The relation between stochasticity and terminal stacking performance of import containers

A simulation study

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by

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Preface

This report marks the end of my student life at the TU Delft. I would like to present to you my master's thesis for the study Transport, Infrastructure & Logistics at the TU Delft. This means that after quite some years, the final result is here, or maybe I should say the result is finally here. It might feel a little bit odd, I am definitely looking back with a positive feeling on all these years. I am very gratefull for all the opportunities I have been given and the things I have learned.

Firstly, I would shortly like to thank my thesis supervisors. Alexander, thank you for your sharp vision on constant improvement and your help with my simulation model. Yilin, thank you for helping me with my reporting style and constant focus on quality. Mark, thank you for your advice on report structure and terminology and the discussions we had on the subject. Wim, thank you for all of your insights into the world of container terminals. And Pepijn, thank your for your ever critical but constructive feedback on my thoughts. Thanks to all of you, I was motivated to improve the quality of my research constantly and to obtain a lot of new knowledge on the subject of container terminal operations.

Besides the research, it was a wonderful opportunity to work on my master's thesis research at Rebel. I have gotten to know the company quite well in the last couple of months, and I definitely hope to stay in touch in the future. Thanks to everyone at Rebel who was willing to have a brainstorm on my subject or a coffee to temporarily forget about it.

I would also like to thank everyone who made time to have a discussion or interview with me to deepen my knowledge on container terminal operations. Thanks to all of you, I really have been able to first scope my research and later to put my findings in perspective.

Finally, I would really like to thank my parents who have made it possible for me to follow this education. I know that they are very excited about the fact that they don't longer need to provide support, but I would like you to know that your support has definitely been my number 1 motivation throughout all these years. A small apology to my brother, who has not been able to finish his study before I did. I know for sure that you will master your problems the next coming weeks and the reward (or relief) in the end will be even bigger! Last but not least, I would like to thank Rolf, who might have even been happier than I was with my green light. Thank you so much for being my light in a sometimes darker period, for putting up with my mood swings and for making fun of my fascination for containers.

N. E. Mutters
Delft, April 2019

Executive Summary

Containerisation has lead to a decrease of sea transportation costs and more cost effective transport, as well as advantages in terms of handling processes at container terminals and protection of the goods inside (Steenken et al., 2004). Since the amount of container terminals has grown, competition has risen. Therefore it has become more and more important for terminal operators to conduct their work as efficient as possible. Efficient terminal operations are hindered by stochasticity, which is defined as random and uncertain variation in a parameter value. Stochasticity can affect many aspects of terminal operations. It is for example present in crane operations, indicated by a varying job handling time or varying frequency and time of equipment breakdowns. The stochasticity researched in this study is focused on stochasticity in arrival times and types of hinterland transport modes generating container retrieval requests. It is partially caused by the actors involved in the practice of container shipment. Stochasticity in arrival times of hinterland transport modes makes it harder for a terminal to organise the import yard in a way that the containers that will be retrieved first are on top of the stack. Stochasticity in types of hinterland transport modes complicates the process of storing containers together that will be retrieved by the same type of hinterland transport mode. Since import containers are confronted with the highest level of stochasticity in comparison to export and transshipment containers, this research is scoped towards stacking operations of import containers. Due to the lack of information on exact arrival times, requested containers are often stored underneath other containers, which will then need to be reshuffled to reach the requested container. This type of reshuffling is performed while a hinterland transport mode is waiting for the requested container, and therefore increases service times for the hinterland transport modes. Reshuffling performed during peak hours especially puts pressure on the terminal system, since the limited amount of available yard operating equipment is already scheduled for many tasks during peak hours.

The goal of this research is to quantify the relation between stochasticity in container retrieval times on the performance of stacking operations of import containers. The main research question is: *What is the effect of stochasticity in import container information on stacking performance at a container terminal?* As could be concluded from an extensive literature review, no other researches before have looked into the effects of stochasticity on stacking performance of a multimodal container terminal. The scientific contribution of this research hence consists of an analysis of the effect of stochasticity on defined performance indicators. The performance indicators that represent stacking performance are based on a literature review. Based on this review the following indicators have been defined: the number of reshuffles, the truck service time and the maximum straddle carrier (SC) utilisation rate per hour. The practical contribution of this research is aimed at terminal operators. The outcomes of this study quantify the effect stochasticity has on their operations, specified in three different performance indicators. Moreover, the study identifies improvement directions for terminal operators to decrease the level of stochasticity.

As seen in the literature review, the main share of research into container terminal operations are optimisation or simulation studies. The main methodology used in this research is a simulation study since it is more suited for modelling complex interrelated components of a system and representing stochasticity.

The model designed in this research is based on a SC operated multimodal container terminal. Data has been provided by the MSC PSA European Terminal (MPET) in Antwerp on terminal layout, retrieved volumes per hinterland transport mode over a period of 46 weeks, truck arrival distributions, average dwell time and average truck service times. The main processes in the model are arrivals of import containers from the seaside and arrival of hinterland transport modes from the landside. During storage and retrieval a levelling stacking strategy is implemented as well as reshuffle logic that specifies to which location a container that is stacked on top of a requested container should be relocated. The conceptual model is implemented and specified in Simio Simulation Software, a modelling framework based on intelligent objects.

Different experiments have been run to test the effect of stochasticity on stacking performance. In the experiments two configurations have been specified: the implementation of housekeeping moves during non-peak

hours (from 10:00 PM until 5:30 AM) and the non-housekeeping configuration. For these two configurations, results of experiments in which the level of stochasticity is varied are achieved. The results show that the implementation of housekeeping moves improves the performance of stacking operations. In all the different stochasticity scenarios statistically significant improvements (based on a 95% confidence level) of the three performance indicators have been found in comparison of the housekeeping configuration with the non-housekeeping configuration. In Table 1 the effects of housekeeping moves in the lowest level of stochasticity (StochLevel = 1) and the highest level of stochasticity (StochLevel = 30) in this research are given. Implementing housekeeping moves in the scenario with low stochasticity could spare 639 764 reshuffles per year, 8 854 hours of truck service time per year and 8 minutes per SC in peak hours based on the total import volume of the terminal. In the scenario with high level of stochasticity, implementing housekeeping moves could save 120 656 reshuffles per year, 883 hours of truck service time per year and 3 minutes per SC in peak hours. In the low stochasticity experiment 10 housekeeping SC shifts are needed each night to obtain the benefits and the total SC working hours increase with 60 714 hours per year for the entire import yard. In the high stochasticity experiment 8 housekeeping SC shifts are needed and the total SC working hours increase with 58 735 hours per year.

Table 1: Effect of housekeeping moves on performance indicators for minimal stochasticity and maximal stochasticity scenario

KPI	**Parameter value change**		**Interpretation of savings**
	No HK	HK	
Low stochasticity (StochLevel = 1)			
Reshuffles per retrieval	0.95	0.27	639 764 reshuffles per year
Truck service time (min)	3.32	2.42	8 854 hours per year
Max SC utilisation per hour	0.36	0.22	8 min per peak hour
Total SC working hours	132.5	303.5	60 714 hours per year
Number of HK SC shifts needed per night		10	-
High stochasticity (StochLevel = 30)			
Reshuffles per retrieval	0.91	0.78	120 656 reshuffles per year
Truck service time (min)	3.25	3.16	883 hours per year
Max SC utilisation per hour	0.35	0.30	3 min per peak hour
Total SC working hours	129.0	294.4	58 735 hours per year
Number of HK SC shifts needed per night		8	-

The results of this research should be interpreted with respect to the assumptions that have been made in order to design a simulation model that is able to answer the research question in the available time scope. Because the model only includes containers of 1 TEU size, the amount of container moves is slightly overestimated in this research as well as the effects of housekeeping moves and stochasticity on the performance indicators. Moreover, the model represents one single row of the entire import yard. Hence, the total SC fleet in the import yard area and other transport requests the SCs have to perform are not taken into account when a container is requested. Instead, a SC is immediately available for retrieval of the container out of this single row. Likewise, the waiting time of trucks for a SC to become available is not included in the truck service time. This leads to an underestimation of the the maximum SC utilisation rate per hour and the truck service time.

Based on this research it can be concluded that a terminal can improve stacking operations by implementing housekeeping moves, even in scenarios with high stochasticity. The lower the level of stochasticity is, the stronger the improvements on stacking operations are. However, in order to decrease stochasticity the stakeholder network should be consulted. The main stakeholder that could help in contributing to a lower level of stochasticity is the shipping agent. However, current benefits for the shipping agents are limited compared to the sacrifice they have to make in terms of flexibility. The main favoured party of a lower level of stochasticity is the terminal operator. Hence, future research to incentives for shipping agents to cooperate in sharing information is recommended.

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List of Acronyms

ACT	Automated Container Terminal
AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
ALV	Automated Lifting Vehicle
ASC	Automated Stacking Crane (also: ATC)
AShC	Automated Shuttle Carrier
ATC	Automated Transfer Crane (see: ASC)
AutoStrads	Automated Straddle Carriers
CC	Container Crane (see: QC)
CT	Container Terminal
DOS	Duration Of Stay
EDT	Expected Departure Time
ESC	Electric Straddle Carrier
FEU	Forty-foot Equivalent Unit
GCR	Gross Crane Rate
I/B	Inbound (import)
I/O points	Input/output points
IMO	International Maritime Organisation (refers to containers carrying dangerous goods)
ISA	Intermediate Stacking Area
IT	Internal Truck (also: YT or YTT))
IWT	Inland Waterway container Terminal
MHC	Mobile Harbour Crane
MT	Empty Container
O/B	Outbound (export)
OOG	Out Of Gauge container
OOS	Object-oriented Simulation
OR	Operations Research
POD	Port Of Destination
QC	Quay Crane (also: CC, STS)
QCR	Quay Crane Rate [lifts/hour]
RMG/RMGC	Rail Mounted Gantry Crane
RTG/RTGC	Rubber Tired Gantry Crane
SC	Straddle Carrier (not: stacking crane)
STS	Ship-To-Shore gantry crane (see: QC)
SWGS	Same Weight Group Stacking
TC	Transfer Crane (see: YC)
TEU	Twenty-foot Equivalent Unit
TGS	TEU Ground Slot
XT	External Truck
YC	Yard Crane (eithe RTGC or RMGC, also: stacking crane or TC)
YT	Yard Truck (see: IT)
YTT	Yard Terminal Truck (see: IT)

Definitions

(Shipping) agents	Company responsible for handling shipments and cargo as well as taking care of the general interest of its customers at ports worldwide. The agent takes care of various tasks of a shipping company, such as (customs) documentations and their arrangements with port authorities.
Aisle	Space between stacks of containers allowing access for mobile equipment.
Apron	Area of the terminal between the quay and the container stacking area.
Automated Lifting Vehicle	Automated horizontal and vertical transport equipment. Can load and unload its own containers, but can not stack containers.
Barge	Means of hinterland transportation via which containers are transported on rivers and channels into the hinterland.
Bay	Row of containers placed end-to-end.
Bay plan	Profile per bay in stowage plan.
Berth	Slot on the quay for mooring and service of a single vessel, place where the vessel moors in the port.
Block stack	Grouping of containers without leaving easy access to all containers, often used for storage of empty containers.
Bow	Front of ship.
Call size	Volume of containers (TEU) that is to be loaded onto or unloaded from a vessel calling at a terminal.
Carrier	Person who transports the container physically. Carriers generally carry lighter loads than hauliers.
Carrier haulage	Transport from A to B under control of shipping line (shipping line is responsible for any damage during transport).
Consignee	Party to whom the container is directed to.
Consignment	Container group in which all containers have the same retrieval time from the yard (retrieval sequence within consignment is thus unimportant).
Constacker	See: reach stacker.
Container Crane	See: quay crane.
Container owner	Either shipping line of Container Leasing Company.
Container yard	Container stacking area of the terminal where containers are temporarily stored while they await further transport.
Container	Metal box structure of standard design, used for carrying general cargo in unitised form.
Cutoff time	Time after which cargo for a certain ship is nog longer received in order to meet ship departure schedules.
Cyle time	Total time it takes for several jobs to be performed from beginning to end (in minutes). Similar to: turnaround time.
Demurrage costs (export)	Charge levied by the shipping line to the shipper when the packed container is at the terminal but the shipper is unable to ship the container within the free days.
Demurrage costs (import)	Charge levied by the shipping line to the consignee. When a container is still full and under the control of the shipping line, but has not been picked up by the consignee within the free days (maximum time limit set by the shipping line).
Detention costs (export)	Charge levied by the shipping line to the consignee when the container is not delivered in time at the terminal.
Detention costs (import)	Charge levied by the sipping line to the consignee when a consignee holds onto the carrier's container outside of the terminal area longer than the allowed free days (maximum time limit set by the shipping line).

Discharge	Removal or unloading of a container from a vessel.
Dock crane	See: quay crane.
Downtime	Period during which a certain equipment item, or terminal component cannot be used for its primary function.
Dwell time	The time in days that containers remain in the container yard.
Feeder	Feeder vessels (barges or small ships, generally with a capacity of 100-1200 TEU) link smaller regional ports with oversea (hub) ports delivering containers for deep-sea vessels. Many feeders have their own cranes on board to handle containers.
Freight forwarder	Freight forwarders are the link between individuals who want to ship a container and the carriers. In addition they often provide additional services such as advising, completing paperwork, providing insurances and custom clearing services. They are a type of shipping agent, but in contrast they oversee the shipping process from door-to-door, while the control of the shipping agents generally covers the consolidated part of transport.
Gantry crane	Crane used to store and retrieve containers in/from the yard (see: yard crane).
Gate	The entrance point of road trucks entering and leaving the terminal.
Ground slot	The area required for the footprint of a container (including surrounding safety margin).
Haulier	Person who transports the container physically. Hauliers generally carry heavier loads than carriers.
Idle time	Time equipment is not busy and not waiting for a next task (in minutes).
Laden container	Non-empty container.
Makespan	Total time it takes for several jobs to be performed from beginning to end (in minutes). Similar to: turnaround time.
Merchant haulage	Transport from A to B directly by the consignee (merchant responsible for any damage during transport).
Mooring	Securing a ship to a fixed place at the quay by means of lines and cables.
Moves	Actual containers handled as opposed to TEU handled.
Multi Trailer System	Internal movement equipment of multiple chassis pulled by a single tractor.
Portainer	See: quay crane.
Productivity	General performance measure of equipment used in this research [moves/h].
Quay	The terminal area parallel to the shoreline, accommodating ships on only one side.
Quay crane	Crane that handles containers from/to vessels to/from the quayside (AGV, inside truck, etc.). Also referred to as: dock crane, ship to shore crane, container crane or portainer.
Reefer	Refrigerated container that requires an external power source.
Rehandle	See: reshuffle.
Remarshalling move	See: reshuffle.
Reorganisation	See: reshuffle.
Reshuffle	Movement of the yard crane to reach a container that is stacked underneath other containers (1 reshuffle is the relocation move of 1 container).
Re-stacking move	See: reshuffle.
Row	In stack: line of containers place side-to-side; In ship: position across the width of the ship; odd numbers on the right (starboard) and even number on the left (port); 01 in the centre.
Ship to shore crane	see: quay crane.
Shipping line	Company that operates a ship that carries containers and cargo from load port to discharge port.
Shuttle carrier	Straddle carrier able to stack up to 2 tiers high.
Slot	Place to store a single container, not to be confused with ground slot.
Spreader	A framework device enabling the lifting of containers by their corner castings.

Stack	The stack of containers in the yard.
Stern	Back of the ship.
Stowage planning	Act of allocating space to containers on board of a vessel in the order of the discharge ports, results in stowage plan.
Straddle carrier	Horizontal and vertical transport vehicle. Used for transport of containers between the quayside and the stack, stacking containers in the yard, as well as loading and unloading trucks.
Throughput	Measurement of equipment productivity [moves/hour].
Tier	Height level of the container stack.
Total throughput	Sum of all cargo handled by the terminal, normally measured at the quay [TEU or containers].
Transshipment cargo	Cargo discharged at the terminal and shipped out again on another vessel without leaving the port area in between.
Transtainer	Mobile gantry crane for stacking containers (see: yard crane).
Turnaround time	Time of external transport equipment between arrival at and departure from the terminal. Includes waiting time and service/handling time (in minutes).
Twistlock	Device that is inserted into the corner castings of a container and is turned or twisted, interlocking the container for the purpose of securing or lifting.
Vessel	General term for any watercraft or ship.
Workload	Working time expected or assigned to equipment [hour].
Yard crane	Crane used to store and retrieve containers in/from the yard.

I

Main Report

1

Introduction and Problem Description

This chapter introduces the topic of container terminals in general and the topic of this research in detail. First, the research context will be defined in 1.1, which will lead to the relevance of the research topic. The research objective will be described in Section 1.2, both from the perspective of scientific relevance and practical relevance. In Section 1.3 the research scope will be presented. After that, the research questions addressing the problem will be formulated in 1.4 and the methodology and methods to answer these questions is presented in 1.5. Then the deliverables are presented in Section 1.6. Lastly, in Section 1.7, the remaining structure of this report is presented.

1.1. Research Context

Containerisation has lead to a change in the way how industrial production and distribution takes place globally (Sharif Mohseni, 2011). Not only did it lead to a decrease of sea transportation costs and more cost effective transport, containers have also lead to advantages in terms of handling processes at terminals and protection of the goods inside (Steenken et al., 2004). As mentioned by Li et al. (2009), different studies describe the significant current share of container transport up to 90% of the world trade that is transported via containers. Along with the increase of transported volume by containers, the vessel itself has increased in size as well. Current deep sea vessels can carry up to 20 000 Twenty Foot Equivalent Units (TEU)(Stahlbock & Voß, 2008a). In 2017 the largest container vessel, the Orient Overseas Container Line (OOCL) Hong Kong, even had a capacity of 21 413 TEU (MI News Network, 2017).

Different actors are involved in the practice of container shipment. The main players are the shipper that wishes to transport goods by container; the shipping line that is responsible for the transport of containers overseas; and the consignee to whom the content of the container is directed. Besides these three players, a terminal operator plays an important role in container shipment. The terminal operator is concerned with the loading of export containers that arrive by train, truck or barge onto deep sea vessels and the unloading of import or transshipment containers from deep sea vessels to subsequently load them onto hinterland transport modes. In this way the main function of a container terminal is to connect sea transport and hinterland transport of containers. There is a delay between the containers' arrival at and departure from the terminal of typically several days, this delay is referred to as *dwell time*. The average dwell time of containers at large container terminals is 3-5 days (Steenken et al., 2004). During the dwell time the containers await their next mode of transport at the container yard. This illustrates another function of the terminal, namely the temporarily storage of containers.

Container terminals are confronted with increasing competition (Froyland et al., 2008; Güven & Eliiyi, 2014; Kim, 1997). Since the number of TEU to be transported has increased, new terminals have been created. This makes it possible for shipping lines to choose between terminals, creating a weak bargaining position for the terminals (Stahlbock & Voß, 2008a). Therefore it becomes more and more important for a terminal to operate as efficient as possible. The performance of a terminal is for example measured by the average berthing time for ships. Shipping lines want to minimise the berthing time since this time is considered as unproductive in terms of direct financial gains (Preston & Kozan, 2001; Vis & De Koster, 2003). In relation to the berthing time,

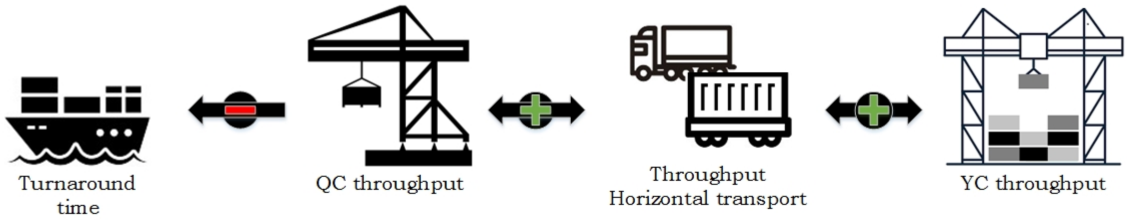


Figure 1.1: Interdependence cranes and handling equipment

the work rates of the quay cranes (QCs) must be kept as high as possible to serve vessels in a fast way and to use a terminal's resources in an efficient way (Petering & Murty, 2009). While containers await their further transport, either by deep sea vessels or by truck, train or barge towards the hinterland, the processes in the yard influence the work rates of the QCs. To prevent the QCs from becoming idle, the yard operating equipment must be well aligned to the QCs. Moreover, the yard operating equipment also facilitates a balanced workload of the QCs, by avoiding peak operations and providing a more constant throughput. Improving a container terminal's efficiency at the seaside is thus already affected by the yard operations. Yard operations, in its turn, depend on the way the containers are stored into the yard. The efficiency of the yard itself heavily depends on the operations of yard equipment (Li et al., 2009). This interdependence is presented in Figure 1.1, with the example of a Yard Crane (YC) as yard operating equipment. The plus and minus sign respectively represent a positive and negative relation. When the QC's throughput for example increases, the turnaround time of a vessel decreases (negative relation). The QC, horizontal equipment and YC all affect each others performance. Naturally, these influences are limited by maximum levels of productivity.

Another performance indicator of container terminals is the amount of reshuffles necessary to reach a container (Gharehgozli, 2012). A reshuffle is described as the digging process needed to reach a container that is stored underneath another container that is not yet needed at the time the lower one is required. The amount of reshuffles can be measured in either reshuffle movements or reshuffle occasions, the latter one can consist of multiple movements. Reshuffles are also called reorganisations, rehandles, and re-stacking or remarshalling moves. Since storage space is a critical resource of a terminal (Kim & Park, 2003), the stacking strategy also significantly affects the the efficiency of the terminal (Gharehgozli, 2012). The goal of every terminal is to maintain its competitiveness by providing low cost and high quality service to perform efficiently (Liu et al., 2002). As already mentioned above, the pressure on terminals to provide this high quality service is increasing by the growing competition (Sharif Mohseni, 2011). With the Just-in-Time (JIT) movement of recent logistics improving efficiency is even considered to be more important than ever (Petering et al., 2009). Moreover, increasing efficiency of container terminals also has its benefits for promoting intermodal transport (Konings, 1996).

Improving the performance of container terminal's operations is made difficult by stochasticity in their operations. Stochasticty is referred to as random variation in a parameter value. Dekker et al. (2006) for example mention the variations in cycle time of crane loading. These vary both for QCs as for YCs. Also the yard operating equipment (such as Yard Trucks or Straddle Carriers) travelling speed and gantrying speeds differ per operator style, amount of error in the operations, and real time traffic conditions in the terminal (Petering, 2010). Roy & de Koster (2014) also point out the stochastic interactions between ship arrival, container handling, and vehicle transport. Moreover, terminal operators are not often aware of a container's exact weight (Kang et al., 2006), neither of the exact arrival times of the deep sea vessels (Li et al., 2009) or trucks (Froyland et al., 2008; Kim, 1997; Steenken et al., 2004) picking up or delivering containers. Therefore an important problem for terminals is how to operate efficiently under high levels of uncertainty (Meersmans & Dekker, 2001). To determine the most efficient way to place containers in the yard, information such as weight, arrival time, and departure time are desired. With this information heavier export or transshipment containers can be stacked on top of lighter containers, which increases efficiency because heavier containers should be loaded onto a vessel first, due to stability restrictions. Besides weight information, information on arrival time and departure time is useful for a terminal as well, because the yard should be set up in a way that the containers that are requested the first are positioned on top of containers that are requested later. Unfortunately, in practice these data are often still unknown for arriving containers at the yard (Güven & Eliiyi, 2014).

1.2. Research Objective

The research objective of this study is to estimate quantitative effects of stochasticity in container data on the performance of terminal stacking operations. The research is thus scoped towards the relationship between stochasticity and performance. Identifying the performance indicators applied to evaluate the performance of stacking operations will form part of the research. Stochasticity is referred to as random variation in a parameter value. In the case of pick-up times, a certain expected time can be applied. This expected pick-up time can for example be determined based on average dwell time of containers or based on maximum amount of free days before demurrage costs will be charged by the shipping line. Stochasticity causes the pick-up time to vary from the expected time in either a positive or negative direction. Stochasticity in the next mode of transport is based on an expected next mode of transport, following from average modal split values. This next mode of transport can change to one of the other two modes present at the terminal, and therefore is classified as stochastic rather than uncertain (when the possible decision space would be unlimited) in this research .

The contribution to the literature of this research consists of an analysis of the effect of stochasticity on performance indicators of terminal stacking operations. The performance indicators themselves are based on literature study. As could also be concluded from the literature review, effects of stochasticity on specific performance indicators of a container terminal has not been researched before. Two studies that are found touch upon the subject of stochasticity and performance, but the scope of those studies are either only focused at the effects of uncertain information from trucks (Zhao & Goodchild, 2010) or do not explore the quantitative relation between stochasticity and performance indicators (Kang et al., 2006). This is further discussed in Section 3.4.
The practical contribution of this research is aimed at terminal operators. In current practice the terminal operators are forced to take stochasticity for granted in their attempt to operate as efficient as possible. Based on the results of this research, the extent to which a decrease in stochasticity could contribute to the operating performance is presented. In other words, insight is provided in the relation between stochasticity and their performance. Terminal operators could try to focus on achieving data that strongly affects terminal performance, based on the results of this research. Moreover, this research explores improvement directions for terminal operators in terms of ways to decrease the level of stochasticity.

1.3. Research Scope

This research is focused on deep sea gateway container terminals that handle containers loaded onto or unloaded from deep sea vessels or feeders, trucks, trains and preferably also barges. The type of containers included will be import containers, since the stochasticity in import container data is generally larger than in export container data (Steenken et al., 2004). Special container types such as refrigerated containers (reefers) or containers that contain dangerous goods (MIO containers) are shortly discussed in Section 3.3. However, they will not be included in the model described in Chapter 4, since container volumes of these types are relatively small and the containers have a separate location in the yard. A model as detailed as possible is intended with respect to the time scope of 20 weeks.

The main focus of this research is on the stacking operations at a deep sea gateway terminal. Therefore, detailed problems outside the area of the yard such as QC scheduling, berth allocation, vehicle routing or truck scheduling, however relevant, are not included in this research. Neither are these processes included in the model, which will be discussed in Chapter 4.

The type of the terminal including its handling equipment is also further specified in Chapter 4.

The scope of this research is presented by the rectangle in Figure 1.2. As can be seen, the yard including yard operating equipment (in this example an automated stacking crane), is included in the scope. Moreover, the specific yard layout will also form part of this research. Besides that, a selection of processes at the landside is included, which is illustrated by the rectangle boundary that crosses the landside through the middle. This decision is made because the retrieval request of import containers by train, truck or barges will be included in the model, but the further transport of these containers towards the hinterland will be left out of scope, as well as specific distances to the pick-up points of the respective hinterland transport modes. The loading process of containers on these modes or decisions related to that will neither be included. In a similar way, a selection of processes concerning the AGV (the horizontal transport vehicle in this terminal example) in the Figure 1.2 is included. This represents the decision to model horizontal transport vehicles as present in the terminal when containers are retrieved from the yard, but also represents the choice to not analyse different types of horizontal transport vehicles, nor to model the arrival of containers from the seaside explicitly.

The problem of container stacking operations is complex to such a large extent, that many interesting aspects cannot be included in this research due to time limitations. Performance of different stacking strategies, for example, related to dealing with stochasticity, will not be included. A specific stacking strategy will be chosen and implemented in the model. This strategy will be based on a reference terminal that is willing to cooperate, as discussed in Chapter 4.

Another currently important type of research that will be out of scope of this research, is data analysis. It is expected that terminals are able to decrease the stochasticity in pick-up times and next mode of transport by analysing historic data. Certain patterns are likely to be found, based on which a prediction for the future can be made that increases terminal performance. Although this is a very interesting topic, it will be a recommendation for further research in Section 6.3, since the time and scope of this research does not allow to perform data analysis in addition to the simulation study.

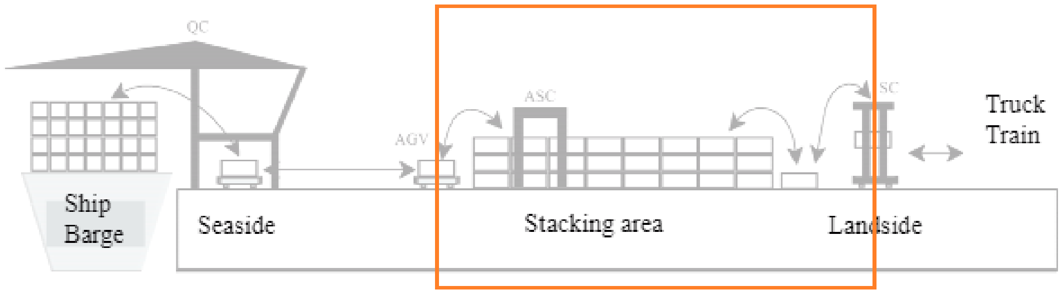


Figure 1.2: Scope of research illustrated for a container terminal example (adopted from Gharegozli, 2012)

1.4. Research Questions

The main research question of this study is:

> ***What is the effect of stochasticity in import container information on stacking performance at a container terminal?***

To answer the research question, multiple sub-questions have been formulated:

1. *What are terminal stacking operations?*
2. *What is stochasticity in import container information?*
3. *How to model the relation between stochasticity in import container information and the performance of stacking operations?*
4. *What is the effect of stochasticity in the parameters on the performance indicators?*

1.5. Methodology

Both simulation and optimisation are common Operations Research (OR) techniques to analyse container terminal operations.

Stahlbock & Voß (2008a) mention the contrast between isolated optimisation studies mainly focused at one aspect, such as transport optimisation, and a more integrative approach. Integrative research can be performed following an analytic approach, simulation approach or multi-agent approach. As Dekker et al. (2006) describe, analytic calculations provide insight in relationships between parameters on a more abstract level, while simulation studies provide more detail. Especially for a research topic with that many interrelated components as in container terminals, simulation provides a suitable research option (Petering et al., 2009).

Hartmann (2004) also point out that simulation models can be used to evaluate dynamic processes at container terminals and identify potential bottlenecks as well as provide a testing environment for optimisation algorithms.

Moreover, the research goal of this study is not to invent an optimal way to operate, as is often the case in optimisation studies. The goal is to evaluate terminal performance based on stochastic information which is present in reality, while previous research has been mainly focused on improving terminal performance while assuming the ideal situation of complete certainty. This research will estimate the quantitative effects of this stochastic environment on performance indicators of stacking operations. Since this research is aimed at quantifying the effects of stochasticity, optimisation does not seem an appropriate technique. This will further be motivated in Section 3.1. Optimisation is one of the two main streams of research found on the topic of container terminals, and therefore could not be excluded from a relevant literature analysis in Chapter 3.

Different studies mention simulation to be an appropriate methodology for research confronted with an uncertain environment (e.g. Petering, 2011; Petering et al., 2009). As Stahlbock & Voß (2008a) mention, the problem of stochasticity is usually tackled by simulation. In previous research, simulation has already been used to include stochastic processes of handling equipment. It is for example possible to include variation in cycle times in a simulation program, representing different speeds for manually operated equipment. However, in this research the stochasticity is not related to the handling equipment, but to the retrieval process of import containers.

Simulation studies can be used when building a new terminal or when analysing or modifying an existing one (Hartmann, 2004). Moreover it can be used as a decision support system for terminal management. Simulation is a widespread technique to evaluate system performance before a certain layout or expansion is implemented to postpone high investment costs up until the moment the effectiveness of the investment is made likely. It enables an estimation of benefits based on which a large investment will or will not be made. In this research however, simulation will be used to evaluate the performance based on the current state of a terminal, instead of a future sate.

With respect to the time scope, this study will not deliver a simulation model of a fully integrated containers terminal. The main focus will be on stacking operations and retrieval of import containers. Elements affecting the input and output of containers to and from the stack will not be ignored in this study, although these elements will not be a focus of research in the model.

As described above, simulation will be the main method used to answer the research question. However, several sub-questions related to the main question are answered as well. For each of the sub-questions below, the goal and planned methods are described.

1. *What are terminal stacking operations?*

   Goals:

   - Describe the processes in stacking operations.
   - Determine the goals of stacking operations.
   - Describe what determines performance in stacking operations.
   - Determine the actors that are involved in stacking operations.

   Methods: Literature study, desk study and expert interviews.

2. *What is stochasticity in import container information?*

   Goals:

   - Describe how stacking operations are confronted with stochasticity.
   - Decide on which stochastic parameters should be included in the research.

   Methods: Literature study and expert interviews.

3. *How to model the relation between stochasticity in import container information and the performance of stacking operations?*

   Goals:

   - Analyse previous research on terminal (stacking) operations.
   - Motivate the technique to be used to model the relation between stochasticity and stacking performance.

- Determine the KPIs to be included in this research.
- Select conceptual model.

Method: Literature study.

4. *What is the effect of stochasticity in the parameters on the performance indicators?*

   Goals:

   - Implement conceptual model.
   - Design the simulation model.
   - Run experiments to estimate the relation between stochasticity and stacking performance.

   Method: Modelling, simulation, and data analysis.

The relation between the main research question and the sub-questions is illustrated in Figure 1.3. It presents the research method to be used for each question and the outputs. Moreover it shows the relation between the outputs of each separate question in the light of the research as a whole.

The literature study will be performed to outline previous research and trends in container terminal studies. Based on previous research, decisions related to the performance indicators and stochastic parameters that will be included will be made. As described under sub-question 3, the choice of the method, its input parameters and the Key Performance Indicators (KPIs) are also based on literature study.

Desk study differs from literature study in a sense that desk study is focused on exploring different sources to find information, while literature study is mainly focused on analysing scientific literature. A desk study can for example look into websites, newspaper articles, and flyers to find information on the stakeholders involved in terminal operations.

Expert interviews will be used to validate the findings from the literature study, as well as to explore the practical importance of performance indicators and stochastic parameters. Results from the desk study related to stakeholders will again be validated in and extended with expert interviews.

Data analysis can be performed on data retrieved from a terminal, this is described in Chapter 4 and Appendix C. Additionally, data analysis will be performed on the output data from the simulation experiments.

1.6. Research deliverables

This research will lead to a thesis report and a scientific paper in which the research is presented in a summarised way. Besides these two outputs, the research will lead to two more concrete outputs:

- A quantitative relationship between stochasticity and performance indicators.

- An indication of performance that can be improved by decreasing stochasticity and to which advantages this will lead for terminal operators.

1.7. Report Structure

The main structure of the research can be divided in four parts, as also shown in Figure 1.3. These parts are: a definition phase, a research phase, an analysis phase and an evaluation phase.

The research findings will be discussed in the following chapters:

Chapter 1: Introduction and Problem Description

Chapter 2 Container Terminals

Chapter 3: Literature Analysis

Chapter 4: Model Design

Chapter 5: Experimentation

Chapter 6: Conclusion

Each phase will result in different chapters, which is discussed in detail below.

Part I: Define

In the definition phase, a detailed overview of the research topic will be presented. This phase will present and explore the basis for the remaining of the research. Used definitions and concepts will be determined and a more detailed context of the research will be presented. Lastly, a motivation for stochastic parameters will be provided.

Related chapter(s): 1 and 2

Part II: Research

In the research phase, a literature review will be presented to place this research in the light of previous research. Moreover, it will lead to a motivation for the method used in this research. Also, the KPIs that will be used in this research will be determined.

Related chapter(s): 3

Part III: Analyse

The analysis phase will consist of the implementation of the conceptual model in a simulation model and research into the relationship between stochasticity and performance in stacking operations. In this phase experiments with the simulation model will be performed and reported. Moreover a reflection on the results will be performed from the point of view of different terminal types and stakeholders.

Related chapter(s): 4 and 5

Part IV: Evaluate

In the evaluation phase the main findings of the research will be presented, as well as a discussion of the research limitations and recommendations for further research.

Related chapter(s): 6

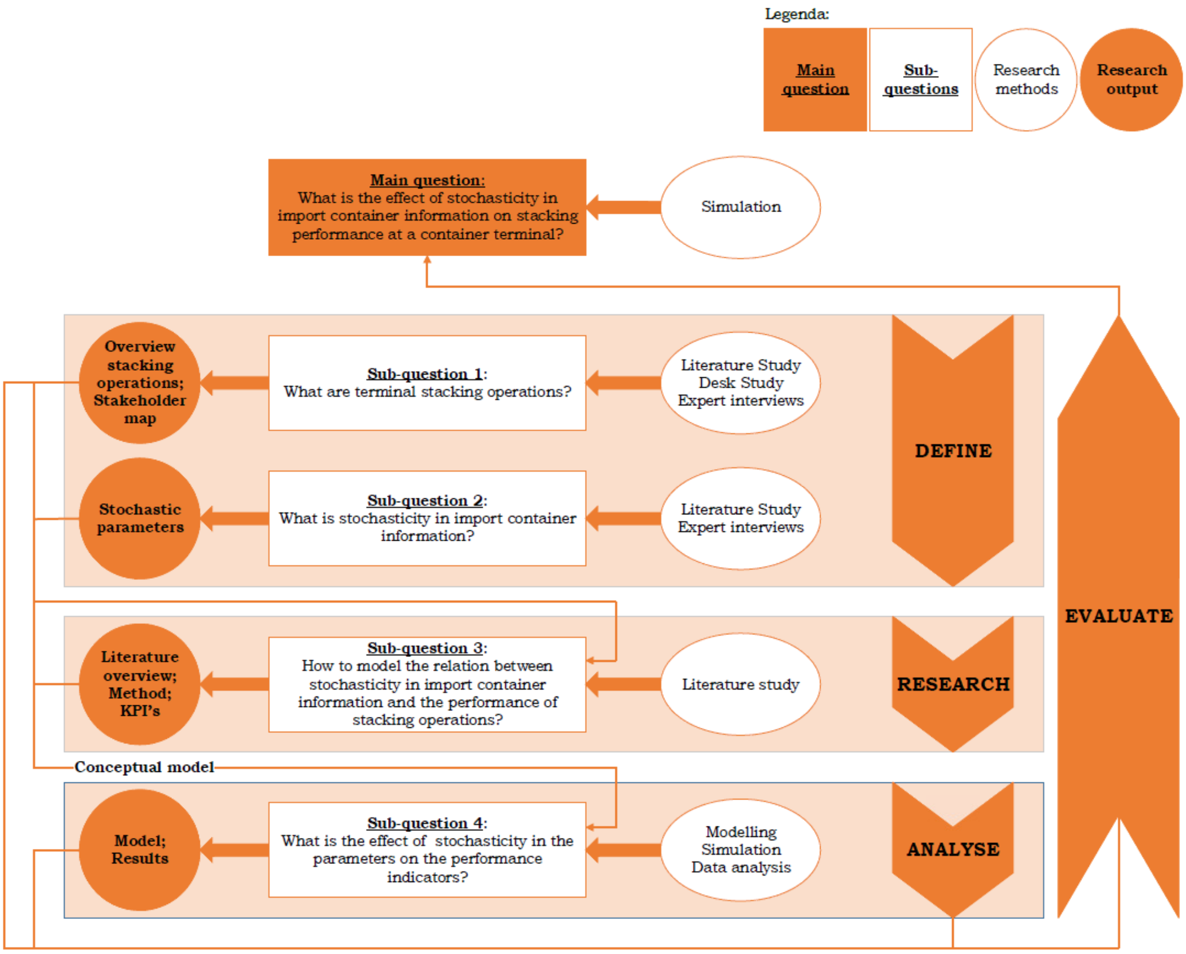


Figure 1.3: Research Flow Diagram

2
Container Terminals

This chapter will answer sub-questions 1: *What are terminal stacking operations?* and 2: *What is stochasticity in import container information?* To do so, a detailed description of what a container terminal is, what functions it fulfils and how it does so is provided.

As already shortly explained in Section 1.1, a container terminal can be seen as the link between sea transport and hinterland transport of containers. Its main function is connecting seaside and landside. Three sub-functions of the terminal are determined: loading export containers that arrive by hinterland transport modes onto deep sea vessels; unload import or transshipment containers from deep sea vessels to subsequently load them onto hinterland transport modes; and temporarily store containers that await further transport in the yard. A schematic overview of a container is presented in Figure 1.2. The area within the orange rectangle in the figure presents the scope of this research, hence a sub-selection of a container terminal is made to investigate further.

A container terminal is involved in different operational areas. The main distinction can be made between the quayside (also called wharfside or seaside), and the landside (or waterside in case of transshipment) operations (Sharif Mohseni, 2011; Steenken et al., 2004). Brinkmann (2011) distinguishes the operational areas between the quay wall, the container yard or stacking area, and the terminal area for landside operations. The processes at the quay wall are concerned with the arrival of vessels and the loading/unloading of containers onto/from these vessels. The container yard is the area where containers await further transport, either to the quayside or to the landside. Lastly, the terminal area of landside operations consists of gates for hinterland transport modes to deliver and pick up containers. In the case of a multimodal terminal, a train and barge connection can exist besides the more common truck connection. The train connection is often located near the truck gates at the landside. The barge connection is realised at the quayside, either at a dedicated barge quay or at the same quay as where the larger deep sea vessels are handled. The contrast between seaside, landside, and stacking area is also described in Gharehgozli (2012). Wiese et al. (2010) divide the processes in and around the container yard in two separate groups: horizontal transport and storage yard operation. As the name already implies, horizontal transport relates to the movement of containers either from/to the yard towards/from the incoming vessels or from/to the yard towards/from the landside area. Storage yard operation refers to vertical transport of containers in the yard where they are placed on top of each other in a specific location of the yard. The specific storage position of containers in the yard will be discussed in Section 2.2.

