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Performance prediction model for automated container yard cranes

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2018.TEL.8294

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Preface

This report is the result of a research assignment on the development of a new yard crane model that is able to accurately predict the container handling performance of an automated yard crane by taking automation systems into account as an important modeling parameter. The report is my thesis required for graduating for the master program Mechanical Engineering, section Transport Engineering and Logistics (TEL), at the Delft University of Technology.

The research assignment was initialized by the Cranes department of Siemens Netherlands N.V. in the Hague under the supervision of Douwe Wagenaar. I want to thank him on his active, continuous support and availability throughout the project. Insights from and continuous contact with employees from the Cranes department helped me form and execute the research assignment, therefore, I would like to thank Avinash Jangir and Niels Tanke.

I want to thank Yusong Pang for his role as daily supervisor from the TEL section, meetings and feedback on the project and progress helped me finishing the research assignment. I also want to thank Rudy Negenborn by providing accurate and critical feedback on the project during major milestones.

Nicolaas Thomas Jongbloed

The Hague, December, 2018

SIEMENS

Summary

Due to technological developments, there is an increasing degree of automation and complex interactions between container handling equipment operating throughout the container terminal. The demand for more accurate models of logistic operations has grown due to the increasing competitiveness between container terminals and high investment and operational costs involved. The performance of the container terminal is influenced most by the storage yard operational area. Automated yard cranes are often used as container handling equipment in storage yards on automated container terminals. The cycle time is a measurement of performance for yard cranes and depends on the performance of the equipped automation systems. Current yard crane performance prediction models do not take automation systems into account, this can result in a deviation between the predicted performance by the model and the operational performance by the automated yard crane. To avoid logistical and financial consequences, a new yard crane performance prediction model has to be developed that can take automation systems into account in order to accurately predict the performance of an automated yard crane.

A literature review on yard crane modeling concludes that there are multiple important modeling parameters that influence the performance prediction of yard crane models. Specifications of the storage yard regarding strategical design and operational planning decisions influence the cycle time of the yard crane. The block length, layout, container handling equipment type and configuration are an example of strategic design decisions. Operational planning decisions mentioned in literature are for example container stacking or crane scheduling strategies. Specifications of the yard crane such as acceleration, deceleration, container handling time and dead time influence the performance prediction of yard crane models. Automation systems were not mentioned in the reviewed literature as an important yard crane modeling parameter.

A new yard crane model is developed that can predict the performance of automated yard cranes based on requirements from literature and experience from Siemens Cranes. The new developed model consists of an operational sequence that represents the container handling cycle of a yard crane. The operational sequence is modularly built from configurable process blocks including automation systems. Depending on the type of crane and job to be executed, the operational sequence can be modified and process blocks can be configures to the required level of detail. Including automation systems in a yard crane model is new, the model is verified using a reference case.

The reference case is regarding a project executed by Siemens Cranes for which automated rail mounted gantry cranes have to be delivered for a storage yard in a container terminal. Since the project is in a commissioning phase, the operational data available was regarding performance tests were shuffle jobs have been executed by the automated yard crane. During verification, assumptions were made for two process blocks including hoist movement of a loaded spreader according to the hoist movement process block of an empty spreader. Other jobs were analyzed for verification so that the performance prediction accuracy of the new developed yard crane model could be compared with the operational performance of the automated yard crane from the reference case.

To determine the performance prediction accuracy of the new developed yard crane model, 216 shuffle jobs executed by the automated yard crane from the reference case are analyzed and used as an input for an experiment. The predicted performance by the new developed yard crane model deviated less than 3% compared with the operational performance of the automated yard crane. To put this into perspective, two competitive yard crane models that do not include automation systems, as described in literature, are also used to predict the performance of the same 216 shuffle jobs. The predicted performance of the two models were more than 30% and 80% higher than the operational performance of the automated yard crane from the reference case. A sensitivity analysis is executed for the three yard crane models to analyze the uncertainty of the performance prediction output regarding the uncertainty of the process block parameter input values.

It was expected that taking automation systems into account is essential when using a yard crane model for the performance prediction of an automated yard crane. The hypothesis is confirmed by the results of comparing the performance prediction of current yard crane models described in literature that do not take automation systems into account with the new developed model regarding the operational performance of the automated yard crane. The new yard crane model can be used for any type of container crane and for any type of job since the operational sequence is modularly built from configurable process blocks. The new model can be used for various studies on logistic problems in the storage yard and container terminal involving automated yard cranes.

Samenvatting

Als gevolg van technologische ontwikkelingen neemt de automatiseringsgraad en complexiteit van interacties tussen de opererende elementen op een container terminal toe. De vraag naar meer accurate modellen voor logistieke processen op container terminals groeit door de competitiviteit tussen container terminals door hoge investerings en operationele kosten. De productiviteit van een container terminal wordt het meest beïnvloed door de prestatie van de processen binnen de containerwerf. Automatische containerkranen worden vaak gebruikt op containerwerven van automatische container terminals. De cyclustijd van een containerkraan wordt gebruikt als maatstaaf voor de productiviteit en is afhankelijk van de geïnstalleerde automatiseringssystemen. Desondanks hebben huidige containerkraanmodellen, die gebruikt worden om de productiviteit te voorspellen, geen mogelijkheid om automatiseringssystemen te implementeren. Dit kan resulteren in een verschil tussen de voorspelde productiviteit door het model en de operationele productiviteit van de automatische containerkraan. Om logistieke problemen en financiële consequenties te vermijden moet er een nieuw containerkraanmodel ontwikkeld worden met de mogelijkheid om automatiseringssystemen te implementeren zodat er nauwkeurigere productiviteitsvoorspellingen gemaakt kunnen worden met betrekking tot automatische containerkranen.

Een literatuuronderzoek op het modeleren van containerkranen concludeerde dat er meerdere belangrijke parameters zijn die invloed hebben op de productiviteitsvoorspellingen van containerkraanmodellen. Specificaties van de containerwerf met betrekking tot het strategische ontwerp en operationele planning hebben invloed op de cyclustijd van een containerkraan. De grootte en de lay-out van de containerwerf maar ook het type containerkraan en de configuratie zijn voorbeelden van strategische ontwerpkeuzes. Operationele planning keuzes zijn bijvoorbeeld gericht op container stapelstrategieën of het coördineren van containerkraaninzet. Er zijn ook specificaties van de containerkraan die invloed hebben op de cyclus tijd zoals versnelling, vertraging, containerverwerkingstijd en tijdsverliezen. In het literatuuronderzoek zijn automatiseringssystemen als belangrijke modelparameters niet gevonden.

Een nieuw containerkraanmodel is ontwikkeld welke gebruikt kan worden voor productiviteitsvoorspellingen van automatische containerkranen volgens de eisen opgesteld vanuit de literatuur en ervaring van Siemens Cranes. Het nieuw ontwikkelde model bestaat uit een operationele procesvolgorde wat de cyclustijd van een containerafhandeling van een containerkraan representeert. De operationele procesvolgorde is modulair opgezet uit configureerbare procesblokken van mechanische en automatiseringssystemen. Afhankelijk van het type containerkraan en opdracht kan zowel de operationele procesvolgorde aangepast worden als de procesblokken afhankelijk van het gewenste niveau van detail. Het implementeren van automatiseringssystemen is nieuw en het ontwikkelde containerkaanmodel is geverifieerd door middel van een referentieproject.

Het referentieproject, uitgevoerd door Siemens Cranes, betreft het opleveren van automatische containerkranen voor een container terminal. Omdat het project zich bevindt in een inbedrijfstellingsfase was de operationele data beschikbaar van productiviteitstesten van uitgevoerde opdrachten binnen de containerwerf door de automatische containerkraan. Tijdens de verificatie zijn er aannames gemaakt voor twee procesblokken gerelateerd aan het hijsen en vieren van een geladen spreader volgens de procesblokken voor het hijsen en vieren van een ongeladen spreader. Andere uitgevoerde opdrachten zijn geanalyseerd zodat de nauwkeurigheid van de productiviteitsvoorspellingen van het nieuw ontwikkelde containerkraanmodel vergeleken kunnen worden met de operationele productiviteit van de automatische containerkraan uit het referentieproject.

Om de nauwkeurigheid van de prestatievoorspellingen van het nieuw ontwikkelde containerkraanmodel te bewijzen is de input van 216 uitgevoerde opdrachten door de automatisch containerkraan van het referentieproject geanalyseerd en gebruikt als invoer voor een experiment. De voorspelde productiviteit door het nieuwe containerkraanmodel week minder dan 3% af vergeleken met de operationele productiviteit van de automatische containerkraan. Om dit in perspectief te plaatsen zijn er ook twee

competitieve containerkraanmodellen, zonder implementatie van automatiseringssystemen zoals beschreven in de literatuur, gebruikt om de productiviteit te voorspellen volgens dezelfde 216 uitgevoerde opdrachten. De voorspelde productiviteit door deze twee modellen was meer dan 30% en 80% hoger dan de operationele productiviteit van de automatische containerkraan uit het referentieproject. Een sensitiviteitsanalyse is uitgevoerd voor de drie containerkraanmodellen om de onzekerheid van de productiviteitsvoorspellingen in relatie met de onzekerheid van de invoerwaarde van de procesblokparameters te analyseren.

Het was verwacht dat het implementeren van automatiseringssystemen in containerkraanmodellen essentieel is wanneer zulke modellen gebruikt worden voor het voorspellen van de productiviteit van een automatische containerkraan. De hypothese is bevestigt door de resultaten van de productiviteitsvoorspellingen van huidige containerkraanmodellen, zonder implementatie van automatiseringssystemen zoals beschreven in de literatuur, te vergelijken met het nieuw ontwikkelde containerkraanmodel met betrekking tot de operationele productiviteit van de automatische containerkraan. Het nieuwe model kan ingezet worden voor elk type containerkraan voor elk type opdracht omdat de operationele procesvolgorde modulair opgezet is met configureerbare procesblokken. Ook kan het gebruikt worden voor verschillende onderzoeken op logistieke problemen in de containerwerf en container terminal waarbij automatische containerkranen betrokken zijn.

Het nieuw ontwikkelde model bewees meer accuraat te zijn in het voorspellen van de productiviteit van een automatische containerkraan van het referentieproject vergeleken met de voorspelde productiviteit van de twee andere modellen volgens de literatuur. De hypothese is bevestigd door de resultaten van de vergelijking tussen de drie containerkraanmodellen en de automatische containerkraan van het referentieproject. Het nieuwe model kan gebruikt worden voor elk type kraan en opdracht doordat de operationele procesvolgorde modulair is opgezet door gebruik te maken van configureerbare procesblokken.

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List of definitions and abbreviations

Definition	
Bay	The container storage position in a block parallel to the gantry movement
Block	One container storage area in the storage yard, consists of bay, rows and tiers
Cycle time	The time required by a yard crane in order to complete a container handling move
Dead time	The combination of start delay and fine positioning time
Job	A container handling move
Operational sequence	Sequence of process blocks used to determine the cycle time
Parameter	An input required for a process block
Process block	A modeled subprocess used in the operational sequence
Row	The container storage position in a block parallel to the trolley movement
Tier	The container storage height in a block
Yard	The container storage area on a container terminal, consists of one or multiple blocks

Abbreviation	
ARMG	Automated rail mounted gantry crane
ASC	Automated stacking crane
ATDIS	Automatic truck identification system
CLPS	Chassis lifting prevention system
CTDS	Container twistlock detection system
FLS	Final landing system
LCPS	Load collision prevention system
m/h	Moves per hour
MMS	Micro motion system
RMG	Rail mounted gantry crane
RTG	Rubber tired gantry crane
SPMS	Spreader position monitoring system
STS	Ship to shore
TEU	Twentyfoot equivalent unit
TOS	Terminal operating system
TPS	Truck positioning system

Contents

1 Introduction

A container terminal serves as a connecting link between different modes of container transportation (truck, rail, ship) [1]. A port container terminal consists of three main areas, the quayside area, the hinterland area and the storage yard area [2] as schematically visualized in Figure 1.

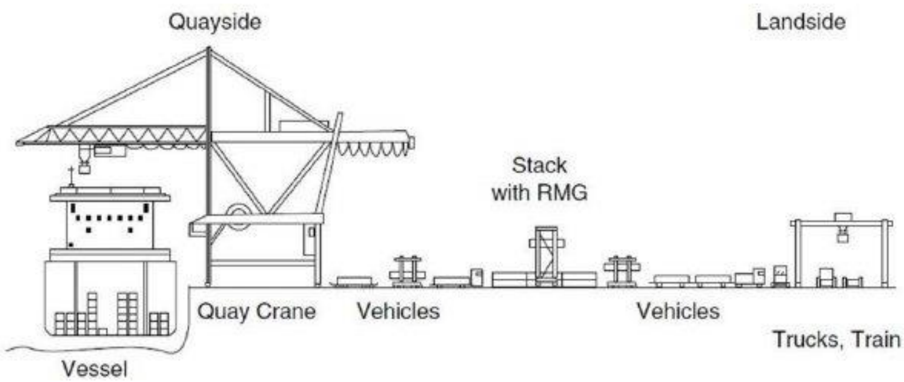

Figure 1 Schematic sideview of a container terminal showing the quayside, storage yard and landside operational areas [2]

Due to technological developments, there is an increasing degree of automation and complex interaction between elements operating throughout the whole container terminal [3]. The demand for more accurate models of container terminal operations has grown due to the increase competitiveness between container terminals and high investment and operational costs involved [4]. The performance of the container terminal is often measured in quay productivity, it is however mostly influenced by the storage yard area [5]. An automated container terminal system in operation can be seen in Figure 2. In this figure, five ship-to-shore (STS) cranes serve one berthed container ship and multiple container storage yard blocks, or also referred to as blocks, are positioned perpendicular to the quay with two cranes operating on one block.

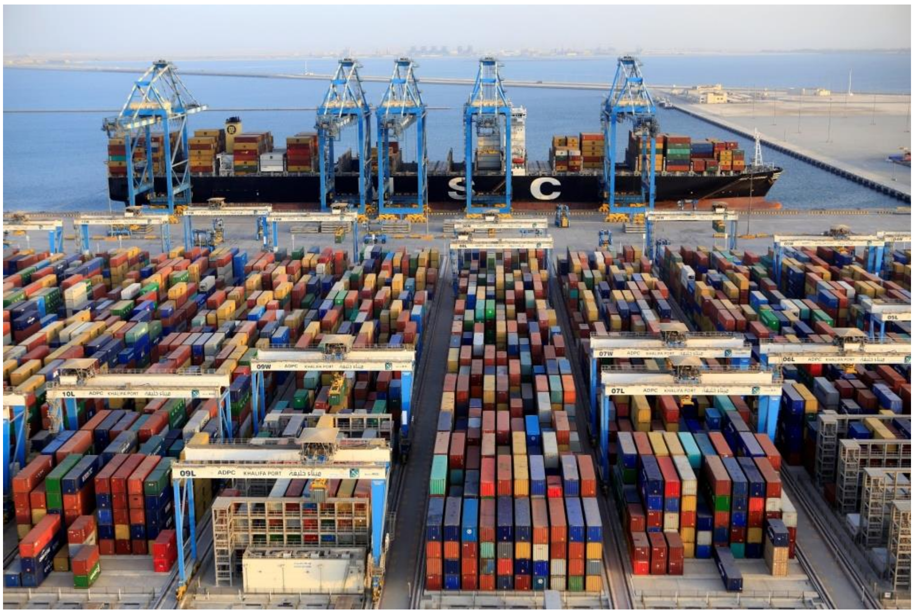

Figure 2 Khalifa port container terminal in Abu Dhabi [6]

1.1 Yard crane modeling

A storage yard consists of multiple blocks with a number of bays, rows and tiers in which containers are stored in length, width and height. Yard cranes operating on these blocks are responsible for storage and retrieval of containers in the block. The three main moving components are the portal of the gantry, the trolley and the spreader which are used to move to different bays, rows and tiers as shown in Figure 3.

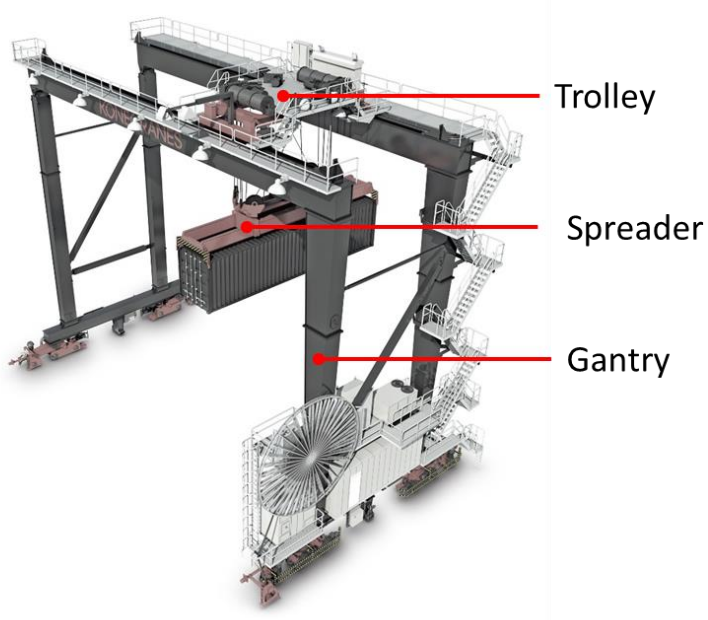

Figure 3 An automated rail mounted gantry crane with the three main moving components highlighted [7]

The performance of a manual yard crane not only depends on the crane specifications but also on the skill of the operator. An automated yard crane is not operated by an operator and therefore requires automation systems in order to operate, the performance of an automated yard crane is not only depending on the crane specifications, but also on the performance of the automation systems.

Various yard crane models are used with varying levels of detail for different logistical studies on container terminals. For example, some models only use the gantry component in combination with a container handling time to model a yard crane. More extensive yard crane models also include the trolley and hoist component of a yard crane and taking acceleration and deceleration into account. A model can be simplified by excluding the trolley and hoist component or accelerations and decelerations, this is often compensated by introducing a lower movement speed or a longer process time for a container handling.

One of the purposes of a yard crane models is to predict the container handling performance of a yard crane, the performance of a yard crane is measured in moves per hour and can be calculated by the cycle time. The cycle time is the time required for a yard crane to handle one container which is based on four basic major processes, an empty move to the container pickup location, picking up the container, a loaded move to the container drop-off location and placing down the container.

1.2 Siemens Cranes

Siemens Netherlands N.V. located in The Hague in The Netherlands includes a Cranes department. Siemens Cranes develops and engineers solutions for container transport equipment operating at a container terminal, for example, STS-cranes, AGV's and ARMG's. The mechanical design and construction of these equipment is handled by a contractor operating for the container terminal operator. Siemens Cranes equips the developed product of the contractor with Siemens equipment such as motors, drives, controls and other electrical equipment. Besides working with the contractor, Siemens Cranes has contact with the container terminal operator.

When a new project is initialized by a container terminal operator, Siemens Cranes offers their engineered solution regarding predicted cost and performance. If the offer of Siemens Cranes is accepted, it has to be proved in practice that the performance of the system matches the predicted performance offered in advance. The performance of the yard crane in practice is tested by measuring the time it takes to complete an agreed sequence of jobs executed by the yard crane. If the performance of the yard crane in practice cannot be proved, there may be logistical problems since the storage yard is connected to both the quayside and landside transport chain which will result in financial consequences for Siemens Cranes.

Current performance prediction models for yard cranes used by Siemens Cranes do not suffice anymore due to the increasing degree of complexity due to automation and interconnectivity. A new yard crane performance prediction model is required by Siemens Cranes that includes this level of complexity so that the performance of yard cranes can be predicted more accurately in advance.

1.3 Problem statement

The current technological development in container terminals regarding automated container handling equipment is not adapted by yard crane models currently used for various logistical studies on container terminals. Automation systems are not taken into account into these models and are also impossible to implement. As the performance of the automated yard crane is influenced by the performance of the equipped automation systems, it is assumed that it is necessary to take automation systems into account when modeling an automated yard crane. Taking automation systems into account in yard crane models can influence the accuracy of the results of various logistical studies on container terminals regarding automated yard cranes.

Using current yard crane models to predict the performance of an automated yard crane systems in advance may result in a deviation compared to the measured performance of the automated yard crane in practice. A deviation between the predicted performance from the yard crane model and the measured performance of the automated yard crane in practice can result in logistical consequences. Since the storage yard has the most influence on the container terminal performance, the deviation can also result in logistical problems in the quayside and the landside operational areas. Delays in the landside and quayside operational area can result in financial consequences since, for example, the handling of a container ship is delayed.

Current yard crane models lack complexity on automation details and are unable to be used for modeling automated yard cranes. A new yard crane model is required that can cope with current ongoing developments on container terminals regarding automation. With this new yard crane model, logistical processes on container terminals can be studied more accurately. The performance I practice of automated yard cranes can be predicted more accurately which will benefit the logistical chain throughout the complete container terminal.

1.4 Research objective

The objective of this research is to develop a new yard crane model for automated yard cranes and to indicate the importance of introducing automation systems in yard crane models. This can be achieved by comparing the performance prediction of the new developed model with the performance of an automated yard crane from practice as well as current yard crane models used in literature.

It is expected that including automation systems in yard crane models is essential when the model is used to predict the performance of an automated yard crane from practice in advance. The predicted performance will be more accurate than current yard crane models in terms of cycle time.

The research question to be answered is:

- What is the influence of taking automation systems into account in yard crane models on the container handling performance prediction of automated yard crane systems?

The answer to the research question is supported by the answers on three sub questions. A chapter on theory and literature review will answer the first sub question, an answer to the second sub question is found in the following chapter automated yard crane model, the last chapter on model performance prediction will answer the third and final sub question.

1. What are the important modeling parameters that influence the performance prediction of a yard crane model?
2. How to develop a verified new yard crane model including all important modeling parameters and automation systems for an automated yard crane?
3. What is the performance prediction difference of the new developed model compared to the current state of yard crane modeling?

1.5 Methodology

Literature will be studied first to review the important modeling parameters that influence the performance prediction of a yard crane model.

The results of the literature review and experience from Siemens Cranes are the combined to set up requirements for the new yard crane model that will be developed. The four basic major processes to complete a crane cycle are worked out in more detail in the form of subprocesses. The process times for these subprocesses are determined and modeled in process blocks, the process blocks are then connected together in an operational sequence which will represent the new performance prediction model. Using the practical data from a reference case, a project executed by Siemens Cranes regarding automated yard cranes, the new developed model will be verified.

The performance prediction of the new developed yard crane model will be compared with the operational performance of an actual automated yard crane from the reference case to determine the accuracy. To answer the research question, the performance prediction of the new developed model is also compared to current yard crane models used in logistic studies on the container terminal as described in literature. Finally, a sensitivity analysis is executed to identify the sensitivity of the performance prediction in relation with the sensitivity of various input parameters and values.

1.6 Structure of the report

The report begins with a chapter on theory and literature review in which a small background on container terminals and the importance of the storage yard is given. In this chapter, the important modeling parameters that influence the performance prediction of a yard crane model are examined. The cycle time as a measurement of performance for yard crane models is elaborated as well.

The following chapter, chapter 3, covers the development process of the new yard crane model including automation systems starting with a description of the requirements and the reference case. The setup of the process blocks is then elaborated and the operational sequence is modeled using these process blocks. To end this chapter, the new developed model is verified using the reference case.

Chapter 4 starts with a setup of the comparison between the performance prediction of the new developed model and the operational performance of an automated yard crane from the reference. This setup also describes the comparison of the performance prediction of the new developed model with the yard crane models currently used in logistic studies on the container terminal as described in literature. The last part described in the setup is the sensitivity analysis to identify the sensitivity of the performance prediction in relation with the sensitivity of various input parameters and values. The results of the comparisons and sensitivity analysis are then described in a paragraph followed by a discussion on the results.

The report ends with a chapter on conclusions and recommendations.

2 Theory and literature review

In this chapter, a small paragraph describing developments in containerized transportation is covered first. The container terminal as a system is mentioned briefly after which a scope is made on the container terminal storage yard and yard crane. The important modeling parameters that influence the performance prediction of a yard crane model are described which will be used in the following chapter on developing a new yard crane model.

2.1 Developments in containerized transportation

Kim and Gunther [1] provide a short summary of the history of containerized transportation by explaining that containers represent the standard unit load device for intercontinental maritime freight transport since the 1960s. A container terminal serves as a connecting link between different modes of transportation (truck, rail, ship). With manufacturers producing goods for global use, the use of containerized transportation continuously increases. The number and capacity of container terminals increases as a consequence. In countries with high labor costs, this means that there is a demand for container terminal configurations which uses automated container handling and transporting equipment to compete with other container terminals. Productivity within container terminals increased because of more advanced terminal layouts and improved logistics control software systems.

What is also mentioned by Kim and Gunther [8] is the effect of the continuous growth of containerized transportation. The size of container ships continuously increases to benefit from the economy of scale. These container ships require a large capital investment and daily operational costs which makes the customer support of a container terminal important and therefore many container terminals decrease the ships turnaround time. Issues related to container terminal operations have been neglected in the academic world for a long time. Due to the increasing importance of containerized transportation and competition between container terminals, operations research problems in container terminals are picked up by the academic community.

Stahlbock and Voß [3] note that the increasing importance of optimizing the logistic operations at a seaport container terminal is indicated by the growth of the number of theoretical and practical oriented papers. As mentioned before, to reduce the unproductive operations is essential for the container terminal operational efficiency and the competitiveness. Keys to efficiency seem to be the automation of in-yard transportation, storing and stacking as well as the application of optimization methods. Competitiveness of a container terminal includes the waterside operation, internal logistics and the landside operations with the transport connection to the hinterland. The high investments as well as high operating costs for ships and port equipment necessitate improvements of terminal operations. Despite simplifications, the models for the optimization problems remain complex. The models can help gaining insight of the container handling processes and problems within the container terminal system but it is extremely difficult to solve practical problems due to their complexity.

Angeloudis and Bell [4] state that when taking the size of investments involved, it is important for container terminals that the quality of the proposed solutions that will be implemented can be ensured and that the risk of design problems that will affect the operational efficiency is minimized. Regardless of the high theoretical operational efficiency of individual equipment, the performance can be constraint by human factors or interactions with other equipment at the container terminal. It is therefore important to study a container terminal as a large complex system, not as simply as the sum of its equipment, the use of computer simulation is a suitable approach for these studies. Simulation models have been developed for use by container terminal operators but only with a limited amount of relevant information being available in the public domain. Simulation technology is now often viewed by container terminal operators to streamline operations and competitiveness. As a result, industrial efforts in this domain are frequently bound by confidentially agreements.

2.2 The container terminal system

Steenken et al. [2] describes a container terminal as an open system of material flow with two external interfaces. One external interface at the quayside with loading and unloading of ships and a second at the landside where containers are loaded and unloaded on and off trucks and trains. A container ship is, when arriving at a container terminal, assigned to a berth equipped with cranes which load and unload the containers. The unloaded import containers are transported to the storage yard by horizontal transport equipment where they will be stored according to the next transshipment. Export containers arrive by truck or rail and are temporarily stored in the storage yard from where they will be picked up and loaded on the container ship. The system as described is visualized in Figure 4.

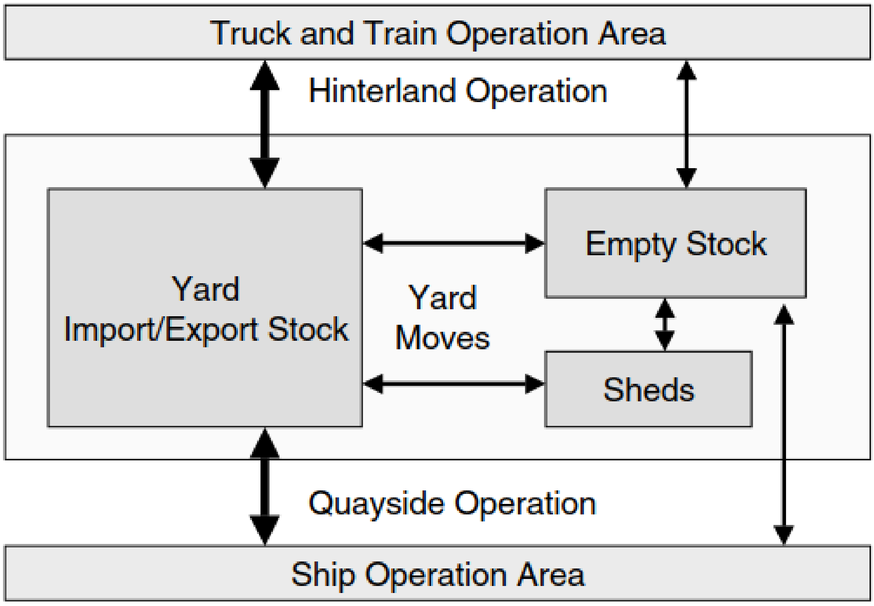

Figure 4 Diagram of operational areas and flow of transports on a container terminal [2]

Wiese et al. [9] splits the container terminal in three major areas, the seaside, landside and storage area which is according to the main three operational areas mentioned by Steenken et al. [2], a schematic top view of a container terminal is shown in Figure 5. Steenken et al. [2] also mentions that the type of container terminal is based on the combination of the container handling equipment. The combination of container handling equipment on a container terminal depends on several factors based on space restriction and economic reasons.

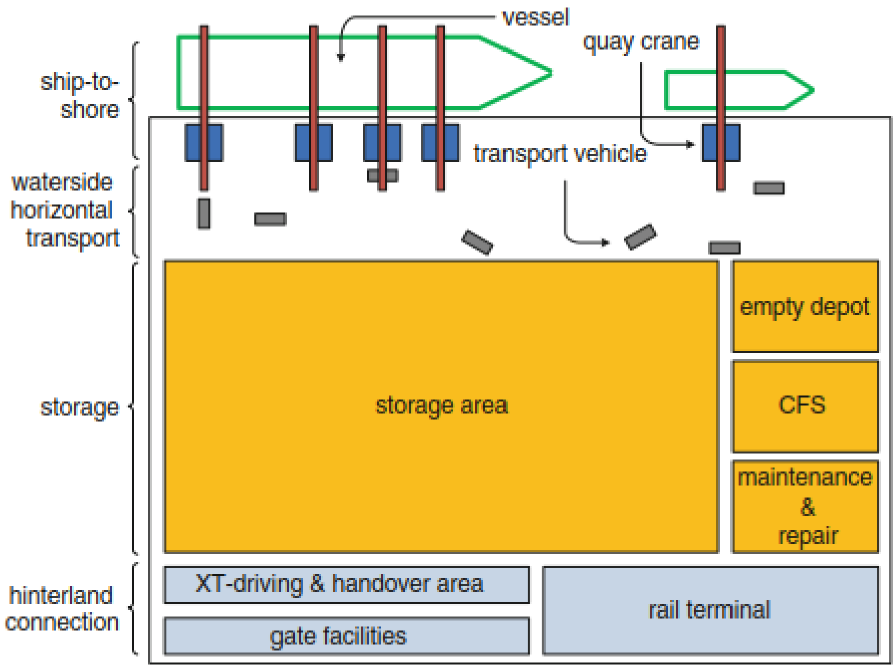

Figure 5 Schematic top view of a container terminal [5]

Kemme [5] elaborates that most automated container terminals use automated container handling equipment for the transport operations between the quay cranes and the storage yard as well as for the internal storage yard operations. The storage yard plays an important role since this is the central part of the container terminal in a geographical and processual point of view. It is also the interface between seaborne and continental transport chains. Most of the container terminal operations are affected by the storage yard operations which makes the container terminal operational efficiency dependent on the performance of the storage yard, nevertheless, the container terminal performance is measured in quay crane productivity or vessel turnaround time.

