follows:

- Price difference between D and C quality steel equals to 12.5 Euro/ton;
- Price difference between D and B quality steel equals to 37.5 Euro/ton.

4. Application of an open gearing transmission

The interests in this topic is to evaluate an existing crane travelling gear and indicate what the effects will be if this gear is converted into an open gearing, thereby also pointing out what the possible cost reduction could be.

The application of an open gearing for the crane travelling gear was a common practice [18], however this type of transmission became unfavorable to clients. There are a number of reasons to state for this.

1. The open gearing, even if housed within the bogie steel structure, will be prone to the accumulation of dirt from the environment;
2. The lubrication of the open gearing is troublesome. As the name already indicates, there will be spillage of lubrication oil on the quayside, requiring clean up;
3. Periodically adding lubrication to the open gearing has to be performed manually;
4. In case an individual wheel is powered by an engine there is a degree of redundancy, which in case of failure will still allow the crane to function.

However there are clients willing to accept these disadvantages, due to distinct issues that are favorable for these clients.

1. With the application of an open gearing both wheels of the bogie can be driven by a single engine. This means that the number of engines is limited to the number of bogies, and that number is lower than the case when all or a number of wheels are individually driven by an engine.
2. By having each wheel driven the use of wheel brakes is no longer necessary and the only brake needed is the one mounted on the engine.
3. The risk of wheel slip is reduced as well as no longer having any skewing forces on the crane rails due to having all engines equally divided over the waterside and the landside. This is in contrast to having most engines placed on the waterside (in case of having each wheel driven individually), because the wheel pressure is highest on this side [19, 20].

4.1 Open gearing concepts

For the development of an open gearing and for the comparison the structure of an existing crane travelling gear has been used. With regards to the application of an open gearing there are a number of situations that are evaluated in order to determine what the effects are on the different components of the travelling gear and on the cost reduction. The following situations are evaluated:

1. Application of an open gearing consisting of 5 gears, whereby the engine drives both wheels (Figure 2, 3);
2. Application of an open gearing consisting of 5 gears, where the engine drives the wheels of two bogies (Figure 3);
3. Application of an open gearing consisting of 3 gears, whereby the engine drives both wheels (in this case it is assumed that only the length of the existing crane travelling gear is shortened).

The outcome of these situations has been compared with the existing crane travelling gear. For the redesign only the main components of the transmission are taken into account (engine, brake, gearbox and open gearing).

4.2 Comparison and conclusion

In order to determine the cost reduction for the situations an existing crane is evaluated. The specifications of this crane with regards to loads and others have been used to determine the required engine power, open gearing, brake and closed gearbox for the open gearing application. Based on these calculations the components for the open gearing have been selected, supporting the cost calculation.

The original situation concerns a Ship-To-Shore container gantry cranes, with 32 cranes wheels (of which 24 are driven). The mass of the crane amounts to 1336 MT (without load). The estimated cost of the main components of the bogie has been estimated to be equal to 295,000 Euro [20].

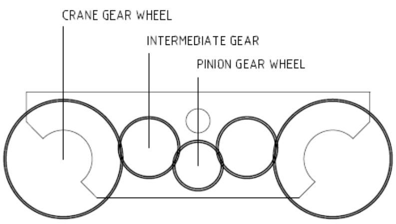

Figure 2 **Open gearing model 1**

Figure 3 **Open gearing application**

For each situation the specifications have been listed with respect to the required engine power, closed gearbox and open gearing (Table 2 and 3).

Table 2 Existing crane travelling gear

Number of driven wheels	24
Engine power per wheel	16
Number of engines	24
Closed gearbox ratio	73.23
Number of closed gearboxes	24

Table 3 Open gearing crane travelling gear

Open gearing concept	1	2	3
Number of driven wheels	32	32	32
Engine power per wheel	28	63	27
Number of engines	16	8	16
Closed gearbox ratio	29.53	29.53	29.53
Number of closed gearboxes	16	16	16
Open gearing ratio	2.48	2.48	2.48
Number of gear wheels	5	5	3

Based on the different situations evaluated the following cost reduction can be listed:

1. With regards to the application of an open gearing consisting of 5 gears, whereby the engine drives both wheels the cost reduction amounts to 61,900 Euro;
2. With regards to the application of an open gearing consisting of 5 gears, where the engine drives the wheels of two bogies the cost reduction amounts to 61,000 Euro;
3. With regards to the application of an open gearing consisting of 3 gears, whereby the engine drives both wheels (in this case it is assumed that only the length of the existing crane travelling gear is shortened) the cost reduction amounts to 87,500 Euro.

A remark with the results is that not all cost with the design and construction of the crane travelling gear have been taken into account. Furthermore the cost during the operational phase (maintenance cost) have not been taken into account.

5. Replacement of bolted flange plate connections

Current practice of Cargotec Netherlands BV for the assembly of the portal frame is to attach components via a bolted flange plate connection. However with this connection there are production and assembly cost that are unwanted from the viewpoint of cost reduction. The goal is to replace the bolted flange plate connection by a welded flange plate connection under the assumption that this will lead to a cost reduction. However it should be determined which connection could be replaced and what the consequences are, next to an economic evaluation. In Table 4 and Figure 4 an overview of the connections and locations is given.

For the determination which connection should be bolted or welded two approaches have been used. Certain connections are mainly influenced by the sea transport and others are mainly influenced by the assembly capacity.

Table 4 Connection overview

Connection no.	Description
1	Connection between the sill beam and the lower legs
2	Connection between the lower legs and the cross girders
3	Connection between the cross girders and the long legs
4	Connection between the long legs and the upper legs
5	Connection between the diagonal tie and the cross girders
6	Connection between the diagonal tie and the long legs
7	Connection between the upper legs and the portal beams
8	Connection between the upper legs WS and the horizontal tie
9	Connection between the upper legs LS and the horizontal tie
10	Connection between the sill beams and the main balance connections
11	Connection between the portal beam and the A frame
12	Connection between the sill beams and the storm brakes
13	Connecting tie WS between the upper legs and portal beam

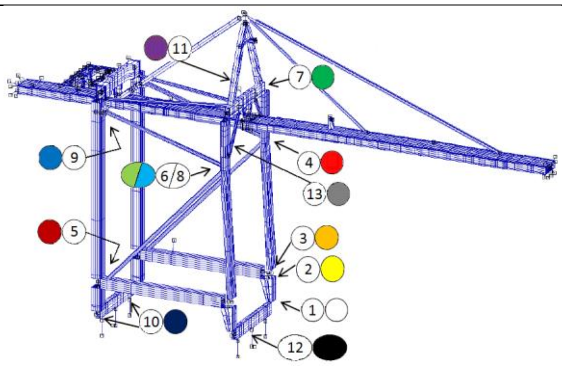

Figure 4 Connection overview

5.1 Sea transport

The connections that are reviewed from the viewpoint of sea transport are (Figure 5):

1. The connection between the portal frame and the upper structure (connection no. 7);
2. The connection between the sill beam and main balance (connection no. 10);
3. The connection between the sill beam and the storm brake (connection no. 12).
4. The connection of the A-frame (connection no. 11)
5. The connection of the ties WS (connection no. 13)

The connection between the portal frame and the upper structure is dependent on whether the crane is fully-erected or semi-erected before transport, the type of loading, the location of the assembly site and in case of semi-erected transport the method of erection at the client's site. Taken all of this into consideration the conclusion is made after an economic evaluation that:

- In case of semi-erected transport the use of a bolted connection is always cheaper;
- In case of fully-erected transport the use of a welded connection can, in certain circumstances, be cheaper.

Having stated these conclusions though the connection is decided to remain bolted due to uncertainties regarding the availability of a vessel (also the type of vessel and the number of cranes it can transport), restrictions during voyage, and others. Flexibility is needed in this case.
The connections no. 10 and 12 are determined by the method of (un-)loading of the crane. Concerning the connection between the sill beam and the main balance the conclusion is made that this connection can be welded if it concerns transport of more than one crane. In case it concerns transport of a single crane it is optional. Regarding the connection between the sill beam and the storm brake this connection is to remain bolted.
The connection of the A-frame is also optional due to possible height restrictions during sea transport and the connection of the tie is bolted because this connection can only be placed after mating the upper structure with the portal frame.

5.2 Assembly capacity

The connections that are reviewed from the viewpoint of the assembly capacity are those remaining (Figure 6).
These connections are influenced by the assembly capacity; hoisting capacity and area capacity.
With the application of a welded connection the assumption has been made to have the assembly of the side portals in a horizontal plane. The reason for this is due to the increased assembly time that is experienced with welded connections compared to bolted connections and thereby the increase in cost for the assembly. In order to limit the increase in cost the components that are to be welded together are placed in a horizontal plane and to have as many connections welded in that case to fully benefit of the removal of the production cost of the bolted flange plates.
Laying out sub-assemblies of a crane horizontally requires a large amount of space. The current situation is that assembly is either done at Taicang Port or at the RCI assembly site. In case of assembly at Taicang Port all hoisting equipment (both main and auxiliary) will have to be rented. In case of assembly at RCI assembly site only the auxiliary hoisting equipment will have to be rented next to any cranes needed for loading the crane onto the vessel for sea transport. Therefore these two assembly sites are taken into account. In case of assembly at Taicang Port the amount of space for horizontal assembly is limited and with increasing number of cranes to be assembled this problem only becomes more restrictive. Therefore different concepts have been evaluated for the assembly at Taicang Port with a combination of a number of bolted and welded connections thereby also taking into account those connections that are influenced by sea transport. These concepts have also been reviewed if assembly should take place at the RCI assembly site, and in turn compared with assembly with bolted connections (the original situation).

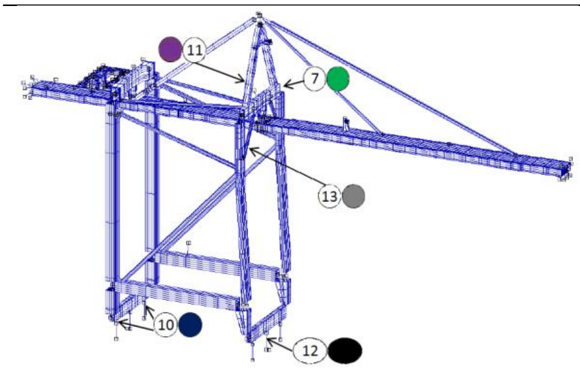

Figure 5 Connections influence sea transport

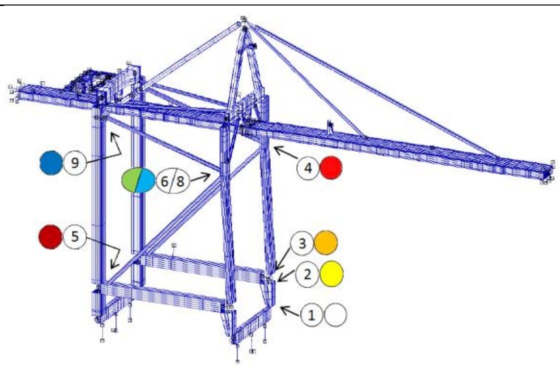

Figure 6 Connections influence assembly capacity

5.3 Concepts

What can be noted in paragraph 5.1 and 5.2 is that the type of connections is dependent on the situation. As such there are a number of observations to be made:

1. Does sea transport concern a single crane or a number of cranes?
2. Does sea transport concern semi or fully erected transport?
3. Does assembly before sea transport take place at Taicang Port or at the RCI assembly site?

Based on these observations and previous assumptions 7 different concepts have been made, which will be looked at from both assembly sites, and will be compared to having the entire portal frame with bolted flange plate connections (Table 5).

Table 5 Concept overview

	Concept							
Connection no.	0	1	2	3	4	5	6	7
1	B	B	B	B	B	B	B	B
2	B	W	W	W	W	B	B	B
3	B	W	W	W	W	W	B	B
4	B	W	W	W	W	W	W	W
5	B	B	B	B	B	B	B	B
6	B	W	W	W	W	W	B	B
7	B	B	B	B	B	B	B	B
8	B	W	W	W	W	W	B	B
9	B	B	B	B	B	B	B	B
10	B	B	W	W	W	W	W	W
11	B	W	W	B	W	W	B	W
12	B	B	B	B	B	B	B	B
13	B	B	B	B	B	B	B	B

5.4 Cost

Based on these concepts a cost calculation has been made to determine what the possible cost reduction could be for the removal of bolted flange plate connections, taking into account the area requirement, hoisting equipment, assembly duration, build-up of the portal frame, personnel involved and the cost of the replacement welded connection, which is varied between 20 to 40% of the bolted flange plate cost for all welded flange plate cost (Table 6, 7) The cost during assembly for the welded flange connections is calculated separately.

Table 6 Concept, cost reduction, assembly Taicang Port

Taicang Port		
Concept no.	Description	Estimated cost reduction range[Euro/crane]
concept 0	All connections are bolted	-
Single crane		
Concept 1	Semi-erected transport, (un-)loading method fork lift	-5,700 to -20,600
Concept 2	Semi-erected transport, (un-)loading method otherwise	10,900 to -7,100
Concept 3	Fully erected transport, height restriction	6,500 to -10,300
Concept 4	Fully erected transport, no height restriction	10,900 to -7,100
Multiple cranes		
Concept 5	Semi-erected transport	40,200 to 25,200
Concept 6	Fully erected transport, height restriction	55,000 to 48,600
Concept 7	Fully erected transport, no height restriction	59,500 to 52,000

Table 7 Concept, cost reduction, assembly RCI assembly site

RCI assembly site		
Concept no.	Description	Estimated cost reduction range [Euro/crane]
concept 0	All connections are bolted	-
Single crane		
Concept 1	Semi-erected transport, (un-)loading method fork lift	70,200 to 55,400
Concept 2	Semi-erected transport, (un-)loading method otherwise	85,200 to 67,300
Concept 3	Fully erected transport, height restriction	79,700 to 63,100
Concept 4	Fully erected transport, no height restriction	85,200 to 67,300
Multiple cranes		
Concept 5	Semi-erected transport	75,600 to 62,000
Concept 6	Fully erected transport, height restriction	40,400 to 34,000
Concept 7	Fully erected transport, no height restriction	45,800 to 38,300

5.5 Conclusion

The following conclusions can be made:

1. If assembly takes place at Taicang Port the fewer welded connections are used the higher the cost reduction will be. This is due to the rental cost of hoisting equipment and the duration of assembly;
2. If assembly takes place at RCI assembly site the more welded connections are used the higher the cost reduction will be. This is due to having no rental cost of hoisting equipment;
3. The type of connection will depend on sea transport, the assembly capacity, client specifications and others, therefore there is no optimal solution to be found that suites all situations.

6. Main Conclusion

The topics discussed in this paper came forth from a comparison with other crane manufacturers and from practice. As a conclusion it can be said that the outcome of the topics will decrease the cost price of the crane and can be applied by Cargotec Netherlands BV. If one looks at each topic separately the following main conclusion can be made.

1. Based on tender documentation an insight is given on the other topics, from which it can be concluded that the other topics are acceptable or desired by client's.
2. For the application of a different steel quality the conclusion can be drawn that the current practice of applying D-quality steel is unnecessary and a combination of B, C and D-quality steel can be applied.
3. Concerning the application of an open gearing the conclusion can be drawn that an open gearing will lead to a reduction in cost even though there are some disadvantages to this type of transmission.
4. With regards to the replacement of bolted flange connections there are a number of connections that can be replaced by a welded connection, but the optimum concept differs due to a number of internal and external factors.

The goal of the cost reduction is to reduce the cost price by 5 to 10 %. When reviewing the possible cost reductions that can be achieved with the topics the following can be stated based on a total manufacturing cost price of the crane of 3,600,000 Euro (the comparison for each topic is based on the same crane; the cost price is based on the cost of production and assembly, excluding transportation cost and cost made at the client's site):

- The application of a different steel quality will result in a cost reduction of 22,500 Euro (0.6 % of the manufacturing cost price of the crane);
- The application of an open gearing will result in a cost reduction of 61,900 Euro (1.7 %) in case a single engine powers two (2) crane wheels, 61,000 Euro (1.7 %) in case a single engine powers four (4) crane wheels, and 87,500 Euro (2.4 %) in case of a shortened bogie length with a single engine powering two (2) crane wheels.
- Depending on the concept, the location of assembly and external factors the cost reduction will vary. The extremes are that the cost reduction is not achieved but a cost increase is met of 20,600 Euro (0.6 %) or the cost reduction is achieved with an decrease of 67,300 Euro (1.9 %) for the most conservative situation.

As a conclusion it can be said that the cost reductions presented in this paper allow to reach the goal of reducing the cost price by 5%.

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Appendix B Crane orders and handling capacity Asia-Pacific market

This appendix displays the crane orders originating from the Asia-Pacific market.

- Table B1 displays the order overview for Ship-To-Shore container gantry cranes for the Asia-Pacific market.
- Table B2 displays the container throughput for the Asia-Pacific market.

Table B1 Ship-To-Shore container gantry crane order overview

	Year								
APAC country	June 2012 – July 2011	June 2011 – July 2010	June 2010 – July 2009	June 2009 – July 2008	June 2008 – July 2007	June 2007 – July 2006	June 2006 – July 2005	June 2005 – July 2004	Total
Bangladesh	0	0	0	0	0	0	2	0	2
Cambodia	0	0	0	0	0	2	0	0	2
P.R. China	42	35	28	32	111	58	115	93	514
India	3	18	0	12	6	6	4	11	60
Indonesia	6	0	2	2	4	0	0	1	15
Japan	3	7	9	8	11	5	1	2	46
Korea	1	6	9	2	13	17	5	14	67
Malaysia	9	10	0	0	33	5	8	8	73
Myanmar	0	2	0	0	0	0	0	0	2
Pakistan	0	2	3	0	0	0	1	1	7
Philippines	3	2	2	0	7	0	0	4	18
Singapore	3	0	0	0	25	15	8	8	59
Sri Lanka	12	4	6	0	1	0	0	0	23
Taiwan	0	3	2	11	6	1	1	5	29
Thailand	0	2	4	0	3	6	3	5	23
Vietnam	9	0	10	0	5	0	3	0	27
Total	93	91	75	67	226	115	156	153	967

Table B2 Container handling capacity

APAC country	Yearly throughput [x 1000 TEU]							Summed increase throughput 2004 – 2010 [TEU]	Equivalent handling capacity number of STS container gantry cranes
	2004	2005	2006	2007	2008	2009	2010		
Bangladesh	714	809	902	978	1,091	1,182	1,356	642	6
Cambodia	-	-	-	253	259	208	224	224	2
P.R. China	74,725	67,245	84,811	103,823	115,061	108,044	129,611	54,885	436
India	4,333	4,982	6,141	7,398	7,672	8,036	9,753	5,420	44
Indonesia	5,369	5,503	4,316	6,583	7,405	7,244	8,371	3,002	24
Japan	16,436	17,055	18,470	19,165	18,944	16,286	18,060	1,624	13
Korea	14,363	15,113	15,514	17,086	17,418	15,699	18,538	4,175	34
Malaysia	11,511	12,198	13,419	14,829	16,025	15,860	18,247	6,736	54
Myanmar	-	-	-	170	180	160	167	167	2
Pakistan	1,269	1,686	1,777	1,936	1,938	2,058	2,149	880	7
Philippines	3,676	3,664	3,676	4,351	4,471	4,307	4,947	1,270	11
Singapore	21,329	23,192	24,792	28,768	30,891	26,593	29,179	7,849	63
Sri Lanka	2,221	2,455	3,079	3,687	3,687	3,464	4,080	1,859	15
Thailand	4,847	5,115	5,574	6,339	6,726	5,898	6,649	1,802	15
Vietnam	2,273	2,537	3,000	4,009	4,394	4,937	5,984	3,711	30
Total	163,068	161,556	185,471	219,375	236,162	219,975	257,313	94,245	748

The equivalent handling capacity STS container gantry crane has been determined by assuming a Ship-To-Shore container gantry crane with an average handling capacity of 35 TEU/hr., for 12 hr/day, 300 day/year. This leads to a handling capacity of 126,000 TEU/year per Ship-To-Shore container gantry crane.

Appendix C Steel quality tables standard

This appendix displays the steel quality tables based on the steel quality selection procedure as defined in the European standard FEM 1.001, NEN-EN 13001 and the Chinese standard GB/T 3811. The steel quality tables have been listed according to the minimum temperature as defined in the standard, namely -55 °C.

- Table C1 displays the steel quality table in case of longitudinal welds.
- Table C2 displays the steel quality table in case of weld accumulations.
- Table C3, C4 display the steel quality table in case of steel type Q345, with varying weld types or shapes.
- Table C5, C6 display the steel quality table in case of steel type Q390, with varying weld types or shapes.
- Table C7 displays the steel quality table in case of longitudinal welds.
- Table C8 displays the steel quality table in case of weld accumulations.

The steel quality has been displayed as follows:

Steel quality	Quality display
A-quality steel	A
B-quality steel	B
C-quality steel	C
D-quality steel	D
E-quality steel	E

Even though the European standard FEM 1.001 and the Chinese standard GB/T 3811 do not define E-quality steel to be required for very low temperatures in combination with large thicknesses, the decision has been made that above a defined boundary in the standard E-quality steel shall be applied.