This chapter continues with Section 2.1, which will describe the resources needed to fulfil the main terminal function of connecting seaside and landside. Later, Section 2.2 introduces the container yard, after which 2.3 will explain stacking operations performed for the storage function of the terminal. Next, Section 2.4 will elaborate on four levels of decision making related to container terminals. In Section 2.5 different classifications of containers are described. In Section 2.6 a stakeholder map will be provided that describes the different stakeholders related to terminal stacking operations and their influence. Lastly, Section 2.7 will describe the stochasticity found in terminal operations, which will lead to the stochastic parameters employed in this research.

2.1. Terminal Resources

To perform the operations as described above, a container terminal relies on several resources. Resources in a container terminal can generally be classified as cranes, vehicles for intra-terminal transport, and resources for the yard or container stacking area (Duinkerken et al., 2001; Güven & Eliiyi, 2014).

Steenken et al. (2004) provide a detailed description of different terminal handling equipment. Amongst cranes, for example, a distinction is made between quay cranes (QCs) and gantry, stacking or yard cranes (YCs). QCs are generally rail mounted or mobile, see Figure 2.1.

Figure 2.1: Mobile Harbour Crane (Harbor.Plandot, 2018) and RMGC (SICK Sensor Intelligence, 2018)

Vehicles for intra-terminal transport can be horizontal or vertical transport vehicles and they can be passive or active. Horizontal vehicles transport containers either between the quayside and the yard or between the yard and the landside. Passive vehicles are not able to lift containers themselves, but they have to be loaded and unloaded by cranes. Active vehicles, in contrast, are able to lift containers independently. The movement of lifting a container is referred to as vertical transport. An example of a horizontal passive transport vehicle is an Automated Guided Vehicle (AGV), see Figure 2.2. Straddle carriers (SCs) are an example of active transport vehicles that are able to move containers both horizontally and vertically, see Figure 2.2. Intra-terminal transport vehicles can be further divided into SCs, automated SCs (autostrads), Automated Lifting Vehicles (ALVs), shuttle carriers, and automated shuttle carriers (AShCs). SCs and shuttle carriers are both horizontal and vertical transport vehicles. In a pure SC terminal, a SC picks up an unloaded container at the quayside, transports it to the stacking area an places it in a position in the yard. This position can either be on top of another container, or on the ground. Modern SCs are able to stack up to 4 tiers or levels high. Shuttle carriers perform similar activities as SCs, but are only able to stack up to 2 tiers high. Both SCs and shuttle carriers have been automated, referred to as autostrads and AShCs respectively. Lastly, ALVs are automated transport vehicles, able to unload and load containers by themselves, but they are not able to stack containers in the yard. In stead, they deliver containers to small trailers located at the yard, after which the containers can be stored in the yard by a YC.

Figure 2.2: AGV (TurboSquid, 2018) and SC (SICK Sensor Intelligence, 2018)

This indicates the overlap between intra-terminal transport vehicles and stacking equipment. SCs or shuttle carriers can be used for both functions. There are two main types of container terminals: pure SC systems or systems that use gantry cranes for containers storage (Steenken et al., 2004). These gantry cranes can be either rail mounted or rubber tyred, see Figure 2.3. The RMGCs are bounded by rails and therefore only available to operate at one yard block, while the RTGC can move freely between yard blocks, although the latter is not preferred because of the time this additional move takes. The difference between the two most common terminal types is also shown in Figure 3.1 in Chapter 3.

Figure 2.3: RMGC and RTGC (SICK Sensor Intelligence, 2018)

Steenken et al. (2004) mention the assisting systems used by terminals as an additional type of terminal resource.

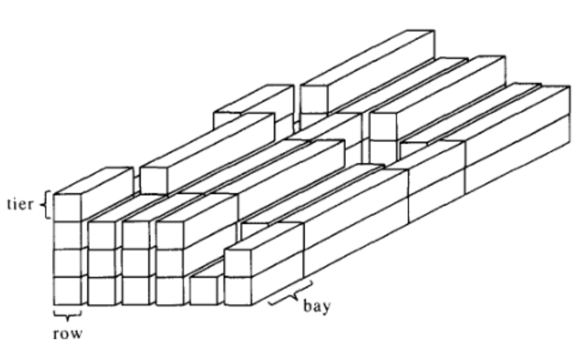
Brinkmann (2011) provides a detailed overview of different container handling systems including their respective advantages and disadvantages.
Along with the different resources a terminal uses, different logistic operations are involved. A few examples of main logistics operations are, based on Steenken et al. (2004),:

- Berth Allocation: *The allocation of quay locations and time slots to a vessel, including the allocation of QCs to that vessel.*
- Stowage Planning: *The individual planning of containers onto a vessel with as main responsibility the balancing of a vessel.*
- Crane Scheduling: *The assignment of load plans to QCs and YCs.*
- Terminal Transport optimisation: *Decide upon the use of transport vehicles in a most efficient way, minimising their downtime.*
- Storage (Yard) Planning: *Storage allocation of containers, including planned time slots.*

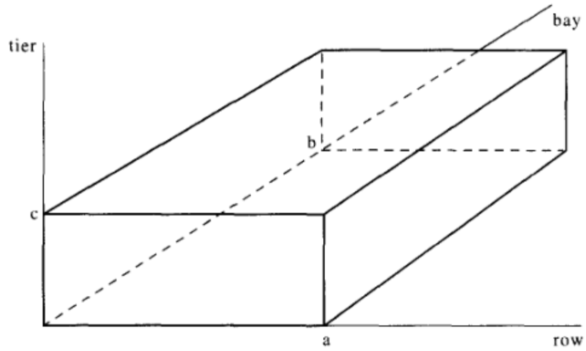
These operations become more complicated when the hinterland connection is not directly accessible at the seaside terminal and additional inter-terminal transport is required for final transportation to the hinterland. In this research a terminal that has all relevant hinterland connections on site will be considered. Another complicating aspect is the case when additional storage areas in the terminal are considered (for example for empty containers). This complicating aspect will also be left out of scope in this research. Lastly, this research will be focused on the yard planning, therefore the other logistic operations mentioned above will not be analysed further.

2.2. The Container Yard

A container's position in the yard depends on stack blocks, which are divided into rows (or stacks), bays, and tiers (Güven & Eliiyi, 2014; Steenken et al., 2004). The row is the end-to-end lane of containers visible once faced towards the front of the container with the container information on it. The bay is the side-to-side lane of containers considered from the side of a block, with the logo of the container owner written on it (if present). The tier is the height level in a block. A picture of a stacking block and its parameters is presented in Figure 2.4. Most of the container yards have stacking lanes or blocks separately reserved for import and export containers (Duinkerken et al., 2001).



(a) Stacking block



(b) Parameters of the stack

Figure 2.4: Stacking block (a) and the parameters involved (b) (Kim, 1997)

Yards can have different layouts, such as a block stack, a linear stack or a high-bay racking stack (Brinkmann, 2011). A block stack is compact and generally has less tiers than a linear stack. The limited height is caused by the fact that a block stack is operated by YCs that have to reach over the containers. A linear stack is operated by SCs that require spacing between container rows. The high-bay racking stack is not often used, but for example exists in Hong Kong where the throughput requirements are high but the available area is small. The containers are stacked up to 12 tiers in this terminal. The most often occurring yard layouts are presented in Figure 3.1 in Chapter 3.

2.3. Stacking Operations

The goal of the yard layout generally is to maximise the stacking capacity and minimise the response time when a container is requested (Duinkerken et al., 2001). The stacking strategy or policy is the set of decision rules based on which yard operating equipment or its operator determines where to store a certain container. The input information for stacking decisions is generally based on the type of container that is handled (Dekker et al., 2006). Duinkerken et al. (2001) describe a number of stacking policies. The stacking process can be random, once each available stacking position is considered to be an option. A terminal can however also perform dedicated stacking, which assigns specific stacking lanes to certain QCs. One speaks of a levelling stacking strategy when the main criterion for storage decisions is that all tiers in a stacking block should be of the same height. Closest position stacking is a strategy where the yard operating equipment places the container close to the previously placed container. Another option is the strategy of maximum remaining stack capacity, which implies to place containers on top of other containers of the same category. What factors determine to which category a container belongs will be discussed in Section 2.5.

Dekker et al. (2006) mention two other stacking strategies. The first one is category stacking in which the same categories of containers are placed on top of each other, similar to the strategy of maximum remaining stack capacity. The second one is the residency time strategy, a strategy where the container that is expected to be retrieved the earliest, is placed on top of containers that are expected to be retrieved later.

Gharehgozli (2012) distinguish between random, dedicated, nearest-neighbourhood, horizontal, vertical, and shared stacking. Nearest-neighbourhood stacking is similar to the closest position stacking strategy mentioned above. In a vertical stacking policy, as opposed to horizontal stacking, an incoming container is placed on top of a container pile of which the first-leaving container is of the same type of the incoming container or will be retrieved later. Shared stacking allows containers of multiple ships to be stacked in one block, as opposed to dedicated stacking where a block is used for of a single ship.

Steenken et al. (2004) lastly mention scattered stacking where containers are stochastically distributed over the yard area based on real-time information.

Furthermore, re-stacking or remarshalling occurs when a container that is stored underneath another container is requested. Duinkerken et al. (2001) make a distinction between reactive and proactive re-stacking. The former one takes place if the process of re-stacking is triggered at the moment the container is needed (reshuffle move), the latter one when the process of re-stacking takes place during idle times of YCs to anticipate for future requests (housekeeping move).

2.4. Decision Making

Decision making concerning container terminals occurs in at least three levels. Sometimes a fourth level is added to this list. At the first level, the strategical level, design decision are made on terminal layout and the choice of vehicles and equipment (Gharehgozli, 2012; Steenken et al., 2004; Vis & De Koster, 2003). At the strategical level a terminal can for example assign fixed locations in the yard to different types of containers (e.g. areas for export, import, and refrigerated containers). Strategic decisions are made for the long-term (Dekker et al., 2006).

At the second level, the tactical level, capacity decisions for the medium-term are made. In manually operated terminals as opposed to automated terminals, decisions of this type have to be made more often, since in automated terminal these processes are programmed. This for example consists of decisions to pre-stack containers based on arriving vessels or to perform stack reorganisations (housekeeping moves during the idle times of QCs) (Dekker et al., 2006). The number of transport vehicles and the applied stacking policy are also considered as tactical decisions (Gharehgozli, 2012; Vis & De Koster, 2003). Although some research considers the choice of stacking policy to be a decision of operational level. Lastly, Meersmans & Dekker (2001) mention the timetables of ships and trains to be tactical decisions as well.

Operational decisions are made for the short-term and are related to the efficient use of storage space, efficient and timely transportation of containers inside the terminal and from the terminal to either the quay-side or the landside, and the avoidance of unproductive moves (Dekker et al., 2006). More generally speaking, operational decisions lead to the allocation of capacity (Meersmans & Dekker, 2001). Vis & De Koster (2003) describe a wide variation of operational decisions, such as the way a ship is allocated to a berth; which crane is responsible to place which container onto a ship and which vehicle transports which container via which route. Lastly, the location where a container is stored in the yard is also an operational decision. Summarising, they describe operational problems to be concerned with minimising and predicting the amount of work. These operational decisions generally follow from a Terminal Operating System (TOS). A TOS is a digital way to manage container flows inside the terminal, as well as incoming and outgoing flows of containers. The TOS can for example calculate the best storage location for a container (based on the determined stacking strategy), indicate where a specific container is located in the yard and keep track of average storage levels. A modern TOS also provides information interchange between shipping lines, agents, carriers and the terminal operator, for example in the form of custom documents.

The last level added by some researches is the real-time decision level. Real-time decision making relates to direct operations and is mainly relevant for automated equipment, since it concerns control decisions that the automated equipment follows when operating (Dekker et al., 2006; Meersmans & Dekker, 2001; Vis & De Koster, 2003).

2.5. Container Classification

As already described above, container information is the input for many stacking strategies. In the category stacking strategy, for example, containers are classified into categories based on specific container information such as weights. Containers of similar categories are stacked on top of each other in this strategy.

Kim & Park (2003) make a distinction of inbound, outbound, and transshipment containers. Güven & Eliiyi (2014) also add transit containers to this list. Inbound containers, also called import containers, are discharged from a vessel and will eventually go towards the hinterland by truck, train or barge. Outbound containers move in the opposite direction and will be loaded onto a deep sea vessel after their arrival at the terminal. Usually, separate areas in the yard are reserved for inbound and outbound containers. Transshipment containers arrive and leave by vessel, their process is quite similar to that of outbound containers. Transit containers require multiple sea-trips to reach their final destination. The terminal processes transit container in exactly the same way as transshipment containers.

Steenken et al. (2004) distinguish containers based on their size (either standard TEU size or not); weight (generally divided in classes of low, medium and high weight); and whether the containers require special handling or not. Special handling is required for refrigerated containers (reefers), that have to be stored connected to a power supply, oversized containers or containers that carry dangerous goods (MIO containers).

Güven & Eliiyi (2014) classify containers based on type, weight, discharge port, destined vessel (in case of outbound containers), and expected departure time.

2.6. Stakeholders

In the transport of a container from A to B, generally 30 different parties are involved. On average, 200 interactions occur during these parties in the process (Sluijs, 2017). Common actors in the container shipping process are the shipping line, shipping agents, freight forwarders, truck companies, rail companies, and governmental authorities such as customs and the waterway police (Steenken et al., 2004).

On high level, a container is shipped from the shipper towards a consignee, using the vessel operated by a shipping line. In practice, however, many more parties are involved. Firstly, a shipping agent or freight forwarder link shippers to carriers. They generally provide additional services related to advice, paperwork, insurances and custom clearing services. Secondly, a carrier picks up an import container or delivers an export container at the deep sea terminal. Since this research is focused on import containers, only the former carrier task will be included. A carrier can be either an individual person or a company that has multiple transport operators at its disposal. Truck drivers, train and barge operators are all referred to as carriers. Lastly, a terminal operator is concerned with the loading and unloading of vessels in a port, as well as the flow of containers from vessels towards hinterland transport and vice versa. The terminal operator hence is directly related to shipping lines and carriers in terms of container exchange. Terminal operations are also affected by stakeholders such as the Port Authority, employee trade unions and governmental or national organisations. Their influence will however not be taken into account in this research, since it is not considered to have a direct influence on the relation between stochasticity and performance of stacking operations.

The different actors that will be included in this research and their relations are presented in Figure 2.5

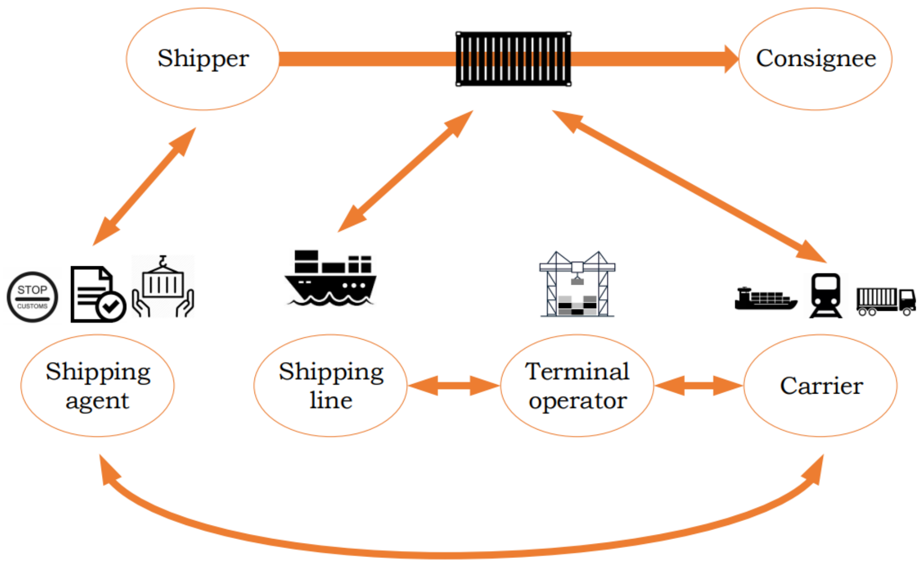


Figure 2.5: Actors in the container shipping market

The interplay of actors leads to two main kinds of transport of a container. Merchant haulage refers to transport from A to B directly arranged by the consignee. In that case the merchant (or consignee) is responsible for any possible damage during transport. The other possibility is carrier haulage, in that case transport from A to B is arranged under control of the shipping line. In that situation the shipping line carries responsibility for any damage during transport. In the Port of Rotterdam, the share of carrier haulage has decreased in the previous years. Now only a rough estimate of 15% of the incoming containers is transported via the carrier haulage way (van Schuylenburgh, 2018). The responsible shipping line generally already arranged hinterland transport when the import containers arrive at the terminal and this information is shared with the terminal operator. The uncertainty in import containers under carrier haulage hence is smaller than in the case of merchant haulage containers.

2.7. Stochasticity in Import Container Information

The interaction of stakeholders can lead to conflicting situations. In general, the stakeholders all desire an operation as cost-efficient as possible from their own, individual perspective. The shipper wants to ship a container against low costs, the consignee wants to pay as little as possible to receive a container. The shipping agent wants to fulfil the shipment of a container against low costs to maximise its profit. The shipping line wants fully loaded ships and short berthing time at ports so it can ship a larger number of containers in a shorter time. The carrier wants short waiting times at terminals, and a high percentage of full trips, so that it can maximise its profit. The terminal operator also wants to operate in a cost-efficient way. However, terminal operators depend largely on the other stakeholders. The planning process of a terminal is dependent on the arrival times of ships. Direct customers of terminals are the shipping lines, and since competition amongst terminals is high, an individual terminal has little power in the shipping line-terminal relationship. When for example a vessel arrives late, the terminal has to cope with unfilled capacity during the expected arrival time of the vessel. Sometimes this capacity of QCs can be used to load or unload other vessels, but in practice that is not always possible. Moreover, each arriving vessel wants to minimise its berthing time, leading to an additional challenge for the terminals when the belated vessel arrives during the arrival of another planned vessel.

The terminal operating system (TOS) is a system that assists a terminal in for example container placement in yards, stowage planning, container flow at gates, and crane split choices. Its goal is to optimise and track the movement and storage of containers. A TOS also allows the terminal to communicate with stakeholders via for example gate appointment systems for truck drivers.

Portbase offers a Port Community System that facilitates communication between different stakeholders in the container supply chain. The Port of Rotterdam, for example, uses Portbase (Portbase, 2018). In Portbase, trucks, barges, and trains can inform a terminal of their arrival. However, in reality the actual arrival time often differs from the planned arrival, so the terminal operators cannot make use of the shared information optimally, or only shortly in advance.

Shipping lines generally inform a terminal some days in advance of their arrival (Li et al., 2009). Hence, timely information sharing concerning export containers that are stored in the yard is common. Regarding information for import containers, shipping agents play a large role. Since the main share of containers is transported via merchant haulage, the terminal is not informed by the shipping line of the next mode of transport or the pick-up time upon delivery of the container in the yard. Shipping agents arrange further transport of the container but want to maintain flexibility. Flexibility is seen in both the pick-up time as the next mode of transport. In reality, a next mode of transport for a container for example often changes after it has been stacked in the yard. And when a later arrived container has a higher priority than an initial container, a shipping agent can also choose to pick-up the container with higher priority in the time slot that was originally planned for the initial container. Moreover, a shipping agent is not inclined to share too much information, since a too transparent market will in the end lead to an exclusion of the agent himself.

Steenken et al. (2004) state that large container terminal in Europe have an average daily yard utilisation of 15 000 to 20 000 containers, that will lead to 15 000 crane movements each day. Furthermore, they mention an average dwell time of 3 to 5 days and the fact that only 10 to 15% of the import containers have information on their next mode of transport at the moment they arrive at the terminal. Also, large container terminals are said to serve 1 000 trucks each day.

Petering et al. (2009) mention that a YC is able to perform 25 lifts per hour on average. Petering (2011) claims that containers spend 0 to 7 days in the yard, which is a broader scope than the 3-5 days mentioned above.

Liu et al. (2002) mention that import containers stay 3 days on average in the yard, as opposed to export containers that stay for 2 days on average. They also mention that the mean service time a YC needs to load containers on an inbound truck is 3 minutes. The service time is regarded as the time between the moment the XT arrives at a specific yard block until the moment it leaves again.

Li et al. (2009) mention that the average job handling time for a YC is 2 to 4 minutes, which corresponds to the 3 minutes mentioned above.

Hartmann (2004) states that the average dwell time in a medium sized terminal differs largely per terminal, but is most likely in the range of 3 to 6 days. Moreover, the number of containers unloaded at the port ranges from 50 to 1 500 containers.

As can be seen, the numbers in literature vary. Parameters used in this research are based upon a reference terminal and partially broadened with parameters from literature. This will be discussed in Chapter 4.

It can be concluded that the different actors contribute to the uncertain circumstance in which a terminal is operating by pursuing their own goals.

2.8. Conclusion

This chapter provides a general description of container terminals, their functions, resources and operations. Sub-question 1 has been answered: *What are terminal stacking operations?* Stacking operations are concerned with storing and retrieving containers and for that task they can rely on many different resources such as YCs or SCs. As can be concluded from this chapter, stacking operations are of crucial importance in both terminal design and daily operations. Within stacking operations many different choices can be made and many research is done. The relevant part of this research will be discussed in the next chapter. A summary of the processes described in this chapter is given in Figure 2.6. Also sub-question 2 has been answered: *What is stochasticity in import container information?* Container terminals operate in a stochastic environment, amongst others caused by the many stakeholders present in their operations. The main stochastic parameters relevant in stacking operations are next mode of transport and arrival times of hinterland transport modes (i.e. container pick-up times).

To summarise the processes described in this chapter an IMAC DEFinition for function modelling (IDEF) model is presented in Figure 2.6. An IDEF model represents a system based on its functions. Each function is presented by a rectangle, with input presented by an in-going arrow on the left side of the rectangle, the output indicated by an out-going arrow on the right side of the rectangle. Control parameters are presented by an in-going arrow on top of the rectangle and resources are indicated by an in-going arrow at the bottom of the rectangle. In Figure 2.6 the IDEF0 or 'black box' model is presented, which is the function model at the highest level of abstraction (with the lowest amount of detail). This IDEF0 model is detailed in the 3 steps presented at the right bottom of the figure.

Subsequently, the process of container retrieval (process 3) is split out further in the IDEF3 model in Figure 2.7.

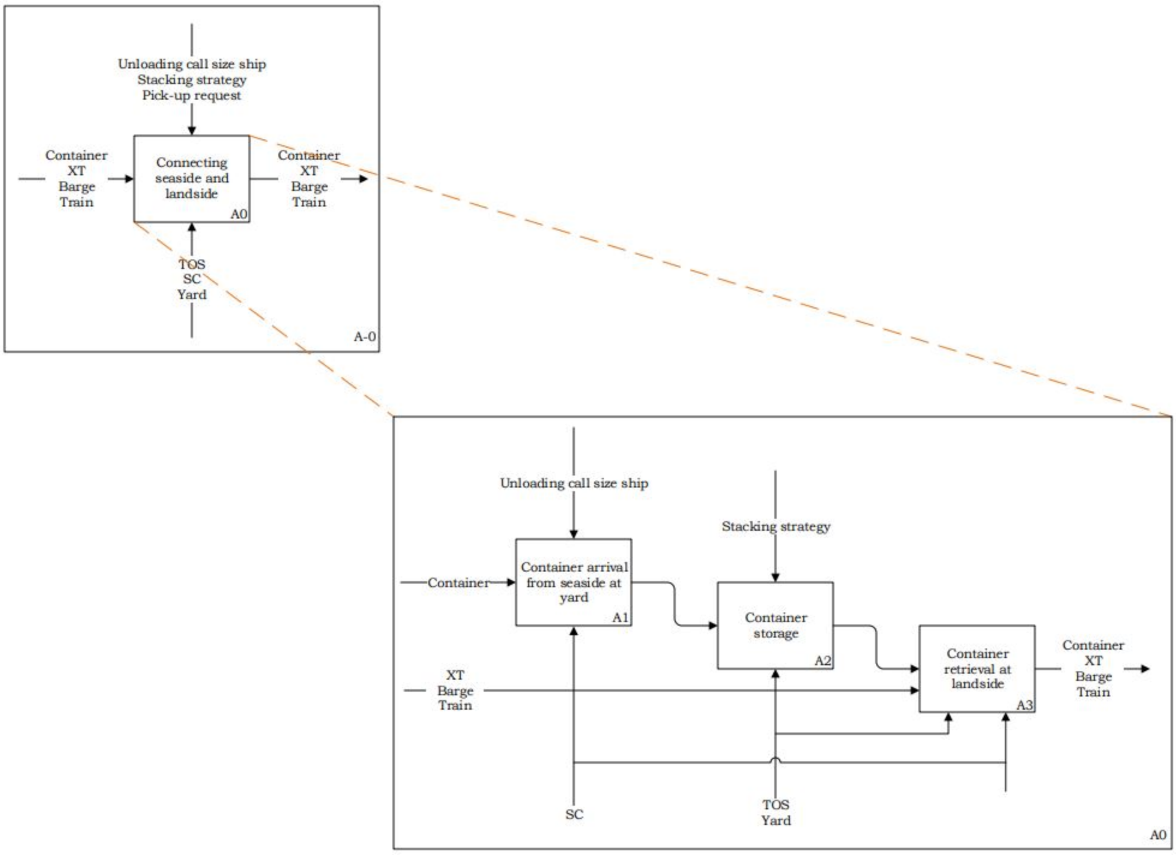


Figure 2.6: IDEF0 model: conceptual model of yard operations

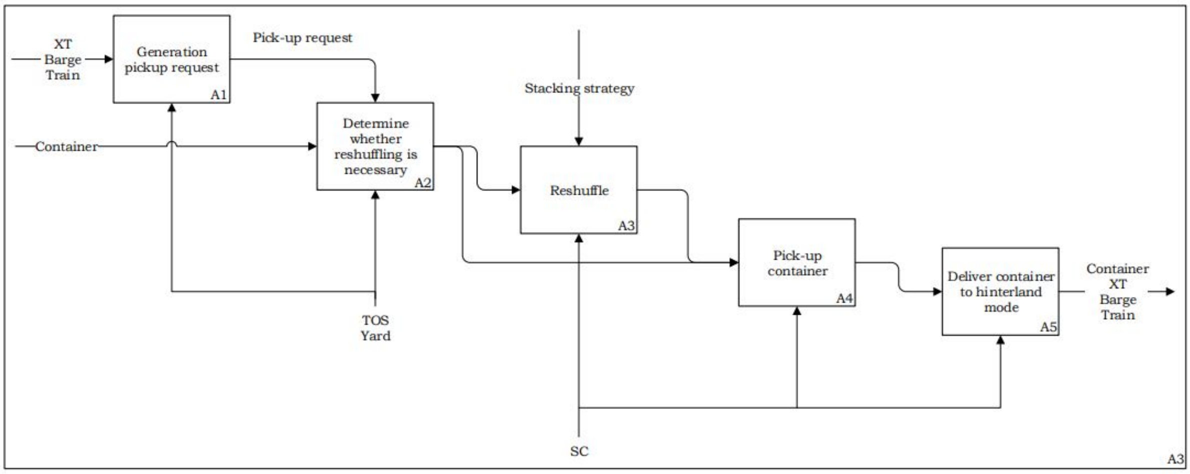


Figure 2.7: IDEF3 model: conceptual model of container retrieval at landside

3
Literature Analysis

In the previous chapter, the concept of stacking operations has been described and the way these operations are confronted with stochasticity. This chapter will answer sub-question 3: *How to model the relation between stochasticity in import container information and the performance of stacking operations?* This question will be answered with an analysis of previous research on terminal operations.

The topic of container terminals' design and operations has been researched extensively already. Design studies are relevant to consider when identifying important variables that should contribute to efficient operations. Operations Research (OR) can contribute to the comparison of different designs before a terminal is constructed or expanded, but can also contribute to an improvement in terminal operations, limited by an already constructed design. This chapter will provide an overview of studies that have already been performed on the subject, leading to a research gap to which this thesis study will contribute. The analysis of different studies will also lead to a motivation for the method used in this research and a list of key performance indicators (KPIs).

The studies broadly vary in type of terminal discussed and methods applied. The main streams of research found related to the topic of this research are based on either optimisation or simulation. Both streams in literature will be discussed in Section 3.1 and Section 3.2 respectively.

Both optimisation and simulation are forms of OR, which is a discipline focused on the application of advanced analytic methods to improve decision-making in a complex context. A first variant of OR is deterministic optimisation, which is a dominant methodology in articles focused on container terminals (Petering et al., 2009; Roy & de Koster, 2014). Another variant is stochastic optimisation which is especially promising in an environment where the state space is relatively small. As this is not the case in container terminal research, stochastic optimisation is not often used in this topic. The last variant mentioned by Petering et al. (2009) is simulation, which is increasingly used in research on the topic of container terminals.

This chapter will firstly present optimisation studies in Section 3.1 and secondly simulation studies in Section 3.2. In Section 3.3 important differences between the studies that affect their results will be discussed. Subsequently, Section 3.4 will present the knowledge gap to which this research will address. In Section 3.5 a literature overview of applied KPIs will be provided, after which a decision for KPIs in this research is made. Lastly, Section 3.6 will present the conclusion of the literature analysis that will provide a base for the conceptual model in Chapter 4.

3.1. Optimisation Studies

Optimisation studies are performed to analyse the performance of terminal functions in a more isolated way, compared to simulation. The optimisation studies presented in this section look into problems such as berth allocation, stowage planning, crane scheduling and assignment, internal transport of containers in a terminal, storage and stacking logistics, and external transport as separate subsystems (Hartmann, 2004; Roy &

de Koster, 2014; Stahlbock & Voß, 2008b; Steenken et al., 2004; Ünlüyurt & Aydin, 2012; van Asperen et al., 2013).

Steenken et al. (2004) present a literature overview of container terminal operation and OR. They mention four types of optimisation research investigated in the literature: yard optimisation, quayside transport optimisation, landside transport optimisation, and crane transport optimisation. Yard optimisation is focused on the minimisation of the number of reshuffles and the maximisation of storage utilisation. Quayside transport optimisation aims to minimise congestion while maximising the number or the speed of transport vehicles at the quayside. Landside transport optimisation from the terminal operator's perspective tries to minimise the number of yard reshuffles, while the objective from a train operator's perspective is the minimisation of shunting movements at the train terminal. Lastly, crane transport optimisation is focused on minimising the waiting times for transport vehicles at the stack interfaces as well as minimising the travel times of YCs.

Stahlbock & Voß (2008a) provide a literature update on the previous research of Steenken et al. (2004). They distinguish relevant literature in three terminal processes: the ship planning process; storage and stacking logistics; and transport optimisation. Amongst the ship planning process the problems of berth allocation, stowage planning, and crane split are discussed. Storage and stacking logistics relates to several aspects. Firstly, the minimisation of the number of reshuffles, both during loading processes, in general, and during pre-marshalling or housekeeping operations. Pre-marshalling is the process of relocating containers in the stack to create an optimal lay-out in preparations for a ship's arrival. A second focus is on the minimisation of time needed for reshuffling containers. Thirdly, maximisation of equipment's efficiency in loading operations is discussed. Fourthly, the minimisation of traffic congestion is an objective of storage and stacking logistics. A fifth objective is the minimisation of the total time required to retrieve containers from the yard. A last objective is more related to the design of container terminals, namely the minimisation of the yard space needed. Transport optimisation is described as being focused on either quayside transport, landside transport or crane transport. The latter one refers to the sequencing of jobs and the assignment of these jobs to cranes. Only few papers focus on YCs, the majority of the research is focused on QCs and on the operations of a single crane.

Stahlbock & Voß (2008b) describe four focuses of optimisation studies and their objectives. The problem of berth scheduling results in a determination of the time and position at which arriving vessels will berth. Objectives of this problem are the minimisation of the total sum of shore to yard distances of containers to be handled (loaded and unloaded) and the minimisation of distances travelled by means of transportation serving the QC. The latter objective is related to the maximisation of ship operations' productivity. A second problem is QC scheduling, which leads to a list of QCs serving a specific vessel as well as the time and sequencing of loading and unloading movements of the QC assigned to that vessel. The objective(s) of this problem can vary among different studies. Thirdly, the problem related to the horizontal transport at the quayside is described. This problem is said to have many goals: to reduce transport times and synchronise transports with planned activities of the QC; to enhance crane productivity; to minimise congestion; to reduce empty distances and transportation times; to reduce crane waiting times; and to minimise crane idle times. The horizontal transport problem has different objectives from the perspective of different actors. The rail operator, for example, strives for a minimisation of shunting activities during train transport. The terminal operator pursues a minimisation of the number of yard reshuffles, crane waiting times, and empty transport distances of cranes and transport vehicles by synchronising the equipment. In the truck operation area the main objective is minimisation of empty distances and travel time. As Stahlbock & Voß (2008b) describe, the main objective of the horizontal transport problem is minimisation of travel times. The last problem they mention is YC transport. This problem results in a sequence of jobs and their assignment to a respective YC. The objective generally is to minimise the waiting time of transport vehicles at the stack or bay interfaces and to minimise the travel times of the cranes. The YC problem is an important problem for terminal operations, since crane operations and operations at both the quayside and landside are interdependent.

In Table B.1 in Appendix B more optimisation studies are presented related to their (sub)problems and objectives.

Although optimisation is a methodology often used in container terminal studies, it has some significant shortcomings. Firstly, optimisation studies are focused on isolated problems. The approach in literature is to develop models for specific components of the entire system and to try to find efficient methods to solve the model (Ünlüyurt & Aydin, 2012). Although the expectation of this approach is to improve the entire system by improving one component, an improved total system performance is not guaranteed when adopting a positive outcome of such a study merely aimed at improving one aspect of the whole. Moreover optimisation models are not that large, and hence ignore many relevant aspects of container terminal operations. Therefore Steenken et al. (2004) recommend decision rules following from optimisation to be tested in a simulated environment before they will be implemented in a real system. Secondly, the optimisation studies described above are all a form of deterministic optimisation. Stochasticity cannot be taken into account in deterministic optimisation, while it plays a significant role in container terminal operations (Petering et al., 2009). This is another argument for taking caution when implementing results from optimisation studies in a real system which is largely affected by stochasticity. Thirdly, Murty et al. (2005) mention that solutions from a deterministic model can only work when the workload at a terminal is evenly distributed over time. In container terminal this is generally not the case, since vessel arrival triggers peak operations and also the arrival of trucks delivering or picking up containers is not evenly distributed over time. Thus it can be questioned how sustainable the optimisation results are in reality.

In addition to the more pure optimisation studies described in Table B.1, Gambardella et al. (1998) describe a decision support system that performs an optimisation of the resource allocation problem and uses simulation as validation. In this way, results of subproblems based on optimisation are combined with each other in a simulation model to estimate overall effects of improving multiple aspects on the total system performance. The simulation model is based on the La Spezia Container Terminal and its performance is evaluated based on throughput of the YC, the time to access containers during storage and retrieval, and net profit.

As opposed to optimisation, simulation is able to model the complex interaction between system components, although it is an expensive and time consuming technique (Roy & de Koster, 2014). As Hartmann (2004) describes, simulation can be used to evaluate the dynamic process at container terminals, to identify potential bottlenecks, and to provide a testing environment for optimisation. It can be used both in the design phase of a new terminal as in the case of analysing or modifying an existing one. Moreover it can be used as a decision support tool for the management department. In Section 3.2 different approaches in and results from simulation studies will be discussed.

3.2. Simulation Studies

As already shortly mentioned in Section 3.1, simulation is an OR technique that is capable of representing dynamic processes that are present in a real life system. Next to the optimisation research overview provided by Steenken et al. (2004), described in Section 3.1, they also discuss simulation studies. As Stahlbock & Voß (2008a) mention in their update on Steenken et al. (2004), simulation helps to show interdependence of different decisions made at for example a container terminal. Moreover, simulation is able to tackle the problem of stochasticity which is present in real life, while optimisation can not deal with stochasticity. They describe six aspects in which the integrative approach of simulation research has proven to be of added value in container terminal research.

Firstly, the impact of different terminal layouts and automation levels on terminal performance has been investigated. This is for example done in Liu et al. (2004). Secondly, different systems can be compared in simulation studies. A comparison between a terminal that uses trucks and multi-trailers, a terminal that uses AGVs, and a terminal that uses ALVs for internal transport is made, for example. Thirdly, the impact of the human factor can be researched with simulation to gain insight into the behaviour of handling equipment. This is useful in comparing manually operated terminals with automated ones. Fourthly, operations can be analysed with simulation based on specified performance indicators. In this analysis parameters can also be adjusted to represent future scenario and predict a terminal's performance in case of increasing or decreasing container volumes to be handled. Fifthly, the effect of different settings for equipment behaviour and the number of storage blocks on the performance of a terminal can be analysed with simulation. Lastly, simulation can be used to assess the performance of different stacking strategies. More specifically, stacking problems in container terminals are generally researched in two ways, either by simplified analytic calculations or with detailed simulation studies (Dekker et al., 2006).

A broader overview of simulation studies is presented in Table B.2 in Appendix B.

Although simulation is a tool that is more capable of showing the effects of adjustments in a system on interrelated components of that system and hence on the system as a whole, it is a time consuming technique and it is difficult to create a model that mimics the real-life system in detail. Therefore many simulation studies work with simplifying assumptions that will affect the suitability of implications following from the model. Moreover, many studies use different reference terminals, which complicates comparing results from different simulation studies. Differences amongst studies will be discussed in Section 3.3

3.3. Terminal Types Studied

As already mentioned in Chapter 2, terminals can have many different resources, yard layouts and operating strategies. In the studies mentioned above, the specific terminal type under consideration will affect the obtained results and the comparability of the studies amongst each other. This section will discuss differences found between studies in terms of yard resources, level of automation, types of containers, and hinterland transport modes and the impact these differences can have on the results.

3.3.1. Resources in the yard

Some studies, for example, consider a container yard operated by an ASC (Dekker et al., 2006; Duinkerken et al., 2001; Gharehgozli, 2012; Güven & Eliiyi, 2014; Liu et al., 2002; van Asperen et al., 2013; Vis & De Koster, 2003; Yang et al., 2004), others base their research on a manually operated terminal by RTGCs (Petering & Murty, 2009; Wiese et al., 2010; Zhang et al., 2003), and the studies of Murty et al. (2005), Murty et al. (2000), and Taleb-Ibrahimi et al. (1993) consider a combined terminal that uses RMGCs as well as RTGCs. In case of different YCs, different yard layouts will be implemented, which will have an effect on simulation as well as optimisation results. The position of RMGCs for example is fixed by rails, while RTGCs can switch from one block to another with a cross-gantry move. RMGCs can interfere with each other since they generally are of different sizes, so multiple cranes can operate one yard block and even make cross overs. This is not the case for RTGCs. On the other hand RTGCs usually span a lesser wide span than RMGCs. Therefore the yard layout of a yard operated by a RTGC consists of more narrow blocks. Another important difference between container yards caused by the type of YC used is the location of container interchange between the yard and a horizontal transport vehicle. RTGC handover points for interference between internal trucks (ITs) and the YC are always located in an additional truck lane alongside the yard block (Petering & Murty, 2009). When RMGCs are deployed, container handover points can be either located alongside the yard blocks, similar to the RTGC case, or at the front and rear ends of a block. The use of ITs is normally the case for an RTGC. At RMGC or ASC terminals different equipment for horizontal transport can be deployed besides ITs, such as SCs, shuttles, AGVs and ALVs. In the case of a pure SC terminal, the yard is linearly shaped with space between each row to allow for a SC to pass. The amount of tiers in the yard also depends on the type of cranes operating the yard. Current SCs or ALVs can for example stack up to 3 or 4 tiers (Steenken et al., 2004). As opposed to SCs, RTGCs or RMGCs are able to stack higher. Murty et al. (2000) even mention stacks up to 15 tiers high. Three main types of terminal layouts with respectively RMGCs, RTGCs and SCs are presented in Figure 3.1. As visible in Figure 3.1, the type of terminal also influences the positioning of containers in the yard. In ASC or RMGC terminals, as well as in SC terminals the containers are generally positioned perpendicular to the quay. In RTGC terminals the containers are generally positioned parallel to the quay.

In many studies the specific type of handling equipment at the yard is not described (e.g. Kim, 1997; Kim & Park, 2003; Kim et al., 2000; Li et al., 2009; Preston & Kozan, 2001; Zhao & Goodchild, 2010).