As stated by Kemme [5], the storage yard is one of the most important subsystem of the container terminal since it is the connection between the waterside and landside container transportation chain. The importance of this subsystem has also grown due to increased container volumes have to be stored in storage yards while space is an increasingly scarce resource. Stacking containers on the ground is the most common technique to store containers. A storage yard consists usually of multiple blocks, one block consists of multiple bays, rows and tiers. The number of bays, rows and tiers depend on the container handling equipment. Usually, blocks are dedicated to attributes of a container such as import, export, transshipment, empty, damaged, etc. Within a block, several bays are often dedicated to different container types such as refrigerated or 20 feet containers. Note that not every container is directly accessible and different container handling equipment with different configurations are used on blocks. A block positioned perpendicular or parallel to the quay are the two most common used block layouts, automated container terminals often use the perpendicular block layout. An schematic overview of a block with a yard crane is displayed in Figure 6.

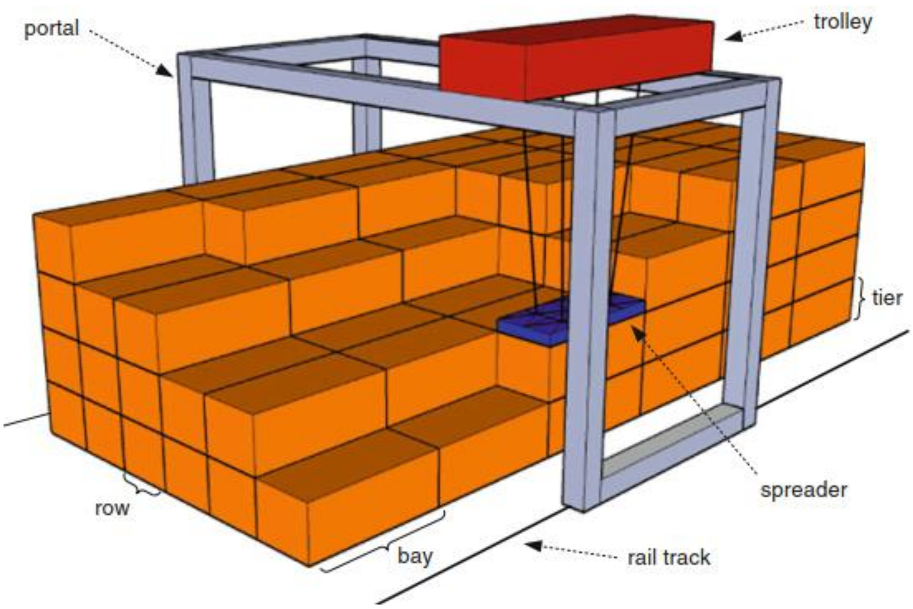

Figure 6 Schematic overview of a yard crane system on a storage yard block, the portal moves on a rail track and supports a trolley, a spreader is suspended from the trolley which can connect to a container [5]

There are different container handling equipment operating at blocks such as straddle carriers, gantry cranes, forklifts and reach stackers. The gantry crane is often used in automated container terminals as an automated storage yard crane. The three main parts of a gantry crane are the portal, the trolley and the spreader as shown in Figure 6. The portal allows for movement along bays and supports the trolley and can be designed with an outreach or cantilever to serve horizontal transport on the truck lane outside the gantry portal ‘legs’. The trolley can move over the portal to reach each row in the block, simultaneous gantry and trolley movement can be used. The spreader is suspended from the trolley using a hoist system, a container can be locked to the spreader in order to process a container. Adjustable spreaders are used that can handle all container sizes or handle two 20 foot containers at the same time. The performance of a crane is measured in container handlings or moves per hour (m/h) and is often referred as to the cycle time.

2.3 Yard crane cycle time

The performance of a yard crane is measured in terms of cycle time, the time it takes for a yard crane to complete one container move. The cycle is based on a sequence of operational processes. Multiple descriptions of the cycle time are found in literature.

Galle et al. [10] describes the typical operational sequence of a gantry crane during storage or retrieval operations to complete a cycle as displayed in Figure 7. The operational sequence starts with an empty move from the position where the crane ended the previous request to the starting location of the new job. The crane then picks up the container with the spreader, moves to the destination and places the container on the destination location.

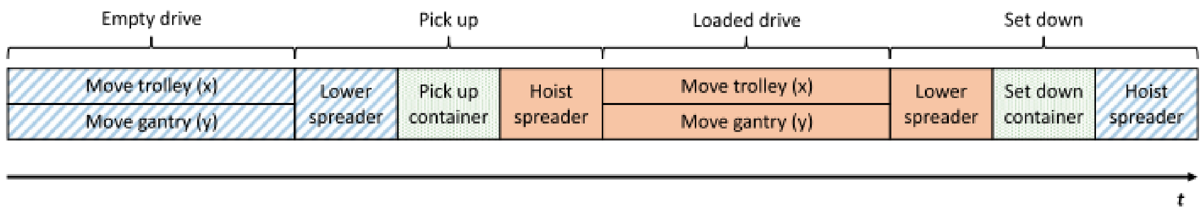

Figure 7 Typical operational sequence of a yard crane container handling cycle [10]

Speer and Fischer [11] describe the typical operation of a gantry crane for any job starting with an empty move, followed by a loaded move to complete a cycle as shown in Figure 8. The only difference with the empty and loaded move is the subprocess of resizing the spreader. Resizing the spreader is important to take into account especially during short gantry moves where resizing the spreader could take more time than the gantry movement time. With more than two cranes, interference can occur which can result in an increased driving time. For an inbound or outbound move, it is possible that the gantry crane has to wait in front the transfer area (TA) if the other crane is still busy in the transfer area because of delays of the horizontal transport (HT) or when the remote operation (RO) is necessary and delayed.

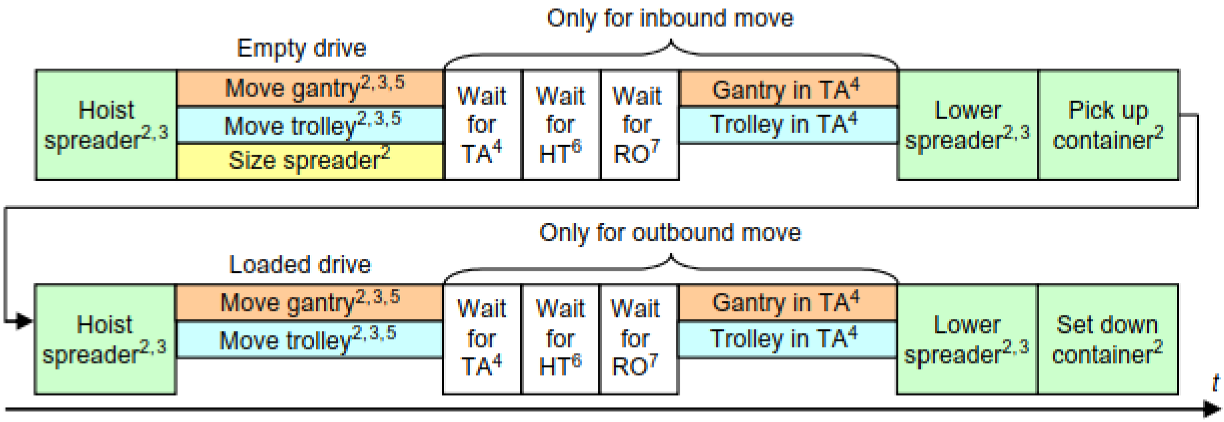

Figure 8 Operational sequence of a yard crane container handling cycle where the transfer area (TA), the horizontal transport (HT) and the remote operation (RO) is taken into account. [11]

In general, there are four basic process steps for a yard crane to complete a container handling cycle shown in Figure 9, the total time taken by these processes determine the cycle time of the yard crane. The actions shown under each process describe the subprocesses that have to be executed in order to complete the corresponding basic process.

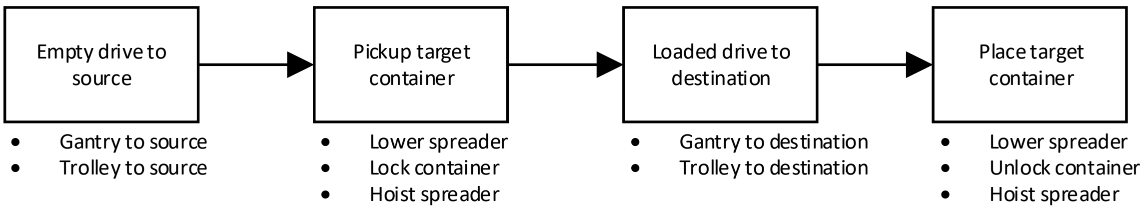

Figure 9 The four basic yard crane processes and subprocesses to complete a container handling cycle

2.4 Performance prediction influences

The performance prediction of a yard crane model in terms of cycle time is not only influenced by specifications of the yard crane itself, but also external influences from the specifications of the storage yard. This paragraphs describes and categorizes the modeling parameters that have influence on the performance prediction of yard crane models.

2.4.1 Yard crane modeling parameters

The yard crane models used in various logistic studies on the container terminal mentioned literature are examined to find performance influencing modeling parameters regarding the yard crane itself.

Dragovic et al. [12] made a literature overview and analysis by research field, application area and tool of simulation modeling in ports and container terminals. The papers included in this literature review range from 1961 to 2015, a classification of the literature on simulation models at container terminals is shown in Figure 10.

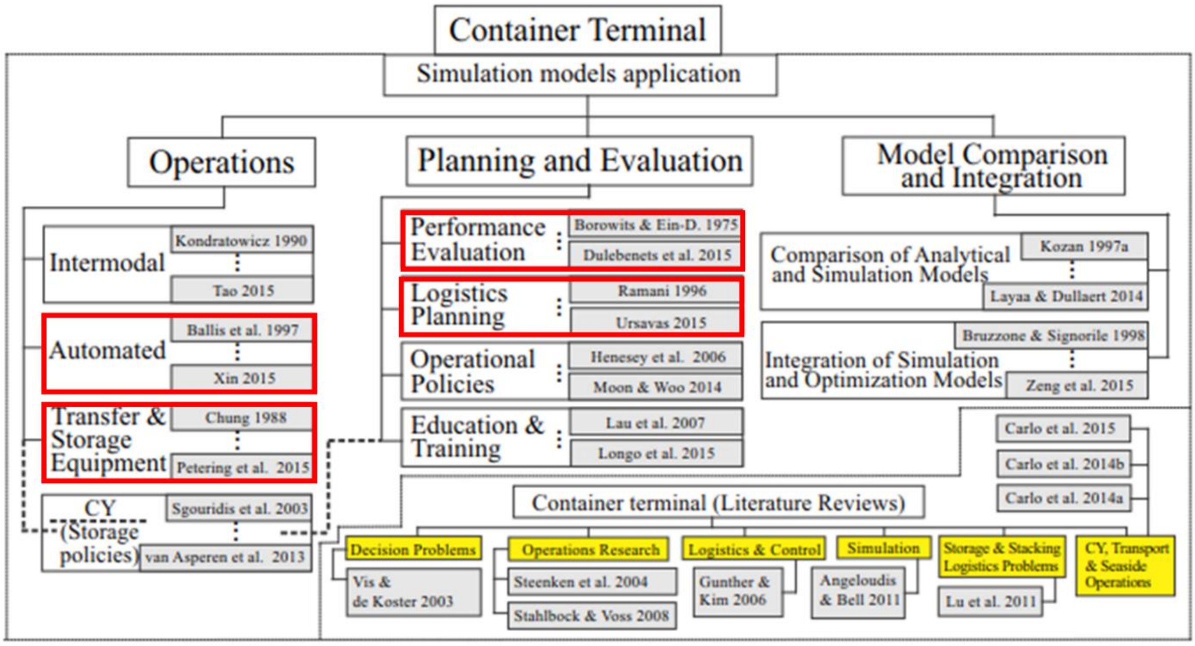

Figure 10 Classification of literature on simulation models at container terminals used in the literature review [12]

Papers listed in the ‘automated’ and the ‘transfer & storage equipment’ blocks were examined that are included in the ‘operations’ block. Also, papers of the ‘performance evaluation’ and ‘logistics planning’ blocks were examined that are included in the ‘planning and evaluation’ block.

Steenken et al. [2] wrote a classification and literature paper on container terminal operation and operations research. In this paper, the literature of the paragraph ‘storage and stacking logistics’, ‘crane transport optimization’ and ‘simulation systems’ were examined. Stahlbock and Voss [3] updated the paper of Steenken et al. [2] and the literature addressed on the same paragraphs were examined. Carlo et al. [13] wrote a paper on literature overview, trends and research directions of storage yard operations in container terminals. A classification scheme is developed and the literature papers that were examined included the description ‘RMGCs are used’, ‘associated with MHE distance traveled-related metrics’ and ‘ utilization of gantry cranes’. Angeloudis and Bell [4] reviewed container terminal simulation models. The simulation models described in this paper are examined as well.

Since the examined review papers only covered literature until 2015, other models were found using Google Scholar and the library of the Delft University of Technology using a combination of the keywords ‘container, terminal, automated, yard, crane, simulation, model’ and filter the results to show literature between 2015 and 2018.

Not all yard crane models found in the examined papers will be mentioned because model details were not clearly described, were not available due to confidentiality or were derived from other papers. The yard crane models can be sorted into container terminal and storage yard focused models. Container terminal focused models are used to determine the performance of the container terminal in terms of quay productivity, storage yard focused models are used for example for yard crane scheduling optimization. Description of the analyzed yard crane models is attached in appendix B.

The analyzed yard crane models showed various modeling parameters regarding crane components, speeds, accelerations, decelerations and container handling times. Some models only used a constant or stochastic container handling time to represent a yard crane model. The input values for the models varied because the yard crane models were based on different cranes. In some models however, very low gantry speeds are used to compensate for the lack of detail of implementing a trolley and hoist. Different values, stochastics or distributions are used by yard crane models for container handling times.

Some additional modeling processes were found regarding positioning and adjusting of the spreader, dead times for each movement, container relocation time and mean time between failure and repair.

Table 1 shows an overview of the analyzed yard crane models mentioned in literature papers. As seen in the table, most yard crane models only include a gantry speed and a container handling time. Four models were found that included both trolley and hoist as crane components. Two of them also included accelerations and decelerations of these components. In general, container terminal focused yard crane models included less detail than models focused on the storage yard.

Table 1 Overview of the yard crane models and included modeling parameters analyzed in the literature review

Year	Literature paper	Gantry Speed	Acc./ Dec.	Trolley Speed	Acc./ Dec.	Hoist Speed	Acc./ Dec.	Container handling time	Comments
2017	Speer and Fischer [11]	✓	✓	✓	✓	✓	✓	✓	0.2m/s spreader resizing
2012	Kemme [14]	✓	✓	✓	✓	✓	✓	✓	Spreader fine positioning time
2018	Galle et al. [10]	✓		✓		✓		✓	
2005	Saanen and Valkengoed [15]	✓		✓		✓		✓	2s dead time
2018	Roy and de Koster [16]	✓		✓				✓	
2018	Yu et al. [17]	✓						✓	
2017	Huang and Li [18]	✓						✓	
2017	Gharehgozli et al. [19]	✓						✓	
2016	Zhou et al. [20]	✓						✓	Average relocation time of 74.2s
2014	Lu and Le [21]	✓						✓	
2012	Guo and Huang [22]	✓						✓	
2009	Petering et al.	✓						✓	
2006	Duinkerken et al. [23]	✓	✓	✓				✓	
2004	Choi [24]	✓						✓	
2004	Liu et al. [25]	✓						✓	
2004	Veenstra and Lang [26]	✓						✓	
2004	Yang et al. [27]	✓						✓	
2002	Liu et al. [28]	✓						✓	
1999	Yun and Choi [29]	✓						✓	

The yard crane models seen in Table 2 cannot be used for performance prediction calculations. Yard crane models mentioned in this table do not include a container handling time which is an essential part of calculating the cycle time. The other models only exist of a container handling time, yard crane components that are an essential part to calculate the cycle time are missing.

Table 2 Overview of non-relevant yard crane models analyzed in the literature review

		Gantry		Trolley		Hoist			
Year	Literature paper	Speed	Acc./ Dec.	Speed	Acc./ Dec.	Speed	Acc./ Dec.	Container handling time	Comments
2017	Gupta et al. [30]	✓		✓					
2015	Gharehgozli et al. [31]	✓		✓		✓			
2014	Xin et al. [32]	✓	✓						
2015	Kavakeb et al. [33]							210s	
2014	Kulak et al. [34]							Tri(2.1, 4.8, 7.6)min	tFail Tri(7, 15, 60)d, tDown Tri(1, 48, 96)h
2014	Lin et al. [35]							180s	
2014	Sauri et al. [36]							Distribution	
2014	Taner et al. [37]							Tri(1.2, 2, 3.5) + Tri(0.3, 0.6, 1.1)	
2006	Bielli et al. [38]							(1.8/2.1)min/ container	
2006	Biskorn et al. [39]							Distribution	
2004	Vis and Harika [40]							Emperical distribution	

2.4.2 Storage yard modeling parameters

Not only do yard crane specifications have influence on the cycle time of yard crane, storage yard specifications also have a significant influence. Two types of storage yard modeling parameters can be identified, strategical yard design and operational planning modeling parameters.

Strategical yard design

The strategical design decisions regard the configuration of the storage yard based on, for example, performance requirements or spatial constraints. The major strategical design decisions for storage yards that influence the performance are described.

Block layout

Carlo et al. [13] and Kemme [14] mention the two main configurations of yard layouts with the main difference being the location of the transfer points where the transfer vehicle and the yard crane exchange containers, the relative positioning of the blocks to the quay and the level of automation.

The side loading block configuration usually has blocks positioned parallel to the quay and is often non-automated. One or more rows in each block is reserved as truck lanes in which internal and external horizontal transport equipment exchange containers with the yard cranes. Horizontal transport equipment move along the block to the specific target bay before getting handled by the yard crane. This layout is common in large Asian container terminals and is shown in Figure 11.

The end loading block configuration is typically used in automated yards which have blocks positioned perpendicular to the quay. The transfer points are located at each end of the block to handle requests from both sea and landside. The seaside transfer points are often served by AGV's while the landside transfer points are served by external trucks, the seaside and landside operations are separated by the block. This configuration was first implemented in large European container terminals and is displayed in Figure 12.

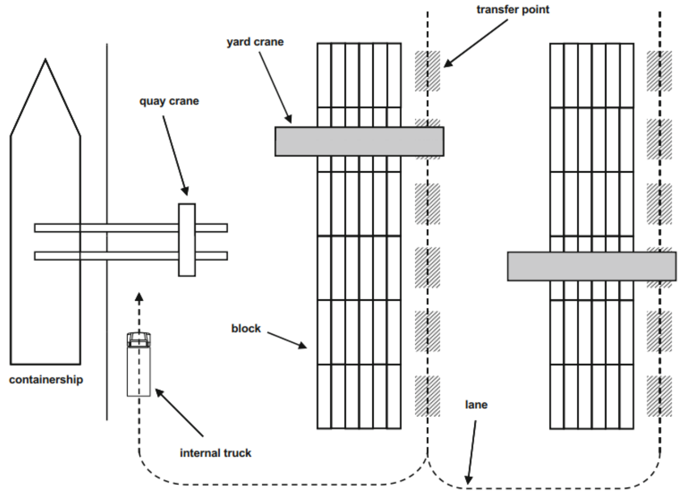

Figure 11 Side loading transfer point block configuration (Asian) [41]

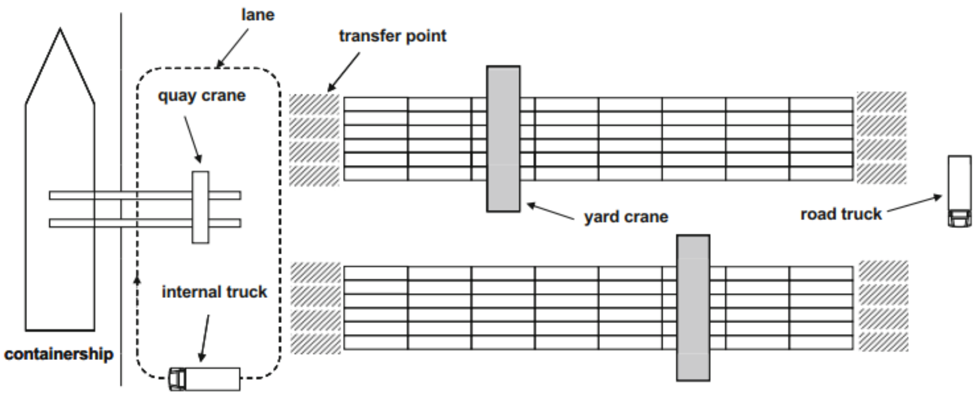

Figure 12 End loading transfer point block configuration (European) [41]

A comparison is made by Carlo et al. [13] between the Asian and European block layout concluding that the European layout has a higher investment cost, lower operational costs, higher crane speeds, more storage capacity per area and minimizes the distance moved by transfer vehicles and external vehicles at the expense of longer yard crane movement distances. To compensate the larger movement distances, the yard cranes are required to accelerate and decelerate quickly which becomes more difficult and costly as yard blocks get wider. Both Lee and Kim [41] as well as Galle et al. [10] mention the importance of transfer point locations at the container stack regarding operational characteristics as well.

Block dimensions

Lee and Kim [42] concluded that the optimal number of bays and rows depend on the location of the transfer points, side or end loading stack configuration. The speed of the trolley affected the optimal block width meaning a wider block can be used if the speed of the trolley is higher. In general, if the speed of the yard crane increases, the block size can be increased. They also mention the tradeoff between the block size in terms of throughput and storage capacity when assuming the same number of yard cranes per block. When it is attempted to increase the throughput of the container block, the block size must be reduced resulting in a smaller block storage capacity and vice versa. Kemme [14] states that the maximum velocity and acceleration of a gantry crane decreases if the block size increases.

A research is done by Petering [43] on the effect of the block width for the yard crane performance. When the blocks are wider, each yard crane straddles more container stacks which means that the number of stacks in close proximity to each yard crane is increased. As a result, there are fewer zones and therefore more yard cranes per zone which means there is less yard crane gantrying. The downside is that the occurrence of yard cranes being and working in close proximity to each other also increases which decreases container handling capacity.

Petering and Murty [44] describes how the block length of the container yard affects the productivity of the quay crane via the horizontal transport and yard cranes. When the blocks are longer, there are fewer blocks and therefore fewer spaces between the blocks for the horizontal transport to pass and therefore optimal routing of the horizontal transport is reduced. For the yard cranes, when the blocks are larger, there are fewer blocks in each zone which makes the stacks in each zone closer together on average. This results in a lower average of gantry movement for the gantry cranes between consecutive container handling operations. The downside of longer block lengths for the yard cranes is the increase in yard crane interference which lowers the productivity.

Vis and de Koster [45] describe that the height of the stack influences the stacking efficiency, consequences of higher stacking are reshuffling moves. To minimize delays, reshuffling moves can be executed in advance when. The advantage with higher stacking is that more containers can be stored in the same area. Furthermore on the height of the stack, Chen et al. [46] proposed a model for basic port storage optimization and stated that the factors that have to most impact on terminal storage capacity are stacking height, net storage area available, storage density (containers per unit area), dwell times for containers and breakbulk cargo.

<u>Yard crane configuration</u>

Speer and Fischer [11], Carlo et al. [13] and Kemme [14] discusses four different yard crane systems for automated container terminals, single RMG, twin RMG, DRMG and TRMG shown in Figure 13.

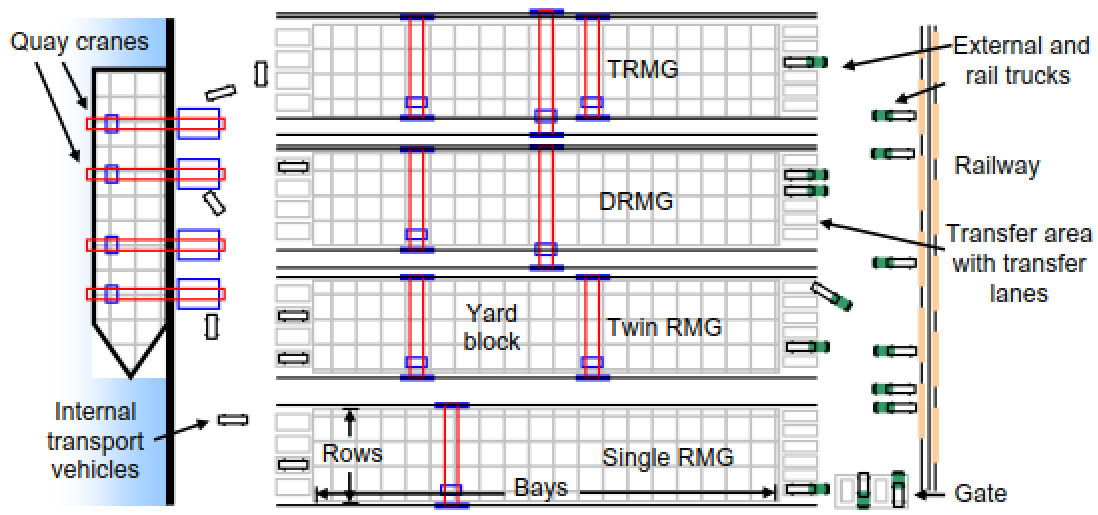

Figure 13 The four yard crane configurations for automated container terminals shown in a schematic top view, each block represents a different yard crane configuration [11]

With a single RMG, one gantry crane operates at one container block. This is a simple but rarely used configuration because of the risk of when a gantry crane fails, the complete block is not accessible anymore. The simple behavior of having one crane on a container block is advantageous for the crane scheduling problem.

Twin RMG systems have two gantry cranes operating on the same rail on one container block. One crane is responsible for the water side and the other crane for the land side service. A higher productivity can be reached compared to a single RMG system but the limitations are that the cranes cannot pass each other. Another disadvantage is that there is more space needed for the second track allowing less space for container storage.

DRMG systems uses two gantry cranes on one container block as well but they move on independent rails. With one crane larger than the other, the larger crane can pass over the smaller crane as displayed in Figure 14, now both cranes can serve the complete block. This setup can realize higher productivity in peak operations and when a crane breaks down, the block is still accessible but with lower container handling rate.

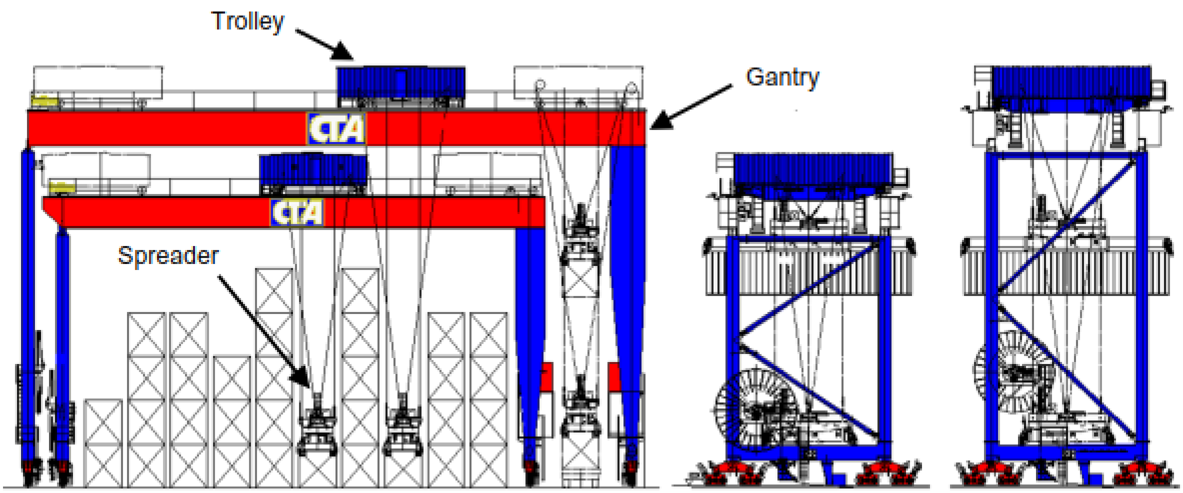

Figure 14 Schematic side view of two yard cranes with a DRMG configuration, the yard cranes can pass each other when the trolley of the large yard crane is on a dedicated position [11]

With a TRMG system, three cranes operate on one block where one larger crane on an individual rail can pass the two smaller cranes that move over the same rail. This setup ensures a high service level at peak situations even with a crane failure. The disadvantage is that the crane scheduling problem becomes very complex when using this crane configuration.

Saanen and Valkengoed [15] compared three ASC configurations by means of simulation covering a single RMG, a twin RMG and a double RMG. The results are evaluated based on productivity, flexibility, area utilization and cost. The single RMG system was the least complex and had the lowest operational and investment costs. The double RMG system has, apart from flexibility, many disadvantages for example costs. The twin RMG configuration does not have a lot of disadvantages but this system requires a higher investment and operational cost than a single RMG system.

Operational yard planning

The operational planning decisions are often made by the terminal operating system (TOS) and regard operational decisions to optimize the performance of the processes in the storage yard. The major operational planning decisions for storage yards that influence the performance are described.

Container stacking

Rules for container stacking is discussed by Borgman et al. [47] stating that every container terminal needs a stacking strategy. This stacking strategy includes three main objectives such as efficient use of storage space, limiting transportation time from quay to stack and beyond, and the avoidance of reshuffles. These objectives are conflicting and therefore needs to be prioritized which depend on the specific container terminal. Various decision horizons can be identified and an often used classification has four temporal categories, long term, medium term, short term and real rime. Long term covers strategic decisions and cover from years to decades, medium term includes tactical capacity decisions which has a scale of months, short term covers operational decisions and is based on days, the real time decisions are made based on minutes or seconds and is regarding stacking processes. Luo et al. [48] also mentions that storage space is an important resource they state that the utilization of the storage space determines the overall performance of the container terminal.

Crane scheduling

Petering [43] emphasizes that to maximize the efficiency of the quay crane, the yard operations have to be coordinated properly so that the horizontal transport and the yard cranes serve the quay cranes adequately, several aspects of real-time yard operations make this a challenging task. In general, the container handling capacity of a yard crane is lower than a quay crane and unlike quay cranes, yard cranes are required to multi-task. For example, when more than one container ship is present at the quay, yard cranes have to store import containers that are unloaded by the quay cranes in the stack while also retrieve stored export containers to serve again to the quay cranes. Yard cranes have to move over the container stack for each container handling while quay cranes do not move during loading or unloading one bay of a container ship. Quay cranes load and unload containers to a container ship corresponding to a job sequence that is predefined with limited flexibility while yard operations have to stay very flexible. The cycle times of the container handling equipment in a container terminal is highly variable. Yard crane slowdowns occur when two yard cranes that operate on the same container block come too close to each other. The above mentioned challenges for yard cranes makes it necessary to have at least 2-3 yard cranes per quay crane.

Unproductive yard crane moves

Speer and Fischer [11] categorize the yard crane operations in four main processes, an inbound move, an outbound move, a reshuffle and a housekeeping move. An inbound move is when the yard crane picks up a container from a transfer area and places the container in the stack on a location determined by the TOS. With an outbound move, a container is picked up from the stack and is placed on a destination in the transfer area. A reshuffle move is necessary when an outbound move is executed and a container is not accessible. With reshuffle moves, containers that are stacked on the container that has to exit the stack are removed. Reshuffling moves are independent moves that can be executed by another crane which improves flexibility. With a housekeeping move, the storage position of container is improved so that these containers can be delivered with a minimum number of reshuffles and short movement times. These moves have a low priority which therefore are often executed when the workload is low.

Murty et al. [49] divide the container handling moves of a gantry crane in a productive move and a unproductive move. A productive move by a gantry crane is a move where a container is moved from the stack to the transfer zone to place it on horizontal transport or vice versa. An unproductive move by a gantry crane is for example a reshuffling move where the movement of a container is necessary to retrieve another container stored underneath it in the same stack. Because of this reshuffled container, an extra reshuffling move is inevitable.