Table C1 Resulting steel qualities based on temperature and plate thickness, FEM 1.001

$\sum Z = Z_A + Z_B + Z_C$ [−] $\rightarrow Z_A = 1$	Temperature T [°C]											
Plate thickness t [mm]	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55
5	1,1	1,2	1,5	1,9	2,6	3,4	4,5	5,6	6,7	7,8	9	10,1
6	1,15	1,25	1,55	1,95	2,65	3,45	4,55	5,65	6,75	7,85	9,05	10,15
7	1,2	1,3	1,6	2	2,7	3,5	4,6	5,7	6,8	7,9	9,1	10,2
8	1,25	1,35	1,65	2,05	2,75	3,55	4,65	5,75	6,85	7,95	9,15	10,25
9	1,3	1,4	1,7	2,1	2,8	3,6	4,7	5,8	6,9	8	9,2	10,3
10	1,4	1,5	1,8	2,2	2,9	3,7	4,8	5,9	7	8,1	9,3	10,4
12	1,5	1,6	1,9	2,3	3	3,8	4,9	6	7,1	8,2	9,4	10,5
15	1,8	1,9	2,2	2,6	3,3	4,1	5,2	6,3	7,4	8,5	9,7	10,8
16	1,9	2	2,3	2,7	3,4	4,2	5,3	6,4	7,5	8,6	9,8	10,9
20	2,45	2,55	2,85	3,25	3,95	4,75	5,85	6,95	8,05	9,15	10,35	11,45
25	3	3,1	3,4	3,8	4,5	5,3	6,4	7,5	8,6	9,7	10,9	12
30	3,5	3,6	3,9	4,3	5	5,8	6,9	8	9,1	10,2	11,4	12,5
35	3,9	4	4,3	4,7	5,4	6,2	7,3	8,4	9,5	10,6	11,8	12,9
40	4,2	4,3	4,6	5	5,7	6,5	7,6	8,7	9,8	10,9	12,1	13,2
45	4,5	4,6	4,9	5,3	6	6,8	7,9	9	10,1	11,2	12,4	13,5
50	4,8	4,9	5,2	5,6	6,3	7,1	8,2	9,3	10,4	11,5	12,7	13,8
55	5	5,1	5,4	5,8	6,5	7,3	8,4	9,5	10,6	11,7	12,9	14
60	5,3	5,4	5,7	6,1	6,8	7,6	8,7	9,8	10,9	12	13,2	14,3
65	5,55	5,65	5,95	6,35	7,05	7,85	8,95	10,05	11,15	12,25	13,45	14,55
70	5,8	5,9	6,2	6,6	7,3	8,1	9,2	10,3	11,4	12,5	13,7	14,8
75	6	6,1	6,4	6,8	7,5	8,3	9,4	10,5	11,6	12,7	13,9	15
80	6,2	6,3	6,6	7	7,7	8,5	9,6	10,7	11,8	12,9	14,1	15,2
85	6,4	6,5	6,8	7,2	7,9	8,7	9,8	10,9	12	13,1	14,3	15,4
90	6,6	6,7	7	7,4	8,1	8,9	10	11,1	12,2	13,3	14,5	15,6
95	6,8	6,9	7,2	7,6	8,3	9,1	10,2	11,3	12,4	13,5	14,7	15,8
100	7	7,1	7,4	7,8	8,5	9,3	10,4	11,5	12,6	13,7	14,9	16

Table C2 Resulting steel qualities based on temperature and plate thickness, FEM 1.001

$\sum Z = Z_A + Z_B + Z_C \; [-]$ $\rightarrow Z_A = 2$	Temperature $T \; [°C]$											
Plate thickness $t \; [mm]$	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55
5	2,1	2,2	2,5	2,9	3,6	4,4	5,5	6,6	7,7	8,8	10	11,1
6	2,15	2,25	2,55	2,95	3,65	4,45	5,55	6,65	7,75	8,85	10,05	11,15
7	2,2	2,3	2,6	3	3,7	4,5	5,6	6,7	7,8	8,9	10,1	11,2
8	2,25	2,35	2,65	3,05	3,75	4,55	5,65	6,75	7,85	8,95	10,15	11,25
9	2,3	2,4	2,7	3,1	3,8	4,6	5,7	6,8	7,9	9	10,2	11,3
10	2,4	2,5	2,8	3,2	3,9	4,7	5,8	6,9	8	9,1	10,3	11,4
12	2,5	2,6	2,9	3,3	4	4,8	5,9	7	8,1	9,2	10,4	11,5
15	2,8	2,9	3,2	3,6	4,3	5,1	6,2	7,3	8,4	9,5	10,7	11,8
16	2,9	3	3,3	3,7	4,4	5,2	6,3	7,4	8,5	9,6	10,8	11,9
20	3,45	3,55	3,85	4,25	4,95	5,75	6,85	7,95	9,05	10,15	11,35	12,45
25	4	4,1	4,4	4,8	5,5	6,3	7,4	8,5	9,6	10,7	11,9	13
30	4,5	4,6	4,9	5,3	6	6,8	7,9	9	10,1	11,2	12,4	13,5
35	4,9	5	5,3	5,7	6,4	7,2	8,3	9,4	10,5	11,6	12,8	13,9
40	5,2	5,3	5,6	6	6,7	7,5	8,6	9,7	10,8	11,9	13,1	14,2
45	5,5	5,6	5,9	6,3	7	7,8	8,9	10	11,1	12,2	13,4	14,5
50	5,8	5,9	6,2	6,6	7,3	8,1	9,2	10,3	11,4	12,5	13,7	14,8
55	6	6,1	6,4	6,8	7,5	8,3	9,4	10,5	11,6	12,7	13,9	15
60	6,3	6,4	6,7	7,1	7,8	8,6	9,7	10,8	11,9	13	14,2	15,3
65	6,55	6,65	6,95	7,35	8,05	8,85	9,95	11,05	12,15	13,25	14,45	15,55
70	6,8	6,9	7,2	7,6	8,3	9,1	10,2	11,3	12,4	13,5	14,7	15,8
75	7	7,1	7,4	7,8	8,5	9,3	10,4	11,5	12,6	13,7	14,9	16
80	7,2	7,3	7,6	8	8,7	9,5	10,6	11,7	12,8	13,9	15,1	16,2
85	7,4	7,5	7,8	8,2	8,9	9,7	10,8	11,9	13	14,1	15,3	16,4
90	7,6	7,7	8	8,4	9,1	9,9	11	12,1	13,2	14,3	15,5	16,6
95	7,8	7,9	8,2	8,6	9,3	10,1	11,2	12,3	13,4	14,5	15,7	16,8
100	8	8,1	8,4	8,8	9,5	10,3	11,4	12,5	13,6	14,7	15,9	17

Table C3 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 1$	Steel type Q345					
	Temperature T [°C]					
Plate thickness t [mm]	0	-10	-20	-30	-40	-50
5	2	3	4	5	6	8
6	2	3	4	5	6	8
7	2	3	4	5	6	8
8	2	3	4	5	6	8
9	2	3	4	5	6	8
10	2	3	4	5	6	8
12	3	4	5	6	7	9
15	3	4	5	6	7	9
16	3	4	5	6	7	9
20	3	4	5	6	7	9
25	4	5	6	7	8	10
30	4	5	6	7	8	10
35	4	5	6	7	8	10
40	3	4	5	6	7	9
45	4	5	6	7	8	10
50	4	5	6	7	8	10
55	4	5	6	7	8	10
60	4	5	6	7	8	10
65	5	6	7	8	9	11
70	5	6	7	8	9	11
75	5	6	7	8	9	11
80	5	6	7	8	9	11
85	6	7	8	9	10	12
90	6	7	8	9	10	12
95	6	7	8	9	10	12
100	6	7	8	9	10	12

Table C4 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 2$	Steel type Q345					
	Temperature T [°C]					
Plate thickness t [mm]	0	-10	-20	-30	-40	-50
5	3	4	5	6	7	9
6	3	4	5	6	7	9
7	3	4	5	6	7	9
8	3	4	5	6	7	9
9	3	4	5	6	7	9
10	3	4	5	6	7	9
12	4	5	6	7	8	10
15	4	5	6	7	8	10
16	4	5	6	7	8	10
20	4	5	6	7	8	10
25	5	6	7	8	9	11
30	5	6	7	8	9	11
35	5	6	7	8	9	11
40	4	5	6	7	8	10
45	5	6	7	8	9	11
50	5	6	7	8	9	11
55	5	6	7	8	9	11
60	5	6	7	8	9	11
65	6	7	8	9	10	12
70	6	7	8	9	10	12
75	6	7	8	9	10	12
80	6	7	8	9	10	12
85	7	8	9	10	11	13
90	7	8	9	10	11	13
95	7	8	9	10	11	13
100	7	8	9	10	11	13

Table C5 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 1$	Steel type Q390					
	Temperature T [°C]					
Plate thickness t [mm]	0	-10	-20	-30	-40	-50
5	2	3	4	5	6	8
6	2	3	4	5	6	8
7	2	3	4	5	6	8
8	2	3	4	5	6	8
9	2	3	4	5	6	8
10	2	3	4	5	6	8
12	3	4	5	6	7	9
15	3	4	5	6	7	9
16	3	4	5	6	7	9
20	3	4	5	6	7	9
25	4	5	6	7	8	10
30	4	5	6	7	8	10
35	4	5	6	7	8	10
40	4	5	6	7	8	10
45	5	6	7	8	9	11
50	5	6	7	8	9	11
55	5	6	7	8	9	11
60	5	6	7	8	9	11
65	6	7	8	9	10	12
70	6	7	8	9	10	12
75	6	7	8	9	10	12
80	6	7	8	9	10	12
85	7	8	9	10	11	13
90	7	8	9	10	11	13
95	7	8	9	10	11	13
100	7	8	9	10	11	13

Table C6 Resulting steel qualities based on temperature and plate thickness, NEN-EN 13001

$\sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \rightarrow Q_4 = 2$	Steel type Q390					
	Temperature T [°C]					
Plate thickness t [mm]	0	-10	-20	-30	-40	-50
5	3	4	5	6	7	9
6	3	4	5	6	7	9
7	3	4	5	6	7	9
8	3	4	5	6	7	9
9	3	4	5	6	7	9
10	3	4	5	6	7	9
12	4	5	6	7	8	10
15	4	5	6	7	8	10
16	4	5	6	7	8	10
20	4	5	6	7	8	10
25	5	6	7	8	9	11
30	5	6	7	8	9	11
35	5	6	7	8	9	11
40	5	6	7	8	9	11
45	6	7	8	9	10	12
50	6	7	8	9	10	12
55	6	7	8	9	10	12
60	6	7	8	9	10	12
65	7	8	9	10	11	13
70	7	8	9	10	11	13
75	7	8	9	10	11	13
80	7	8	9	10	11	13
85	8	9	10	11	12	14
90	8	9	10	11	12	14
95	8	9	10	11	12	14
100	8	9	10	11	12	14

Table C7 Resulting steel qualities based on temperature and plate thickness, GB/T 3811

$\sum Z = Z_A + Z_B + Z_C$ [−] $\rightarrow Z_A = 1.6$	Temperature T [°C]											
Plate thickness t [mm]	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55
5	1,7	1,8	2,1	2,5	3,2	4	5,1	6,2	7,3	8,4	9,6	10,7
6	1,75	1,85	2,15	2,55	3,25	4,05	5,15	6,25	7,35	8,45	9,65	10,75
7	1,8	1,9	2,2	2,6	3,3	4,1	5,2	6,3	7,4	8,5	9,7	10,8
8	1,85	1,95	2,25	2,65	3,35	4,15	5,25	6,35	7,45	8,55	9,75	10,85
9	1,9	2	2,3	2,7	3,4	4,2	5,3	6,4	7,5	8,6	9,8	10,9
10	2	2,1	2,4	2,8	3,5	4,3	5,4	6,5	7,6	8,7	9,9	11
12	2,1	2,2	2,5	2,9	3,6	4,4	5,5	6,6	7,7	8,8	10	11,1
15	2,4	2,5	2,8	3,2	3,9	4,7	5,8	6,9	8	9,1	10,3	11,4
16	2,5	2,6	2,9	3,3	4	4,8	5,9	7	8,1	9,2	10,4	11,5
20	3,05	3,15	3,45	3,85	4,55	5,35	6,45	7,55	8,65	9,75	10,95	12,05
25	3,6	3,7	4	4,4	5,1	5,9	7	8,1	9,2	10,3	11,5	12,6
30	4,1	4,2	4,5	4,9	5,6	6,4	7,5	8,6	9,7	10,8	12	13,1
35	4,5	4,6	4,9	5,3	6	6,8	7,9	9	10,1	11,2	12,4	13,5
40	4,8	4,9	5,2	5,6	6,3	7,1	8,2	9,3	10,4	11,5	12,7	13,8
45	5,1	5,2	5,5	5,9	6,6	7,4	8,5	9,6	10,7	11,8	13	14,1
50	5,4	5,5	5,8	6,2	6,9	7,7	8,8	9,9	11	12,1	13,3	14,4
55	5,6	5,7	6	6,4	7,1	7,9	9	10,1	11,2	12,3	13,5	14,6
60	5,9	6	6,3	6,7	7,4	8,2	9,3	10,4	11,5	12,6	13,8	14,9
65	6,15	6,25	6,55	6,95	7,65	8,45	9,55	10,65	11,75	12,85	14,05	15,15
70	6,4	6,5	6,8	7,2	7,9	8,7	9,8	10,9	12	13,1	14,3	15,4
75	6,6	6,7	7	7,4	8,1	8,9	10	11,1	12,2	13,3	14,5	15,6
80	6,8	6,9	7,2	7,6	8,3	9,1	10,2	11,3	12,4	13,5	14,7	15,8
85	7	7,1	7,4	7,8	8,5	9,3	10,4	11,5	12,6	13,7	14,9	16
90	7,2	7,3	7,6	8	8,7	9,5	10,6	11,7	12,8	13,9	15,1	16,2
95	7,4	7,5	7,8	8,2	8,9	9,7	10,8	11,9	13	14,1	15,3	16,4
100	7,6	7,7	8	8,4	9,1	9,9	11	12,1	13,2	14,3	15,5	16,6

Table C8 Resulting steel qualities based on temperature and plate thickness, GB/T 3811

$\sum Z = Z_A + Z_B + Z_C\ [-]$ $\rightarrow Z_A = 2.6$	Temperature $T\ [°C]$											
Plate thickness $t\ [mm]$	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55
5	2,7	2,8	3,1	3,5	4,2	5	6,1	7,2	8,3	9,4	10,6	11,7
6	2,75	2,85	3,15	3,55	4,25	5,05	6,15	7,25	8,35	9,45	10,65	11,75
7	2,8	2,9	3,2	3,6	4,3	5,1	6,2	7,3	8,4	9,5	10,7	11,8
8	2,85	2,95	3,25	3,65	4,35	5,15	6,25	7,35	8,45	9,55	10,75	11,85
9	2,9	3	3,3	3,7	4,4	5,2	6,3	7,4	8,5	9,6	10,8	11,9
10	3	3,1	3,4	3,8	4,5	5,3	6,4	7,5	8,6	9,7	10,9	12
12	3,1	3,2	3,5	3,9	4,6	5,4	6,5	7,6	8,7	9,8	11	12,1
15	3,4	3,5	3,8	4,2	4,9	5,7	6,8	7,9	9	10,1	11,3	12,4
16	3,5	3,6	3,9	4,3	5	5,8	6,9	8	9,1	10,2	11,4	12,5
20	4,05	4,15	4,45	4,85	5,55	6,35	7,45	8,55	9,65	10,75	11,95	13,05
25	4,6	4,7	5	5,4	6,1	6,9	8	9,1	10,2	11,3	12,5	13,6
30	5,1	5,2	5,5	5,9	6,6	7,4	8,5	9,6	10,7	11,8	13	14,1
35	5,5	5,6	5,9	6,3	7	7,8	8,9	10	11,1	12,2	13,4	14,5
40	5,8	5,9	6,2	6,6	7,3	8,1	9,2	10,3	11,4	12,5	13,7	14,8
45	6,1	6,2	6,5	6,9	7,6	8,4	9,5	10,6	11,7	12,8	14	15,1
50	6,4	6,5	6,8	7,2	7,9	8,7	9,8	10,9	12	13,1	14,3	15,4
55	6,6	6,7	7	7,4	8,1	8,9	10	11,1	12,2	13,3	14,5	15,6
60	6,9	7	7,3	7,7	8,4	9,2	10,3	11,4	12,5	13,6	14,8	15,9
65	7,15	7,25	7,55	7,95	8,65	9,45	10,55	11,65	12,75	13,85	15,05	16,15
70	7,4	7,5	7,8	8,2	8,9	9,7	10,8	11,9	13	14,1	15,3	16,4
75	7,6	7,7	8	8,4	9,1	9,9	11	12,1	13,2	14,3	15,5	16,6
80	7,8	7,9	8,2	8,6	9,3	10,1	11,2	12,3	13,4	14,5	15,7	16,8
85	8	8,1	8,4	8,8	9,5	10,3	11,4	12,5	13,6	14,7	15,9	17
90	8,2	8,3	8,6	9	9,7	10,5	11,6	12,7	13,8	14,9	16,1	17,2
95	8,4	8,5	8,8	9,2	9,9	10,7	11,8	12,9	14	15,1	16,3	17,4
100	8,6	8,7	9	9,4	10,1	10,9	12	13,1	14,2	15,3	16,5	17,6

Appendix D Steel quality crane steel structure

Table D1 displays the steel quality division of the main structural steel components of the crane steel structure based on varying temperatures.

The steel quality division has been defined according to the following temperatures:

- T = -10 °C
- T = -15 °C
- T = -20 °C
- T = -25 °C

The total evaluated mass amounts to 1007 MT.

In Table D2 the cost savings for each temperature have been listed.

Table D2 Steel quality division and cost reduction

Temp. [°C]	B [%]	C [%]	D [%]	Cost reduction [Euro]
0	72.8	27.2	0.0	30,900
-5	63.4	32.8	3.8	28,100
-10	63.4	32.8	3.8	28,100
-15	52.9	43.3	3.8	25,400
-20	42.2	52.5	5.3	22,500
-25	8.2	80.5	11.3	13,200

For temperatures lower than -25 °C it can be noted in Table C1 and C2 that B-quality steel is no longer to been seen at a temperature of -30 °C and C-quality steel at a temperature of -45 °C.

Table D1 Steel quality division for case study under varying operational temperatures

Steel structure Ship-To-Shore container gantry crane																
	Temperature	T = 0 °C			T = -5 °C = -10 °C			T = -15 °C			T = -20 °C			T = -25 °C		
Component	Total mass [MT]	% B	% C	% D	% B	% C	% D	% B	% C	% D	% B	% C	% D	% B	% C	% D
Bogie WS steel structure	8.9	10.2	89.8	0.0	10.2	89.8	0.0	4.9	95.1	0.0	0.0	85.8	14.2	0.0	48.1	51.9
Balance WS steel structure	12.7	55.8	44.2	0.0	37.7	62.3	0.0	20.5	79.5	0.0	20.5	54.5	27.0	0.0	59.8	40.2
Main balance WS steel structure	26.7	35.5	64.5	0.0	8.0	64.4	27.6	0.3	72.2	27.6	0.3	72.2	27.6	0.0	72.4	27.6
Bogie LS steel structure	9.7	36.5	63.5	0.0	11.8	88.2	0.0	11.4	88.6	0.0	4.9	92.0	3.0	0.0	83.8	16.2
Balance LS steel structure	9.7	49.0	51.0	0.0	49.0	51.0	0.0	46.1	53.9	0.0	7.8	92.2	0.0	0.0	69.2	30.8
Main balance LS steel structure	21.5	64.3	33.2	2.5	31.9	65,5	2.6	0.3	97.1	2.6	0.3	71.9	27.8	0.0	72.2	27.9
Sill beam WS	43.7	57.8	42.2	0.0	32.0	68.0	0.0	30.7	69.3	0.0	21.2	78.8	0.0	2.6	90.6	6.8
Sill beam LS	40.1	8.5	91.5	0.0	37.0	63.0	0.0	38.9	61.1	0.0	25.0	75.0	0.0	13.1	79.9	7.0
Lower leg PS WS (SB WS)	20.7 (sum)	52.7	47.3	0.0	51.7	48.3	0.0	39.7	60.3	0.0	13.7	86.3	0.0	13.7	69.1	17.2
Lower leg PS LS (SB LS)	8.0 (7.4)	69.3	30.7	0.0	67.8	32.2	0.0	66.0	34.0	0.0	62.0	38.0	0.0	12.7	72.6	14.7
Cross girder PS (SB)	81.8 (sum)	77.6	22.4	0.0	74.6	25.4	0.0	72.3	27.7	0.0	53.1	46.9	0.0	18.4	65.9	15.7
Long leg PS WS (SB WS)	56.4 (sum)	90.2	9.8	0.0	80.3	19.7	0.0	69.3	30.7	0.0	43.6	56.4	0.0	14.7	80.1	5.2
Long leg PS LS (SB WS)	24.4 (24.4)	91.4	8.6	0.0	91.4	8.6	0.0	89.0	11.0	0.0	88.8	11.2	0.0	24.8	70.1	5.1
Upper leg PS WS (SB WS)	35.0 (sum)	85.1	14.9	0.0	75.3	24.7	0.0	45.0	55.0	0.0	24.1	75.9	0.0	9.2	86.4	4.5
Upper leg PS LS (SB LS)	20.9 (20.1)	78.4	21.6	0.0	76.7	23.3	0.0	69.0	31.0	0.0	63.6	36.4	0.0	10.9	89.1	0.0
Portal beam WS	36.0	74.4	25.6	0.0	57.4	42.6	0.0	39.3	60.7	0.0	15.7	84.3	0.0	6.8	81.2	12.1
Portal beam LS	39.5	50.5	49.5	0.0	40.8	59.2	0.0	39.3	60.7	0.0	39.3	60.7	0.0	12.1	53.0	35.0
A frame	14.7	100.0	0.0	0.0	89.5	10.5	0.0	77.8	22.2	0.0	10.3	89.7	0.0	0.0	100.0	0.0
Diagonal tie PS (SB)	20.5 (sum)	90.9	9.1	0.0	90.9	9.1	0.0	90.9	9.1	0.0	90.9	9.1	0.0	0.0	100.0	0.0
Tie portal frame WS	5.6 (sum)	75.4	24.6	0.0	75.4	24.6	0.0	75.4	24.6	0.0	75.4	24.6	0.0	0.0	100.0	0.0
Pylon head	11.7	24.7	75.3	0.0	16.9	83.1	0.0	3.4	96.6	0.0	0.4	99.6	0.0	0.0	100.0	0.0
Connection A frame and pylon head	7.4	98.4	1.6	0.0	93.2	6.8	0.0	51.7	48.3	0.0	8.7	91.3	0.0	4.1	95.9	0.0
Boom latch support	3.6	74.9	25.1	0.0	74.9	25.1	0.0	15.5	84.5	0.0	0.4	99.6	0.0	0.0	100.0	0.0
Pylon head pully block	1.2	95.1	4.9	0.0	1.5	98.5	0.0	1.5	98.5	0.0	1.5	98.5	0.0	0.0	100.0	0.0
Boom hook	1.3	30.2	69.8	0.0	30.2	48.5	21.4	30.2	46.2	23.6	30.2	46.2	23.6	0.0	51.1	48.9
Bridge girder	99.6	82.6	17.4	0.0	70.3	29.7	0.0	53.5	46.5	0.0	40.7	59.3	0.0	0.0	100.0	0.0
	20.4	64.4	35.6	0.0	62.9	30.1	7.1	58.1	34.9	7.1	57.4	35.5	7.1	45.5	46.4	8.1
	13.3	31.2	68.8	0.0	31.2	26.0	42.8	25.7	31.5	42.8	14.2	43.0	42.8	2.7	54.5	42.8
	1.2	95.4	4.6	0.0	94.5	5.5	0.0	89.2	10.8	0.0	53.9	46.1	0.0	18.2	81.8	0.0
Boom girder	47.3	95.6	4.4	0.0	92.1	7.9	0.0	84.2	15.8	0.0	82.5	17.5	0.0	0.0	100.0	0.0

	51.4	100.0	0.0	0.0	100.0	0.0	0.0	90.0	10.0	0.0	90.0	10.0	0.0	0.0	100.0	0.0
	21.2	88.3	11.7	0.0	79.9	20.1	0.0	66.8	33.2	0.0	66.8	33.2	0.0	46.7	53.3	0.0
	9.0	28.0	72.0	0.0	28.0	72.0	0.0	23.2	76.8	0.0	16.5	41.1	42.4	7.2	50.4	42.4
Boom end construction	2.2	100.0	0.0	0.0	99.5	0.5	0.0	71.2	28.8	0.0	71.2	28.8	0.0	13.5	86.5	0.0
Boom trim/list support	3.7	88.5	11.5	0.0	88.5	11.5	0.0	88.5	11.5	0.0	13.6	78.0	8.4	2.7	88.9	8.4
Short forestay	10.2	68.6	31.4	0.0	16.5	52.1	31.4	15.9	52.6	31.4	15.9	52.6	31.4	0.0	68.6	31.4
Short forestay link	1.2	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
Long forestay	30.2	13.8	86.2	0.0	13.8	56.9	29.3	13.5	57.2	29.3	7.5	63.1	29.3	0.0	70.7	29.3
Long forestay link	1.3	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
Bridge girder, back reach sheave supports	4.8	84.6	15.4	0.0	82.2	17.8	0.0	58.8	33.9	7.3	57.0	34.6	8.4	0.0	91.6	8.4
Bridge girder, back reach sheave supports	8.4	79.5	20.5	0.0	79.5	20.5	0.0	79.5	20.5	0.0	79.5	20.5	0.0	0.0	100.0	0.0
Pylon tie	24.5	91.2	8.8	0.0	67.1	32.9	0.00	31.71	68.3	0.0	31.4	68.6	0.0	0.0	100	0.00
Horizontal V-tie	9.0	93.3	6.6	0.0	9.4	6.6	83.9	6.3	9.8	83.9	6.3	9.8	83.9	0.0	16.1	83.9
Machinery house floor structure	1.2	86.0	14.0	0.0	8.5	91.5	0.0	8.5	91.5	0.0	7.5	92.5	0.0	0.0	86.0	14.0
	11.9	90.5	9.5	0.0	73.2	26.8	0.0	73.3	26.7	0.0	70.3	29.7	0.0	0.0	98.2	1.8
	8.4	90.5	9.5	0.0	47.7	52.3	0.0	47.7	52.3	0.0	47.7	50.3	2.0	0.0	98.0	2.0
	487	50.3	49.7	0.0	37.5	62.5	0.0	37.5	62.5	0.0	37.5	46.7	15.8	0.0	73.9	26.1
Machinery floor, main hoist pad	4.1	67.4	32.6	0.0	57.2	42.8	0.0	56.3	43.7	0.0	38.4	60.8	0.7	0.0	99.3	0.7
Machinery floor, boom hoist support	2.7	68.3	31.7	0.0	62.2	37.8	0.0	61.3	38.7	0.0	36.1	63.9	0.0	0.0	100.0	0.0
Machinery floor support to bridge girder	0.6	28.4	71.6	0.0	28.4	71.6	0.0	28.4	71.6	0.0	28.4	71.6	0.0	0.0	100.0	0.0
Main trolley bogie	0.7	88.7	11.3	0.0	29.8	70.2	0.0	23.8	76.2	0.0	9.1	90.9	0.0	1.7	98.3	0.0
Main trolley structure	6.2	73.6	26.4	0.0	66.8	29.4	3.8	53.6	42.7	3.8	47.0	49.2	3.8	0.0	95.7	4.3
	5.4	80.0	20.0	0.0	71.4	19.4	9.2	67.0	23.8	9.2	38.3	52.6	9.2	0.0	88.7	11.3
	1.6	99.7	0.3	0.0	99.7	0.3	0.0	99.0	1.0	0.0	98.0	2.0	0.0	0.0	100.0	0.0
	1.1	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	92.1	0.0	0.0	0.0	100.0	0.0
	0.4	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0
	0.3	78.8	21.2	0.0	78.8	21.2	0.0	78.8	21.2	0.0	17.5	82.5	0.0	0.0	100.0	0.0

Appendix E Steel quality component steel structure

Table E1 displays the steel quality division for the sill beam waterside of an existing Ship-To-Shore container gantry crane for the European standards FEM 1.001, NEN-EN 13001 and the Chinese standard GB/T 3811.