In other studies the use of a YC is mentioned, although it is not clear whether this is an automated one or a manually operated one, nor if it represents an RTGC or an RMGC (Hwan Kim & Bae Kim, 1999; Kim & Hong, 2006; Kim & Kim, 1999; Ünlüyurt & Aydin, 2012).

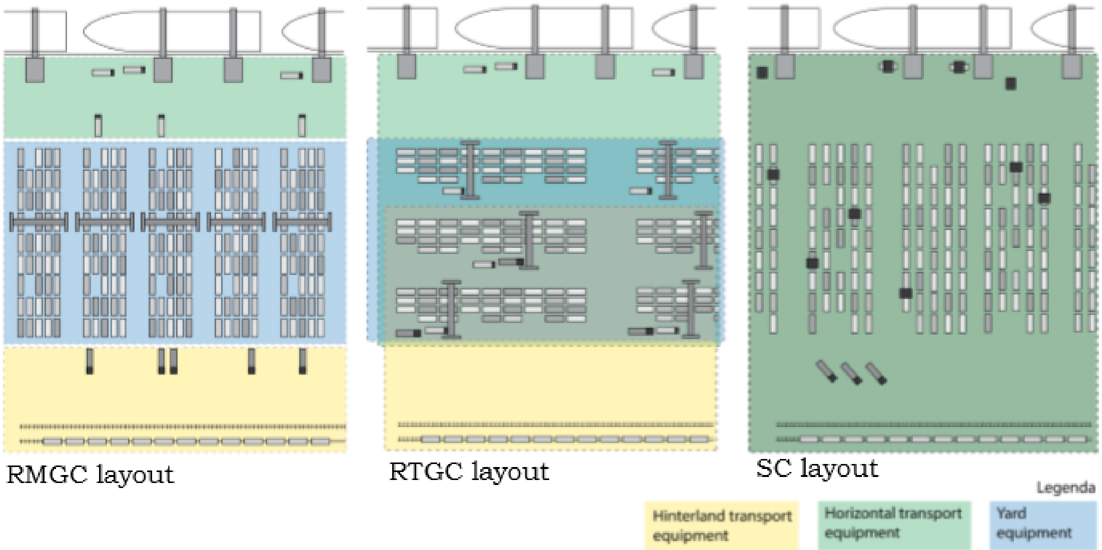


Figure 3.1: Different terminal layouts (adopted from van Rhijn (2015))

3.3.2. Level of automation

Another important aspect of terminal types is the level of automation. Many terminals have implemented ASCs in the last years and also the use of automated QCs is increasing. The first automation in container terminals occurred in 1993 at the ECT Delta Terminal in Rotterdam (PEMA, 2018). This automation consisted of the deployment of unmanned RMGCs. In the beginning, automation in container terminals did not spread that fast. In 2016 however, more than 1 100 ASCs were reported operating in Asia, Europe, US, the Middle East and Australia. In the USA AShCs are used in addition to AGVs, while in Australia, some terminals are equipped with autostrads. The use of remotely operated and automated QCs is currently increasing as well, although this number is still significantly lower than the number of ASCs. In the same way, automation of horizontal transport has not been that widespread either. In many terminals, automated yards are served by manually operated transport vehicles, such as ITs (PEMA, 2018).

As well as the type of YC applied in simulation and optimisation research, the level of automation also affects the results of the studies. Automated equipment has different operating specifications than manually operated equipment, and the level of stochasticity in cycle times of equipment is expected to be less in automated equipment. That is because the degree of freedom is larger in manually operated systems, since operational staff will operate equipment based on their own experience, while for automated equipment operations are programmed.

Kim & Kim (1999) consider a SC terminal with Yard Trucks (YTs) in their optimisation study. Wiese et al. (2010) mention that 20.2% of the terminals worldwide are of this type.

63.2% of the terminals worldwide use RTGCs (Wiese et al., 2010), while this percentage is 75.5 in Asia (Gharehgozli, 2012). Wiese et al. (2010) optimise a terminal yard which is served by a RTGC.

In the studies of Petering (2011), Petering & Murty (2009) Petering et al. (2009), and Petering (2010) a terminal is considered in which the QC, YT, and YC are all manually operated. This is usually the case for terminals in the USA.

Most of the research mentioned in Table B.1 and Table B.2 in Appendix B however investigate operations in automated terminals, either fully or partially automated. Dekker et al. (2006), for example, compare different stacking strategies by simulation of a terminal with ASCs and AGVs that transport the containers between the quayside and the yard. Duinkerken et al. (2001) evaluate the performance of different stack layouts and strategies on the stacking performance of a similar terminal with ASC and AGVs. Froyland et al. (2008) optimise a semi-automated RMGC system based on a terminal in Sydney. They mention the model being suitable for adjustment to autostrads in the future. Gharehgozli (2012) presents an optimisation study in which the total travel time of an ASC is minimised, amongst other objectives. Liu et al. (2002) evaluate different design concepts for ACTs in their simulation study. A similar question is asked in Yang et al. (2004). Liu et al. (2004) evaluate the impact of automation in terms of an AGV System (AGVS) in their simulation model which is validated with data from a terminal in the USA. Roy & de Koster (2014) compare a system operated by AGVs to a system that is operated by ALVs. Lastly, van Asperen et al. (2013) also simulate an automated terminal.

3.3.3. Types of containers

Besides the type of YC used in stacking operations and the level of automation, the type of containers also differs amongst studies. Kang et al. (2006), Kim & Bae (1998), Kim & Hong (2006), Kim & Kim (1999), Kim et al. (2000), Kim & Kim (1997), and Taleb-Ibrahimi et al. (1993) for example strictly focus on export containers.

Other studies merely consider import containers, such as de Castilho & Daganzo (1993), Hwan Kim & Bae Kim (1999), Kim (1997), van Asperen et al. (2013), and Zhao & Goodchild (2010). Generally speaking, operations regarding export containers are researched more often than import container operations. This can be explained by the fact that quayside operations are considered as more critical for a terminal's performance, since shipping lines can charge a terminal when a shipping schedule or service level agreement on maximum berthing time is not met. On the landside a terminal generally does not encounter a similar risk directly, although indirectly a terminal can be harmed by slow processes at the landside. Since carriers are clients of a terminal's client, and therefore generally not directly related by a contract to the terminals, terminals tend to scale landside carriers in a group of lower priority than their direct clients, namely the shipping lines (van Schuylenburgh, 2018). However, landside carriers can report back to the shipping lines on customer service levels of terminals and thus indirectly affect the attractiveness and competitiveness of terminals.

Other research is strictly focused on transshipment containers (Petering, 2011; Petering & Murty, 2009; Petering, 2010). They justify this decision by the fact that the world's most crowded container terminal in 2006 was Singapore, which consisted of 80% transshipment volume. Moreover, two other ports in this list of ten most crowded container ports, Kaohsiung and Dubai, also had high shares of transshipment volume (up to 40%) (Petering et al., 2009).

Other studies consider both export and import containers (e.g. Chen, 1999; Froyland et al., 2008; Hartmann, 2004; Li et al., 2009; Liu et al., 2002; Murty et al., 2000; Preston & Kozan, 2001; Roy & de Koster, 2014; Shabayek & Yeung, 2002; Yang et al., 2004).

Lastly, the studies of Güven & Eliiyi (2014) and Zhang et al. (2003) consider all three types of containers: import, export and transshipment containers. However, it must be said that the process around transshipment containers can be seen as a specific type of export containers, arriving by deep sea vessel (Kim & Park, 2003). Therefore studies focused at both import and export containers, can be regarded as covering the processes of import, export and transshipment as well.

The more types of containers considered, the more representative the model will be for the real system. Especially for QC operations that can be concerned with loading export on and unloading import containers from a single vessel simultaneously. However in most terminals import and export containers are stacked in separate areas, therefore considering merely one type of containers can still give an accurate description of stacking operations at one part of the terminal.

Besides the distinction between import, export, and transshipment containers, many other types of containers exists. The specific size of a container influences its position in the yard. Generally, containers of the same type are stacked together in a bay, row or even block. A standard 1 TEU container is 5.898 meters long, 2.352 meters wide and 2.394 meters high. A 2TEU container is twice as long as a 1TEU container. However, more size variants exists, such as high cube containers. Stacking containers on top of each other is complicated by their different sizes.

Another distinction can be made between refrigerated containers (reefers), containers with dangerous goods (MIO containers) or shipments of odd sizes (Out of Gauge, OOG). These are stored at separate locations in the yard.

A last distinction that is mentioned is between loaded and empty containers (MTs). The largest share of containers in a terminal consists of loaded containers. However, many shipping lines fill up spare capacity with MTs, that can also be stored at a terminal. MTs are located in a separate stacking block, generally stacked higher and closer together.

3.3.4. Hinterland transport modes

A last important difference in container terminal studies relevant for this research, is the mode of transport considered at the landside. Some research only takes the delivery and retrieval of containers by trucks into account (e.g Hwan Kim & Bae Kim, 1999; Murty et al., 2005; Taleb-Ibrahimi et al., 1993; van Asperen et al., 2013). Most of the studies mention the landside modes of both truck and train (e.g. Froyland et al., 2008; Gambardella et al., 1998; Hartmann, 2004; Liu et al., 2002; Petering et al., 2009; Preston & Kozan, 2001; Yang et al., 2004). The study of Chung (1986) is focused on the Port of Portland, and thus should refer to both truck and train deliveries and retrievals. However, this study does not specifically mention the truck landside mode. Similarly, the studies of Murty et al. (2000), Murty et al. (2005) and Shabayek & Yeung (2002) are related to the terminals of Hong Kong. These authors also do not mention the possibility of train specifically. This can be explained by the fact that when focused specifically on performance of the stacking operations of a terminal, the specific modes are less relevant to consider. Additionally, little research mention barge transport as hinterland method. The studies presented above, which do consider barge, are all published by Dutch authors (Dekker et al., 2006; Konings, 1996; Vis & De Koster, 2003). This can be explained by the fact that barge is a relevant container transport mode in the West of Europe, while it is considerably used less in the USA or Asia. In this research the focus will be on a multimodal gateway terminal with preferably also barge transport. This is presented in Figure 3.2.

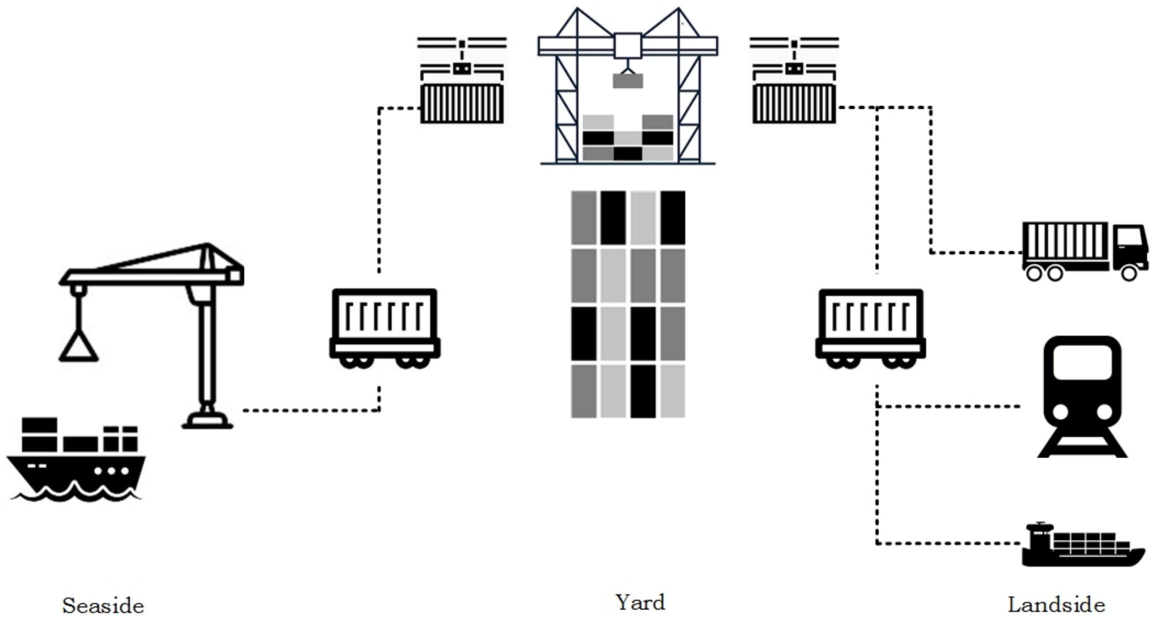


Figure 3.2: Yard operations with 3 hinterland transport modes

3.4. Knowledge Gap

In many of the studies described above, the performance of different stacking strategies is investigated. Stacking strategies are, amongst others, based on destination, arrival time and departure time of containers (Güven & Eliiyi, 2014). In category stacking, as an example, containers are placed together based on weight type and expected time of departure. In reality, however, many data related to the arriving containers is unknown at the time of arrival and may even change when the containers are already placed into the stack. So a study might result in an optimal stacking strategy, while this strategy cannot be implemented in reality due to missing information. Because decisions made related to stacking policies are based on studies where full information is assumed, actual performance of current practices can be reduced significantly. A lot of information, even though it not always directly interferes with operational activities, is needed to optimise the work flow in terminals (Steenken et al., 2004).

Different studies mention the deficiency of certainty in container information (e.g. Dekker et al., 2006; Froyland et al., 2008; Petering, 2010; Steenken et al., 2004), but only little studies look into the effects of these uncertainties. Uncertainty or more specifically stochasticity is presented as a given circumstance, and while changing that situation might be difficult, it is surprising to see such a small number of studies that looked into the consequences of it on terminal operations. Both Rashidi & Tsang (2013) and Stahlbock & Voß (2008a) mention the relevance of further research in stochastic optimisation and scenario based scheduling of container terminals, which already indicates the relevance of research that copes with missing certainty faced in reality.

Two studies that look into a type of uncertainty have been found. Kang et al. (2006) present a research on stacking strategies for export containers while weight information is uncertain. Export containers in a yard are usually divided into different weight groups to make it easier to load heavier containers onto a ship earlier than lighter ones. This way of stacking the containers is expected to lead to fewer reshuffles, hence more efficient loading operations. That is an important constraint in the loading process of containers onto a ship, related to the ship's balance. It is mandatory for trucking companies to send specific container information before arrival of the trucks to the terminal. However, this information, especially regarding the weight of the containers, is often not accurate. Often the terminal is informed of accurate weights of containers only a day before the scheduled loading, while the majority of the containers are already in the yard multiple days before loading. Kang et al. (2006) also mention the majority of research being conducted while assuming complete information and the little amount of researches in reducing the amount of reshuffles while information is inaccurate. They also point out that ordering constraints for inbound containers are not related to weight groups, since there is no balancing need.

The research of Zhao & Goodchild (2010) looks into the impact of truck arrival information on the amount of reshuffles. The goal of a reduction in reshuffles is to improve the YC productivity and reduce truck transaction and delay time as well as improve container throughput on the yard. They split the problem into two aspects: unknown truck arrival information and unknown truck sequencing information. Truck arrival information is unknown when there is absolutely no certainty on when trucks will arrive. Truck sequencing information is unknown when for example a time slot of one hour has been booked for truck arrivals, but the exact sequence in which the trucks of a same time slot arrive is unknown. The arrival time in the latter case is not only uncertain, but is similar to the definition of stochasticity that is used in this research, i.e. random variation around a parameter value. They conclude that a significant reduction in the amount of reshuffles can be achieved with small improvements in terminal information regarding truck arrivals. This research aims to continue in the same direction.

The fact that only two studies were found that take stochasticity into account, and only one of these studies looks into the effects of stochasticity indicates the current research gap on this topic.

Furthermore, the studies described above mostly consider terminals that handle containers delivered and picked up by the hinterland transportation mode truck. Some studies also describe train as a second mode of hinterland transport, but barge transport is hardly ever mentioned. With respect to the two studies mentioned considering stochasticity, Kang et al. (2006) do not mention the hinterland transportation methods available at the terminal, while Zhao & Goodchild (2010) only consider stochasticity in truck arrivals. In reality however, stochasticity occurs in arrivals of deep sea vessels, trucks, trains and barges. Stochasticity is not only related to arrival or pick-up times of containers, but also to the mode on its own. The next mode of transport for import containers, for example, is still unknown in many cases when the container is discharged from the vessel. Steenken et al. (2004) even mention only 10-15% of the import containers that arrive at a terminal have information on the landside transportation mode upon arrival. When this information is available, changes in the next mode of transport occur frequently while the container is already stored in the yard. The lack of information on next mode of transport complicates storing containers of the same next mode of transport together.

This research aims to contribute to knowledge of a multimodal terminal that serves deep sea vessels, feeder vessels, trucks, trains and barges. Moreover it will attempt to quantify the effects of stochasticity on the performance of stacking operations for import containers at a gateway terminal.

3.5. Key Performance Indicators

Following from the literature study, 48 studies are presented in Table 3.1 based on their performance indicators. In simulation studies the authors generally refer directly to performance indicators, while performance indicators from optimisation studies are subtracted based on the objectives described. Both are presented as performance indicators in Table 3.1. The performance indicators are divided into the following definitions: utilisation (U), reshuffles (R), throughput (TP), time (T), stacking capacity (SCap), costs (C) and distance (D).

According to Table 3.1, the most used performance indicators are related to reshuffles, throughput and time. These indicators also seem relevant for this research, that is why they are explored further below.

Table 3.1: Performance indicators in literature, divided into Utilisation (U), Reshuffles (R), Throughput (TP), Time (T), Stacking Capacity (SCap), Costs (C) and Distance (D)

Study	**U**	**R**	**TP**	**T**	**SCap**	**C**	**D**
Chen (1999)		x					
Chung (1986)	x	x		x			
Chung et al. (1988)	x			x			
Dekker et al. (2006)	x	x					
Duinkerken et al. (2001)	x	x		x			
Esmer (2008)	x	x	x	x			
Froyland et al. (2008)			x	x			
Gambardella et al. (1998)				x		x	
Gharehgozli (2012)		x	x	x			
Golbabaie et al. (2012)			x	x	x	x	
Güven & Eliiyi (2014)		x		x			
Hartmann (2004)		x	x	x			x
Hwan Kim & Bae Kim (1999)		x					
Kang et al. (2006)		x					
Kim (1997)		x	x	x			
Kim & Bae (1998)		x		x			x
Kim & Hong (2006)		x					
Kim & Kim (1999)							x
Kim & Park (2003)				x			x
Kim et al. (2000)		x					
Kim & Kim (1997)				x			
Li et al. (2009)				x			
Liu et al. (2002)	x		x	x		x	
Liu et al. (2004)	x		x				
Meersmans & Dekker (2001)		x					x
Murty et al. (2000)	x	x	x	x		x	
Murty et al. (2005)		x	x	x		x	
Petering (2011)	x		x	x			
Petering (2010)	x		x	x			
Petering & Murty (2009)			x				
Petering et al. (2009)			x				
Preston & Kozan (2001)				x			
Rashidi & Tsang (2013)	x	x		x		x	
Rebollo et al. (2000)				x			
Roy & de Koster (2014)	x			x			
Shabayek & Yeung (2002)	x		x	x			
Stahlbock & Voß (2008a)	x	x		x		x	
Stahlbock & Voß (2008b)		x	x	x			x
Steenken et al. (2004)	x	x		x		x	x
Taleb-Ibrahimi et al. (1993)	x						
Ünlüyurt & Aydin (2012)		x		x			x
van Asperen et al. (2013)		x		x			
Vis & De Koster (2003)	x	x		x	x		
Wiegmans & Witte (2017)			x		x		
Wiese et al. (2010)						x	
Yang et al. (2004)			x	x			
Zhang et al. (2003)			x	x		x	x
Zhao & Goodchild (2010)		x					
Total	**17**	**25**	**19**	**33**	**3**	**10**	**9**

Reshuffle performance indicators are referred to as the number of reshuffles (pure amount of container replacements), the number of reshuffle occasions (possibly consisting of multiple reshuffle moves), the percentage of containers that needed reshuffle moves to be accessible, or the reshuffle volume (in containers or TEU). The use of different measures for the amount of reshuffles is presented in Table 3.2. The amount of reshuffles is directly related to the handled volume of a container terminal and the fill rate of the yard. To facilitate comparability of the results of this research with other terminals, the amount of reshuffles will be expressed in reshuffles per retrieval.

Table 3.2: Performance indicators related to reshuffles

Study	**Number**	**Occasions**	**Percentage**	**Volume**
Chen (1999)	x			
Chung (1986)	x			
Dekker et al. (2006)	x	x		
Duinkerken et al. (2001)		x		
Esmer (2008)	x			
Gharehgozli (2012)	x			
Güven & Eliiyi (2014)	x	x		
Hartmann (2004)	x			
Hwan Kim & Bae Kim (1999)	x			
Kang et al. (2006)	x			
Kim (1997)	x			
Kim & Bae (1998)	x			
Kim & Hong (2006)	x			
Kim et al. (2000)	x			
Meersmans & Dekker (2001)	x			
Murty et al. (2000)				x
Murty et al. (2005)				x
Rashidi & Tsang (2013)	x			x
Stahlbock & Voß (2008a)	x			
Stahlbock & Voß (2008b)	x			
Steenken et al. (2004)	x			
Ünlüyurt & Aydin (2012)	x			
van Asperen et al. (2013)		x	x	
Vis & De Koster (2003)	x			
Zhao & Goodchild (2010)	x			
Total	**21**	**4**	**1**	**3**

Throughput indicators are also described in various ways. One refers to throughput as crane moves or lifts per hour, yard moves per hour, TEU per hour per berth (handling capacity), productivity in moves per hour, gross QC rate (average number of lifts per QC working hour), and containers placed on a YT per hour active time. The differences in throughput measures amongst studies is displayed in Table 3.3. The various options are summarised as movements of containers per time unit, YC moves per time unit or the QC rate. The latter one is mentioned in several studies as an important performance measurement of terminal service quality. It is presented by the (average) amount of moves per QC per time unit. The measures differ also in average or global values over a time period, or average measures per working hour. The latter one is for example referred to as Gross Crane Rate (GCR), throughput per working hour or net productivity. In this research the yard throughput is directly related to the input variables of container arrivals and departures, as discussed in Section 4.6 and Section 4.8. Hence, the throughput is not likely to represent stacking performance accurately in this model. Instead, the maximum utilisation rate per hour of yard operating equipment is chosen as relevant performance indicator. In case this maximum rate could be decreased, especially during peak hours, throughput of the yard could increase since yard operating equipment would spend less time on retrieval requests. Moreover, the yard operating equipment becomes available sooner for other transport requests.

Table 3.3: Performance indicators related to throughput

Study	**Containers/time**	**YC moves/time**	**QC rate**
Esmer (2008)	x		
Froyland et al. (2008)		x	
Gharehgozli (2012)			x
Golbabaie et al. (2012)	x		
Hartmann (2004)			x
Kim (1997)	x		
Liu et al. (2002)			x
Liu et al. (2004)	x	x	x
Murty et al. (2000)			x
Murty et al. (2005)			x
Petering (2011)	x	x	x
Petering (2010)	x	x	x
Petering & Murty (2009)			x
Petering et al. (2009)			x
Shabayek & Yeung (2002)	x		
Stahlbock & Voß (2008b)	x		
Wiegmans & Witte (2017)	x		
Yang et al. (2004)			x
Zhang et al. (2003)			x
Total	**9**	**4**	**12**

The use of time indicators also varies amongst different studies. Some studies mention the container dwell time as performance indicator, others classify performance in terms of the total turnaround time of XTs or container vessels; the waiting time of a transport vehicle at the yard, a QC, a YC, or an XT; the travel times of cranes (subdivided into full and empty travel times); time spent on reshuffles; total time required to retrieve containers; average ship waiting time; makespan of the QC jobs; berthing time of ships; or crane idle times.

To provide a general overview, Table 3.4 divides the time performance indicators in travelling time, loading time, handling time, waiting time and turnaround time. Travelling time simply refers to the time a horizontal movement takes. This for example can be a crane movement between blocks (YC gantrying) or within blocks (YC or RMGC), YT transport time between the quayside and the container yard or container travelling time (via other transport vehicles), the movement of a SC, the empty travel times of an XT inside a terminal or, which is mentioned most often, the horizontal movement of transport vehicles. These transport vehicles can be specified as YTs, but can also refer to AGVs, ALVs, shuttles or SCs.

The loading time refers to QC operations. In the considered studies the QC loading time is described in different ways. Besides from the literal 'loading time', makespan of QC jobs is used to identify loading times (Gharehgozli, 2012), as well as the terms "handling times of all containers onto a ship" (Preston & Kozan, 2001), "stowage time" (Rebollo et al., 2000), "total sum of travel time of a QC and waiting time of an AGV at a QC during ship berth" (Roy & de Koster, 2014), "service time" (Shabayek & Yeung, 2002), "total completion time of all QCs for one vessel" (Stahlbock & Voß, 2008a,b; Yang et al., 2004; Zhang et al., 2003) or the "time needed for loading, unloading and transshipment" (Vis & De Koster, 2003). Although these definitions might differ slightly in meaning, and it is not always clear whether the research takes the complete (un)loading time from the first container until the last into account, or sums up individual container loading times (the times a container is handled by a QC), all the mentioned descriptions above are classified under loading time.

Handling time refers to the total sum of service time and waiting time of containers (and the transport vehicles that retrieve or deliver them) at the yard. YC handling time is in Duinkerken et al. (2001) for example described as "stack response time", which relates to the time it takes for a YC to move towards a container in the stack, pick it up and deliver it at a truck or transport vehicle at the yard exchange point. Other research refers to the YC handling time as the "total time needed for storage and retrieval of containers" (Gambardella et al., 1998; Güven & Eliiyi, 2014; Li et al., 2009; Roy & de Koster, 2014; Stahlbock & Voß, 2008a; Ünlüyurt & Aydin, 2012) or "the travel time of a YC towards and from a container" (Gharehgozli, 2012). Golbabaie et al. (2012) use the term "transfer cycle time" and Kim & Kim (1997) and Vis & De Koster (2003) employ "container handling time". The latter one refers to container handling times for YCs and SCs seperately. Lastly, Stahlbock & Voß (2008b) use "yard operation time". All descriptions above are assumed to refer to the process YC (or SC) handling in case a container is retrieved from or stored in the yard. While most research only includes handling time of a YC at the moment an XT or transport vehicle is waiting at the stack, Stahlbock & Voß (2008a) also include reshuffling time of the YC. Moreover, they mention not only YC handling time, but also XT handling time from the moment the XT arrives at the stack until it is ready to depart again.

Table 3.4: Performance indicators related to time

Study	Travelling	Loading	Handling	Waiting	Turnaround
Chung (1986)		QC			
Chung et al. (1988)		QC			
Duinkerken et al. (2001)			YC		
Esmer (2008)					Ship; XT; Rail
Froyland et al. (2008)				Container dwell time; XT	
Gambardella et al. (1998)			YC	Containers at YC	
Gharehgozli (2012)		QC	YC		
Golbabaie et al. (2012)			YC		
Güven & Eliiyi (2014)			YC	Container dwell time	
Hartmann (2004)				Ship; QC	
Kim (1997)					XT
Kim & Bae (1998)					Ship
Kim & Park (2003)				DOS(A)	
Kim & Kim (1997)			YC		
Li et al. (2009)			YC		
Liu et al. (2002)				Container dwell time	Ship; XT
Murty et al. (2000)				XT; YT; QC	Ship
Murty et al. (2005)				XT; YT; QC	Ship
Petering (2011)	YC gantrying; YT; Containers			QC; YC	
Petering (2010)	YT			QC; YT	
Preston & Kozan (2001)		QC			Ship
Rashidi & Tsang (2013)	RMGC			RTGC; QC; XT	
Rebollo et al. (2000)		QC			
Roy & de Koster (2014)	Transport vehicles	QC	YC	Transport vehicles	
Shabayek & Yeung (2002)		QC			Ship
Stahlbock & Voß (2008a)	SC; RMGC; Transport vehicles	QC	YC; XT	Container dwell time; Transport vehicles; Ship; QC; XT	Ship
Stahlbock & Voß (2008b)	Transport vehicles; XT	QC	YC	QC; Transport vehicles;	Ship
Steenken et al. (2004)	YC			Transport vehicles	XT; Ship
Ünlüyurt & Aydin (2012)			YC		Ship
van Asperen et al. (2013)					XT
Vis & De Koster (2003)	Transport vehicles	QC	YC; SC		
Yang et al. (2004)	Transport vehicles	QC		Transport vehicles; QC	
Zhang et al. (2003)		QC			

Waiting time is used for container dwell times, waiting time of XTs that are retrieving or delivering containers, waiting times of containers or the transport vehicles at container interchange points, waiting times of cranes, and the waiting time of ships before they are able to berth in the port. Kim & Park (2003) use the term Duration Of Stay (DOS) or the maximum DOS Allowed (DOSA). DOS is similar to the container dwell time, while DOSA refers to the maximum amount of 'free days' a container can be stored in the yard until demurrage costs will be charged. Waiting times for transport vehicles sometimes refer only to YTs, but can also refer to AGVs, ALVs, SCs or other transport vehicles used in a terminal to transport containers between the quayside and the yard and between the yard and the landside. Waiting times of cranes, either QCs or the RTGC mentioned in Rashidi & Tsang (2013) consider both the idle time of the equipment (when it has no future task assigned) and the waiting time of the equipment when a container is already being transported to the equipment.

Lastly, the turnaround time is the time for a transport mode between the moment of entering the terminal system and leaving it after being served. For ships this includes waiting time, berthing time, service time and sailing delay. For XT the turnaround time is the time between the two moments they pass the terminal gate. For the other hinterland modes, train and barge, the turnaround time can be calculated in a similar way.

Since the focus of this research is on the stacking area and landside operations, travelling time between the quayside and the stack, as well as QC loading times and ship turnaround times will not be calculated. However, handling time of yard operating equipment, waiting time of transport vehicles or XTs at the yard and turnaround time of hinterland transport modes will we interesting performance parameters. The average container dwell time will be used as an input parameter for the simulation model, as described in Section 2.7 and 4.8, hence this is not regarded as a performance indicator in this research. Since handling time of yard operating equipment is already approached by the maximum utilisation rate per hour and the reshuffles per retrieval, and the model described in Chapter 4 is not suited to accurately measure waiting times or turnaround times of hinterland transport vehicles, the performance indicator that will be taken account in this research is truck service time.

3.6. Conclusion

This chapter started to answer sub-question 3: *How to model the relation between stochasticity in import container information and the performance of stacking operations?* A more detailed description, hence a further answer to the sub-question, can be found in Chapter 4. As can be concluded from the literature review in this chapter, the method that will be used in this research to model the relation is a simulation study. The KPIs that are most relevant for the goal of this research are reshuffles per retrieval, truck service time and maximum utilisation rate per hour of yard operating equipment.

In the simulation study the following KPIs will be implemented:

- **Reshuffles per retrieval**
  The reshuffles per retrieval will be monitored by counting the reshuffle moves yard operating equipment makes. Subsequently, the total number of reshuffle moves is divided by the total amount of container retrievals that have been modelled. In case the number of reshuffles decreases, turnaround times of hinterland transport mode will decrease and yard operating equipment productivity will increase.

- **Truck service time**
  The truck service time will be calculated by the difference between the time a truck generates a retrieval request and the moment the yard operating equipment has delivered the container. In the model described in Chapter 4, these moments are identified by the time a truck has arrived at the row interchange point to retrieve a container and the moment the container is released by the yard operating equipment. As further explained in Chapter 4 the travel time between the row and the truck gate is not taken into account.

- **Maximum utilisation rate per hour of yard operating equipment**
  The maximum utilisation rate per hour of yard operating equipment is especially interesting during peak hours. When this KPI could be decreased, one can assume that the utilisation of yard operating equipment is more spread over the entire day, in stead of clustered during peak hours, since the total volume through the container yard will be kept the same. The utilisation will be calculated each hour by looking back at the percentage of time the equipment was busy in that hour.

4 Model Design

This chapter will provide additional answers to sub-question 3: *How to model the relation between stochasticity in import container information and the performance of stacking operations?* Chapter 3 already analysed previous research on terminal (stacking) operations, motivated the technique to model the relation between stochasticity and stacking performance and determined the KPIs to be included to evaluate stacking performance. This chapter will describe the conceptual model in more detail. It will also describe the simulation model design on high level and the model specification on low level.

The process presented in Chapter 2 in Figure 2.6 and Figure 2.7 is implemented in a model to answer sub-question 4: *What is the effect of stochasticity in the parameters on the performance indicators?*. This implementation leads to a performance measure of the processes by the KPIs presented in Chapter 3. This chapter describes firstly the model requirements, then the model input and assumptions made. Section 4.5 describes how the KPIs from Section 4.2 are measured in the model. In Section 4.6 the main objects, their attributes and processes. Section 4.7 explains the choice for the modelling software used and additional information on the way how specific processes are modelled and implemented in the software. Lastly, Section 4.9 is about verification and validation of the model.

4.1. Model Requirements

The research objective is to quantify the relationship between stochasticity in arrival time (input 1) as well as type of hinterland transport mode (input 2) and the stacking performance (output). To fulfil this objective, the model should meet the following requirements:

1. The model should capture the main dynamics of import containers: their arrival time in the yard area, storage duration in the yard and departure time out of the yard again once a hinterland transport mode has requested the containers.
2. The model should monitor reshuffle moves once a container is requested that is not the highest one in a bay.
3. The model should represent stochasticity in arrival times of hinterland transport modes.
4. The model should represent the stacking performance by calculating the performance indicators (reshuffles per retrieval, service time of hinterland transport modes and maximum SC utilisation per hour)

4.2. Conceptual Model

The conceptual model is presented in the form of an IDEF diagram in Figure 2.6 and Figure 2.7. The terminal process of connecting the seaside and landside is split up into three processes. First, the model generates container arrivals at the yard. This is done based on a container arrival rate, which will be discussed in Section 4.8. Secondly, the model stores the incoming containers. Dependent on the bay in which the container is

stored, the SC will need more or less time to store the container. This delay is also discussed in Section 4.8. The third process is the retrieval of containers at the landside. This latter process is split up into 5 sub-processes. Upon the arrival of an XT, barge or train, a pick-up request is generated (1) that determines which container(s) is/are requested. Then, the model needs to determine whether the requested container(s) is/are on top, or whether a reshuffle is necessary (2). It then either performs this reshuffle (3), or it directly picks up the requested container (4). Both sub-processes 3 and 4 entail another delay, which is elaborated on in Section 4.8. Lastly, it delivers the container to the hinterland transport mode, after which this latter one leaves the model with container(s) loaded onto it (5).
Based on the level of stochasticity, the hinterland transport mode will retrieve containers that were expected to be picked up later, since their ETD is later than another container present in the yard. The way of implementation of stochasticity in the model is further specified in Section 4.8.

Besides the conceptual model a Unified Modelling Language (UML) class diagram is constructed to represent the system to be modelled with information on classes, objects, their attributes and the relations amongst the objects. The UML diagram is presented in Figure 4.4.

4.3. Model Input

To achieve realistic model input, a data request has been sent out to different container terminals (see Appendix C.1). As no complete response to this request was available, this research will cope with the missing data in a way that is discussed in detail in Section 4.8. This simplification has its shortcomings, which will be discussed in Section 6.2, besides the assumptions and constraints already described in Section 4.4. When more data becomes available in future research, the results can be compared and might be improved in terms of reliability and validity. This is further discussed in Section 6.3.

The model input that is used in this research follows from different types of data.

Firstly, the model is based on the MSC PSA European Terminal (MPET) in Antwerp. This straddle carrier (SC) operated terminal is the largest container terminal in Europe (MSC PSA European Terminal, 2018). Information related to the terminal is retrieved from different resources, namely expert interviews at MPET, the layout print of the terminal, a visit to the terminal and a data sheet. MPET's handled volume consists of 55% transshipment.[1] Generally, the quayside is occupied with a high fill rate and operations are quite efficient. The main focus of MPET is on the export and transshipment area in the yard, and not on the import area. This leads to relatively less advanced import operations in comparison to export and transshipment operations. It is expected that import operations can be improved to a large extent, since this topic has not yet been a main focus for improvement. For example, there is no yard planning for the import area that considers container attributes such as expected pick-up time or mode of transport. Import containers are stored into one of the import blocks and many reshuffles take place when a hinterland transport mode arrives to pick up a container. This will be explained more detailed in Section 4.6. As already indicated above, separate areas are reserved in the yard for respectively export, transshipment and import. A single row of a block section of the import area will be modelled. The block under examination consists of 41 rows of 14 bays in total. The bays are stacked 3 high and served with SCs that are able to stack 4 high. However, a bay will only be filled to its maximum in rare cases during some reshuffle moves, preventing blockage of an entire row for further SC moves. In normal operations, import containers that will be retrieved by train, truck, or containers of which the next mode of transport is unknown will be placed in the import area. Containers that will be retrieved by barge, remain in the export area since their operations are similar to those of export containers. However, in practice the terminal is notified of the containers that will be picked up by barge only one day in advance, so almost all the barge containers will first be put into the import area. When placed in the import area, manually operated SCs choose a position for the containers. In this process the (expected) retrieval date of the container or the (expected) next mode of transport is not taken into account. Generally, this information is unknown. The SC operators are more or less free to choose a suited position, normally based on a levelling strategy. This means, SC operators place the container in a row that has a relatively low fill rate in relation to the other rows. In a row, a bay will be chosen that is empty or in which relatively little containers are currently stored. Since the 4-high SCs only operate at the import area, their availability does not coincide with quayside operations. A 3-high SC will pick up a container from underneath a quay crane (QC), after which it will store the container in the import area.

[1] Information based on expert interview at MPET

Secondly, publicly available data from the APM Terminal at Maasvlakte II in the Netherlands is used. For a period of 28 days the arrival and departures of vessels at the terminal have been observed via `https://www.apmterminals.com/en/operations/europe/maasvlakte/procedures/termview`. Once a day the changes in arrival and departure times have been updated. Changes made at most 2 days in advance have been taken into account, as MPET indicated that changes made in that time frame allow for housekeeping moves to update the position of the containers.[2] Currently, housekeeping moves are only performed in the transshipment and export area. Introducing housekeeping moves is however considered as possible improvement, as is explained in Chapter 5. In other words, the Expected Time of Arrivals (ETAs) were monitored and updated once a day for all arriving barges at AMPT-II. When the Actual Time of Arrival (ATA) of a barge is known, the ETA is saved that was known 2 days in advance of the ATA. The differences between the ETAs and ATAs of barges is the stochasticity in their arrival times. This data is used to gain insight in the level of stochasticity a container terminal is confronted with.

4.4. Assumptions and Constraints

Regarding the (time) scope of this research, assumptions to construct a useful model are inevitable. Main assumptions and constraints in the model are:

- All containers are assumed to be 1 TEU (see Section 4.8).
- Containers filled with dangerous goods (IMO), as well as refrigerated containers (reefers) and other special types of containers are left out of scope of the model, since they are located in a separate area in the yard and therefore their retrievals will not coincide with the modelled yard operations except for seizing of the same resources.
- The arrival rate of containers at containers is assumed to be constant over a week (see Section 4.8). However, the model will randomly select inter arrival times based on the arrival rate of 1 week each time it produces an individual container.
- No prior information regarding pick-up time is assumed for import containers, therefore housekeeping moves do not take place in the import area. This is the current practice at the MPET terminal. However, introducing housekeeping moves will be a configuration, as discussed in Section 5.3.
- Import containers located in the modelled yard block have as next mode of transport either barge, truck or rail. This is not known at the moment of discharge from the deep sea vessel nor upon arrival of the containers at the yard. Barge containers will eventually be located at the export area. However, since a barge communicates which containers it will pick up only a day in advance, all barge containers will first pass through the import area. In this model the relocation of barge containers back at the seaside is not taken into account. Hence, barge containers will be directly retrieved from the general import yard in case of a barge request.
- Infinite availability of SCs is assumed at first. Only one SC a time can occupy the modelled row, to prevent multiple SCs blocking each other's way. During the model run the amount of SCs needed will be determined in terms of maximum SC utilisation per hour.
- Customs inspection are not implemented in the model.
- The container volume that arrives at the modelled yard block is calculated respective to the total amount of import containers ground slots. This is explained in Section 4.8.
- When a hinterland transport mode arrives, the container it requests is always present in the yard. This means that there are no lost containers.
- A truck always requests 1 container at most in the model. In reality, a train requests approximately 90 TEU and a barge 60 TEU in total.[3] Since these containers can be retrieved over the entire import yard with some time in between multiple requests by the same mode, the model simulates retrievals one by one. Hence, it is not monitored whether multiple requests belong to a same mode, although this could be possible. The retrieval process is further explained in Section 4.8.

The impact of these assumptions and constraints is further discussed in Section 4.6 and 6.2.

[2] Refers to footnote 1

[3] Refers to footnote 1

4.5. Performance Measures

As mentioned in Section 3.6, the KPIs that should be captured in the model are reshuffles per retrieval, truck service time and maximum SC utilisation per hour. The number of reshuffles needed to determine the reshuffles per retrieval is calculated each time a container is retrieved that is not on top in the bay. In the process that will be explained in detail in section 4.6, the decision logic behind deciding when a reshuffle is needed is discussed in Figure 4.2. The truck service time is calculated by a measurement that keeps track of the time between the generation of a retrieval request and the delivery of the container to the truck, this is explained in Appendix D. Lastly, the maximum SC utilisation will be determined per hour. This is also explained in Appendix D.