Chen [50] concludes that several major factors which influences operational efficiency and cause unproductive container movements. The ‘pre-marshalling strategy’ when receiving containers that will be exported. These containers will be stored in a temporary storage area until the confirmed export list of containers to be loaded into the container ship is sent by the shipping line. A shortage of storing capacity will result in container stacks with containers having mixed conditions, additional shuffling moves are necessary. When the quality of the container information received is poor, container stacks may have to be reorganized. Operational rules may state that housekeeping moves may have to be taken to make storage capacity available for the anticipated import containers. The number of reshuffling moves increase when the height of the container storage is increased.

3 Model development

In this chapter, a new yard crane model will be developed that takes automation subsystems into account. The requirements from both the literature review and experience from Siemens Cranes is described as well as a reference case in order to verify the new developed model. The cycle time is worked out in more detailed subprocesses which will be modeled into process blocks. The process blocks are defined and described which are the building blocks for the operational sequence which represents the cycle time prediction calculation model.

3.1 Requirements

There are requirements extracted from literature as well as from experience from Siemens Cranes. The requirements are grouped based on strategical design and operational planning characteristics.

3.1.1 From literature

The requirements for the new developed yard crane model that are extracted from the literature review in chapter 2 are given in this subparagraph.

Strategical design

- Block dimensions
  - The width, height and length of the block plays an important role for example the relocation of containers and speeds of equipment.
- Transfer point locations
  - Depending on the type of container terminal, the location of the transfer points of the storage yard is an influencing parameter.
- Type of equipment
  - The type of equipment used on a block influences the throughput performance of the system.
- Equipment configuration
  - The configuration of the equipment used on the block is a requirement to take into account when developing a simulation model.
- Horizontal transport.
  - The type of horizontal transport makes a difference according to literature, for example, it takes more time to load or unload a container from or to an manual operated truck than an AGV.

Operational planning

- Equipment scheduling
  - The TOS schedules the container handling equipment on the block and the efficiency of the crane scheduling is an influencing parameter.
- Job scheduling
  - The job scheduling is related to the equipment scheduling and is also handled by the TOS and plays an important role as well.
- Crane specifications
  - The speed, acceleration and deceleration of the crane, trolley and hoist influence the throughput performance of the block system.
  - The resizing speed of the spreader is mentioned in literature and dead times between movements.
  - Different crane sequences to complete a container move are mentioned in literature, some include more details than other simulation models.
- Storage yard filling rate
  - The filling rate of the storage yard influences the chance of a container relocation and flight path and therefore has to be taken into account when developing a simulation model.

- Horizontal transport
    - The scheduling of horizontal transport can impact the throughput performance of the block as a system.

3.1.2 From Siemens Cranes

Experience from Siemens Cranes is also used to identify requirements for the new yard crane model that will be developed and is described in this subparagraph.

Strategical design

- Block dimensions
    - The block dimensions influence the size of the crane and therefore the required motors, drives and control to ensure a certain speed, this plays a role in the throughput performance.
- Transfer point locations
    - The location of the transfer points is often related to the type of container terminal, an end-loading configuration is often associated with an import/export container terminal, a side-loading configuration is often associated with a transshipment container terminal. The characteristic of one container move by a crane is very different for the two different types of transfer point locations.
- Type of equipment
    - There is a large difference between for example a rail mounted gantry crane and a RTG, the crane used depends on the project and has to be implemented in the simulation model.
- Equipment configuration
    - If there are multiple cranes on one track, for example, deadlocks have to be prevented. This can also determine the characteristics of the container handling move and gantry crane movement and therefore has to be taken into account.

Operational planning

- Crane specifications
    - Optimal flight path can be interesting but only if the stack profile is low. If not, hoisting to the highest points results in faster stabilization of the spreader. Sometimes this is not possible because for example, the trolley has a predefined position before gantry movement is possible to reduce mechanical wear and increase accuracy.
    - As mentioned at the block dimensions, the crane dimensions can differ depending on the project which influences the engineered solution for a crane regarding motors, drives and control and therefore speeds, acceleration and deceleration of the gantry, trolley and hoist movement.
    - Automated cranes are equipped with multiple automated systems but not all are used in every project, the configuration of the equipped automation systems influences the throughput performance of the crane.
    - The sequence of the internal processes of a crane determines the time it takes to complete one container handling, it is necessary to take this into account.
    - Siemens Cranes wants to use the simulation model to identify bottlenecks in the internal crane processes for optimization purposes. The cycle time of a crane can be optimized if unnecessary operational time for each internal crane process can be eliminated.
- Uncertainties
    - For horizontal transport, the effect of AGV's breaking down or a delay of an external truck influences the system, a path could be blocked or the wrong container could be connected with the wrong horizontal transport. Parallel to horizontal transport, the crane could also breakdown, block a path, pick up a wrong container or be delayed which influences not only that current container handling time, but also connected elements.

Siemens Cranes wants to have the ability to implement failures into the yard crane model.

3.2 Reference case

A reference case regarding ARMG's will be used from a project executed by Siemens Cranes to develop, verify and compare the new yard crane model.

Limited operational data regarding automated yard cranes from the project is available since it is a current ongoing project in the commissioning phase. This means that there is only operational data available from performance tests. The performance tests are regarding executed shuffle jobs, moving containers between various locations within the stack. No operational data is available from container handlings between yard crane and truck. However, sufficient data is available from shuffle jobs that also include automation systems which can be used. Each delivered automated yard crane for the project is identical, data from multiple cranes can be used. Interactions between multiple automated yard cranes is managed by TOS and therefore is not included in the performance tests.

3.2.1 Storage yard specifications

The strategical design decisions made by the container terminal operator determines the storage yard dimensions, layout, container handling equipment type and configuration. A schematic overview of the specifications of the storage yard is displayed via a top view in Figure 15. The width and length of the storage yard is specified as well as the location of the truck lane. In detail, the space between the container is shown in the zoom in. One container block in the storage yard exists of 54 bays, 12 rows and 6 tiers. The block layout consists of a side loading configuration with two truck lanes, one of each side of the block. Three ARMG's operate on one block on the same rail with each yard crane having a cantilever at both sides to serve the truck lane.

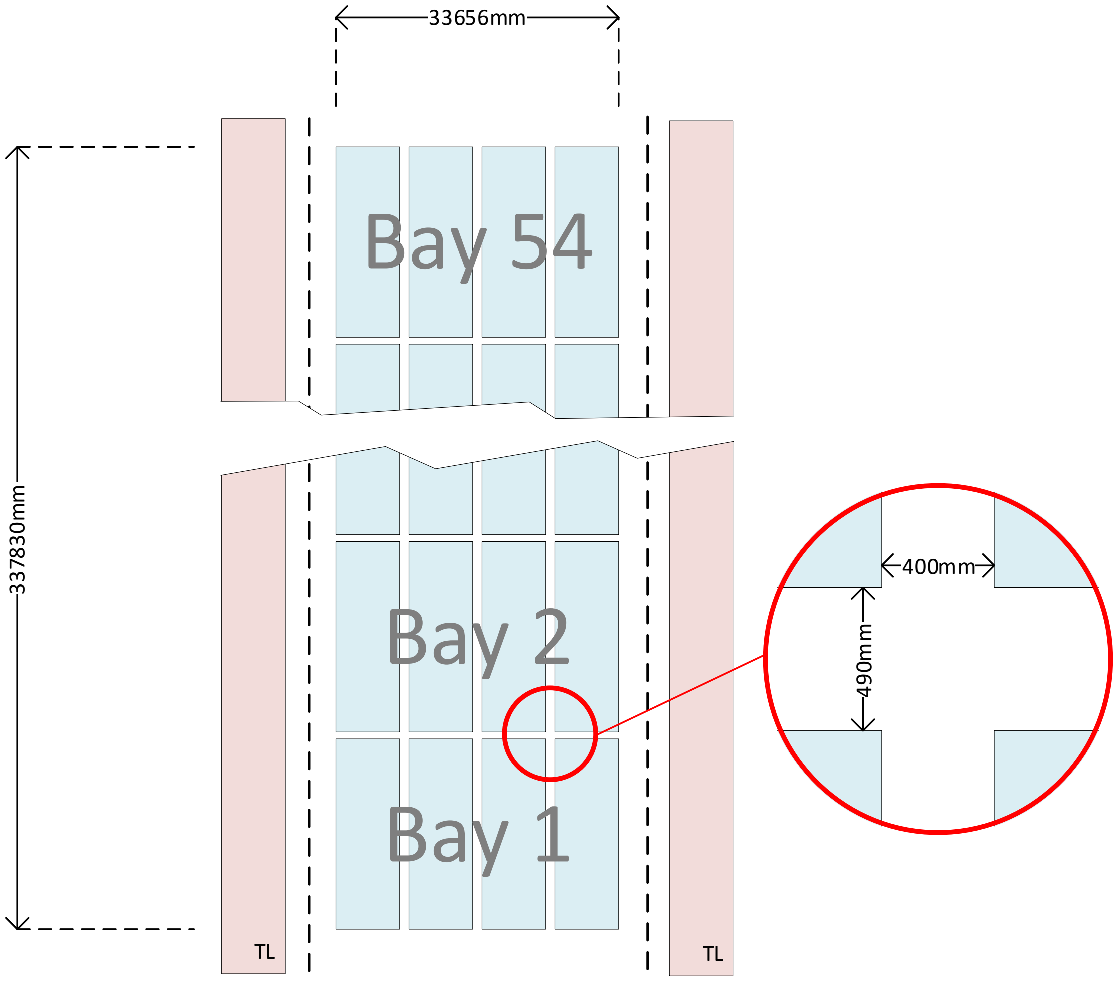

Figure 15 Schematic top view of the reference case storage yard layout

A side view of the block from the reference case is shown in Figure 16. The cantilever of the yard crane is shown as well as a truck parked in the truck lane. All dimensions shown in both figures are retrieved from the technical specification and are part of the influencing parameters that will be used in modeling the yard cranes and comparing the yard crane models. The twelve rows as well as the six tiers are shown in the figure and the stack height depends on the height of the containers stored. If a container is stored in or taken from a truck in the truck lane, an extra height and safe height has to be taken into account due to the height of the trailer.

3.2.2 Yard crane specifications

Before gantry movement is allowed, the trolley has to be positioned on a predefined position on the gantry. Before positioning the trolley on the predefined location to allow gantry movement, the hoist has to hoist the spreader to the maximum height. This strategy is also referred to as a rectangular container flight path and this strategy is also used in the reference case.

Technical specifications of the reference case show that the gantry crane has a defined movement speed of $3m/s$ and an acceleration and deceleration of $0.3m/s^2$. The trolley has a specified speed of $2.5m/s$ and an acceleration and deceleration of $0.5m/s^2$. There are different hoisting and lowering speeds of the spreader associated with the type of movement, but for all movements, an acceleration and deceleration of $0.45m/s^2$ is defined. The technical specification of the hoisting and lowering speed of the spreader when a container is handled is set to $0.8m/s$. An empty spreader has a higher speed since field weakening is applied in the electric motors, a speed of $1.6m/s$ is defined for this movement. When the process of soft landing is initiated, the speed of hoisting and lowering the spreader is set to $0.08m/s$.

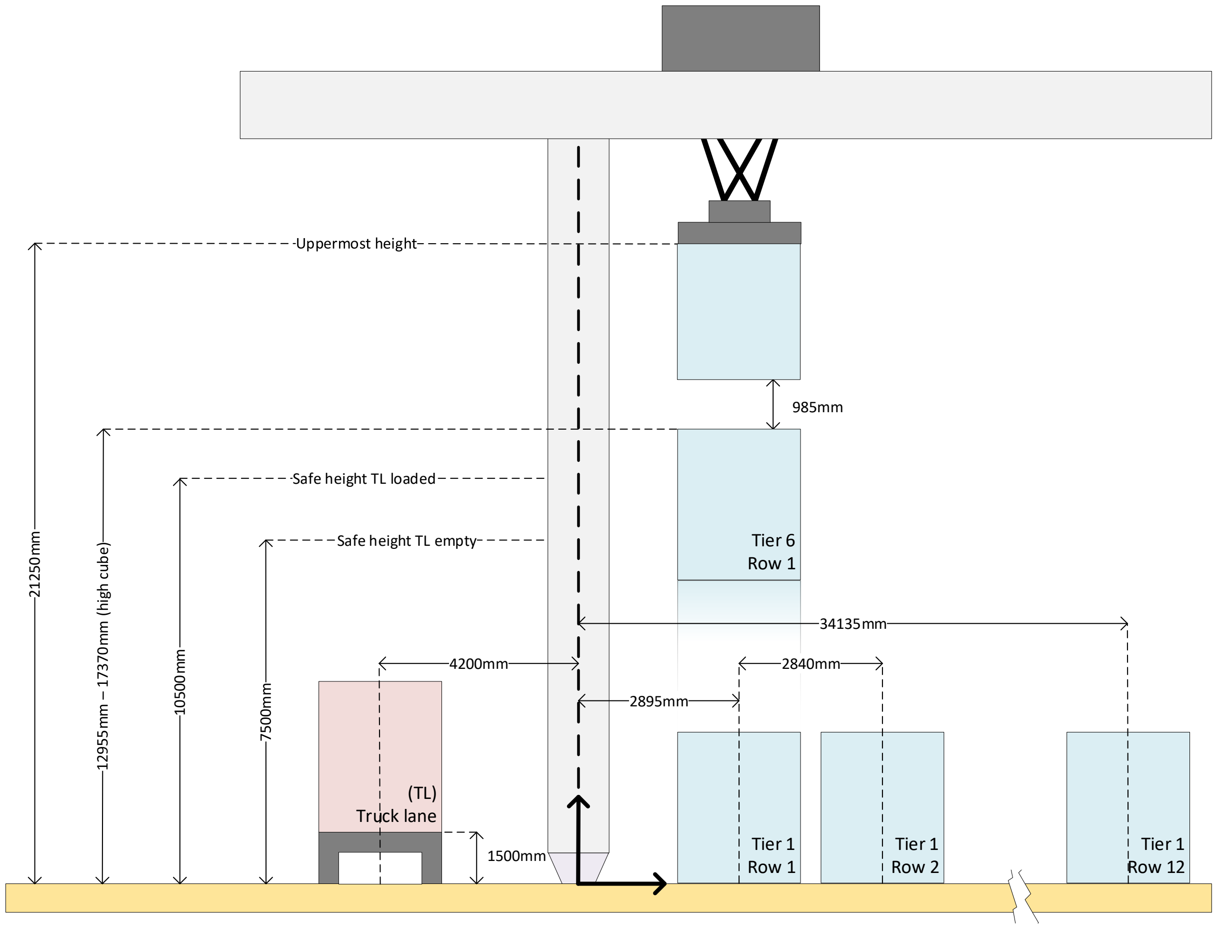

Figure 16 Schematic side view of the reference case storage yard configuration

3.3 Operational sequence

A job for a yard crane can be categorized in three move types: load, shuffle and unload. When a container is received from a truck to store in the container stack, the job type is called load. Vice versa, when a container from the container stack is loaded on a truck, the job type is called unload. When a container handling is completed within the container stack, the job type is called shuffle. These three main job types include handling a container from a source to a destination, the source and destination can either be a truck or a stack as seen in Table 3. In order to develop a general yard crane model for any type of job, the different job types have to be included in the operational sequence despite of the reference case only including shuffle jobs.

Table 3 The three job types related to source and destination

Job type	Source	Destination
Load	Truck	Stack
Shuffle	Stack	Stack
Unload	Stack	Truck

3.3.1 Basic yard crane operational sequence

The four basic yard crane processes and subprocesses to complete a container handling cycle as seen in Figure 9 are broken down into more detailed subprocesses. The operational sequence shown in Table 4Table 5 is modularly built from process blocks that represent the subprocesses and is based on the operational sequences found in literature and technical specifications from the reference case. The operational sequence shows a rectangular movement of the yard crane in order to complete a container handling cycle. This means that the crane movement processes gantry, trolley and hoist are always executed in sequence, not in parallel. This is also the case in the reference case to improve stability, safety and the maintenance interval. The spreader adjustment process can be executed parallel to the gantry movement to source process as seen in sequence 5 of the operational sequence. Note that depending on the source and destination, the operational sequence can be used for all three job types described in Table 3.

Table 4 Basic operational sequence of a yard crane model

1	Start	
2	Job received from TOS	
3	Hoist spreader to upper	
4	Trolley to safe	
5	Gantry to source	Spreader adjustment
6	Trolley to source	
7	Lower spreader to source	
8	Lock container	
9	Hoist spreader to upper	
10	Trolley to safe	
11	Gantry to destination	
12	Troley to destination	
13	Lower spreader to destination	
14	Unlock container	
15	Hoist spreader to safe	
16	Send completed job to TOS	
17	Finish	

The process blocks in the operational sequence are categorized with a color based on the type of process. Red process blocks indicate processes related to job management, blue process blocks are related to crane movement processes and green process blocks indicate spreader processes.

3.3.2 Automated yard crane operational sequence

In order to develop a general yard crane operational sequence for automated yard cranes, automation systems have to be included into the basic yard crane operational sequence. Automation systems are required to replace an operator in order to operate a yard crane automatically. Automation systems on the yard crane are installed for automation purposes as well as for safety purposes.

Some automation systems do not have a processing time but are continuously monitoring during yard crane movement processes. In order to set up a general operational sequence for an yard crane model for automated yard cranes, monitoring automation systems are taken into account despite of not having a process time, these automation systems can influence the cycle time in case of a failure. For example, if an automation system fails to measure, calculate, execute or monitor a task, a manual intervention is triggered that stops automatic operation and initiates remote control of the crane. A manual operator can solve the problem remotely and after the problem is solved, the crane can continue to operate automatically. The automation systems that are required in order to operate a yard crane automatically are:

ATIDS
Automatic truck identification system (ATIDS), this automation system checks the identification of the truck that the crane has to load or unload via RFID scanners. The RFID scanner equipped on the crane will check the unique ID of the truck, this ID is also provided in the crane's job details. ATIDS will be activated at load or unload move types after the gantry is positioned at the source location.

CLPS
Chassis lifting prevention system (CLPS), this prevention system will prevent lifting of the truck and trailer during hoisting in the trucklane. The system will detect if the trailer is lifted up using a laser sensor system and load measurement. CLPS is used for load or unload move types. For load move types, the CLPS will be activated when hoisting a container from a truck. For unload move types, the CLPS will be activated after dropping-off a container on a truck.

CTDS
Container twistlock detection system (CTDS), this video based automation system is used for the detection of a twistlock stuck in the bottom side of a container. This can happen and using a system to detect these allows for automation of the crane. CTDS is only activated at a load move type when the container is hoisted from the truck and the spreader is on the highest hoisted safe position.

FLS
Final landing system (FLS), an automated landing function determines the position of a container in a yard cell relative to the position of the trolley. This measurement is used to automatically land a container onto another container or to land an empty spreader on a container using a dynamic slowdown to allow soft-landing. FLS will calculate positions before lowering the spreader to a target.

LCPS
Load collision prevention system (LCPS), a collision protection functionality will be integrated based on 3D laser sensors equipped on the trolley. The system scans the stack profile while the trolley is moving, a virtual safety box around the spreader with container is created and varies according to speed and sway. If an object is detected in this virtual safety box, a slowdown followed by a controlled stop will be initiated automatically. LCPS is a monitoring system that is active during gantry, trolley and hoist movements.

MMS
Micro motion system (MMS), a fine positioning procedure will be implemented to position the spreader before landing in line with the target. This target is defined by the final landing measurement from the FLS. In approach of the landing target, the remaining deviation in trolley, gantry and skew direction is calculated and an additional target setpoint is transferred to micro motion control. The micro motion must be finished before landing, the fine positioning procedure will release landing based on the reached micro motion movement. The MMS is activated during lowering of the spreader to the target. When approaching the target, the MMS will start to adjust the spreader position one meter before the target.

SPMS
Spreader position monitoring system (SPMS), the spreader position will be determined with lasers using reflector plates on the headblock of the spreader. The system can measure the spreader position deviation regarding the trolley position and give feedback to the spreader position control system. SPMS is a monitoring system as well and is active only during hoist movement.

TPS
Truck positioning system (TPS), this automation system will align the truck and trailer using a 3D laser platform consisting of two 3D laser systems. The system will detect the accurate position of the truck and trailer and will guide the truck driver to park accurately for the job. The TPS is active during load and unload move types and is scheduled sequentially after the ATIDS.

The automation systems are included in the basic yard crane operational sequence to develop a new operational sequence to determine the container handling cycle of an automated yard crane as seen in Table 5Table 4. The yellow process blocks in the new operational sequence represent the automation systems and are in sequence as well as in parallel to the other process blocks.

In order to automate a yard crane, two additional process blocks are introduced that are related to yard crane components which will be further elaborated in 3.4. Soft landing is a process block regarding the hoist movement, it is a procedure where the spreader reaches the target location with a low speed. This procedure starts within one meter above the target position and prevents a hard impact when reaching the target position and is therefore considered a crane movement process. The stacking guide process block is a mechanical system attached to the spreader that helps positioning the spreader when stacking one container onto another in the block.

Table 5 The new operational sequence including automation systems

1	Start			
2	Job received from TOS			
3	Hoist spreader to upper	LCPS		
4	Trolley to safe	LCPS		
5	Gantry to source	LCPS	Spreader adjustment	
6	ATIDS			
7	TPS			
8	Trolley to source	LCPS		
9	FLS			
10	Lower spreader to source	LCPS	SPMS	MMS
11	Soft landing	LCPS	SPMS	
12	Lock container			
13	CLPS			
14	Hoist spreader to upper	LCPS	SPMS	Lower stacking guides
15	CTDS			
16	Trolley to safe	LCPS		
17	Gantry to destination	LCPS		
18	Troley to destination	LCPS		
19	FLS			
20	Lower spreader to destination	LCPS	SPMS	MMS
21	Soft landing	LCPS	SPMS	
22	Hoist stacking guides			
23	Unlock container			
24	CLPS			
25	Hoist spreader to safe	LCPS	SPMS	
26	Send completed job to TOS			
27	Finish			

3.4 Process blocks

The new developed operational sequence including automation systems is built from process blocks to determine the container handling cycle of an automated yard crane. The cycle time is determined by the process times of the process blocks, in order to calculate the cycle time, the process times of the process blocks have to be determined. Depending on the type of crane, level of detail and automation included in the crane model, the process blocks can be configured and modeled to the required level of detail. The modeling details implemented in the process blocks are according to the level of detail stated by the requirements.

3.4.1 Crane movement

Modeling the gantry, trolley and hoist movement is done by assuming a constant acceleration, deceleration and top speed. Both the gantry, trolley and hoist each have two extra times associated with a move, start delay time and fine positioning time.

The start delay time is the time difference between the signal of moving and actual movement. This time difference is the result of releasing the brakes, magnetizing the electric motors etc. note that also different sizes of electric motors can result in different magnetizing times. Motors may be magnetized already or brakes may not be applied at other process steps in the cycle, it is therefore important to find these times for the same move at different process steps in the cycle. For example, the start delay time of a loaded or empty hoist may be different when hoisting.

Fine positioning time is associated with the extra time needed to reach the target location. When approaching the location, the gantry, trolley or hoist may overshoot and have to correct its position or it may be that dynamic effects have to settle. These elements in a movement process needs to be taken into account.

Gantry

The mechanical structure of the crane, the portal, is named the gantry of the crane. The gantry moves over the track and allows for movement along the bays in the block. The dimensions and configuration of the gantry depends on the type of crane. According to the reference case, gantry movement is only possible if the trolley is on a predefined position on the gantry. The movement of the gantry is modeled according to the graph shown in Figure 17.

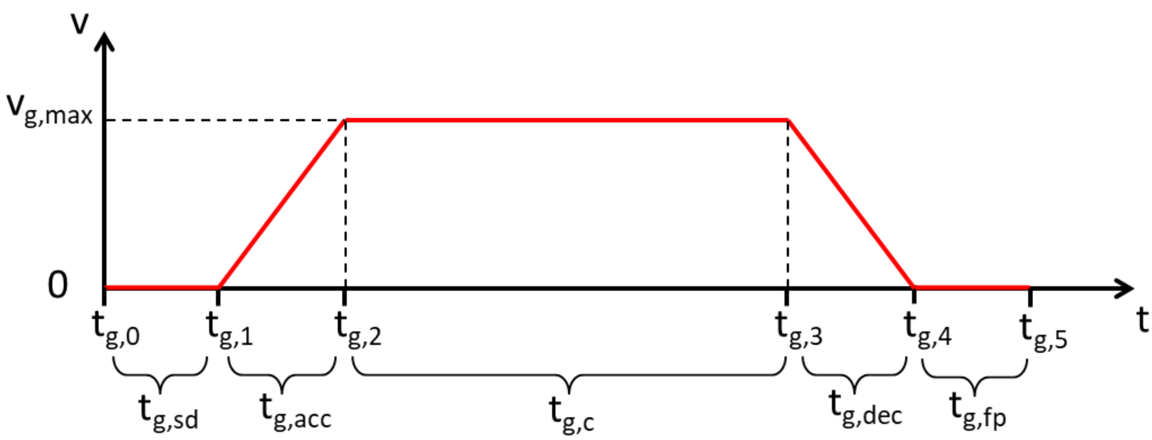

Figure 17 Modeling the gantry movement process block

The process of moving the gantry consists of five parts:

1. Gantry start delay
2. Gantry acceleration
3. Gantry constant speed

4. Gantry deceleration
5. Gantry fine positioning

The inputs for the gantry movement process block are:

- Gantry start delay time $(t_{g,sd})$
- Gantry acceleration $(a_{g,acc})$
- Gantry maximum speed $(v_{g,max})$
- Gantry deceleration $(a_{g,dec})$
- Gantry fine positioning time $(t_{g,fp})$
- Gantry movement distance (s_g)

The time taken by the gantry movement process is the sum of the time taken by the gantry parts start delay, acceleration, maximum speed, deceleration and fine positioning time of the gantry. The equation to calculate this time is:

$$t_g = t_{g,sd} + t_{g,acc} + t_{g,c} + t_{g,dec} + t_{g,fp}$$

The time required to reach the maximum gantry speed with a constant acceleration is equal to:

$$t_{g,acc} = \frac{v_{g,max}}{a_{g,acc}}$$

The distance to cover by the gantry while moving at maximum speed equals the total gantry distance without the distance covered by acceleration and deceleration. The distance covered by accelerating the gantry can be calculated using:

$$s_{g,acc} = \frac{a_{g,acc} \cdot t_{g,acc}^2}{2} = \frac{a_{g,acc}\left(\frac{v_{g,max}}{a_{g,acc}}\right)^2}{2} = \frac{v_{g,max}^2}{2a_{g,acc}}$$

The distance covered by decelerating the gantry is calculated the same way by:

$$s_{g,dec} = \frac{a_{g,dec} \cdot t_{g,dec}^2}{2} = \frac{a_{g,dec}\left(\frac{v_{g,max}}{a_{g,dec}}\right)^2}{2} = \frac{v_{g,max}^2}{2a_{g,dec}}$$

The time for constant gantry movement at maximum speed can be calculated using:

$$t_{g,c} = \frac{s_{g,c}}{v_{g,max}} = \frac{s_g - s_{g,acc} - s_{g,dec}}{v_{g,max}} = \frac{s_g - \frac{v_{g,max}^2}{2a_{g,acc}} - \frac{v_{g,max}^2}{2a_{g,dec}}}{v_{g,max}} = \frac{s_g}{v_{g,max}} - \frac{v_{g,max}}{2a_{g,acc}} - \frac{v_{g,max}}{2a_{g,dec}}$$

The time required to brake the gantry to a speed of zero with a constant deceleration is equal to:

$$t_{g,dec} = \frac{v_{g,max}}{a_{g,dec}}$$

The total equation to calculate the time taken for the gantry movement is equal to:

$$t_g = t_{g,sd} + \frac{v_{g,max}}{a_{g,acc}} + \left(\frac{s_g}{v_{g,max}} - \frac{v_{g,max}}{2a_{g,acc}} - \frac{v_{g,max}}{2a_{g,dec}}\right) + \frac{v_{g,max}}{a_{g,dec}} + t_{g,fp}$$

$$= t_{g,sd} + \frac{v_{g,max}}{2a_{g,acc}} + \frac{s_g}{v_{g,max}} + \frac{v_{g,max}}{2a_{g,dec}} + t_{g,fp}$$

Trolley

The trolley can move over the gantry and includes the hoist. The trolley allows for movement over the rows of the block and is only allowed if the spreader is on the maximum hoisted safe height. The movement of the trolley is modeled according to the graph displayed in Figure 18.

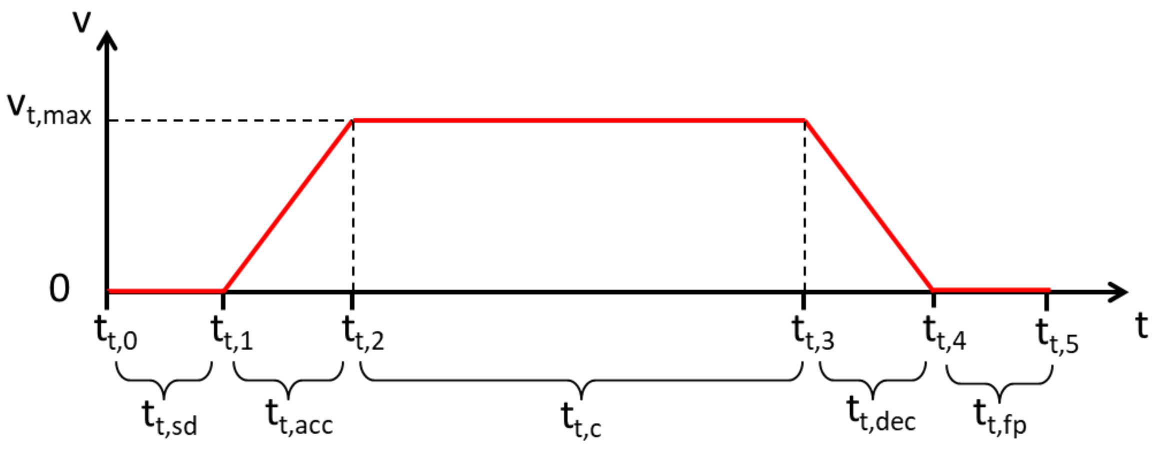

Figure 18 Modeling the trolley movement process block

The process of moving the trolley consists of five parts:

1. Trolley start delay
2. Trolley acceleration
3. Trolley constant speed
4. Trolley deceleration
5. Trolley fine positioning

The inputs for the trolley movement process block are:

- Trolley start delay time $(t_{t,sd})$
- Trolley acceleration $(a_{t,acc})$
- Trolley maximum speed $(v_{t,max})$
- Trolley deceleration $(a_{t,dec})$
- Trolley fine positioning time $(t_{t,fp})$
- Trolley movement distance (s_t)

The time taken by the trolley movement process is the sum of the time taken by the trolley parts start delay, acceleration, maximum speed, deceleration and fine positioning time of the trolley. The equation to calculate the total time required for a trolley movement equals:

$$t_t = t_{t,sd} + \frac{v_{t,max}}{2a_{t,acc}} + \frac{s_t}{v_{t,max}} + \frac{v_{t,max}}{2a_{t,dec}} + t_{t,fp}$$

Hoist with soft landing

The spreader is suspended from the hoist and the hoist allows for vertical movement along the tiers of the block. The movement of the hoist is modeled according to the graph shown in Figure 19.