Total mass of the sill beam waterside has been listed as 43.7 MT.

Table E1 Steel quality according to FEM 1.001, GB/T 3811 and NEN-EN 13001

Item	description	Z_A [1]	Z_B	Z_C	$\sum Z_i$	FEM 1.001	Z_A [2]	GB/T 3811	Q_1	Q_2	Q_3	Q_4 [3]	Q_5	$\sum Q_i$	NEN-EN 13001
1	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
2	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
3	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
4	Plate 50 mm: Q390-D Z25	2	3,8	0,4	6,2	C	2.6	C	1	1	3	2	0	7	C
5	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
6	Plate 25 mm: Q345-D	2	2	0,4	4,4	C	2.6	C	1	1	2	2	0	6	C
7	Plate 12 mm: Q345-D	2	0,5	0,4	2,9	B	2.6	B	1	1	1	2	0	5	B
8	Plate 16 mm: Q345-D	2	0,9	0,4	3,3	B	2.6	B	1	1	1	2	0	5	B
9	Angle uneq. 125x75x8 Q345-D	2	0,25	0,4	2,65	B	2.6	B	1	1	0	2	0	4	B
10	Angle uneq. 125x75x8 Q345-D	2	0,25	0,4	2,65	B	2.6	B	1	1	0	2	0	4	B
11	Plate 12 mm: Q345-D	1	0,5	0,4	1,9	A	1.6	B	1	1	1	2	0	5	B
12	Plate 12 mm: Q345-D	1	0,5	0,4	1,9	A	1.6	B	1	1	1	2	0	5	B
13	Pipe 40x3 AISI 316	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	Angle uneq. 125x75x8 Q345-D	2	0,25	0,4	2,65	B	2.6	B	1	1	0	2	0	4	B
15	Plate 40 mm: Q390-D	1	3,2	0,4	4,6	C	1.6	C	1	1	2	2	0	6	C
16	Plate 25 mm: Q345-D	1	2	0,4	3,4	B	1.6	B	1	1	2	2	0	6	C
17	Plate 8 mm: Q345-D	1	0,25	0,4	1,65	A	1.6	B	1	1	0	2	0	4	B
18	Plate 20 mm: Q345-D	1	1,45	0,4	2,85	B	1.6	B	1	1	1	2	0	5	B
19	Plate 12 mm: Q345-D	2	0,5	0,4	2,9	B	2.6	B	1	1	1	2	0	5	B
20	Plate 60 mm: Q390-D	2	4,3	0,4	6,7	C	2.6	C	1	1	3	2	0	7	C
21	Plate 50 mm: Q390-D	2	3,8	0,4	6,2	C	2.6	C	1	1	3	2	0	7	C
22	Plate 40 mm: Q390-D Z25	2	3,2	0,4	5,6	C	2.6	C	1	1	2	2	0	6	C
23	Bar round 20: Q235-B hfn	2	0,5	0,4	2,9	B	2.6	B	1	0	1	2	0	4	B
24	Plate 8 mm: Q345-D	2	0,25	0,4	2,65	B	2.6	B	1	1	0	2	0	4	B
25	Plate 40 mm: Q390-D	2	3,2	0,4	5,6	C	2.6	C	1	1	2	2	0	6	C
26	Tube 60.3 x 2.9 : AISI316	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
27	Elbow 180 deg LR : AISI316	-	-	-	-	-	-	-	-	-	-	-	-	-	-
28	Plate 20 mm: Q345-D	2	1,45	0,4	3,85	B	2.6	C	1	1	1	2	0	5	B
29	Plate 20 mm: Q345-D	2	1,45	0,4	3,85	B	2.6	C	1	1	1	2	0	5	B
30	Plate 16 mm: Q345-D	2	0,9	0,4	3,3	B	2.6	B	1	1	1	2	0	5	B

31	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
32	Angle uneq. 125x75x8 Q345-D	1	0,25	0,4	1,65	A	1.6	B	1	1	0	2	0	4	B
33	Plate 40 mm: Q390-D	2	3,2	0,4	5,6	C	2.6	C	1	1	2	2	0	6	C
34	Angle uneq. 100x75x7 Q345-D	1	0,2	0,4	1,6	A	1.6	B	1	1	0	2	0	4	B
35	Angle uneq. 125x75x8 Q345-D	1	0,25	0,4	1,65	A	1.6	B	1	1	0	2	0	4	B
36	Angle uneq. 125x75x8 Q345-D	1	0,25	0,4	1,65	A	1.6	B	1	1	0	2	0	4	B
37	Plate 20 mm: Q345-D	2	1,45	0,4	3,85	B	2.6	C	1	1	1	2	0	5	B
38	Plate 12 mm: Q345-D	2	0,5	0,4	2,9	B	2.6	B	1	1	1	2	0	5	B
39	Plate 8 mm: Q345-D	2	0,25	0,4	2,65	B	2.6	B	1	1	0	2	0	4	B
40	Plate 35 mm: Q390-D	2	2,9	0,4	5,3	C	2.6	C	1	1	2	2	0	6	C
41	Plate 25 mm: Q345-D	2	2	0,4	4,4	C	2.6	C	1	1	2	2	0	6	C
42	Plate 20 mm: Q345-D	2	1,45	0,4	3,85	B	2.6	C	1	1	1	2	0	5	B

[1] For cross and length stiffeners the appropriate value for Z_A equals to 1 in this case (longitudinal welds). If the component is longer multiple length stiffeners will be welded together lengthwise thereby requiring Z_A to be equal to 2. The other plates have weld accumulations, thereby resulting in a value of Z_A equal to 2.
[2] For GB/T 3811 only the value for Z_A differs compared to FEM 1.001.
[3] The characteristic value for the stress range has been taken conservatively as being equal to $Q_4 = 2$.

Appendix F High strength steel application regarding the steel quality

Table F1 and F2 display the steel quality division for the crane travelling gear of a Ship-To-Shore container gantry crane.

- Table F2 displays the steel quality division based on the application of steel types Q345 and Q390.
- Table F3 displays the steel quality division based on the application of steel type S690.

Discussion on high strength steel

What could be interesting is to point out if there is a possible alternative when D quality steel is to be applied. An approach could be to apply high strength steel of C or B-quality (for example S460 or S690) (an alternative would be to change the steel structure). The application of high strength steels leads to a reduction in plate thickness, thereby reducing the influence of tri-axial stress states. It must be said that high strength steels are not favorable within applications that experience large numbers of load cycles due to its small difference in allowable tension and compression stresses for fatigue, when it concerns a commonly occurring notch group for welding such as K2 and K3 [36]. To overcome this a higher notch groups, such as K1, have to be applied, though this brings with it a more expensive and difficult welding procedure. The application of high strength steels would be interesting for components such as the crane travelling gear, due to the large plate thicknesses. Since this thesis focusses on the crane travelling gear the application of high strength steel will be limited to this.

From a preliminary initial, if the dimensions are not changed (both component dimensions and plate thicknesses), and Q345, Q390 are replaced by S460 or S690, the following consequences can be noted with regards to the steel quality for the bogie set.

With regards to the tensile stress assessment coefficient; based on an evaluation of existing crane designs the ratio between the residual stresses and the permissible stresses the maximum ratio between is at most 0.30 for S690 (for S460 the difference with Q345 and Q390 will be insignificant).

$$\frac{\sigma_G}{\sigma_a} \leq 0.30$$

This results in the following values for the residual tensile stress assessment coefficient (Table F1):

Table F1 Residual tensile stress assessment coefficient FEM 1.001

Z_A	Q345/Q390	S690	Reduction [%]
Longitudinal welds	1.0	0.6	40
Weld accumulations	2.0	1.6	20

The other assessment coefficients remain the same if the case study is used; in this case the bogie set, balance and main balance are evaluated. The result has been listed for the application of S690. What can be concluded is that with decreasing temperatures the difference with Q345 and Q390 becomes negligible. It would in this case be more beneficial to reduce the plate thickness and then evaluate what the steel quality should be. However as stated before High strength steel is only of interest with a small number of load cycles. With regards to the case study the number of load cycles equals to 1,000,000 – 2,000,000 load cycles. In this case this will not lead to a significant increase in fatigue stress. The application of high strength steel in the travelling gear will only be effective if the number of load cycles the crane steel structure experiences is lower than 1,000,000 [67].
Since an example crane has been taken as case study for the entire thesis and this crane is modeled from more than 1,000,000 load cycles the application of high strength steel has not been further investigated.

Regarding the cost associated with high strength steel it can be said that even though the application of high strength steel will result in a reduced steel quality this does not mean that it will result in a cost reduction. For this the material cost for S690 should be compared with that of Q345 and Q390, for varying steel qualities.
However, even if the price of the material is higher, the use of high strength steel brings with it a number of advantages which can result in an eventual cost reduction (though not from a material usage point of view). The use of high strength steel results in a decreased weight and thereby a decrease in wheel pressure and power consumption for the crane travelling gear. Furthermore different production aspects are influenced.

It must be stated though, that it is unclear whether FEM 1.001 can be applied for high strength steels.

Table F2 Q345 and Q390 steel quality division crane travelling gear

Steel structure Ship-To-Shore container gantry crane													
Q345 and Q390		T = -10 °C			T = -15 °C			T = -20 °C			T = -25 °C		
Component	Total mass [MT]	% B	% C	% D	% B	% C	% D	% B	% C	% D	% B	% C	% D
Bogie WS steel structure	8.9	10.2	89.8	0.0	4.9	95.1	0.0	0.0	85.8	14.2	0.0	48.1	51.9
Balance WS steel structure	12.7	37.7	62.3	0.0	20.5	79.5	0.0	20.5	54.5	27.0	0.0	59.8	40.2
Main balance WS steel structure	26.7	8.0	64.4	27.6	0.3	72.2	27.6	0.3	72.2	27.6	0.0	72.4	27.6
Bogie LS steel structure	9.7	11.8	88.2	0.0	11.4	88.6	0.0	4.9	92.0	3.0	0.0	83.8	16.2
Balance LS steel structure	9.7	49.0	51.0	0.0	46.1	53.9	0.0	7.8	92.2	0.0	0.0	69.2	30.8
Main balance LS steel structure	21.5	31.9	65,5	2.6	0.3	97.1	2.6	0.3	71.9	27.8	0.0	72.2	27.8

Table F3 S690 steel quality division crane travelling gear

Steel structure Ship-To-Shore container gantry crane													
S690		T = -10 °C			T = -15 °C			T = -20 °C			T = -25 °C		
Component	Total mass [MT]	% B	% C	% D	% B	% C	% D	% B	% C	% D	% B	% C	% D
Bogie WS steel structure	8.9	10.2	89.8	0.0	10.2	89.8	0.0	4.9	81.0	14.2	0.0	48.1	51.9
Balance WS steel structure	12.7	55.8	44.2	0.0	37.7	62.3	0.0	20.5	52.5	27.0	0.0	73.0	27.0
Main balance WS steel structure	26.7	35.5	64.5	0.0	7.9	64.4	27.6	0.3	72.2	27.6	0.0	72.4	27.6
Bogie LS steel structure	9.7	63.5	36.5	0.0	11.8	88.2	0.0	4.9	92.0	3.0	0.0	97.0	3.0
Balance LS steel structure	9.7	51.0	49.0	0.0	49.0	51.0	0.0	46.1	53.9	0.0	0.0	100.0	0.0
Main balance LS steel structure	21.5	31.9	68.1	0.0	31.9	65.5	2.6	0.3	71.9	27.8	0.00	72.2	27.8

Appendix G Metallurgical properties steel

The metallurgical properties are of importance for the quality of the steel, whereby the sulphur content plays a significant role [68].

- Table G1 provides an overview of the different steel types used by Cargotec Netherlands BV.
- Table G2 displays the metallurgical composition of the steel types used for the secondary structural steel components: Q235B and S235JR.
- Table G3 displays the metallurgical composition of steel type Q345, B, C and D-quality.
- Table G4 displays the metallurgical composition of steel type Q390, B, C and D-quality steel, including steel type S355J2.

Table G1 Materials applied

Country	Europe	P.R. China
Main Construction	S355J2	Thickness t ≤ 35 mm Q345D
		Thickness t ≥ 40 mm Q390D
Secondary Parts	S235JR	Q235B

Table G2 Steel types used for secondary parts construction

Material	Standard	Material thickness t [mm]	Yield strength Min. [MPa]	Tensile strength [MPa]	Charpy-V impact energy KV. Min [J]		C [%] Max	Mn [%] Max	Si [%] Max	P [%] Max	S [%] Max
Q235B	GB/T 700 – 1988	t ≤ 16	235	375-500	+20 °C	27	0.20	0.70	0.30	0.045	0.045
		16 < t ≤ 40	225								
S235JR	EN 10025 - 2	t ≤ 16	235	360-510	+20 °C	27	0.19	1.50	-	0.045	0.045
		16 < t ≤ 40	225								

Table G3 Steel types used for main parts construction

Material	standard	Thickness t [mm]	Yield strength Min. [MPa]	Tensile strength [MPa]	Charpy-V impact energy KV min. [J]		C[%] Max	Mn [%] Max	Si [%] Max	P [%] Max	S [%] Max
Q345D	GB/T 1591-1994	t ≤ 16	345	470-630	-20 °C	34	0.18	1.60	0.55	0.03	0.03
		16 < t ≤ 35	325								
		35 < t ≤ 50	295								
		50 < t ≤ 100	275								
Q345C	GB/T 1591-1994	t ≤ 16	345	470-630	0 °C	34	0.20	1.60	0.55	0.035	0.035
		16 < t ≤ 35	325								
		35 < t ≤ 50	295								
		50 < t ≤ 100	275								
Q345B	GB/T 1591-1994	t ≤ 16	345	470-630	+20 °C	34	0.20	1.60	0.55	0.04	0.04
		16 < t ≤ 35	325								
		35 < t ≤ 50	295								
		50 < t ≤ 100	275								

Table G4 Steel types used for main parts construction

Material	standard	Thickness t [mm]	Yield strength Min. [MPa]	Tensile strength [MPa]	Charpy-V impact energy KV min. [J]		C [%] Max	Mn [%] Max	Si [%] Max	P [%] Max	S [%] Max
Q390D	GB/T 1591-1994	t ≤ 16	390	490-650	-20 °C	34	0.20	1.60	0.55	0.03	0.03
		16 < t ≤ 35	370								
		35 < t ≤ 50	350								
		50 < t ≤ 100	330								
Q390C	GB/T 1591-1994	t ≤ 16	390	490-650	0 °C	34	0.20	1.60	0.55	0.035	0.035
		16 < t ≤ 35	370								
		35 < t ≤ 50	350								
		50 < t ≤ 100	330								
Q390B	GB/T 1591-1994	t ≤ 16	390	490-650	+20 °C	34	0.20	1.60	0.55	0.035	0.035
		16 < t ≤ 35	370								
		35 < t ≤ 50	350								
		50 < t ≤ 100	330								
S355J2	EN 10025-2	t ≤ 16	355	470-630	-20 °C	27	0.23	1.70	0.60	0.035	0.035
		16 < t ≤ 40	345				0.23				
		40 < t ≤ 63	335				0.24				
		63 < t ≤ 80	325				0.24				
		80 < t ≤ 100	315				0.24				

Appendix H Power calculation

For the calculation of the different power requirements the variables and calculations listed below have to be defined or made. The variables have been defined as follows:

Weight of the crane

W_{Crane} [MT]

Weight of the load

W_{Load} [MT]

Total weight

$W_{Total} = W_{Crane} + W_{Load}$

Crane travel speed

v_C [m/s]

Efficiency of gearing

η_{G_i} [-]

Wheel resistance of crane wheels

f [kN/MT]

Acceleration time

t_a [s]

Acceleration

$$\mathrm{a}_C = \frac{v_C}{t_a} \text{ [m/s}^2\text{]}$$

Influence of wind

q wind pressure [N/m^2]

A [m^2]

C_f shape coefficient [-]

Engine speed

n_M [rpm]

Crane wheel diameter

D_W [m]

Reduction between engine and crane wheel

$$i = \frac{n_M \bullet \pi \bullet D_W}{v_C} \text{ [-]}$$

Inertia of rotating parts

J [kgm^2]

Based on the variables defined the definition of the power calculation of each influence has been stated.

1. Resistance due to nominal crane travelling involves the power required to overcome the rolling resistance over the crane track, Eq. H.1.

$$F_f = W_{Total} \bullet f \text{ [kN]}$$
$$P_f = F_f \bullet v_C \text{ [kW]} \quad \text{(H.1)}$$

2. The resistance due to wind is the power required due to travelling against the prevailing wind direction, Eq. H.2.

$$F_W = \frac{\sum(A \bullet C_f) \bullet q}{1000} \text{ [kN]}$$
$$P_W = F_W \bullet v_W \text{ [kW]} \quad \text{(H.2)}$$

3. The resistance due to the acceleration of rotating masses involves all elements, such as wheels, disk brakes, and etcetera, Eq. H.3.

$$\omega = \frac{n_M \bullet 2\pi}{60} \text{ [rad/s]}$$
$$M_R = \frac{J \bullet \omega}{t_a} \text{ [Nm]} \quad \text{(H.3)}$$
$$P_R = \frac{M_R \bullet n_M}{9550} \text{ [kW]}$$

4. Resistance due to the acceleration of linear moving masses, Eq. H.4.

$$F_L = \frac{W_{Total} \bullet v_C}{t_a} \text{ [kN]}$$
$$P_L = F_L \bullet v_C \text{ [kW]} \quad \text{(H.4)}$$

For the power of the different models see Table H1 – H5.

Table H1 Power calculation of the resistance due to nominal crane travel (rolling resistance)

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
W_{Crane} [metric tonnes]	1336	1336	1336	1336	1336	1336	1336	1336	1336
W_{Load} [metric tonnes]	84	19	84	19	84	84	17	19	19
f [kN/tonne]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Original situation η_{G_i} [-]	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Open gearing model 1 η_{G_i} [-]	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Open gearing model 2 η_{G_i} [-]	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Open gearing model 3 η_{G_i} [-]	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
v_C [m/s]	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
$W_{Total} = W_{Crane} + W_{Load}$	1420	1355	1420	1355	1420	1420	1353	1355	1355
Original situation $P_f = \frac{W_{total} \bullet f \bullet v_c}{\eta_G}$ [kW]	62	59	62	59	62	62	59	59	59
Open gearing model 1 P_f [kW]	67	64	67	64	69	67	64	64	64
Open gearing model 2 P_f [kW]	76	72	76	72	76	76	72	72	72
Open gearing model 3 P_f [kW]	64	61	64	61	64	64	61	61	61

Table H2 Power calculation of the resistance due to the wind

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
$F_W = \frac{\sum(A \bullet C_f) \bullet q}{1000}$ [kN]	399	399	200	200	399	622	622	396	617
Original situation η_{G_i} [-]	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Open gearing model 1 η_{G_i} [-]	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Open gearing model 2 η_{G_i} [-]	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Open gearing model 3 η_{G_i} [-]	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
v_C [m/s]	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Original situation $P_W = \frac{F_W \bullet v_W}{\eta_G}$ [kW]	346	346	173	173	346	539	539	343	535
Open gearing model 1 P_W [kW]	375	375	188	188	375	585	585	372	581
Open gearing model 2 P_W [kW]	424	424	212	212	424	662	662	421	656
Open gearing model 3 P_W [kW]	360	360	180	180	360	562	562	357	558

Table H3 Power calculation of the resistance due to the acceleration of rotating masses

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
Original situation J $[\mathrm{kgm}^2]$	5.04	5.04	5.04	5.04	5.04	5.04	5.04	5.04	5.04
Open gearing model 1 J $[\mathrm{kgm}^2]$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Open gearing model 2 J $[\mathrm{kgm}^2]$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Open gearing model 3 J $[\mathrm{kgm}^2]$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
n_M [rpm]	1500	1500	1500	1500	1500	1500	1500	1500	1500
t_a [s]	10	6	10	6	10	8,1	8,1	10	8,1
$\omega = \frac{n_M \bullet 2\pi}{60}$ [rad/s]	158	158	158	158	158	158	158	158	158
Original situation $M_R = \frac{J \bullet \omega}{t_a}$ [Nm]	79.17	131.95	79.17	131.95	79.17	97.74	97.74	79.17	97.74
Open gearing model 1 M_R [Nm]	31.42	52.36	31.42	52.36	31.42	38.79	38.79	31.42	38.79
Open gearing model 2 M_R [Nm]	31.42	52.36	31.42	52.36	31.42	38.79	38.79	31.42	38.79
Open gearing model 3 M_R [Nm]	31.42	52.36	31.42	52.36	31.42	38.79	38.79	31.42	38.79
Original situation $P_R = \frac{M_R \bullet n_M}{9550}$ [kW]	13	21	12	21	13	16	16	13	16
Open gearing model 1 P_R [kW]	4.93	8.22	4.93	8.22	4.93	6.09	6.09	4.93	6.09
Open gearing model 2 P_R [kW]	4.93	8.22	4.93	8.22	4.93	6.09	6.09	4.93	6.09
Open gearing model 3 P_R [kW]	4.93	8.22	4.93	8.22	4.93	6.09	6.09	4.93	6.09

Table H4 Power calculation of the resistance due to the acceleration of linear moving masses

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
$W_{Total} = W_{Crane} + W_{Load}$	1420	1355	1420	1355	1420	1420	1353	1355	1355
v_C [m/s]	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
t_a [s]	10	6	10	6	10	8,1	8,1	10	8,1
Original situation η_G [-]	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Open gearing model 1 η_G [-]	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Open gearing model 2 η_G [-]	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Open gearing model 3 η_G [-]	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
$F_L = \frac{W_{Total} \bullet v_C}{t_a}$ [kN]	119	189	119	189	119	147	140	113	140
Original situation $P_L = \frac{F_L \bullet v_C}{\eta_G}$ [kW]	103	163	103	163	103	127	121	98	121
Open gearing model 1	112	177	112	177	112	138	131	107	132
Open gearing model 2	126	200	126	200	126	155	148	120	148
Open gearing model 3	107	170	107	170	107	132	126	102	126

Table H5 Power condition

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
f_A [-]	1.8		1.8		1.8	1.8		1.8	
Original situation $P_{Nominal}$ [kW]	408	405	235	232	408	602	599	402	595
Original situation $P_{Acceleration}$ [kW]	516	577	343	404	516	734	726	505	722
Original situation $P_{Acceleration} \leq f_A \bullet P_{Nominal}$	1.27	1.43	1.46	1.75	1.27	1.23	1.22	1.26	1.22
Open gearing model 1 $P_{Nominal}$ [kW]	442	439	255	252	442	652	649	436	644
Open gearing model 1 $P_{Acceleration}$ [kW]	558	624	371	437	558	795	786	547	781
Open gearing model 1 $P_{Acceleration} \leq f_A \bullet P_{Nominal}$	1.27	1.43	1.46	1.74	1.27	1.23	1.22	1.26	1.22
Open gearing model 2 $P_{Nominal}$ [kW]	499	495	287	284	499	736	732	492	727
Open gearing model 2 $P_{Acceleration}$ [kW]	629	703	418	492	629	897	886	617	881
Open gearing model 2 $P_{Acceleration} \leq f_A \bullet P_{Nominal}$	1.26	1.43	1.46	1.74	1.27	1.22	1.21	1.26	1.22
Open gearing model 3 $P_{Nominal}$ [kW]	425	422	245	242	425	627	624	419	619
Open gearing model 3 $P_{Acceleration}$ [kW]	537	600	357	420	537	765	756	526	751
Open gearing model 3 $P_{Acceleration} \leq f_A \bullet P_{Nominal}$	1.27	1.43	1.46	1.74	1.27	1.23	1.22	1.26	1.22

Appendix I Torque calculation

For the calculation of the different torque requirements the variables and calculations listed below have to be defined or made (identical to the power calculation). The variables have been defined as follows:

Weight of the crane

$$W_{Crane} \text{ [metric tonnes]}$$

Weight of the load

$$W_{Load} \text{ [metric tonnes]}$$

Total weight

$$W_{Total} = W_{Crane} + W_{Load}$$

Crane travel speed

$$v_C \text{ [m/s]}$$

Efficiency of gearing

$$\eta_{G\_i} \text{ [-]}$$

Wheel resistance of crane wheels

$$f \text{ [kN/tonne]}$$

Influence of wind

$$q \text{ wind pressure [N/m}^2\text{]}$$

$$A \text{ [m}^2\text{]}$$

$$C_f \text{ shape coefficient [-]}$$

Acceleration time

$$t_a \text{ [s]}$$

Acceleration

$$\mathrm{a}_C = \frac{v_C}{t_a} \text{ [m/s}^2\text{]}$$

Engine speed

$$n_M \text{ [rpm]}$$

Crane wheel diameter

$$D_W \text{ [m]}$$

Reduction between engine and crane wheel

$$i = \frac{n_M \cdot \pi \cdot D_W}{v_C} \text{ [-]}$$

Inertia of rotating parts

$$J \text{ [kgm}^2\text{]}$$

Based on the variables defined the definition of the torque calculation of each influence has been stated per wheel.