4.6. Objects, Attributes and Processes

In this section the main objects and their relations will be presented in a UML class diagram (see Figure 4.4). This diagram represents the modelled system related to its objects. Each object can have attributes and processes, represented by the two boxes below the object name. Moreover an object can belong to a class, in that case the object from the 'child class' inherits the attributes and processes from its 'parent class'. That is for example the case with *Hinterland transport mode* (parent class) and *Truck*, *Train* and *Barge* (child classes). This inheritance relation is presented by an open arrow from the child classes towards the parent class. Furthermore other relations between objects are presented in the UML diagram. The arrow indicates the direction of these relations, for example the yard operating equipment that uses a retrieval request or the stacking strategy that determines container slots. Lastly, the numbers in the diagram represent the quantities in the relations. A hinterland transport mode (1) can retrieve one or multiple containers (1..*), while the yard operating equipment (1) is considered to only carry one import container (1) at a time.

4.6.1. Arrival rate import containers

The arrival rate of import containers from seaside to the import yard block is based upon data from MPET. The arrival of containers is assumed to be equal to the departure of containers from the import yard, since over a longer run the amount of containers in the yard is not expected to increase or decrease significantly. The received data refers to the registered imported volumes. These rates are further discussed in Section 4.8. When a container arrives at the yard, it will be stored in a slot in the yard dependent on the stacking strategy, which is explained below. The process is illustrated in Figure 4.1.

Figure 4.1: Stacking Strategy of Arriving Containers from Seaside

4.6.2. Arrival Hinterland transport modes

Data from MPET shows that the total amount of full import containers retrieved from the seaside, leave the terminal by rail, barge or truck with respectively 11%, 29% and 61%. When transferring the number of container to amount of TEU, the modal split per TEU is 11%, 26% and 63% for trains, barges and trucks respectively. These latter numbers are taken as modal split per container in the model, since only 1 TEU containers are modelled. That means, from all the retrieval requests, the above mentioned percentages show the distribution of next modes of transport per container. As presented in Figure 4.4, hinterland transport modes can collect one or more containers. The number of containers a hinterland transport mode requests is not monitored in the model, as mentioned in Section 4.4. The yard operating equipment (in this case a SC) uses the pick-up request generated by the hinterland transport mode to retrieve the specific container from the yard. This process is illustrated in Figure 4.2.

One of the parameters that will be varied in the experiments is the level of stochasticity concerning the selection of containers by hinterland transport mode. The way this is represented in the model is explained in Section 4.8 and the experiments are discussed in Chapter 5.

4.6.3. Stacking strategy and reshuffle logic

As shown in Figure 4.4, the stacking strategy consists of a set of rules and based on these rules a location is determined to store or to relocate a container. The rules implemented in the model are as follows. Upon arrival of the containers in the import yard block, a random non-full row is selected to store the container in. Since the model represents a single row, this first selection process is not modelled. Within the row, the bay that is closest by and has the least amount of containers in it will be selected. This corresponds to a levelling strategy within one row while freeing SC capacity as soon as possible. The process is shown in Figure 4.1. In reality however, the process of storing a container is performed by the human SC drivers, based on information of the TOS and available container slots so the process might be more intelligent than modelled in this research. That will be further discussed in Section 6.2.

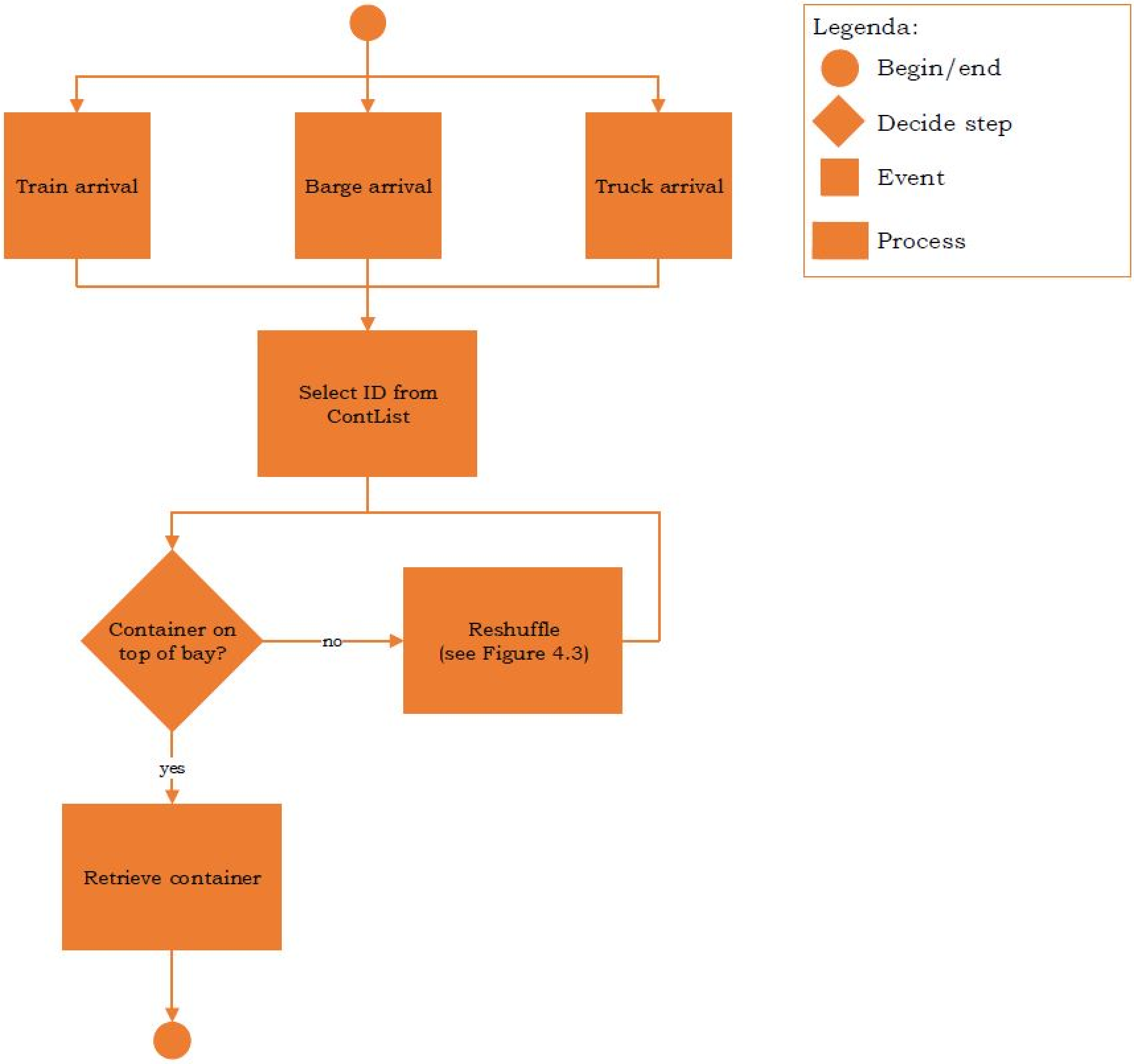


Figure 4.2: Arrival of hinterland transport modes

Once a hinterland transport mode has selected one or more containers out of the yard to be retrieved, the model determines whether the requested container is at the top of the bay or not. In case it is not, the model chooses one directly neighbouring bay and determines whether the number of containers in that specific bay is less than three (maximum operational stacking height). In case it is, the top container of the first

bay is relocated to that neighbouring bay. In case it is not, the process continues to the other neighbouring bays, until a bay has been found that contains less than three containers. In case no bay with less than three containers is available, the model temporarily relocates the container(s) that are top of the requested container to a bay that is already 3-high. This temporarily 4-high stacking takes place in the direction of the quayside, so that the SC can exit the row with the requested container at the landside. Once the SC has left the row, the 4-high stacked containers are immediately placed back into their original bay, to prevent the row from being blocked by a container that is stacked 4 high (absolute maximum stacking height). Once a single containers has been relocated, the number of reshuffles is increased by one. Then the process starts again, to determine whether the requested container is on top in the new situation. The reshuffle logic is presented in Figure 4.3.
Since only one row is modelled in this study, the model is less capable of dealing with fluctuations in container arrivals and retrievals. In reality, it can occur that a certain row is relatively full, and available spaces in an adjacent row will be claimed. Because this model is unable to deal with these fluctuations, a buffer has been created to represent this temporarily storage of containers while the yard block in total is capable of dealing with the demanded capacity, while the single row is not. The buffer logic is explained in detail in Appendix D.

4.6.4. Yard operating equipment

The yard operating equipment in the model is limited to SCs. In other types of terminals Yard Cranes (YCs) and other horizontal and vertical transport vehicles can be used. Differences in terms of model logic and results related to the use of SCs in stead of other yard operating equipment are discussed in Section 5.6. In this model, no restrictions to the availability of SCs is included. This means that once a container is generated to simulate an arrival from the seaside, or when a container is requested by a hinterland transport mode request, there is always a SC available. In reality, this is not a likely scenario, since SCs might be temporarily unavailable due to many other transport requests during peak hours, maintenance or once a failure occurs. This is not implemented in the model. However, during the model runs the maximum SC utilisation rate per hour is monitored. This value will hence be an underestimation of the SC utilisation rate in reality. This is explained in Chapter 5. Moreover, the model assumes all SCs to enter the row at the side of the quay (bay 1) and to exit the row at the landside (bay 14). Once a SC is present in a row, either because of a container delivery (from the landside or the buffer) or a container retrieval (including a reshuffle move), the row will be blocked for other SCs to enter. Once the SC that was present first in the row has finished its operations, the second SC can enter the row. Priority is given to container deliveries from the seaside and container retrievals from the landside with respect to relocating containers from the buffer and future housekeeping moves. The housekeeping logic will be illustrated in Chapter Section 5.3 and Figure D.1.

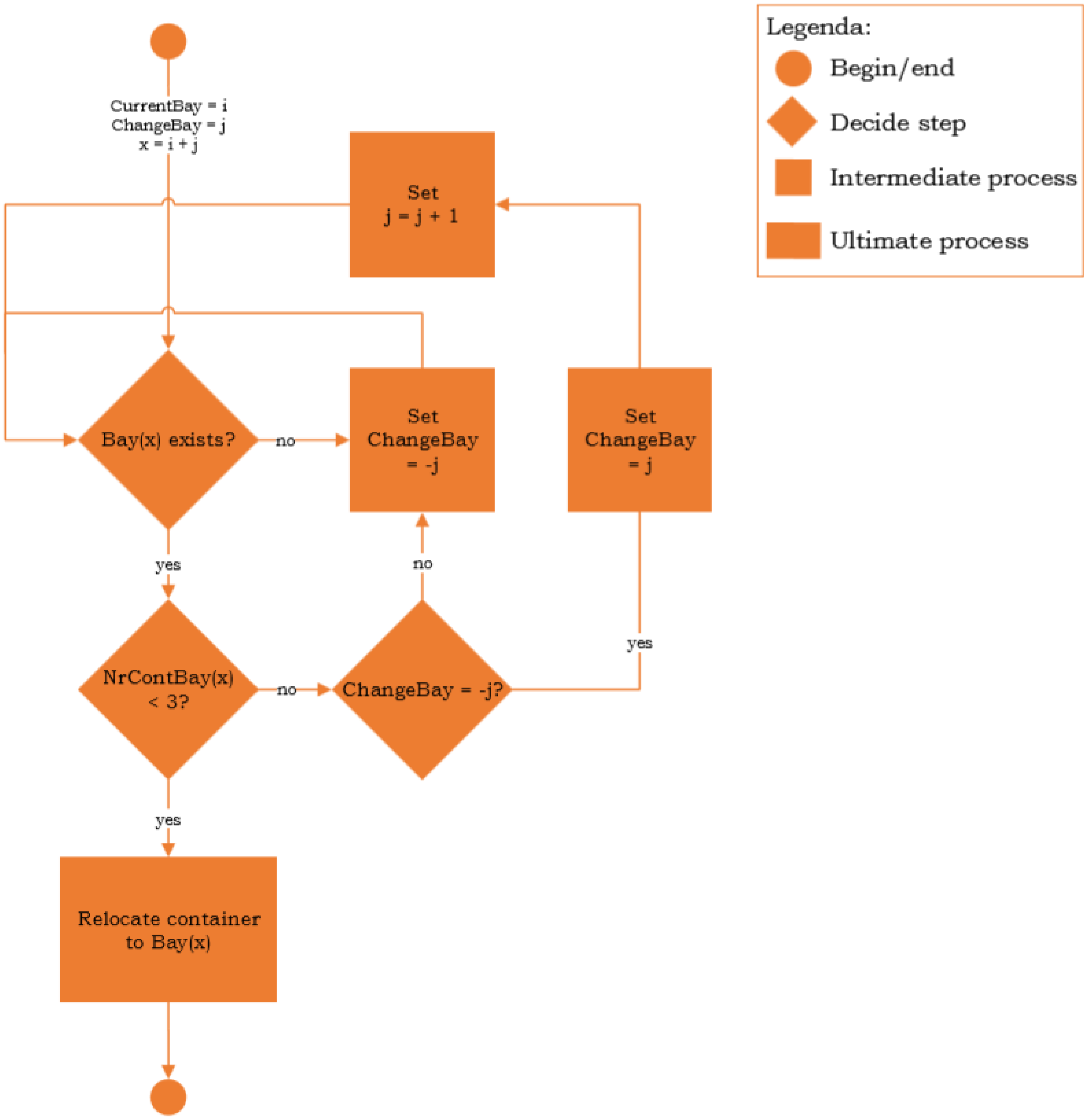


Figure 4.3: Reshuffle Logic

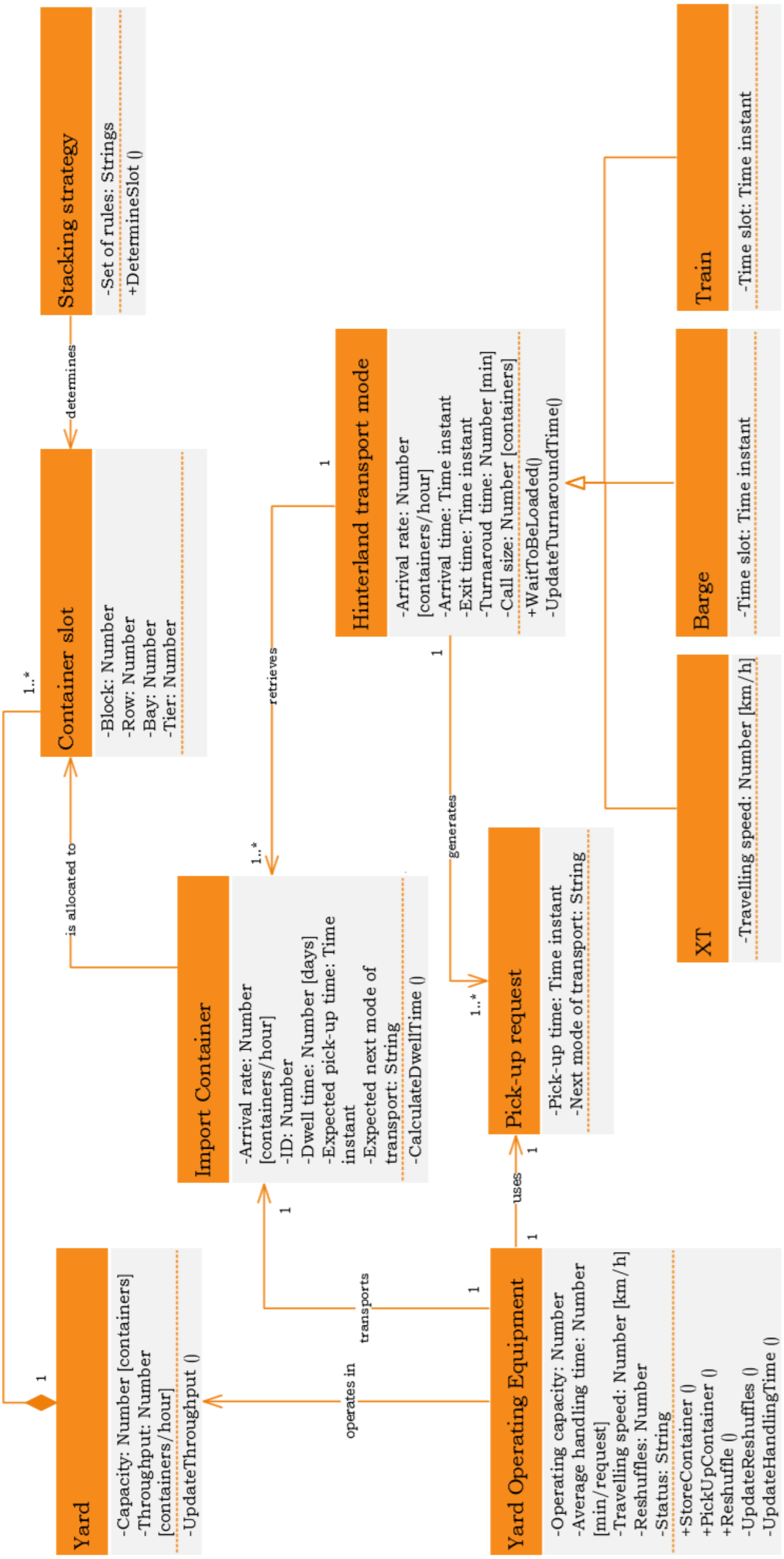


Figure 4.4: UML diagram

4.7. Discrete Event Simulation and Simio

To gain insight in the way stochasticity affects the performance of stacking operations at a container terminal, a simulation model is constructed. As concluded from Chapter 3, the main research method in this study is simulation. Regarding simulation, generally three types of simulation can be used: System Dynamics, Discrete Event and Agent Based Modelling (Borshchev & Filippov, 2004). A container terminal, or more specifically an import yard block which is the subject under investigation in this research, represents a relatively detailed system with low abstraction and on operational (micro) level. System Dynamics generally focuses on continuous processes, while Discrete Event and Agent Based models work more on a discrete time scale. That means that the model will evolve when a discrete event has taken place or based on discrete time steps. A difference between Discrete Event and Agent Based Models is that the first one generally is used to model systems with middle or high detail (low abstraction level), while the latter one can be used to represent high to low abstracted systems. Another important difference is that Agent Based Models work with agents of which their behaviour is defined at individual level, while Discrete Events are defined on a more central level. Based on the differences described above and the ability of Discrete Event Simulation to model queues and shared resources, the operations concerning the container yard block are best captured in a Discrete Event Model.

Many different Discrete Event modelling tools are available. In this research the models and process logic described above are implemented in Simio Simulation Software. Simio is a simulation modelling framework based on intelligent objects (Pegden, 2019). The object orientation in Simio allows to model the system based on the objects that are present in it, rather than for example a process oriented way of modelling. Moreover, within Simio one can use objects from the standard library without the need for programming code. Besides that, building an object is similar to building a model in Simio, which allows for easy creating submodels that can be replicated in higher level models. The last two reasons to use Simio is that the Simio Simulation Software is available via Delft University of Technology and it is possible to import data from and export data to excel from Simio.

4.7.1. Implementation in Simio

The model logic as described in high level above, is implemented in Simio version 10.174.16986 (64 bit). The licensing type is University Enterprise, provided by Delft University of Technology. The processes described above in Figures 4.1, 4.3 and 4.2 could be implemented directly in Simio. In order to facilitate the selection of containers upon arrivals of hinterland transport modes, additional data lists have been created in Simio, referred to as state variables of dimension type 'Matrix' in Simio. The containers that are present in the yard are for example saved in the list 'ContTimes'. In the Base Case (see Section 5.2), containers will be selected out of this list based on their ETD upon arrival of a hinterland transport mode. Once a truck, train or barge has selected containers from this list to be picked up, they are placed respectively in the lists 'TruckConts', 'RailConts' and 'BargeConts'. To create stochasticity, an additional list 'StochasticConts' is created. Adding stochasticity to the model will be further explained in Chapter 5.

The Simio model creates two different entity types, 'Container' and 'HTM'(hinterland transport mode). The HTM entity can be presented as a truck, train or barge. In the main model the containers arrive, are stored in a row of 14 bays or a buffer, and are picked up by a hinterland transport mode. The model also performs reshuffles once a requested container is stored below others. Since it is not possible to store containers visually on top of each other in Simio, each bay is presented by a green line that shows the lowest container in the bay the closest to the 'InputBay' node. Containers that will be placed on top of each other in a bay are represented as further away from the node. A picture of the model is presented in Figure 4.5.

The main objects and their attributes are explained in Appendix D.

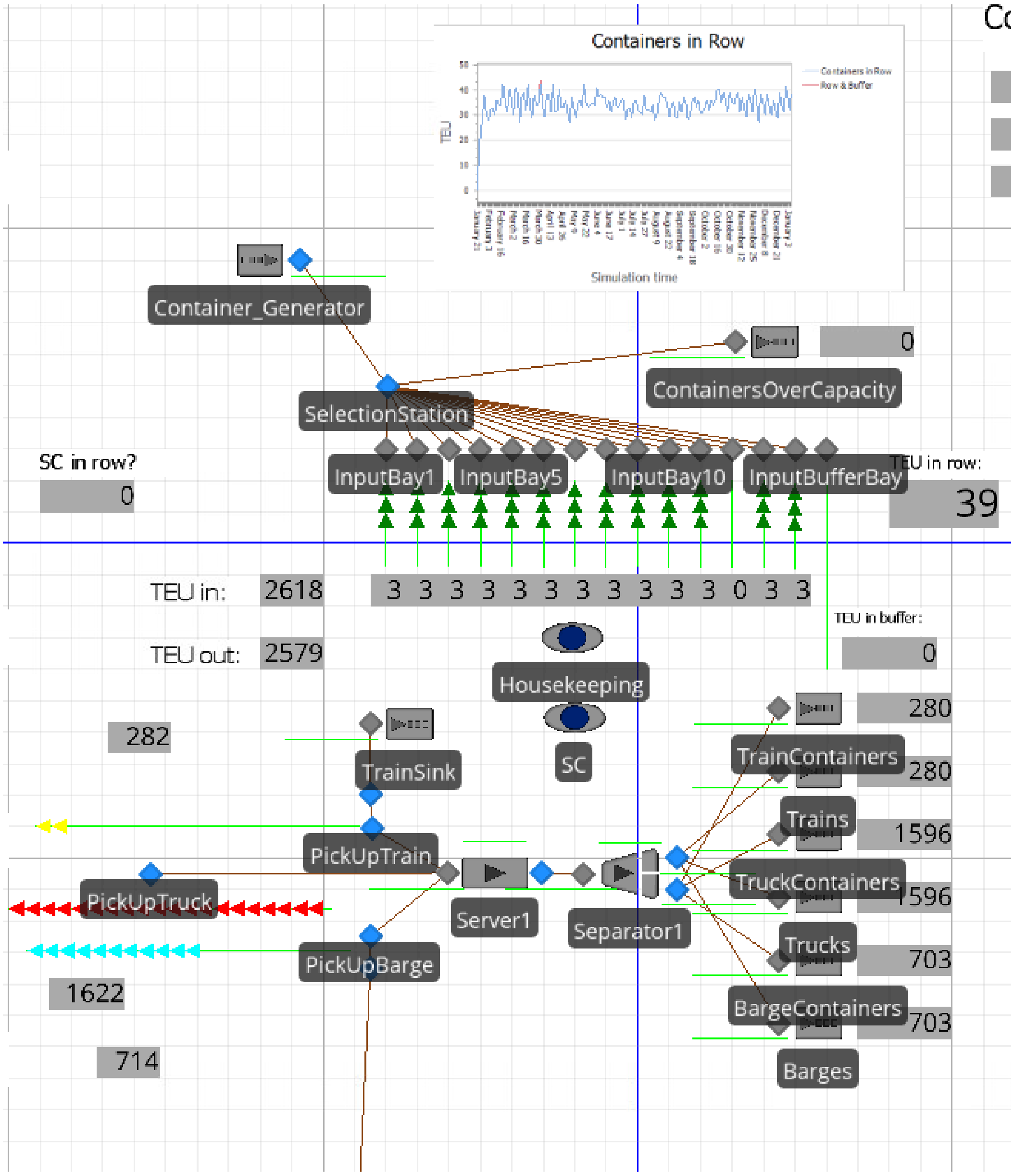


Figure 4.5: Simio Model

4.8. Data specification in the model

The previous sections have described the model in high level of abstraction and the implementation of this logic in a Simio simulation model. As mentioned, many factors of the model design are based on data from MPET. This section will describe the quantitative specification of the data in the model separately for the arrival rate of containers and hinterland transport modes, travel times and the selection process of containers in which stochasticity plays a large role. Moreover, it will describe the way this research has coped with the lack of available data. Most of the data that is described in this section is data related to configuration, i.e. data that construct the static model and will not be varied during experimentation. The other type of data is related to different scenarios that will be compared in Chapter 5, this is described in subsection 4.8.4.

4.8.1. Total TEU volume

MPET has provided data on the number of discharged containers per mode (deep sea vessel, truck, train or barge) per week and the number of loaded containers per mode per week.

As shown in Figure 4.6, the number of discharged containers from ships is available per week over a period of 46 weeks in 2018.

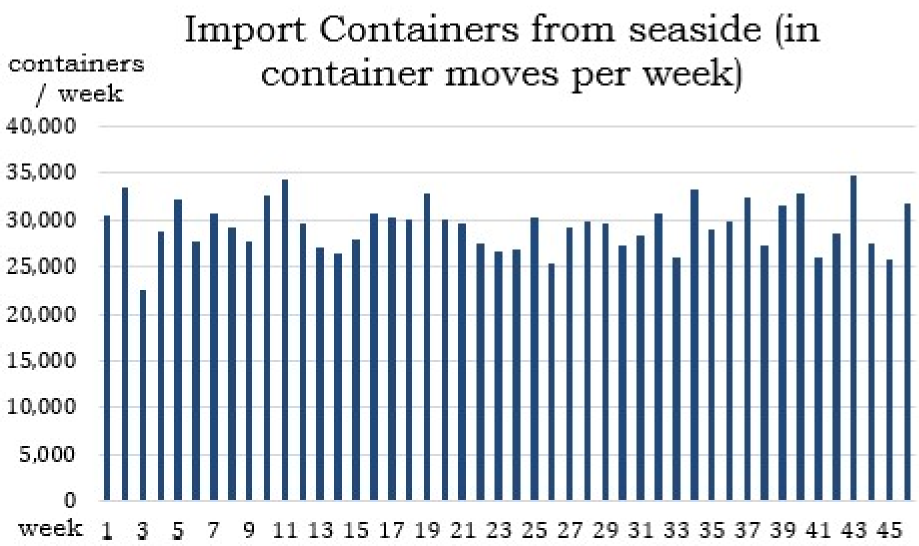


Figure 4.6: Arrival of import containers MPET per week 2018

However, the majority of these containers are transshipment containers, and thus will never arrive at the import yard area that represents the scope of this research. The number of full containers retrieved by each of the modes is also known per week over the same period. It is assumed that the number of container departures equals the number of container arrivals at the modelled row over the long run. This can be assumed since it is known that the amount of TEU in the yard is not decreasing nor increasing on average over a longer time. Moreover it is assumed that each container that is delivered to the yard will be picked up eventually. The model represents one import container row of a block of 41 rows with each row consisting of 14 TEU ground slots. Based on the total number of retrieved full import containers (IC) and a TEU factor (TEUf) of 1.612 resulting from a weighted average of the TEU factors per mode, the average dwell time (DT) for import containers of 4.78 days, the number of days in 46 weeks (d), the maximum stacking height (SH) of 3 containers and a yard efficiency of 1/1.15 (Yeff), the average total number of TEU ground slots (TGS) can be calculated with the following equation:

$$TGS = \frac{IC * TEUf * DT}{d * SH * Yeff} \tag{4.1}$$

This results in an average value of 4770 TEU per day. As mentioned already in the chapters above, stochasticity plays a large role in container terminal operations. Hence, this number is not a fixed number, but represents an average value to scale the container volumes of the entire terminal to the single-row model in this study.

The relative size of the yard block (574 TEU) compared to the TGS per day, results in a volume percentage of 12 of the total container volume that goes through the block. Based on this percentage and the fact that the model works with container arrivals per hour, the weekly amount of arriving TEUs is divided equally over the hours in a week and proportionally to the size of the block. In the model this arrival rate is divided by 41 to represent arrivals for 1 row.

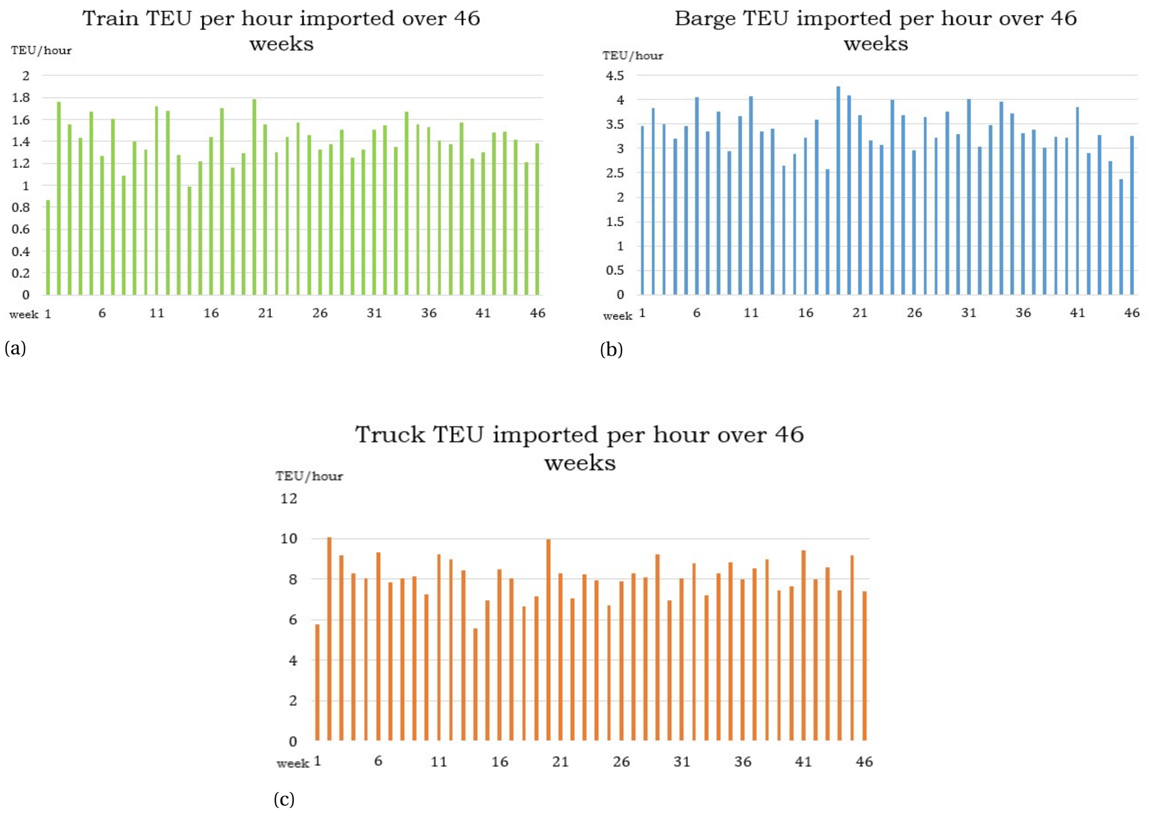


Figure 4.7: Arrivals per hour of import TEUs week 1-46 MPET

4.8.2. Arrivals

The arrival rate for incoming containers from the seaside to the yard is calculated respective to the total amount of import container ground slots, as discussed above. The hinterland transport mode arrival rates are calculated based on data from MPET. The amount of containers loaded onto each of the transport modes (barge, truck and train) per week are provided over a period of 46 weeks in 2018. These numbers are transformed into TEU with the TEU-factor per mode (also provided by MPET). Hence, the departure rates in TEU per week are specified per mode.

Based on data of container retrievals per mode over a period of 46 weeks in 2018, a table of average IAT in hours per week is constructed. The model selects a random row of this table to define the IAT it will implement each time a container is generated. Hence, the IAT for containers can differ per container generation. On average it will results in an arrival rate of 52.29 containers per week in the modelled row. A container arrival triggers hinterland transport mode creation. When a hinterland transport mode is created, it will arrive at the yard after the determined container dwell time. This latter value follows from a triangular distribution with minimum, mean and maximum values of respectively 1, 4.78 and 8 days. When the arrival day of the hinterland transport mode is selected, a specific hour and minute will be selected based on random uniform distributions as described in Table D.3.

The amount of trucks is also based on the container volume per week from MPET data. As mentioned, 12% of the TEU volume is expected to go through the considered block on average. A truck is assumed to retrieve 1 container from a specific row which is allocated to the truck upon arrival at the terminal gate. The trucks arrive from 6:00 AM on Monday morning until 6:00 AM on Saturday morning. MPET provided a rate table on the amount of truck arrivals over a week for week 2 of 2019 in intervals of 1 hour. Out of this data, the average TEU requests for the considered block spread over 1 week in intervals of 1 hour are calculated (see Figure 4.8). In determining the arrival time of trucks after a truck container generation, the truck arrival distribution is taken into account as described in Table D.3. There can be a small mismatch in data since the retrievals are based on 46 weeks of 2018 and the truck arrival distribution is based on information of 1 week in 2019. However, the average truck distribution is assumed to stay relatively constant over the weeks. Hence, this mismatch is not expected to affect the results to a large extent.

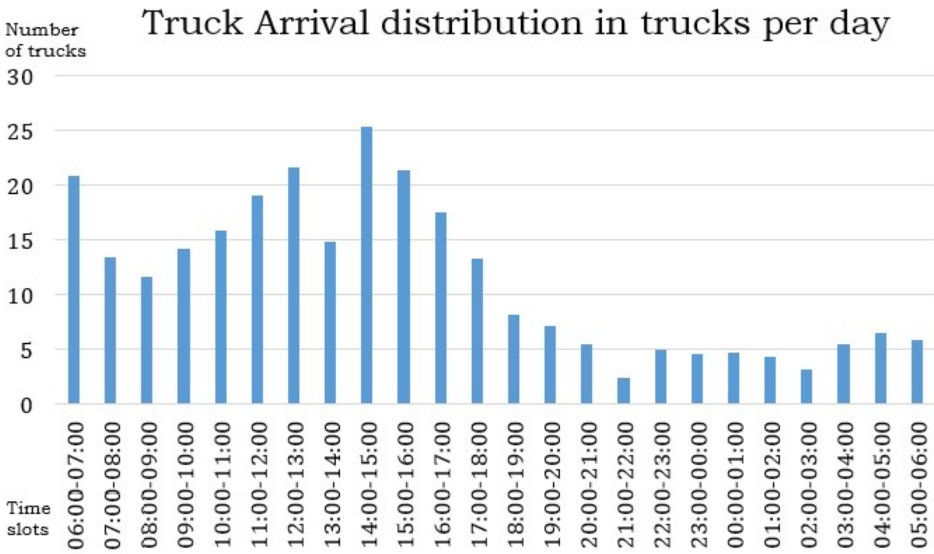


Figure 4.8: Average truck arrival distribution Monday-Friday

4.8.3. Travel times

The SC from MPET has an average operating speed of 15 km/h.[4] Upon arrival of a container to the row, the model determines in which bay to store the container. Since the first bay from the quayside (bay 1) takes less SC travel time than the last bay (bay 14) (which is the first one from the landside), a different travel time is assigned to the model dependent on the bay in which the container is stored. The assumption is made that a SC needs 40 seconds to store a container and 2 seconds travel time per bay from the quayside. The travel time per bay is based on the length of 1 TEU and the average operating speed with the following equation:

$$Bay\ travel\ time = \frac{6,09m}{15[km/h]/3.6} \tag{4.2}$$

Based on these numbers it will take the model 52 seconds when a SC is for example directed to bay number 6. Again, due to stochasticity these values can differ and should not be interpreted as fixed values. The goal of the equation however is to determine an average SC travel time that can be compared in different experiments.

At the moment a reshuffle is performed, the model also takes into account SC travel times. In the reshuffle process, the bay to which the container is relocated to is tracked with the variable 'ChangeBay' relative to the current position of the container. Once a bay is found with space available for the container to be reshuffled, the container is assigned with a variable 'BaysToMove'. In the relocation process of the container the container pickup time (40 seconds), the travel time of the SC with the container to be reshuffles (2 * BaysToMove) and the container storage time (40 seconds) is implemented. A similar delay occurs when a container is transferred from the buffer to another bay in the row, although here the BaysToMove is set on an average of 7 bays, representing a buffer with an average travel time to an available location. Lastly, when a container is picked up for a transport request, the travel time of the SC is also be taken into account.

4.8.4. Stochasticity

Since actual data on stochasticity was not available from MPET, firstly an exploratory research to stochasticity in barge arrivals of another terminal (APMT-II) was done, as described in Section 4.3. Data of 542 barges is gathered over a period of 28 days. The deviations in arrival time (difference between ETA and ATA) of the barges are represented in figure 4.9.

[4]refers to footnote 1

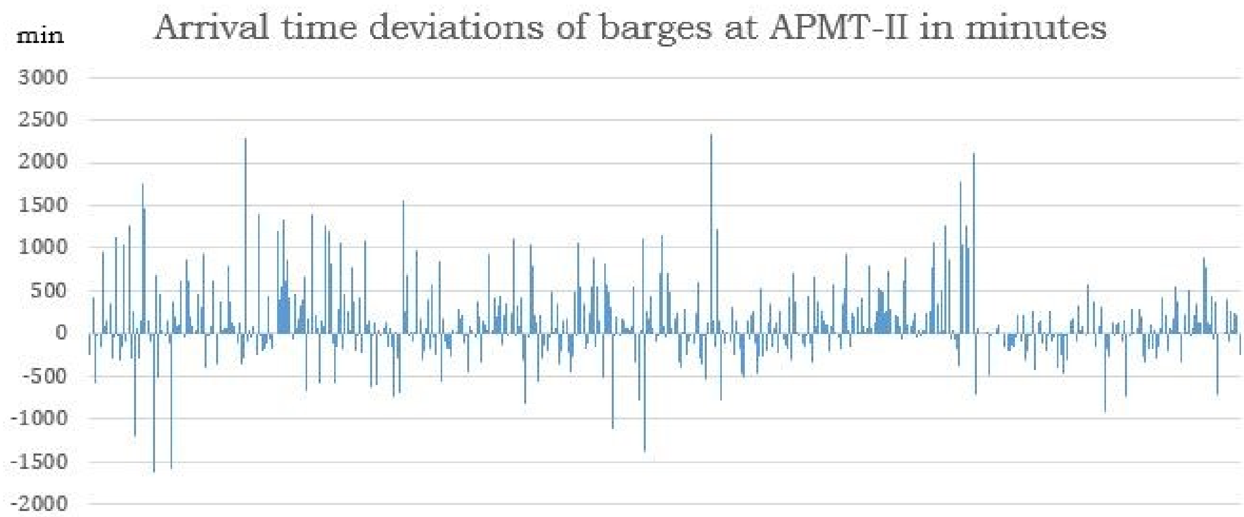


Figure 4.9: Deviations of barge arrival times APMT-II

Since this data only relates to barge arrivals, it will not directly be implemented in the model. Hence, another way to implement stochasticity in the model is chosen. Once containers arrive in the model they are attributed with an ETD based on a triangular distribution with a minimum of 1, an average of 4.78 and a maximum of 8 days. This distribution is based on the distribution of the dwell time of import containers in the yard.[5] In the container selection process when hinterland transport modes arrive, the model will search for a container with the lowest assigned ETD. In case of full certainty, the picked up container will always be the one with the lowest ETD, since the sequence of container retrievals is fully known in that case. However, when stochasticity is simulated, multiple containers with the lowest ETD values will be placed in a sub-list upon arrival of the hinterland transport mode. The hinterland transport will then randomly select a container out of this sub-list to pick-up. The more containers are in the sub-list, the higher the level of stochasticity is. In the base case experiment, which will be discussed in Section 5.2, the number of containers in the sub-list will be 1. Moreover, the effect of stochasticity in the next mode of transport on stacking performance can not be measured in this model, since the next mode of transport is not taken into account in the stacking strategy. In current operations in the model containers that are retrieved by each of the three hinterland transport modes are all placed in the same yard area. It is a recommendation for further research to also model the effects of stochasticity in next mode of transport, as will be further discussed in Section 6.3.

4.9. Verification and Validation

This section will assess whether the conceptual model is implemented in a correct way in the simulation model and whether the simulation model renders expected results.

4.9.1. Verification

Verification is aimed at the question whether the conceptual models are implemented correctly in the simulation model, and thus whether the simulation model runs as expected. During model development the model has been verified in an iterative way.