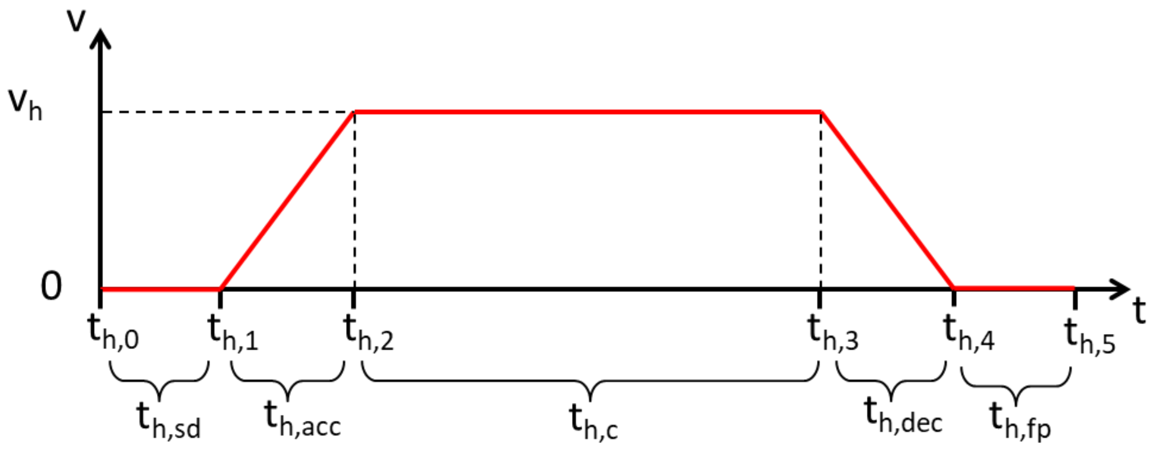

Figure 19 Modeling the hoist movement process block

The process of moving the hoist consists of five parts:

1. Hoist start delay
2. Hoist acceleration
3. Hoist maximum speed
4. Hoist deceleration
5. Hoist fine positioning

The inputs for the Hoist movement process block are:

- Hoist start delay time $(t_{h,sd})$
- Hoist acceleration $(a_{h,acc})$
- Hoist nominal speed $(v_{h,nominal})$
- Hoist double speed $(v_{h,double})$
- Hoist soft landing speed $(v_{h,sl})$
- Hoist deceleration $(a_{h,dec})$
- Hoist fine positioning time $(t_{h,fp})$
- Hoist movement distance (s_h)

The time taken by the hoist movement process is the sum of the time taken by the hoist parts start delay, acceleration, maximum speed, deceleration and fine positioning time of the hoist. The speed v_h mentioned in Figure 19 depends on the type of hoist movement. When a container is locked to the spreader, the nominal speed is used. An empty spreader is hoisted and lowered using field weakening in the electric motors which results in a speed that is equal to double the nominal speed and is referred to as double speed. For the soft landing procedure, a soft landing speed is used. Soft landing is an automation procedure used to land a spreader, with or without a container, on a target. The time required for a hoist movement can be calculated using:

$$t_h = t_{h,sd} + \frac{v_h}{2a_{h,acc}} + \frac{s_h}{v_h} + \frac{v_h}{2a_{h,dec}} + t_{h,fp}$$

3.4.2 Spreader systems

The spreader system process blocks are regarding the spreader size adjustment, twistlocks and stacking guide process blocks.

Spreader adjustment
The spreader is the equipment on the crane that can lock to a container and is connected with the hoist by cables. The spreader can adjust its size according to the dimensions of the target container. This process runs in parallel when the gantry moves to the source target.

Twistlocks
Once the spreader is landed on a container, the twistlocks on the spreader lock the container with the spreader. The twistlocks unlock the container from the spreader if the container is positioned on the target. This process is executed when the spreader has landed on the target without a container, or after the stacking guide is hoisted when the spreader is loaded.

Stacking guide
The spreader is also equipped with a stacking guide. As the name states, it is a guide for the spreader to help stack a container onto another container. the stacking guide is not used for stacking on the ground or truck. The stacking guide is lowered during the process of hoisting the container from the source. Before lowering the container to the destination, the process of lowering the stacking guide has to be completed. When the spreader is on the destination target, the stacking guide has to be hoisted first before unlocking the container. The stacking guide is not only a spreader system, it is also related to automation.

3.4.3 Automation systems

The automation system process blocks are already elaborated in 3.3.2. The process time of the automation system process blocks are briefly explained in this subparagraph.

ATIDS
ATIDS process block considers a fixed or stochastic operational time.

CLPS
CLPS process block is a monitoring system which is not associated with an operational time but can trigger a failure.

CTDS
CTDS process block is a monitoring system which is not associated with an operational time but can trigger a failure.

FLS
FLS process block considers a fixed or stochastic operational time.

LCPS
LCPS process block is a monitoring system which is not associated with an operational time but can trigger a failure.

MMS
MMS process block considers a fixed or stochastic operational time.

SPMS
SPMS process block is a monitoring system which is not associated with an operational time but can trigger a failure.

TPS
TPS process block considers a fixed or stochastic operational time.

3.5 Verification

In order to verify the new developed yard crane model for the container handling cycle of an automated yard crane, operational data of an automated yard crane from the reference case is used. As described in 3.2, there are multiple identical automated yard cranes in the commissioning phase. There is limited operational data available since only shuffle jobs are executed in practice to determine the performance of the automated yard crane. The method to collect the operational data from the reference project is elaborated first, the operational data used to verify the new developed model is extracted from a dataset from crane 1.

3.5.1 Retrieve operational data

Data from every crane can be collected using PLC traces and syslog-files, PLC traces monitor the signals going into the PLC, syslog-files monitor the active processes in the crane.

Syslog-files

An example of the first reference job is given in Table 6 where the syslog-file is used to determine the current activity of the yard crane at a certain time. The current and target position of the hoist, trolley and gantry as well as the automation systems are also mentioned in the syslog-file which will be used to verify the model. In order to extract the syslog-file example shown in Table 6 from the raw operational data was a time intensive process.

Table 6 An example of analyzing yard crane job activities via the syslog-file

Time	Syslog process	Activity
08:43:38,768	Procedure - Standby HO= +13222 TR= +5743 GA= +71312	
08:43:38,816	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**
08:43:48,910	Traject Block Movement: Moving Trolley to target position +14255 mm	**Trolley to source**
08:43:59,664	Procedure - Travel to Source HO= +5791 TR= +14255 GA= +71326	
08:44:02,310	Traject Block Movement: Hoisting/Lowering to Target +5791 mm	**Hoist to source + FLS**
08:44:23,225	AAPM_FINE: Adjust Stage started at HO=+6890	**MMS**
08:44:26,912	AAPM_FINE: Land Stage started at HO=+6407	
08:44:26,913	New setpoint Reached: TR=+13 GA=+9 S=+237	
08:44:28,306	Traject Block Movement: Lowering onto container	**Soft landing**
08:44:33,853	Traject Block Movement: End Position Reached	**Lock container**
08:44:37,408	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**
08:44:58,596	Traject Block Movement: Moving Trolley to target position +5735 mm	**Trolley to destination**
08:45:09,444	Procedure - Travel to Destination HO= +14173 TR= +5735 GA= +71326	
08:45:12,350	Traject Block Movement: Hoisting/Lowering to Target +14173 mm	**Hoist to destination + FLS**
08:45:29,511	AAPM_FINE: Adjust Stage started at HO=+15265	**MMS**
08:45:35,014	AAPM_FINE: Land Stage started at HO=+14781	
08:45:35,014	MM Task: New setpoint Reached: TR=+1 GA=-53 S=+211	
08:45:37,352	Traject Block Movement: Lowering onto container	**Soft landing**
08:45:42,650	Traject Block Movement: End Position Reached	**Unlock container**
08:45:59,696	Traject Block Movement: Hoisting/Lowering to Target +14637 mm	

The difference in time and covered distance of the hoist, trolley and gantry as well as automation systems can be examined using the same syslog-file as displayed in Table 7.

Table 7 An example of analyzing the job process times via the syslog-file

Subprocess	startTime	endTime	deltaTime	startPos (mm)	endPos (mm)	deltaPos (mm)
Hoist to upper	08:43:38,816	08:43:48,910	**00:10,094**	13222	21500	**8278**
Trolley to source	08:43:48,910	08:44:02,310	**00:13,400**	5743	14255	**8512**
Hoist to source + FLS	08:44:02,310	08:44:26,913	**00:24,603**	21500	6407	**15093**
MMS	08:44:23,225	08:44:26,913	**00:03,688**	6890	6407	**483**
Soft landing	08:44:26,913	08:44:33,853	**00:06,940**	6407	5791	**616**
Lock container	08:44:33,853	08:44:37,408	**00:03,555**			
Hoist to upper	08:44:37,408	08:44:58,596	**00:21,188**	5791	21500	**15709**
Trolley to destination	08:44:58,596	08:45:12,350	**00:13,754**	14255	5735	**8520**
Hoist to destination + FLS	08:45:12,350	08:45:35,014	**00:22,664**	21500	14781	**6719**
MMS	08:45:29,511	08:45:35,014	**00:05,503**	15265	14781	**484**
Soft landing	08:45:35,014	08:45:42,650	**00:07,636**	14781	14173	**608**
Unlock container	08:45:42,650	08:45:59,696	**00:17,046**			
			02:20,880			

PLC-traces

The speed, acceleration and deceleration of the hoist and trolley are verified using a PLC-trace. In Figure 20, an example is shown of a trolley movement.

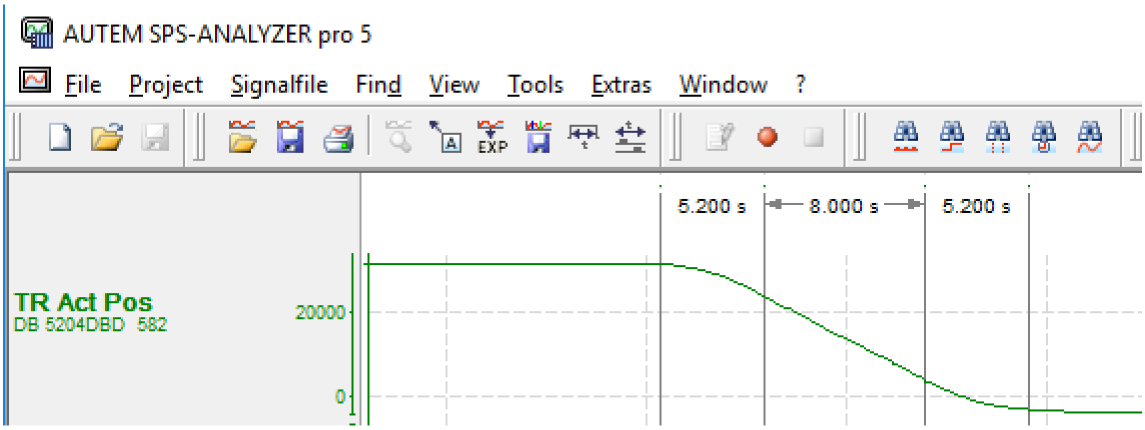

Figure 20 An example of measurements of a trolley move process from a PLC-trace

An example job is given in Table 8 where the difference in time and speed is used to verify the acceleration and deceleration of the trolley, the difference in time and position is used to verify the speed.

Table 8 An example of analyzing trolley acceleration, deceleration and speed via a PLC-trace

Unloaded	Position (mm)	Time	deltaPos	deltaTime	Result
Start acc.	31308	46:54,740	7405mm	5,200s	492mm/s^2
Stop acc.	23903	46:59,940	20459mm	8,000s	2557mm/s^2
Start dec.	3444	47:07,940	6747mm	5,200s	492mm/s^2
Stop dec.	-3303	47:13,140			

Dead time

For trolley and hoist movements, the start delay and fine positioning cannot be determined using syslog-files or PLC-traces. However, it can be calculated by measuring the time taken for a particular crane movement in practice, and compare this with the movement model shown in Figure 21. The movement model shown in Figure 21 calculates the theoretical exact time required to execute a movement. The time difference measured between this model and the measured time from the movement in practice is related to both the start delay and fine positioning and is referred to as the dead time. It is expected that the dead time is independent of the moved distance and therefore to have a constant time for each movement type.

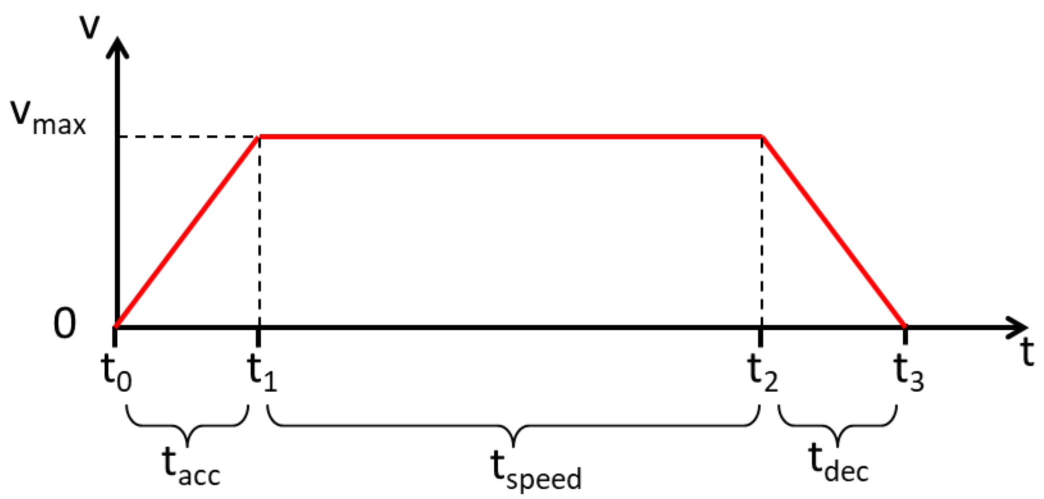

Figure 21 A model of the theoretical exact movement time

For example, the PLC-trace shows an acceleration and deceleration of $500mm/s^2$ and a speed of $2500mm/s$, the distance to cover is $17500mm$. If a constant acceleration is assumed, the acceleration or deceleration time will be equal to $\frac{2500mm/s}{500mm/s^2} = 5s$, which will result in a distance covered of $\frac{5s*2500mm/s}{2} = 6250mm$. Both acceleration and deceleration will cover a total of $2 * 6250mm = 12500mm$. The rest of the distance $17500mm - 12500mm = 5000mm$ will be covered with constant speed of $2500mm/s$ which will take $\frac{5000mm}{2500mm/s} = 2s$. The time of the movement is equal to $5s + 2s + 5s = 12s$. If a time for the movement process in practice is measured at $15s$, the resulting dead time for this movement process is equal to $3s$.

3.5.2 Process block parameter input

The limited operational data available from the executed performance tests by the automated yard crane from the reference project were regarding shuffle jobs in the same row. Not all process blocks are therefore used in the operational sequence of the new developed yard crane model, the gantry movement process block, the automation system process blocks regarding trucks and failures are not used for example.

The operational sequence of the new developed yard crane model can be verified using shuffle jobs for which only the process blocks of trolley and hoist movement, twistlocks, stacking guide, FLS and MMS are used. In order to verify the process blocks, first the parameter input values for these process blocks have to be determined. Eleven jobs executed by crane 1 with varying trolley and hoist movement distances are used to verify the input parameter values of the process blocks, these are shown in Table 9, the detailed data from these eleven jobs are added in appendix C. Using various trolley and hoist movement distances, a wide range of the trolley and hoist process block parameter input values are verified.

Table 9 The eleven reference jobs that were analyzed for parameter input verification including job specifications

		Source		Destination		Difference	
RefJob	**Date+Time**	**Row**	**Tier**	**Row**	**Tier**	**Row**	**Tier**
1	8-8-2018 08:46	5	2	2	5	-3	+3
2	8-8-2018 09:36	3	5	5	2	+2	-3
3	8-8-2018 12:33	9	5	5	2	-4	-3
4	8-8-2018 17:51	7	3	1	2	-6	-1
5	8-8-2018 17:54	9	1	2	1	-7	0
6	8-8-2018 17:57	7	2	2	2	-5	0
7	8-8-2018 17:59	11	1	3	1	-8	0
8	8-8-2018 18:05	8	3	1	3	-7	0
9	8-8-2018 18:08	8	2	2	3	-6	1
10	8-8-2018 18:10	8	1	3	3	-5	2
11	8-8-2018 18:16	12	2	4	2	-8	0

For the trolley and hoist process block parameter regarding acceleration, speed and deceleration, the input values are verified by comparing the extracted input values from operational data to the technical specifications of the reference case. The dead times for the trolley and hoist movement blocks are assumed to be constant with a small standard deviation. Process times for the process blocks regarding stacking guide, twistlocks, FLS and MMS are assumed to be constant with a small standard deviation as well. It is assumed that the performance of an automated crane is consistent due to the automated control.

Trolley movement

The technical specifications of the trolley speed, acceleration and deceleration are verified using PLC-traces, a constant dead time with a small standard deviation is verified using measurements from the syslog-files, the results are displayed in Table 10. Based on a 95% confidence interval and eleven measurements for trolley dead times, the uncertainty of the average dead time to source and to destination are $\pm 0.195s$ and $\pm 0.198s$ respectively.

Table 10 Trolley process block parameter input values

Parameter	**Value**	
Acceleration	$500mm/s^2$	
Deceleration	$500mm/s^2$	
Max speed	$2500mm/s$	
Dead time	Average (s)	σ (s)
To source	5.686	0.329
To destination	5.613	0.335

Hoist movement

The PLC-traces verified the double speed, soft landing speed, accelerations and decelerations and using the syslog-files. The dead time verified for hoisting an unloaded spreader was according to expectations, lowering an unloaded spreader resulted in a higher dead time with a higher standard deviation. When a container is locked to the spreader, the hoisting and lowering speed of the spreader varied between nominal speed and double speed shown by the PLC-traces and syslog-files. According to the technical specifications, a nominal hoisting speed should always be used when hoisting or lowering a loaded spreader, however, the hoist movement of the automated yard crane in practice is programmed in another way. Depending on the mass of the container, the hoisting and lowering speed of the spreader is increased to save time in the operational cycle. This was not described in the technical specification and the mass of the container is not measured in the PLC-traces or syslog-files.

The hoisting and lowering speed of a loaded spreader was not verified and therefore, the dead times for these process blocks were also not verified. The technical specification of the nominal speed will be used in the yard crane model. Since the hoist speed of the automated yard crane in practice is higher, the process time calculated by the process block for similar hoist movement distance will be higher when a container is locked to the spreader. It is assumed that the process blocks of a loaded hoist have the same dead time as the process blocks of an empty hoist since the type of movement is similar. The hoist process block input values are shown in Table 11. The nine valid measurements used to determine the average dead time of an empty hoist movement resulted in an uncertainty of $\pm 0.089s$ based on a 95% confidence interval. The dead time for the movement of lowering an empty spreader, the uncertainty of the average is $\pm 0.742s$ and is based on eleven measurements according to a 95% confidence interval.

Table 11 Hoist process block parameter input values, the red values are assumptions

Parameter	Value	
Acceleration	$450 mm/s^2$	
Deceleration	$450 mm/s^2$	
Nominal speed	$800 mm/s$	
Double speed	$1600 mm/s$	
Soft landing speed	$80 mm/s$	
Dead time	**Average (s)**	**σ (s)**
Empty hoist	1.316	0.136
Loaded hoist	1.316	0.136
Empty lower	4.173	1.256
Loaded lower	4.173	1.256

In order to fully verify these process blocks, the relation between nominal hoisting speed and container mass should be included as a level of detail. This can be determined and implemented in this model, however, since the PLC-traces and syslog files do not include information on container mass, the implementation cannot be verified with the current dataset from the reference project. Another solution can be to determine the average weight of a container or hoisting and lowering speed of a loaded spreader and use this to verify the process block. However, the data from the reference case is limited and was therefore not feasible in this research.

Stacking guide

The time for the stacking guide process was not directly verified using the syslog-file, stacking guides are not used when placing containers on the ground. A constant stacking guide process time was measured and verified by comparing operational data of jobs that required a container to be placed on the ground and on another container. The stacking guide process time is seen in Table 10 and has no standard deviation since this value was not directly verified.

Table 12 Stacking guide process block parameter input values

Parameter	Value
Stacking guide lowering/hoisting time (s)	13.480

Twistlocks

The constant twistlock lock and unlock process time is measured and verified by comparing the time when the spreader lands and hoists again which is shown in the syslog-files. The value for this process block is given in Table 13. Based on a 95% confidence interval and thirteen measurements, the uncertainty of the average is $\pm 0.022s$.

Table 13 Twistlock process block parameter input values

Parameter	Value	
	Average (s)	σ (s)
Twistlock lock/unlock time	3.552	0.040

FLS

The process time for FLS was not directly available in the reference jobs since only the start of the FLS process was mentioned in the operational data. The constant process time for FLS was measured and verified using a dataset containing multiple jobs with FLS errors. The time between starting the FLS measurement and confirmation of the FLS measurement error is measured which represents the FLS process time, this process time is displayed in Table 14. Based on a 95% confidence interval and only five measurements, the uncertainty of the average is $\pm 0.746s$.

Table 14 FLS process block parameter input values

Parameter	Value	
	Average (s)	σ (s)
FLS process time	8.003	0.851

MMS

The constant MMS process time was directly measured and verified using the syslog-files, the average process time and standard deviation are shown in Table 15. Based on a 95% confidence interval and 22 measurements, the uncertainty of the average is $\pm 0.347s$.

Table 15 MMS process block parameter input values

Parameter	Value	
	Average (s)	σ (s)
MMS process time	4.367	0.831

3.5.3 Process block output verification

The output of the process blocks used in the operational sequence for a job are compared to the operational performance of the automated yard crane from the reference case. Using the parameter input values for the process blocks found in 3.5.2, the process block output is verified using twelve varying jobs executed by crane 1. The twelve jobs used for process block output verification are shown in Table 16, the detailed data from these twelve jobs are also added in appendix C.

Table 16 Twelve verification jobs for process block output verification including job specifications

		Source		Destination	
JobNr	**Date+Time**	**Row**	**Tier**	**Row**	**Tier**
394	8-8-2018 12:59	7	6	3	1
395	8-8-2018 13:02	7	5	3	2
396	8-8-2018 13:04	7	4	3	3
397	8-8-2018 13:07	7	3	3	4
398	8-8-2018 13:10	7	2	3	5
399	8-8-2018 13:12	7	1	3	6
406	8-8-2018 13:29	5	6	1	1
407	8-8-2018 13:31	5	5	1	2
408	8-8-2018 13:34	5	4	1	3
409	8-8-2018 13:36	5	3	1	4
410	8-8-2018 13:39	5	2	1	5
411	8-8-2018 13:41	5	1	1	6

For each verification job, the average output of every process block is estimated by ten repetitions since stochastic values are used in some process block parameter inputs. This resulted in an uncertainty less than one second for all reference jobs based on a 95% confidence interval except for the loaded hoist movement process block. The deviation of each process block compared with the operational data for the twelve reference jobs are combined in an average deviation, a standard deviation and an uncertainty based on a 95% confidence interval as seen in Table 17.

Since parameter input values for some process blocks were not able to be extracted from the operational data directly, it was not possible to identify the process time for each process blocks. Therefore, MMS, FLS and stacking guide are measured in combination with other process blocks as seen in the table. The largest deviation, standard deviation and uncertainty of the estimated average are found in the hoist to upper and hoist to destination process blocks. This can be explained because the assumptions made for the loaded hoist movement are incorrect or it is due to the combination with the process blocks FLS, MMS and stacking guide. The detailed data from these twelve reference jobs are added in appendix C.

Table 17 Average process block output results of the twelve reference jobs compared to operational data including standard deviation and uncertainty

Process	**Average (s)**	**σ (s)**	**±95%**
Hoist to upper	-00,694	01,478	00,873
Trolley to source	-00,128	00,277	00,164
Hoist to source +MMS +FLS	02,079	01,332	00,787
Soft landing	00,320	00,859	00,507
Lock	00,004	00,055	00,032
Hoist to upper +SG	-01,655	04,264	02,520
Trolley to destination	-00,996	01,341	00,792
Hoist to destination +MMS +FLS	06,907	04,246	02,509
Soft landing	00,248	00,487	00,288
Unlock +SG	00,182	00,217	00,128
Difference	05,114	04,234	02,502

4 Performance prediction

In order to answer the research question, the influence of taking automation systems into account in yard crane models on the performance prediction of automated yard cranes has to be indicated. Therefore, the performance prediction of the new developed yard crane model will have to be compared with yard crane models that do not take automation systems into account. Since the new developed model is verified using the dataset from crane 1, the dataset from an identical automated yard crane, crane 2, is used in this chapter. In this chapter, the yard crane models and jobs that will be used in experiments are elaborated, the experimental setup for the performance prediction accuracy and the sensitivity analysis are described. At the end of the chapter, the results from the performance prediction accuracy experiments and sensitivity analysis are described with a discussion on the results.

4.1 Comparison models

For the performance prediction accuracy and sensitivity analysis, three yard crane models will be used named model A, B and C. Model A represents the new developed yard crane model, models B and C are models described in literature that will be used for comparison.

Model A is the new developed yard crane model that uses the operational sequence including automation systems as seen in Table 5 in section 3.3.2. The three yard crane components gantry, trolley including acceleration, deceleration and dead time is taken into account in this model.

Model B is based on the two high level models described in literature papers from Speer and Fischer [11] and Kemme [14] as displayed in Table 1 in section 2.4.1. These two models use gantry, trolley and hoist movement speeds, accelerations and decelerations and the operational sequence is based on the basic yard crane operational sequence described in Table 4 in section 3.3.1. Model B is used as a comparison model since this model represents the most complete yard crane model found in literature in terms of component details.

Model C is based on the medium level models mentioned in the literature papers of Galle et al. [10] and Saanen and Valkengoed [15] as seen in Table 1 in section 2.4.1 and will also use the basic yard crane operational sequence described in Table 4 in section 3.3.1. These models lack details on accelerations and decelerations, however, the model of Saanen and Valkengoed [15] does use a dead time between each component movement. The dead times for this model is determined using the same strategy used to determine the dead times for model A. Model C is included as a comparison model since dead time is assumed to be an important yard crane modeling parameter by the literature paper of Saanen and Valkengoed [15] which corresponds to the requirements set up according to experience from Siemens Cranes.

An overview of the differences between the three yard crane models is given in Table 18.

Table 18 The differences between the included model parameters of the three yard crane models

	Model A	Model B	Model C
Automation systems	✓	-	-
Acceleration/deceleration	✓	✓	-
Dead time	✓	-	✓

4.2 Job batches

In order to compare the performance prediction of the three yard crane models with the operational performance of crane 2, job batches are used. A job batch is a set of six sequentially executed jobs where the yard crane moves six stacked containers from one row to another as seen in Figure 22. A job batch is used in the reference case during the commissioning phase as a performance test to determine the performance of the automated yard crane. A job batch is characterized by the difference between the source and destination row and the initial starting position of the trolley with respect to the source row.

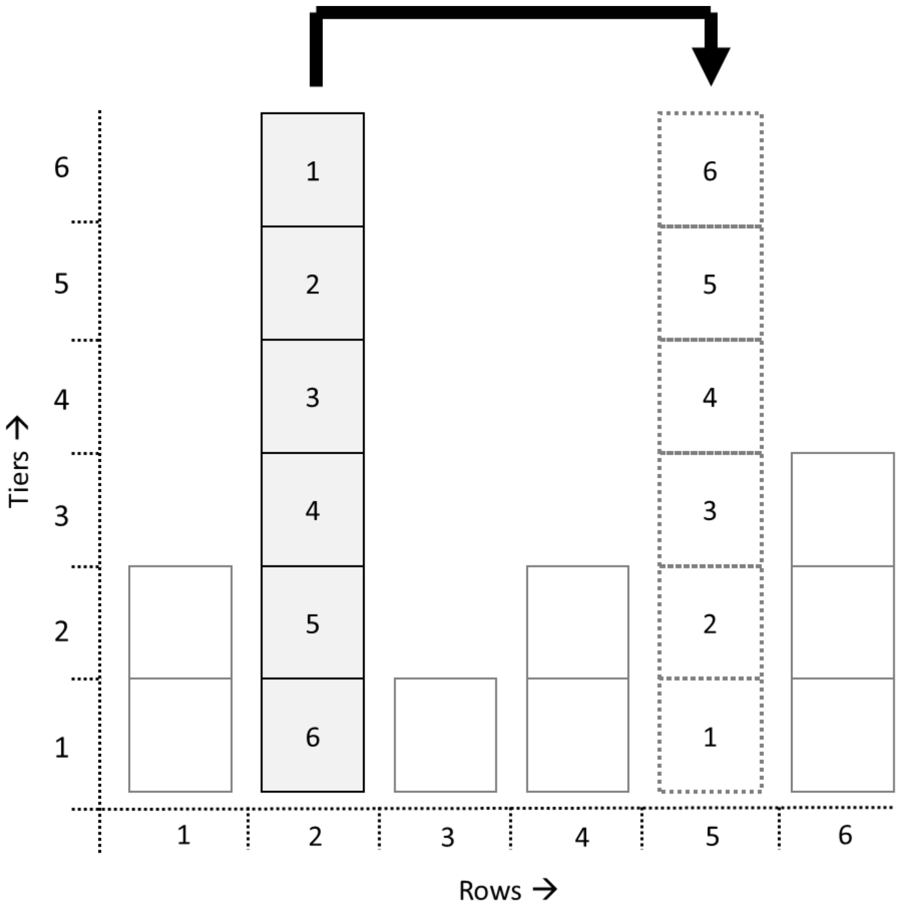

Figure 22 A schematic view of an example of a job batch procedure

4.3 Performance prediction experiments

The dataset of crane 2 included multiple executed performance tests, three different types of job batches were identified as shown in Table 19. The table shows for each batch number the source row, destination row and the resulting row difference, the trolley start position difference regarding the source row is given. The last column of the table displays the corresponding batch type according to the batch characteristics. The type of job batch represents the characterizations of that job batch and is given in a two digit number. The first digit represents the difference between the source and destination row, the second digit corresponds to the initial starting position of the trolley with respect to the source row.

Table 19 The job batches from the dataset of crane 2 including job specifications

Batch number	Source	Destination	Difference	Trolley start	Batch type
1	2	6	4	1	41
2	6	10	4	1	41
3	2	6	4	-1	41
4	4	8	4	-1	41
5	6	10	4	-1	41
6	8	12	4	-1	41
7	9	5	-4	1	41
8	7	3	-4	1	41
9	5	1	-4	1	41
10	11	7	-4	-1	41
11	9	5	-4	-1	41
12	7	3	-4	-1	41
13	5	7	2	3	23
14	7	9	2	3	23
15	3	5	2	-3	23
16	5	7	2	-3	23
17	7	9	2	-3	23
18	9	11	2	-3	23
19	8	6	-2	3	23
20	6	4	-2	3	23
21	4	2	-2	3	23
22	12	10	-2	-3	23
23	10	8	-2	-3	23
24	8	6	-2	-3	23
25	6	8	2	1	21
26	7	9	2	1	21
27	8	10	2	1	21
28	12	10	-2	1	21
29	11	9	-2	-1	21
30	10	8	-2	-1	21
31	9	7	-2	-1	21
32	8	6	-2	-1	21
33	7	5	-2	-1	21
34	6	4	-2	-1	21
35	5	3	-2	-1	21
36	4	2	-2	-1	21

For each identified batch type, twelve job batches are analyzed. Since each batch consists of six jobs, a total of 216 jobs are analyzed for the comparison. The operational data regarding the executing time of the job batches from crane 2 is compared with the predicted execution time by the three different models in order to determine the performance prediction accuracy of the three models. The results of the performance prediction accuracy experiments are elaborated in section 4.5.1, the discussion on the results can be found in section 4.6.1, more detailed results are added in appendix D.