1. Torque due to nominal crane travelling, Eq. I.1.

$$M_f = W_{Total} \cdot f \cdot R_{wheel} \text{ [kNm]}$$

$$M_{f/wheel} = \frac{M_f \cdot 1000}{n_{wheel} \cdot i} \text{ [Nm]} \quad \text{(I.1)}$$

2. Torque due to wind, Eq. 3.23.

$$F_{wind} = \sum \left(A \bullet C_f \right) \bullet q \text{ [kNm]}$$
$$M_{wind} = F_{wind} \bullet R_{wheel} \text{ [kNm]} \quad (I.2)$$
$$M_{wind/wheel} = \frac{M_{wind} \bullet 1000}{n_{wheel} \bullet i} \text{ [Nm]}$$

3. Torque due to the acceleration of rotating masses, Eq. I.2.

$$M_R = \frac{J \bullet \omega}{t_a} \text{ [Nm]}$$
$$M_{R/wheel} = \frac{M_R}{n_{wheel}} \text{ [Nm]} \quad (I.3)$$

4. Torque due to the acceleration of linear moving masses, Eq. I.3.

$$M_{lin} = W_{Total} \bullet \frac{v_c}{t_a} \bullet R_{wheel} \text{ [kNm]}$$
$$M_{lin/wheel} = \frac{M_{lin} \bullet 1000}{n_{wheel} \bullet i} \text{ [Nm]} \quad (I.4)$$

The nominal torque per wheel can be calculated by summing the torque due to nominal crane travelling and the torque due to wind. The maximum torque is a summation of all torque requirements, Eq. I.4.

$$M_{nom\_engine} = \frac{M_{nominal}}{n \bullet i} \text{ [Nm]}$$
$$M_{acc\_engine} = \frac{M_{acceleration}}{n \bullet i} \text{ [Nm]} \quad (I.5)$$

Whereby n [-] is defined as the number of driven wheels or bogies.

The torque calculation has been listed in Table I1 – I4. The outcome for the original situation have been left out of the tables.

Table I1 Torque calculation for the rolling resistance

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
$W_{Total} = W_{Crane} + W_{Load}$ [tonne]	1420	1355	1420	1355	1420	1420	1353	1355	1355
f [kN/tonne]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$F_{friction} = W_{Total} \bullet f$ [kN]	71	67.75	71	67.75	71	71	67.65	71	67.75
R_{wheel} [m]	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
$M_f = F_{friction} \bullet \mathrm{R}_{wheel}$ [kNm]	23	22	23	22	23	23	22	23	22
Open gearing model 1 $M_{f/bogie} = \frac{M_f \bullet 1000}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	10.78	10.28	10.78	10.78	10.78	10.78	10.27	10.78	10.28
Open gearing model 2 $M_{f/muliple\_bogie}$ [Nm]	12.16	11.61	12.16	11.61	12.16	12.16	11.59	12.16	11.61
Open gearing model 3 $M_{f/bogie}$ [Nm]	10.36	9.82	10.36	9.82	10.36	10.36	9.87	10.36	9.89

Table I2 Torque calculation for the wind resistance

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
F_{wind} [kN]	399	399	200	200	399	622	622	396	617
R_{wheel} [m]	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
$M_{wind} = F_{wind} \bullet R_{wheel}$ [kNm]	126	126	63	63	126	196	196	125	195
Open gearing model 1 $M_{wind/bogie} = \frac{M_{wind} \bullet 1000}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	60.44	60.44	30.22	30.22	60.44	94.28	94.28	59.96	93.54
Open gearing model 2 $M_{wind/mul.bogie} = \frac{M_{wind} \bullet 1000}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	68.22	68.22	34.11	34.11	68.22	106.42	106.42	67.69	105.59
Open gearing model 3 $M_{wind/bogie} = \frac{M_{wind} \bullet 1000}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	58.11	58.11	29.06	29.06	58.11	90.65	90.65	57.65	89.94

Table I3   Torque calculation for the linear acceleration resistance

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
$W_{Total} = W_{Crane} + W_{Load}$	1420	1355	1420	1355	1420	1420	1353	1355	1355
v_C [m/s]	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
t_a [s]	10	6	10	6	10	8,1	8,1	10	8,1
$F_{linear} = W_{Total} \bullet \frac{v_c}{t_a}$ [kN]	119	189	119	189	119	147	140	113	140
R_{wheel} [m]	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
$M_{linear} = F_{linear} \bullet R_{wheel}$ [kNm]	38	60	38	60	38	47	44	36	44
$M_{lin/bogie} = \frac{M_{linear} \bullet 1000}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	17.96	28.55	17.96	28.55	17.96	22.17	21.12	17.13	21.15
$M_{lin/mul.bogie} = \frac{M_{linear} \bullet 1000}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	20.27	32.23	20.27	32.23	20.27	25.02	23.84	19.34	23.88
$M_{lin/bogie} = \frac{M_{linear} \bullet 1000}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	17.26	27.45	17.26	27.45	17.26	21.31	20.31	16.47	20.34

The torque due to the rotational acceleration has already been calculated with the power calculation in Appendix H.

Table I4 Nominal engine torque calculation

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load $\left[N/mm^2\right]$	250		125		250	390		250	
Open gearing model 1									
$M_{nominal}$ [kNm]	148	147	86	85	148	219	218	147	216
$M_{acceleration}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{nominal}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	143	142	82	81	143	211	210	142	208
$M_{acc\_engine} = \frac{M_{acceleration}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	184	208	124	148	184	262	259	182	257
Open gearing model 2									
$M_{nominal}$ [kNm]	148	147	86	85	148	219	218	147	216
$M_{acceleration}$ [kNm]	186	207	123	144	186	265	262	183	260
$M_{nom\_engine} = \frac{M_{nominal}}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	322	320	186	183	322	475	472	320	469
$M_{acc\_engine} = \frac{M_{acceleration}}{\left(\frac{n_{bogie}}{2}\right) \bullet i \bullet \eta_{G\_i}}$ [Nm]	408	457	272	321	408	581	574	402	571
Open gearing model 3									
$M_{nominal}$ [kNm]	148	147	86	85	148	219	218	147	216
$M_{acceleration}$ [kNm]	186	207	123	144	186	265	261	183	260

$M_{nom\_engine} = \frac{M_{nominal}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	137	136	79	78	137	202	202	137	200
$M_{acc\_engine} = \frac{M_{acceleration}}{n_{bogie} \bullet i \bullet \eta_{G\_i}}$ [Nm]	174	195	116	137	174	248	245	172	243

Appendix J Brake calculation

For the calculation of the different brake requirements the variables and calculations listed below have to be defined or made. The variables have been defined as follows:

Corner load from the mechanical calculation of Cargotec Netherlands BV listed per corner

F_{ci} [kN]

Rolling friction coefficient

f [N/kN]

Crane heel diameter

D_W [mm]

Number of wheels

n_{wheel} [-]

Number of wheels per corner

$n_{wheel/corner}$ [-]

Wind load from the mechanical calculation of Cargotec Netherlands BV

F_{wind} [kN]

Inertia of drive, brake, coupling and gearing

i_{drive} [kgm^2]

i_{brake} [kgm^2]

$i_{coupling}$ [kgm^2]

$i_{gearing}$ [kgm^2]

Transmission ratio

i [-]

Efficiency gearing

η_g [-]

Number of brakes

n_{brake} [-]

Brake torque as provided by the manufacturer

M_{brake} [Nm]

The maximum rotation speed of the engine

n_{drive} [rpm]

Brake closing time

t_{brake} [s]

Weight of the crane

W_{crane} [tonnes]

Weight of the load

W_{load} [tonnes]

Speed of the crane

v_c [m/s]

Allowable number of revolutions of the brake

$n_{brake\_allowable}$ [rpm]

Brake efficiency

η_{brake} [-]

Sliding friction coefficient

μ [-]

Gravitational constant

g [m/s^2]

Based on the variables defines the definition of the brake calculation of each influence can be stated. The discussion of the calculation as presented in this appendix is based on the calculation practice of Cargotec Netherlands BV.

The torque due to friction can be calculated by Eq. J.1.

$$M_f = \sum_i F_{ci} \bullet f \bullet \frac{D_W}{2000} \text{ [kNm]} \quad (J.1)$$

The torque due to the wind load can be calculated by Eq. J.2.

$$M_W = F_{wind} \bullet \frac{D_W}{2000} \text{ [kNm]} \quad (J.2)$$

The torque that can be delivered by the brake can be calculated by Eq. J.3.

$$M_{brake\_total} = \frac{M_{brake} \bullet n_{brake} \bullet i \bullet \eta_g}{1000} \text{ [kNm]} \quad (J.2)$$

Maximum brake speed check

The maximum brake speed check requires a comparison of the occurring brake speed due to the acceleration during the brake activation time with the allowable brake speed of the brake.

The total inertia can be calculated by Eq. J.4.

$$I_{inertia} = 1.1\left(I_{inertia\_1} + I_{inertia\_2}\right) \text{ [kgm}^2\text{]}$$
$$I_{inertia\_1} = \left(\left(\frac{n_{wheel}}{2}\right) \bullet \left(I_{brake} + I_{coupling} + I_{gearing}\right) \bullet i^2\right) \quad (J.4)$$
$$I_{inertia\_2} = \left(\left(\frac{n_{wheel}}{2}\right) \bullet I_{drive} \bullet i^2\right)$$

The acceleration of the crane during the brake activation time can be calculated by Eq. J.5.

$$a_c = \frac{\left(M_W - M_f\right) \bullet \left(\frac{D_W}{2000}\right)}{\left(W_{crane} + W_{load}\right) \bullet \left(\frac{D_W}{2000}\right)^2 + I_{inertia}} \text{ [m/s}^2\text{]} \quad (J.5)$$

The crane speed after the brake activation time is calculated by Eq. J.6.

$$v_{c\_brake} = v_c + a_c \bullet t_{brake} \text{ [m/s]} \quad (J.6)$$

The following condition must be checked in order to determine whether the maximum permissible revolutions are not crossed (Eq. J.7).

$$n_{c\_brake} = \frac{v_{c\_brake} \bullet i \bullet \frac{\pi}{30}}{\left(\frac{D_W}{2000}\right)} \text{ [rpm]} \tag{J.7}$$

$$n_{c\_brake} \leq n_{brake\_allowable}$$

Braking torque and braking distance check

The type of brake is important for determining whether there is enough braking force to stop the crane within a certain distance (to limit the crane travelling distance). The total real braking torque can be calculated by Eq. J.8.

$$M_{brake\_total\_real} = M_{brake\_total} \bullet \eta_{brake} \text{ [kNm]} \tag{J.8}$$

By setting up a moment equilibrium the crane deceleration can be calculated by Eq. J.9.

$$a_{c\_brake} = \frac{\left(M_W - M_f - M_{brake\_total\_real}\right) \bullet \left(\frac{D_W}{2000}\right)}{\left(W_{crane} + W_{load}\right) \bullet \left(\frac{D_W}{2000}\right)^2 + I_{inertia}} \tag{J.9}$$

The braking distance can be calculated by Eq. J.10.

$$t_{braking} = \frac{v_{c\_brake}}{a_{c\_brake}} \text{ [s]} \tag{J.10}$$

$$s_{c\_braking} = v_{c\_braking} \bullet t_{braking} + 0.5 \bullet \left|a_{brake}\right| \bullet t_{braking}^2 \text{ [m]}$$

Wheelslip check

With regards to the wheelslip check, this calculation is performed based on the corner loads experienced by the crane. The experienced friction force per wheel corner can be calculated by Eq. J.11.

$$F_{\mu i} = F_{ci} \bullet \mu \text{ [kN]} \tag{J.11}$$

The total maximum brake force per wheel equals to Eq. J.12.

$$F_{brake\_slip} = \frac{M_{brake\_total}}{n_{wheel} \bullet 2 \bullet \left(\frac{D_W}{2000}\right)} \text{ [kN]} \tag{J.12}$$

The maximum brake force per corner equals to Eq. J.13.

$$F_{brake\ i} = \min\left(F_{brake\_slip} \bullet n_{wheel/corner}, F_{\mu i}\right) \text{ [kN]} \tag{J.13}$$

The total brake slip force equals to Eq. J.14.

$$F_{brake\_slip\_total} = \sum_{i=1}^{4} F_{brake\ i} \text{ [kN]} \tag{J.14}$$

The safety for wheel slip can be calculated by Eq. J.15.

$$V = \frac{\sum_{i=1}^{4} F_{c\ i} \bullet \mu + F_{brake\_slip\_total}}{F_{wind}} \text{ [-]} \tag{J.15}$$

Heat absorption limit check

With regards to the heat absorption limit of the brake, what is of importance is the amount of energy that comes free during braking (due to friction) and the amount of energy that can be absorbed by the brake. The kinetic energy released during braking equals to Eq. J.16.

$$E_{kin} = 0.5 \bullet (W_{crane} + W_{load}) \bullet v_{c\_brake}^2 \text{ [kJ]} \tag{J.16}$$

For the inertia of the brake disk the rotational energy equals to E. J.17.

$$\text{E}_{rot} = 0.5 \bullet I_{inertia} \bullet \left(\frac{n_{c\_brake} \bullet \frac{30}{\pi}}{i} \right)^2 \text{ [kJ]} \tag{J.17}$$

The friction energy released can be calculated by Equation J.18.

$$s_{brake} = \frac{s_{c\_braking} \bullet i}{\left(\frac{D_{wheel}}{2000} \right)} \text{ [rad]}$$

$$E_{friction} = \frac{(W_{crane} + W_{load}) \bullet g \bullet \mu \bullet s_{brake}}{1000} \text{ [kJ]} \tag{J.18}$$

The friction energy due to the wind force equals to Eq. J.19.

$$E_{friction\_wind} = F_{wind} \bullet (s_{brake} + s_{c\_braking}) \text{ [kJ]} \tag{J.19}$$

The total energy released equals to Eq. J.20.

$$E_{total} = E_{friction} + E_{friction\_wind} + E_{kin} + \text{E}_{rot} \text{ [kJ]} \tag{J.20}$$

Whereby the energy absorbed per brake equals to Eq. J.21.

$$E_{absorbed\_per\_brake} = \frac{E_{total}}{n_{brake}} \text{ [kJ]} \tag{J.21}$$

In order to determine the suitability of the brake for the energy absorbance the following condition must hold, Eq. J.22.

$$E_{absorbed\_per\_brake} \leq E_{allowable\_per\_brake} \tag{J.22}$$

In this case the detailed tabulated data has not been listed. Results from Appendix H and I, including the outcomes listed in Table 3.16 – 3.19 (paragraph 3.8.4) have been considered to be sufficient.

Appendix K Influence of the removal of bolted flange plates

Of interest is what the weight influence is of replacing bolted flange plate connections (or the removal of flange plates and inspection platforms) on the wheel pressure and on the engine power.

If a number of flange plates are removed the associated inspection platforms can also be removed, which in turn has its influence on the wheel pressure on each crane wheel. Under the assumption that the entire portside portal frame and starboard side portal frame will be welded, the following result can be listed on the weight reduction, Table K1.

Table K1 Summed masses of bolted flange plates pairs for different components

Components	Mass [MT]
Lower leg WS	3.5
Lower leg LS	2.3
Cross girder	14.9
Long legs WS	3.4
Long legs LS	2.0
Upper legs WS	1.6
Upper legs LS	0.8
Diagonal ties[23]	0.9
Ties portal beam	0.7
Inspection platforms and ladders	4.1
Total mass	34.3

The total crane weight (without spreader, head block combination and the load) has been noted to be 1336 MT. The reduced weight will amount to 1301.7 MT. The additional removal of minor masses have not been taken into account. The mass that return with the welded flange plate connections have been left out. The goal is to provide a general insight on what the influence is.

For the reduction of the wheel pressure it must be noted that the reduction of the weight is not equally distributed over the crane structure. For convenience of calculation it is assumed that the weight reduction of the flange plates is equally distributed over all corners, however the weight reduction due to the removal of the inspection platforms and ladders is limited to the corner waterside starboard (WS SB) and the corner waterside portside (WS PS). For the WS SP and WS PS this means a reduction of 9.6 tons, for the landside starboard (LS SB) and landside portside (LS PS) the reduction will amount to 7.6 tons (Table K2). The listed corner loads originate from the calculation provided by Cargotec Netherlands BV.

[23] The assumption has been made that one end of the diagonal ties are welded the other is bolted.

It must be stated though that it is assumed in this calculation that the welded connection will not bring any weight with it, however this is not realistic. The actual weight reduction due to the removal of the bolted flange plates will therefore be smaller.

Even though the wheel load is reduced, based on the smallest corner load reduction this will not lead to a reduction in wheel size (according to the method described in Appendix M). The reduction is not large enough for this. Of interest though would be what the actual weight reduction should be if a smaller wheel size is desirable. Based on Appendix M it can be stated that if the maximum wheel load without wind and the minimum wheel load without wind are both equally reduced by 92 kN a smaller wheel size may be selected (from 630 mm crane wheel diameter to 500 mm crane wheel diameter). This means that the total weight reduction should amount to 300 MT which seems infeasible from every aspect.

Table K2 Corner load reduction

Loading situation		Corner WS SB	Corner WS PS	Corner LS SB	Corner LS PS
Boom down, trolley at outreach no wind	Corner load [MT]	603.1	603.2	106.9	106.8
	Reduced corner load [MT]	593.5	593.6	99.3	99.2
	Reduction [%]	1.59	1.59	7.11	7.12
Boom down, trolley at outreach, wind 250 N/mm^2	Corner load [MT]	657.1	549.3	52.9	160.7
	Reduced corner load [MT]	647.5	539.7	45.3	153.1
	Reduction [%]	1.46	1.75	14.37	4.73
Boom down, trolley at outreach, wind 390 N/mm^2	Corner load [MT]	687.3	519.1	22.7	190.9
	Reduced corner load [MT]	677.7	509.5	15.1	183.3
	Reduction [%]	1.40	1.85	33.48	3.98
Boom down, trolley at back reach, no wind	Corner load [MT]	390.4	390.5	319.6	319.8
	Reduced corner load [MT]	380.8	380.9	312.0	312.2
	Reduction [%]	2.46	2.46	2.38	2.38
Boom down, trolley at back reach, wind 250 N/mm^2	Corner load [MT]	437.3	336.5	235.5	403.7
	Reduced corner load [MT]	427.7	326.9	227.9	396.1
	Reduction [%]	2.20	2.85	3.23	1.88
Boom down, trolley at back reach, wind 390 N/mm^2	Corner load [MT]	474.5	840.4	746.5	403.7
	Reduced corner load [MT]	464.9	830.8	738.9	396.1
	Reduction [%]	2.02	1.14	1.02	1.88
Boom up, trolley at parking position, no wind	Corner load [MT]	385.7	385.7	291.9	291.7
	Reduced corner load [MT]	376.1	376.1	284.3	284.1
	Reduction [%]	2.49	2.49	2.60	2.61
Boom up, trolley at parking position, wind 1960 N/mm^2	Corner load [MT]	-69.0	840.4	746.5	-162.9
	Reduced corner load [MT]	-78.6	830.8	738.9	-170.5
	Reduction [%]	-	1.14	1.02	-

For the power requirement the weight reduction has an influence on the power requirement for overcoming the rolling resistance and an influence on the power requirement for the acceleration of linear moving masses, because the total weight of the crane, W_{Total}, is lowered. Reviewing both influences individually it can be stated that the power requirement for the rolling resistance (Eq. L1.1) and the acceleration of a linear moving mass (Eq. L1.2) are both lowered by 2.6 %.

Rolling resistance power reduction:

$$F_f = W_{Total} \cdot f \text{ [kN]}$$

$$P_f = \frac{F_f \cdot v_C}{\eta_G} \text{ [kW]} \rightarrow \left(1 - \frac{P_{f\_reduced\_weight}}{P_f}\right) \cdot 100\% = 2.57\% \qquad \text{(L1.1)}$$

Acceleration of a linear moving mass power reduction:

$$F_L = \frac{W_{Total} \cdot v_C}{t_a} \text{ [kN]}$$

$$P_L = \frac{F_L \cdot v_C}{\eta_G} \text{ [kW]} \rightarrow \left(1 - \frac{P_{L\_reduced\_weight}}{P_L}\right) \cdot 100\% = 2.57\% \qquad \text{(L1.2)}$$

Of interest however, is the influence on the total power requirement, both nominal and during acceleration (Table K3), and whether a smaller engine can be selected based on the reduction of the total power of open gearing model 1 (5 gears, one engine powers 2 wheels).

Table K3 Power requirement open gearing model 1

Description	Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum outreach		Boom down; Trolley at maximum back reach	Boom down; Trolley at maximum outreach		Boom up; Crane parked	
Wind load [N/mm^2]	250		125		250	390		250	
P_f [kW]	66	63	66	63	66	66	63	63	63
P_W [kW]	375	375	188	188	375	585	585	372	580
P_R [kW]	13	21	12	21	13	16	16	13	16
P_L [kW]	109	173	109	173	109	135	128	104	128
$P_{Nominal} = P_f + P_W$ [kW]	441	438	254	251	441	651	648	435	643
$P_{Acceleration} = \sum P$ [kW]	563	632	448	445	563	802	792	552	787
$P_{Acceleration} \leq f_A \cdot P_{Nominal}$	1.28	1.45	1.77	1.78	1.28	1.24	1.23	1.27	1.23

The nominal power requirement for the crane model is 442 kW. The reduced power requirement for the open gearing model 1 is 441 kW (as in with the deduction of the mass of the bolted flange plates and associated inspection platforms). The power reduction can be assumed to be negligible. The main reason for this is because the wind load is the main influence on the power requirement of the crane, the power necessary for overcoming the rolling resistance is small compared to the wind load.