In an early stage, for example, only a single hinterland transport mode was simulated and containers would arrive with fixed time intervals. Upon arrival of the hinterland transport mode, the model should select a container randomly from the yard, retrieve it and batch it together with the mode that requested the container. Model runs have proven for the model to work as expected in terms of retrieving containers. In a later stage, reshuffles have been implemented. The model selects a specific container and relocates containers on top of the requested containers to other bays if necessary. Again, model runs show the model to perform reshuffles in a way as specified in the conceptual model. Another example of an iteration that has been verified is the temporarily 4-high stacking of containers when the yard is relatively full. The model indeed only stacks 4 high when there is no other available slot in the yard. After the leaving of the SC out of

[5] refers to footnote 1

the row, another SC is seized to replace the 4-high stacked container to its original bay and thereby prevent row blocking by this 4-high container.

Furthermore, verification is done visually by animation, by tracing of specific entities in the model, as well as with extreme conditions testing. These tests are described in Appendix E. Lastly, in all the verification runs, the amount of containers that are generated are eventually picked up, or are still in the yard row when the model run ends. On the other hand, hinterland transport modes that have been generated have either exited the model with a retrieved container or are still in the queue to collect containers at the end of a model run. This means that no containers nor hinterland transport modes disappear from the model without a retrieval request that combines them. Based on the results of the verification, it can be concluded that model behaviour is in line with the conceptual specifications.

4.9.2. Validation

Validation is aimed at determining whether the simulation model generates results that are correct in terms of the right accuracy. That will be checked based on historical data on container retrievals and container dwell time.

The arrival rate of containers and modal split as described leads to an average expected number of created entities for the model. This expected values over a test run of 50 weeks are presented in Table 4.1.

On average, the row volume is in sufficient balance over the complete test run, because 2 611 TEU arrives from the seaside and 2 572 TEU will be retrieved from the landside. At the end of the test run, not all containers have been retrieved yet, since there all still 39 containers in the yard waiting to be retrieved.

The test run of 50 weeks produces entities in number and TEU as presented in Table 4.1. The deviations show that the model causes a slight underestimation of the amount of retrievals of barges and trucks and a slight overestimation of the amount of train retrievals. This can be explained by variation in the arrivals of hinterland transport modes due to the distribution in container arrivals and the dwell time distribution. Moreover, the model starts with an empty row, which is likely to affect the results slightly as well. Still, the deviations are considered small enough to conclude that the model generates container arrivals and departures per mode as expected.

Table 4.1: Expected values compared to generated values of created entities for model test run of 50 weeks

Entity	Expected values in TEU	Test run values in TEU	Deviation
Containers	2 614	2 611	-0.13%
Trains	290	292	+0.79%
Barges	666	659	-1.10%
Trucks	1 654	1 621	-2.02%

The average dwell time based on the model test run is 109.9 hours (4.58 days). The expected dwell time is 4.78 days, so there is a deviation of -4.18%. In reality the dwell time has a minimum of 1 day and a maximum of 7 days for 90% of the containers (a small percentage remains in the yard for longer than 7 days). The small percentage of containers that remain in the yard for longer than 7 days is not taken into account in this model, hence it follows expectations that the dwell time is slightly underestimated.

Lastly, the model logic has also been validated in discussions with experts in the field of container terminals. Based on these discussions and the model results described above, it can be concluded that for the goal of this research the model is considered to produce sufficiently accurate results. In the next chapter the experiments performed with this model are described.

4.10. Conclusion

This chapter has elaborated further on the answer given in Chapter 3 on sub-question 3: *How to model the relation between stochasticity in import container information and the performance of stacking operations?* As can be concluded from this chapter, the relation between stochasticity and performance will be modelled with a Simio simulation model that represents stacking operations of one container yard row. Firstly, a broad model description has been provided that can also be used for further research. Next, a detailed description has been given on the way the model was specified for this research. Lastly, tests have been performed to determine the usefulness and accuracy of the model. Based on the validity tests, it is concluded that the model produces sufficiently accurate results to perform the experiments described in Chapter 5. In these experiments, different scenarios will be compared based on the amount of reshuffles, SC utilisation and the truck service times.

5 Experimentation

This chapter will answer sub-question 4: *What is the effect of stochasticity in the parameters on the performance indicators?* As concluded from chapter 3, stochastic parameters as well as KPIs have been identified. Chapter 4 described the design and implementation of a model to accurately investigate the relation between these two. In this chapter the experimental setup as well as results from the model will be presented.

5.1. Experimental Setup

Before experiments are performed, several model settings need to be determined for the model runs. These settings are: warm-up period, run length and the number of replications that will be performed in the experiments. In the experiments the model settings as described in Table 5.1 are used. The motivation for these values is given in appendix F.

Table 5.1: Model settings for experiments

Model parameter	**Settings**
Warm-up period	28 days
Run length	50 weeks
Number of replications	50

To describe the experimental setup, firstly the base case experiment will be described. This base case experiment represents current practice at MPET in case of full certainty, i.e. no stochasticity. This will be described in Section 5.2. In the second experiment, housekeeping moves will be introduced in terminal operations. This experiment is described in Section 5.3. In the remaining even numbered experiments (4, 6, 8, 10, 12 and 14) the level of stochasticity will be increased to determine the effect of stochasticity on the performance indicators while housekeeping moves are implemented. These experiments are referred to as Stoch_X, where X represents the stochasticity scenario. The remaining uneven numbered experiments (3, 5, 7, 9, 11 and 13) represent control experiments for the same level of stochasticity without housekeeping moves. These experiments are referred to as Stoch_X_Control, where X represents the stochasticity scenario. A summary of the experimental setup is provided in Table 5.2.

Table 5.2: Experimental setup with 2 configurations (No HK moves and HK moves) and 7 scenarios, resulting in 14 experiments referred to Stoch_X for the HK configuration and Stoch_X_Control for the Non-HK configuration, where X represents the stochasticity scenario

Configuration	**Scenarios: level of stochasticity**						
	1	**5**	**10**	**15**	**20**	**25**	**30**
No housekeeping moves	Base case (1)	3	5	7	9	11	13
Housekeeping moves	Housekeeping (2)	4	6	8	10	12	14

5.2. Base Case Experiment

In the base case experiment, no housekeeping moves are performed, therefore the *Housekeeping_CapacityType* control is set to *Fixed*. Since housekeeping operations are triggered when the housekeeping SC in the model turns on shift, no housekeeping moves will take place when the housekeeping SC capacity type is set to fixed (which represents constant capacity instead of capacity according to a work schedule). As described in Section 4.3, improving stacking operations at the import yard is currently not a main focus. Stacking operations are currently performed in a levelling way to maintain yard capacity and preference is given to available slots nearby to be able to free SC capacity as soon as possible. The amount of stochasticity is represented by the variable *StochLevel*, which is equal to 1 in the base case experiment. That means that the exact order of container retrievals is known, although this information is not used in the stacking strategy in the base case.

5.3. Housekeeping

The goal of the experiments is to estimate the effect of stochasticity on the performance of stacking operations. In order to do so, housekeeping moves are implemented to represent the use of information in stacking operations. The housekeeping moves are performed by a separate resource in the model (Housekeeping) which operates in a shift from 10:00 PM until 5:30 AM. The *Housekeeping_Capacitytype* control is now set to *WorkSchedule* to implement housekeeping moves in the model. When there is no other SC in the row at the moment the housekeeping SC becomes on shift (i.e. no container arriving from the seaside and no container being retrieved by a request from the landside), it will consecutively check each bay, starting with bay 14 which is the bay the closest to the landside. After reshuffling one bay into the sequence of the container ETDs, the model will check again whether no other SC is waiting to deliver or retrieve a container. In case there is not, the housekeeping SC continues to the next bay. In case there is, the housekeeping SC will wait for the other SC to perform its activities, after which the first one will continue with housekeeping moves in the next bay. The housekeeping logic is presented in Figure D.1.

When housekeeping moves are implemented, the influence of different levels of stochasticity on the stacking performance can be tested . In the second experiment in which housekeeping moves are implemented for the first time, the level of stochasticity is equal to the base case experiment (*StochLevel* = 1). In the fourth experiment, the level of stochasticity is increased to 5. In the 6th, 8th, 10th, 12th and 14th experiment, the level of stochasticity is increased to 10, 15, 20, 25 and 30 respectively.

It is expected that housekeeping moves will increase stacking performance, i.e. lead to a lower number of reshuffles per retrieval, a shorter truck service time and a lower maximum SC utilisation per hour. When stochasticity increases, the effect of housekeeping moves is expected to become less, since the terminal is less capable of preparing itself for future retrievals, because the order of retrievals is less certain.

The experiments are run on a Dell Computer with an Intel® Core™ i5-6500 CPU 3.20 GHz processor. The run time for all 14 experiments simultaneously is 922.7 seconds.

5.4. Results

The results described in this section show a comparison between the 14 experiments (base case experiment, Housekeeping experiment, experiments of different levels of stochasticity and their control experiments). The output of the simulation model with respect to the number of reshuffles per retrieval (RPR), the number of housekeeping shifts (HK shifts), the average housekeeping shift duration (HSD), the truck service time (TST) and the maximum SC utilisation per hour (Max SC U) and the total SC working hours (SC WH) of both SCs (the non-housekeeping and the housekeeping SC) for different experiments is presented in Table 5.3.

The output of the simulation model is analysed with SPSS Statistics software. Next, an independent samples t-test is performed to test whether differences in means between 2 experiments are statistically significant based on a 95% confidence level. To determine which results to use from the t-test, a Levene's test for equal variances is performed first. The null-hypothesis in the Levene's test is that the variances of both groups (experiments) are equal. When the significance level of the Levene's test is less than 0.05, the null-hypothesis can be rejected and one can conclude that based on a 95% confidence level the variances of the two experiments are not equal. Dependent on the outcomes of the Levene's test one should look at different results from the t-test, which is indicated in the SPSS analysis. When comparing KPIs per experiment, the null-hypothesis is that both means are the same. Once the significance level is less than 0.05, the null-hypothesis can be rejected with a 95% confidence level.

Next, the results per experiment are shown in the forms of box plots, where one can easily see the spread of the data distribution around the median. An illustration on the information presented in a box plot is given in Figure 5.1.

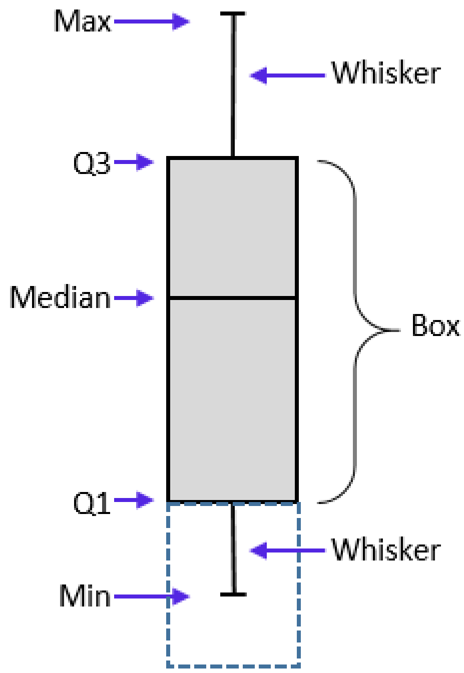


Figure 5.1: Box plot description (bioST@TS, 2019)

Table 5.3: Results per experiment on reshuffles per retrieval (RPR), number of housekeeping shifts (HK shifts), average housekeeping shift duration (HSD), truck service time (TST), maximum SC utilisation per hour (Max SC U), and total SC working hours (SC WH)

Experiment	**RPR**	**HK shifts**	**HSD (h)**	**TST (min)**	**Max SC U**	**SC WH (h)**
Base case (1)	0.95 ± 0.02	0	0	3.32 ± 0.03	0.36 ± 0.05	132.5 ± 2.0
HK (2)	0.27 ± 0.01	322 ± 2	0.66 ± 0.01	2.42 ± 0.03	0.22 ± 0.04	303.5 ± 3.9
Stoch_5_c (3)	0.95 ± 0.02	0	0	3.32 ± 0.03	0.33 ± 0.05	132.0 ± 1.7
Stoch_5 (4)	0.35 ± 0.01	323 ± 2	0.65 ± 0.01	2.52 ± 0.03	0.23 ± 0.05	305.1 ± 3.7
Stoch_10_c (5)	0.95 ± 0.02	0	0	3.32 ± 0.03	0.35 ± 0.06	132.3 ± 2.3
Stoch_10 (6)	0.46 ± 0.01	322 ± 2	0.62 ± 0.01	2.69 ± 0.03	0.26 ± 0.06	300.4 ± 4.4
Stoch_15_c (7)	0.94 ± 0.02	0	0	3.30 ± 0.03	0.35 ± 0.06	131.4 ± 2.1
Stoch_15 (8)	0.57 ± 0.02	322 ± 3	0.59 ± 0.01	2.84 ± 0.04	0.26 ± 0.04	295.9 ± 4.2
Stoch_20_c (9)	0.94 ± 0.02	0	0	3.30 ± 0.04	0.34 ± 0.06	131.0 ± 2.1
Stoch_20 (10)	0.66 ± 0.02	322 ± 3	0.56 ± 0.01	2.98 ± 0.04	0.28 ± 0.05	293.0 ± 3.5
Stoch_25_c (11)	0.92 ± 0.02	0	0	3.27 ± 0.03	0.33 ± 0.06	129.7 ± 2.0
Stoch_25 (12)	0.75 ± 0.02	321 ± 3	0.54 ± 0.01	3.12 ± 0.04	0.29 ± 0.04	291.2 ± 4.1
Stoch_30_c (13)	0.91 ± 0.02	0	0	3.25 ± 0.03	0.35 ± 0.08	129.0 ± 1.8
Stoch_30 (14)	0.78 ± 0.02	322 ± 3	0.54 ± 0.01	3.16 ± 0.04	0.30 ± 0.04	294.4 ± 4.5

When comparing the base case experiment with the Housekeeping experiment while the level of stochasticity (StochLevel) is kept the same, it is expected that the number of reshuffles per retrieval, the truck service time and the maximum SC utilisation per hour is higher in the base case experiment. The number of housekeeping shifts is equal to 0 in the base case experiment, and is expected to be close to the amount of simulated days (350) in the Housekeeping experiment. This amount of housekeeping moves is expected because the row is relatively full and new containers will arrive each day, hence the row is no longer in the right order of expected retrievals and housekeeping moves are requested almost every night.

Table 5.4: Base case (1) compared to Housekeeping experiment (2)

KPI	**F-value**	**Sig.**	**t-value**	**Sig.**	**Difference**
Reshuffles per retrieval	10.231	0.002	220.801	0.000	-71.4%
Nr of HK shifts	106.589	0.000	-1066.680	0.000	-
Truck service time (min)	0.000	0.985	154.881	0.000	-27.2%
Max SC utilisation per hour	0.434	0.512	14.204	0.000	-37.9%
Total SC working hours	17.571	0.000	-273.924	0.000	129.1%

The results of Table 5.4 show that the number of reshuffles per retrieval and the number of housekeeping shifts are significantly different in the two experiments. Since a lower amount of reshuffles per retrieval is expected in the Housekeeping experiment and a higher number of housekeeping shifts is expected in the Housekeeping experiment, these tests should be 1-sided in stead of 2-sided. In that case the significance level should be less than 0.025 to reject the null-hypothesis, which is true according to Table 5.4. The results of the Levene's test in Table 5.4 point out that the null hypothesis of equal variances can be rejected on a 95% confidence level for the number of reshuffles per retrieval and the number of housekeeping shifts. This means that a different row in the output table of SPSS should be consulted to determine whether the differences in KPI means are statistically significant. For the mean truck service time and maximum SC utilisation per hour the null-hypothesis of equal variances cannot be rejected. The means of these variables are significantly lower in the Housekeeping experiment. The results indicate that an implementation of housekeeping moves leads to a lower amount of reshuffles per retrieval (-71.4%), truck service time (-27.2%) and maximum SC utilisation per hour (-37.9%). The reshuffles per retrieval decrease from 0.95 to 0.27 (-0.68) in the housekeeping experiment. Based on the entire import volume of the terminal[1], this implies a saving of 639 764 reshuffles per

[1] 18 044 TEU per week

year[2]. The truck service time decreases from 3.32 to 2.42 minutes (-0.9 min). Based on the total truck import volume of the terminal[3], this implies a saving of 8 854 hours per year[4]. The maximum SC utilisation per hour decreases from 0.36 to 0.22 (-0.14). This means that 8 minutes per SC is freed in a peak hour to spend on other tasks. In order to achieve these benefits, housekeeping moves are performed during non-peak hours. In the Housekeeping experiment, an average of 322 shifts is performed over the simulation runs of 50 weeks (350 days). The shifts on average have a duration of 0.66 hours (39.8 minutes), with a mean minimum and mean maximum value of respectively 0.15 hours (8.82 minutes) and 1.17 hours (70.3 minutes). This means that on average a housekeeping SC is able to serve 11 rows[5] in its 7.5 hour shift. Based on the relatively low housekeeping SC utilisation per night in Figure E.6, a housekeeping SC is not expected to be needed to operate in the same row every day. Assuming it is sufficient to perform housekeeping moves once every 3 days, approximately 10 housekeeping SCs shifts[6] per night are required to obtain the results as presented above for the entire import yard. Due to the housekeeping moves, the system can be more efficient during peak hours. However, additional investments in work force might be necessary to free one or multiple SCs and employees for housekeeping moves during non-peak hours. This can be seen in the increase of total SC working hours, which represent the hours both regular SCs and the housekeeping SC are busy during the entire simulation run of 50 weeks. In the housekeeping scenario, the total SC working hours have increased from 132.5 hours to 303.5 hours on average (171.0 hours) over the entire simulation run of 50 weeks, i.e. 129.1%. This implies an increase in total SC working hours of 60 714 hours[7] for the entire import yard per year.

For the experiments with higher level of stochasticity, the results on the KPIs have been compared with those of their control experiments (without housekeeping moves). The results are presented in appendix G in Tables G.1, G.2, G.3, G.4, G.5 and G.6.

[2] savings number of reshuffles per year = difference in parameter value of reshuffles per retrieval * total TEU volume per week * number of weeks = 0.68.. * 18 044.. * 52

[3] 1 1295 TEU per week

[4] savings truck service time per year in hours = difference in parameter value of truck service time * total TEU truck volume per week * amount of weeks / 60 minutes = 0.9.. * 11 295.. * 52 / 60

[5] number of rows a housekeeping SC can service per shift = total shift duration / average housekeeping shift duration = 7.5 / 0.66..

[6] numbr of housekeeping SC shifts needed for improvements = total rows in import block / volume percentage of import block with respect to total import yard / number of rows that can be served per shift / 3 days = 41 rows / 0.12 / 11.. / 3

[7] effect on total SC working hours per year = difference in parameter value of total SC working hours * number of rows in yard block / volume percentage of modelled block compared to entire terminal * (52 weeks / 50 weeks simulation time) = 171.0.. * 41 / 0.12.. *(52/50)

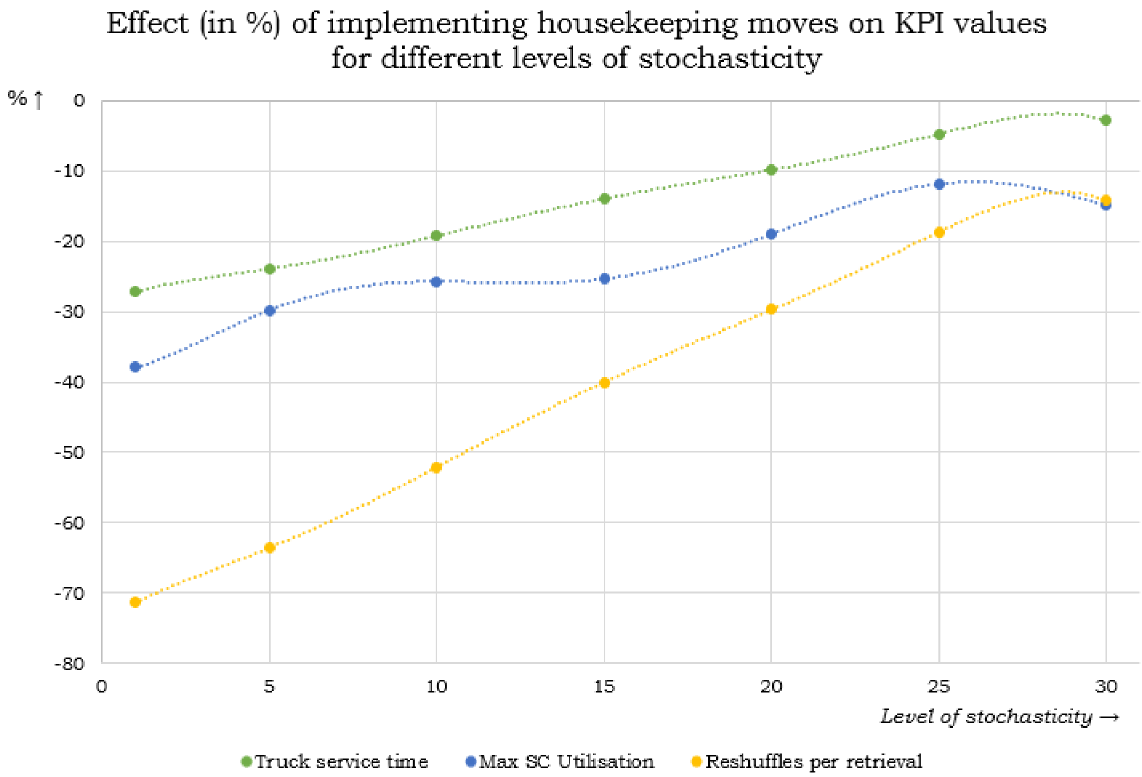


Figure 5.2: Effects (in %) of implementing housekeeping moves on KPIs (Truck service time, Max SC Utilisation and Reshuffles per retrieval) for different levels of stochasticity

As the results show, in each of the experiments the implementation of housekeeping moves leads to a significant decrease in reshuffles per retrieval, truck service time and maximum SC utilisation per hour, in exchange for housekeeping shifts. This indicates that even when the level of stochasticity increases, stacking operations can be improved by implementing housekeeping moves. However, the improvement on the performance indicators declines when the level of stochasticity increases, as can be seen in Figure 5.2.

Due to the way how stochasticity is modelled in this study, when the level of stochasticity reaches 35 reliable results can no longer be achieved. This is because the model selects 34 containers additionally to the container with the lowest ETD for the StochasticConts sub-list, when the level of stochasticity is 35, as explained in Appendix D. In case there are no 34 additional containers to select from the row, the model skips this step of adding stochasticity and selects the single container with the lowest ETD, i.e. equal operations as when StochLevel = 1. Since the average number of containers in the row is 34 for all experiments, it will often happen that the model skips this step when the level of stochasticity is set to 35. The mean minimum amount of containers in the row is 33 for all experiments and the mean maximum is 35. Hence, on average the results for lower levels of stochasticity will not be affected by the way stochasticity is modelled. However, there might be some cases in which the model also skips the step of adding stochasticity for lower levels of stochasticity, which could be an explanation for the flattening lines in Figure 5.2 for truck service time and reshuffles per retrieval when the level of stochasticity is 30. A future model could, for example, improve the way stochasticity is modelled by making it equal to the current amount of containers in the row (i.e. maximum level of stochasticity), when there are not enough containers in the row to select for the sub-list with respect to the stochasticity level.

One can see in Figure 5.2 that both the improvements in truck service time and number of reshuffles per retrieval seem to flatten out when the level of stochasticity increases. The improvement in reshuffles per retrieval reaches a value of -14.2% in the scenario with the highest level of stochasticity (StochLevel = 30). This is a difference between 0.91 and 0.78 (0.13) reshuffles per retrieval. Taking the entire import yard volume into account[8], implementing housekeeping moves could spare 120 656 reshuffles per year[9] on average based

[8]refers to footnote 1
[9]0.13.. * 18 044.. * 52

on the experiment with the highest level of stochasticity. The improvement in truck service time reaches a value of -2.8% in the scenario with the highest level of stochasticity (StochLevel = 30). This is a difference between 3.25 and 3.16 (0.09) minutes per truck. Based on the average number of trucks per week for the total import yard[10], implementing housekeeping moves could spare 883 hours[11] per year on average in the experiment with the highest stochasticity level. The maximum SC utilisation per hour shows more fluctuations when the level of stochasticity increases. Still, at a stochasticity level of 30, an improvement of -14.8% can be found. This is a difference between a utilisation rate per hour of 0.35 and 0.30. Hence, by implementing housekeeping moves the maximum SC utilisation per hour can decrease by 5 percent points on average in the experiment with the highest stochasticity level. This means that 5% of the peak hour (3 minutes) is freed for other activities. To obtain these benefits the housekeeping SC operates for 0.54 hours (32 minutes) per shift on average, with a mean minimum value of 0.09 hours (5 minutes) and a mean maximum value of 1.1 hours (67 minutes). This means that on average a housekeeping SC is able to serve almost 14 rows[12] in a 7.5 hour shift. Moreover, as assumed above, it could already be sufficient to have housekeeping moves performed once every 3 days in a row. In that case, approximately 8 SC housekeeping SC shifts[13] are needed each night to serve the entire import yard. The total SC working hours will increase by 128.2% on average from 129.0 hours to 294.4 hours over the simulation run of 50 weeks. This implies an increase in total SC working hours of 58 735 hours per year[14] for the entire import yard.

A terminal should decide whether the additional investment for housekeeping SC shifts is worth the improvement in terms of reshuffles per retrieval, truck service time and maximum SC utilisation per hour during peak hours.

When comparing 2 housekeeping experiments with different levels of stochasticity (experiment 2 and 4), the mean values of the amount of reshuffles per retrieval, the truck service time and the maximum SC utilisation per hour seem lower in the experiment with less stochasticity. That follows expectations, since stochasticity will deteriorate the effectiveness of housekeeping moves. Housekeeping moves will reorganise the yard based on expected retrieval order of the containers. Because of stochasticity this retrieval order deviates from the order that was expected, hence the reorganised stack does not match the retrieval order perfectly, leading to additional SC moves and truck service time. As shown in Table 5.5, the number of reshuffles per retrieval and the truck service time are significantly higher with respectively 26.6% and 4.3% in the Stoch_5 experiment (experiment 4) compared to the Housekeeping experiment (experiment 2). The difference in maximum SC utilisation per hour is not statistically significant, which can be explained by the fact that the difference in stochasticity between the two experiments is very small. The difference in number of housekeeping shifts is neither statistically significant. This matches expectations again. The number of housekeeping shifts is not expected to differ when the level of stochasticity changes, because in each of the scenarios the row is relatively full and new containers will arrive each day, hence influencing the bay sequences and requiring housekeeping shifts. In contrast, the difference in average duration of housekeeping shifts is statistically significant. In the Stoch_5 experiment this is 1.4% lower. That can be explained by the fact that organisation of the stack based on housekeeping moves matches the expected retrieval order for a longer period in the experiment with more stochasticity, since retrievals are not always as expected. When, for example, a bay with 3 containers is reorganised with housekeeping moves, the top container is expected to be retrieved first. When the middle container is however requested first (due to stochasticity), reshuffles are required at the moment of retrieval. In case of a full yard, the top container that has been reshuffled for this retrieval will be placed back in its bay, hence the sequence of that specific bay still matches the housekeeping planning. This matches the idea that the number of housekeeping moves, hence the duration of the average housekeeping shift, will increase when more knowledge is available on container retrievals (when the level of stochasticity is lower). Lastly, the total SC working hours is slightly higher (0.5%) in the Stoch_5 experiment. This indicates that in the experiment with more stochasticity the SCs need more time for reshuffling, retrieving containers and housekeeping moves together.

Table 5.5: Housekeeping (2) compared to Stoch_5 experiment (4)

[10] refers to footnote 3
[11] 0.09.. * 1 1295.. * 52 / 60
[12] 7.5 / 0.54..
[13] 41 rows / 0.12.. / 14.. / 3
[14] 165.4.. * 41 / 0.12.. * (52/50)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.276	0.601	-29.843	0.000	26.6%
Nr of HK shifts	0.313	0.577	-1.076	0.284	0.2%
Duration housekeeping shift (h)	1.965	0.164	3.751	0.000	-1.4%
Truck service time (min)	0.350	0.555	-17.638	0.000	4.3%
Max SC utilisation	1.033	0.312	-1.358	0.178	5.7%
Total SC working hours	0.285	0.595	-2.130	0.036	0.5%

When comparing the housekeeping (2) experiment with the Stoch_20 (10) experiment, the differences in maximum SC utilisation per hour is statistically significant. This confirms the assumption that the difference in maximum SC utilisation per hour is statistically significant when the magnitude of stochasticity level difference is of sufficient size. As Table 5.6 shows, when the difference in stochasticity level is this large, the amount of reshuffles per retrieval increases with 142.6% compared to the Housekeeping experiment, while the truck service time and maximum SC utilisation per hour increase with respectively 23.2% and 25.7%. The difference in number of housekeeping shifts again is not statistically significant, while the difference in duration is. In the Stoch_20 experiment the average duration of a housekeeping shift is 15.8% lower than in the Housekeeping experiment. Lastly, the total SC working hours is lower (-3.5%) in the Stoch_20 experiment, while in the previous comparison the SC working hours increased when stochasticity increased. This indicates that in the experiment with more stochasticity the SCs need less time for reshuffling, retrieving containers and housekeeping moves together. The two contrasting findings can be explained by the fact that the maximum SC utilisation rate per hour fluctuates per experiment (as already could be seen in Figure 5.2). Hence, SC utilisation for reshuffles and retrieving containers does not necessarily increase when the level of stochasticity does and therefore the total SC working hours does not increases necessarily either.

Table 5.6: Housekeeping (2) compared to Stoch_20 experiment (10)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	2.440	0.121	-144.597	0.000	142.6%
Nr of HK shfits	1.770	0.186	1.275	0.205	-0.2%
Duration housekeeping shift (h)	3.799	0.054	43.118	0.000	-15.8%
Truck service time (min)	1.176	0.281	-83.784	0.000	23.2%
Max SC utilisation per hour	0.853	0.358	-5.811	0.000	25.7%
Total SC working hours	0.619	0.433	14.009	0.000	-3.5%

Lastly, comparison is done between the two most extreme stochasticity scenarios in the experiments, namely the Housekeeping experiment (2) and the Stoch_30 experiment (14). The results are shown in Table 5.7. Again, all differences in mean values are statistically significant except for the number of housekeeping shifts. Between the two extreme cases of stochasticity, the reshuffles per retrieval increase with 185.9%, the truck service time increases with 30.6% and the maximum SC utilisation per hour increases with 34.3%. The average housekeeping shift duration decreases with 18.8% compared to the Housekeeping experiment. Lastly, the total SC working hours again decreases in this comparison, with 3.0%.

Table 5.7: Housekeeping (2) compared to Stoch_30 experiment (14)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	13.743	0.000	-159.319	0.000	185.9%
Nr of HK shfits	0.970	0.327	1.413	0.161	-0.2%
Duration housekeeping shift (h)	0.581	0.448	48.170	0.000	-18.8%
Truck service time (min)	6.335	0.013	-109.129	0.000	30.6%
Max SC utilisation per hour	0.001	0.980	-8.870	0.000	34.3%
Total SC working hours	0.707	0.402	10.666	0.000	-3.0%

In Figures 5.3, 5.4, 5.5 and 5.6 the box plots of the results for the different experiments with housekeeping moves are shown. In some of the experiments, outliers are visible in the box plots. These outliers indicate a result from one specific replication that deviates from the results of the other replications, as already shown in Figure 5.1. In case there are no outliers, the upper and lower whiskers correspond to the minimum and maximum data point values. In case there are outliers, the whiskers indicate the minimum and maximum data points without the outliers taken into account (bioST@TS, 2019). Mild outliers on the lower side of the box plot consist of data points between the lower part of the box minus 1.5 times the area within the box (i.e. the interquartile (IQ) range) and the lower part of the box minus 3 times the IQ range. Mild outliers on the upper side of the box plot consist of data points between the upper part of the box plus 1.5 times the IQ range and the upper part of the box plot plus 3 times the IQ range. When data points are below the lower part of the box minus 3 times the IQ range or above the upper part of the box plus 3 times the IQ range they are considered as extreme outliers. Mild outliers are indicated by SPSS with open circles, while extreme outliers are indicated by stars.

As can be seen in Figure 5.3, a mild outlier is visibile in one of the replications of the Stoch_5 experiment. This outlier indicates that in data point 710 the reshuffles per retrieval is relatively low, compared to the reshuffles per retrieval in rest of the replications (0.31 compared to the mean of 0.35). This can be explained by the variation in the data and the level of stochasticity. Due to the stochastic nature of container arrivals and retrievals, it is not an unlikely scenario that in one of the replications the amount of containers that has arrived is relatively low.

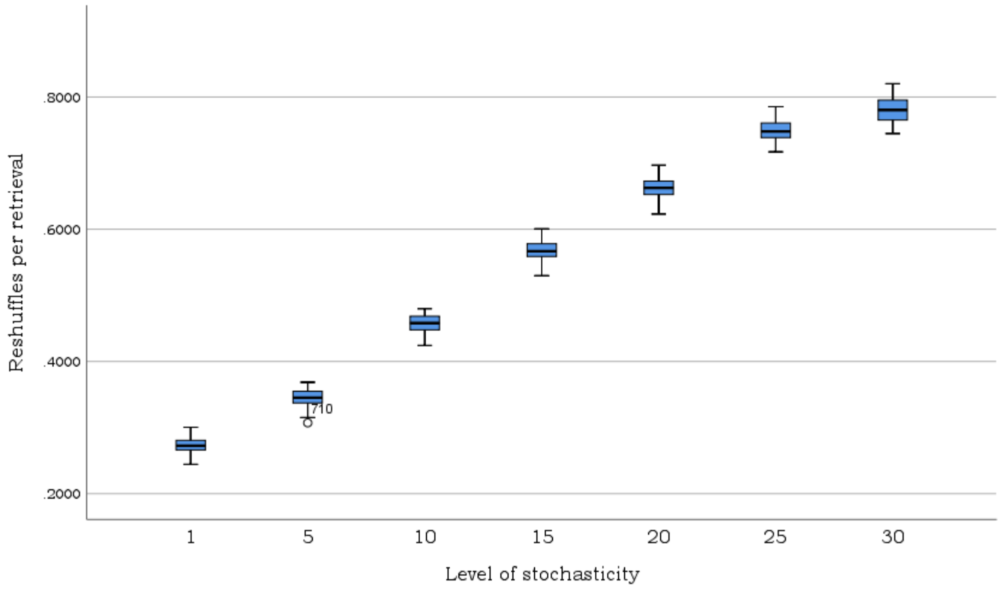


Figure 5.3: Box plot of reshuffles per retrieval for the experiments with housekeeping moves

In Figure 5.4 more outliers are visible in the variable average housekeeping shift duration. Experiments Stoch_5, Stoch_10 and Stoch_15 show 3 mild outliers. In addition to that, experiment Stoch_15 also shows one extreme outlier. Based on this figure, it can be concluded that the average housekeeping duration shows more variation than the reshuffles per retrieval from Figure 5.3. When focusing on the outlier data points, one can see that in the replication of data point 748 (causing the mild outlier in the Stoch_5 scenario) the average duration of a housekeeping shift is relatively high (0.69 hours compared to the mean of 0.65 hours). The amount of housekeeping moves in this replication is also relatively high (10 424 compared to the mean of 9 968), which can explain the higher average housekeeping shift duration. Also in this case the outliers do not represent an unlikely scenario when looking at the nature of the system. Due to the variation in the data and the level of stochasticity it can occur that a yard is organised worse compared to other replications, hence requiring more housekeeping moves. Especially when stochasticity in the retrieval order starts increasing, the chance of a better or worse organised stack increases, so even more outliers can be expected. A better organised stack is visible in the outlier in experiment Stoch_10. In the replication results of data point 125, a relatively low housekeeping shift duration is found (0.59 hours compared to the mean of 0.62 hours). In experiment Stoch_15 a mild outlier is found for data point 224 and an extreme outlier for data point 242. Data point 224 shows a relatively high housekeeping shift duration (0.61 hours compared to the mean of 0.59 hours). Data point 242 shows a relatively low housekeeping shift duration (0.54 hours compared to the mean of 0.59 hours). Likewise, these outliers are assigned to the variation in the nature of the system.

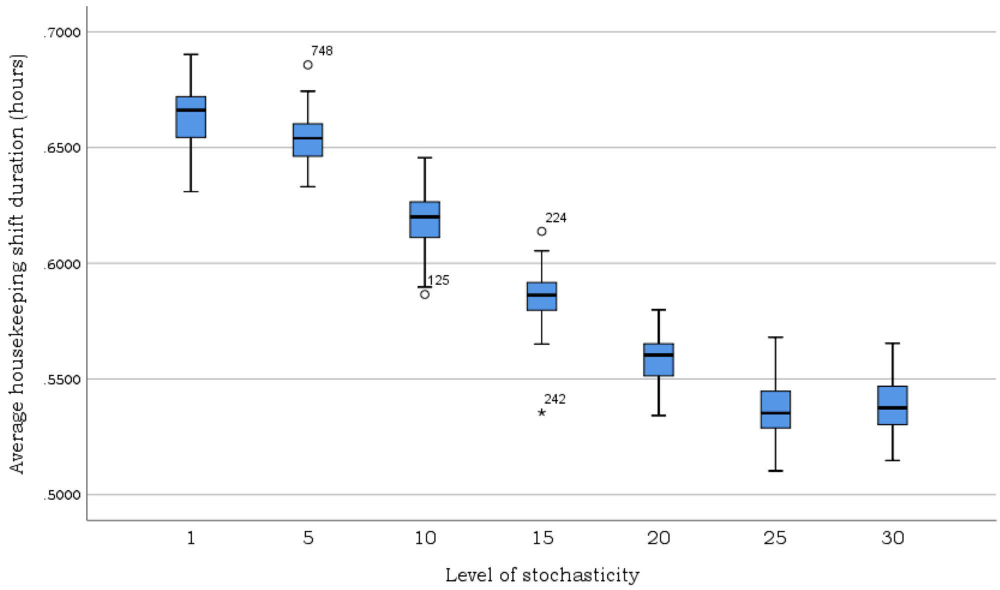


Figure 5.4: Box plot of the average housekeeping shift duration for the experiments with housekeeping moves

When looking at the data distribution on truck service time in Figure 5.5, all the outliers are found in experiment Stoch_20. The outliers seen are all mild outliers. Similar as above, the outliers in truck service time can be assigned to the variation in container arrivals and stochasticity in the system.

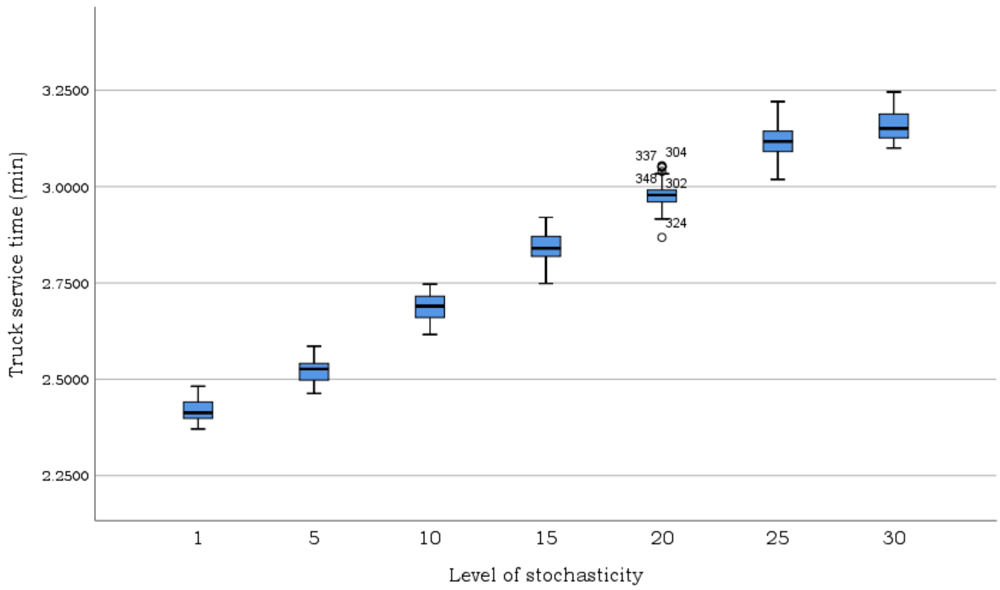


Figure 5.5: Box plot of truck service times for the experiments with housekeeping moves

In Figure 5.6 the data distribution on maximum SC utilisation per hour is presented. The variation in this KPI is relatively large, compared to the variables in the previous box plots. This indicates that the maximum SC utilisation per hour is relatively sensitive to the stochastic nature of the system. As seen earlier in Tables 5.5 and 5.6, the difference in maximum SC utilisation per hour only shows statistically significant differences when the difference in stochasticity level is large enough. The outliers seem to slightly overestimate the mean value for maximum SC utilisation per hour, since they are all at the upper side of the box plot. However, since this study checks whether differences found are statistically significant based on a 95% confidence level, the effect of the outliers on the final conclusions is expected to be negligible.