4.4 Sensitivity analysis

An important quantitative technique in order to determine which model parameters have a significant impact on the model output is sensitivity analysis, in other words, how does the uncertainty in the output of a model can be associated to uncertainties in the model inputs. A sensitivity analysis is performed for all three models A, B and C and the output of the models is the predicted performance measured in moves per hour. Not only can the sensitivity be examined of each individual model, the performance prediction difference between the three models can be analyzed as well. A one-at-a-time sensitivity analysis is executed which is a local type of sensitivity analysis where one input value for a process block is varied at a time.

4.4.1 One-at-a-time

The three models have the trolley and hoist movement process blocks in common, both process blocks have multiple parameters. The trolley speed, trolley movement distance, hoist speed and hoist movement distance are parameters in these two process blocks that all three models have in common. In order to vary the input value for the trolley and hoist speed parameters, input values are used for these parameters mentioned in yard crane models described in literature in section 2.4.1. The parameter input variation for the trolley movement distance is based on the difference in container source and destination row. In order to vary the hoist movement distance input parameter, a job batch of two jobs will be used which allows variation in source and destination storage tier.

The experiments performed in the sensitivity analysis are jobs based on the job batch as explained in 4.2, the storage yard specifications from the reference case are used. It is assumed that the second job is executed directly after the first job is executed. Also, the starting position of the trolley is set on the source row of the first job, the job is finished after the spreader is hoisted to the maximum height. The two containers are stored on the same tier as they were picked from.

Hoist speed

Hoist speeds ranged from $0.5m/s$ ([10], [15]) to $0.8m/s$ ([14]) for a loaded spreader and from $1.0m/s$ ([14], [15]) to $1.5m/s$ ([11]) for an unloaded spreader. To cover all hoist speeds for the sensitivity analysis, the loaded hoist speed parameter input value will vary from $0.25m/s$ to $1.25m/s$, the unloaded hoist speed parameter input value will vary from $0.5m/s$ to $2.5m/s$. Both ranges are equally split up in nine sub-ranges to analyze values in between as seen in Table 20.

Table 20 Hoist speed parameter input value range

Experiment		1	2	3	4	5	6	7	8	9
Hoist speed [m/s]	Loaded	0,25	0,38	0,50	0,63	0,75	0,88	1,00	1,13	1,25
	Unloaded	0,50	0,75	1,00	1,25	1,50	1,75	2,00	2,25	2,50

In general, it is expected that all three models will have an increasing performance prediction as the hoist speed parameter input value increases over the experiments one to nine.

Acceleration and deceleration is taken into account in the hoist movement process block in models A and B. The acceleration and deceleration time depends on the maximum speed of the hoist and is therefore not a constant time when the input value for the hoist speed parameter is varied for experiments one to nine. At low hoisting speeds, less time is required for the hoist to reach its maximum speed but the total hoist movement process time to cover a certain distance is higher compared with high hoisting speeds. Since the movement distance is kept constant for experiments one to nine, increasing the hoist speed increases the time share of acceleration and deceleration in the total hoist movement process time. It can be that at a certain hoist speed, further increasing the hoist speed does not affect the performance prediction. At this hoist speed, the hoist does not reach its maximum speed and has to decelerate directly after accelerating in order to reach the target location, the hoist movement process then only consists of accelerating and decelerating. It is expected that for models A and B the rate of change decreases due to the implementation of acceleration and deceleration.

Dead time does not depend on the hoist speed and is included in the hoist movement process block of models A and C. At low hoist speeds, the time share of dead time in the total hoist movement process time is small since it requires more time for the hoist to move over a certain distance. The time share of dead time in the total hoist movement process will increase when increasing the hoist speed parameter input value. It is expected that for models A and C the rate of change decreases due to the implementation of dead times.

It is expected that the performance prediction of model A is the most insensitive to the varying hoist speed parameter input value since this model both includes dead times, acceleration and deceleration.

Trolley speed

Trolley speeds ranged from $1.0m/s$ ([11], [14], [10], [15]) up to $3m/s$ ([16]). The parameter input values for the trolley speed will vary according to the range from $1.0m/s$ to $3.0m/s$ to cover all trolley speeds in nine equal sub-ranges as shown in Table 21.

Table 21 Trolley speed parameter input value range

Experiment	10	11	12	13	14	15	16	17	18
Trolley speed [m/s]	1,00	1,25	1,50	1,75	2,00	2,25	2,50	2,75	3,00

Since the trolley movement process block is similar to the hoist movement process block, the same arguments can be used to expect that the performance prediction of all models increase when the trolley speed parameter input value is increased over the experiments. It is also expected that for models A and B, the rate of change of the performance prediction decreases due to the implementation of acceleration and deceleration. Furthermore, it is expected that for models A and C, the rate of change of the performance prediction decreases due to the implementation of dead times. As a result, it is expected that the performance prediction of model A is the most insensitive to the varying trolley speed parameter input value since this model both includes dead times as well as acceleration and deceleration.

Hoist movement distance

The hoist movement distance parameter input value is varied using two jobs in a job batch. In this way, the stacking height can be varied over six tiers which is displayed in Table 22.

Table 22 Hoist movement distance parameter input value range

Experiment			19	20	21	22	23
Job	1	Source tier	2	3	4	5	6
		Destination tier	1	2	3	4	5
	2	Source tier	1	2	3	4	5
		Destination tier	2	3	4	5	6

It is expected that increasing the hoist movement distance parameter input value results in a decreased performance prediction of all three models. However, increasing the hoist movement distance parameter input value results in a smaller time share of acceleration and deceleration time in the total hoist movement process. It is expected that this decreases the rate of change of the performance prediction of models A and B. When the movement distance of the hoist is increased, the time share of dead time in the total process time decreases. It is therefore expected that the rate of change of the performance prediction of models A and C decreases. It is expected that the performance prediction of model A is the most insensitive to the varying hoist movement distance parameter input value since this model both includes dead times, acceleration and deceleration.

Trolley movement distance

The storage yard from the reference case has 12 rows, to vary the trolley movement distance parameter input value, the difference between the source row and the destination row is varied according to the table seen in Table 23.

Table 23 Trolley movement distance parameter input value range

Experiment	24	25	26	27	28	29
Source row	1	1	1	1	1	1
Destination row	2	4	6	8	10	12

Since the trolley movement process block is similar to the hoist movement process block, the same arguments can be used to expect that the performance prediction of all models increase when the trolley movement distance parameter input value is increased over the experiments. It is also expected that for models A and B, the rate of change of the performance prediction decreases due to the implementation of acceleration and deceleration. Furthermore, it is expected that for models A and C, the rate of change of the performance prediction decreases due to the implementation of dead times. As a result, it is expected that the performance prediction of model A is the most insensitive to the varying trolley movement distance parameter input value since this model both includes dead times as well as acceleration and deceleration.

4.4.2 Parameter input value combinations

In order to execute the local one-at-a-time sensitivity analysis type, the parameter input values will be varied according to a reference set of parameter input values. The speed values for this reference set are $0.75m/s$ nominal and $1.5m/s$ double speed for the hoist and $2.0m/s$ for the trolley. The two jobs executed in the experiments are regarding two containers picked up from row 1 tier 4 and 3 and are placed on row 6 tier 3 and 4 sequentially.

An overview of all experiments and corresponding parameter input values is given in Table 24. The reference set of parameter input values can be seen in experiment 5, 14, 21 and 26. The result of the sensitivity analysis is elaborated in section 4.5.2, a discussion on the results can be found in section 4.6.2, more detailed results are added in appendix E.

Table 24 Experiments for all parameter input value combinations

	Speed [m/s]			Job 1				Job 2			
	Hoist		Trolley	Source		Destination		Source		Destination	
ExpNr	Nominal	Double		Row	Tier	Row	Tier	Row	Tier	Row	Tier
1	0,25	0,50	2,00	1	4	6	3	1	3	6	4
2	0,38	0,75	2,00	1	4	6	3	1	3	6	4
3	0,50	1,00	2,00	1	4	6	3	1	3	6	4
4	0,63	1,25	2,00	1	4	6	3	1	3	6	4
5	0,75	1,50	2,00	1	4	6	3	1	3	6	4
6	0,88	1,75	2,00	1	4	6	3	1	3	6	4
7	1,00	2,00	2,00	1	4	6	3	1	3	6	4
8	1,13	2,25	2,00	1	4	6	3	1	3	6	4
9	1,25	2,50	2,00	1	4	6	3	1	3	6	4
10	0,75	1,50	1,00	1	4	6	3	1	3	6	4
11	0,75	1,50	1,25	1	4	6	3	1	3	6	4
12	0,75	1,50	1,50	1	4	6	3	1	3	6	4
13	0,75	1,50	1,75	1	4	6	3	1	3	6	4
14	0,75	1,50	2,00	1	4	6	3	1	3	6	4
15	0,75	1,50	2,25	1	4	6	3	1	3	6	4
16	0,75	1,50	2,50	1	4	6	3	1	3	6	4
17	0,75	1,50	2,75	1	4	6	3	1	3	6	4
18	0,75	1,50	3,00	1	4	6	3	1	3	6	4
19	0,75	1,50	2,00	1	6	6	1	1	5	6	2
20	0,75	1,50	2,00	1	5	6	2	1	4	6	3
21	0,75	1,50	2,00	1	4	6	3	1	3	6	4
22	0,75	1,50	2,00	1	3	6	4	1	2	6	5
23	0,75	1,50	2,00	1	2	6	5	1	1	6	6
24	0,75	1,50	2,00	1	4	2	3	1	3	2	4
25	0,75	1,50	2,00	1	4	4	3	1	3	4	4
26	0,75	1,50	2,00	1	4	6	3	1	3	6	4
27	0,75	1,50	2,00	1	4	8	3	1	3	8	4
28	0,75	1,50	2,00	1	4	10	3	1	3	10	4
29	0,75	1,50	2,00	1	4	12	3	1	3	12	4

4.5 Results

The results for the performance prediction accuracy experiments and the sensitivity analysis are described in this paragraph. All three models A, B and C use stochastic values for some parameter inputs used in certain process blocks. The performance prediction results by the models mentioned in this paragraph are an estimated average based on a number of experiment repetitions, increasing the number of repetitions increases the reliability of the estimated average. The uncertainty of the estimated average performance prediction was lower than 0.5 second when using 1000 repetitions per experiment based on a 95% confidence interval. Using the same amount of repetitions per experiment for the sensitivity analysis, the uncertainty of the estimated average output result was lower than 0.1 second based on a 95% confidence interval.

4.5.1 Performance prediction

The results for job batch type 41 are displayed in Table 25. Based on twelve batches, crane 2 from the reference case completes a batch of type 41 on average in 14 minutes and 48 seconds with a standard deviation of 21 seconds. This translates to a performance of around 24 moves per hour. For this batch type, model A predicts a yard crane performance of around 24 moves per hour as well, but with a smaller standard deviation of 6 seconds. Model B predicts a performance of around 45 moves per hour without any standard deviation. Model C has the largest standard deviation of the three models of 14 seconds and predicts a performance of around 32 moves per hour.

Table 25 Performance prediction results for job batch type 41

Type 41	Crane 2	Model A	Model B	Model C
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	14:48	14:48 (+0,00%)	07:56 (-46,40%)	11:06 (-25,00%)
σ	00:21	00:06	00:00	00:14
m/h	24,32	24,32 (+0,00%)	45,38 (+86,55%)	32,43 (+33,33%)

The results for job batch type 23 are shown in Table 26. Crane 2 has a performance for this batch type of around 25 moves per hour and a standard deviation of around 22 seconds. All yard crane models have the same standard deviation compared to the previous analyzed batch type. Model A predicts that more time is needed to execute a job batch from type 23 but also predicts a performance of around 25 moves per hour. Model B and C predict a performance of around 48 and 34 moves per hour respectively.

Table 26 Performance prediction results for job batch type 23

Type 23	Crane 2	Model A	Model B	Model C
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	14:09	14:21 (+1,41%)	07:29 (-47,11%)	10:43 (-24,26%)
σ	00:22	00:06	00:00	00:14
m/h	25,44	25,09 (-1,39%)	48,11 (+89,09%)	33,59 (+32,04%)

The results for job batch type 21 are given in Table 27. A larger standard deviation is measured for the performance of crane 2 compared to the other two batch types. The performance of this crane according to the operational data from the reference case is around 26 moves per hour. All three models again have similar standard deviations compared to the other batch types. Model A predicts a lower performance of the crane at around 25 moves per hour. Model B and C predict a performance of around 49 and 34 moves per hour respectively.

Table 27 Performance prediction results for job batch type 21

Type 21	Crane 2	Model A	Model B	Model C
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	13:59	14:18 (+2,26%)	07:25 (-46,96%)	10:41 (-23,60%)
σ	00:37	00:06	00:00	00:14
m/h	25,74	25,17 (-2,21%)	48,54 (+88,54%)	33,70 (+30,89%)

4.5.2 Sensitivity analysis

The results of the sensitivity analysis are elaborated per varied parameter input value.

Hoist speed

The results for the experiments that vary the hoist speed parameter input value is shown in Table 28. The performance prediction of each model is displayed in the table as well as the increments in performance prediction of each model for each experiment relative to the previous experiment is given.

Table 28 Hoist speed parameter input value results

	Exp Nr	1	2	3	4	5	6	7	8	9
Model A	**m/h**	15,40	18,93	21,14	22,73	23,76	24,54	25,04	25,42	25,66
			+22,97%	+11,66%	+7,51%	+4,57%	+3,26%	+2,06%	+1,49%	+0,97%
Model B	**m/h**	21,47	29,47	35,45	40,35	43,87	46,69	48,63	50,12	51,13
			+37,25%	+20,30%	+13,81%	+8,72%	+6,42%	+4,16%	+3,07%	+2,02%
Model C	**m/h**	17,37	22,54	26,24	29,29	31,62	33,63	35,23	36,66	37,82
			+29,72%	+16,43%	+11,63%	+7,95%	+6,37%	+4,75%	+4,05%	+3,18%

All three models show an increase of the performance prediction when the hoist speed parameter input value is increased. However, the rate of change of the performance prediction increments of the three models decreases when the hoist speed is increased.

Trolley speed

The results for the experiments that vary the trolley speed parameter input value is displayed in Table 29. The performance prediction of each model is shown in the table as well as the increments in performance prediction of each model for each experiment relative to the previous experiment is displayed.

Table 29 Trolley speed parameter input value results

	Exp Nr	10	11	12	13	14	15	16	17	18
Model A	**m/h**	22,62	23,13	23,45	23,64	23,76	23,83	23,86	23,87	23,87
	%		+2,26%	+1,36%	+0,84%	+0,51%	+0,29%	+0,13%	+0,02%	+0,00%
Model B	**m/h**	40,13	41,76	42,80	43,46	43,87	44,10	44,21	44,23	44,23
	%		+4,07%	+2,48%	+1,54%	+0,94%	+0,53%	+0,24%	+0,04%	+0,00%
Model C	**m/h**	28,92	29,94	30,66	31,20	31,62	31,95	32,22	32,45	32,64
	%		+3,54%	+2,42%	+1,76%	+1,34%	+1,05%	+0,85%	+0,70%	+0,59%

All three models show an increase of the performance prediction when the trolley speed parameter input value is increased. However, the rate of change of the performance prediction increments of the three models decreases. At the last experiment, experiment 18, the speed of the trolley does not affect the performance prediction of models A and B anymore.

Hoist movement distance

The results for the experiments that vary the hoist movement distance parameter input value is shown in Table 30. The performance prediction of each model is displayed in the table as well as the increments in performance prediction of each model for each experiment relative to the previous experiment is given.

Table 30 Hoist movement distance parameter input value results

	Exp Nr	19	20	21	22	23
Model A	**m/h**	28,07	25,73	23,76	22,08	21,44
			-8,33%	-7,65%	-7,10%	-2,88%
Model B	**m/h**	61,17	51,08	43,87	38,44	34,21
			-16,50%	-14,11%	-12,37%	-11,01%
Model C	**m/h**	39,71	35,20	31,62	28,70	26,27
			-11,35%	-10,17%	-9,23%	-8,45%

All three models show a decrease of the performance prediction when the hoist movement distance parameter input value is increased. However, the rate of change of the performance prediction increments of the three models decreases when the hoist movement distance is increased.

Trolley movement distance
The results for the experiments that vary the trolley movement distance parameter input value is displayed in Table 31. The performance prediction of each model is shown in the table as well as the increments in performance prediction of each model for each experiment relative to the previous experiment is given.

Table 31 Trolley movement distance parameter input value results

	Exp Nr	24	25	26	27	28	29
Model A	**m/h**	25,36	24,45	23,76	23,11	22,50	21,92
			-3,56%	-2,81%	-2,74%	-2,66%	-2,59%
Model B	**m/h**	49,61	46,27	43,87	41,70	39,74	37,96
			-6,74%	-5,19%	-4,94%	-4,70%	-4,49%
Model C	**m/h**	34,18	32,85	31,62	30,48	29,42	28,43
			-3,89%	-3,74%	-3,61%	-3,48%	-3,36%

All three models show a decrease of the performance prediction when the trolley movement distance parameter input value is increased. However, the rate of change of the performance prediction increments of the three models decreases when the trolley movement distance is increased.

4.6 Discussion

The results from the performance prediction and sensitivity analysis are discussed in this paragraph.

4.6.1 Performance prediction

The results from every batch type showed a varying performance of the automated yard crane with standard deviations of 21, 22 and 37 seconds. This result was not expected since the automated yard crane operation is controlled automatically. The deviations can be explained by external influencing factors on the automation systems such as wind or rain for example. Also, the container mass influenced the hoisting and lowering speed of a loaded spreader which can cause a deviation in hoist movement process time of jobs with identical properties.

The results of the job batch types show that model A predicts the performance of the automated yard crane the most accurate, compared to the other yard crane models, with a deviation of around 1 or 2 percent. This can be explained because this model includes both dead times, automation systems and accelerations and decelerations. Model A is also the only model that predicts a lower performance compared to the operational performance of the automated yard crane. This can be caused by the assumption of hoisting and lowering the spreader loaded with a container is done with nominal speed while in practice, the speed is higher depending on the mass of the container.

For the three job batch types, model B almost predicts a doubled performance compared to the reference crane from the reference case. This can be caused not taking automation systems and dead times into account. For example, for each container handling, the FLS process is executed two times which equal a process time of around $2 * 8s = 16s$. Since a batch consists of six jobs, this equals a total FLS process time of around $6 * 16s = 96s$ per job batch which is only one automation system. The hoist and trolley process blocks are addressed multiple times per container handling which also includes dead times, these are also not taken into account by model B. Because of this, there is only one stochastic process block which is the locking and unlocking of the container to the spreader. The stochastic value for these process blocks has a low standard deviation which can results in the low standard deviation seen for model B.

Model C does not take acceleration and deceleration into account but does include dead times. Due to the approach on determining the dead time for the process blocks, acceleration and deceleration affect the dead times. This resulted in relatively large dead times for this model and can explain the high standard deviation measured for model C. However, this model predicts the performance more accurately than model B that does take acceleration and deceleration into account but does not include dead times. Nevertheless, model C is not as accurate as model A on predicting the performance of the automated yard crane from the reference case which can be caused by not taking automation systems into account.

4.6.2 Sensitivity analysis

The discussion on the results of the sensitivity analysis are elaborated per varied parameter input value.

Hoist speed

The results show that an increased hoist speed parameter input value results in an increased performance prediction of all three models which was expected. It was also expected that the rate of change of the increased predicted performance would decrease which is also confirmed by the results. Model A is the least sensitive to the changing hoist speed which was expected and can be explained because this model includes accelerations, decelerations and dead times. For experiments two to six, model B appears to be the most sensitive to an increasing hoist speed, model C is more sensitive than mode B for experiments seven to nine.

The hoist speed for which the hoist movement process only consists of acceleration and deceleration is higher than the highest hoist speed used in the experiments since the performance prediction of models A and B are affected for all experiments.

Trolley speed

The expected results for varying trolley speed parameter input value are confirmed by the results. An increased trolley speed results in an increased performance prediction of all three models, the rate of change of the increased predicted performance decreases. Model A is the least sensitive to the changing trolley speed which can be explained because this model includes accelerations, decelerations and dead times. For experiments elven and twelve, model B is more sensitive to an increased trolley speed but model C is more sensitive than model B for experiments thirteen to eighteen.

The trolley speed used in experiment 18 did not affect the performance predictions of models A and B. It was expected that at a certain trolley speed, the trolley movement process only consists of acceleration and deceleration. The results at experiment 18 can be explained with this theory, the trolley speed can be too high to affect the performance prediction of models A and B.

Hoist movement distance
Increasing the hoist movement distance parameter input value resulted in a decreased performance prediction of all three models which was expected. Increasing the hoist movement distance decreased the rate of change of the predicted performance which was also expected.

Model A showed the lowest sensitivity to a varying hoist movement distance which was expected and can be explained because this model includes accelerations, decelerations and dead times.

Trolley movement distance
An increased trolley movement distance parameter input value resulted in a decreased performance prediction as well as a decreased rate of change of all three models which was expected. Model A is the least sensitive to a varying trolley movement distance was expected and can be explained because this model includes accelerations, decelerations and dead times.

5 Conclusions and recommendations

5.1 Conclusions

A new yard crane model is developed with an operational sequence that includes automation systems. It was expected that automation systems are necessary to take into account in order to accurately predict the performance of automated yard cranes. With the use of a reference case, operational data from practice regarding an automated yard crane is used in order to determine the performance prediction accuracy of the new developed yard crane model. For various testing cases, the new developed yard crane model predicted a performance that deviated less than 3% compared to the operational performance of the automated yard crane from the reference case. To put this into perspective, two competitive yard crane models described in literature, that did not take automation systems into account and were used for logistical studies in the storage yard, predicted a performance that was 30% and 80% higher respectively. To answer the research question, the influence on taking automation systems into account in yard crane models on the performance prediction of automated yard crane systems is substantial. It is therefore necessary to include automation systems if a yard crane model is used to accurately predict the performance of an automated yard crane.

The new developed yard crane model can be used with the current development regarding automation and interconnecting elements on container terminals. With the new model predicting the performance of automated yard cranes more accurately, the deviation between the predicted performance and the operational performance of the automated yard crane can be reduced. Since the performance of the container terminal is most influenced by the storage yard, processes connected with the storage yard can be optimized. This can result in an increased efficiency of the logistical processes towards the landside and quayside operational areas and therefore reduce the financial consequences caused by logistical inefficiencies. With the new developed yard crane model, Siemens Cranes is now able to predict the performance of their engineered solution offered to the customer more accurately.

The new developed yard crane model can be used for any type of crane and any configuration. The process blocks used in the operational sequence can be configured to the required level of detail. The operational sequence is set up modularly and can be modified, process blocks can be excluded from the operational sequence as well as new process blocks can be developed and added. The new developed yard crane model can therefore be used for various logistic studies, the model can be used for yard crane performance analysis by analyzing the detailed cycle time, but also for crane scheduling problems as well as container terminal performance studies.

5.2 Recommendations

More detail is required in the process block of lowering and hoisting a loaded spreader if the process time of this process block has to be determined more accurately. Extracting process block parameter input values from operational data learned that the hoist speed can be varied depending on the container mass. This modeling detail in the process block of the hoist movement was not found in the reviewed literature nor in the technical specification of the automated yard crane in the reference case. This detail can be implemented in the hoist movement process block by defining a relation between the container mass and the hoist speed and the mass of the handled container has to be known. Otherwise, it is also possible to adjust the hoist speed of a loaded spreader according to an assumed average container weight.

It was assumed that eleven jobs with varying trolley and hoist movement distances were sufficient in order to accurately determine the process block parameter input values, however, some values for process block input parameters had a relative high uncertainty. It was expected that an automated yard crane has a consistent performance due to automation and therefore, eleven reference jobs were assumed to be sufficient. Also, the operational data was not directly ready to use, extracting usable data from the raw syslog-files was time consuming and time in the project was limited. In order to have a higher process block output accuracy, more jobs will have to be analyzed to have a lower uncertainty on the used process block parameter input values.

Only shuffle jobs from performance tests in the commissioning phase of an automated yard crane were used to verify and analyze the performance prediction of the new developed yard crane model. Since the storage yard is connected to the quayside and landside operational area, the validity of the new developed model can be increased by verifying the performance prediction according to loading and unloading jobs which involves horizontal transport. The validity of the new developed yard crane model can also be increased by verifying the model using various other projects involving automated yard cranes.

As the operational sequence of the new developed yard crane model is modularly built from process blocks with a configurable level of details, the model can be used for various logistic studies on the storage yard and container terminal. New technological yard crane developments can be adapted in the operational sequence and process blocks to test the impact on the cycle time performance. The new developed model can be used for crane scheduling studies regarding any configuration automated yard cranes operating on a block. Logistic problems on the interaction between automated yard cranes and horizontal transport can be studied with more detail and accuracy and can be extended to a logistic study of container handlings over a complete container terminal.

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7 Appendix

A. Scientific paper

Container handling performance prediction model for automated yard cranes

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Current yard crane models used for studies on various logistic processes in container terminals involving automated yard cranes do not take automation systems into account. The operational container handling performance of automated yard cranes are therefore inaccurately predicted by current models. To avoid logistical problems and financial consequences, it is assumed that taking automation systems into account in yard crane models is essential in order to accurately predict the performance of automated yard cranes. Therefore, a new yard crane model that takes automation systems into account is developed verified and compared. The new model is modularly set up using process blocks with a configurable level of detail. Operational data from a reference case involving automated yard cranes is used to verify and to compare the new developed model with current yard crane models.

Keywords – yard crane, modeling, cycle time, performance, automation

I. Introduction

A container terminal serves as a connecting link between different modes of container transportation [1]. A port container terminal consists of three main areas: the quayside area, the hinterland area and the storage yard area [2]. Due to technological developments, there is an increasing degree of automation and complex interaction between elements operating throughout the container terminal [3]. The demand for more accurate models of container terminal operations has grown due to the increased competitiveness between container terminals and high investment and operational costs involved [4]. The performance of the container terminal is influenced most by the storage yard area on which yard cranes are the main container handling equipment [5]. The container handling performance of yard cranes is often measured in moves per hour and can be determined by calculating the time to complete a container handling cycle, the cycle time.

When developing a new, or updating an existing container terminal with new automated yard cranes, the expected performance of the new yard cranes is predicted in advance using a yard crane model. A deviation between the predicted performance of the yard crane model and the operational performance of the automated yard crane system in practice can result in logistical problems. These logistical problems can extend to the complete terminal since the storage yard influences the performance of the container terminal the most. The logistical problems can decrease efficiency of the container terminal and therefore can result in financial consequences.

A storage yard consists of multiple blocks with a number of bays, rows and tiers in which containers are stored in length, width and height. The most common type of automated container handling equipment operating in the storage yard is a yard crane. Yard cranes operating on these blocks are responsible for storage and retrieval of containers. The three main moving components within a yard crane are the portal of the gantry, the trolley and the spreader which are used to move to different bays, rows and tiers as shown in Figure 1.

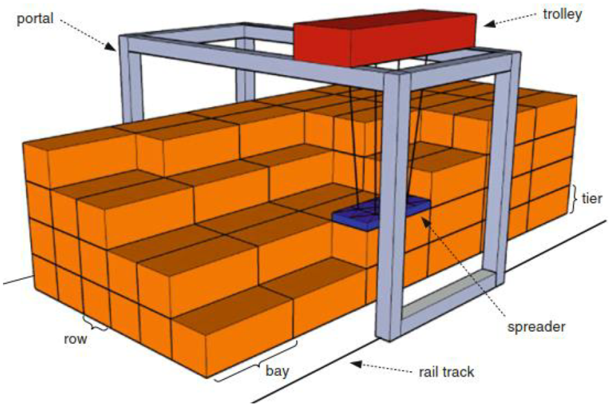

Figure 1 Schematic overview of a yard crane system on a storage yard block, the portal moves on a rail track and supports a trolley, a spreader is suspended from the trolley which can connect to a container. [5]

The performance of a manual yard crane not only depends on the yard crane specifications but also on the skill of the operator. An automated yard crane is not operated by an operator and therefore requires automation systems in order to operate. The performance of an automated yard crane is not only depending on the yard crane specifications, but also on the performance of the automation systems. It is therefore assumed that taking automation systems into account in yard crane models is essential in order to accurately predict the performance of automated yard cranes.

A. Current state of yard crane modeling

The current state of yard crane modelling is addressed in, for example ([6] [2], [3], [7], [4]). These yard crane models are used in various studies on logistic problems on the storage yard and container terminal. The level of detail used in the modeling parameters of the yard crane models varied depending on the logistic problem that was studied. Yard crane models used for crane scheduling studies often include the most detail by taking the gantry, trolley and hoist movement speed, acceleration and deceleration into account. Some models compensate for the less detailed modeling parameters by including stochastic container handling times or lowered movement speeds. Other models use modeling parameters that are related to the spreader, failures, container relocation or dead times.

Storage yard modeling parameters, that influence the cycle time of the yard crane model, can be categorized into strategical decision and operational planning parameters. Strategical decision parameters are related to storage yard block dimensions, layout, container handling equipment and configuration. Operational planning parameters are regarding stacking strategy and crane scheduling. An overview of the modeling parameters is given in Table 1.

Table 1 Overview of modeling parameters that influence the cycle time of a yard crane.

Yard crane	
Gantry	Speed, acceleration, deceleration, dead time
Trolley	Speed, acceleration, deceleration, dead time
Hoist	Speed, acceleration, deceleration, dead time
Spreader	Size adjustment
Storage yard	
<u>Strategical design</u>	
Block	Dimensions, layout
Handling equipment	Type, configuration
<u>Operational planning</u>	
Stacking strategy	
Crane scheduling	

B. Basis for cycle time calculations

The yard crane operational sequence exists of four basic processes to complete a container handling cycle as displayed in Figure 2.

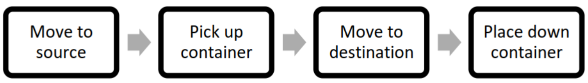

Figure 2 The four basic yard crane processes in an operational sequence to complete a container handling cycle.

II. Method

A. Yard crane modeling

A new yard crane model is developed based on the four basic crane processes in the operational sequence and is extended with automation systems that are required for automated yard crane operation. The new model takes the gantry, trolley and hoist movement speed, acceleration and deceleration into account as well as dead time. Movement of the gantry, trolley and hoist are modeled according to the graph as seen in Figure 3. The sum of the start delay (t_{sd}), acceleration (t_{acc}), constant speed (t_c), deceleration (t_{dec}) and fine positioning (t_{fp}) time equal the process time of the movement. The start delay and fine positioning time combined represent the dead time for the modeled movement.

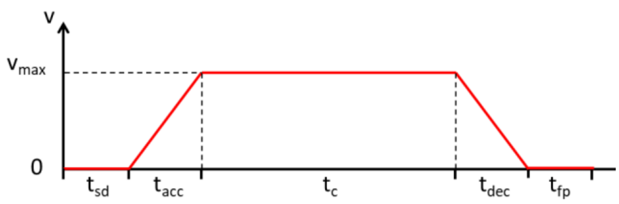

Figure 3 The model to determine the process time of a yard crane component movement process where v_{max} is the maximum speed.

The automation systems required for automated yard crane operation are:

- Automatic truck identification system (ATIDS), used to verify the identification of the truck to be loaded or unloaded
- Chassis lifting protection system (CLPS), safety system to prevent lifting the truck's chassis when loading or unloading.
- Container twistlock detection system (CTDS), detects twistlocks stuck on a container.
- Final landing system (FLS), measures and calculates the landing trajectory of the spreader.
- Load collision prevention system (LCPS), safety system that detects objects in the container flight path.
- Micro motion system (MMS), adjusts the spreader position according to the FLS measurements.
- Spreader position monitoring system (SPMS), monitors the position of the spreader.
- Truck positioning system (TPS), aligns the trailer when loading or unloading a truck.