It would be interesting to have an idea of the necessary weight reduction in order to change to a smaller engine size. The currently selected engine has a nominal power of 30 kW, the smaller engine has a listed nominal power of 26 kW, the actual engine power needed equals to 28 kW, which means that a 2 kW power reduction is necessary. In case 16 engines are applied, this means that the total nominal power requirement has to be reduced with 32 kW. A reduction in power of this size that only comes forth from the weight reduction requires a weight reduction of 257 MT. This is in every way infeasible. The engine power is largely determined by the wind load and not by the mass of the crane. If a smaller engine would be desirable a reduction of the surface area (e.g. lattice girder instead of a box girder) of the crane would be desirable. Though it could also be possible to reduce the mass of the boom only, due to its eccentric position compared to the rest of the crane.

Appendix L Wheelslip

The effect of wheel slip has to be checked. Wheelslip occurs when the wheel does not experience enough vertical loading from the crane. The calculation of wheel slip can be made as follows according to the data provided by Cargotec Netherlands BV, Eq. L1.1 [2].

$$\mu_{Calculation} = \frac{F_2}{F_1} \quad \text{(L1.1)}$$

The conditions must be checked if $\mu_{Calculation} \leq 0.12$. The force F_1 [kN] is defined as the minimum wheel load on a driven crane wheel. This force will be calculated by the stability calculation of the crane structure.

The force F_2 [kN] is defined as the maximum driving force of the gantry travelling motor on the circumference of the driven crane wheel and it expressed by Eq. L1.2.

$$F_2 = \frac{f_A \cdot N \cdot \eta_G}{v_C} \text{ [kN]} \quad \text{(L1.2)}$$

With f_A [-] defined as the overload factor of the engine, N [kW] defined as the total available driving power of the engine, η_G [-] defined as the efficiency of the travelling gear transmission and v_C [m/s] defined as the gantry travelling speed. For the case study the result regarding the wheelslip has been listed in Table L1 (in case each wheel is powered by its own engine).

Table L1 Wheelslip calculation result; engine powers a single wheel

Variable	Result	Additional data	
F_1 [kN]	493.9	-	
F_2 [kN]	33.3	f_A [-]	1.80
		N [kW]	16.00
		η_G [-]	0.96
		v_C [m/s]	0.83
$\mu_{Calculation} = \frac{F_2}{F_1}$	0.07	< 0.12	

It can be concluded that wheel slip will not occur, when each wheel has its own engine. The question is now what happens when both wheels are powered by a single engine or when two bogies are powered by a single engine.

In general it can be said that from the perspective of wheel slip it is desirable to place the drives at the waterside instead of the landside due to the higher wheel pressure at the waterside. However this leads to higher skewing forces on the rails and on the flanges of the crane wheels. This in turn will result in a larger wheel diameter. A smaller wheel diameter is more favorable compared to a large wheel diameter due to the occurring stresses below the surface of the rail and because the wheel pressure per wheel will be smaller (assuming that with a smaller wheel diameter more wheels will be used). Skewing occurs when two wheels (or two bogies) roll along a rail, and thereby form a couple by the horizontal forces normal to the rail.

What must be noted however, is that when the wear of one wheel in a single bogie is larger than the other wheel in the same bogie wheel slip may occur at one of the wheels. The bogie set is no longer 'horizontal', compared to the starting situation. This results in a higher loading at the wheel which experienced a higher wear (thus wheel slip is to be expected at the wheel which has the least amount of wear).

For the wheel slip calculation in case the engine powers two wheels it must be noted that the power of the engine is equally divided onto both wheels of the bogie. The total available driving power is therefore divided over both wheels, Eq. L1.3 (in case the engine powers the wheels of 2 bogies, Eq. L1.4 should be applied). Furthermore it must be noted that the transmission efficiency dependent on the open gearing model applied.

$$F_2 = \frac{f_A \bullet \left(\frac{N}{2}\right) \bullet \eta_G}{v_C} \text{ [kN]} \qquad \text{(L1.3)}$$

$$F_2 = \frac{f_A \bullet \left(\frac{N}{4}\right) \bullet \eta_G}{v_C} \text{ [kN]} \qquad \text{(L1.4)}$$

For the case study the result regarding the wheelslip has been listed in Table L1.2 for the different open gearing models.

Table L1.2 Wheelslip calculation result

	Original crane	Open gearing model 1	Open gearing model 2	Open gearing model 3
f_A [-]	1.80	1.80	1.80	1.80
N [kW]	16.00	30.00	64.00	26.00
η_G [-]	0.96	0.89	0.79	0.92
v_C [m/s]	0.83	0.83	0.83	0.83
F_1 [kN]	493.9	493.9	493.9	493.9
F_2 [kN]	33.31	28.95	27.07	25.94
$\mu_{Calculation} = \frac{F_2}{F_1}$	0.07	0.06	0.05	0.05

$\mu_{Calculation} \leq 0.12$	<0.12	<0.12	<0.12	<0.12

What firstly must be noted is that the use of a single engine for powering both wheels does not lead to wheel slip. Secondly the use of a single engine to power both wheels results in a situation where wheel slip is less likely to occur than in the situation where each engine powers a single wheel. In case the engine powers the wheels of two bogies the occurrence of wheelslip is even less likely to occur. Thirdly due to the higher transmission efficiency of a 3 gears open gearing transmission wheel slip is also less likely to occur. If, however, wheelslip would have been a problem for the crane the solution would be to have more wheels driven.

Appendix M Wheel size calculation

The calculation of the appropriate wheel diameter is performed according to DIN 15070 with the data from the tender document and the calculation made by Cargotec Netherlands BV respectively. The limiting factor for the rail is the pressure that is experience at the contact point of the wheel with the rail head. The resulting wheel pressure can be calculated by Eq. M1.1.

$$p = p_{zul} \bullet c_1 = \frac{R_{mean}}{c_2 \bullet c_3 \bullet D_{wheel} \bullet (k - 2 \bullet r_1)} \ [\text{N/mm}^2] \qquad \text{(M1.1)}$$

p_{zul} [N/mm^2] is defined as the wheel pressure, D_{wheel} [m] as the crane wheel diameter, k [mm] as the width of the rail head, r_1 [mm] as the radius of curvature of the edges of the rail head, and c_1, c_2, c_3 [-] are constants based on the utilization rate of the travelling gears, the crane speed and the chemical composition of the rail (Table S2, S3, S4). The average wheel load is calculated according to Equation M1.2.

$$R_{mean} = \frac{2 \bullet R_{max} + R_{min}}{3} \ [\text{kN}] \qquad \text{(M1.2)}$$

The maximum wheel load is defined as R_{max} [kN] and the minimum wheel load as R_{min} [kN].

The wheel diameter can be calculated by Equation M1.3.

$$D_{wheel} = \frac{R_{mean}}{p_{zul} \bullet c_1 \bullet c_2 \bullet c_3 \bullet (k - 2 \bullet r_1)} \ [\text{m}] \qquad \text{(M1.3)}$$

Based on data from the tender document and the calculation made by Cargotec Netherlands BV, respectively, Table M1 has been constructed.

Table M1 Wheel data for calculation

Calculation wheel diameter	
R_{min} [kN] (excluding wind load)	493.9
R_{max} [kN] (excluding wind load)	769.5
p_{zul} [N/mm^2]	5.6
c_1 [-]	1.25
c_2 [-]	1.03
c_3 [-]	1.25
k [mm]	150
r_1 [mm]	10

$R_{mean} = \frac{2 \cdot R_{max} + R_{min}}{3}$ [kN]	677.63
$D_{wheel} = \frac{R_{mean}}{p_{zul} \cdot c_1 \cdot c_2 \cdot c_3 \cdot (k - 2 \cdot r_1)}$ [m]	0.578

The resulting wheel diameter equals to 630 mm according to DIN15070 (wheel diameter range is defined as follows: 200, 250, 315, 400, 500, 630, 710, 800, 900, 1000, 1120, 1250 mm).

The tables for selecting the values of the variables c_1, c_2, and c_3 have been listed below (Table M2, M3, M4).

Table M2 Determination of c_1

Werkstoff Zugfestigkeit mindestens N/mm² Schiene	Laufrad	p_{zul} N/mm²	c_1
590	≦ 330	2,8	0,5
	410	3,6	0,63
	490	4,5	0,8
	590	5,6	1,00
≧ 690	≧ 740	7,0	1,25

The rail has been specified as A150 rail type, with a steel grade 900.

Table M3 Determination of c_2

Laufrad-Durchmesser d_1 mm	c_2 für v in m/min 10	12,5	16	20	25	31.5	40	50	63
200	1.09	1.06	1,03	1	0.97	0.94	0.91	0.87	0,82
250	1.11	1.09	1,06	1,03	1	0,97	0.94	0.91	0,87
315	1,13	1,11	1,09	1.06	1,03	1	0,97	0.94	0.91
400	1,14	1,13	1.11	1,09	1,06	1,03	1	0,97	0,94
500	1,15	1,14	1,13	1,11	1,09	1,06	1,03	1	0,97
630	1,17	1,15	1,14	1,13	1,11	1,09	1.06	1,03	1
710	–	1,16	1,14	1.13	1,12	1,1	1.07	1,04	1,02
800	–	1,17	1.15	1,14	1,13	1.11	1,09	1,06	1,03
900	–	–	1,16	1,14	1.13	1,12	1,1	1,07	1,04
1000	–	–	1,17	1,15	1,14	1,13	1,11	1,09	1,06
1120	–	–	–	1,16	1,14	1,13	1,12	1,1	1,07
1250	–	–	–	1.17	1,15	1.14	1,13	1,11	1,09

The crane speed has been specified to be v_C = 50 m/min.

Table M4 Determination of c_3

Betriebsdauer des Fahrantriebes (bezogen auf 1 Stunde)	c_3
bis 16 %	1,25
über 16 bis 25 %	1,12
über 25 bis 40 %	1
über 40 bis 63 %	0,9
über 63 %	0,8

The utilization rate of the bogie has been defined to be within the range of 16% utilization per hour.

Appendix N Engine redundancy

In case a single engine with engine-mounted brake fails, the remaining engines and engine-mounted brakes will have to be able to deliver enough power and braking torque for facilitating the crane travelling motion and to stop the crane within a certain distance. For the application of an open gearing this situation is more acute than with having a single engine power a single wheel, due to the smaller number of engines available (and thereby the larger drop in remaining engine power in case of engine failure). When reviewing the number of engines and the required nominal power for the crane travelling motion the loss in nominal power can be calculated in case of a single engine failure (Table N1).

Table N1 Nominal power requirement in case of engine failure

	Number of engines [-]	Nominal power requirement per engine [kW]	Total nominal power [kW]	Total nominal power in case of a single engine failure [kW]	Loss in nominal power [%]
Existing crane	24	16	384	368	4.2
Open gearing model 1	16	28	448	420	6.3
Open gearing model 2	8	63	504	441	12.5
Open gearing model 3	16	27	432	405	6.3

In order to accommodate this situation two decisions can be made:

1. Increase the engine power and braking torque such that, in case of engine failure, there is still sufficient capacity available. This does mean that the engine and brake size will increase in size and cost. The focus will only be on having a single engine failure; in case of more than one engine failure this will be considered as an insurmountable situation. This demand is sometimes stated in tender documents.
2. The crane travelling gear can be composed of a combination of engines powering a single wheel and engines powering two wheels. This can be realized if it concerns a crane travelling gear build-up of J-bogies. This solution will lead to a smaller cost reduction.

Appendix O Bolted flange plate overview

This appendix provides an overview of the bolted flange plates in the steel structure of the portal frame.

- Table O1 displays a flange plate overview for the portal frame.

Table O1 Flange plate overview portal frame

Item	Amount	Description	Length [mm]	Width [mm]	Mass [kg]	Comments
Lower legs WS	2	Plate 50mm Q390-D Z25	2,740	2,326	3,505	Bottom welded to sill beam, bolted connection at the top
Lower legs LS	2	Plate 50mm Q390-D Z25	2,326	2,280	2,306	Bottom welded to sill beam, bolted connection at the top
Sill beam WS	2	Plate 50mm Q390-D Z25	1,840	1,340	1,826	Bolted connection for the main balance
	1	Plate 40mm Q390-D Z25	2,240	1,240	394	Bolted connection for the storm brake
Sill beam LS	2	Plate 50mm Q390-D Z25	1,840	1,340	1,826	Bolted connection for the main balance
	1	Plate 40mm Q390-D Z25	2,240	1,240	394	Bolted connection for the storm brake
Cross girder PS/ SB	2	Plate 50mm Q390-D Z25	2,326	1,545	2,536	Bolted connection at the top WS
	2	Plate 50mm Q390-D Z25	2,515	2,326	2,720	Bolted connection at the top LS
	2	Plate 50mm Q390-D Z25	3,001	2,326	4,846	Bolted connection at the bottom WS
	2	Plate 50mm Q390-D Z25	2,515	2,326	2,720	Bolted connection at the bottom LS
	2	Plate 30mm Q345-D	2,962	1,441	1,061	Bottom connection diagonal tie
	2	Plate 30mm Q345-D	2,962	1,441	1,061	Bottom connection diagonal tie
	4	Plate 30mm Q345-D	1,018	886	604	-
Long leg WS	2	Plate 50mm Q390-D Z25	2,326	1,650	1,569	Bolted connection at the top WS
	2	Plate 50mm Q390-D Z25	2,326	1,270	1,342	Bolted connection at the bottom WS
	2	Plate 30mm Q345-D	1,589	1,029	458	Top connection diagonal tie
	4	Plate 30mm Q345-D	1,018	120	46	Top connection diagonal tie
Long leg LS	2	Plate 50mm Q390-D Z25	2,326	2,280	1,174	Bolted connection at top LS
	2	Plate 35mm Q390-D Z25	2,326	2,280	822	Bolted connection at bottom LS
Upper leg LS	2	Plate 35mm Q390-D Z25	3,480	2,300	1,760	Bolted connection with portal beam LS
	2	Plate 35mm Q390-D Z25	2,326	2,280	840	Bolted connection with long leg LS
Upper leg WS	2	Plate 35mm Q390-D Z25	3,020	1,280	1,812	Bolted connection with portal beam WS
	2	Plate 50mm Q390-D Z25	2,326	1,650	1,569	Bolted connection with long leg WS
	2	Plate 30mm Q345-D	1,505	638	287	Bolted connection ties portal frame
Portal beam WS	2	Plate 35mm Q390-D Z25	2,800	1,280	1,970	Bolted connection portal beam WS with upper legs WS
	2	Plate 35mm Q390-D Z25	2,000	980	965	Bolted connection ties portal frame with portal beam WS
Portal beam LS	2	Plate 35mm Q390-D Z25	2,300	3,300	3,518	Bolted connection portal beam LS with upper legs LS
Diagonal tie	4	Plate 30mm Q345-D	1,470	1,194	966	Bolted connection with cross girder (both WS and LS) and long leg WS
	8	Plate 30mm Q345-D	1,470	535	893	Bolted connection with cross girder (both WS and LS) and long legs WS
Storm pin	2	Plate 40mm Q390-D Z25	2,240	1,240	787	Bolted connection between storm pin and sill beam
Crane travelling support	4	Plate 50mm Q390-D Z25	1,340	1,340	2,707	Bolted connection for the main balance connection

Ties portal construction	2	Plate 35mm Q390-D	1,732	967	414	Bolted connection with portal beam WS
	2	Plate 45mm Q390-D	3,022	975	965	Bolted connection with upper legs WS
Number of bolted flange plates	78			Total mass	50,663	
Bolted connections for sea transport have been left out of the overview						

Appendix P Production cost bolted flange plate

This appendix displays the estimated production cost of the bolted flange plates.

- Table P1 displays the production cost of the bolted flange plates.

The production cost cannot be compared very easily with the production cost of a different crane. The reason for this is because the cost are entirely dependent on the dimensions of the bolted flange plates. Furthermore, expressing the cost of the different production and purchase steps as percentage of the total production cost is difficult. This is entirely dependent on the size of the flange plate, number of bolts (including nuts), etcetera.

The production cost have been build-up as follows:

- Material cost involves the purchase cost of the material;
- Bolt cost involves the purchase of bolt, nut and ring;
- Plate cutting cost are the cost made during cutting of the steel plate (type of machine, plate size, plate thickness);
- Welding cost involves the welding of the flange plate to the girder (including the cost of welders, equipment, and others);
- Milling cost involves machinery cost (dependent on the size of the area to be milled) and personnel cost;
- Drilling and boring cost are outsourced.

Table P1 Total production cost flange plates

Flange plate component	Material cost [Euro]	Bolt cost [Euro]	Plate cutting cost [Euro]	Welding cost [Euro]	Milling cost [Euro]	Drilling and boring cost [Euro]	Total production cost [Euro]
Sill beam connection storm brake WS	271	1,512	17	89	634	244	2,767
Sill beam connection main balance WS	628	139.5	10	225	634	244	1,880
Sill beam connection storm brake LS	271	1,512	17	89	634	244	2,767
Sill beam connection main balance LS	628	139.5	10	225	634	244	1,880
Lower leg connection sill beam WS		Estimated cost; reviewed project has this connection welded					2,500
Lower leg connection sill beam LS		Estimated cost; reviewed project has this connection welded					2,250
Lower leg connection cross girder WS	1,205	628	29	306	854	269	3,288
Lower leg connection cross girder LS	793	628	25	306	854	269	2,872
Cross girder connection long leg WS	872	419	15	183	915	195	2,597
Cross girder connection long leg LS	935	559	25	117	915	195	2,744
Cross girder connection lower leg WS	1,666	628	25	298	915	269	3,799
Cross girder connection lower leg LS	935	628	25	117	915	269	2,886
Cross girder connection diagonal tie PS	664	281	7	179	125	113	1,367
Long leg connection cross girder WS	462	419	20	113	854	195	2,060
Long leg connection upper leg WS	543	503	22	123	854	244	2,287
Long leg connection diagonal tie PS	158	281	3	179	125	113	857
Upper leg connection long leg WS	543	503	22	183	854	244	2,346
Upper leg connection portal beam WS	623	455	15	123	854	317	2,386
Upper leg connection tie portal frame	90	128	2	118	125	38	500
Long leg connection cross girder LS	283	559	24	53	854	195	1,966
Long leg connection upper leg LS	404	312	20	77	854	244	1,909
Upper leg connection portal beam LS	605	637	20	196	854	317	2,627
Upper leg connection long leg LS	289	312	24	91	854	244	1,813
Portal beam connection upper leg WS	678	910	13	986	1,128	317	4,030
Portal beam connection tie portal frame	332	128	8	118	125	38	748
Portal beam connection upper leg LS	1,210	1,274	21	213	1,128	317	4,161
Tie portal frame connection upper leg	302	128	11	118	125	38	721
Tie portal frame connection portal beam	130	128	8	118	125	38	545
Diagonal tie connection cross girder PS	291	281	3	179	125	113	991
Diagonal tie connection long leg PS	291	281	3	179	125	113	991
A frame connection							1,500

Appendix Q Production cost welded flange plate

The cost presented in this appendix only represent the production cost associated with the welded flange plate. As stated in paragraph 4.6 the cost of a welded flange plate connection has been estimated to be 20% in the most favorable situation and 40% in the most unfavorable situation, based on a review of the cost for a bolted flange plate connection.

Table Q1 Welded flange plate production cost

Flange plate component	Total production cost bolted flange plate connection [Euro]	Production cost welded flange plate connection 20% [Euro]	Production cost welded flange plate connection 30% [Euro]	Production cost welded flange plate connection 40% [Euro]
Sill beam connection storm brake WS	2,767	553	830	1,107
Sill beam connection main balance WS	1,880	376	564	752
Sill beam connection storm brake LS	2,767	553	830	1,107
Sill beam connection main balance LS	1,880	376	564	752
Lower leg connection sill beam WS	2,500	500	750	1,000
Lower leg connection sill beam LS	2,250	450	675	900
Lower leg connection cross girder WS	3,288	658	986	1,315
Lower leg connection cross girder LS	2,872	574	862	1,149
Cross girder connection long leg WS	2,597	519	779	1,039
Cross girder connection long leg LS	2,744	549	823	1,098
Cross girder connection Lower leg WS	3,799	760	1,140	1,520
Cross girder connection Lower leg LS	2,886	577	866	1,154
Cross girder connection diagonal tie PS	1,367	273	410	547
Long leg connection cross girder WS	2,060	412	618	824
Long leg connection upper leg WS	2,287	457	686	915
Long leg connection diagonal tie PS	857	171	257	343
Upper leg connection long leg WS	2,346	469	704	938
Upper leg connection portal beam WS	2,386	477	716	954
Upper leg connection tie portal frame	500	100	150	200
Long leg connection cross girder LS	1,966	393	590	786
Long leg connection upper leg LS	1,909	382	573	764
Upper leg connection portal beam LS	2,627	525	788	1,051
Upper leg connection long leg LS	1,813	363	544	725
Portal beam connection upper leg WS	4,030	806	1,209	1,612
Portal beam connection tie portal frame	748	150	224	299
Portal beam connection upper leg LS	4,161	832	1,248	1,664
Tie portal frame connection upper leg	721	144	216	288
Tie portal frame connection portal beam	545	109	164	218
Diagonal tie connection cross girder PS	991	198	297	396
Diagonal tie connection long leg PS	991	198	297	396
A frame connection	1,500	300	450	600

Appendix R Assembly concept

This appendix provides an overview of the different assembly concepts that can be made, with various combinations of sub-assemblies, under the different assumptions made in Chapter 4.

Table R1 – R6 display the different assembly concepts for the portal frame.