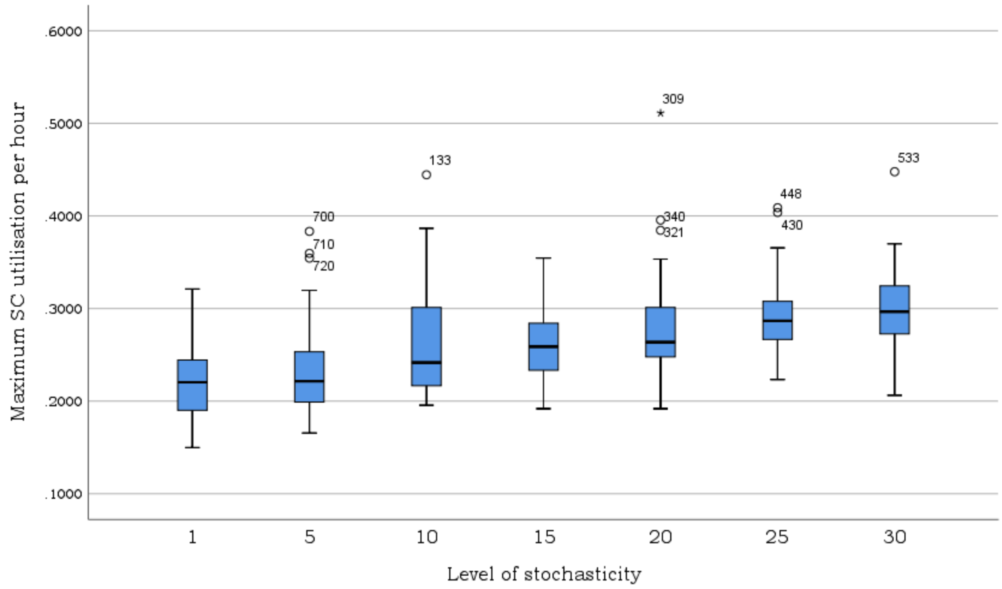


Figure 5.6: Box plot of maximum SC utilisation per hour for the experiments with housekeeping moves

Lastly, in Figure 5.7 the data distribution for the total SC working hours per experiment is presented. The variation in this parameter is relatively large, as was already expected based on the variation is average housekeeping shift duration and maximum SC utilisation per hour. Moreover, the change in mean values is sometimes positive and sometimes negative. This confirms the fluctuation as found in the comparisons in Tables 5.5, 5.6 and 5.7. Also, some outliers are visible that indicate either a relatively high amount of total SC working hours in some of the replications or a relatively low amount. Hence, it can be concluded that the total SC working hours show relatively large differences between different simulation runs. Still, statistically significant differences between experiments were found based on a 95% confidence level.

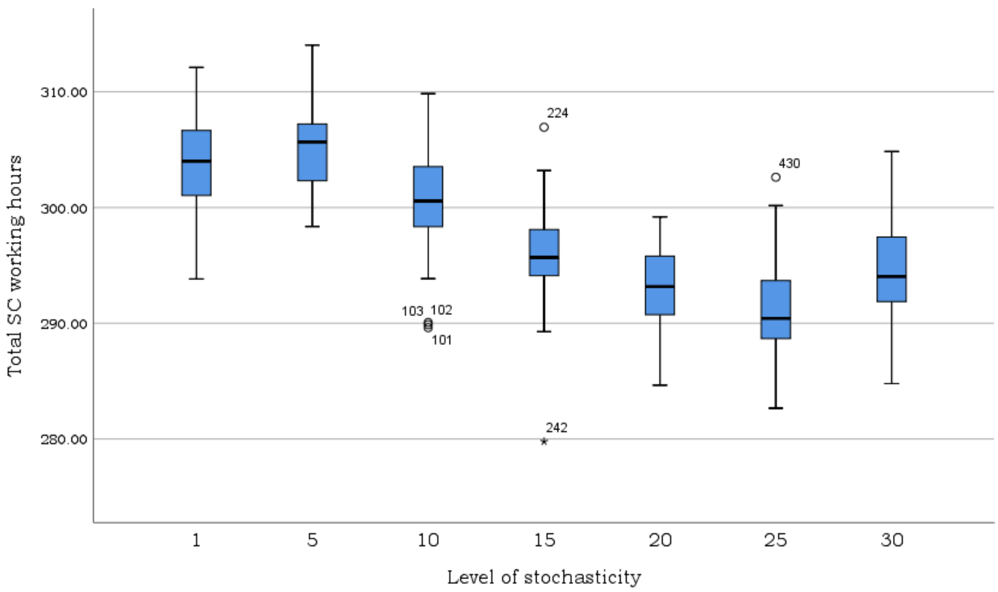


Figure 5.7: Box plot of total SC working hours for the experiments with housekeeping moves

An additional test has been performed to check whether the numbers of generated containers, the average number of containers in the row, the container retrievals per mode and the average dwell time do not differ between the 14 different experiments. It is not expected that these values differ, since the arrival rates of containers and hinterland transport modes should be the same on average for all experiments, as well as the dwell time and the average number of containers in the row. Stacking operations are expected to differ per scenario, but the average volumes handles in the modelled row are not. In order to test this, a one-way ANOVA test has been performed. The null hypothesis of the ANOVA test is that the variances in different experiments are the same. When the significance value is below 0.05, the null hypothesis can be rejected based on a 95% confidence interval. Based on the results of the tests, which are presented in Figure G.1 in Appendix G, the null hypothesis could not be rejected. Hence, it is concluded that there is no need to assume that the handled container volume in the modelled row nor the dwell time of the containers in the row differ statistically between the different experiments.

Quantifying the exact impact of stochasticity is more complicated, since the way stochasticity is modelled in this research does not match a measure for the level of stochasticity in reality. As known from current practices queried in this research, terminal operators do not measure the level of stochasticity at all. However, the model has shown significantly different results on performance indicators between the experiments with relatively low and high levels of stochasticity.

As Figure 5.2 and Tables 5.5, 5.6 and 5.7 show, increasing the level of stochasticity has the highest impact on the KPI reshuffles per retrieval.

An increase in stochasticity from the Housekeeping experiment to the Stoch_20 experiment namely increases the reshuffles per retrieval with 142.6%, the truck service times with 23.2% and the maximum SC utilisation per hour with 25.7% in the experiments. The effect on the truck service time and the maximum SC utilisation per hour might be relatively smaller, still it indicates a significant impact on the performance of stacking operations when stochasticity increases. A 142.6% increase in reshuffles per retrieval is based on a difference in parameter value of 0.27 to 0.66 (0.39). Based on the average amount of container retrievals per week for the modelled yard, this increase in stochasticity implies 7 020 additional reshuffles per week (365 029 per year[15]). A 23.2% increase in truck service time is based on a difference in parameter value of 2.42 to 2.98 (0.56) minutes. Based on the average amount of trucks per week retrieving containers from the yard, this increase in stochasticity implies 106 hours per week (5 488 hours per year[16]) additionally spent on serving trucks. Lastly, a 25.7% increase in maximum SC utilisation per hour is based on a difference in parameter value of 0.22 to 0.28 (0.06). This increase in stochasticity implies 3.4 minutes time loss in peak hours per SC.

An increase in stochasticity from the Housekeeping experiment to the Stoch_30 experiment even shows larger effects on the KPIs. This increase in stochasticity increases the reshuffles per retrieval with 185.9%, the truck service times with 30.6% and the maximum SC utilisation per hour with 34.3% in the experiments. In terms of reshuffles per retrieval an increase in parameter value from 0.27 to 0.78 is observed (0.51), i.e. 475 998 reshuffles per year[17] in the entire import yard. In terms of truck service time, an increase from 2.42 to 3.16 minutes (0.74) is observed, i.e. 7 237 hours per year[18] for the entire terminal. Lastly, the increase in maximum SC utilisation per hour is from 0.22 to 0.30 (0.08), i.e. 4.6 minutes time loss in peak hours per SC.

It is also tested whether significant differences exist between the results on performance indicators in the experiments without housekeeping moves, when increasing the level of stochasticity in comparison to the base case experiment. It is not expected that stochasticity deteriorates stacking performance when housekeeping moves are not performed. The results of these tests are represented in Appendix G in Tables G.7, G.8, G.9, G.10, G.11 and G.12. The results show that in comparison of the results from the base case experiment with the Stoch_5_control experiment (see Table G.7), the maximum SC utilisation per hour is (-6.5%) significantly different in the 2 experiments. Because the significance value is hardly lower than 0.05, and the result does not hold for one-sided tests, this difference is not taken into account further.

When comparing the results of the base case experiment and the Stoch_10_control experiment (see Table G.8), none of the differences in mean KPI values are statistically significant.

When comparing the results of the base case experiment with the Stoch_15_control experiment (see Table G.9), the reshuffles per retrieval (-1.0%) and the truck service time (-0.6%) are significantly lower in the Stoch_15_control experiment.

When comparing the results of the base case experiment with the Stoch_20_control experiment (see Table G.10), the reshuffles per retrieval (-1.6%) and the truck service time (-0.6%) again are significantly lower in the Stoch_20_control experiment.

[15] 0.39.. * 18 044.. * 52
[16] 0.56.. * 11 295.. * 52 / 60
[17] 0.51.. * 18 044.. * 52
[18] 0.74.. * 11 295.. * 52 / 60

When comparing the results of the base case experiment with the Stoch_25_control experiment (see Table G.11), the reshuffles per retrieval (-3.5%), the truck service time (-1.6%) and the maximum SC utilisation (-7.7%) are all statistically significant lower in the Stoch_25_control experiment.

When comparing the results of the base case experiment with the Stoch_30_control experiment (see Table G.12), the reshuffles per retrieval (-4.8%) and the truck service time (-2.3%) are significantly lower in the Stoch_30_control experiment.

These results indicate that when the level of stochasticity increases, the number of reshuffles and the truck service time slightly decreases (in 4 of the 6 comparisons). In the comparison of the base case experiment with the Stoch_25_control experiment, the maximum SC utilisation also decreases. This result is not expected, although it might be caused by the instability in the system due to stochasticity. Since the differences are relatively small, especially in comparison with the differences found between the different housekeeping experiments, the level of stochasticity is not expected to really change stacking performance in case housekeeping moves are not implemented. Hence, it is concluded that only when implementing housekeeping moves, notable differences of the effect of the level of stochasticity on stacking performance will be observed.

5.5. Sensitivity Analysis

Specifically identified input parameters in Simio enable a sensitivity analysis with respect to the KPIs. Simio is able to generate Tornado charts that show the sensitivity of defined performance indicators to changes in input parameters. It varies one input parameter at a time between a lower and upper bound and shows its effect on the respective KPI. When the sensitivity analysis coefficient is negative, an increase in the parameter will lead to a decrease in the KPI and the other way around. Response sensitivity is recommended by Simio when real data is lacking in the model to explore which input parameters influence the KPIs to which extent. Since this model uses a distribution based on real data, it is explored to which extent this defined distribution affects the KPI reshuffles per retrieval.

The only input parameter in this model is *IATContainers*. Since tornado charts provide a good representation of sensitivity analysis coefficients of different input parameters compared to each other and in this model only one input parameter is specified, showing the tornado chart itself in this report is not considered to have an added value. The sensitivity analysis in Simio result in a sensitivity analysis coefficient of -0.417 with respect to the reshuffles per retrieval. This means that when the inter arrival time of containers increases with 1%, the amount of reshuffles per retrieval will decrease with 0.417%. The direction of this effect matches expectations, since a large IAT between containers will lead to less containers in the yard and therefore less reshuffles per retrieval.

5.6. Reflection on Results For Different Terminals

The results described above are based on the reference case at MPET. MPET is a SC operated terminal, while the majority of the terminals in the world use yard cranes (YCs) in their stacking operations (Wiese et al., 2010). The use of YCs as opposed to SCs firstly leads to large differences in terminal layout, as already described in Section 3.3. These differences will also lead to other model design and model specification choices than the ones made in this study that are described in Chapter 4. Firstly, an additional handshake point should be introduced into the model, in which the yard crane picks up or delivers a container to a horizontal transport vehicle. This means that the processes of storing and retrieving containers rely on the same resource (the YC), while in this research the storing SCs are considered to be of a different group than the retrieving SCs. Moreover, there are multiple SCs in the current model that can retrieve a container subsequently. Their only restriction in the current model is that there should be no other SC operating in the row. In case of a YC, the model should specifically prioritise which request is more important. In the current model this is only done in case of housekeeping moves and relocating containers from the buffer into the row. These processes are postponed or interrupted when SCs from the seaside are waiting to store a container in the yard or when an SC from the landside is waiting to retrieve a container, as described in Appendix D in the Buffer and Housekeeping processes.

Moreover, in a YC operated stack a yard block is operated by one or maybe 2 cranes at once, while in a SC operated stack each row can have at least one SC in it. This means that the same amount of containers should rely on a lower amount of maximum available resources in stacking operations. Of course, it depends on how many SCs are available whether the containers rely on relatively less or more resources per row. Still, the way of seizing resources is performed differently and should therefore be modelled in a different way.

Furthermore, reshuffle and housekeeping moves might also be performed differently. In the current model the assumption is made that reshuffle and housekeeping moves are performed within a row, while it might make sense for a YC to perform these movement over different rows in the same bay. This would also require different logic in the model.

Besides the points above, a more expanded model is advised to also take failures into account. As one would expect, failure frequencies and their consequences are different in SC operated terminals as opposed to YC operated terminals.

Lastly, in a YC operated terminal, the modeller should consider which horizontal transport vehicles to take into account and the consequences of their different capabilities.

On the other hand, MPET handles a relatively large container volume. It is tested whether the implementation of housekeeping moves also lead to improvements in a terminal with a lower volume. The results of the t-tests to compare 2 scenarios are presented in Appendix G in Tables G.13 and G.14.. The results of implementing housekeeping moves for a terminal that handles $\frac{2}{3}$ of the container volume is presented in Table 5.8. Since the container volume is $\frac{2}{3}$ of the container volume in the reference case, the average amount of containers in the row is 23. Hence, the maximum level of stochasticity which is able to produce reliable results in these experiments is 20.

Table 5.8: Effect of housekeeping moves in a terminal with $\frac{2}{3}$ of the volume of the reference terminal

KPI	**Parameter value change**		**Interpretation of savings**
	No HK	HK	
Low stochasticity (StochLevel = 1)			
Reshuffles per retrieval	0.62	0.14	300 657 reshuffles per year
Truck service time	2.79	2.14	4 221 hours per year
Max SC utilisation per hour	0.20	0.14	3.3 min per peak hour
Total SC working hours	71.6	148.9	27 471 hours per year
Number of HK SC shifts needed per night	-	5	-
High stochasticity (StochLevel = 20)			
Reshuffles per retrieval	0.56	0.47	56 369 reshuffles per year
Truck service time	2.69	2.60	548 hours per year
Max SC utilisation per hour[19]	0.19	0.18	0.5 min per peak hour
Total SC working hours	69.0	142.1	25 966 hours per year
Number of HK SC shifts needed per night		3	-

Implementing housekeeping moves when the container volume is smaller in the experiment without stochasticity (StochLevel = 1) leads to a decrease in reshuffles per retrieval from 0.62 to 0.14 (-77.0%), i.e. 300 657 reshuffles per year. The truck service time is decreased from 2.79 to 2.14 (-23.3%), i.e. 4 221 hours per year. The maximum SC utilisation per hour could be decreased from 0.20 to 0.14 (-27.6%), which implies a time saving of 3.3 minutes in peak hours. To obtain these benefits, housekeeping moves are performed with an average shift duration of 0.30 hours, so 5 housekeeping SC shifts are needed to perform housekeeping moves once every 3 nights per row in the entire import terminal. The total SC working hours increase from 71.6 to 148.9. Over an entire year this would imply 27 471 additional SC hours.

When the level of stochasticity increases to 20, implementing housekeeping moves will still have a significant effect on the KPIs reshuffles per retrieval and truck service time. The difference in maximum SC utilisation per hour is however not statistically significant, as can be seen in Table G.14. The reshuffles per retrieval decrease from 0.56 to 0.47 (-16.2%) when implementing housekeeping moves. This implies a saving of 56 369 reshuffles per year for the entire import yard. The truck service time decreases from 2.69 to 2.60 minutes (-3.1%). This implies a saving of 548 hours per year for the entire terminal. To obtain these benefits, housekeeping moves are performed with an average shift duration of 0.25 hours. Assuming it will be sufficient to perform housekeeping moves in a row once every 3 nights, 3 housekeeping SC shifts are in the entire import terminal.

Based on the results above, it can be concluded that the implementation of housekeeping moves also improves stacking performance in a terminal with a smaller container volume. The improvements are smaller

[19] difference is not statistically significant

in size compared to the reference case. However, the improvements in terms of percentages are of a similar size. It can also be concluded that the improvements become less when the level of stochasticity increases. Although, even with a very high level of stochasticity, significant improvements in reshuffles per retrieval and truck service time could still be found.

5.7. Reflection on Results for Different Stakeholders

As the results point out, a lower level of stochasticity improves stacking operations. The stakeholder map in Figure 2.5 show that the terminal operator has direct contact with the shipping lines and the carriers. If these actors could provide accurate information in advance, the terminal operator could improve its stacking operations with housekeeping moves. However, often the carrier does not know its transport order much time in advance, or it might be changed which specific container(s) a carrier will retrieve while this latter one is already heading towards the terminal. Therefore, the carrier is not the final solution in providing more information. The shipping agents behind the transport orders are more likely to be. Since the shipping agents commission transport orders, they have an overview of future requests and possible carriers to address for these requests. In case shipping agents would provide terminal operators with accurate retrieval information, the terminal operator could improve its stacking operations. Indirectly the shipping agents could also profit from this improvement, since the trucks they send are likely to have less waiting time. However, the predicted improvement in truck service time might be relatively small compared to a truck's total trip time. Therefore, the improvement on the shipping agent's side is small and it might not be likely that they would share information. Moreover, an important aspect for shipping agents is their flexibility. In current practice, they are able to change the container request up until the moment the truck arrives at the terminal. In an information sharing scenario, the terminal should only be benefited by information on the request once they are made at least 1 day, but preferably 2 days in advance. In that case the shipping agent's flexibility would be jeopardised to a large extent, which makes an information sharing scenario even less attractive.

Additional research is recommended into incentives for shipping agents to cooperate in sharing information. Moreover, the number of requests that indeed are changed at the last moment could be determined. It might for example be the case that the majority of the requests could be shared with terminal operators 2 days in advance. In that case, terminal operators and shipping agents could agree upon a small share of requests that are open for changes at the last moment.

Besides the terminal operator, the carriers could also profit from a situation with less stochasticity. Their turnaround time could be decreased because of the decrease in service time. When this advantage becomes large enough, they can increase their total number of handled transport requests. The other actors from the stakeholder map in Figure 2.5 are not likely to achieve significant benefits from the lower level of stochasticity. The terminal operator will be the main favoured actor of the benefits.

5.8. Conclusion

This chapter has provided an answer to sub-question 4: *What is the effect of stochasticity in the parameters on the performance indicators?* As can be concluded from the results, stacking operations can be improved by implementing housekeeping moves. The implementation of housekeeping moves in the base case experiment decreases the reshuffles per retrieval, truck service time and maximum SC utilisation per hour with respectively 71.4%, 27.2% and 37.9%. In other words, this leads to a decrease of 639 764 reshuffles per year, 8 854 hours per year in serving trucks and 8 minutes per SC in peak hours, based on the entire import volume of the terminal. In order to achieve these benefits, the terminal should deploy 10 housekeeping SCs during non-peak hours (from 10:00 PM to 5:30 AM). With these additional SC shifts, the total SC working hours will increase with 60 714 hours per year for the entire import yard.

When the level of stochasticity increases, the benefits achieved by implementing housekeeping moves decrease. Still, in the experiment with the highest level of stochasticity (StochLevel = 30) the reshuffles per retrieval, truck service time and maximum SC utilisation per hour can be decreased with 14.2%, 2.8% and 14.8% respectively. This means that housekeeping moves could spare 120 656 reshuffles per year, 883 hours in truck service time per year and 3 minutes per SC in peak hours on average. To obtain these benefits, approximately 8 housekeeping SC shifts should be deployed each night. With these additional SC shifts, the total SC working hours will increase with 58 735 hours per year for the entire import yard.

Moreover, the higher the level of stochasticity is, the worse the stacking performance is. An increase in stochasticity from the Housekeeping experiment (StochLevel = 1) and the Stoch_20 experiment (StochLevel = 20) namely increases the reshuffles per retrieval with 142.6%, the truck service times with 23.2% and the maximum SC utilisation per hour with 25.7% in the experiments. In other words, this increase in stochasticity implies an increase in reshuffles per retrieval from 0.27 to 0.66, i.e. 7 020 additional reshuffles per week or 365 029 per year for the entire terminal. Moreover, the truck service time increases from 2.42 to 2.98 minutes, which entails 106 additional hours a week or 5 488 hours per year. Lastly, an increase in maximum SC utilisation per hour from 0.22 to 0.28, leads to a time loss of 3.4 minutes per hour per SC in peak hours. When the level of stochasticity increases even further, the effect on the KPIs becomes stronger. In comparison of the Housekeeping experiment with the Stoch_30 experiment, 475 998 additional reshuffles per year, 7 237 hours per year truck service time and 4.6 minutes time loss in peak hours per SC are observed.

When considering a different terminal type, many changes should be made to the model. Mainly because of different yard resources the configuration choices will be different. Moreover, YCs are more likely to use multiple rows in the yard block in their reshuffle or housekeeping moves in contrast to the current model that represents one row of a SC operated terminal in which these processes occur within the row. Hence, reshuffle and housekeeping logic will be different. When testing whether the effects of housekeeping moves also hold for terminals that handle a smaller container volume than the reference terminal, it can be concluded that even with $\frac{2}{3}$ of the reference volume, implementing housekeeping will improve stacking performance. Moreover, these tests also confirm that the improvements on the KPIs due to housekeeping moves become less when the level of stochasticity increases.

In terms of stakeholders that could help to reduce stochasticity, shipping agents are key. However, sharing information would jeopardise their flexibility, while their benefits seem limited in comparison to the benefits for the terminal operator. Additional research into stakeholder cooperation is recommended to explore incentives for shipping agents to share information or to explore scenarios in which they are likely to do so.

6 Conclusion

The goal of this research was to estimate quantitative effects of stochasticity in container data on the performance of terminal stacking operations. Based on the results of this study, conclusions are drawn that are presented in Section 6.1. Section 6.2 discusses the impact of certain assumptions made in this research on the results and the limitations of the conclusions. Lastly, Section 6.3 will provide recommendations for further research.

6.1. Conclusion

The main research question of this study is: *What is the effect of stochasticity in import container information on stacking performance at a container terminal?* To answer the main question, several sub-questions have been formulated. In Chapter 2 the goal, processes, performance and actors related to stacking operations has been clarified. By doing so, an answer to the sub-question *What are terminal stacking operations?* has been given. Moreover, the role stochasticity plays in stacking operations has been illustrated in Chapter 2. With that, an answer to the second sub-question (*What is stochasticity in import container information?*) is provided. Both Chapter 3 and 4 answered sub-question 3: *How to model the relation between stochasticity in import container information and the performance of stacking operations?* In these chapters previous research has been analysed and the choice for simulation has been motivated. Moreover, three KPIs have been chosen that provide a detailed view on stacking performance: reshuffles per retrieval, truck service time and maximum SC utilisation per hour. Lastly, the conceptual model is described, as well as the objects, attributes and processes and the way they are implemented in the simulation model. Chapter 5 answers sub-question 4 (*What is the effect of stochasticity in the parameters on the performance indicators?*) by running experiments with the simulation model. In these experiments, the effect of housekeeping moves and stochasticity on stacking performance is determined. Based on statistical analysis of the results, it could be concluded that the implementation of housekeeping moves during non-peak hours improves stacking performance in all of the experiments. Table 6.1 shows that implementing housekeeping moves in the scenario with minimum level of stochasticity could spare 639 764 reshuffles per year, 8 854 hours of truck service time per year and 8 minutes per SC in peak hours based on the total import volume of the terminal. In the scenario with a maximum level of stochasticity, implementing housekeeping moves could save 120 656 reshuffles per year, 883 hours of truck service time per year and 3 minutes per SC in peak hours. In the experiment with minimal stochasticity 10 housekeeping SC shifts are needed each night to obtain the benefits and 60 714 additional total SC working hours are observed. In the experiment with maximal stochasticity 8 housekeeping SC shifts are needed and 58 735 additional total SC working hours are observed.

Table 6.1: Effect of housekeeping moves for minimal stochasticity and maximal stochasticity scenario

KPI	**Parameter value change**		**Interpretation of savings**
	No HK	HK	
Low stochasticity (StochLevel = 1)			
Reshuffles per retrieval	0.95	0.27	639 764 reshuffles per year
Truck service time	3.32	2.42	8 854 hours per year
Max SC utilisation per hour	0.36	0.22	8 min per peak hour
Total SC working hours	132.5	303.5	60 714 hours per year
Number of HK SC shifts needed per night		10	-
High stochasticity (StochLevel = 30)			
Reshuffles per retrieval	0.91	0.78	120 656 reshuffles per year
Truck service time	3.25	3.16	883 hours per year
Max SC utilisation per hour	0.35	0.30	3 min per peak hour
Total SC working hours	129.0	294.4	58 735 hours per year
Number of HK SC shifts needed per night		8	-

Another conclusion that is drawn is that an increasing level of stochasticity significantly deteriorates the stacking performance. When the level of stochasticity increases from the experiment with the lowest level (StochLevel = 1) to the experiment with the level (StochLevel = 20), the reshuffles per retrieval increase with 142.6% (i.e. 365 029 additional reshuffles per year), the truck service time with 23.2% (i.e. 5 488 additional hours per week) and the maximum SC utilisation increases with 25.7% (500 hour per SC per year). When the level of stochasticity increases to 30, the effect becomes even stronger, i.e. 475 998 additional reshuffles per year, 7 237 additional hours truck service time per year and 4.6 minutes time less in peak hours per SC are observed.

The conclusions are scientifically relevant since no other research has been found that quantifies the relation between stochasticity and stacking performance. This research has contributed to the existing knowledge gap of quantitative effects of stochasticity on performance. Moreover, the conclusions are also practically relevant, since they give an indication for improvements on stacking performance parameters that can be achieved when the level of stochasticity could be decreased. In that case, less reshuffles are needed when retrieving containers, leading to a lower SC utilisation during peak hours. Instead, housekeeping moves should be implemented by a SC that operates at night, during non-peak hours. Furthermore, this research indicates that even with a high level of stochasticity, stacking operations can be improved by implementing housekeeping moves. In order to decrease the level of stochasticity, the stakeholder network should be consulted, which leads to new challenges.

6.2. Discussion

The results of this study should be interpreted with respect to the assumptions that have been made in order to design a simulation model that is able to answer the research question in the available time scope. One important assumption is that only 1 TEU containers have been modelled, while in reality many of the containers going through the terminal are 40-foot containers instead of 20-foot. This will lead to less storage and retrieval occasions compared to the current situation in the model, while the total volume remains the same. When the number of containers is lower, the amount of reshuffles probably is also lower, as well as the pressure of the system on the SC fleet. It is expected that this leads to a lower truck service time. Hence, the effects of housekeeping moves and stochasticity on the performance indicators could be overestimated in this research.

A second limitation of the model is that the travel time of SCs from the yard row to the gate of the hinterland transport mode that requested a specific container has been left out of scope. Therefore, the service time of trucks is underestimated. However, even when underestimating the service times, statistically significant differences between the service times in different experiments have been found. Moreover, the travel times of these SCs to the hinterland transport modes is not expected to differ when improvements are implemented, while the time of a SC in the yard row is.

A third limitation is that the booking of truck slots is not modelled. In reality, trucks book a time slot in which they are expected to arrive at the terminal to retrieve a container. During that time slot, no other trucks can collect containers at the same terminal location. Time slots set a kind of minimum truck service time to the system, since decreasing the service time while maintaining the size of truck slots will not cause improvements in terms of a higher amount of trucks that can be served. However, improvements in terms of SC utilisation can still be noticed. Since the retrieval time of a container will decrease when implementing housekeeping moves, the occupied SC becomes available for a new task earlier. Therefore, less SCs would have to be employed for the same amount of requests. The model in this study differs from reality, because it allows multiple trucks to arrive shortly after each other and to queue up. Therefore the service time in this research is underestimated, and the effects of a shorter service time will have an immediate effect on the stacking performance.

Another important limitation of the model is that it only considers 1 yard row. Hence, the total SC fleet in the import yard area and other transport requests they have to perform is not taken into account when a container out of this single row is requested. Because of this limitation the maximum SC utilisation per hour resulting from the experiments is not a reliable number, since the utilisation of the same SC by containers in another row is not taken into account. Still, the difference in maximum SC utilisation per hour in the different experiments based on the single row model can still provide an indication for less SC use over the terminal as a whole. It can also occur that a hinterland transport mode has to wait for a SC to become available, since the SC first needs to finish one or more other requests. This is not modelled in this research, which indicates that the truck service time and the maximum SC utilisation per hour might be underestimated.

Also, the benefits of improving stacking performance should be compared to the additional investments of adding a housekeeping SC to the system during non-peak hours. Based on this research, a financial trade-off of this implementation could not be made. However, this is recommended in Section 6.3.

Lastly, the way stochasticity is modelled in this research has a large effect on the results. The results give an indication of what the effects are when stochasticity increases, but it is unlikely that stochasticity can be measured in a same way in reality as it is done in this research. Since data on stochasticity was missing, the decision is made to model it in a way of sub-selecting containers from the yard in a stochasticity list out of which the final container for retrieval would be selected. However, based on these results it cannot be concluded that a the decrease of stochasticity of a certain magnitude will lead to a specific quantitative change in performance indicators. Instead, scenarios with different levels of stochasticity and the effects on the performance indicators are compared in the experiments.

6.3. Recommendations for Further Research

Many indications for future research are already given in the previous chapters. One of the most important recommendations is that the degree to which the results of this single row research are representative for an entire container terminal should be investigated. It is recommended to expand the model or to create a new model with a broader scope that takes an entire import yard block or the entire import yard into account. In that way the total use of SCs can be monitored, and the proposed improvements can be tested when taking all transport requests and the total SC fleet into account. Moreover, turnaround times or service times of trains and barges can also be measured in a model with a broader scope. Another addition to the future model is to take exact travel times to hinterland transport mode gates into account. In that way the SC utilisation and hinterland transport mode service times can me monitored in a more realistic way. When the model would be designed with even more detail, SC breakdown and repair time should also be taken into account.

In the current research, stochasticity in next mode of transport is not implemented in the model, although classified as a relevant type of stochasticity. That can be explained by the fact that all containers in the referenced terminal are stacked in a same yard block. In other container terminals, separate yard blocks might be dedicated to a specific next mode of transport. Future research to the effects of stochasticity in the next mode of transport on the stacking performance would also be interesting. However, the use of information on next mode of transport in the stacking strategy is a crucial condition when that relation would be investigated.

Another recommended topic of research is aimed at the way the level of stochasticity should be measured. This is crucial in defining the relation between stochasticity and performance indicators.

Another important area of future research relates to data analysis. The goal of this research is to quantify the relation between stochasticity and stacking performance. Additional research is recommended in decreasing the level of stochasticity. In order to do so, it firstly is of crucial importance that data is available on current levels of stochasticity. It is expected that data analysis research can explore patterns in container retrievals in order to decrease the level of stochasticity related to container retrievals at the landside.

In addition, research into optimal levels of stochasticity could be performed. As is expected, decreasing the level of stochasticity to a situation where there is full certainty will lead to the largest benefits for a terminal operator. However, the benefits might already be sufficient while leaving some room for stochasticity. In that way, stakeholders can maintain a part of their flexibility, and it might lead to a win-win situation. This research should be of an economical kind, expressing costs and benefits in monetary terms to enable a comparison of investments and economic gains. A financial overview of terminal operations could also argue for the investment of an additional housekeeping SC during non-peak hours compared to the benefits the terminal would obtain with the improvement in stacking operations. This research could also be performed with a certain performance level already in mind. In that case the research could be focused at the decrease in stochasticity that is needed to reach certain performance. In relation to this topic, different ways of sharing information could also be explored in further research. With the recent attention for block chain, it might also be interesting to explore the use of block chain in decreasing stochasticity for terminal operators. Lastly, as already indicated in Section 6.2, research into incentives for shipping agents to cooperate in sharing information could lead to interesting results for terminal operators.

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II

Appendices

A

Scientific Paper

This appendix presents the scientific paper created based on this study an the results. It consists of a summary of the research, but especially highlights the main contribution of this research to the existing knowledge en practice.

The relation between stochasticity and terminal stacking performance of import containers

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***Abstract*—With an increase in amount of container terminals, competition between terminals has risen. Therefore it has become more and more important for terminal operators to conduct their work as efficient as possible. Efficient terminal operations are hindered by stochasticity, which is defined as random variation in parameter values. Due to missing information on exact arrival times, requested containers are often stored underneath other containers, which will then need to be reshuffled to reach the requested container. This reshuffling is performed while a hinterland transport mode is waiting for the requested container and therefore increases service times and SC utilisation during peak hours. This research investigates the relation between stochasticity and terminal stacking performance of import containers with a simulation model. Terminal stacking performance is subdivided into the Key Performance Indicators reshuffles per retrieval, truck service time and maximum straddle carrier utilisation per hour. The results show that implementing housekeeping moves can spare the entire import yard up to 639 764 reshuffles per year, 8 854 hours in truck serving per year and 8 minute per peak hour per SC. Even in the experiments where the level of stochasticity is high, a saving of 120 656 reshuffles per year, 883 hours truck service time and 3 minutes per SC peak hour are observed. The higher the level of stochasticity, the smaller the improvement on the KPIs is. Lastly, it can be concluded that stacking performance also deteriorates when the level of stochasticity becomes higher.**

Keywords*—*Container terminals, Stacking operations, Stochasticity, Discrete Event Simulation

I. Introduction

Containerisation has lead to a change in the way how industrial production and distribution takes place globally (Sharif Mohseni, 2011). Not only did it lead to a decrease of sea transportation costs and more cost effective transport, containers have also lead to advantages in terms of handling processes at terminals and protection of the goods inside (Steenken, Voß, & Stahlbock, 2004). As mentioned by Li, Wu, Petering, Goh, and Souza (2009), different studies describe the significant current share of container transport up to 90% of the world trade that is transported via containers. Along with the increase of transported volume by containers, the vessel itself has increased in size as well. Current deep sea vessels can carry up to 20,000 Twenty Foot Equivalent Units (TEU) (Stahlbock & Voß, 2008a). In 2017 the largest container vessel, the Orient Overseas Container Line (OOCL) Hong Kong, even had a capacity of 21 413 TEU (MI News Network, 2017).

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Different actors are involved in the practice of container shipment. The main players are the shipper that wishes to transport goods by container; the shipping line that is responsible for the transport of containers overseas; and the consignee to whom the content of the container is directed. Besides these three players, a terminal operator is concerned with two main functions: the loading of export containers that arrive by train, truck or barge onto deep sea vessels and the unloading of import or transshipment containers from deep sea vessels. In this way the terminal can be seen as the link between sea transport and hinterland transport of containers. There is a delay between the containers' arrival at and departure from the terminal of typically several days, this delay is referred to as *dwell time*. The average dwell time of containers at large container terminals is 3-5 days (Steenken et al., 2004). During the dwell time the containers await their next mode of transport at the container yard. This illustrates a third function of the terminal, namely the temporary storage of containers.

Container terminals are confronted with increasing competition (Froyland, Koch, Megow, Duane, & Wren, 2008; Güven & Eliiyi, 2014; Kim, 1997). Since the number of TEU to be transported has increased, new terminals have been created. This makes it possible for shipping lines to choose between terminals, creating a weak bargaining position for the terminals (Stahlbock & Voß, 2008a). Therefore it becomes more and more important for a terminal to operate as efficient as possible.

A general performance indicator of container terminals is the amount of reshuffles necessary to reach a container (Gharehgozli, 2012). This performance indicator is related to yard performance and stackng operations, which are the subject of investigation in this research. A reshuffle is described as the digging process needed to reach a container that is stored underneath another container that is not yet needed at the time the lower one is required. The amount of reshuffles can be measured in reshuffle movements or reshuffle occasions, the latter one can consist of multiple movements. Since storage space is a critical resource of a terminal (Kim & Park, 2003), the stacking strategy also significantly affects the the efficiency of the terminal (Gharehgozli, 2012). The goal of every terminal is to maintain its competitiveness by providing low cost and high quality service to perform efficiently (Liu, Jula, & Ioannou, 2002).

Improving the performance of container terminal's operations is made difficult by stochasticity in their operations, which is defined as random variation in a parameter value. Stochasticity is, amongst others, present in container information. Exact information on import containers' weight, arrival times, next mode of transport and retrieval times is often missing upon arrival of the containers in the yard (Güven & Eliiyi, 2014). In rare cases when the information is known upon arrival, it is often changed again when the container is stored. The stochasticity researched in this study is focused on stochasticity in arrival times and types of hinterland transport modes generating container retrieval requests. This is partially caused by the actors involved in the practice of container shipment. Stochasticity in arrival times of hinterland transport modes makes it harder for a terminal to organise the import yard in a way that the containers that will be retrieved first are on top of the stack. Stochasticity in types of hinterland transport modes complicates the process of storing containers together that will be retrieved by the same type of hinterland transport mode. Since import containers are confronted with the highest level of stochasticity, in comparison to export and transshipment containers, this research is scoped towards stacking operations of import containers. Due to missing information on exact arrival times, requested containers are often stored underneath other containers, which will then need to be reshuffled to reach the requested container. This reshuffling is performed while a hinterland transport mode is waiting for the requested container, and therefore increases service times. Reshuffling performed during peak hours especially puts pressure on the terminal system, since the limited amount of yard operating equipment is already scheduled for many tasks during peak hours.

The research objective of this study is to quantify the relation between stochasticity on the performance of stacking operations of import containers. The main research question is: *What is the effect of stochasticity in import container information on stacking performance at a container terminal?* As could be concluded from an extensive literature review, no other researches before have looked into the effects of stochasticity on stacking performance of a multimodal container terminal. The scientific contribution of this research hence consists of an analysis of the effect of stochasticity on defined performance indicators. The practical contribution of this research is aimed at terminal operators. The outcomes of this study quantify the effect stochasticity has on their operations, specified in three different performance indicators. Moreover, the study identifies improvement directions for terminal operators to decrease the level of stochasticity.

II. LITERATURE REVIEW

The literature review is focused on determination of the research gap, the research method and performance indicators that will be used to assess stacking performance.

A. Research gap

The topic of container terminals' design and operations has been already researched extensively. Design studies are relevant to consider when identifying important variables that should contribute to efficient operations. Operations Research (OR) can contribute to the comparison of different designs before a terminal is constructed or expanded, but can also contribute to an improvement in terminal operations, limited by an already constructed design. The studies broadly vary in type of terminal discussed and methods applied. The main streams of research found related to the topic of this research are based on either optimisation or simulation.

In many of the relevant studies, the performance of different stacking strategies is investigated. Stacking strategies are, amongst others, based on destination, arrival time and departure time of containers (Güven & Eliiyi, 2014). In category stacking, as an example, containers are placed together based on weight type and expected time of departure. In reality, however, many data related to the arriving containers is unknown at the time of arrival and may even change when the containers are already placed into the stack. So a study might result in an optimal stacking strategy, in reality this cannot be implemented due to lacking information. Because decisions made related to stacking policies are based on studies where full information is assumed, actual performance of current practices can be reduced significantly. A lot of information, even though it not always directly interferes with operational activities, is needed to optimise the work flow in terminals (Steenken et al., 2004).

Different studies mention the lack of certainty in container information (e.g. Dekker, Voogd, & Van Asperen, 2006; Froyland et al., 2008; M. E. H. Petering, 2010; Steenken et al., 2004), but only little studies look into the effects of these uncertainties. Uncertainty or more specifically stochasticity is presented as a given circumstance, and while changing that situation might be difficult, it is surprising to see such a small number of studies that looked into the consequences of it on terminal operations. Both Rashidi and Tsang (2013) and Stahlbock and Voß (2008a) mention the relevance of further research in stochastic optimisation and scenario based scheduling of container terminals, which already implies the relevance of research that copes with lack of certainty faced in reality.

Two studies that look into a type of uncertainty have been found. Kang, Ryu, and Kim (2006) present a research on stacking strategies for export containers while weight information is uncertain. Export containers in a yard are usually divided into different weight groups to make it easier to load heavier containers onto a ship before lighter ones. This way of stacking the containers is expected to lead to fewer reshuffles and thus more efficient loading operations. That is an important constraint in the loading process of containers onto a ship, related to the ship's balance. It is mandatory for trucking companies to send specific container information before arrival of the trucks to the terminal.