The new developed yard crane model including automation systems will be referred to as model A. The operational sequence used for model A is shown in Table 2 and is derived from and developed by zooming in on the four basic yard crane processes. Blue blocks indicate yard crane component movement processes, yellow blocks indicate automation system processes and green blocks indicate spreader system processes. There are no processing times associated with the red process blocks. In the operational sequence, in order to proceed to the next sequence, all processes must be completed at the current sequence. The process time for a process block depends on the type of process. The process time for a process block can be modeled as a constant time, stochastic time or can be depending on the job. Automation systems can represent monitoring systems which are not associated with a process time.

Table 2 New yard crane operational sequence model including automation systems used for model A.

1	Start				
2	Job received from TOS				
3	Hoist spreader to upper	LCPS			
4	Trolley to safe	LCPS			
5	Gantry to source	LCPS	Spreader adjustment		
6	ATIDS				
7	TPS				
8	Trolley to source	LCPS			
9	FLS				
10	Lower spreader to source	LCPS	SPMS	MMS	
11	Soft landing	LCPS	SPMS		
12	Lock container				
13	CLPS				
14	Hoist spreader to upper	LCPS	SPMS	Lower stacking guides	
15	CTDS				
16	Trolley to safe	LCPS			
17	Gantry to destination	LCPS			
18	Troley to destination	LCPS			
19	FLS				
20	Lower spreader to destination	LCPS	SPMS	MMS	
21	Soft landing	LCPS	SPMS		
22	Hoist stacking guides				
23	Unlock container				
24	CLPS				
25	Hoist spreader to safe	LCPS	SPMS		
26	Send completed job to TOS				
27	Finish				

To determine the accuracy of model A, the performance prediction is compared to the operational performance of an automated yard crane in practice from a reference case. Model A will also be compared to two competitive models as described in literature, model B (based on [8], [9]) and C (based on [10], [11]). Model A can then also be compared with the performance prediction of yard crane models that do not take automation systems into account. Model B does not take dead times into account, model C does include dead times but does not take accelerations and decelerations into account. The basic yard crane operational sequence without automation systems used for model B and C is displayed in Table 3.

Table 3 Basic operational sequence used for models B and C.

1	Start	
2	Job received from TOS	
3	Hoist spreader to upper	
4	Trolley to safe	
5	Gantry to source	Spreader adjustment
6	Trolley to source	
7	Lower spreader to source	
8	Lock container	
9	Hoist spreader to upper	
10	Trolley to safe	
11	Gantry to destination	
12	Troley to destination	
13	Lower spreader to destination	
14	Unlock container	
15	Hoist spreader to safe	
16	Send completed job to TOS	
17	Finish	

An overview of the differences between the modeling parameters taken into account by the models A, B and C are shown in Table 4.

Table 4 Overview on the modeling parameter differences in between the yard crane models A, B and C.

	Model A	Model B	Model C
Automation systems	✓	-	-
Acceleration/deceleration	✓	✓	-
Dead time	✓	-	✓

B. Model verification

Operational data of the automated yard crane from the reference case is extracted and used for verification and to determine input values for the process block parameters of model A. Other operational data is used to verify the performance prediction by model A by comparing the outputs of the process blocks with the operational performance from the reference case. Eleven container handling moves with varying hoist and trolley movement distances are used to verify and determine input values for the process block parameters. Twelve container handling moves were analyzed to verify the output of the process blocks in the operational sequence of model A.

The performance prediction of model A can now be compared with models B and C regarding the operational performance of the automated yard crane. Since the reference case is in a commissioning phase, the operational data consists of executed performance tests for which shuffle jobs are used. A shuffle job is a container handling movement of a yard crane that consists of picking and placing a container in the same storage yard block.

C. Comparison setup

For the comparison, a different operational data set from an identical automated yard crane from the reference case is used which included shuffle job batches. A job batch is a batch of six jobs executed in sequence were the containers are picked up from one row and placed down on another row as displayed in Figure 4.

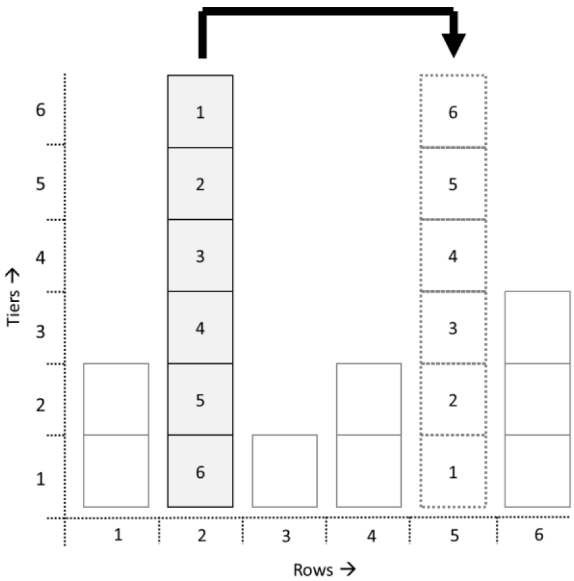

Figure 4 Schematic representation of a job batch procedure executed by the automated yard crane from the reference case.

A job batch is categorized based on the difference in source and destination row as well as on the difference in the starting position of the trolley with respect to the source row. Three types of job batches have been identified from the operational data and can be described by two numbers. The first number of the job batch type indicates the difference in source and destination row, the second number indicates the starting position difference of the trolley with respect to the source row. The three job batch types identified are 41, 23 and 21.

For each job batch type, twelve executed batches are extracted from the operational data. With each batch consisting of six jobs, a total of 216 jobs are analyzed and used in the comparison. The results of job batch type 41, 23 and 21 are shown in Table 5, Table 6 and Table 7 respectively.

III. Results

The average time and difference compared to the operational performance for each job batch type shown in the tables is the average time for completing a job batch based on twelve job batches per job batch type. The standard deviation regarding the average is given as well as the uncertainty of the average based on a 95% confidence interval. The time to execute a job batch is converted into a performance measured in moves per hour (m/h).

Table 5 Results for shuffle job batch type 41

Type 41	**Ref. case**	**Model A**	**Model B**	**Model C**
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	14:48	14:48 (+0,00%)	07:56 (-46,40%)	11:06 (-25,00%)
σ	00:21	00:06	00:00	00:14
±95%	00:12	00:04	00:00	00:08
m/h	24,32	24,32 (+0,00%)	45,38 (+86,55%)	32,43 (+33,33%)

Table 6 Results for shuffle job batch type 23

Type 23	**Ref. case**	**Model A**	**Model B**	**Model C**
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	14:09	14:21 (+1,41%)	07:29 (-47,11%)	10:43 (-24,26%)
σ	00:22	00:06	00:00	00:14
±95%	00:12	00:04	00:00	00:08
m/h	25,44	25,09 (-1,39%)	48,11 (+89,09%)	33,59 (+32,04%)

Table 7 Results for shuffle job batch type 21

Type 21	Ref. case	Model A	Model B	Model C
	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)	Time (mm:ss)
Average	13:59	14:18 (+2,26%)	07:25 (-46,96%)	10:41 (-23,60%)
σ	00:37	00:06	00:00	00:14
±95%	00:21	00:04	00:00	00:08
m/h	25,74	25,17 (-2,21%)	48,54 (+88,54%)	33,70 (+30,89%)

The results show a large standard deviation of the automated yard crane in practice for every job batch type. The standard deviation of model B is equal to 0 since no automation system or dead times are taken into account in this model, no stochastics are involved in this model. Model A shows the most accurate performance prediction regarding the operational performance of the automated yard crane from the reference case. Both the automated yard crane and model A show a performance of around 25 moves per hour. Model B predicts a performance of more than 45 moves per hour, this is 80% more than the operational performance of the automated yard crane. Model C predicts a performance of more than 32 moves per hour, this is 30% more than the operational performance of the automated yard crane.

D. Sensitivity analysis

A sensitivity analysis is executed to determine how the uncertainty in the output of a model can be associated to uncertainties in the model inputs. The three models have the trolley and hoist movement process blocks in the operational sequence. The trolley speed, trolley movement distance, hoist speed and hoist movement distance are parameters in these two process blocks that all three models have in common. The values for these parameter inputs are varied according to values for yard crane models used for various logistic studies.

Increasing the hoist and trolley speed resulted in an increased performance prediction for all three models. Also, increasing the hoist and trolley movement distance resulted in a decreased performance prediction. Model A takes both dead times and accelerations and decelerations into account and is least affected by varying input parameter values compared to models B and C.

IV. Discussion

The large standard deviation measured from the operational performance of the automated yard crane from the reference case was not expected, a constant operational performance was expected due to the automated operation. The deviation can be explained by, for example, external factors that can have an influence on the cycle time. For example, the hoisting and lowering speed of a loaded spreader depends on the mass of the container. Also for example, the wind can have an influence on the process time of the MMS automation system.

The high predicted performance by model B can be explained since this model does not take automation systems nor dead times into account which have a share in the cycle time. Model C takes dead times into account but no accelerations or decelerations, however, this model is more accurate on the performance prediction.

Model A predicts the performance of the automated yard crane the most accurate, this can be explained because this model takes all important modeling parameters into account as well as automation systems which have an influence on the cycle time.

V. Conclusions

The results show that taking automation systems into account as a modeling parameter in yard crane models is essential in order to accurately predict the performance of an automated yard crane. Parameters regarding accelerations, decelerations and dead times are also cycle time influencing modeling details. With the new model predicting the performance of automated yard cranes more accurately, the deviation between the predicted performance and the operational performance of the automated yard crane can be reduced. Since the performance of the container terminal is most influenced by the storage yard, processes connected with the storage yard can be optimized. This can result in an increased efficiency of the logistical processes towards the landside and quayside operational areas and therefore reduce the financial consequences caused by logistical inefficiencies.

VI. References

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B. Literature review on yard crane models

B.1 Container terminal focused yard crane models

Liu et al. [28] developed a simulation model for designing, simulating and evaluating automated container terminals. The specifications of the yard crane include the crane's speed of 5mi/h, it takes 15 seconds to line up with the stack and an average time of 65/45 (gate buffer/import export yard) seconds to unload and load an AGV. These characteristics are chosen to conclude a performance of around 36 moves per hour by assuming 15+65+20=100 s/move where an average of 20s are used for the lateral motion of the crane along the stack and a stack height of up to four containers high.

Liu et al. [25] researched an automated guided vehicle system for two container yard layouts. In this simulation model, it is assumed that the yard cranes are modeled using a movement speed of 5mph, the crane then needs 15 seconds for lining up with the stack and the average time of loading/unloading a container is 50 seconds.

Vis and Harika [40] compared vehicle types at an automated container terminal using simulation. In this simulation model, the ASC cycle is modeled as an empirical distribution as seen in Table 32. These values are elaborated in the paper by stating that the cycle time of an ASC includes the time to lift a container from an AGV, store it in the stack and return to the pickup and delivery point. The value of the cycle time depends on, for example, the storage location of the container and the specifications of the ASC. In practice, the cycle time of an ASC equals on average three times the cycle time of a quay crane. The data in Table 32 is obtained by multiplying the values of the intervals of the distribution of the quay crane with a factor three. The result is an average cycle time of 197.7 seconds which means a throughput performance of 18 containers per hour. The stack mentioned in the paper consists of several blocks, a block consists of six rows with containers and are positioned next to each othe rand on top of each other. One ASC serves one block and one block has a length of 300m and is 25m wide. Sixteen ASC's serve one ship and the block has a European layout.

Table 32 Empirical distribution of the cycle times of an ASC [40]

Fraction	Cycle time in seconds
0.05	90–120
0.15	120–150
0.25	150–180
0.20	180–210
0.17	210–240
0.11	240–270
0.04	270–360
0.02	360–450
0.01	450–540

Yang et al. [27] researched Simulation-based performance evaluation of transport vehicles at automated container terminals. In this research, the automated container cranes are simulated by using movement speed of 2m/s and loading/unloading time of 30s. The yard has 6 blocks and each block is served by 2 ASC's. The block dimensions are 40 bays, 10 rows and 5 tiers.

Duinkerken et al. [23] compared transportation systems for inter terminal transport. A handling center is present at each terminal that can serve the transport equipment, this handling center contains the individual handling equipment but is not modeled individually but as a 'super crane'. The individual components in the barge and rail handling center are modeled in more detail. The crane max speed is modeled using 2m/s with an acceleration of 0.35m/s^2. Creep speed is set to 0.2m/s an the trolley speed to 1.3m/s. Container loading time takes 20±5s and unloading time 15±5s to place the container on an AGV for example.

Briskorn et al. [39] modelled the waiting time for an AGV at the yard to receive a container as a transfer time distribution. The behavior of the stacking cranes is not modelled in this simulation model, the transfer time distribution contains all other activities of the stacking crane such as shuffling containers and serving the landside but were not mentioned in the paper due to confidentiality.

Xin et al. [32] developed a simulation model for an automated container terminal. In this simulation model, the yard cranes are modeled using a maximum speed of 4m/s, an acceleration of 0.4m/s^2 and a weight of 240t. The service time of an ASC is ignored and a container of one TEU is assumed to have a mass of 15t. The simulation model consists of six stacking blocks with one ASC per block. Each stack has a length of 36 TEU, a width of 10 TEU and a height of 6 TEU.

Kavakeb et al. [33] assumed a cycle time of 210 seconds for a yard crane in the simulation model.

Yun and Choi [29] developed a simulation model of a container terminal using an object oriented approach. In this simulation model, the yard crane has a speed of 2.7km/h and an operation time which is an exponential distribution of 2 min.

Choi [24] executed a simulation study for performance measures of resources in a port container terminal. In this simulation study, the speed of a yard crane is set to 8.04km/h and a yard crane has a operational time according to a normal distribution of N(87, 193).

Bielli et al. [38] used two different mean times for a yard crane container handling of 1.8 and 2.1 min/container in their container terminal distributed simulation object oriented model. This mean time is the time needed to move a container from a yard position to the shuttle truck waiting for service for each yard crane and vice versa.

Taner et al. [37] did a research on layout analysis affecting strategic decisions in artificial container terminals and used a combination of two triangular distributions for the container handling time of an ASC. The container handling time for an ASC was calculated using Triangular (1.2, 2, 3.5) + Triangular (0.3, 0.6, 1.1).

Lin et al. [35] developed a simulation-based investment planning for Humen Port and made some assumptions for the simulation model. These assumptions stated that the cranes always work well, the time when a crane breaks down is ignored. The moving time of crane is neglected and it is mentioned that this may be too much to ignore, especially in the process of rescheduling. Operational efficiency of the cranes is described as a constant value of 3 minutes.

Guo and Huang [22] executed a simulation study for dynamic space and time partitioning for yard crane workload management in container terminals. The parameters that were set for the yard crane in this simulation model included a linear gantry speed of 7.8km/hour. No reshuffling of containers in the yard were taken into account since it was assumed that this was done during lull periods. The processing time for a yard crane to handle a container was set to a fixed time of 120s.

Sauri et al. [36] compared manned and automated horizontal container handling equipment at container terminals using a simulation study. In this study, the container handling rate of yard cranes is assumed according to a distribution as seen in Figure 23. This distribution is based on the quay crane by multiplying this service time with two. The service time of the quay crane is based on the performance of the quay cranes in the Barcelona Europe South Terminal which approaches a productivity of 40 moves per hour at peak times and 30 moves per hour on average.

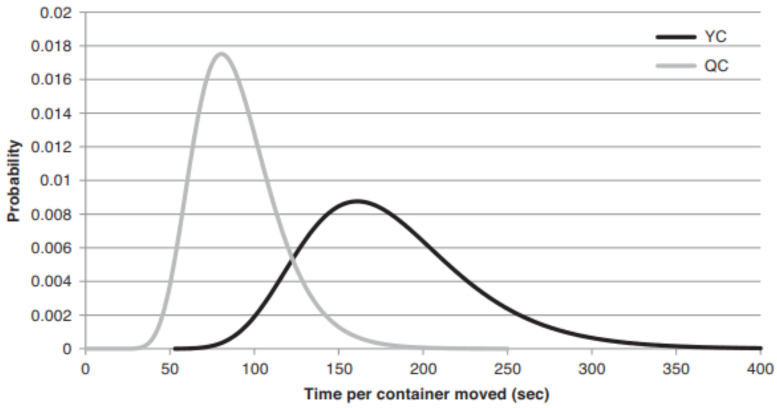

Figure 23 Service time distribution for quay cranes and yard cranes [36]

Veenstra and Lang [26] investigated the economic analysis of a container terminal simulation. In this simulation model, the ASC has a fixed operation time for picking and dropping of a container of 5 seconds. The movement time of an one way trip of the ASC is a stochastic time defined by a uniform distribution (35,58).

Huang and Li [18] used a gantry speed of 7.8km/h in their simulation model with a time for a yard crane to move one container from its stack to a vehicle ranges from 75 to 120s.

Yu et al. [17] used the same parameters as Petering et al. [51] for a yard crane, setting the container handling time to a triangular distribution of tri(1.2, 2.0, 3.4) and a gantry speed of 100m/min as an input for their research on performance comparison of real-time yard crane dispatching strategies at nontransshipment container terminals. Without consideration of gantry movement time, the maximum container handling capacity of a yard crane is around 30 lifts per hour. Gantry speed is set to 100m/min. The block dimensions are set to 42 bays, 6 rows and 5 tiers.

Zhou et al. [20] researched simulation-based optimization for yard design at mega container terminal under uncertainty. In this research, they used input parameters for the yard crane of 0.45 seconds per meter of yard crane movement, a cycle time for handling a container of 77.1 seconds and an average relocation time of 74.2 seconds. The length of a block is considered 210m and a width of 16.63m.

Lu and Le [21] did a research on integrated optimization of container terminal scheduling with uncertain factors. In this research, the speed of the yard crane is set to 3m/s with a standard deviation of 1% of the moving time, the time of hoisting and lowering is set to 60s with a standard deviation of 3%.

Roy and de Koster [16] developed a simulation model to investigate stochastic modeling of unloading and loading operations at a container terminal using automated lifting vehicles. The ASC in this model have a speed of 3m/s including trolley speed and a pick-up and put-down time of 20 seconds. There are 40 bays, 6 rows and 5 tiers in one container block and is served by one ASC.

Gupta et al. [30] used a trolley speed of 1m/s and a gantry speed of 4m/s in their simulation model to find the optimal stack layout in a sea container terminal with automated lifting vehicles.

Kulak et al. [34] used in their simulation model, which researched strategies for improving a terminals performance, a container handling time of yard cranes defined by a triangular distribution of Tri(2.1, 4.8, 7.6)min but also a time between failure of yard cranes of Tri(7, 15, 60)days and a down time of yard cranes of Tri(1, 48, 96)hours.

B.2 Storage yard focused yard crane models

Kemme [14] modeled a simulation with different yard crane setups. The parameters that were set for these yard cranes were a maximum driving speed of 4m/s for the small crane and 3.5m/s for a larger portal. Acceleration and deceleration were also taken into account using 0.8 and 1.0m/s^2 for the laden and unladen driving respectively. For the trolley, the maximum speed was set to 1m/s independently of the load. The maximum lifting speed of the spreader is set to 0.8m/s if laden and 1.0m/s if empty. Acceleration and deceleration of the trolley and hoist were set to 0.4 and 0.5m/s^2 for laden and empty movement respectively. The gamma-distributed time in seconds for fine positioning of the spreader is parametrized with ($\mu = 10.0$, $\sigma^2 = 20.0$) s for the waterside handover area, (40.0, 400.0) s for the landside handover area, and (6.0, 7.2) s for inside the yard block. Multiple different yard block layouts were tested, more details about the simulation model are not accessible.

A simulation study done by Galle et al. [10] on yard crane scheduling for container storage, retrieval and relocation included a simulation model including multiple variables including, gantry, trolley and hoisting speed when empty and loaded, and a fixed time to handle and stabilize a container as seen in Table 33. No acceleration and deceleration is assumed, the speeds are derived from Liebherr.

Table 33 Inputs for the simulation study of [10]

Variable	Value
Trolley speed without load of the YC	1.17 meter/second
Trolley speed with load of the YC	1.17 meter/second
Gantry speed without load of the YC	2.17 meter/second
Gantry speed with load of the YC	1.17 meter/second
Hoisting speed without load of the YC	0.93 meter/second
Hoisting speed with load of the YC	0.47 meter/second
Container width	2.35 meter
Container length	5.90 meter
Container height	2.39 meter
Time to handle and stabilize container	20 second

Speer and Fischer [11] did a simulation study on scheduling different automated yard crane systems at container terminals. The parameter settings for the simulation model for the yard crane is shown in Table 34. The block dimensions used are 37 bays, 10 rows and up to 4 containers high.

Table 34 Parameter settings for the simulation model used in [11]

Device	Speed (m/s)	Acceleration (m/s^2)	Pick/set-time
Gantry RMG	3	0.5	
Trolley RMG	1	0.33	
Lift RMG	1.5	0.4	
Spreader RMG	0.2 (resizing)		5 s

Saanen and Valkengoed [15] compared three automated stacking alternatives by means of simulation. All three alternatives include simultaneous trolley and gantry movements, a dead time between movements of 2 seconds, positioning time on a truck of 30 seconds and a positioning time on an AGV of 10 seconds. One of the alternatives is a single RMG that uses the simulation input values of 4.0m/s gantry speed, 1.0m/s trolley speed, 0.5-1.0m/s hoist speed depending on load. For the cross-over RMG alternative, the same trolley speed is assumed. The speed of the small gantry crane is set to 3.5m/s and 3.0m/s for the larger gantry crane, hoist speed is set to 1.0m/s-1.5m/s depending on the load. The last alternative is regarding a twin RMG setup. The gantry speed is set to 4.0m/s, trolley speed is set to 1.0m/s, hoist speed is set to 1.0m/s-1.5m/s depending on the load. All alternatives operate on a stack that is 40 TEU long (240m), the single RMG block is 6 containers wide, the other two alternatives operate on a block that is 10 containers wide. It is assumed that no time is lost at the interchange zone, a new job is always available after finishing a job and no reshuffles are assumed.

Petering et al. [51] investigated the development and simulation analysis of real-time yard crane control systems for seaport container transshipment terminals. In this simulation model, all experiments used a gantry movement of four seconds per container storage slot and the container handling time of a container was triangularly distributed using the parameters (1.2, 2.0, 3.4) min. More details on this model are not accessible.

Gharehgozli et al. [19] executed a simulation study of the performance of twin ASC's at a seaport container terminal. In this simulation study, it is assumed that the ASC's move with a speed of 1m/s which also accounts for the acceleration and deceleration as well as other operational and safety measures common in a terminal. Furthermore, the time required to lower the spreader, lock or unlock the container and hoist the spreader is assumed to be 30 seconds. The block consists of 30 bays of only 20' containers.

Gharehgozli et al. [31] also used a gantry speed of 240m/min, trolley speed of 60m/min and a hoisting speed of 72m/min in another simulation study about scheduling twin yard cranes in a container block. No acceleration or deceleration is assumed. The block dimensions are set to 40 bays, 10 rows and 5 tiers.