Table R1 Assembly concept

Connection consideration															
Connection	Current design		Concept												Tender specification
			1	2	3	4	5	6	7	8	9	10	11	12	
Connection between the sill beam and the lower legs	B	W	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the lower legs and the cross girder	B	B	W1	W1	W1	W1	W1	W1	B	B	B	B	B	B	W
Connection between the cross girders with the long legs	B	B	B	B	W1	W1	W1	W1	W1	W1	W1	W1	B	B	W
Connection between the long legs and the upper legs	B	B	B	B	B	B	W1	W1	B	B	W1	W1	W1	W1	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W1	B	W1	B	W1	B	W1	B	W1	B	W1	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W1	B	W1	B	W1	B	W1	B	W1	B	W1	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W

Table R2 Assembly concept

Connection consideration															
Connection	Current design		Concept												Tender specification
			13	14	15	16	17	18	19	20	21	22	23	24	
Connection between the sill beam and the lower legs	B	W	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the lower legs and the cross girder	B	B	W1	W1	W1	W1	W1	W1	B	B	B	B	B	B	W
Connection between the cross girders with the long legs	B	B	B	B	W1	W1	W1	W1	W1	W1	W1	W1	B	B	W
Connection between the long legs and the upper legs	B	B	B	B	B	B	W1	W1	B	B	W1	W1	W1	W1	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W1	B	W1	B	W1	B	W1	B	W1	B	W1	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W1	B	W1	B	W1	B	W1	B	W1	B	W1	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W

Table R3 Assembly concept

Connection consideration															
Connection	Current design		Concept												Tender specification
			25	26	27	28	29	30	31	32	33	34	35	36	
Connection between the sill beam and the lower legs	B	W	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W
Connection between the lower legs and the cross girder	B	B	W2	W2	W2	W2	W2	W2	B	B	B	B	B	B	W
Connection between the cross girders with the long legs	B	B	B	B	W2	W2	W2	W2	W2	W2	W2	W2	B	B	W
Connection between the long legs and the upper legs	B	B	B	B	B	B	W2	W2	B	B	W2	W2	W2	W2	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W2	B	W2	B	W2	B	W2	B	W2	B	W2	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W2	B	W2	B	W2	B	W2	B	W2	B	W2	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W

Table R4 Assembly concept

Connection consideration															
Connection	Current design		Concept												Tender specification
			37	38	39	40	41	42	43	44	45	46	47	48	
Connection between the sill beam and the lower legs	B	W	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W1	W
Connection between the lower legs and the cross girder	B	B	W2	W2	W2	W2	W2	W2	B	B	B	B	B	B	W
Connection between the cross girders with the long legs	B	B	B	B	W2	W2	W2	W2	W2	W2	W2	W2	B	B	W
Connection between the long legs and the upper legs	B	B	B	B	B	B	W2	W2	B	B	W2	W2	W2	W2	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W2	B	W2	B	W2	B	W2	B	W2	B	W2	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W2	B	W2	B	W2	B	W2	B	W2	B	W2	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	W2	W2	W2	W2	W2	W2	W2	W2	W2	W2	W2	W2	W

Table R5 Assembly concept

Connection consideration															
Connection	Current design		Concept												
			49	50	51	52	53	54	55	56	57	58	59	60	Tender specification
Connection between the sill beam and the lower legs	B	W	B	B	B	B	B	B	W1	W1	W1	W1	W1	W1	W
Connection between the lower legs and the cross girder	B	B	W1	W1	W1	W1	W1	W1	W2	W2	W2	W2	W2	W2	W
Connection between the cross girders with the long legs	B	B	W2	W2	W1	W1	W2	W2	W3	W3	W2	W2	W3	W3	W
Connection between the long legs and the upper legs	B	B	W3	W3	W2	W2	W2	W2	W4	W4	W3	W3	W3	W3	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W4	B	W3	B	W3	B	W5	B	W4	B	W4	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W5	B	W4	B	W4	B	W6	B	W5	W4	W5	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W

Table R6 Assembly concept

Connection consideration															
Connection	Current design		Concept												
			61	62	63	64	65	66	67	68	69	70	71	72	Tender specification
Connection between the sill beam and the lower legs	B	W	B	B	B	B	B	B	W1	W1	W1	W1	W1	W1	W
Connection between the lower legs and the cross girder	B	B	W1	W1	W1	W1	W1	W1	W2	W2	W2	W2	W2	W2	W
Connection between the cross girders with the long legs	B	B	W2	W2	W1	W1	W2	W2	W3	W3	W2	W2	W3	W3	W
Connection between the long legs and the upper legs	B	B	W3	W3	W2	W2	W2	W2	W4	W4	W3	W3	W3	W3	W
Connection between the diagonal tie and the cross girders	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between the diagonal tie and the long legs	B	B	B	W4	B	W3	B	W3	B	W5	B	W4	B	W4	W
Connection between the upper legs and the portal beams	B	B	B	B	B	B	B	B	B	B	B	B	B	B	W
Connection between upper legs WS (or long legs WS) and the horizontal tie	B	B	B	W5	B	W4	B	W4	B	W6	B	W5	B	W5	W
Connection between upper legs LS (or long legs LS) and the horizontal tie	B	B	W4	W5	W3	W4	W3	W4	W5	W6	W4	W5	W5	W5	W

Appendix S Production and assembly site

Hoisting capacity for the production site has been listed in Table S1.

Table S1 Hoisting capacity production site

Area or workshop	Hoisting capacity [MT]	Amount	Area or workshop	Hoisting capacity [MT]	Amount
Preparation workshop	20	2	Component storage area	100	2
	10	1			
	5	1			
Fabrication workshop	20	3	Work yard area (area for loading components onto a barge)	100	1
	30	2		120	1
Machine workshop 1	50	2	Sub-assembly workshop	20	4
	100	1		50	2
Machine workshop 2	32	1	Sub-assembly area	20	4
	75	1		50	2

Hoisting capacity for the Taicang port assembly site has been listed in Table S2. For Taicang Port it must be noted that all hoisting equipment is rented; mobile cranes and FCBs.

Table S2 Hoisting capacity Taicang Port assembly site

Type of crane	Hoisting capacity [MT]	Type of crane	Hoisting capacity [MT]
Mobile crane	25	Mobile crane	160
Mobile crane	50	Mobile crane	200
Mobile crane	70	Mobile crane	300
Mobile crane	100	Floating crane barge (FCB)	1,800

Hoisting capacity for the RCI assembly site has been listed in Table S3. All hoisting equipment is property of the company, except for the FCB.

Table S3 Hoisting capacity RCI assembly site

Type of crane	Hoisting capacity [MT]	Amount
Jib crane	100	1
Overhead crane	100	5
Overhead crane	150	2
Overhead crane (Goliath crane)	700	1

Also available at the RCI assembly site is a FCB of 1,800 MT for the lifting of the Ship-To-Shore container gantry crane (though rented), in case this is necessary (depending on the loading method on the vessel for sea transport).

Appendix T Assembly cost area rental

In Table T1 an overview of the area rental cost for individual components is listed.

Table T1 Rental cost for quayside at Taicang Port, storage area of components

Component	Area [m2]	Area rental cost per day [RMB[24]/day]
Sill beam WS	53.3	27
Sill beam LS	53.3	27
Lower leg PS WS (SB WS)	11.8	6
Lower leg PS LS (SB LS)	11.0	5
Cross girder PS (SB)	71.0	36
Long leg PS WS (SB WS)	86.7	43
Long leg PS LS (SB LS)	65.1	33
Upper leg PS WS (SB WS)	22.9	11
Upper leg PS LS (SB LS)	32.3	16
Portal beam WS	80.6	40
Portal beam LS	80.6	40

The orientation of the components in the storage area should be such that it leads to a minimum of handlings for positioning the components in the right orientation for sub-assembly. In Table T2 an overview of the area rental cost for sub-assemblies is listed.

Table T2 Area rental cost

Component combination	Maximum surface area [m2]	Area rental cost per day [RMB/day]
Sill Beam + Main Balance connection (WS)	93.1	47
Sill Beam + Main Balance connection (LS)	90.7	45
Sill Beam + Lower Legs (WS) (WS view)	166.3	83
Sill Beam + Lower Legs (LS) (WS view)	171.7	86
Lower Legs (PS LS + PS WS) + Cross Girder (PS)	316.4	158
Lower Legs (SB LS + SB WS) + Cross Girder (SB)	316.4	158
Cross Girder + Long Legs + Diagonal Tie (PS) (PS view)	71.1	36
Cross Girder + Long Legs + Diagonal Tie (SB) (PS view)	981.6	491
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS) (PS view)	1424.1	712
Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB) (PS view)	1424.1	712
Long Leg + Upper Leg (PS, WS) (PS view)	127.4	64
Long Leg + Upper Leg (PS, LS) (PS view)	96.1	48
Long Leg + Upper Leg (SB, WS) (PS view)	127.4	64
Long Leg + Upper Leg (SB, LS) (PS view)	96.1	48
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (PS) (PS view)	1596.3	798
Lower Legs + Cross Girder + Long Legs + Diagonal Tie + Upper Legs (SB)	1596.3	798

[24] Currency ratio Renminbi – Euro equals to 1 : 0.125

Appendix U Assembly sequence portal frame

Assembly sequence portal frame in case of horizontal assembly of the entire side portal (Figure U1).

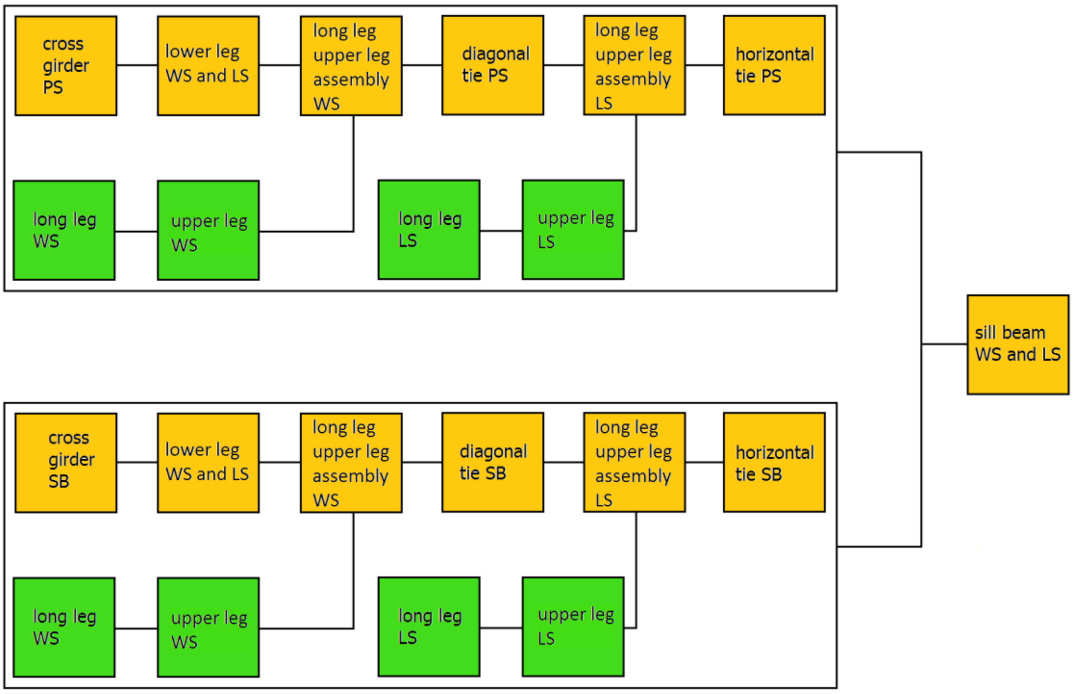


Figure U1Schematic assembly portal frame (horizontal assembly entire side portal)

Assembly sequence portal frame in case of horizontal assembly of part of the side portal (Figure U2).

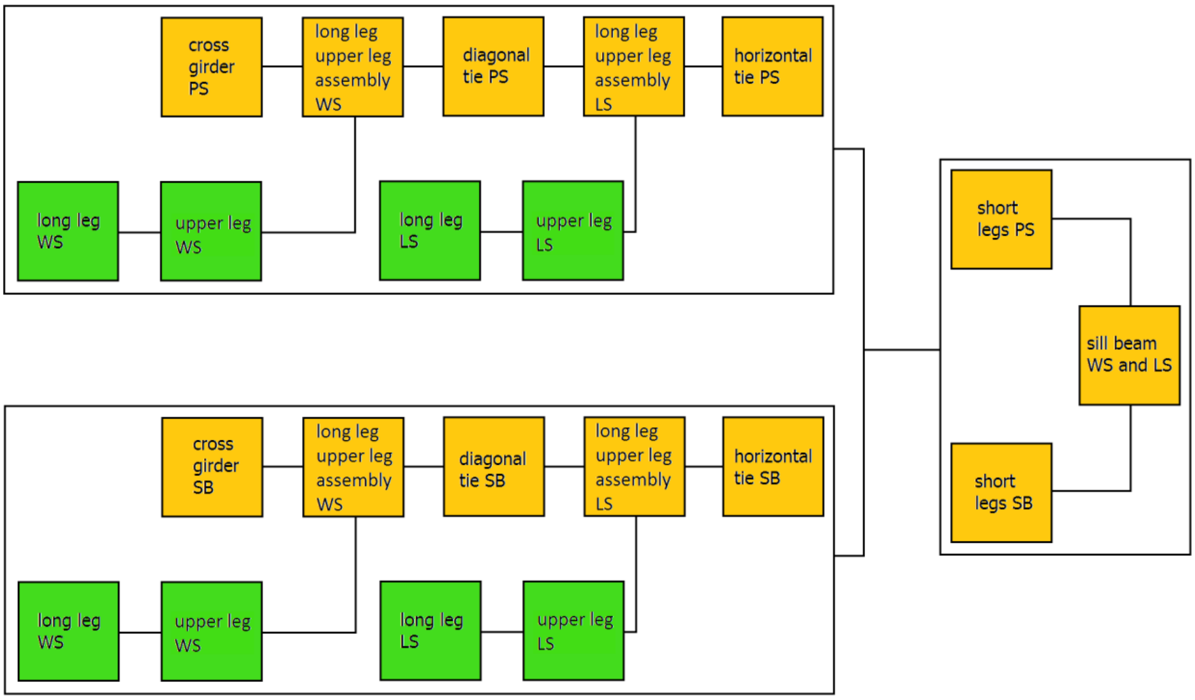


Figure U2Schematic assembly portal frame (horizontal assembly part of the side portal)

Appendix V Sea transport bolted and welded connection

Table V1 Cost in case of a bolted connection

Cost (un-)loading method

Method	description	Cost [Euro]
FCB	One (1) 1800 MT; 3,125 Euro/hr; Duration of (un-)loading is 8 hr	25,000
	One (1) building site manager; 55 Euro/hr	440
	Four (4) dedicated workers; 15 Euro/hr	120
SPMTs	Two (2) 22 line; 9,375 Euro/hr (total), Duration of (un-)loading is 8 hr	75,000
	One (1) building site manager; 55 Euro/hr	440
	Four (4) dedicated workers; 15 Euro/hr	120

Cost erection method bolted

Method	Description	Cost [Euro]
Self erection	Strand jacking, bolted, duration is 48 hr	40,000
	One (1) building site manager; 55 Euro/hr	2,640
	Four (4) dedicated workers; 15 Euro/hr	720
	Securing the bolted connection	
	Four (4) cherry pickers; 180 Euro/hr; 8 hr	5,760
	Two (2) persons per cherry picker; 15 Euro/hr; 8 hr	960
Erection	FCB, bolted, duration is 8 hr	25,000
	One (1) building site manager; 55 Euro/hr	440
	Four (4) dedicated workers; 15 Euro/hr	120
	Securing the bolted connection	
	Four (4) cherry pickers; 180 Euro/hr; 8 hr	5,760
	Two (2) persons per cherry picker; 15 Euro/hr; 8 hr	960

Transportation cost vessel

Cost post	Description	Cost [Euro]
Fixed cost		900,000
Variable cost	55 Euro/km; distance is 19,000 km	1,045,000

Miscellaneous

Description	Cost [Euro]
Sea fastening cost	102,700
Transport cost to return components, semi-erected transport	6,500
Transport cost to return components, fully erected transport	2,800
Overhead cost strand jacking, bolted; 12.5 Euro/hr; 48 hr	600
Overhead cost FCB, bolted; 12.5 Euro/hr; 16 hr	200

In case of assembly at the RCI assembly site the erection cost for FCB is not present. The overhead cranes (owned by the company) will be used.

Duration of the erection method for a bolted flange connection:

- For strand jacking 5 days are noted (of each 8 hours) for erection (of which one day is allocated to the actual lifting of the portal frame)
- For a FCB the duration of erection of the crane takes a total of 8 hours.

The transportation cost of the vessel will have to be divided over the number of cranes transported.

Table V2 Cost in case of a welded connection

Cost (un-)loading method

Method	description	Cost [Euro]
FCB	One (1) 1800 MT; 3,125 Euro/hr; Duration of (un-)loading is 8 hr	25,000
	One (1) building site manager; 55 Euro/hr	440
	Four (4) dedicated workers; 15 Euro/hr	120
SPMTs	Two (2) 22 line; 9,375 Euro/hr (total), Duration of (un-)loading is 8 hr	75,000
	One (1) building site manager; 55 Euro/hr	440
	Four (4) dedicated workers; 15 Euro/hr	120

Cost erection method welded

Method	Description	Cost [Euro]
Self erection	Strand jacking, welded, duration is 62.5 hr	52,000
	One (1) building site manager; 55 Euro/hr	3,438
	Four (4) dedicated workers; 15 Euro/hr	3,750
	Securing the welded connection	
	Four (4) cherry pickers; 180 Euro/hr; 22.5 hr	16,200
	Two (2) persons per cherry picker; 15 Euro/hr; 22.5 hr	2,700
	Welding cost and welding plate	5,000
	cost due to the removal of bolted flange plates	-26,150
Erection	FCB, welded, duration is 27 hr	84,375
	One (1) building site manager; 55 Euro/hr	1,485
	Four (4) dedicated workers; 15 Euro/hr	1,590
	Securing the welded connection	
	Four (4) cherry pickers; 180 Euro/hr; 27 hr	19,440
	Two (2) persons per cherry picker; 15 Euro/hr; 27 hr	3,240
	Cost of welded flange plate	5,230
	Cost due to the removal of bolted flange plates	-26,150

Transportation cost vessel

Cost post	Description	Cost [Euro]
Fixed cost		900,000
Variable cost	55 Euro/km; distance is 19,000 km	1,045,000

Miscellaneous

Description	Cost [Euro]
Sea fastening cost	102,700
Transport cost to return components, semi-erected transport	6,500
Transport cost to return components, fully erected transport	2,800
Overhead cost strand jacking, welded; 12.5 Euro/hr; 62.5 hr	782
Overhead cost FCB, welded; 12.5 Euro/hr; 27 hr	338

In case of assembly at the RCI assembly site the erection cost for FCB is not present. The overhead cranes (owned by the company) will be used.

Duration of erection method for a welded flange connection:

- For strand jacking 62.5 hours (estimated) are noted for erection and securing the connection;
- For a FCB the duration of erection of the crane and securing the connection takes a total of 27 hours.

The transportation cost of the vessel will have to be divided over the number of cranes transported.

Concept 1 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	-
Transport	589,000
Erection at client's site	33,000
Miscellaneous	110,000
Total	731,000

Concept 2 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	-
Transport	589,000
Erection at client's site	113,000
Miscellaneous	110,000
Total	811,000

Concept 3 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	26,000
Transport	638,000
Erection at client's site	51,000
Miscellaneous	110,000
Total	823,000

Concept 4 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	26,000
Transport	638,000
Erection at client's site	57,000
Miscellaneous	110,000
Total	830,000

Concept 5 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	-
Transport	589,000
Erection at client's site	33,000
Miscellaneous	110,000
Total	731,000

Concept 6 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	-
Transport	589,000
Erection at client's site	113,000
Miscellaneous	110,000
Total	811,000

Concept 7 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	1,000
Transport	789,000
Erection at client's site	51,000
Miscellaneous	110,000
Total	949,000

Concept 8 semi-erected transport	
Description	Cost [Euro]
Semi-erection on site	1,000
Transport	789,000
Erection at client's site	57,000
Miscellaneous	110,000
Total	956,000

Concept 9 fully erected transport	
Description	Cost [Euro]
Erection on site	33,000
Transport	538,000
Miscellaneous	107,000
Total	676,000

Concept 10 fully erected transport	
Description	Cost [Euro]
Erection on site	8,000
Transport	638,000
Miscellaneous	107,000
Total	751,000

Concept 11 fully erected transport	
Description	Cost [Euro]
Erection on site	8,000
Transport	538,000
Miscellaneous	107,000
Total	651,000

Concept 12 fully erected transport	
Description	Cost [Euro]
Erection on site	5,000
Transport	538,000
Miscellaneous	106,000
Total	648,000

Concept 13 fully erected transport	
Description	Cost [Euro]
Erection on site	87,000
Transport	538,000
Miscellaneous	106,000
Total	731,000

Concept 14 fully erected transport	
Description	Cost [Euro]
Erection on site	5,000
Transport	638,000
Miscellaneous	106,000
Total	748,000

Appendix W Assembly resources

The cost calculation is based on those aspects that are different compared to concept 0 during the production, pre-assembly and (semi-) erection phase. For the different cost Table W1 – W5 can be reviewed. Table W6 – W13 provides an overview of the different cost posts for each concept.

Table W1 Rental cost main hoisting equipment Taicang Port

Main hoisting equipment		
Type of crane	Hoisting capacity [MT]	Rental cost [Euro/hr.]
Mobile crane	25	29
Mobile crane	50	47
Mobile crane	70	75
Mobile crane	100	125
Mobile crane	160	200
Mobile crane	200	260
Mobile crane	300	438
FCB	1,800	3,125

Table W2 Utilization cost main hoisting equipment RCI assembly site

Main hoisting equipment		
Type of crane	Hoisting capacity [MT]	Usage cost [Euro/hr.]
Jib crane	100	10
Overhead crane	100	10
Overhead crane	150	10
Overhead crane (Goliath crane)	700	25

Table W3 Rental cost auxiliary hoisting equipment

Auxiliary hoisting equipment	
Type of crane	Rental cost [Euro/hr.]
Lifting platform	50
Cherry picker	180

Table W4 Personnel cost

Personnel cost	
Type of crane	Rental cost [Euro/hr.]
Dedicated worker	15
(building site) Manager	55

Table W5 Additional cost

Other cost		
Site rental cost	0.003 Euro/hr./m^2	See Appendix U
Additional cost for other equipment and administration, etcetera	50 Euro/hr.	-

Concept 0

Placement of sill beams WS and LS with travelling gear (bolted connection between the sill beam and the main balances)

Mobile crane (2) (160 T)
Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
Placing sill beam WS and LS (welded connection, duration 8 hr. per bogie, parallel placement, bolting time is removed)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (4)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of lowers legs WS PS, WS SB, LS PS and LS SB (bolted)

Mobile crane (2) (50 MT mobile crane)
Placing first WS PS and LS SB followed by WS SB and LS PS (parallel placement, bolted connection, duration 8 hr. per lower leg)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the cross girders PS and SB (bolted connection)

Mobile crane (2) (160 MT mobile crane)
Placing first PS and then SB (duration 8 hr. per girder)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Cherry picker (2)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Placement of the long legs WS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Placement of the diagonal ties

Mobile crane (2) (300 MT)
Placing first the diagonal tie PS and then the diagonal tie SB (bolted, duration 8 hr. per diagonal tie)
Personnel (2 dedicated workers, 1 building site manager)
Cherry picker (2)
Personnel (2 dedicated workers, 1 manager)

Placement of the long legs LS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Placement of the upper legs

Mobile crane (2) (300 MT)
Placing first WS PS and LS SB, followed by WS SB and LS PS (bolted connection duration 8 hr. per upper leg)
Personnel (2 dedicated workers per crane, 1 building site manager)
Cherry picker (2)

Personnel (2 dedicated per crane, 1 manager)

Placement of the horizontal ties

Mobile crane (2) (300 MT)

Placing first the horizontal tie PS and then the horizontal tie SB (bolted, duration 8 hr. per diagonal tie)

Personnel (2 dedicated workers, 1 building site manager)

Cherry picker (2)

Personnel (2 dedicated workers, 1 manager)

The A-frame is bolted

Mobile crane (1) (70 MT)

Personnel (2 dedicated workers per crane, 1 building site manager)

Lifting platform (2)

Personnel (2 dedicated workers per lifting platform, 1 manager)

Table W6 gives an overview of the required hoisting equipment for the assembly of concept 0.

Table W6 Overview hoisting equipment concept 0

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Placement of lower legs WS PS, WS SB, LS PS and LS SB	Mobile crane 50 MT	2	Lifting platform	2
Placement of cross girders PS and SB	Mobile crane 160 MT	2	Cherry picker	2
Placement of long legs WS	FCB 1800 MT	1	Cherry picker	2
Placement of diagonal ties	Mobile crane 300 MT	2	Cherry picker	2
Placement of long legs LS	FCB 1800 MT	1	Cherry picker	2
Placement of upper legs	Mobile crane 300 MT	2	Cherry picker	2
Placement of horizontal ties	Mobile crane 300 MT	2	Cherry picker	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 1

Placement of sill beam WS and LS with travelling gear (bolted connection between the sill beam and the main balance)

Mobile crane (2) (160 MT)
Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
Placing sill beam WS and LS (bolted connection, duration 8 hr. per bogie, parallel placement)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (4)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS)

Horizontal assembly of side portal
Mobile crane (2)
Total assembly time horizontal assembly side portal
Personnel (2 dedicated workers per mobile crane, 1 building site manager)
Area rental cost for horizontal assembly
Removal of bolted flange plate cost of the side portal
Addition of welded flange plate cost
Additional cost for the assembly for smaller auxiliary hoisting equipment and others
Vertical assembly of side portal with sill beam
FCB (1)
Bolted connection (Taicang Port) Welded connection (RCI assembly site)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Additional is the placement of the A-frame (welded)

Mobile crane (1) (70 MT)
Personnel (2 dedicated workers per crane, 1 building site manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Removal of sheering cost from after the sill beams up to the cross girder.