However, this information, especially regarding the weight of the containers, is often not accurate. Often the terminal is informed of accurate weights of containers a day before the scheduled loading, while the majority of the containers are already in the yard a week before loading. Kang et al. (2006) mention the majority of research being conducted while assuming complete information and the little amount of researches in reducing the amount of reshuffles while information is inaccurate. They also point out that ordering constraints for inbound containers are not related to weight groups, since there is no balancing need.

The research of Zhao and Goodchild (2010) looks into the impact of truck arrival information on reshuffling. The goal of a reduction in reshuffles is to improve the YC productivity and reduce truck transaction and delay time as well as improve container throughput on the yard. They split the problem in two aspects: unknown truck arrival information and unknown truck sequencing information. Truck arrival information is unknown when there is absolutely no certainty on when trucks will arrive. Truck sequencing information is unknown when for example a time slot of one hour has been booked for truck arrivals, but the exact sequence in which the trucks of a same time slot arrive is unknown. The arrival time in the latter case is not only uncertain, but is similar to the definition of stochasticity that is used in this research. They conclude that a significant reduction in the amount of reshuffles can be achieved with small improvements in terminal information regarding truck arrivals. This research aims to continue in the same direction.

The fact that only two studies were found that presented research into the effects of stochasticity or uncertainty, already indicates the current research gap on this topic.

Furthermore, research mostly considers terminals that handle containers delivered and picked up by the hinterland transportation mode truck. Some studies also describe train as a second mode of hinterland transport, but barge transport is hardly ever mentioned. Of the two studies mentioned considering uncertainties, Kang et al. (2006) do not mention the hinterland transportation methods available at the terminal, while Zhao and Goodchild (2010) only consider uncertainties in truck arrivals. In reality however, stochasticity occurs in arrivals of deep sea vessels, trucks, trains and barges. Moreover, stochasticity is not only related to arrival or pick-up times of containers, but also to the mode on its own. The next mode of transport for import containers, for example, is still unknown in many cases when the container is discharged from the vessel. Steenken et al. (2004) even mention only 10-15% of the import containers that arrive at a terminal have information on the landside transportation mode upon arrival. When this information is available, changes in the next mode of transport occur frequently while the container is already stored in the yard.

B. Method

Both optimisation and simulation are forms of OR, which is a discipline focused on the application of advanced analytic methods to improve decision-making in a complex context. A first variant of OR is deterministic optimisation, which is a dominant methodology in articles focused on container terminals (M. E. Petering, Wu, Li, Goh, & de Souza, 2009; Roy & de Koster, 2014). Another variant is stochastic optimisation which is especially promising in an environment where the state space is relatively small. As this is not the case in container terminal research, stochastic optimisation is not often used in this topic. The last variant mentioned by M. E. Petering et al. (2009) is simulation, which is increasingly used in research on the topic of container terminals.

Optimisation studies are performed to analyse the performance of terminal functions in a more isolated way compared to simulation. The optimisation studies found, look into problems such as berth allocation, stowage planning, crane scheduling and assignment, internal transport of containers in a terminal, storage and stacking logistics, and external transport as separate subsystems (Hartmann, 2004; Roy & de Koster, 2014; Stahlbock & Voß, 2008b; Steenken et al., 2004; Ünlüyurt & Aydin, 2012; van Asperen, Borgman, & Dekker, 2013). Steenken et al. (2004) present a literature overview of container terminal operation and OR. They mention four types of optimisation research investigated in the literature: yard optimisation, quayside transport optimisation, landside transport optimisation, and crane transport optimisation.

Although optimisation is a methodology often used in container terminal studies, it has some significant shortcomings. Firstly, optimisation studies are focused on isolated problems. The approach in literature is to develop models for specific components of the entire system and try to find efficient methods to solve the model (Ünlüyurt & Aydin, 2012). Although the expectation of this approach is to improve the entire system by improving one component, an improved total system performance is not guaranteed when adopting a positive outcome of such a study merely aimed at improving one aspect of the whole. Moreover the optimisation models are not that large, and thus ignore many relevant aspects of container terminal operations. Therefore Steenken et al. (2004) recommend decision rules following from optimisation to be tested in a simulated environment before they will be implemented in a real system. Secondly, the optimisation studies described above are all a form of deterministic optimisation. Stochasticity cannot be taken into account in deterministic optimisation, while it plays a significant role in container terminal operations (M. E. Petering et al., 2009). This is another argument for taking caution when implementing results from optimisation studies in a real system which is largely affected by stochasticity. Thirdly, Murty, Liu, Wan, and Linn (2005) mention that solutions from a deterministic model can only work when the workload at a terminal is evenly distributed over time. In a container terminal this is not the case, since vessel arrival triggers peak operations and also the arrival of trucks delivering or picking up containers is not evenly distributed over time. Thus it can be questioned how sustainable the optimisation results are in reality.

As opposed to optimisation, simulation is able to model the complex interaction between system components (Roy & de Koster, 2014). As Hartmann (2004) describes, simulation can be used to evaluate the dynamic process at container terminals, to identify potential bottlenecks, and to provide a testing environment for optimisation. It can be used both in the design phase of a new terminal as in the case of analysing or modifying an existing one. Moreover it can be used as a decision support tool for the management department. This research will use simulation as the main method to gain insight in the way stochasticity affects the performance of stacking operations.

Regarding simulation, generally three types of simulation can be used: System Dynamics, Discrete Event and Agent Based Modelling (Borshchev & Filippov, 2004). A container terminal, or more specifically an import yard block which is the subject under investigation in this research, represents a relatively detailed system with low abstraction and on operational (micro) level. System Dynamics generally focuses on continuous processes, while Discrete Event and Agent Based models work more on a discrete time scale. That means that the model will evolve when a discrete event has taken place or based on discrete time steps. A difference between Discrete Event and Agent Based Models is that the first one generally is used to model systems with middle or high detail (low abstraction level), while the latter one can be used to represent high to low abstracted systems. Another important difference is that Agent Based Models work with agents of which their behaviour is defined at individual level, while Discrete Events are defined on a more central level. Based on the differences described above and the ability of Discrete Event Simulation to model queues and shared resources, the operations concerning the container yard block are best captured in a Discrete Event Model.

C. Performance Indicators

Based on this review the following indicators have been defined to represent stacking performance: the number of reshuffles, the truck service time and the maximum yard operating equipment utilisation rate per hour. The number of reshuffles will be calculated by counting the reshuffle moves yard operating equipment has to make and dividing them by the total number of retrievals, hence the KPI will be reshuffles per retrieval. In case the reshuffles per retrieval decrease, service times of hinterland transport modes will decrease and yard operating equipment productivity will increase. The truck service time will be calculated by the difference between the time a hinterland transport mode arrives at the row and the moment it leaves the row again after being served. The SC travel time from the row to the hinterland transport mode gate is not taken into account in this KPI. The maximum yard operating equipment utilisation per hour is an interesting measurement during peak hours. When this KPI could be decreased, one can assume that the utilisation of yard operating equipment is more spread over the entire day, in stead of clustered during peak hours. The utilisation will be calculated each hour by looking back at the percentage of time the equipment was busy for that hour.

III. MODELLING

The model designed in this research is based on a SC operated multimodal container terminal. Data has been provided by the MSC PSA European Terminal (MPET) in Antwerp on terminal layout, retrieved volumes per hinterland transport mode over a period of 46 weeks, truck arrival distributions, average dwell time and average truck service times. MPET is the largest container terminal in Europe (MSC PSA European Terminal, 2018).

A. Conceptual model

The main processes in the model are arrivals of import containers from the seaside and arrival of hinterland transport modes from the landside. The high level terminal process of connecting the seaside and landside is split up into three processes. First, the model generates container arrivals at the yard. This is done based on a container arrival rate.

Secondly, the model stores the incoming containers. Dependent on the bay in which the container is stored, the SC will need more or less time to store the container, hence a certain delay is assigned to the storage process.

The third process is the retrieval of containers at the landside. This latter process is split up into 5 sub-processes. Upon the arrival of an external truck (XT), barge or train, a pick-up request is generated (1) that notifies the model of which container is requested. Then, the model needs to determine whether the requested container is on top, or whether a reshuffle is necessary (2). It then either performs this reshuffle (3), or it directly picks up the requested container (4). Both sub-processes 3 and 4 entail another delay based on the bay the container is in. Lastly, it delivers the container to the hinterland transport mode, after which this latter one leaves the model with container loaded onto it (5).

During storage and retrieval a levelling stacking strategy is implemented, as well as reshuffle logic that specifies to which location a container that is stacked on top of a requested container should be relocated. Based on the level of stochasticity, the hinterland transport mode have a larger chance to retrieve containers that were expected to be picked up later, i.e. with an Expected Time of Departure (ETD) later than another container present in the yard.

The research objective is to quantify the relationship between stochasticity in arrival time (input 1) as well as type of hinterland transport mode (input 2) and the stacking performance (output). To fulfil this objective, the model should meet the following requirements:

1) The model should capture the main dynamics of import containers: their arrival time in the yard area, storage duration in the yard and departure time out of the yard again once a hinterland transport mode has requested the containers.
2) The model should monitor reshuffle moves once a container is requested that is not the highest one in a bay.
3) The model should represent stochasticity in arrival times of hinterland transport modes.

4) The model should represent the stacking performance by calculating the performance indicators (reshuffles per retrieval, truck service time and maximum SC utilisation per hour)

The arrival rate of import containers from seaside to the import yard block is based upon data from MPET. The arrival of containers is assumed to be equal to the departure of containers from the import yard.

Data from MPET provides information on the modal split per import container. These numbers are converted to modal split per TEU in the model. That means, from all the retrieval requests, the distribution of next modes of transport per TEU is 11% for rail, 26% for barge and 63% for trucks. Since the simulation model generates containers based on TEU instead of container numbers, the terms TEU and container are used interchangeable.

The stacking strategy consists of a set of rules and based on these rules a location is determined to store or to relocate a container. The rules implemented in the model are as follows:

- Upon arrival of the containers in the import yard block, a random non-full row is selected to store the container in. Since the model represents a single row, this first selection process is not modelled.
- Within the row, the bay that is closest by and has the least amount of containers in it will be selected. This corresponds to a levelling strategy within one row.
- Once a hinterland transport mode has selected a container out of the yard to be retrieved, the model determines whether the requested container is at the top of the bay or not.
- In case it is not, the model chooses one directly neighbouring bay and determines whether the number of containers in that specific bay is less than three (maximum operational stacking height). In case it is, the model retrieves the requested container from the top of the bay and the retrieval request is fulfilled.
- In case the number of containers in the neighbouring bay is less than 3, the top container of the first bay is relocated to that neighbouring bay.
- In case it is not, the process continues to the other neighbouring bays, until a bay has been found that contains less than three containers.
- In case no bay with less than three containers is available, the model temporarily stores the container(s) on top of the requested container on top of a bay that is already 3-high. This temporarily 4-high stacking takes place in the direction of the quayside, so that the SC can exit the row with the requested container at the landside.
- Once the SC has left the row, the 4-high stacked containers are immediately placed back into their previous bay, to prevent the row from being blocked by a container that is stacked 4 high (absolute maximum stacking height).
- Once one container has been relocated, the number of reshuffles is increased by one.
- Then the process starts again, to determine whether the requested container is on top in the new situation.

The conceptual model is implemented and specified in Simio Simulation Software, a modelling framework based on intelligent objects. The bays are stacked 3 high and served with SCs that are able to stack 4 high. However, a bay will only be filled to its maximum in rare cases during some reshuffle moves, preventing blockage of an entire row for further SC moves.

B. Data specification

MPET has provided data on the number of full containers retrieved by each of the modes over a period of 46 weeks in 2018. It is assumed that the number of container departures equals the number of container arrivals at the modelled row over the long run. This can be assumed since it is known that the amount of TEU in the yard is not decreasing nor increasing on average over a longer time. Moreover, it is assumed that each container that is delivered to the yard will be picked up eventually. The model represents one import container row of a block of 41 rows with each row consisting of 14 TEU ground slots. Based on the total number of retrieved full import containers (IC) and a TEU factor (TEUf) of 1.612 resulting from a weighted average of the TEU factors per mode, the average dwell time (DT) for import containers of 4.78 days, the number of days in 46 weeks (d), the maximum stacking height (SH) of 3 containers and a yard efficiency of 1/1.15 (Yeff), the total number of TEU ground slots (TGS) can be calculated with the following equation:

$$TGS = \frac{IC * TEUf * DT}{d * SH * Yeff} \tag{1}$$

This results in an average value of 4770 TEU per day.

However, stochasticity plays a large role in container terminal operations. Hence, this equation does not represent a fixed number, but an average value to scale the container volumes of the entire terminal to the single-row model in this study.

The relative size of the yard block (574 TEU) compared to the TGS per day, results in a volume percentage of 12 of the total container volume that goes through the block. Based on this percentage and the fact that the model works with container arrivals per hour, the weekly amount of arriving TEUs is divided equally over the hours in a week and proportionally to the size of the block. In the model the arrival rate is divided by 41 to represent arrivals for 1 row. Based on this data, a table of average Inter Arrival Times (IATs) in hours per week is constructed. The model selects a random row of this table to define the IAT it will implement each time a container is generated. Hence, the IAT for containers can differ per container generation. On average it will results in an arrival rate of 52.29 containers per week in the modelled row. A container arrival triggers hinterland transport mode creation. When a hinterland transport mode is created, it will arrive at the yard after the determined container dwell time. This latter value follows from a triangular distribution with minimum, mean and maximum values of respectively 1, 4.78 and 8 days. When the arrival day of the hinterland transport mode is selected, a specific hour and minute will be selected based on random uniform distributions. With respect to trucks, this process is slightly different, since trucks can only arrive from 6:00 AM on Monday morning until 6:00 AM on Saturday morning. MPET has provided a rate table on the amount of truck arrivals over a week for week 2 of 2019 in intervals of 1 hour. Out of this data, the average TEU requests for the considered block spread over 1 week in intervals of 1 hour are calculated (see Figure 1). In determining the arrival time of trucks after a truck container generation, these arrival rates are taken into account, i.e. peak hours have a larger chance of generating a truck request than non-peak hours. There can be a small mismatch in data since the retrievals are based on 46 weeks of 2018 and the truck arrival distribution is based on information of 1 week in 2019. However, the average truck distribution is assumed to stay relatively constant over the weeks. Hence, this mismatch is not expected to affect the results to a large extent.

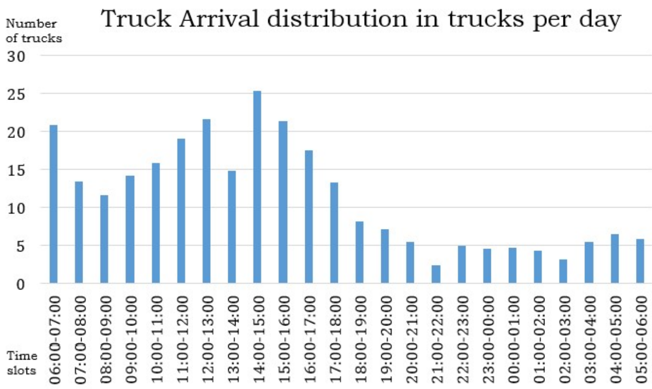

Fig. 1. Average truck arrival distribution Monday-Friday

Stochasticity is implemented in the model in the following way. Once containers arrive in the model they are attributed with an ETD based on a triangular distribution with a minimum of 1, an average of 4.78 and a maximum of 8 days. This distribution is based on the distribution of the dwell time of import containers in the yard.[1] In the container selection process when hinterland transport modes arrive, the model will search for a container with the lowest assigned ETD. In case of full certainty, the picked up container will always be the one with the lowest ETD, since the sequence of container retrievals is known in that case. However, when stochasticity is simulated, multiple containers with the lowest ETD values will be placed in a sub-list upon arrival of the hinterland transport mode. The hinterland transport will then randomly select a container out of this sub-list to pick-up. The more containers are in the sub-list, the higher the level of stochasticity is. In the base case experiment, the number of containers in the sub-list will be 1. Moreover, the effect of stochasticity in the next mode of transport on stacking performance can not be measured in this model, since the next mode of transport is not taken into account in the stacking strategy. It is a recommendation for further research to include stochasticity in next mode of transport in a model. In current operations in the model containers that are retrieved by each of the three hinterland transport modes are all placed in the same yard area.

[1] based on expert interview at MPET

IV. Results

Fourteen experiments have been run to test the effect of stochasticity on the stacking performance. In the experiments two configurations where tested: the implementation of housekeeping moves during non-peak hours (HK) or the non-housekeeping configuration (No HK). For these two configurations, results of experiments in which the level of stochasticity is varied, are achieved. The experimental setup is presented in Table I.

TABLE I. Experimental setup with 2 configurations (No HK moves and HK moves) and 7 scenarios, resulting in 14 experiments referred to as Stoch_X for the HK configuration and Stoch_X_Control for the non-HK configuration, where X represents the stochasticity scenario

Configuration	Scenarios: level of stochasticity						
	1	5	10	15	20	25	30
No Housekeeping moves	1	3	5	7	9	11	13
Housekeeping moves	2	4	6	8	10	12	14

The goal of the experiments is to estimate the effect of stochasticity on the performance of stacking operations. In order to do so, housekeeping moves are implemented to represent the use of information in stacking operations. The housekeeping moves are performed by a separate resource in the model (Housekeeping) which has a shift from 10:00 PM until 5:30 AM. When there is no other SC in the row at the moment the SC becomes on shift (i.e. no container arriving from the seaside and no container being retrieved by a request from the landside), it will consecutively check each bay, starting with bay 14 which is the bay the closest to the landside. After reshuffling a bay into the sequence of their ETDs, the model will check whether no other SC is waiting to deliver or retrieve a container. In case there is not, the housekeeping SC continues to the next bay. In case there is, the housekeeping SC will wait for the other SC to perform its activities, after which it will continue with housekeeping moves in the next bay.

In the base case (experiment 1), no housekeeping moves are performed. Stacking operations are performed in a levelling way, to maintain yard capacity and preference is given to available slots closer by to be able to free SC capacity as soon as possible. The amount of stochasticity is shown in the variable *StochLevel*, which is equal to 1 in the base case experiment. That means that the container with the lowest ETD is always selected from the yard. When stochasticity plays a role, multiple containers from the yard are selected in a sub-list out of which eventually 1 container is selected for a request. The higher the level of stochasticity, the larger the sub-list.

In the second experiment, where housekeeping moves are implemented for the first time, the level of stochasticity is equal to the base case experiment (*StochLevel* = 1). In the other experiments the level of stochasticity is increased with steps of 5 up until a stochasticity level of 30.

It is expected that housekeeping moves will increase stacking performance, i.e. lead to less reshuffles per retrieval, a shorter truck service time and a lower maximum SC utilisation per hour. When stochasticity increases, the effect of housekeeping moves is expected to become less, since the terminal is less capable of preparing itself for future retrievals, because the order of retrievals is less certain.

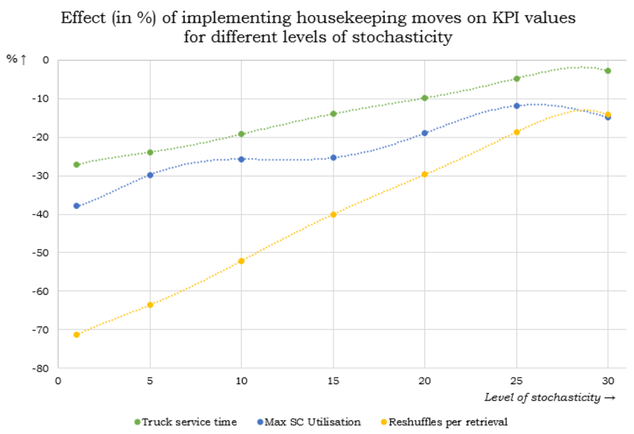

Fig. 2. Effect of housekeeping moves on KPIs per experiment

The results (see Figure 2) show that the implementation of housekeeping moves increases stacking performance in all of the stochasticity scenarios. In the base case experiment the reshuffles per retrieval, truck service time and maximum SC utilisation per hour decrease with respectively 71.4%, 27.2% and 37.9%. In order to achieve these benefits, the terminal should deploy a housekeeping SC during non-peak hours (from 10:00 PM to 5:30 AM). To serve the entire import yard, the number of SC shifts needed is 10. When the level of stochasticity increases, the benefits achieved by implementing housekeeping moves decrease. Still, in the experiment with the highest level of stochasticity the reshuffles per retrieval, truck service time and maximum SC utilisation per hour can be decreased with 14.2%, 2.8% and 14.8% respectively. This means that housekeeping moves could spare 120 656 reshuffles per year, 883 hours in truck service time per year and 3 minutes per SC in peak hours in the scenario with high stochasticity. To obtain these benefits, approximately 8 housekeeping SC shifts should operate each night. The total SC working hours (operating hours for both the housekeeping SC and the SC that fulfils retrieval requests together) increase with 58 735 hours per year for the entire import yard. The results are also shown in Table II.

Moreover, it can be concluded that the higher the level of stochasticity is, the worse the stacking performance is. An increase in stochasticity from the Housekeeping experiment

TABLE II. EFFECT OF HOUSEKEEPING MOVES ON PERFORMANCE INDICATORS (RESHUFFLES PER RETRIEVAL (RPR), TRUCK SERVICE TIME (TST), MAXIMUM SC UTILISATION PER HOUR (SC_U), TOTAL SC WORKING HOURS (SC_WH) AND NUMBER OF HK SHIFTS NEEDED TO OBTAIN THE IMPROVEMENTS) FOR MINIMAL STOCHASTICITY AND MAXIMAL STOCHASTICITY SCENARIO

KPI	**Parameter value change**		**Interpretation of savings**
	No HK	HK	
Low stochasticity (StochLevel = 1)			
RPR	0.95	0.27	639 764 reshuffles per year
TST (min)	3.32	2.42	8 854 hours per year
SU_U	0.36	0.22	8 min per peak hour
SC_WH	132.5	303.5	60 714 hours per year
Number of HK SC shifts needed per night: 10			
High stochasticity (StochLevel = 30)			
RPR	0.91	0.78	120 656 reshuffles per year
TST (min)	3.25	3.16	883 hours per year
SC_U	0.35	0.30	3 min per peak hour
SC_WH	129.0	294.4	58 735 hours per year
Number of HK SC shifts needed per night: 8			

(StochLevel = 1) and the Stoch_20 experiment (StochLevel = 20) namely increases the reshuffles per retrieval with 142.6%, the truck service times with 23.2% and the maximum SC utilisation per hour with 25.7% in the experiments. In other words, a large increase in stochasticity implies an increase in reshuffles per retrieval from 0.27 to 0.66, i.e. 365 029 additional reshuffles per year for the entire terminal. Moreover, the truck service time increases from 2.42 to 2.98 minutes, which entails 5 488 additional hours a year. Lastly, an increase in maximum SC utilisation per hour from 0.22 to 0.28, leads to a time loss of 3.4 minutes per hour per SC during peak hours. When the level of stochasticity increases even further, the effect on the KPIs becomes stronger. In comparison of the Housekeeping experiment with the Stoch_30 experiment, 475 998 additional reshuffles per year, 7 237 hours per year truck service time and 4.6 minutes time loss in peak hours per SC are observed.

The results of this research should be interpreted with respect to the assumptions that have been made in order to design a simulation model that is able to answer the research question in the available time scope. Because the model only includes containers of 1 TEU size, the amount of container moves is slightly overestimated in this research as well as the effects of housekeeping moves and stochasticity on the performance indicators. Moreover, the model represents one single row of the entire import yard. Hence, the total SC fleet in the import yard area and other transport requests the SCs have to perform are not taken into account when a container is requested. Instead, a SC is immediately available for retrieval of the container out of this single row. Likewise, the waiting time of trucks for a SC to become available is not included in the truck service time. This leads to an underestimation of the the maximum SC utilisation rate per hour and the truck service time.

In terms of stakeholders that could help to reduce stochasticity, shipping agents are key. However, sharing information would jeopardise their flexibility, while their benefits seem limited in comparison to the benefits for the terminal operator. Additional research into stakeholder cooperation is recommended to explore incentives for shipping agents to share information or to explore scenarios in which they are likely to do so.

V. Conclusion & Future Research

Based on this research it can be concluded that a terminal can improve stacking operations by implementing housekeeping moves, even in scenarios with high stochasticity. The lower the level of stochasticity is, the stronger the improvements on stacking operations are. However, in order to decrease stochasticity the stakeholder network should be consulted. The main stakeholder that could help in contributing to a lower level of stochasticity is the shipping agent. However, current benefits for the shipping agents are limited compared to the sacrifice they have to make in terms of flexibility. The main favoured party of a lower level of stochasticity is the terminal operator. Hence, future research to incentives for shipping agents to cooperate in sharing information is recommended.

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B

Previous studies

Table B.1 gives an overview of optimisation studies, organised based on their (sub)problems and objectives.

Table B.1: Literature overview optimisation studies

Study	**(Sub)problem**	**Objective**
Gharehgozli (2012)	Efficient container stacking operations	Minimise total travel time ASC Minimise makespan Minimise expected number of reshuffles
Hwan Kim & Bae Kim (1999)	Storage allocation import containers	Minimise expected total numbers of reshuffles
Kang et al. (2006)	Derive a good stacking strategy	Minimise the number of rehandles
Kim & Bae (1998)	Re-marshalling export containers	Minimise number of reshuffles Minimise total travel distance
Kim & Hong (2006)	Determine storage location of outbound containers (by 3 stages: space allocation, locating individual containers, locating relocated containers during pickup operations)	Minimise number of relocations during pickup operations
Kim & Kim (1999)	Routing SC	Minimise total travel distance of SCs between bays
Kim & Park (2003)	Space allocation for outbound containers in a yard	Minimise travel distance of handling equipment
	Sequencing containers	Minimise handling effort Maintain stability of vessel Satisfy loading requirements
Kim et al. (2000)	Optimal storage locations of arriving export containers	Minimise number of expected relocations for the loading operations
Kim & Kim (1997)	Routing algorithm for single YC to load export containers	Minimise total handling time YC
Li et al. (2009)	Yard crane scheduling	Minimise linear combination of the retrieval earliness and storage and retrieval delays
Murty et al. (2000) and Murty et al. (2005)	Develop decision support tool	Minimise time taken to process the vessels (berthing time) Minimise resources needed for handling the workload Minimise waiting time for XTs Minimise congestion on the roads inside the terminal, at the storage blocks, and docks inside the terminal Make best possible use of storage space available

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Table B.1 – *Continued from previous page*

Study	**(Sub)problem**	**Objective**
Preston & Kozan (2001)	Optimal storage strategy	Minimise turnaround time of container ships
Rashidi & Tsang (2013)	Allocation of berths to arriving vessels and QCs to docked vessels	Minimise total penalty (vessel) costs Maximise utilisation of berths and QCs
	Storage space assignment	Minimise distribution of total number of containers among blocks in the secondary storage Minimise the sum of transportation costs between both storage types Minimise reshuffling or reorganising volumes Minimise the costs of containers
	RTGC deployment	Minimise remaining workload at each block Minimise travelling time of RTGCs among blocks during planning horizon
	Scheduling and routing of vehicles	Minimise jobs's costs Minimise transportation costs Minimise waiting time of QCs and RTGCs
	Appointment times XTs	Minimise gate cost Minimise waiting time of XTs Minimise congestion at the gate of the terminal
Ünlüyurt & Aydin (2012)	Minimise the time required to retrieve containers from a bay	Minimise number of relocations Minimise number of relocations and total horizontal distance travelled by the YC
Wiese et al. (2010)	Optimal container terminal yard layout	Minimise handling costs
Zhang et al. (2003)	Efficient container handling	Reduce transportation costs and keep shipping schedules
	Storage allocation problem	Minimise total transport distance between yard and berth
	Assignment of total numbers of containers to a block	Balance workload of RTGCs and QCs
	Allocation of containers of each vessel to blocks	Minimise distance travelled between yard and berth

Table B.2 provides an overview of simulation studies, their goals and the performance indicator(s) mentioned in the research.

Table B.2: Literature overview simulation studies

Study	**Goal**	**Performance indicator(s)**
Chung (1986)	Develop and test strategies that can reduce unproductive movements of material handling equipment during loading process. Evaluate use of buffer space under different system parameters.	Load performance Material handling efficiency
Chung et al. (1988)	Evaluate use of buffer space to increase utilisation of material handling equipment and reduce total container loading time by reducing the unproductive movements of the YC during loading.	Total loading time Material handling equipment utilisation
Dekker et al. (2006)	Evaluate the performance of different stacking strategies	Number of reshuffles Number of reshuffle occasions 'No positions available' ASC utilisation Utilisation ground locations

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Table B.2 – *Continued from previous page*

Study	Goal	Performance indicator(s)
Duinkerken et al. (2001)	Evaluate the performance of different stacking strategies, different stack layouts and the number of AGVs	Stack response time (average move time for inbound and outbound moves) QC utilisation Percentage of containers that need re-stacking ASC utilisation
Gambardella et al. (1998)	Validation for la Spezia Container Terminal of Decision Support System based on optimisation	YC performance Net profit
Güven & Eliiyi (2014)	Increase efficiency of yard via consideration of the containers stacking optimisation problem	Utilisation ground locations Number of reshuffles Number of reshuffle occasions Posibility to add a new container
Liu et al. (2002)	Design, analyse and evaluate four different types of ATCs	Throughput Throughput per acre Ship turnaround time Truck turnaround time Gate utilisation Container dwell times Idle rate of equipment Average costs for moving a container
Liu et al. (2004)	Evaluate impact of automation (an AGVS) and terminal layout on terminal performance	Yard throughput Maximum speed QC Crane throughput Average idle rate QCs Average idle rate YCs Average idle rate AGVs Waiting rate per equipment (% of total simulation time waiting) Stop rate per equipment (% of total simulation time stopped to avoid collision) Average waiting rate Average stop rate
Petering (2011)	Develop a Decision Support Tool based on the effects of different studies on a terminal's long-run average QC rate. Study 1) Yard storage capacity; 2) Number of YCs deployed; 3) Number of YTs deployed; 4) Substitutability of YTs and YCs 5) YC linear gantrying, YC container handling, YT travel speeds; 6) Variability in YC and YT process times; 7) minimum YC separation distance; 8) Terminal operating system's ability to accommodate for YT substitutability; 9) Compare performance of different-sized terminals (different number of single-berth modules).	GCR Berth utilisation Storage volume utilisation Storage area utilisation QC waiting time YC waiting time (during storage/retrieval separately) YC gantrying time YT travelling time Container travelling time Average YC productivity Average YT productivity
Petering & Murty (2009)	Evaluate how a terminal's long-run average QC rate depends on 1) the length of storage blocks in the yard and 2) the system that deploys YCs among blocks in the same zone	Gross Crane Rate (GCR)
Petering et al. (2009)	Develop real-time yard control system and show that a terminal's long run average QC rate depends on he portion of this system that dispatches YCs in the storage area in real time	GCR

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Table B.2 – *Continued from previous page*

Study	Goal	Performance indicator(s)
Petering (2010)	Show how the long-run average QC rate depends on the system that automatically assigns YTs to container transportation jobs in the terminal in real time	GCR Berth utilisation Storage volume utilisation Storage area utilisation QC waiting time YC waiting time (during storage/retrieval separately) YC gantrying time YT travelling time Container travelling time Average YC productivity Average YT productivity
Roy & de Koster (2014)	New integrated queuing network model for rapid design evaluation of containers terminals with ALVs and AGVs, the models offer flexibility to analyse alternate design variations and to develop insights.	Expected throughput times Utilisation of vehicles, QCs and YCs Average number of vehicles waiting in buffer Expected queue length Variation of inter-departure times
Shabayek & Yeung (2002)	Investigate to what extent a simulation model can predict the anual container terminal operations at the Kwai Chung container terminal in Hong Kong better than current practices.	Handling capacity Average service time per vessel at a berth Utilisation of terminals Average system time
van Asperen et al. (2013)	Evaluating impact of truck arrival announcements on container stacking efficiency	Time in system Crane workload Number of reshuffle Number of reshuffle occasions Direct access to a container during retrieval by trucks
Yang et al. (2004)	Analyse how increases in the use of ALVs rather than AGVs affect the productivity of ACTs. Determine the number of ALVs and AGVs needed at a given service level and their impact of the cycle time.	Completion time QC QC waiting time QC productivity Mean waiting time in buffer or apron Mean waiting time for loading or unloading Mean moving time between apron and yard Mean waiting time in buffer of yard Cycle time AGV or ALV
Zhao & Goodchild (2010)	Evaluate the use of truck arrival information on terminal operations	Number of container rehandles

C
Data requirements

In order to obtain realistic inputs for the simulation model as well as to validate the simulation model, data has been requested at various container terminals. The specification of the data request can be found in Section C.1.

The goals of the data request are the following:

1. Goals of the **attributes per container**:
   (a) Determine differences in planned and actual arrival times of containers.
   (b) Determine differences in planned and actual departure times of containers.
   (c) Determine the share of containers for which a departure time is unknown upon arrival (only possible when information is not overwritten, see point 5b).
   (d) Determine share of container sizes, types, weight classes and directions (this research will be mainly focused on import containers, but the share of container directions is interesting to know in terms of terminal type and comparison to other terminals).
   (e) Determine modal split of next mode of transport.
   (f) Determine the share of containers for which a next mode of transport is unknown upon arrival (only possible when information is not overwritten, see point 5c).
2. Goals of the **general information** about the **terminal**:
   (a) In case detailed data is not available, an artificial data set can be based on this higher-level information.
   (b) In case detailed data is available, it is still nice to know these higher-level numbers for validation of the model and for comparison of this terminal to others in terms of vessel and container flow. However in that case it is also possible to calculate some variables, based on the detailed data on container attributes.
3. Goals of information about **changes in container data** concerning both **vessels** and **individual containers**:
   (a) Determine the (average) number of changes in *pick-up times* and in *next mode of transport*.
   (b) Determine the number of *reshuffles*.
   (c) Determine the (average) time in advance a change in information is made before container retrieval.

The possibility that the data are unavailable in time is considered, in that case the list in Section C.1 above provides a good indication for assumptions that have to be made. Another option is to construct an artificial database, preferably based on higher-level terminal data. Hartmann (2004) provides an example of an approach to generate realistic scenario data of port container terminals as input for simulation studies and as a test for optimisation algorithms.

C.1. Data Request

The list below shows the data request that has been sent to different terminals. In the expected situation that data will not be available in time, an artificial data set can be created based on assumptions that have to be made related to the points in the list. In that case, higher-level data as described under point 4, can provide a starting point for the data set and validation.

1. Minimum 1 year of data
2. Ideally data for a sizeable amount of containers should be available
3. The following attributes **per container** should (preferably) be included:
   (a) *Expected* date and time of *arrival* at the terminal
   (b) *Actual* date and time of *arrival* at the terminal ('time in system')
   (c) *Expected* date and time of *departure* from the terminal
   (d) *Actual* date and time of *departure* from the terminal ('time out of system')
   (e) Times at which information for *pick-up time* is provided (after/before arrival of container at the yard, or specific timestamp, if available)
   (f) Container *size* (20-ft, 40-ft, other)
   (g) Container *type* (e.g. reefer, empty container (MT), containers with dangerous goods (IMO), out of gauge (OOG))
   (h) Container *weight* (class)
   (i) Container *direction* (import, export, transshipment)
   (j) *Next mode of transport*
   (k) Times at which information for *next mode of transport* is provided (after/before arrival of container at the yard, or specific timestamp, if available)
   (l) Number of *housekeeping moves*
   (m) Number of *reshuffles* necessary because a requested container is stacked underneath other containers
   (n) Used *position(s)* on the yard (either more general block location or more specific row, bay and tier)
4. General information about the **terminal** that has handled the containers (can also be partially calculated from detailed list of container attributes):
   (a) *Number* and *type* of handling equipment
      i. Quay Cranes
      ii. Stacking cranes (e.g. Rail Mounted Gantry Cranes (RMGCs), Rubber Tyred Gantry Cranes (RTGCs), automated, manual)
      iii. Transport vehicles (e.g. straddle carriers (SCs), automated lifting vehicles (ALVs), forklifts, reach stackers, internal trucks, automated guided vehicles (AGVs))
   (b) *Expected* date and time of vessel *arrival* (ETA)
   (c) *Actual* date and time of vessel *arrival* (ATA)
   (d) *Expected* data and time of vessel *departure* (ETD)
   (e) *Actual* date and time of vessel *departure* (ATD)
   (f) (Average) number of *vessels* served per week/month
   (g) (Average) number of *containers* loaded and unloaded per week/month
   (h) (Average) *dwell time* of containers at the terminal
   (i) Share of *container sizes* and *types* handled
   (j) Share of import/export/transshipment *volumes*
   (k) *Modal split* next mode of transport (% train, truck, barge, ship)

(l) *Layout* of the yard (size; position with respect to seaside and landside; input/output points of yard from/to seaside and landside)

(m) *Stacking strategy* (current rules based on which is decided where to store a container in the yard)

(n) *Utilisation rates* of handling equipment (workload or % of time the equipment is busy, if available)

(o) How is the *arrival of containers* planned and logged (both planned and actual arrivals)?

  i. Based on vessel arrivals (e.g. 500 containers are planned at 10 a.m., in that case the planned arrival of containers is equal to the ETA of the vessel and the actual arrival of containers is equal to the ATA of the vessel)

  ii. Based on vessel arrival and quay crane lists (e.g. at 10 a.m. the vessel is ready to be unloaded, so the first container on the list will be unloaded at 10 a.m., the second on the list at 10:05, etc.)

  iii. Based on time slot at the berth (e.g. the vessel has a reserved time slot from 10 a.m. to 8 p.m., so there are 10 hours to unload 500 containers, container 1 will arrive at 10 a.m., container 2 at 10:01,2, etc.)

  iv. Other?

(p) How is the dwell time of containers logged (from actual arrival to actual departure of a container)?

  i. Is there a timestamp assigned to a container that is discharged from a deep sea vessel? If yes, when and how is this measured (e.g. arrival of the vessel, timestamp at which the QC picks up the container, timestamp at which the QC drops the container onto a transport vehicle for horizontal transport to the container yard, timestamp at which the container arrives at the yard, etc.)?

  ii. Is there a timestamp assigned to containers leaving the terminal at the landside? If yes, when and how is this measured?

  iii. In which time unit is the dwell time measured (days, hours, etc.)?

(q) How is the departure of containers planned and logged (planned departures)?

  i. How does a terminal make a planning for containers to be retrieved?

  ii. When is this planning made?

  iii. What is the share of containers that have an unknown departure time upon arrival at the terminal?

  iv. What is the share of containers that have an unknown next mode of transport upon arrival at the terminal?

5. Information about **changes in container data** concerning both **vessels** and **individual containers**

(a) When a vessel is known to be delayed, is this information updated in the system or does an initial planning remain unchanged in a database?

(b) When the expected pick-up time of a container is unknown upon arrival, does that ('empty') information remain in a 'log file', or will it be overwritten when the information is available? (and in the case this information is changed later on?)

(c) When the next mode of transport of a container is unknown upon arrival at the terminal, will this ('empty') information remain in a log file, or will it be overwritten when the information is available? (and in the case this information is changed later on?)

(d) Are changes in the position of a container in the yard logged? If yes, how?

  i. By specific *position* (e.g. 1st position of container X: row 1, bay 2, tier 3; 2nd position: row 3, bay 2, tier 1, etc.)

  ii. By number of *reshuffles* (e.g. the position of container X changed 3 times)

  iii. By *reshuffle occasion* (e.g. the position of container X is changed: yes/no)

  iv. Other?

(e) In case updated information is logged, are timestamps of updated information known (e.g. 2 days before pick-up of a container the next mode of transport was truck, 1 day before pick-up this is changed to train)? This relates to updates in the following information:

i. Planned *arrival time* of a container at the terminal
ii. Planned *pick-up time* of a container at the terminal
iii. *Next mode of transport*
iv. *Position* of containers in the yard

D

Simio model specification

This appendix chapter will describe the Simio simulation model in detail based on its processes and variables. First the container and hinterland transport mode variables will be discussed, then the model variables will be discussed based on the processes they are in.

D.1. Container and HTM variables

As shown in figure 4.5, the model consists of 1 source that generates container entities. Triggered by a container arrival at the yard, hinterland transport modes (HTMs) entities are created and temporarily stored in their respective parking station. The container variables are clarified in Table D.1. The variables for HTMs are illustrated in Table D.2.