C. Model verification

C.1 The eleven analyzed reference jobs

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
299	08:43:38,768	Procedure - Standby HO= +13222 TR= +5743 GA= +71312							
	08:43:38,816	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	08:43:38,816	08:43:48,910	**00:10,094**	13222	21500	**8278**
	08:43:48,910	Traject Block Movement: Moving Trolley to target position +14255 mm	**Trolley to source**	08:43:48,910	08:44:02,310	**00:13,400**	5743	14255	**8512**
	08:43:59,664	Procedure - Travel to Source HO= +5791 TR= +14255 GA= +71326							
	08:44:02,310	Traject Block Movement: Hoisting/Lowering to Target +5791 mm	**Hoist to source**	08:44:02,310	08:44:26,913	**00:24,603**	21500	6407	**15093**
	08:44:23,225	AAPM_FINE: Adjust Stage started at HO=+6890	**MMS adjusting**	08:44:23,225	08:44:26,913	**00:03,688**	6890	6407	**483**
	08:44:26,912	AAPM_FINE: Land Stage started at HO=+6407							
	08:44:26,913	New setpoint Reached: TR=+13 GA=+9 S=+237							
	08:44:28,306	Traject Block Movement: Lowering onto container	**Soft landing**	08:44:26,913	08:44:33,853	**00:06,940**	6407	5791	**616**
	08:44:33,853	Traject Block Movement: End Position Reached	**Lock container**	08:44:33,853	08:44:37,408	**00:03,555**			
	08:44:37,408	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	08:44:37,408	08:44:58,596	**00:21,188**	5791	21500	**15709**
	08:44:58,596	Traject Block Movement: Moving Trolley to target position +5735 mm	**Trolley to destination**	08:44:58,596	08:45:12,350	**00:13,754**	14255	5735	**8520**
	08:45:09,444	Procedure - Travel to Destination HO= +14173 TR= +5735 GA= +71326							
	08:45:12,350	Traject Block Movement: Hoisting/Lowering to Target +14173 mm	**Hoist to destination**	08:45:12,350	08:45:35,014	**00:22,664**	21500	14781	**6719**
	08:45:29,511	AAPM_FINE: Adjust Stage started at HO=+15265	**MMS adjusting**	08:45:29,511	08:45:35,014	**00:05,503**	15265	14781	**484**
	08:45:35,014	AAPM_FINE: Land Stage started at HO=+14781							
	08:45:35,014	MM Task: New setpoint Reached: TR=+1 GA=-53 S=+211							
	08:45:37,352	Traject Block Movement: Lowering onto container	**Soft landing**	08:45:35,014	08:45:42,650	**00:07,636**	14781	14173	**608**
	08:45:42,650	Traject Block Movement: End Position Reached	**Unlock container**	08:45:42,650	08:45:59,696	**00:17,046**			
	08:45:59,696	Traject Block Movement: Hoisting/Lowering to Target +14637 mm					14637	14173	**464**
					Total time	**02:20,880**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
317	09:33:37,812	Procedure - Standby HO= +4898 TR= +14251 GA= +71312							
	09:33:37,861	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	09:33:37,861	09:33:53,261	**00:15,400**	4898	21500	**16602**
	09:33:53,261	Traject Block Movement: Moving Trolley to target position +8575 mm	**Trolley to source**	09:33:53,261	09:34:05,217	**00:11,956**	14251	8575	**5676**
	09:34:02,382	Procedure - Travel to Source HO= +14478 TR= +8575 GA= +71326							
	09:34:05,217	Traject Block Movement: Hoisting/Lowering to Target +14478 mm	**Hoist to source**	09:34:05,217	09:34:28,342	**00:23,125**	21500	15086	**6414**
	09:34:23,801	AAPM_FINE: Adjust Stage started at HO=+15574	**MMS adjusting**	09:34:23,801	09:34:28,342	**00:04,541**	15574	15086	**488**
	09:34:28,341	AAPM_FINE: Land Stage started at HO=+15086							
	09:34:28,342	MM Task: New setpoint Reached: TR=+0 GA=-32 S=+366							
	09:34:30,677	Traject Block Movement: Lowering onto container	**Soft landing**	09:34:28,342	09:34:36,012	**00:07,670**	15086	14478	**608**
	09:34:36,012	Traject Block Movement: End Position Reached	**Lock container**	09:34:36,012	09:34:39,592	**00:03,580**			
	09:34:39,592	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	09:34:39,592	09:34:54,952	**00:15,360**	14478	21500	**7022**
	09:34:54,952	Traject Block Movement: Moving Trolley to target position +14255 mm	**Trolley to destination**	09:34:54,952	09:35:06,872	**00:11,920**	8575	14255	**5680**
	09:35:04,095	Procedure - Travel to Destination HO= +5792 TR= +14255 GA= +71326							
	09:35:06,872	Traject Block Movement: Hoisting/Lowering to Target +5792 mm	**Hoist to destination**	09:35:06,872	09:35:32,703	**00:25,831**	21500	6400	**15100**
	09:35:27,880	AAPM_FINE: Adjust Stage started at HO=+6884	**MMS adjusting**	09:35:27,880	09:35:32,703	**00:04,823**	6884	6400	**484**
	09:35:32,702	AAPM_FINE: Land Stage started at HO=+6400							
	09:35:32,703	MM Task: New setpoint Reached: TR=+32 GA=-15 S=+241							
	09:35:35,072	Traject Block Movement: Lowering onto container	**Soft landing**	09:35:32,703	09:35:40,700	**00:07,997**	6400	5792	**608**
	09:35:40,700	Traject Block Movement: End Position Reached	**Unlock container**	09:35:40,700	09:35:57,438	**00:16,738**			
	09:35:57,438	Traject Block Movement: Hoisting/Lowering to Target +6237 mm					6237	5792	**445**
	00:02:19,577				Total time	**02:19,577**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
383	12:30:45,423	Procedure - Standby HO= +4629 TR= +14266 GA= +71312							
	12:30:45,481	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	12:30:45,481	12:31:01,018	**00:15,537**	4629	21500	**16871**
	12:31:01,018	Traject Block Movement: Moving Trolley to target position +25615 mm	**Trolley to source**	12:31:01,018	12:31:16,540	**00:15,522**	14266	25615	**11349**
	12:31:13,280	Procedure - Travel to Source HO= +14478 TR= +25615 GA= +71326							
	12:31:16,540	Traject Block Movement: Hoisting/Lowering to Target +14478 mm	**Hoist to source**	12:31:16,540	12:31:39,835	**00:23,295**	21500	15086	**6414**
	12:31:35,332	AAPM_FINE: Adjust Stage started at HO=+15573	**MMS adjusting**	12:31:35,332	12:31:39,835	**00:04,503**	15573	15086	**487**
	12:31:39,834	AAPM_FINE: Land Stage started at HO=+15086							
	12:31:39,835	MM Task: New setpoint Reached: TR=+14 GA=-31 S=+426							
	12:31:42,153	Traject Block Movement: Lowering onto container	**Soft landing**	12:31:39,835	12:31:47,577	**00:07,742**	15086	14478	**608**
	12:31:47,577	Traject Block Movement: End Position Reached	**Lock container**	12:31:47,577	12:31:51,155	**00:03,578**			
	12:31:51,155	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	12:31:51,155	12:32:06,815	**00:15,660**	14478	21500	**7022**
	12:32:06,815	Traject Block Movement: Moving Trolley to target position +14255 mm	**Trolley to destination**	12:32:06,815	12:32:22,577	**00:15,762**	25615	14255	**11360**
	12:32:18,918	Procedure - Travel to Destination HO= +5487 TR= +14255 GA= +71326							
	12:32:22,577	Traject Block Movement: Hoisting/Lowering to Target +5487 mm	**Hoist to destination**	12:32:22,577	12:32:47,564	**00:24,987**	21500	6103	**15397**
	12:32:43,879	AAPM_FINE: Adjust Stage started at HO=+6580	**MMS adjusting**	12:32:43,879	12:32:47,564	**00:03,685**	6580	6103	**477**
	12:32:47,563	AAPM_FINE: Land Stage started at HO=+6103							
	12:32:47,564	MM Task: New setpoint Reached: TR=+17 GA=-10 S=-120							
	12:32:48,961	Traject Block Movement: Lowering onto container	**Soft landing**	12:32:47,564	12:32:54,554	**00:06,990**	6103	5487	**616**
	12:32:54,554	Traject Block Movement: End Position Reached	**Unlock container**	12:32:54,554	12:33:11,859	**00:17,305**			
	12:33:11,859	Traject Block Movement: Hoisting/Lowering to Target +5936 mm					5936	5487	**449**
	00:02:26,378				Total time	**02:26,378**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
428	17:49:02,862	Procedure - Standby HO= +4549 TR= +2898 GA= +32090							
	17:49:02,917	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:49:02,917	17:49:12,218	**00:09,301**	4549	21500	**16951**
	17:49:12,218	Main Drive Positions: HO:+18860 TR:+2860 GA:+32090	**Trolley to source**	17:49:12,218	17:49:36,008	**00:23,790**	2898	19935	**17037**
	17:49:33,244	Procedure - Travel to Source HO= +8723 TR= +19935 GA= +32081							
	17:49:36,008	Traject Block Movement: Hoisting/Lowering to Target +8723 mm	**Hoist to source**	17:49:36,008	17:50:01,327	**00:25,319**	21500	9335	**12165**
	17:49:55,961	AAPM_FINE: Adjust Stage started at HO=+9823	**MMS adjusting**	17:49:55,961	17:49:59,903	**00:03,942**	9823	9335	**488**
	17:49:59,902	AAPM_FINE: Land Stage started at HO=+9335							
	17:49:59,903	MM Task: New setpoint Reached: TR=+15 GA=-23 S=-248				**00:01,424**			
	17:50:01,327	Traject Block Movement: Lowering onto container	**Soft landing**	17:50:01,327	17:50:07,226	**00:05,899**	9335	8723	**612**
	17:50:07,226	Traject Block Movement: End Position Reached	**Lock container**	17:50:07,226	17:50:10,787	**00:03,561**			
	17:50:10,787	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:50:10,787	17:50:29,805	**00:19,018**	8723	21500	**12777**
	17:50:29,805	Traject Block Movement: Moving Trolley to target position +2895 mm	**Trolley to destination**	17:50:29,805	17:50:47,167	**00:17,362**	19935	2895	**17040**
	17:50:44,406	Procedure - Travel to Destination HO= +5816 TR= +2895 GA= +32081							
	17:50:47,167	Traject Block Movement: Hoisting/Lowering to Target +5816 mm	**Hoist to destination**	17:50:47,167	17:51:15,806	**00:28,639**	21500	6424	**15076**
	17:51:08,407	AAPM_FINE: Adjust Stage started at HO=+6911	**MMS adjusting**	17:51:08,407	17:51:13,443	**00:05,036**	6911	6424	**487**
	17:51:13,442	AAPM_FINE: Land Stage started at HO=+6424							
	17:51:13,443	MM Task: New setpoint Reached: TR=+5 GA=-43 S=+274				**00:02,363**			
	17:51:15,806	Traject Block Movement: Lowering onto container	**Soft landing**	17:51:15,806	17:51:21,462	**00:05,656**	6424	5816	**608**
	17:51:21,462	Traject Block Movement: End Position Reached	**Unlock container**	17:51:21,462	17:51:38,618	**00:17,156**			
	17:51:38,618	Traject Block Movement: Hoisting/Lowering to Target +6259 mm					6259	5816	**443**
					Total time	**02:35,701**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
429	17:51:45,920	Procedure - Standby HO= +7821 TR= +2897 GA= +32090							
	17:51:45,978	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:51:45,978	17:51:59,100	**00:13,122**	7821	21500	**13679**
	17:51:59,100	Traject Block Movement: Moving Trolley to target position +25615 mm	**Trolley to source**	17:51:59,100	17:52:18,906	**00:19,806**	2897	25615	**22718**
	17:52:15,736	Procedure - Travel to Source HO= +2908 TR= +25615 GA= +32081							
	17:52:18,906	Traject Block Movement: Hoisting/Lowering to Target +2908 mm	**Hoist to source**	17:52:18,906	17:52:47,087	**00:28,181**	21500	3526	**17974**
	17:52:41,242	AAPM_FINE: Adjust Stage started at HO=+4003	**MMS adjusting**	17:52:41,242	17:52:44,803	**00:03,561**	4003	3526	**477**
	17:52:44,802	AAPM_FINE: Land Stage started at HO=+3526							
	17:52:44,803	MM Task: New setpoint Reached: TR=+17 GA=-2 S=-114				**00:02,284**			
	17:52:47,087	Traject Block Movement: Lowering onto container	**Soft landing**	17:52:47,087	17:52:52,883	**00:05,796**	3526	2908	**618**
	17:52:52,883	Traject Block Movement: End Position Reached	**Lock container**	17:52:52,883	17:52:56,477	**00:03,594**			
	17:52:56,477	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:52:56,477	17:53:19,781	**00:23,304**	2908	21500	**18592**
	17:53:19,781	Traject Block Movement: Moving Trolley to target position +5735 mm	**Trolley to destination**	17:53:19,781	17:53:38,001	**00:18,220**	25615	5735	**19880**
	17:53:35,300	Procedure - Travel to Destination HO= +2908 TR= +5735 GA= +32081							
	17:53:38,001	Traject Block Movement: Hoisting/Lowering to Target +2908 mm	**Hoist to destination**	17:53:38,001	17:54:06,721	**00:28,720**	21500	3526	**17974**
	17:54:00,908	AAPM_FINE: Adjust Stage started at HO=+4001	**MMS adjusting**	17:54:00,908	17:54:04,437	**00:03,529**	4001	3526	**475**
	17:54:04,437	AAPM_FINE: Land Stage started at HO=+3526							
	17:54:04,437	MM Task: New setpoint Reached: TR=+7 GA=-5 S=+326				**00:02,284**			
	17:54:06,721	Traject Block Movement: Lowering onto container	**Soft landing**	17:54:06,721	17:54:12,425	**00:05,704**	3526	2908	**618**
	17:54:12,425	Traject Block Movement: End Position Reached	**Unlock container**	17:54:12,425	17:54:15,980	**00:03,555**			
	17:54:15,980	Traject Block Movement: Hoisting/Lowering to Target +3348 mm					3348	2908	**440**
					Total time	**02:30,002**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
430	17:54:22,928	Procedure - Standby HO= +4500 TR= +5744 GA= +32090							
	17:54:22,988	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:54:22,988	17:54:38,467	**00:15,479**	4500	21500	**17000**
	17:54:38,467	Traject Block Movement: Moving Trolley to target position +19935 mm	**Trolley to source**	17:54:38,467	17:54:54,925	**00:16,458**	5744	19935	**14191**
	17:54:52,042	Procedure - Travel to Source HO= +5815 TR= +19935 GA= +32081							
	17:54:54,925	Traject Block Movement: Hoisting/Lowering to Target +5815 mm	**Hoist to source**	17:54:54,925	17:55:23,207	**00:28,282**	21500	6423	**15077**
	17:55:16,065	AAPM_FINE: Adjust Stage started at HO=+6912	**MMS adjusting**	17:55:16,065	17:55:20,786	**00:04,721**	6912	6423	**489**
	17:55:20,785	AAPM_FINE: Land Stage started at HO=+6423							
	17:55:20,786	MM Task: New setpoint Reached: TR=+34 GA=-23 S=+152				**00:02,421**			
	17:55:23,207	Traject Block Movement: Lowering onto container	**Soft landing**	17:55:23,207	17:55:29,127	**00:05,920**	6423	5815	**608**
	17:55:29,127	Traject Block Movement: End Position Reached	**Lock container**	17:55:29,127	17:55:32,676	**00:03,549**			
	17:55:32,676	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	17:55:32,676	17:55:54,026	**00:21,350**	5815	21500	**15685**
	17:55:54,026	Traject Block Movement: Moving Trolley to target position +5735 mm	**Trolley to destination**	17:55:54,026	17:56:10,697	**00:16,671**	19935	5735	**14200**
	17:56:07,696	Procedure - Travel to Destination HO= +5816 TR= +5735 GA= +32081							
	17:56:10,697	Traject Block Movement: Hoisting/Lowering to Target +5816 mm	**Hoist to destination**	17:56:10,697	17:56:37,947	**00:27,250**	21500	6425	**15075**
	17:56:32,204	AAPM_FINE: Adjust Stage started at HO=+6911	**MMS adjusting**	17:56:32,204	17:56:36,467	**00:04,263**	6911	6425	**486**
	17:56:36,466	AAPM_FINE: Land Stage started at HO=+6425							
	17:56:36,467	MM Task: New setpoint Reached: TR=+4 GA=-29 S=+316				**00:01,480**			
	17:56:37,947	Traject Block Movement: Lowering onto container	**Soft landing**	17:56:37,947	17:56:43,746	**00:05,799**	6425	5816	**609**
	17:56:43,746	Traject Block Movement: End Position Reached	**Unlock container**	17:56:43,746	17:57:00,645	**00:16,899**			
	17:57:00,645	Traject Block Movement: Hoisting/Lowering to Target +6249 mm					6249	5816	**433**
					Total time	**02:37,657**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
431	17:57:07,707	Procedure - Standby HO= +7457 TR= +5744 GA= +32090							
	17:57:07,764	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	17:57:07,764	17:57:21,388	00:13,624	7457	21500	14043
	17:57:21,388	Traject Block Movement: Moving Trolley to target position +31295 mm	Trolley to source	17:57:21,388	17:57:42,765	00:21,377	5744	31295	25551
	17:57:39,166	Procedure - Travel to Source HO= +2908 TR= +31295 GA= +32081							
	17:57:42,765	Traject Block Movement: Hoisting/Lowering to Target +2908 mm	Hoist to source	17:57:42,765	17:58:13,440	00:30,675	21500	3516	17984
	17:58:05,128	AAPM_FINE: Adjust Stage started at HO=+4003	MMS adjusting	17:58:05,128	17:58:10,187	00:05,059	4003	3516	487
	17:58:10,186	AAPM_FINE: Land Stage started at HO=+3516							
	17:58:10,187	MM Task: New setpoint Reached: TR=+9 GA=-44 S=+201				00:03,253			
	17:58:13,440	Traject Block Movement: Lowering onto container	Soft landing	17:58:13,440	17:58:19,343	00:05,903	3516	2908	608
	17:58:19,343	Traject Block Movement: End Position Reached	Lock container	17:58:19,343	17:58:22,906	00:03,563			
	17:58:22,906	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	17:58:22,906	17:58:46,426	00:23,520	2908	21500	18592
	17:58:46,426	Traject Block Movement: Moving Trolley to target position +8575 mm	Trolley to destination	17:58:46,426	17:59:06,163	00:19,737	31295	8575	22720
	17:59:03,123	Procedure - Travel to Destination HO= +2908 TR= +8575 GA= +32081							
	17:59:06,163	Traject Block Movement: Hoisting/Lowering to Target +2908 mm	Hoist to destination	17:59:06,163	17:59:33,743	00:27,580	21500	3566	17934
	17:59:29,064	AAPM_FINE: Adjust Stage started at HO=+3998	MMS adjusting	17:59:29,064	17:59:31,308	00:02,244	3998	3566	432
	17:59:31,307	AAPM_FINE: Land Stage started at HO=+3566							
	17:59:31,308	MM Task: New setpoint Reached: TR=-2 GA=-3 S=+118				00:02,435			
	17:59:33,743	Traject Block Movement: Lowering onto container	Soft landing	17:59:33,743	17:59:39,429	00:05,686	3566	2908	658
	17:59:39,429	Traject Block Movement: End Position Reached	Unlock container	17:59:39,429	17:59:42,981	00:03,552			
	17:59:42,981	Traject Block Movement: Hoisting/Lowering to Target +3348 mm					3348	2908	440
					Total time	02:35,217			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
433	18:03:07,360	Procedure - Standby HO= +21485 TR= +8575 GA= +32090							
	18:03:07,417	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	18:03:07,417	18:03:07,440	00:00,023	21485	21500	15
	18:03:07,440	Traject Block Movement: Moving Trolley to target position +22775 mm	Trolley to source	18:03:07,440	18:03:23,864	00:16,424	8575	22775	14200
	18:03:21,007	Procedure - Travel to Source HO= +8723 TR= +22775 GA= +32081							
	18:03:23,864	Traject Block Movement: Hoisting/Lowering to Target +8723 mm	Hoist to source	18:03:23,864	18:03:49,359	00:25,495	21500	9334	12166
	18:03:43,862	AAPM_FINE: Adjust Stage started at HO=+9820	MMS adjusting	18:03:43,862	18:03:47,981	00:04,119	9820	9334	486
	18:03:47,980	AAPM_FINE: Land Stage started at HO=+9334							
	18:03:47,981	MM Task: New setpoint Reached: TR=+1 GA=-30 S=-6				00:01,378			
	18:03:49,359	Traject Block Movement: Lowering onto container	Soft landing	18:03:49,359	18:03:55,307	00:05,948	9334	8723	611
	18:03:55,307	Traject Block Movement: End Position Reached	Lock container	18:03:55,307	18:03:58,857	00:03,550			
	18:03:58,857	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	18:03:58,857	18:04:18,021	00:19,164	8723	21500	12777
	18:04:18,021	Traject Block Movement: Moving Trolley to target position +2895 mm	Trolley to destination	18:04:18,021	18:04:36,209	00:18,188	22775	2895	19880
	18:04:33,543	Procedure - Travel to Destination HO= +8723 TR= +2895 GA= +32081							
	18:04:36,209	Traject Block Movement: Hoisting/Lowering to Target +8723 mm	Hoist to destination	18:04:36,209	18:05:01,237	00:25,028	21500	9335	12165
	18:04:55,942	AAPM_FINE: Adjust Stage started at HO=+9820	MMS adjusting	18:04:55,942	18:04:59,900	00:03,958	9820	9335	485
	18:04:59,899	AAPM_FINE: Land Stage started at HO=+9335							
	18:04:59,900	MM Task: New setpoint Reached: TR=+1 GA=-23 S=+311				00:01,337			
	18:05:01,237	Traject Block Movement: Lowering onto container	Soft landing	18:05:01,237	18:05:06,966	00:05,729	9335	8723	612
	18:05:06,966	Traject Block Movement: End Position Reached	Unlock container	18:05:06,966	18:05:23,839	00:16,873			
	18:05:23,839	Traject Block Movement: Hoisting/Lowering to Target +9159 mm					9159	8723	436
					Total time	02:16,422			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
434	18:05:31,042	Procedure - Standby HO= +10454 TR= +2897 GA= +32090							
	18:05:31,100	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	18:05:31,100	18:05:42,744	00:11,644	10454	21500	11046
	18:05:42,744	Traject Block Movement: Moving Trolley to target position +22775 mm	Trolley to source	18:05:42,744	18:06:01,786	00:19,042	2897	22775	19878
	18:05:58,204	Procedure - Travel to Source HO= +5815 TR= +22775 GA= +32081							
	18:06:01,786	Traject Block Movement: Hoisting/Lowering to Target +5815 mm	Hoist to source	18:06:01,786	18:06:30,240	00:28,454	21500	6423	15077
	18:06:22,879	AAPM_FINE: Adjust Stage started at HO=+6912	MMS adjusting	18:06:22,879	18:06:27,802	00:04,923	6912	6423	489
	18:06:27,801	AAPM_FINE: Land Stage started at HO=+6423							
	18:06:27,802	MM Task: New setpoint Reached: TR=+26 GA=-42 S=+216				00:02,438			
	18:06:30,240	Traject Block Movement: Lowering onto container	Soft landing	18:06:30,240	18:06:36,119	00:05,879	6423	5815	608
	18:06:36,119	Traject Block Movement: End Position Reached	Lock container	18:06:36,119	18:06:39,684	00:03,565			
	18:06:39,684	Traject Block Movement: Hoisting up to +21500 mm	Hoist to upper	18:06:39,684	18:07:01,180	00:21,496	5815	21500	15685
	18:07:01,180	Traject Block Movement: Moving Trolley to target position +5735 mm	Trolley to destination	18:07:01,180	18:07:18,589	00:17,409	22775	5735	17040
	18:07:15,788	Procedure - Travel to Destination HO= +8723 TR= +5735 GA= +32081							
	18:07:18,589	Traject Block Movement: Hoisting/Lowering to Target +8723 mm	Hoist to destination	18:07:18,589	18:07:43,784	00:25,195	21500	9335	12165
	18:07:38,405	AAPM_FINE: Adjust Stage started at HO=+9818	MMS adjusting	18:07:38,405	18:07:42,398	00:03,993	9818	9335	483
	18:07:42,397	AAPM_FINE: Land Stage started at HO=+9335							
	18:07:42,398	MM Task: New setpoint Reached: TR=+0 GA=-24 S=+265				00:01,386			
	18:07:43,784	Traject Block Movement: Lowering onto container	Soft landing	18:07:43,784	18:07:49,629	00:05,845	9335	8723	612
	18:07:49,629	Traject Block Movement: End Position Reached	Unlock container	18:07:49,629	18:08:06,642	00:17,013			
	18:08:06,642	Traject Block Movement: Hoisting/Lowering to Target +9150 mm					9150	8723	427
					Total time	02:35,542			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
435	18:08:13,763	Procedure - Standby HO= +10349 TR= +5742 GA= +32090							
	18:08:13,824	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	18:08:13,824	18:08:25,677	**00:11,853**	10349	21500	**11151**
	18:08:25,677	Traject Block Movement: Moving Trolley to target position +22775 mm	**Trolley to source**	18:08:25,677	18:08:42,903	**00:17,226**	5742	22775	**17033**
	18:08:40,182	Procedure - Travel to Source HO= +2908 TR= +22775 GA= +32081							
	18:08:42,903	Traject Block Movement: Hoisting/Lowering to Target +2908 mm	**Hoist to source**	18:08:42,903	18:09:14,281	**00:31,378**	21500	3516	**17984**
	18:09:05,202	AAPM_FINE: Adjust Stage started at HO=+4006	**MMS adjusting**	18:09:05,202	18:09:10,986	**00:05,784**	4006	3516	**490**
	18:09:10,984	AAPM_FINE: Land Stage started at HO=+3516							
	18:09:10,986	MM Task: New setpoint Reached: TR=+33 GA=-62 S=-2				**00:03,295**			
	18:09:14,281	Traject Block Movement: Lowering onto container	**Soft landing**	18:09:14,281	18:09:20,065	**00:05,784**	3516	2908	**608**
	18:09:20,065	Traject Block Movement: End Position Reached	**Lock container**	18:09:20,065	18:09:23,617	**00:03,552**			
	18:09:23,617	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	18:09:23,617	18:09:47,069	**00:23,452**	2908	21500	**18592**
	18:09:47,069	Traject Block Movement: Moving Trolley to target position +8575 mm	**Trolley to destination**	18:09:47,069	18:10:03,720	**00:16,651**	22775	8575	**14200**
	18:10:00,698	Procedure - Travel to Destination HO= +8723 TR= +8575 GA= +32081							
	18:10:03,720	Traject Block Movement: Hoisting/Lowering to Target +8723 mm	**Hoist to destination**	18:10:03,720	18:10:28,281	**00:24,561**	21500	9341	**12159**
	18:10:23,418	AAPM_FINE: Adjust Stage started at HO=+9814	**MMS adjusting**	18:10:23,418	18:10:26,923	**00:03,505**	9814	9341	**473**
	18:10:26,922	AAPM_FINE: Land Stage started at HO=+9341							
	18:10:26,923	MM Task: New setpoint Reached: TR=+1 GA=-8 S=+456				**00:01,358**			
	18:10:28,281	Traject Block Movement: Lowering onto container	**Soft landing**	18:10:28,281	18:10:33,984	**00:05,703**	9341	8723	**618**
	18:10:33,984	Traject Block Movement: End Position Reached	**Unlock container**	18:10:33,984	18:10:51,180	**00:17,196**			
	18:10:51,180	Traject Block Movement: Hoisting/Lowering to Target +9158 mm					9158	8723	**435**
					Total time	**02:37,356**			

JobNr	Time	Process	Activity	startTime	endTime	deltaTime	startPos	endPos	deltaPos
437	18:13:34,386	Procedure - Standby HO= +4580 TR= +11426 GA= +32090							
	18:13:34,443	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	18:13:34,443	18:13:50,026	**00:15,583**	4580	21500	**16920**
	18:13:50,026	Traject Block Movement: Moving Trolley to target position +34135 mm	**Trolley to source**	18:13:50,026	18:14:09,710	**00:19,684**	11426	34135	**22709**
	18:14:06,690	Procedure - Travel to Source HO= +5815 TR= +34135 GA= +32081							
	18:14:09,710	Traject Block Movement: Hoisting/Lowering to Target +5815 mm	**Hoist to source**	18:14:09,710	18:14:38,867	**00:29,157**	21500	6423	**15077**
	18:14:30,805	AAPM_FINE: Adjust Stage started at HO=+6906	**MMS adjusting**	18:14:30,805	18:14:36,520	**00:05,715**	6906	6423	**483**
	18:14:36,512	AAPM_FINE: Land Stage started at HO=+6423							
	18:14:36,520	MM Task: New setpoint Reached: TR=+58 GA=-17 S=-5				**00:02,347**			
	18:14:38,867	Traject Block Movement: Lowering onto container	**Soft landing**	18:14:38,867	18:14:44,771	**00:05,904**	6423	5815	**608**
	18:14:44,771	Traject Block Movement: End Position Reached	**Lock container**	18:14:44,771	18:14:48,190	**00:03,419**			
	18:14:48,190	Traject Block Movement: Hoisting up to +21500 mm	**Hoist to upper**	18:14:48,190	18:15:09,700	**00:21,510**	5815	21500	**15685**
	18:15:09,700	Traject Block Movement: Moving Trolley to target position +11415 mm	**Trolley to destination**	18:15:09,700	18:15:29,306	**00:19,606**	34135	11415	**22720**
	18:15:26,402	Procedure - Travel to Destination HO= +5816 TR= +11415 GA= +32081							
	18:15:29,306	Traject Block Movement: Hoisting/Lowering to Target +5816 mm	**Hoist to destination**	18:15:29,306	18:15:57,882	**00:28,576**	21500	6424	**15076**
	18:15:50,502	AAPM_FINE: Adjust Stage started at HO=+6911	**MMS adjusting**	18:15:50,502	18:15:55,490	**00:04,988**	6911	6424	**487**
	18:15:55,489	AAPM_FINE: Land Stage started at HO=+6424							
	18:15:55,490	MM Task: New setpoint Reached: TR=+35 GA=-44 S=+170				**00:02,392**			
	18:15:57,882	Traject Block Movement: Lowering onto container	**Soft landing**	18:15:57,882	18:16:03,684	**00:05,802**	6424	5816	**608**
	18:16:03,684	Traject Block Movement: End Position Reached	**Unlock container**	18:16:03,684	18:16:20,740	**00:17,056**			
	18:16:20,740	Traject Block Movement: Hoisting/Lowering to Target +6247 mm					6247	5816	**431**
					Total time	**02:46,297**			

C.2 Acceleration, deceleration and speed

Table 35 Trolley acceleration, deceleration and speed results from analyzing PLC-traces

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	31308	46:54,740	7405	5,200	**492**	**mm/s2**	**acc**
Stop acc	23903	46:59,940	20459	8,000	**2557**	**mm/s**	**speed**
Start dec	3444	47:07,940	6747	5,200	**492**	**mm/s2**	**dec**
Stop dec	-3303	47:13,140					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	31228	28:48,540	8027	5,400	**482**	**mm/s2**	**acc**
Stop acc	23201	28:53,940	19259	7,400	**2603**	**mm/s**	**speed**
Start dec	3942	29:01,340	7246	5,400	**482**	**mm/s2**	**dec**
Stop dec	-3304	29:06,740					

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5734	02:39,139	7799	5,200	**477**	**mm/s2**	**acc**
Stop acc	13533	02:44,339	20087	8,100	**2480**	**mm/s**	**speed**
Start dec	33620	02:52,439	6720	5,200	**477**	**mm/s2**	**dec**
Stop dec	40340	02:57,639					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5918	06:12,138	7697	4,600	**542**	**mm/s2**	**acc**
Stop acc	13615	06:16,738	18953	7,600	**2494**	**mm/s**	**speed**
Start dec	32568	06:24,338	7242	4,600	**542**	**mm/s2**	**dec**
Stop dec	39810	06:28,938					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	31288	26:42,939	7416	5,000	**492**	**mm/s2**	**acc**
Stop acc	23872	26:47,939	22407	9,100	**2462**	**mm/s**	**speed**
Start dec	1465	26:57,039	5008	5,000	**492**	**mm/s2**	**dec**
Stop dec	-3543	27:02,039					

Table 36 Empty hoist acceleration, deceleration and speed results from analyzing PLC-traces

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	21476	16:51,639	2345	3,600	**465**	**mm/s2**	**acc**
Stop acc	19131	16:55,239	9377	5,600	**1674**	**mm/s**	**speed**
Start dec	9754	17:00,839	3495	4,000	**419**	**mm/s2**	**dec**
Stop dec	6259	17:04,839					

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5679	17:25,839	2574	3,400	**464**	**mm/s2**	**acc**
Stop acc	8253	17:29,239	9457	6,000	**1576**	**mm/s**	**speed**
Start dec	17710	17:35,239	3428	4,000	**394**	**mm/s2**	**dec**
Stop dec	21138	17:39,239					

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5860	21:33,440	3592	6,000	**277**	**mm/s2**	**acc**
Stop acc	9452	21:39,440	8628	5,200	**1659**	**mm/s**	**speed**
Start dec	18080	21:44,640	3338	5,400	**307**	**mm/s2**	**dec**
Stop dec	21418	21:50,040					

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	21473	22:29,040	2420	3,000	**549**	**mm/s2**	**acc**
Stop acc	19053	22:32,040	9225	5,600	**1647**	**mm/s**	**speed**
Start dec	9828	22:37,640	3278	3,800	**434**	**mm/s2**	**dec**
Stop dec	6550	22:41,440					

Table 37 Loaded hoist acceleration, deceleration and speed results from analyzing PLC-traces

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5921	57:59,839	1947	3,600	**265**	**mm/s2**	**acc**
Stop acc	7868	58:03,439	12416	13,000	**955**	**mm/s**	**speed**
Start dec	20284	58:16,439	1117	3,600	**265**	**mm/s2**	**dec**
Stop dec	21401	58:20,039					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	21490	58:42,439	1276	2,000	**475**	**mm/s2**	**acc**
Stop acc	20214	58:44,439	12359	13,000	**951**	**mm/s**	**speed**
Start dec	7855	58:57,439	1600	2,800	**340**	**mm/s2**	**dec**
Stop dec	6255	59:00,239					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	5905	23:05,840	1880	3,400	**358**	**mm/s2**	**acc**
Stop acc	7785	23:09,240	11305	9,300	**1216**	**mm/s**	**speed**
Start dec	19090	23:18,540	2058	3,200	**380**	**mm/s2**	**dec**
Stop dec	21148	23:21,740					

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc	21485	23:48,940	1534	2,300	**522**	**mm/s2**	**acc**
Stop acc	19951	23:51,240	11761	9,800	**1200**	**mm/s**	**speed**
Start dec	8190	24:01,040	1945	2,800	**429**	**mm/s2**	**dec**
Stop dec	6245	24:03,840					

Table 38 Soft landing speed results from analyzing PLC-traces

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc						mm/s2	acc
Stop acc	3504	01:36,241	664	8,000	**83**	mm/s	speed
Start dec	2840	01:44,241				mm/s2	dec
Stop dec							

Unloaded	Position	Time	deltaPos	deltaTime	Result		
Start acc						mm/s2	acc
Stop acc	6211	53:05,240	378	4,500	**84**	mm/s	speed
Start dec	5833	53:09,740				mm/s2	dec
Stop dec							

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc						mm/s2	acc
Stop acc	5915	17:06,740	420	5,000	**84**	mm/s	speed
Start dec	5495	17:11,740				mm/s2	dec
Stop dec							

Loaded	Position	Time	deltaPos	deltaTime	Result		
Start acc						mm/s2	acc
Stop acc	3405	48:54,741	608	7,500	**81**	mm/s	speed
Start dec	2797	49:02,241				mm/s2	dec
Stop dec							

C.3 Dead times

Table 39 Trolley to source dead time results from analyzing syslog-files

Trolley to source			JobNr	Constant speed time	Total travel time	Dead time
			299		8,25	5,148
acc/dec	500	mm/s^2	317		6,74	5,217
speed	2500	mm/s^2	383		9,53	5,994
acc/dec time	5,00	s	428	1,81	11,81	11,975
distance	6250,00	mm	429	4,09	14,09	5,719
acc+dec time	10,00	s	430	0,68	10,68	5,782
acc+dec dist	12500,00	mm	431	5,22	15,22	6,157
			433	0,68	10,68	5,744
			434	2,95	12,95	6,091
			435	1,81	11,81	5,413
			437	4,08	14,08	5,600
					average	**5,686**
					stdev	**0,329**

Table 40 Trolley to destination dead time results from analyzing syslog-files

Trolley to destination			JobNr	Constant speed time	Total travel time	Dead time
			299		8,26	5,498
acc/dec	500	mm/s^2	317		6,74	5,179
speed	2500	mm/s^2	383		9,53	6,229
acc/dec time	5,00	s	428	1,82	11,82	5,546
distance	6250,00	mm	429	2,95	12,95	5,268
acc+dec time	10,00	s	430	0,68	10,68	5,991
acc+dec dist	12500,00	mm	431	4,09	14,09	5,649
			433	2,95	12,95	5,236
			434	1,82	11,82	5,593
			435	0,68	10,68	5,971
			437	4,09	14,09	5,518
					average	**5,613**
					stdev	**0,335**

Table 41 Hoist empty spreader dead time results from analyzing syslog-files

Hoist to upper (empty)			JobNr	Constant speed time	Total travel time	Dead time
			299	1,62	8,73	1,365
acc/dec	450	mm/s^2	317	6,82	13,93	1,468
speed	1600	mm/s^2	383	6,99	14,10	1,437
acc/dec time	3,56	s	428			
distance	2844,44	mm	429	4,99	12,10	1,017
acc+dec time	7,11	s	430	7,07	14,18	1,298
acc+dec dist	5688,89	mm	431	5,22	12,33	1,292
			433			
			434	3,35	10,46	1,185
			435	3,41	10,52	1,328
			437	7,02	14,13	1,452
					average	**1,316**
					stdev	**0,136**

Table 42 Lower empty spreader dead time results from analyzing syslog-files

Lower to source			JobNr	Constant speed time	Total travel time	Dead time
			299	5,88	9,43	3,481
acc/dec	450	mm/s^2	317	0,45	4,01	6,574
speed	1600	mm/s^2	383	0,45	4,01	6,782
acc/dec time	3,56	s	428	4,05	7,60	4,349
distance	2844,44	mm	429	7,68	11,23	3,101
acc+dec time	7,11	s	430	5,87	9,42	3,716
acc+dec dist	5688,89	mm	431	7,68	11,24	3,122
			433	4,05	7,60	4,393
			434	5,87	9,42	3,669
			435	7,68	11,24	3,057
			437	5,87	9,42	3,664
					average	**4,173**
					stdev	**1,256**

C.4 Process times

Table 43 FLS process time results from analyzing syslog-files

Time	Process	Time difference
18:17:58,746	Measurements - FLS enable command on	8,145
18:18:06,891	Master State - FLS General Error	
10:10:44,695	Measurements - FLS enable command on	8,905
10:10:53,600	Master State - FLS General Error	
10:13:43,488	Measurements - FLS enable command on	8,924
10:13:52,412	Master State - FLS General Error	
12:01:23,544	Measurements - FLS enable command on	6,978
12:01:30,522	Master State - FLS General Error	
12:20:10,298	Measurements - FLS enable command on	7,061
12:20:17,359	Master State - FLS General Error	
	average	**8,003**
	stdev	**0,851**

Table 44 MMS process time results from analyzing syslog-files

MMS adjusting time		
JobNr	Empty spreader	Loaded spreader
299	03,688	05,503
317	04,541	04,823
383	04,503	03,685
428	03,942	05,036
429	03,561	03,529
430	04,721	04,263
431	05,059	02,244
433	04,119	03,958
434	04,923	03,993
435	05,784	03,505
437	05,715	04,988
	average	**4,367**
	stdev	**0,831**

Table 45 Twistlock process time with stacking guide process time results from analyzing syslog-files

Twistlocks						
JobNr	**Lock**		**Unlock**			
299	03,555		17,046			
317	03,580		16,738			
383	03,578		17,305			
428	03,561		17,156			
429	03,594	03,555				
430	03,549		16,899			
431	03,563	03,552				
433	03,550		16,873			
434	03,565		17,013			
435	03,552		17,196			
437	03,419		17,056			
average	**3,552**		**17,031**	**13,480**	**Stacking guide time**	
stdev	**0,040**		**0,166**			