Table W7 gives an overview of the required hoisting equipment for the assembly of concept 1.

Table W7 Overview hoisting equipment concept 1

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Horizontal assembly of side portal PS	Mobile crane 160 MT	2	-	-
Horizontal assembly of side portal SB	Mobile crane 160 MT	2	-	-
Vertical assembly side portal PS	FCB 1800 MT	1	Lifting platform	2
Vertical assembly side portal SB	FCB 1800 MT	1	Lifting platform	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 2

Placement of sill beam WS and LS with travelling gear (welded connection between the sill beam and the main balance)

- Mobile crane (2) (160 MT)
- Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
- Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
- Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
- Lifting platform (4)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS)

- Horizontal assembly of side portal
  - Mobile crane (2) (160 MT)
  - Total assembly time horizontal assembly side portal
  - Personnel (2 dedicated workers per mobile crane, 1 building site manager)
  - Area rental cost for horizontal assembly
- Removal of bolted flange plate cost of side portal and sill beam main balance connections
- Addition of welded flange plate cost
- Additional cost for the assembly for smaller auxiliary hoisting equipment and others
- Vertical assembly of side portal with sill beam
  - FCB (1)
  - Bolted connection (Taicang Port) Welded connection (RCI assembly site)
  - Personnel (2 dedicated workers per FCB, 1 building site manager)
  - Lifting platform (2)
  - Personnel (2 dedicated workers per lifting platform, 1 manager)

Additional is the placement of the A-frame (welded)

- Mobile crane (1) (70 MT)
- Personnel (2 dedicated workers per crane, 1 building site manager)
- Removal of bolted flange plate cost
- Addition of welded flange plate cost
- Lifting platform (2)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Removal of sheering cost from after the sill beams up to the cross girder.

Table W8 gives an overview of the required hoisting equipment for the assembly of concept 2.

Table W8 Overview hoisting equipment concept 2

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Horizontal assembly of side portal PS	Mobile crane 160 MT	2	-	-
Horizontal assembly of side portal SB	Mobile crane 160 MT	2	-	-
Vertical assembly side portal PS	FCB 1800 MT	1	Lifting platform	2
Vertical assembly side portal SB	FCB 1800 MT	1	Lifting platform	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 3

Placement of sill beam WS and LS with travelling gear (welded connection between the sill beam and the main balance)

Mobile crane (2) (160 MT)
Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (4)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS)

Horizontal assembly of side portal
  Mobile crane (2) (160 MT)
  Total assembly time horizontal assembly side portal
  Personnel (2 dedicated workers per mobile crane, 1 building site manager)
  Area rental cost for horizontal assembly
Removal of bolted flange plate cost of side portal and sill beam main balance connections
Addition of welded flange plate cost
Additional cost for the assembly for smaller auxiliary hoisting equipment and others
Vertical assembly of side portal with sill beam
  FCB (1)
  Bolted connection (Taicang Port) Welded connection (RCI assembly site)
  Personnel (2 dedicated workers per FCB, 1 building site manager)
  Lifting platform (2)
  Personnel (2 dedicated workers per lifting platform, 1 manager)

The A-frame is bolted

Mobile crane (1) (70 MT)
Personnel (2 dedicated workers per crane, 1 building site manager)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Removal of sheering cost from after the sill beams up to the cross girder.

Table W9 gives an overview of the required hoisting equipment for the assembly of concept 3.

Table W9 Overview hoisting equipment concept 3

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Horizontal assembly of side portal PS	Mobile crane 160 MT	2	-	-
Horizontal assembly of side portal SB	Mobile crane 160 MT	2	-	-
Vertical assembly side portal PS	FCB 1800 MT	1	Lifting platform	2
Vertical assembly side portal SB	FCB 1800 MT	1	Lifting platform	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 4

Placement of sill beam WS and LS with travelling gear (welded connection between the sill beam and the main balance)

- Mobile crane (2) (160 MT)
- Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
- Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
- Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
- Lifting platform (4)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the side portal PS and SB (the side portal PS consists of the lower leg WS PS and LS PS, cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS)

- Horizontal assembly of side portal
  - Mobile crane (2) (160 MT)
  - Total assembly time horizontal assembly side portal
  - Personnel (2 dedicated workers per mobile crane, 1 building site manager)
  - Area rental cost for horizontal assembly
- Removal of bolted flange plate cost of side portal and sill beam main balance connections
- Addition of welded flange plate cost
- Additional cost for the assembly for smaller auxiliary hoisting equipment and others
- Vertical assembly of side portal with sill beam
  - FCB (1)
  - Bolted connection (Taicang Port) Welded connection (RCI assembly site)
  - Personnel (2 dedicated workers per FCB, 1 building site manager)
  - Lifting platform (2)
  - Personnel (2 dedicated workers per lifting platform, 1 manager)

Additional is the placement of the A-frame (welded)

- Mobile crane (1) (70 MT)
- Personnel (2 dedicated workers per crane, 1 building site manager)
- Removal of bolted flange plate cost
- Addition of welded flange plate cost
- Lifting platform (2)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Removal of sheering cost from after the sill beams up to the cross girder.

Table W10 gives an overview of the required hoisting equipment for the assembly of concept 4.

Table W10 Overview hoisting equipment concept 4

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Horizontal assembly of side portal PS	Mobile crane 160 MT	2	-	-
Horizontal assembly of side portal SB	Mobile crane 160 MT	2	-	-
Vertical assembly side portal PS	FCB 1800 MT	1	Lifting platform	2
Vertical assembly side portal SB	FCB 1800 MT	1	Lifting platform	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 5

Placement of sill beam WS and LS with travelling gear (welded connection between the sill beam and the main balance)

- Mobile crane (2) (160 MT))
- Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
- Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
- Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
- Lifting platform (4)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the lower legs WS PS, WS SB, LS PS and LS SB

- Mobile crane (2) (50 MT mobile crane)
- Placing first WS PS and LS SB followed by WS SB and LS PS (parallel placement, bolted connection, duration 8 hr. per lower leg)
- Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
- Lifting platform (2)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the side portal PS and SB (the side portal PS consists of the cross girder PS, long leg WS PS and LS PS, upper leg WS PS and LS PS, diagonal tie PS and horizontal tie PS)

- Horizontal assembly of semi-side portal
  - Mobile crane (2) (160 MT)
  - Total assembly time horizontal assembly side portal
  - Personnel (2 dedicated workers per mobile crane, 1 building site manager)
  - Area rental cost for horizontal assembly
- Removal of bolted flange plate cost of semi-side portal and sill beam main balance connections
- Addition of welded flange plate cost
- Additional cost for the assembly for smaller auxiliary hoisting equipment and others
- Vertical assembly of side portal with lower legs
  - FCB (1)
  - Bolted connection (Taicang Port) Welded connection (RCI assembly site)
  - Personnel (2 dedicated workers per FCB, 1 building site manager)
  - Cherry picker (2)
  - Personnel (2 dedicated workers per cherry picker, 1 manager)

Additional is the placement of the A-frame (welded)

- Mobile crane (1) (70 MT)
- Personnel (2 dedicated workers per crane, 1 building site manager)
- Removal of bolted flange plate cost
- Addition of welded flange plate cost
- Lifting platform (2)
- Personnel (2 dedicated workers per lifting platform, 1 manager)

Table W11 gives an overview of the required hoisting equipment for the assembly of concept 5.

Table W11 Overview hoisting equipment concept 5

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Placement of short legs WS PS, WS SB, LS PS and LS SB	Mobile crane 50 MT	2	Lifting platform	2
Horizontal assembly of side portal PS	Mobile crane 160 MT	2	-	-
Horizontal assembly of side portal SB	Mobile crane 160 MT	2	-	-
Vertical assembly side portal PS	FCB 1800 MT	1	Lifting platform	2
Vertical assembly side portal SB	FCB 1800 MT	1	Lifting platform	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 6

Placement of sill beams WS and LS with travelling gear (welded connection between the sill beam and the main balances)

Mobile crane (2) (160 T)
Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (4)
Personnel (2 dedicated workers per lifting platform, 1 manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost

Placement of lowers legs WS PS, WS SB, LS PS and LS SB (bolted)

Mobile crane (2) (50 MT mobile crane)
Placing first WS PS and LS SB followed by WS SB and LS PS (parallel placement, bolted connection, duration 8 hr. per lower leg)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the cross girders PS and SB (bolted connection)

Mobile crane (2) (160 MT mobile crane)
Placing first PS and then SB (duration 8 hr. per girder)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Cherry picker (2)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Placement of the welded assembly of the long legs – upper legs WS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg – upper leg assembly)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost (no additional assembly cost allocated, connection is realized at the production site)

Placement of the diagonal ties

Mobile crane (2) (300 MT)
Placing first the diagonal tie PS and then the diagonal tie SB (bolted, duration 8 hr. per diagonal tie)
Personnel (2 dedicated workers, 1 building site manager)
Cherry picker (2)
Personnel (2 dedicated workers, 1 manager)

Placement of the welded assembly of the long legs – upper legs LS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg – upper leg assembly)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Removal of bolted flange plate cost
Addition of welded flange plate cost (no additional assembly cost allocated, connection is realized at the production site)

Placement of the horizontal ties
Mobile crane (2) (300 MT)
Placing first the horizontal tie PS and then the horizontal tie SB (bolted, duration 8 hr. per diagonal tie)
Personnel (2 dedicated workers, 1 building site manager)
Cherry picker (2)
Personnel (2 dedicated workers, 1 manager)

The A-frame is bolted
Mobile crane (1) (70 MT)
Personnel (2 dedicated workers per crane, 1 building site manager)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Table W12 gives an overview of the required hoisting equipment for the assembly of concept 6.

Table W12 Overview hoisting equipment concept 6

Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Placement of lower legs WS PS, WS SB, LS PS and LS SB	Mobile crane 50 MT	2	Lifting platform	2
Placement of cross girders PS and SB	Mobile crane 160 MT	2	Cherry picker	2
Placement of long legs – upper legs WS	FCB 1800 MT	1	Cherry picker	2
Placement of diagonal ties	Mobile crane 300 MT	2	Cherry picker	2
Placement of long legs – upper legs LS	FCB 1800 MT	1	Cherry picker	2
Placement of horizontal ties	Mobile crane 300 MT	2	Cherry picker	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Concept 7

Placement of sill beams WS and LS with travelling gear (welded connection between the sill beam and the main balances)

Mobile crane (2) (160 T)
Placing travelling gear PS WS, SB WS, PS LS, SB LS (sheering)
Placing sill beam WS and LS (welded connection, duration 4 hr. per bogie, parallel placement, bolting time is removed)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (4)
Personnel (2 dedicated workers per lifting platform, 1 manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost

Placement of lowers legs WS PS, WS SB, LS PS and LS SB (bolted)

Mobile crane (2) (50 MT mobile crane)
Placing first WS PS and LS SB followed by WS SB and LS PS (parallel placement, bolted connection, duration 8 hr. per lower leg)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Placement of the cross girders PS and SB (bolted connection)

Mobile crane (2) (160 MT mobile crane)
Placing first PS and then SB (duration 8 hr. per girder)
Personnel (2 dedicated workers per mobile crane, 1 building site manager per crane)
Cherry picker (2)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Placement of the welded assembly of the long legs – upper legs WS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg – upper leg assembly)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost (no additional assembly cost allocated, connection is realized at the production site)

Placement of the diagonal ties

Mobile crane (2) (300 MT)
Placing first the diagonal tie PS and then the diagonal tie SB (bolted, duration 8 hr. per diagonal tie)
Personnel (2 dedicated workers, 1 building site manager)
Cherry picker (2)
Personnel (2 dedicated workers, 1 manager)

Placement of the welded assembly of the long legs – upper legs LS

FCB (1) (no mobile crane is suitable for this weight with the appropriate lifting height)
Placing first WS PS, followed by WS SB and (bolted connection duration 8 hr. per long leg – upper leg assembly)
Personnel (2 dedicated workers per FCB, 1 building site manager)
Cherry picker (1)
Personnel (2 dedicated workers per cherry picker, 1 manager)

Removal of bolted flange plate cost
Addition of welded flange plate cost (no additional assembly cost allocated, connection is realized at the production site)

Placement of the horizontal ties
Mobile crane (2) (300 MT)
Placing first the horizontal tie PS and then the horizontal tie SB (bolted, duration 8 hr. per diagonal tie)
Personnel (2 dedicated workers, 1 building site manager)
Cherry picker (2)
Personnel (2 dedicated workers, 1 manager)

Additional is the placement of the A-frame (welded)
Mobile crane (1) (70 MT)
Personnel (2 dedicated workers per crane, 1 building site manager)
Removal of bolted flange plate cost
Addition of welded flange plate cost
Lifting platform (2)
Personnel (2 dedicated workers per lifting platform, 1 manager)

Table W13 gives an overview of the required hoisting equipment for the assembly of concept 7.

Table W13 Overview hoisting equipment concept 7

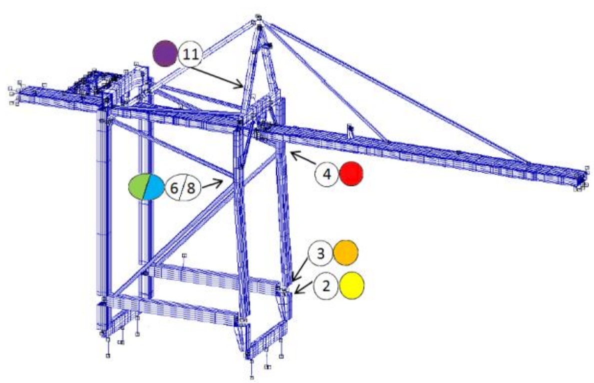
Placement of components	Main hoisting equipment	Amount	Auxiliary hoisting equipment	Amount
Placement of sill beams WS and LS	Mobile crane 160 MT	2	Lifting platform	4
Placement of lower legs WS PS, WS SB, LS PS and LS SB	Mobile crane 50 MT	2	Lifting platform	2
Placement of cross girders PS and SB	Mobile crane 160 MT	2	Cherry picker	2
Placement of long legs – upper legs WS	FCB 1800 MT	1	Cherry picker	2
Placement of diagonal ties	Mobile crane 300 MT	2	Cherry picker	2
Placement of long legs – upper legs LS	FCB 1800 MT	1	Cherry picker	2
Placement of horizontal ties	Mobile crane 300 MT	2	Cherry picker	2
A-frame	Mobile crane 70 MT	1	Lifting platform	2

Duration of securing a bolted connection amounts to 8 hours in total. The welded flange plate connection has a duration as stated in paragraph 4.6.

Appendix X Concept bolted flange plate cost

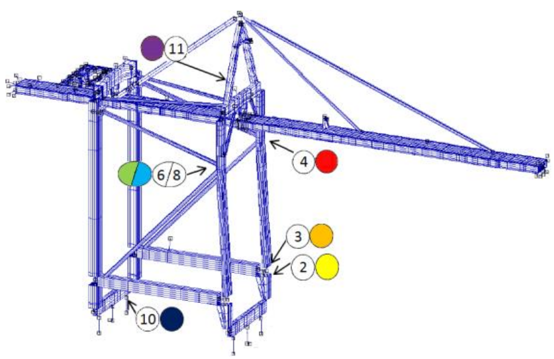
In Table X1 - X7 an overview is provided of which bolted flange plate cost are removed for each concept.

Table X1 Concept 1



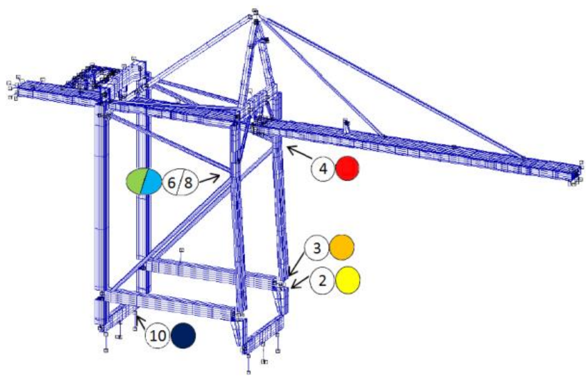
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
2	Lower leg to cross girder WS	3,300	2	6,600
	Cross girder to lower leg WS	3,800	2	7,600
	Lower leg to cross girder LS	2,900	2	5,800
	Cross girder to lower leg LS	2,900	2	5,800
3	Cross girder to long leg WS	2,600	2	5,200
	Long leg to cross girder WS	2,100	2	4,200
	Cross girder to long leg LS	2,800	2	5,600
	Long leg to cross girder LS	2,000	2	4,000
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
6	Diagonal tie to long leg WS	1,000	2	2,000
	Long leg to diagonal tie WS	900	2	1,800
8	Horizontal tie to upper leg WS	900	2	1,800
	Upper leg to horizontal tie WS	900	2	1,800
11	Portal beam onset to A-frame	1,500	2	3,000
	A-frame to portal beam onset	1,500	2	3,000

Table X2 Concept 2



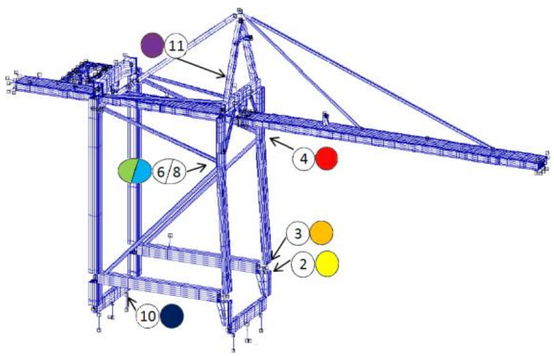
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
10	Sill beam to main balance WS	1,900	2	3,800
	Main balance to sill beam WS	1,900	2	3,800
	Sill beam to main balance LS	1,900	2	3,800
	Main balance to sill beam LS	1,900	2	3,800
2	Lower leg to cross girder WS	3,300	2	6,600
	Cross girder to lower leg WS	3,800	2	7,600
	Lower leg to cross girder LS	2,900	2	5,800
	Cross girder to lower leg LS	2,900	2	5,800
3	Cross girder to long leg WS	2,600	2	5,200
	Long leg to cross girder WS	2,100	2	4,200
	Cross girder to long leg LS	2,800	2	5,600
	Long leg to cross girder LS	2,000	2	4,000
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
6	Diagonal tie to long leg WS	1,000	2	2,000
	Long leg to diagonal tie WS	900	2	1,800
8	Horizontal tie to upper leg WS	900	2	1,800
	Upper leg to horizontal tie WS	900	2	1,800
11	Portal beam onset to A-frame	1,500	2	3,000
	A-frame to portal beam onset	1,500	2	3,000

Table X3 Concept 3



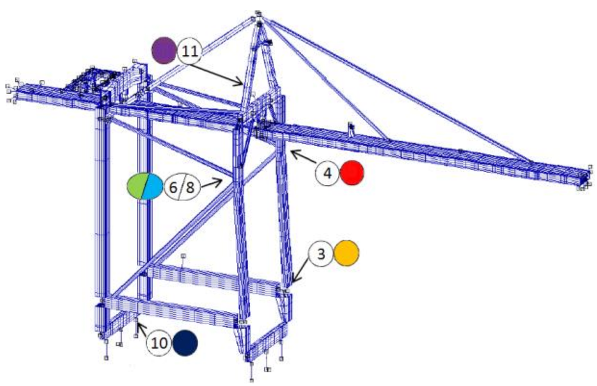
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
2	Lower leg to cross girder WS	3,300	2	6,600
	Cross girder to lower leg WS	3,800	2	7,600
	Lower leg to cross girder LS	2,900	2	5,800
	Cross girder to lower leg LS	2,900	2	5,800
3	Cross girder to long leg WS	2,600	2	5,200
	Long leg to cross girder WS	2,100	2	4,200
	Cross girder to long leg LS	2,800	2	5,600
	Long leg to cross girder LS	2,000	2	4,000
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
6	Diagonal tie to long leg WS	1,000	2	2,000
	Long leg to diagonal tie WS	900	2	1,800
8	Horizontal tie to upper leg WS	900	2	1,800
	Upper leg to horizontal tie WS	900	2	1,800

Table X4 Concept 4



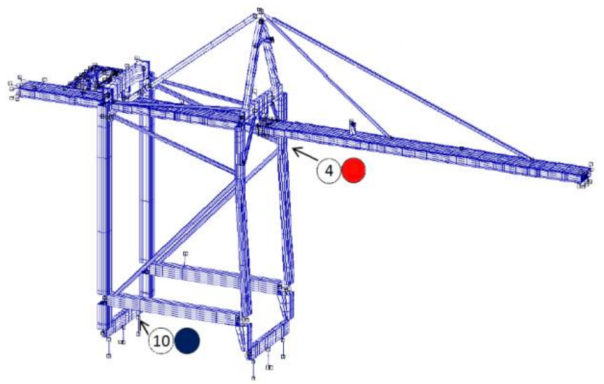
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
10	Sill beam to main balance WS	1,900	2	3,800
	Main balance to sill beam WS	1,900	2	3,800
	Sill beam to main balance LS	1,900	2	3,800
	Main balance to sill beam LS	1,900	2	3,800
2	Lower leg to cross girder WS	3,300	2	6,600
	Cross girder to lower leg WS	3,800	2	7,600
	Lower leg to cross girder LS	2,900	2	5,800
	Cross girder to lower leg LS	2,900	2	5,800
3	Cross girder to long leg WS	2,600	2	5,200
	Long leg to cross girder WS	2,100	2	4,200
	Cross girder to long leg LS	2,800	2	5,600
	Long leg to cross girder LS	2,000	2	4,000
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
6	Diagonal tie to long leg WS	1,000	2	2,000
	Long leg to diagonal tie WS	900	2	1,800
8	Horizontal tie to upper leg WS	900	2	1,800
	Upper leg to horizontal tie WS	900	2	1,800
11	Portal beam onset to A-frame	1,500	2	3,000
	A-frame to portal beam onset	1,500	2	3,000

Table X5 Concept 5



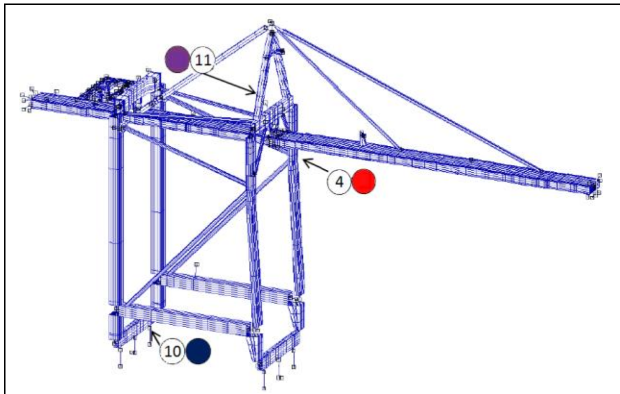
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
10	Sill beam to main balance WS	1,900	2	3,800
	Main balance to sill beam WS	1,900	2	3,800
	Sill beam to main balance LS	1,900	2	3,800
	Main balance to sill beam LS	1,900	2	3,800
3	Cross girder to long leg WS	2,600	2	5,200
	Long leg to cross girder WS	2,100	2	4,200
	Cross girder to long leg LS	2,800	2	5,600
	Long leg to cross girder LS	2,000	2	4,000
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
6	Diagonal tie to long leg WS	1,000	2	2,000
	Long leg to diagonal tie WS	900	2	1,800
8	Horizontal tie to upper leg WS	900	2	1,800
	Upper leg to horizontal tie WS	900	2	1,800
11	Portal beam onset to A-frame	1,500	2	3,000
	A-frame to portal beam onset	1,500	2	3,000

Table X6 Concept 6



Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
10	Sill beam to main balance WS	1,900	2	3,800
	Main balance to sill beam WS	1,900	2	3,800
	Sill beam to main balance LS	1,900	2	3,800
	Main balance to sill beam LS	1,900	2	3,800
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800