C.5 The twelve verification jobs

JobNr	Process from practice	Process time	Process from model	Process time		Difference
394				Average	Stdev	
	Hoist to upper	00:10,696	Hoist to upper	00:06,938	00,144	-00:03,758
	Trolley to source	00:10,027	Trolley to source	00:10,417	00,234	00:00,390
			FLS	00:07,688	00,640	
	Hoist to source +FLS +MMS	00:23,274	Hoist to source +MMS	00:12,546	01,169	00:03,040
	Soft landing	00:07,706	Soft landing	00:07,678	00,000	-00:00,028
	Lock	00:03,579	Lock	00:03,557	00,041	-00:00,022
	Hoist to upper	00:18,652	Hoist to upper +SG	00:08,266	00,136	-00:10,386
	Trolley to destination	00:15,704	Trolley to destination	00:15,273	00,367	-00:00,431
			FLS	00:08,141	00,559	
	Hoist to destination +FLS +MMS	00:26,507	Hoist to destination +MMS	00:30,988	01,031	00:12,623
	Soft landing	00:07,979	Soft landing	00:07,678	00,000	-00:00,301
			Hoist stackingguides	00:00,000	00,000	
	Unlock	00:03,554	Unlock	00:03,533	00,030	00:00,021
	Total	02:07,678	**Total**	02:02,703		
			Difference	-00:04,975		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
395				Average	Stdev	
	Hoist to upper	00:15,373	Hoist to upper	00:15,244	00,132	-00:00,129
	Trolley to source	00:15,535	Trolley to source	00:15,431	00,334	-00:00,104
			FLS	00:07,982	00,615	
	Hoist to source +FLS +MMS	00:23,325	Hoist to source +MMS	00:15,006	01,259	00:00,337
	Soft landing	00:07,787	Soft landing	00:07,678	00,000	-00:00,109
	Lock	00:03,578	Lock	00:03,558	00,037	-00:00,020
	Hoist to upper	00:15,173	Hoist to upper +SG	00:11,796	00,099	-00:03,377
	Trolley to destination	00:15,704	Trolley to destination	00:15,209	00,360	-00:00,495
			FLS	00:07,994	00,800	
	Hoist to destination +FLS +MMS	00:24,817	Hoist to destination +MMS	00:27,583	01,059	00:10,760
	Soft landing	00:07,002	Soft landing	00:07,678	00,000	00:00,676
			Hoist stackingguides	00:13,480	00,000	
	Unlock	00:17,742	Unlock	00:03,570	00,045	00:00,692
	Total	02:26,036	**Total**	02:32,208		
			Difference	00:06,172		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
396				Average	Stdev	
	Hoist to upper	00:13,255	Hoist to upper	00:13,339	00,082	00:00,084
	Trolley to source	00:15,542	Trolley to source	00:15,351	00,349	-00:00,191
			FLS	00:07,820	00,881	
	Hoist to source +FLS +MMS	00:22,247	Hoist to source +MMS	00:16,598	01,836	00:02,171
	Soft landing	00:06,600	Soft landing	00:07,678	00,000	00:01,078
	Lock	00:03,559	Lock	00:03,550	00,039	-00:00,009
	Hoist to upper	00:17,163	Hoist to upper +SG	00:15,528	00,122	-00:01,635
	Trolley to destination	00:15,738	Trolley to destination	00:15,114	00,229	-00:00,624
			FLS	00:07,622	00,818	
	Hoist to destination +FLS +MMS	00:24,792	Hoist to destination +MMS	00:23,406	01,328	00:06,235
	Soft landing	00:07,999	Soft landing	00:07,678	00,000	-00:00,321
			Hoist stackingguides	00:13,480	00,000	
	Unlock	00:17,170	Unlock	00:03,543	00,038	00:00,147
	Total	02:24,065	**Total**	02:30,706		
			Difference	00:06,641		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
397				Average	Stdev	
	Hoist to upper	00:11,924	Hoist to upper	00:11,726	00,120	-00:00,198
	Trolley to source	00:15,541	Trolley to source	00:15,333	00,300	-00:00,208
			FLS	00:07,791	00,636	
	Hoist to source +FLS +MMS	00:23,403	Hoist to source +MMS	00:18,386	01,757	00:02,774
	Soft landing	00:06,912	Soft landing	00:07,678	00,000	00:00,766
	Lock	00:03,545	Lock	00:03,560	00,044	00:00,015
	Hoist to upper	00:18,913	Hoist to upper +SG	00:19,128	00,126	00:00,215
	Trolley to destination	00:15,720	Trolley to destination	00:15,119	00,137	-00:00,601
			FLS	00:08,167	00,994	
	Hoist to destination +FLS +MMS	00:22,070	Hoist to destination +MMS	00:20,205	01,429	00:06,303
	Soft landing	00:06,710	Soft landing	00:07,678	00,000	00:00,968
			Hoist stackingguides	00:13,480	00,000	
	Unlock	00:17,021	Unlock	00:03,536	00,039	00:00,005
	Total	02:21,759	**Total**	02:31,787		
			Difference	00:10,028		

JobNr	Process from practice	Process time	Process from model	Process time		Difference
398				Average	Stdev	
	Hoist to upper	00:09,434	Hoist to upper	00:09,652	00,149	00:00,217
	Trolley to source	00:15,537	Trolley to source	00:15,030	00,217	-00:00,507
			FLS	00:07,867	00,405	
	Hoist to source +FLS +MMS	00:26,529	Hoist to source +MMS	00:20,057	00,986	00:01,395
	Soft landing	00:08,200	Soft landing	00:07,678	00,000	-00:00,522
	Lock	00:03,560	Lock	00:03,547	00,029	-00:00,013
	Hoist to upper	00:21,201	Hoist to upper +SG	00:22,699	00,176	00:01,498
	Trolley to destination	00:15,713	Trolley to destination	00:15,119	00,295	-00:00,594
			FLS	00:08,256	00,762	
	Hoist to destination +FLS +MMS	00:21,399	Hoist to destination +MMS	00:16,185	01,341	00:03,041
	Soft landing	00:06,802	Soft landing	00:07,678	00,000	00:00,876
			Hoist stackingguides	00:13,480	00,000	
	Unlock +SG	00:17,023	Unlock	00:03,554	00,039	00:00,011
	Total	02:25,398	**Total**	02:30,801		
			Difference	00:05,403		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
399				Average	Stdev	
	Hoist to upper	00:05,682	Hoist to upper	00:05,877	00,098	00:00,195
	Trolley to source	00:15,537	Trolley to source	00:15,363	00,322	-00:00,174
			FLS	00:07,633	00,692	
	Hoist to source +FLS +MMS	00:27,977	Hoist to source +MMS	00:21,483	01,298	00:01,139
	Soft landing	00:09,181	Soft landing	00:07,678	00,000	-00:01,503
	Lock	00:03,438	Lock	00:03,569	00,034	00:00,131
	Hoist to upper	00:23,228	Hoist to upper +SG	00:26,419	00,097	00:03,191
	Trolley to destination	00:15,755	Trolley to destination	00:15,179	00,195	-00:00,576
			FLS	00:08,367	00,817	
	Hoist to destination +FLS +MMS	00:20,836	Hoist to destination +MMS	00:12,591	01,303	00:00,121
	Soft landing	00:07,560	Soft landing	00:07,678	00,000	00:00,118
			Hoist stackingguides	00:13,480	00,000	
	Unlock	00:17,181	Unlock	00:03,542	00,053	00:00,159
	Total	02:26,375	**Total**	02:28,859		
			Difference	00:02,484		

JobNr	Process from practice	Process time	Process from model	Process time		Difference
406				Average	Stdev	
	Hoist to upper	00:10,704	Hoist to upper	00:06,829	00,142	-00:03,875
	Trolley to source	00:10,019	Trolley to source	00:10,467	00,322	00:00,448
			FLS	00:08,357	00,950	
	Hoist to source +FLS +MMS	00:21,940	Hoist to source +MMS	00:12,669	01,104	00:00,914
	Soft landing	00:06,580	Soft landing	00:07,677	00,001	00:01,098
	Lock	00:03,451	Lock	00:03,544	00,042	00:00,093
	Hoist to upper	00:16,768	Hoist to upper +SG	00:08,582	00,121	-00:08,186
	Trolley to destination	00:15,735	Trolley to destination	00:15,172	00,219	-00:00,563
			FLS	00:07,773	00,775	
	Hoist to destination +FLS +MMS	00:26,144	Hoist to destination +MMS	00:31,612	01,533	00:13,241
	Soft landing	00:07,903	Soft landing	00:07,678	00,000	-00:00,225
			Hoist stackingguides	00:00,000	00,000	
	Unlock	00:03,572	Unlock	00:03,560	00,048	00:00,012
	Total	02:02,816	**Total**	02:03,921		
			Difference	00:01,105		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
407				Average	Stdev	
	Hoist to upper	00:15,281	Hoist to upper	00:15,154	00,125	-00:00,128
	Trolley to source	00:15,495	Trolley to source	00:15,173	00,496	-00:00,322
			FLS	00:08,167	00,929	
	Hoist to source +FLS +MMS	00:22,688	Hoist to source +MMS	00:14,462	01,756	00:00,058
	Soft landing	00:06,812	Soft landing	00:07,678	00,000	00:00,866
	Lock	00:03,560	Lock	00:03,549	00,017	-00:00,011
	Hoist to upper	00:15,706	Hoist to upper +SG	00:12,370	00,162	-00:03,336
	Trolley to destination	00:15,754	Trolley to destination	00:15,119	00,142	-00:00,635
			FLS	00:07,852	00,834	
	Hoist to destination +FLS +MMS	00:25,141	Hoist to destination +MMS	00:27,031	01,182	00:09,742
	Soft landing	00:06,786	Soft landing	00:07,678	00,001	00:00,892
			Hoist stackingguides	00:13,480	00,000	
	Unlock +SG	00:17,461	Unlock	00:03,554	00,044	00:00,427
	Total	02:24,684	**Total**	02:31,266		
			Difference	00:06,582		

JobNr	Process from practice	Process time	Process from model	Process time		Difference
408				Average	Stdev	
	Hoist to upper	00:13,631	Hoist to upper	00:13,544	00,181	-00:00,087
	Trolley to source	00:15,501	Trolley to source	00:15,311	00,396	-00:00,190
			FLS	00:08,612	00,996	
	Hoist to source +FLS +MMS	00:21,601	Hoist to source +MMS	00:17,021	01,143	00:04,032
	Soft landing	00:06,163	Soft landing	00:07,678	00,000	00:01,515
	Lock	00:03,555	Lock	00:03,530	00,030	-00:00,025
	Hoist to upper	00:17,391	Hoist to upper +SG	00:15,861	00,203	-00:01,530
	Trolley to destination	00:15,770	Trolley to destination	00:15,206	00,260	-00:00,564
			FLS	00:08,065	00,707	
	Hoist to destination +FLS +MMS	00:24,103	Hoist to destination +MMS	00:24,720	01,055	00:08,682
	Soft landing	00:07,856	Soft landing	00:07,678	00,000	-00:00,178
			Hoist stackingguides	00:13,480	00,000	
	Unlock +SG	00:17,166	Unlock	00:03,556	00,038	00:00,130
	Total	02:24,684	**Total**	02:31,266		
			Difference	00:06,582		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
410				Average	Stdev	
	Hoist to upper	00:09,895	Hoist to upper	00:09,885	00,128	-00:00,010
	Trolley to source	00:15,484	Trolley to source	00:15,158	00,512	-00:00,326
			FLS	00:08,109	00,966	
	Hoist to source +FLS +MMS	00:24,781	Hoist to source +MMS	00:19,742	01,905	00:03,070
	Soft landing	00:06,939	Soft landing	00:07,678	00,000	00:00,739
	Lock	00:03,581	Lock	00:03,548	00,017	-00:00,033
	Hoist to upper	00:21,295	Hoist to upper +SG	00:23,244	00,174	00:01,949
	Trolley to destination	00:15,758	Trolley to destination	00:15,112	00,145	-00:00,646
			FLS	00:07,941	00,969	
	Hoist to destination +FLS +MMS	00:22,125	Hoist to destination +MMS	00:16,142	01,161	00:01,957
	Soft landing	00:07,639	Soft landing	00:07,677	00,000	00:00,038
			Hoist stackingguides	00:13,480	00,000	
	Unlock +SG	00:17,436	Unlock	00:03,561	00,046	00:00,395
	Total	02:24,933	**Total**	02:31,276		
			Difference	00:06,343		

JobNr	Activity practice	Process time	Activity simulation	Process time		Difference
411				Average	Stdev	
	Hoist to upper	00:08,260	Hoist to upper	00:08,315	00,122	00:00,055
	Trolley to source	00:15,502	Trolley to source	00:15,277	00,443	-00:00,225
			FLS	00:08,698	00,832	
	Hoist to source +FLS +MMS	00:27,022	Hoist to source +MMS	00:22,267	01,328	00:03,943
	Soft landing	00:08,060	Soft landing	00:07,678	00,000	-00:00,382
	Lock	00:03,592	Lock	00:03,529	00,028	-00:00,063
	Hoist to upper	00:23,299	Hoist to upper +SG	00:26,685	00,224	00:03,386
	Trolley to destination	00:15,761	Trolley to destination	00:10,529	00,263	-00:05,232
			FLS	00:08,283	00,587	
	Hoist to destination +FLS +MMS	00:22,524	Hoist to destination +MMS	00:17,517	01,044	00:03,276
	Soft landing	00:07,492	Soft landing	00:07,678	00,000	00:00,186
			Hoist stackingguides	00:13,480	00,000	
	Unlock +SG	00:17,030	Unlock	00:03,551	00,035	00:00,001
	Total	02:28,542	**Total**	02:33,487		
			Difference	00:04,945		

D. Results performance prediction accuracy

D.1 Job batches

Table 46 Results from single job batches regarding batch type 41

Type 41	**Practice** Time (mm:ss)	**Model A** Time (mm:ss)	Δ (mm:ss)	**Model B** Time (mm:ss)	Δ (mm:ss)	**Model C** Time (mm:ss)	Δ (mm:ss)
Average	**14:48**	**14:48**	**00:00**	**07:56**	**-06:52**	**11:06**	**-03:42**
BatchNr 1	14:22		**+00:26**		**-06:26**		**-03:16**
2	14:34		**+00:14**		**-06:38**		**-03:28**
3	14:40		**+00:08**		**-06:44**		**-03:34**
4	14:17		**+00:31**		**-06:21**		**-03:11**
5	14:34		**+00:14**		**-06:38**		**-03:28**
6	15:14		**-00:26**		**-07:18**		**-04:08**
7	14:46		**+00:02**		**-06:50**		**-03:40**
8	15:20		**-00:32**		**-07:24**		**-04:14**
9	15:23		**-00:35**		**-07:27**		**-04:17**
10	14:52		**-00:04**		**-06:56**		**-03:46**
11	14:53		**-00:05**		**-06:57**		**-03:47**
12	14:45		**+00:03**		**-06:49**		**-03:39**

Table 47 Results from single job batches regarding batch type 23

Type 23	**Practice** Time (mm:ss)	**Model A** Time (mm:ss)	Δ (mm:ss)	**Model B** Time (mm:ss)	Δ (mm:ss)	**Model C** Time (mm:ss)	Δ (mm:ss)
Average	**14:09**	**14:21**	**00:12**	**07:29**	**-06:40**	**10:43**	**-03:26**
BatchNr 1	13:41		**+00:40**		**-06:12**		**-02:58**
2	14:01		**+00:20**		**-06:32**		**-03:18**
3	14:06		**+00:15**		**-06:37**		**-03:23**
4	13:48		**+00:33**		**-06:19**		**-03:05**
5	13:34		**+00:47**		**-06:05**		**-02:51**
6	14:25		**-00:04**		**-06:56**		**-03:42**
7	14:31		**-00:10**		**-07:02**		**-03:48**
8	14:35		**-00:14**		**-07:06**		**-03:52**
9	14:52		**-00:31**		**-07:23**		**-04:09**
10	14:02		**+00:19**		**-06:33**		**-03:19**
11	14:10		**+00:11**		**-06:41**		**-03:27**
12	14:05		**+00:16**		**-06:36**		**-03:22**

Table 48 Results from single job batches regarding batch type 21

Type 21	Practice Time (mm:ss)	Model A Time (mm:ss)	Δ (mm:ss)	Model B Time (mm:ss)	Δ (mm:ss)	Model C Time (mm:ss)	Δ (mm:ss)
Average	**13:59**	**14:18**	**00:19**	**07:25**	**-06:34**	**10:41**	**-03:18**
BatchNr 1	13:33		**+00:45**		**-06:08**		**-02:52**
2	13:56		**+00:22**		**-06:31**		**-03:15**
3	13:41		**+00:37**		**-06:16**		**-03:00**
4	14:12		**+00:06**		**-06:47**		**-03:31**
5	13:46		**+00:32**		**-06:21**		**-03:05**
6	14:00		**+00:18**		**-06:35**		**-03:19**
7	13:30		**+00:48**		**-06:05**		**-02:49**
8	14:03		**+00:15**		**-06:38**		**-03:22**
9	13:38		**+00:40**		**-06:13**		**-02:57**
10	13:59		**+00:19**		**-06:34**		**-03:18**
11	13:37		**+00:41**		**-06:12**		**-02:56**
12	15:55		**-01:37**		**-08:30**		**-05:14**

D.2 Individual jobs

Table 49 Results from individual jobs 1, 6 and 4 for each batch type

Batch Type,Seq	Practice Time (mm:ss)	Model A Time (mm:ss)	Δ (mm:ss)	Model B Time (mm:ss)	Δ (mm:ss)	Model C Time (mm:ss)	Δ (mm:ss)
41,1	02:04,86	02:01,72	**-00:03,14**	01:04,69	**-01:00,16**	01:36,77	**-00:28,09**
41,6	02:22,36	02:33,95	**+00:11,60**	01:20,27	**-01:02,09**	01:52,94	**-00:29,42**
41,4	02:24,20	02:31,12	**+00:06,92**	01:20,27	**-01:03,93**	01:53,09	**-00:31,10**
23,1	02:02,09	02:04,03	**+00:01,95**	01:05,42	**-00:56,66**	01:39,18	**-00:22,91**
23,6	02:15,51	02:25,73	**+00:10,22**	01:14,68	**-01:00,83**	01:47,79	**-00:27,73**
23,4	02:15,67	02:25,60	**+00:09,92**	01:14,67	**-01:01,00**	01:48,33	**-00:27,35**
21,1	01:53,66	01:55,58	**+00:01,91**	00:57,19	**-00:56,47**	01:33,20	**-00:20,47**
21,6	02:12,56	02:24,63	**+00:12,07**	01:14,41	**-00:58,15**	01:48,49	**-00:24,07**
21,4	02:12,70	02:25,77	**+00:13,06**	01:14,54	**-00:58,17**	01:47,34	**-00:25,36**
		Average	**+00:07,17**	Average	**-00:59,72**	Average	**-00:26,28**
		σ	**00:05,34**	σ	**00:02,39**	σ (s)	**00:03,17**

D.3 Process blocks

Table 50 Hoist empty spreader process block results, individual jobs 1, 6 and 4 for each batch type

Batch	**Practice**	**Model A**		**Model B**		**Model C**	
Type,Seq	Time (s)	Time (s)	Δ (s)	Time (s)	Δ (s)	Time (s)	Δ (s)
41,1	10,41	06,55	**-03,86**	05,27	**-05,14**	06,83	**-03,58**
41,6	08,17	08,42	**+00,25**	06,98	**-01,19**	08,32	**+00,15**
41,4	11,57	11,97	**+00,40**	10,56	**-01,01**	11,91	**+00,33**
23,1	10,74	06,62	**-04,12**	05,29	**-05,45**	06,88	**-03,86**
23,6	08,20	08,30	**+00,10**	06,97	**-01,23**	08,25	**+00,04**
23,4	11,62	11,87	**+00,25**	10,57	**-01,05**	11,87	**+00,26**
21,1	00,02	01,87	**+01,85**	00,55	**+00,52**	04,83	**+04,80**
21,6	07,64	07,96	**+00,33**	06,67	**-00,97**	07,97	**+00,34**
21,4	11,38	11,72	**+00,34**	10,45	**-00,93**	11,80	**+00,42**
		Average	**-00,50**	Average	**-01,83**	Average	**-00,12**
		σ	**01,93**	σ	**01,92**	σ	**02,38**

Table 51 Hoist loaded spreader process block results, individual jobs 1, 6 and 4 for each batch type

Batch	**Practice**	**Model A**		**Model B**		**Model C**	
Type,Seq	Time (s)	Time (s)	Δ (s)	Time (s)	Δ (s)	Time (s)	Δ (s)
41,1	17,94	08,39	**-09,55**	06,94	**-11,00**	10,04	**-07,90**
41,6	25,61	26,35	**+00,74**	25,03	**-00,58**	28,16	**+02,55**
41,4	22,55	19,09	**-03,46**	17,79	**-04,76**	20,86	**-01,69**
23,1	17,06	08,19	**-08,87**	06,94	**-10,12**	10,01	**-07,04**
23,6	23,12	26,38	**+03,26**	25,03	**+01,91**	28,10	**+04,98**
23,4	18,85	19,13	**+00,29**	17,79	**-01,06**	20,88	**+02,03**
21,1	18,72	08,30	**-10,41**	06,94	**-11,78**	10,09	**-08,63**
21,6	23,09	26,33	**+03,25**	25,03	**+01,94**	28,05	**+04,96**
21,4	18,86	19,17	**+00,31**	17,79	**-01,07**	20,86	**+01,99**
		Average	**-02,72**	Average	**-04,06**	Average	**-00,97**
		σ	**05,23**	σ	**05,23**	σ	**05,22**

Table 52 Lower empty spreader process block results, individual jobs 1, 6 and 4 for each batch type

Batch Type,Seq	Practice Time (s)	Model A Time (s)	Δ (s)	Model B Time (s)	Δ (s)	Model C Time (s)	Δ (s)
41,1	28,02	27,94	**-00,08**	06,06	**-21,96**	13,89	**-14,13**
41,6	33,10	38,27	**+05,18**	15,18	**-17,92**	22,17	**-10,92**
41,4	30,84	33,50	**+02,66**	11,56	**-19,28**	18,20	**-12,64**
23,1	27,76	28,50	**+00,74**	06,06	**-21,70**	13,16	**-14,60**
23,6	32,83	37,66	**+04,82**	15,18	**-17,65**	21,32	**-11,51**
23,4	34,70	33,71	**-00,99**	11,56	**-23,14**	18,14	**-16,56**
21,1	31,06	28,32	**-02,74**	06,06	**-25,00**	13,03	**-18,02**
21,6	33,95	36,38	**+02,43**	15,18	**-18,77**	22,05	**-11,90**
21,4	28,91	33,66	**+04,75**	11,56	**-17,35**	18,50	**-10,40**
		Average	**+01,86**	Average	**-20,31**	Average	**-13,41**
		σ	**02,65**	σ	**02,57**	σ	**02,47**

Table 53 Lower loaded spreader process block results, individual jobs 1, 6 and 4 for each batch type

Batch Type,Seq	Practice Time (s)	Model A Time (s)	Δ (s)	Model B Time (s)	Δ (s)	Model C Time (s)	Δ (s)
41,1	36,64	46,24	**+09,60**	25,03	**-11,61**	34,60	**-02,04**
41,6	26,92	29,94	**+03,02**	06,94	**-19,98**	15,72	**-11,20**
41,4	30,74	35,43	**+04,69**	14,18	**-16,56**	23,07	**-07,67**
23,1	34,06	47,05	**+12,99**	25,03	**-09,04**	33,45	**-00,62**
23,6	29,35	27,92	**-01,43**	06,94	**-22,41**	14,94	**-14,41**
23,4	29,23	35,44	**+06,21**	14,18	**-15,05**	22,68	**-06,55**
21,1	34,80	47,38	**+12,57**	25,03	**-09,78**	33,80	**-01,00**
21,6	25,72	28,44	**+02,72**	06,94	**-18,78**	15,83	**-09,89**
21,4	31,71	35,92	**+04,21**	14,18	**-17,54**	22,69	**-09,03**
		Average	**+06,06**	Average	**-15,64**	Average	**-06,93**
		σ	**04,53**	σ	**04,39**	σ	**04,56**

Table 54 Trolley to source process block results, individual jobs 1, 6 and 4 for each batch type

Batch	**Practice**	**Model A**		**Model B**		**Model C**	
Type,Seq	Time (s)	Time (s)	Δ (s)	Time (s)	Δ (s)	Time (s)	Δ (s)
41,1	10,02	10,37	**+00,35**	04,75	**-05,27**	12,10	**+02,07**
41,6	15,58	15,18	**-00,40**	09,53	**-06,05**	15,70	**+00,12**
41,4	15,52	15,30	**-00,23**	09,53	**-05,99**	15,76	**+00,23**
23,1	13,47	14,16	**+00,70**	08,25	**-05,22**	13,77	**+00,31**
23,6	12,06	12,58	**+00,51**	06,73	**-05,33**	13,51	**+01,44**
23,4	11,32	12,51	**+01,18**	06,75	**-04,58**	13,85	**+02,53**
21,1	10,02	10,31	**+00,29**	04,76	**-05,26**	13,77	**+03,75**
21,6	11,98	12,51	**+00,53**	06,74	**-05,25**	12,83	**+00,85**
21,4	11,87	12,50	**+00,63**	06,73	**-05,13**	14,15	**+02,28**
		Average	**+00,40**	Average	**-05,34**	Average	**+01,51**
		σ	**00,45**	σ	**00,42**	σ	**01,17**

Table 55 Trolley to destination process block results, individual jobs 1, 6 and 4 for each batch type

Batch	**Practice**	**Model A**		**Model B**		**Model C**	
Type,Seq	Time (s)	Time (s)	Δ (s)	Time (s)	Δ (s)	Time (s)	Δ (s)
41,1	14,67	15,11	**+00,44**	09,53	**-05,14**	14,97	**+00,30**
41,6	14,65	15,22	**+00,56**	09,53	**-05,12**	15,04	**+00,38**
41,4	14,91	15,26	**+00,35**	09,53	**-05,38**	15,04	**+00,13**
23,1	11,86	12,37	**+00,51**	06,74	**-05,12**	13,27	**+01,41**
23,6	11,89	12,33	**+00,44**	06,74	**-05,15**	12,82	**+00,93**
23,4	11,90	12,36	**+00,46**	06,74	**-05,16**	12,88	**+00,98**
21,1	11,90	12,30	**+00,40**	06,74	**-05,16**	12,89	**+00,99**
21,6	11,86	12,40	**+00,55**	06,74	**-05,12**	13,14	**+01,28**
21,4	11,78	12,21	**+00,43**	06,74	**-05,04**	12,95	**+01,17**
		Average	**+00,46**	Average	**-05,15**	Average	**+00,84**
		σ	**00,06**	σ	**00,09**	σ	**00,43**

E. Results sensitivity analysis

E.1 Hoist speed

Table 56 Hoist speed parameter input value results

Model A	ExpNr	m/h	StDev	Min	Max
	1	15,40	0,11	15,07	15,79
	2	18,93	0,17	18,44	19,53
	3	21,14	0,21	20,53	21,89
	4	22,73	0,24	22,02	23,59
	5	23,76	0,27	22,99	24,71
	6	24,54	0,28	23,72	25,55
	7	25,04	0,30	24,19	26,10
	8	25,42	0,30	24,54	26,51
	9	25,66	0,31	24,77	26,77

Model B	ExpNr	m/h	StDev	Min	Max
	1	21,47	0,00	21,46	21,49
	2	29,47	0,01	29,44	29,50
	3	35,45	0,01	35,41	35,50
	4	40,35	0,02	40,30	40,41
	5	43,87	0,02	43,81	43,94
	6	46,69	0,02	46,62	46,77
	7	48,63	0,02	48,55	48,72
	8	50,12	0,02	50,04	50,22
	9	51,13	0,03	51,05	51,24

Model C	ExpNr	m/h	StDev	Min	Max
	1	17,37	0,15	16,87	17,88
	2	22,54	0,26	21,69	23,40
	3	26,24	0,35	25,10	27,42
	4	29,29	0,44	27,88	30,77
	5	31,62	0,51	29,98	33,35
	6	33,63	0,58	31,79	35,59
	7	35,23	0,63	33,21	37,39
	8	36,66	0,68	34,47	39,00
	9	37,82	0,73	35,50	40,32

E.2 Trolley speed

Table 57 Trolley speed parameter input value results

Model A	ExpNr	m/h	StDev	Min	Max
	10	22,62	0,24	21,92	23,48
	11	23,13	0,25	22,40	24,03
	12	23,45	0,26	22,70	24,37
	13	23,64	0,26	22,88	24,58
	14	23,76	0,27	22,99	24,71
	15	23,83	0,27	23,06	24,79
	16	23,86	0,27	23,09	24,82
	17	23,87	0,27	23,09	24,83
	18	23,87	0,27	23,09	24,83

Model B	ExpNr	m/h	StDev	Min	Max
	10	40,13	0,02	40,08	40,19
	11	41,76	0,02	41,70	41,83
	12	42,80	0,02	42,74	42,87
	13	43,46	0,02	43,40	43,53
	14	43,87	0,02	43,81	43,94
	15	44,10	0,02	44,04	44,18
	16	44,21	0,02	44,14	44,29
	17	44,23	0,02	44,16	44,30
	18	44,23	0,02	44,16	44,30

Model C	ExpNr	m/h	StDev	Min	Max
	10	28,92	0,43	27,54	30,35
	11	29,94	0,46	28,47	31,48
	12	30,66	0,48	29,12	32,29
	13	31,20	0,50	29,61	32,88
	14	31,62	0,51	29,98	33,35
	15	31,95	0,52	30,28	33,72
	16	32,22	0,53	30,52	34,02
	17	32,45	0,54	30,72	34,27
	18	32,64	0,54	30,89	34,48

E.3 Hoist movement distance

Table 58 Hoist movement distance parameter input value results

Model A	ExpNr	m/h	StDev	Min	Max
	19	28,07	0,37	27,00	29,41
	20	25,73	0,31	24,83	26,85
	21	23,76	0,27	22,99	24,71
	22	22,08	0,23	21,41	22,89
	23	21,44	0,22	20,81	22,21

Model B	ExpNr	m/h	StDev	Min	Max
	19	61,17	0,04	61,05	61,32
	20	51,08	0,03	50,99	51,18
	21	43,87	0,02	43,81	43,94
	22	38,44	0,01	38,40	38,50
	23	34,21	0,01	34,17	34,26

Model C	ExpNr	m/h	StDev	Min	Max
	19	39,71	0,80	37,15	42,47
	20	35,20	0,63	33,18	37,35
	21	31,62	0,51	29,98	33,35
	22	28,70	0,42	27,34	30,12
	23	26,27	0,35	25,13	27,46

E.4 Trolley movement distance

Table 59 Trolley movement distance parameter input value results

Model A	ExpNr	m/h	StDev	Min	Max
	24	25,36	0,30	24,48	26,44
	25	24,45	0,28	23,64	25,46
	26	23,76	0,27	22,99	24,71
	27	23,11	0,25	22,38	24,01
	28	22,50	0,24	21,81	23,35
	29	21,92	0,23	21,26	22,72

Model B	ExpNr	m/h	StDev	Min	Max
	24	49,61	0,02	49,53	49,71
	25	46,27	0,02	46,20	46,36
	26	43,87	0,02	43,81	43,94
	27	41,70	0,02	41,65	41,77
	28	39,74	0,02	39,69	39,80
	29	37,96	0,01	37,91	38,01

Model C	ExpNr	m/h	StDev	Min	Max
	24	34,18	0,60	32,27	36,20
	25	32,85	0,55	31,08	34,72
	26	31,62	0,51	29,98	33,35
	27	30,48	0,47	28,95	32,08
	28	29,42	0,44	28,00	30,91
	29	28,43	0,41	27,10	29,82