Table X7 Concept 7



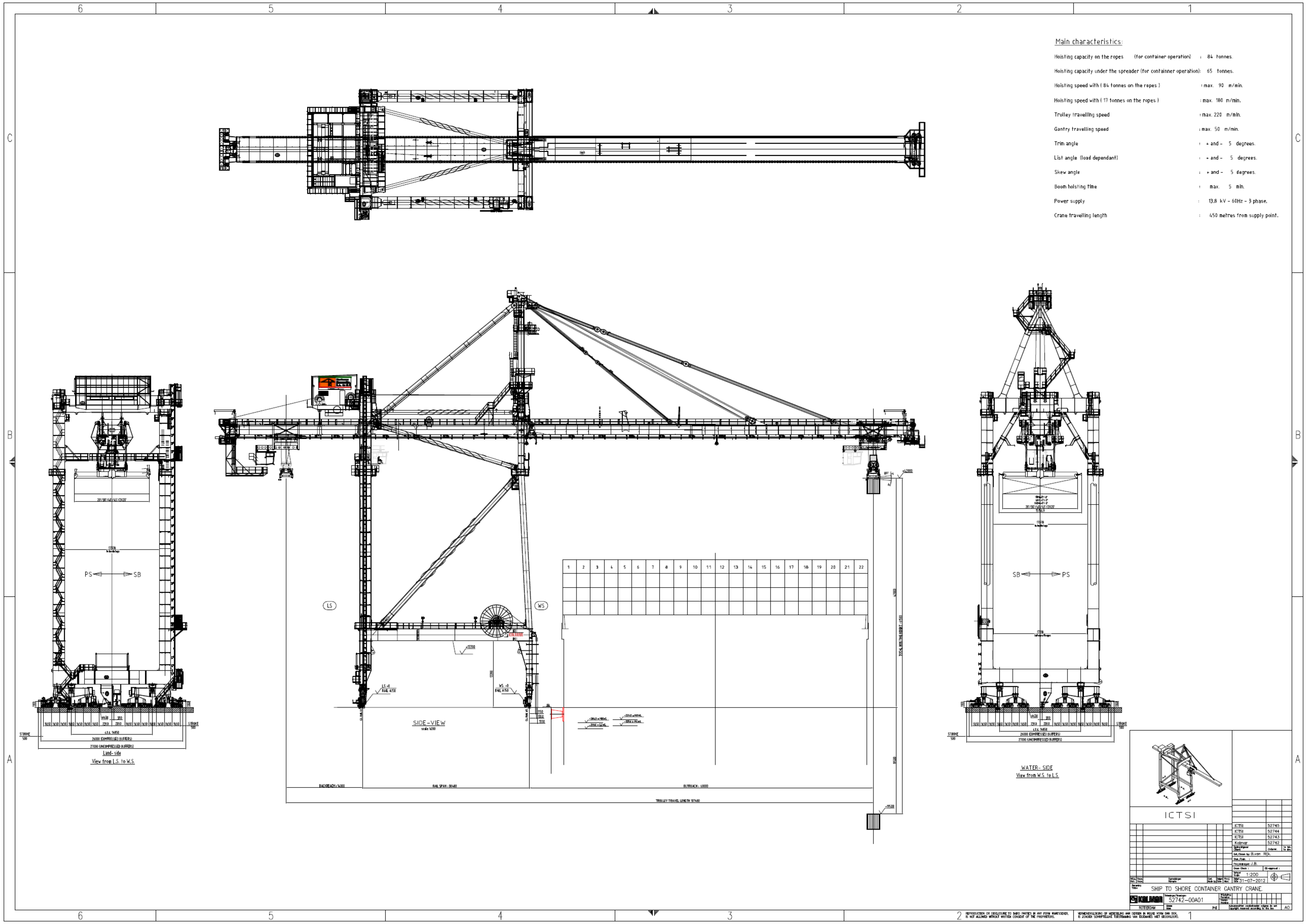
Connection no.	Connection description	Bolted flange plate cost [Euro]	Amount	Total cost [Euro]
10	Sill beam to main balance WS	1,900	2	3,800
	Main balance to sill beam WS	1,900	2	3,800
	Sill beam to main balance LS	1,900	2	3,800
	Main balance to sill beam LS	1,900	2	3,800
4	Long leg to upper leg WS	2,300	2	4,600
	Upper leg to long leg WS	2,400	2	4,800
	Long leg to upper leg LS	2,000	2	4,000
	Upper leg to long leg LS	1,900	2	3,800
11	Portal beam onset to A-frame	1,500	2	3,000
	A-frame to portal beam onset	1,500	2	3,000

Appendix Y Drawings

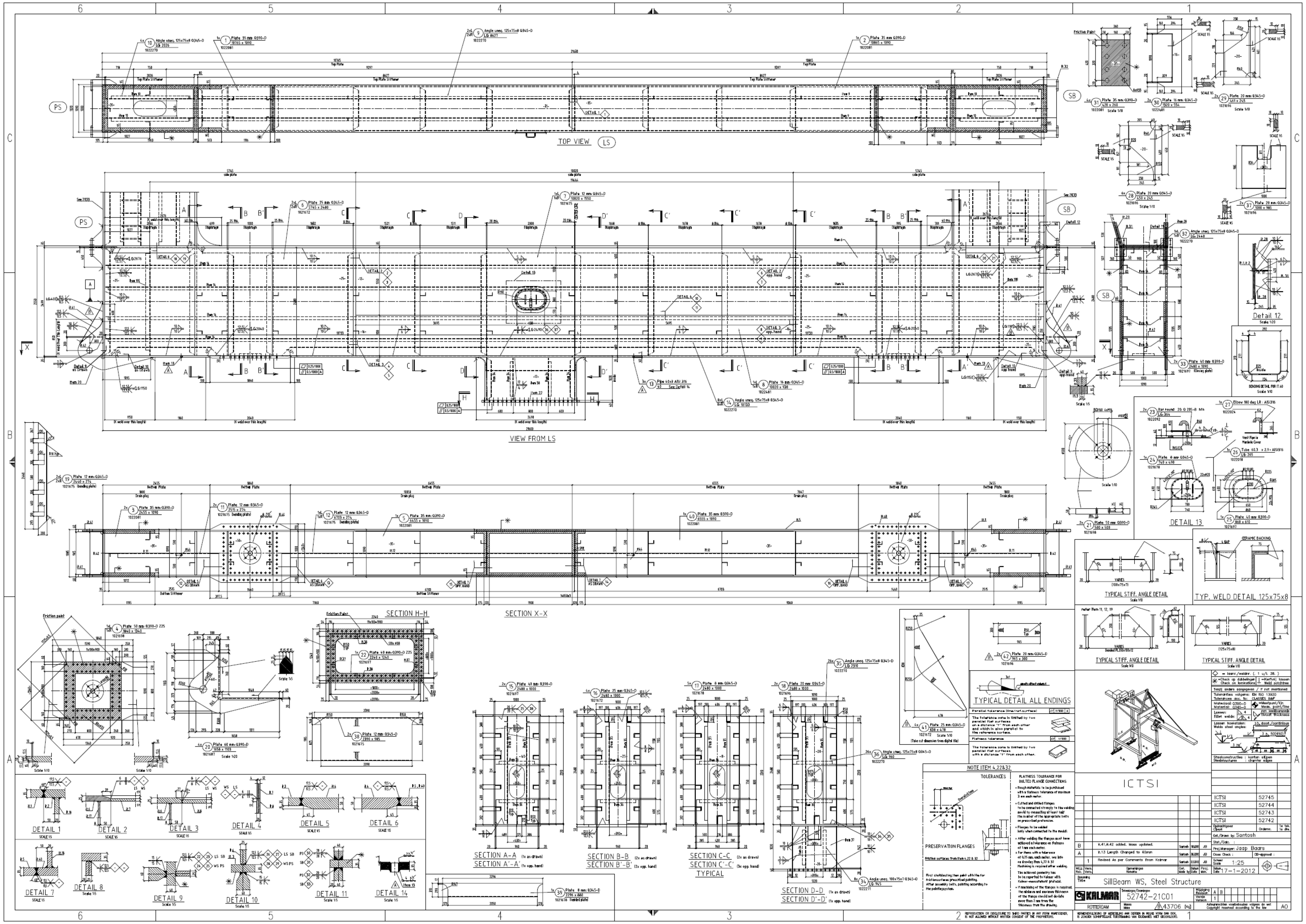
For the report the following drawings have been added:

1. General drawing of the case study Ship-To-Shore container gantry crane
2. Drawing of the sill beam WS
3. Drawing of the bogie set WS
4. Drawing of the open gearing models
5. Drawing of the production site
6. Drawing of Taicang Port assembly site
7. Drawing of RCI assembly site
8. Flange plate connection

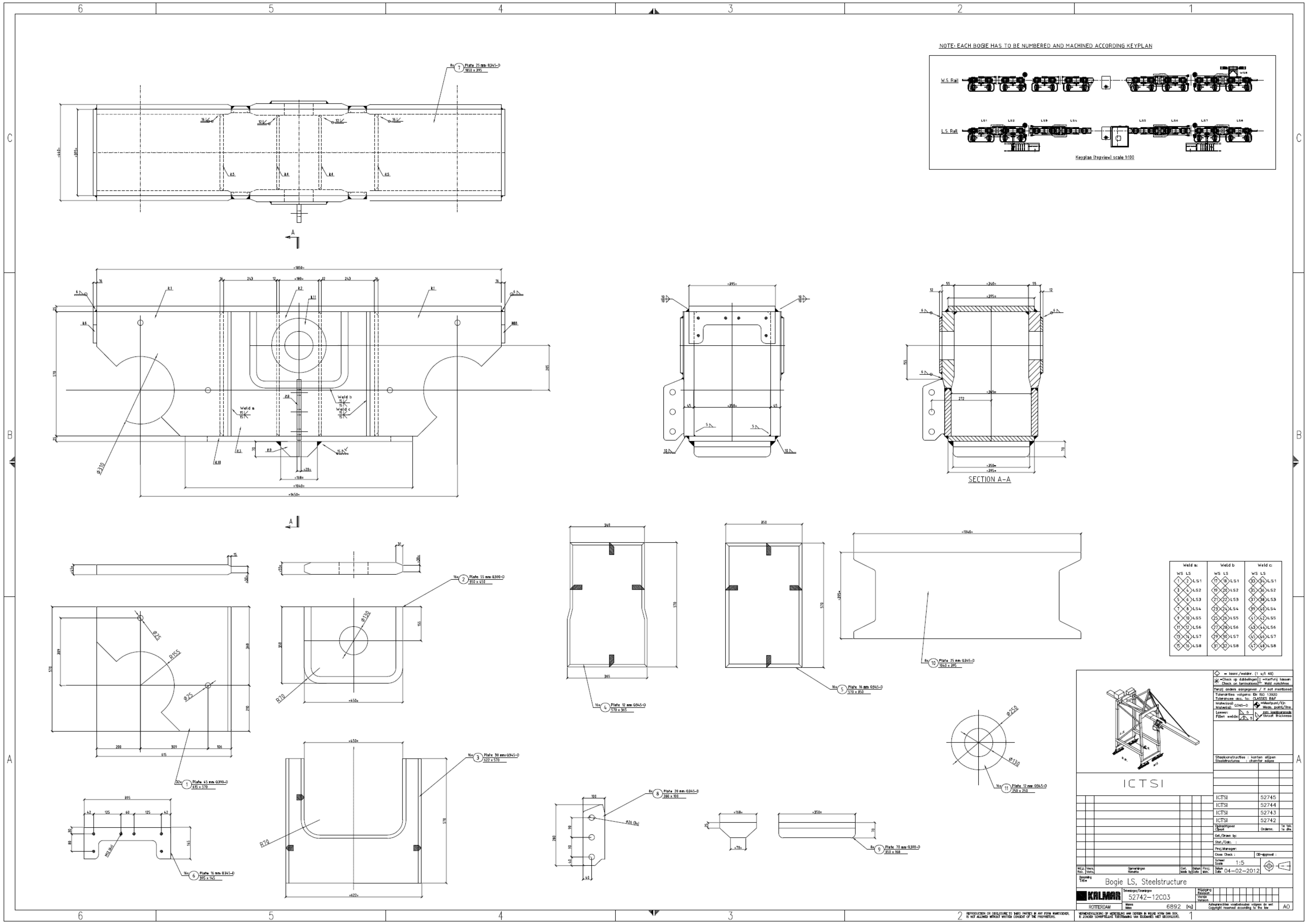
1 General drawing of the case study Ship-To-Shore container gantry crane



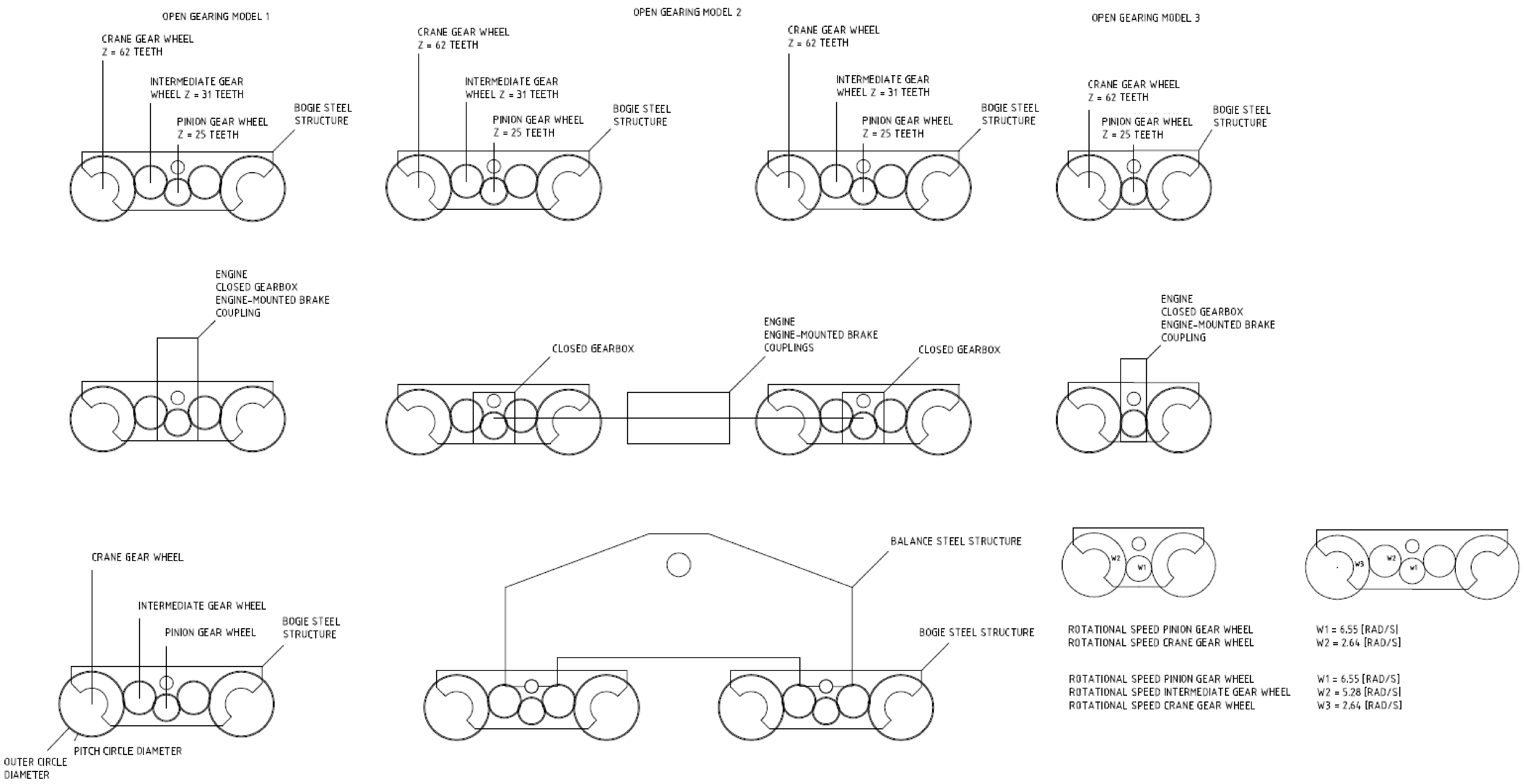
2 Drawing of the sill beam WS



3 Drawing of the bogie set WS



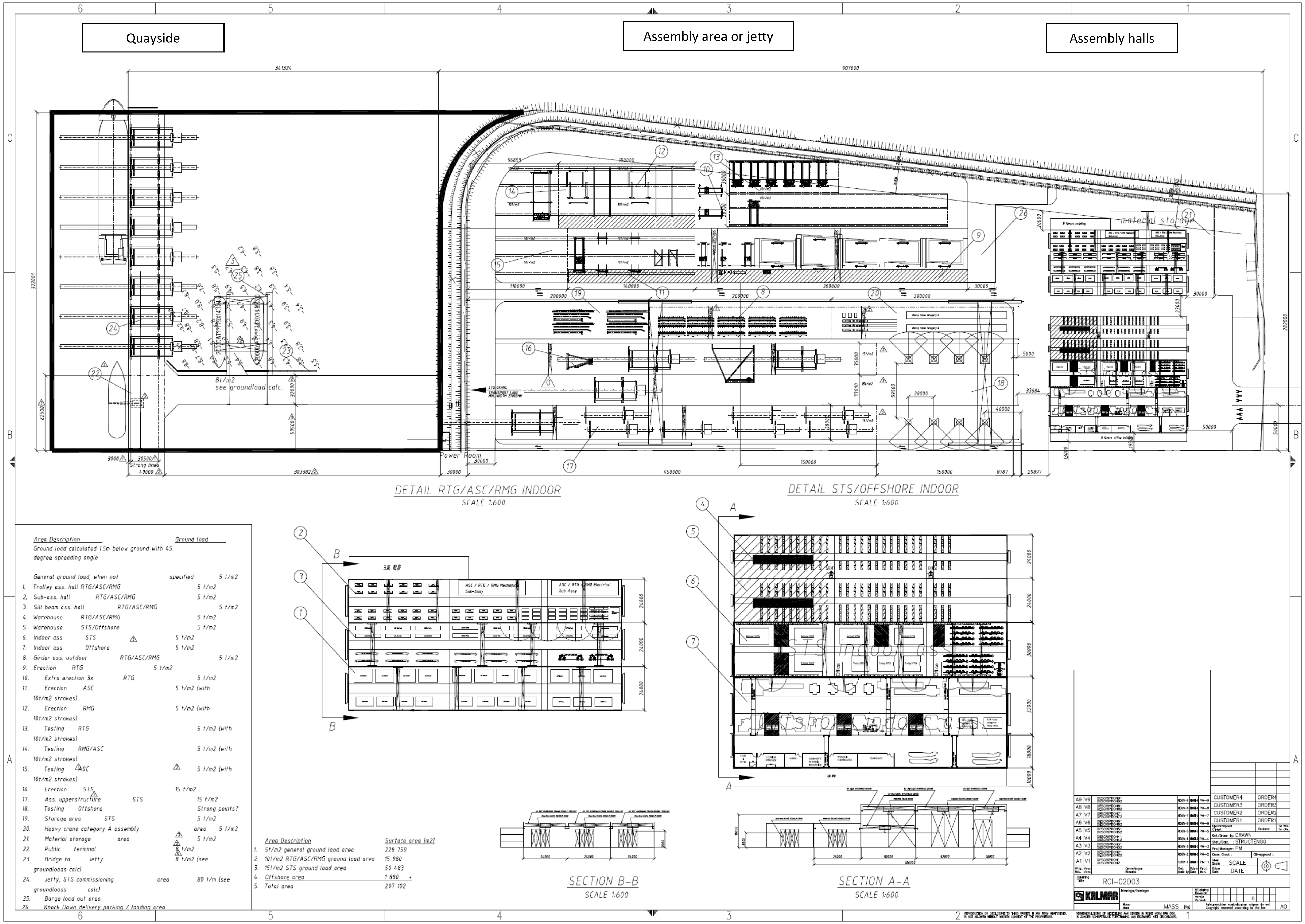
4 Drawing of the open gearing transmission



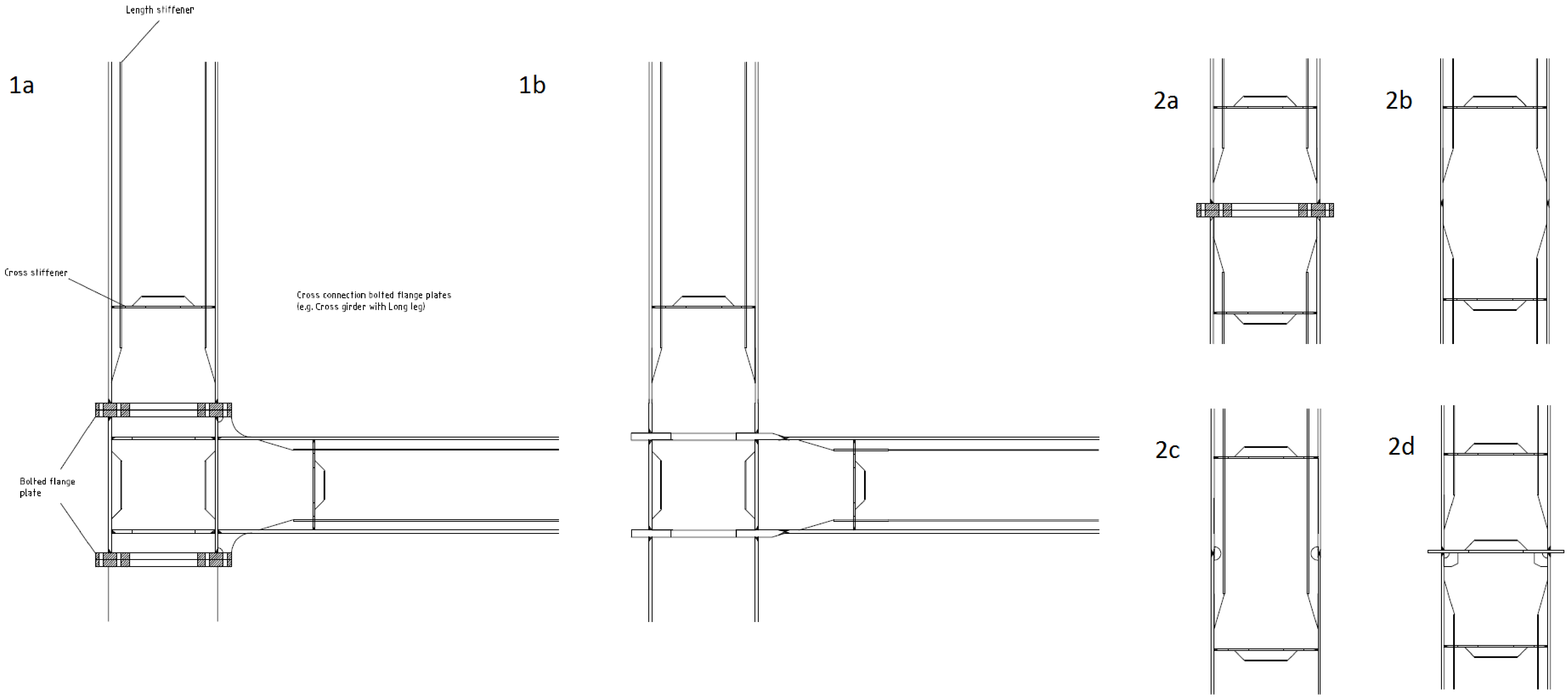
5 Drawing of the production site

6 Drawing of Taicang Port assembly site

7 Drawing of RCI assembly site



8 Welded flange plate connection



1a. Bolted flange plate connection, e.g. between the long leg and the cross girder

1b. Welded flange plate connection, e.g. between the long leg and the cross girder

2a. Bolted flange plate connection, e.g. between the long leg and the upper leg

2b. Welded connection, e.g. between the long leg and the upper leg (without flange plate)

2c. Welded connection, e.g. between the long leg and the upper leg (without flange plate, but with lengthened length stiffeners)

2d. Welded flange plate connection, e.g. between the long leg and the upper leg