Table D.1: Container Variables

Variable name	**State variable type**	**Description**
CurrentBay	Integer	Represents the number of the bay the container is in. This number is updated when a reshuffle or housekeeping move takes place. The buffer is logged ad bay 15. Once a container is being retrieved, the current bay turns 0.
Reshuffled	Boolean	Records whether the container has been reshuffled or not. This information is used in the StoreInBay processes, since information of reshuffled containers should not be stored in the ContTimes matrix again when they enter a new bay.
Buffered	Boolean	Records whether a container has been buffered or not. Once relocated from the buffer bay to another bay in the row, the buffered variable is set to false again. Information on that container is then not stored again into the ContTimes list. The number of containers in the 'new' row is increased with 1 during this relocation.
BaysToMove	Integer	Keeps track on the number of bays to move a container during a reshuffle. This value is then multiplied by the bay travel time to represent SC travel time of the reshuffle move.
ATA	Real	Value assigned to a container upon arrival of the container in the yard.
ETD	Real	Value assigned to a container upon arrival of the yard based on the dwell time distribution (Random.Triangular(1, 4.78, 7)).
Housekeeping	Boolean	Records whether a housekeeping move is performed, which means that a container will be shortly placed into another bay, after which it will be picked up again and positioned in its original bay of which the container sequence has changed because of the housekeeping move.
Housekeeped	Boolean	Records whether a container has been housekeeped, so that no new container information will be stored in the ContTimes list when this container enters a new bay.

Continued on next page

Table D.1 – *Continued from previous page*

Variable name	State variable type	Description
Type	Integer	Determines based on modal split whether the container is a truck, barge or train container. Based on the container type a specific HTM will be generated.

Table D.2: HTM Variables

Variable name	State variable type	Description
ATA	Real	Logs the ATA of trucks to record their service time (ATD - ATA).

D.2. Processes

In this section the model variables will be discussed based on the processes they are in.

Table D.3: Create hinterland transport modes

Variable name	State variable type	Description
ContType	Integer	Based on the function Random.Discrete(1, 0.11, 3, 0.37, 2, 1) the generated container will either be of type train (1, 11%), truck (2, 63%) or barge (3, 26%)). The variable Container.Type will be changed in the following step.
SetDelayTrain	Real	When a train container is generated, a HTM entity train will be created and delayed for a time based on the function Math.Floor(Random.Triangular(1, 4.78, 8)) * 24 + Math.Floor(Random.Uniform(0, 24)) + (Random.Uniform(0,60) / 60) to determine the day, hour and minute at which the train will arrive at the yard.
TrainQueue	Integer	When the train is parked in its respective station, the TrainQueue will be increased with 1 to keep track of the number of trains created.
SetDelayTruck	Real	When a truck container is generated, a HTM entity truck will be created and delayed for a time based on the function Math.Floor(Random.Triangular(1, 4.78, 8)) * 24 + Math.Floor(Random.Discrete(0, 0.017, 1 0.033, 2, 0.044, 3, 0.064, 4, 0.088, 5, 0.110, 6, 0.186, 7, 0.236, 8, 0.279, 9, 0.331, 10, 0.390, 11, 0.460, 12, 0540, 13, 0.594, 14, 0.688, 15, 0.766, 16, 0.831, 17, 0.880, 18, 0.910, 19, 0.937, 20, 0957, 21, 0.965, 22, 0.983, 23, 1)) + (Random.Uniform(0,60) / 60). This function will determine the day, hour (with respect to different arrival chances per hour) and minute for truck arrival. When this time leads to a moment after Saturday 6:00 AM and before Monday 6:00 AM, a new moment will be determined, since the truck terminal is closed during this period.
TruckQueue	Integer	When the truck is parked in its respective station, the TruckQueue will be increased with 1 to keep track of the number of trucks created.
SetDelayBarge	Real	When a barge container is generated, a HTM entity barge will be created and delayed for a time based on the function Math.Floor(Random.Triangular(1, 4.78, 8)) * 24 + Math.Floor(Random.Uniform(0, 24)) + (Random.Uniform(0,60) / 60) to determine the day, hour and minute at which the barge will arrive at the yard.

Continued on next page

Table D.3 – *Continued from previous page*

Variable name	State variable type	Description
BargeQueue	Integer	When the barge is parked in its respective station, the BargeQueue will be increased with 1 to keep track of the number of barges created.

D.2.1. Bay selection

The process of bay selection follows the process as described in Figure 4.1. Additionally however, the process checks whether another SC is present in the row when a container arrives and whether the row still has available slots.

Table D.4 describes the variables that are used in the bay selection process.

Table D.4: BaySelection Variables

Variable name	State variable type	Description
SCinRow	Boolean	Keeps track of whether a SC is present in the row delivering a container, performing a reshuffle or housekeeping move or retrieving a container.
NrContRow	Integer	Keeps track of the number of containers in the row.
NrContBay	Integer	Vector variable of 15 rows that keeps track of the number of containers present in each bay.
BayIndex	Integer	Variable used in the bay selection process to find the minimum bay based on NrContBay[BayIndex]. The BayIndex will then be used to search the table with Bay Inputs that refers to the input node for each separate bay.

D.2.2. Buffer

The buffer processes consist of 3 different processes. Firstly, similar to the store in bay process, a buffer process is fired when the row is at its maximum capacity and there is no available slot for a new incoming container in the bay. The container will then be placed in the buffer. Once a container is picked up by a hinterland transport mode, first the process PlaceBack4High is executed. This process checks whether containers are temporarily stacked 4 high due to a reshuffle in a relatively full row. Since 4-high stacked containers will block the row in case another container needs to be picked up or delivered, this process has high priority. After finishing the PlaceBack4High process, the hinterland transport mode will exit the server and the EmptyBufferBay process is executed. In this process the model checks whether there are buffered containers that can be relocated to an available slot in the row. However, when another hinterland transport mode is waiting to retrieve a container or when another SC is waiting to enter the row to deliver the container, the EmptyBufferBay process is cancelled, since this has less priority. Table D.5 describes the variables used in the buffer processes.

Table D.5: Buffer Variables

Variable name	State variable type	Description
BayToFill	Integer	When containers are temporarily stacked 4 high, this variable keeps track of the original bay they were placed into and should be placed back in after the requested container from the same bay has been picked up.
Bays4HighCounter	Integer	Is set to 1 when a container is stacked 4 high in the bay adjacent to the bay the requested container was in. This variable is used to determine the SC travel time further in the process. When a second container is stacked 4 high 2 bays next to the bay the requested container was in, the model should check whether there already is a SC present in the row that has placed a 4-high stacked container back. In that case the travel time of the SC for the second place-back is namely relatively lower. In case the model has not already placed back one 4-high stacked container, a new SC should be requested and therefore the travel time is higher.
Cont4High	Integer	Matrix of 14 by 2. Keeps track of the Container IDs that are temporarily stacked 4 high and their temporary bays. These values are assigned to the table in the Reshuffle process. In the PlaceBack4High process this matrix is searched for containers to be placed back in their original bay (BayToFill).
Bay4High1	Integer	Searches the Cont4High matrix for 4-high stacked containers adjacent to the BayToFill (Cont4High[Bay4High1,1]).
Bay4High2	Integer	Searches Cont4High matrix for containers 4-high stacked 2 bays next to the BayToFill.
HorizontalMoveTime	Real	Time it takes a SC to perform the horizontal move of picking up a container or storing it.
BayTravelTime	Real	Time it takes a SC to move over 1 bay, based on its average operating speed.

D.2.3. Checks

The checks process keeps track of the number of containers that have entered and left the model. An overview of the checks variables is given in Table D.6.

Table D.6: Checks Variables

Variable name	State variable type	Description
NrInComingContainers	Integer	Is increased with 1 when a container arrives from the source to the SelectionBay node.
NrLeavingContainers	Integer	Is increased with the number of batched containers to a hinterland transport mode when they leave Server1 together after retrieval.

D.2.4. Count departures

When a hinterland transport mode leaves Server1 after retrieval of one or more containers, they will be separated again in the model by Separator1. After separation each container and mode will be sent to a different sink. This to help validation of the model and have a quick view on the amount of hinterland transport modes per type as well as the amount of containers they have picked up. The containers will be separated based on their priority, which is respectively 1, 2 and 3 for train, truck and barge. The priority values have been assigned to containers in the retrieve process.

D.2.5. Housekeeping

Table D.7: Housekeeping Variables

Variable name	State variable type	Description
HKBay	Integer	Starts at 14 and counts back. This variable tracks the bay in which housekeeping moves are performed. When HKBay = 0 the housekeeping process is finished.
HK_Busy	Boolean	Keeps track of whether the model is busy with housekeeping moves or not. In case it is, the EmptyBufferBay process will not start since it is assigned with a lower priority than the housekeeping process.
HK_ID	Integer	Used to keep track of containers that should be placed 2 bays further in the housekeeping process but are currently in bay 14. This is modelled as both containers that should be moved +1 and +2 should be placed in the buffer. When the container that has been placed at +2 should be put back in the bay first, it is not on top of the buffer bay in the model. However, it is assumed that containers can be placed next to each other in buffer logic. The model thus searches for the container that matches the logged HK_ID and removes it from the buffer to place it back in the original bay.

The housekeeping logic is described in Figure D.1. In the model additional checks are added to this process. When the housekeeping SC becomes on shift (each dat at 10:00 PM), the model first checks whether there are no vehicles waiting at the landside to retrieve a container and whether there are no SCs in the row performing other activities. When one of these checks fails, the housekeeping SC will wait for 140 seconds after it will check again. The variables in the housekeeping process are presented in table D.7.

D.2.6. Reshuffle

The reshuffle logic is explained in Figure 4.3. It is triggered by the arrival of a hinterland transport mode with a pick-up request. Next to the total amount of reshuffles (NRReshuffles), the number of reshuffles per retrieval is also monitored. The tally statistic reshuffles per retrieval is used as KPI in the experiments.

Table D.8: Reshuffle Variables

Variable name	State variable type	Description
ChangeBay	Integer	Starts at 1 and counts up. For each bay up and down form the current bay the model checks whether there are spaces available to relocate the containers to that are on top of the requested container. When the row is completely full the containers will be temporarily stacked 4 high, as explained at the buffer process.
NRReshuffles	Integer	Whenever a reshuffle is performed this value is increased with 1.

D.2.7. Retrieve

The retrieval process follows the logic as described in Figure 4.2. Whenever a request is generated from the generate request process, hinterland transport modes arrive at Server1 to pick up one or more containers. Upon arrival of a hinterland transport mode at Server1, the model first checks whether there are no SCs currently operating in the row, in case the row is ’free’ the model sets SCInRow to be true. Based on the type of hinterland transport mode, specific parts of the process are relevant. In case of trucks, only 1 container is retrieved. The model checks whether the requested container is present in the yard. In reality, this is not the case, since a hinterland transport mode will only pick up a container that is present in the yard and will not wait for containers to arrive. However, since the model in this research only represents one row, the model is sometimes not able to bear with the fluctuations in container arrival and departures. Therefore in this model it sometimes occurs that hinterland transport modes will wait for a container to arrive. In case they are waiting, the SCInRow will be set to false again. When the requested container is present, the pick-up process will be executed, including the reshuffle process when needed. Lastly, the PlaceBack4High process will be executed. In the pick-up process the tally statistics for container dwell time, truck service time and the difference between ATD and ETD of a container are calculated as well. Tally statistics can perform observations about specific unit types and give average values of all entities that run through the system over a specific part of the whole system.

Variables used in the retrieve process that have not been mentioned in the processes above, are presented in Table D.10.

D.2.8. SC utilisation

SC Utilisation is a separate process created for the tally statistics SC_Utilisation, SC_HK_Utilisation and SC_HK_Shiftutil (the working time per housekeeping shift). This statistic keeps track of the maximum utilisation rate of SCs per hour over a model run. The SC that performs housekeeping moves is not taken into account, since this is considered to be an additional SC operating in less busy times. The relevant variable in this process is described in Table D.9.

Table D.9: SC Utilisation Variables

Variable name	State variable type	Description
AtBeginning	Real	Represents the total time the SC was busy over the simulation run. This value is updated each hour based on a timer event, so it can be subtracted from the SC.ResourceState.TotalTime(1) the next hour.
AtBeginning_HK	Real	Represents the total time the housekeeping SC was busy over the simulation run. This value is updated each hour based on a timer event, so it can be subtracted from the Housekeeping.ResourceState.TotalTime(1) the next hour.
NrHKShifts		Monitors the number of housekeeping shifts performed in the model by checking the Housekeeping.ResourceState.TotalTime(1) at 22:00 PM to determine whether is is higher than the last recorded value at 22:00 PM the previous day. In case it is not, no new housekeeping moves have been performed. In case it is, the difference between the two values determines the working time for the last housekeeping shift.

D.2.9. Store in bay

For each different bay a separate StoreInBay process is created, which is linked to an input node for the respective bay. In the storage processes the Container.CurrentBay values are assigned. The model also checks in this process whether the process is triggered by the arrival of a 'new' container, or whether it is caused by a reshuffle or housekeeping move, or a container that comes from the buffer. Only in the case of a new container, information should be namely stored in the ContTimes list. In all the other cases information of the container has already been stored.

D.2.10. TAT truck

The TAT truck process is a separate process created for the tally statistic TurnAroundTime which is updated in the retrieve process. Once a truck enters the input node for Server1 the ATA of the truck is logged. Upon retrieval of a container this ATA is compared to the ATD to determine the service time of the truck. Since the model only represents one row, nothing can be concluded on the service times of trains and barges, since they generally collect containers from multiple rows.

Table D.10: Retrieve Variables

Variable name	Object type	Description
ContTimes	Real State Variable	Matrix (or list) of 90 rows and 3 columns which saves information of incoming containers in the yard. The columns respectively log ATA of containers, ETD of containers and container IDs. Later in the model information from this matrix is used to perform house-keeping move and select containers.
ContainerIndex	Integer State Variable	Used to search through ContTimes to find an empty row for new container information or to place back container information from StochasticConts (ContTimes[ContainerIndex, 1] = ContainerIndex.InitialValue) or when selecting containers for pick-up or the StochasticConts list (min(ContTimes[ContainerIndex, 2])) .
StochasticConts	Real State Variable	Matrix (or list) of 10 rows by 4 columns in which information of containers is stored in when selected out of the ContTimes matrix in the pick-up process. The higher the level of stochasticity the model should represent, the more rows of StochasticConts should be filled when selecting a container from ContTimes. The fourth column represents an additional value based on which selection will take place of the containers from the StochasticConts matrix for retrieval by a hinterland transport mode.
Stoch_Nr	Integer State Variable	Used to place container information from ContTimes in the StochasticConts list, as well as to search the StochasticConts list when selecting containers for the TruckConts, BargeConts or RailConts (min(StochasticConts[Stoch_Nr, 4]))
StochLevel	Integer property	Represents the level of stochasticity. Is used in selecting containers from ContTimes for StochasticConts, since the model checks whether Stoch_Nr is equal to the StochLevel. In case it is not, Stoch_Nr will be increased by 1 and another container will be added to StochasticConts.
TruckConts	Real State Variable	Matrix (or list) of 2 rows by 3 columns in which information of the container that is picked up by a truck is stored. This container is selected from the StochasticConts matrix.
TruckContainerNr	Integer State Variable	Used to determine the row in TruckConts. Since a truck in this model only collects one container, this value is always 1.
BargeConts	Real State Variable	Matrix (or list) of 7 rows by 3 columns in which information of the container(s) that is/are picked up by a barge is stored. This/these container(s) is/are selected from the StochasticConts list. 7 rows since in an earlier model version it was included that one barge could collect 7 containers from the row, in the final model this option is no longer specifically modelled.
BargeContainerNr	Integer State Variable	Used to determine the row in BargeConts, with a maximum of 7.
RailConts	Real State Variable	Matrix (or list) of 11 rows by 3 columns in which information of the container(s) that is/are picked up by a train is stored. This/these container(s) is/are selected from the StochasticConts matrix. 11 rows since in an earlier model version it was included that one train could collect up to 11 containers from the row, in the final model this option is no longer specifically modelled.
TrainContainerNr	Integer State Variable	Used to determine the row in RailConts, with a maximum of 11.

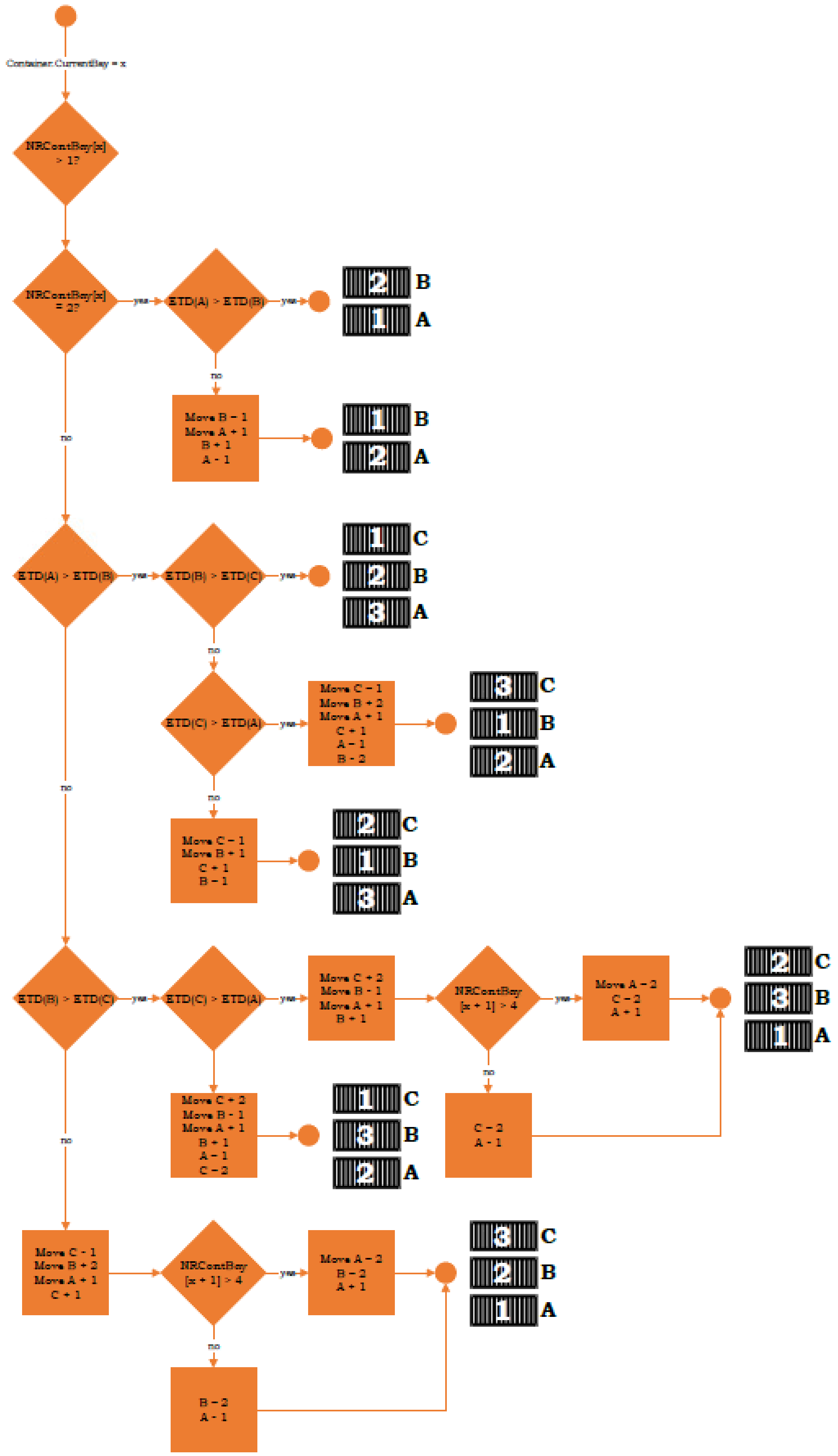

Figure D.1: Housekeeping logic

E

Verification

Verification of the model is performed iteratively during model development as well as at the end of model construction. The methods used for verification were visually by animation, tracing, and with extreme conditions testing.

E.1. Visual verification

Since Simio provides an extensive visual presentation of the model, it could easily be seen whether the model behaves as expected. Firstly, containers should arrive from the container source and trigger the creation of hinterland transport modes that are temporarily stored in their respective station. Upon arrival of a hinterland transport mode at the yard, a container should be retrieved and possible reshuffle movements should be executed to access the retrieved container. After retrieval of the container, the buffer should be checked and containers present in the buffer should be relocated to a position in the bay if there are available slots after the retrieval of a container. Since both container arrival and retrieval vary over time in the model, the fill rate of the bay is expected to vary. As can be seen in Figure E.1, the amount of containers in the yard fluctuates over a test simulation run of 50 weeks around an average value of approximately 35. The row operating capacity is 42, hence this represents a fill rate of 83%. An important not for the test run is that no warm-up period is taken into account, so the model results of the first 28 days should not be taken into account. As could be seen, the model needs some time to reach a steady state, after which the volume of containers in the row fluctuates over time.

Moreover, the simulation time presented on the horizontal axis does not match real points in time. The input data is based on real data from 46 weeks and randomly assigned to points in the simulation time. At small moments in time the capacity of the row exceeds its maximum and the buffer capacity in the model is used, which is represented by the red line in the graph. This is not an unlikely scenario, given the data provided by the reference terminal, which represents a very crowded terminal.

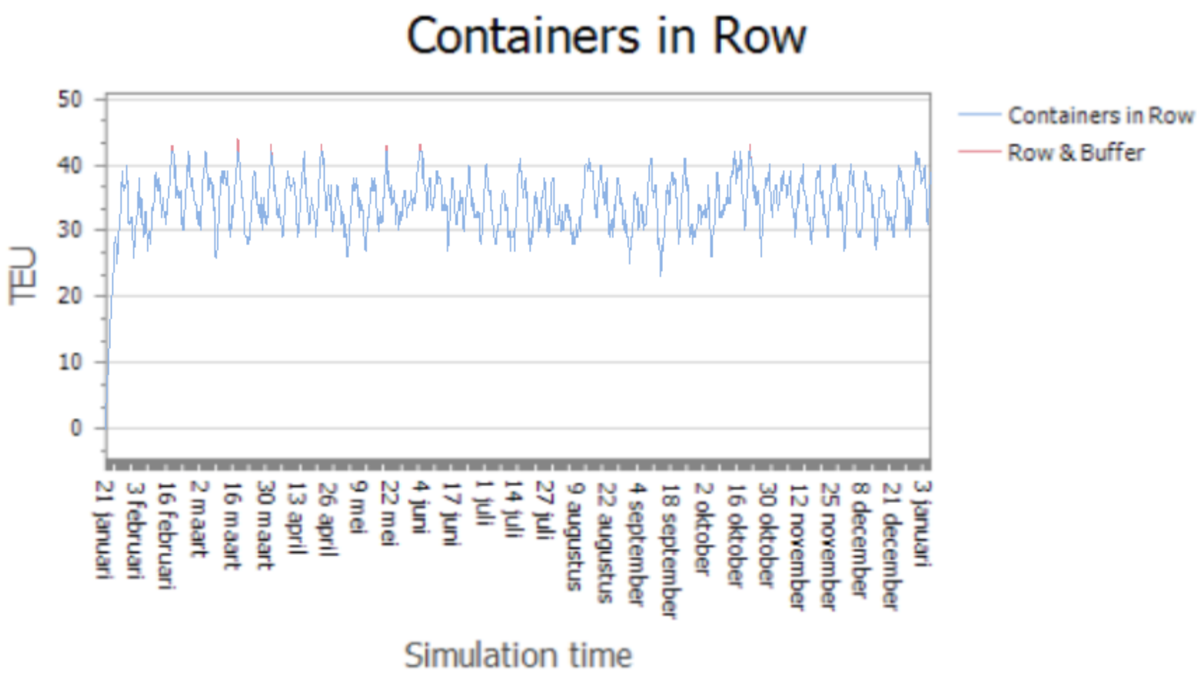

Figure E.1: Amount of containers in yard over time for test run base case experilment

Moreover, in the test run without housekeeping moves it is visible that the SC utilisation calculated each hour of the simulation run varies over time (see Figure E.2. At some point in time the utilisation is 0, when no retrieval requests are done. At other points in time peaks are visible, when for example multiple requests are made in one hour. The SC utilisation is not representative for the terminal as a whole, since only one row is modelled. Hence, it is not taken into account when a hinterland transport mode has to wait for a SC to become available before its request can be fulfilled and the model underestimates the actual utilisation rate. Moreover, the experiment results described in Section 5.4 show that the maximum SC utilisation of the base case experiment is 0.36, which does not match the maximum SC utilisation presented in Figure E.2. The housekeeping SC is not used in the base experiment, hence the housekeeping SC utilisation is 0 over the entire test run.

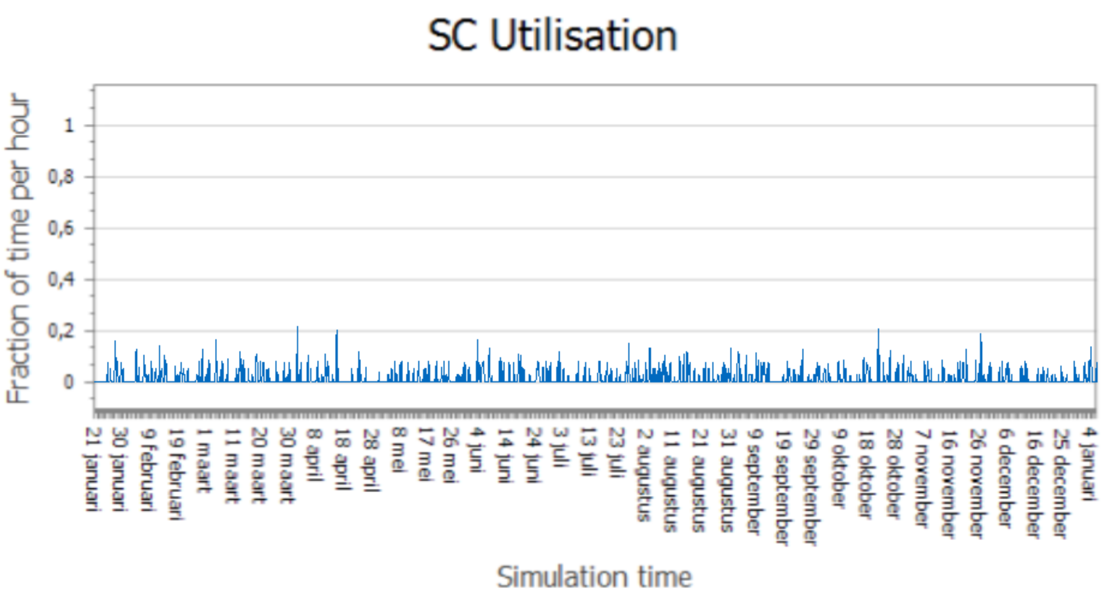

Figure E.2: SC utilisation over time for test run base case experiment

Another test run of 50 weeks is performed with an active housekeeping SC. As expected, the volume of the containers in the row does not vary much from the non-housekeeping (base) scenario (see Figure E.3). However, the SC utilisation is slightly flattened out in the housekeeping scenario, while the housekeeping SC is used extensively at some points in time in the simulation. This follows the expectations, since housekeeping moves will prepare the entire row for expected retrievals. Once this is done, container sequences are expected to match the retrieval sequence for some time (i.e. less SC utilisation during retrievals), after which new containers have been placed on top and new housekeeping moves are requested. Since the row is relatively full, reorganising only a few containers might already ask multiple moves from the housekeeping SC, so the housekeeping SC will be occupied for a large percentage of time per hour. This can also be seen when zoomed in for example for a period of 21 days, as shown in Figure E.6. What can also be seen in this figure is that the housekeeping SC is used each night in this snapshot. However, in some nights it operates only around 40% of the hour (24 minutes). That is why the assumption is made that the implementation of housekeeping moves might be done once every 3 nights per row.

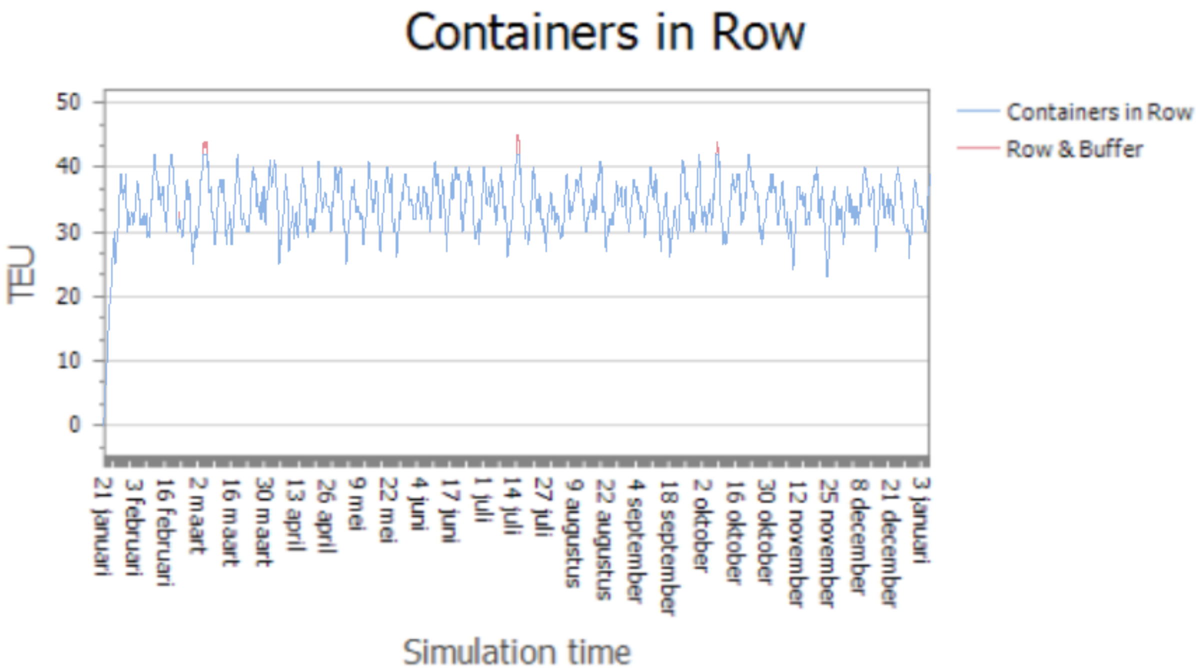

Figure E.3: Amount of containers in yard over time for test run housekeeping experiment

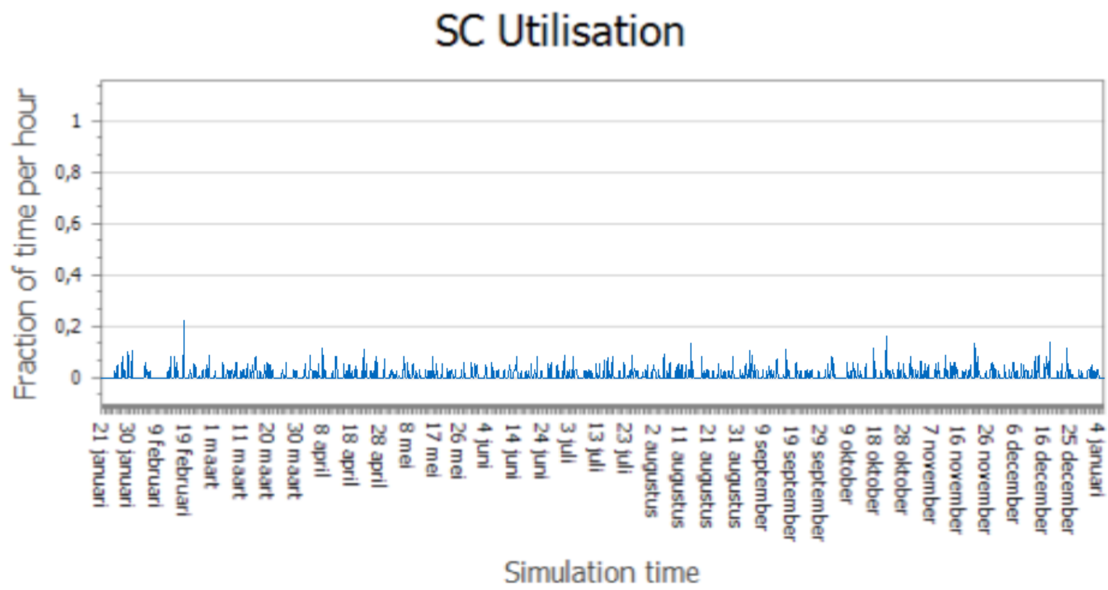

Figure E.4: Amount of containers in yard over time for test run housekeeping experiment

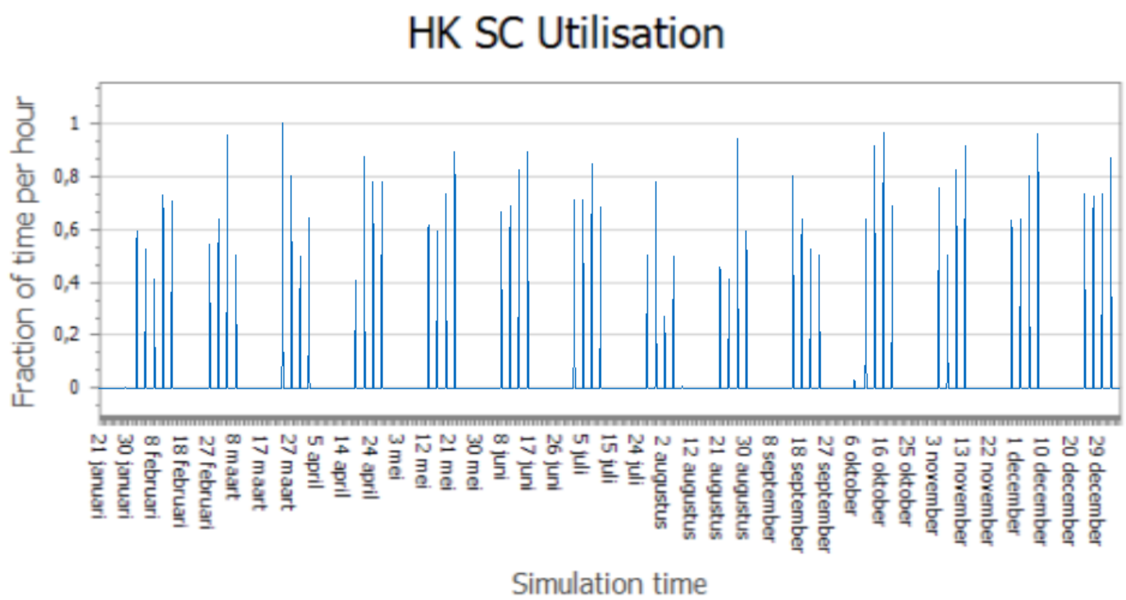

Figure E.5: SC utilisation over time for test run housekeeping experiment

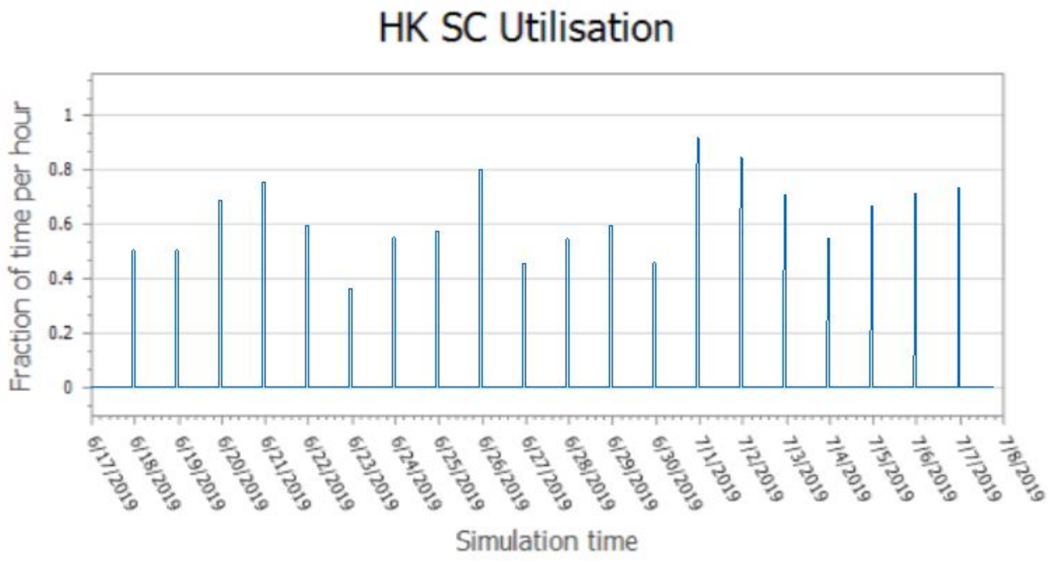

Figure E.6: SC utilisation 21 days for test run housekeeping scenario

E.2. Tracing

During model development tracing has also been performed in an iterative way. In this report 2 tracing will be described. The descriptions are not base don the final model, but the main model behaviour has not changed between the model version used for tracing and the final model. However, exact points in simulation time and entity numbers differ in the descriptions below and the final model version. Still, the descriptions can be used for model verification.

The most important changes between the model described in this section and the final model are the arrivals of hinterland transport modes. In the model version in this sections, hinterland transport modes arrive independently, while in the final model version the arrivals of containers triggers the creation of hinterland transport modes that are parked in their respective station for a period of the dwell time of the container that triggered their creation. Hence, hinterland transport mode arrivals and container arrivals are correlated. However, buffer, reshuffle and retrieval processes are still largely the same, hence the description of model behaviour in this section is maintained.

The first description is of a container (container1.6245) in a relatively empty row. This trace is represented in Table E.1. The second trace is of a container (container1.36568) in a relatively full row, which is represented in Table E.2. Both trace descriptions are simplified to represent model behaviour in an understandable way and to test the model. In both tables the run time in hours is presented in the first column, the second column mentions the entity that generates behaviour. The third column show process descriptions in which the terms in bold represent sub-processes in the model and the terms in italic decision steps in the model.

As can be seen in Table E.1, the model follows the steps:

- Create container.
- Select a bay for the container.
- Store the container in the chosen bay.
- Record the container data in the ContTimes table.
- Generate hinterland transport mode (in this example a truck). NB: in the final model the hinterland transport mode creation is triggered by container generation and the mode will be delayed in its respective parking station for a period equal to the dwell time of the container.
- Select container out of ContTimes (in this example no stochasticity is implemented because there are less container in the ContTimes table than the specified level of stochasticity (5)).
- Pick up container from the row and check whether reshuffles are necessary (in this case not).
- Batch container and hinterland transport mode.
- Check whether containers are temporarily stacked 4 high and need to be placed in another bay (in this case not).
- Check whether containers can be removes from the buffer and places in the row (in this case not).

The trace of container1.36568 differs from the trace of container 1.6245 in the following aspects:

- In the selection process for the container, there is no available slot in the row. Hence, the container is placed in the buffer.
- After departure of truck.36593, a slot becomes available in the row for container1.36568. The container is relocated to bay 11 in the EmptyBufferBay process.
- Upon arrival of Truck.37899 5 containers out of the ContTimes matrix are recorded in the StochasticConts matrix. The model then selects container1.36568 from the StochasticConts matrix for the TruckConts matrix.
- After container1.36568 is batched to Truck.37899 the model checks whether new containers can be placed from the buffer into the model. This is the case, so container1.37882 is relocated from the buffer to bay 11.

Table E.1: Trace of Container1.6245

Runtime (hours)	**Entity**	**Process Description**
692.5399	Container_Generator	Create Entities
	Container1.6245	SelectionStation Entered: Execute SelectBay
		SelectBay: *NoSCInRow?*: True (SCInRow == False) *RowNotFull?*: True (NrContRow < 42) Find lowest NrContBay: Bayindex 3 (min(NrContBay[BayIndex]) DirectContainer: InputBay3
		Set NrIncomingContainers + 1 (= 217)
		Bay3Entered
		StoreInBay3: Container1.6245.CurrentBay == 3 Set NrContBay[3] + 1 (= 1) Set SCInRow == True (1) Delay with SC_TravelTime for 0.01278 hours until 692.5532
692.5531	Container1.6245	Find Empty Row ContTimes Record ATA: ContTimes[ContainerIndex, 1] & Container1.6245.ATA == 692.553 Record ETD: ContTimes[ContainerIndex, 2] & Container1.6245.ETD == 816.9436 Record ID: ContTimes[ContainerIndex, 3] == 6245 Set NrContRow + 1 (= 9) Set SCInRow == False (0)
720.9580	Truck_Generator	Create Entities
	Truck.6600	Input@Server1 Entered: TAT_Truck
		TAT_Truck: Truck.ATA == 720.9595

Continued on next page

Table E.1 – *Continued from previous page*

Runtime	Entity	Process Description
	Truck.6600	**SelectContainers:** *NoSCInRow*? True (SCInRow == False) Set SCInRow == True (1) Seize SC *Truck*?: True (EntityType == Truck) Find LowestETD (min(ContTimes[ContainerIndex,2])) *ContainerInYard*?: True (ContTimes[ContainerIndex,2] is not InitialValue) Record StochasticConts[1,1] == 692.5532 Record StochasticConts[1,2] == 816.9436 Record StochasticConts[1,3] == 6245 Record StochasticConts[1,4] == 2 ResetContTimes (ContTimes.InitialValue) *Enough containers in row for stochasticity*? False (NrContRow >= StochLevel) SelectContainers (min(StochasticConts[Stoch_Nr,4]) Record TruckConts[1,1] == 692.5532 Record TruckConts[1,2] == 816.9436 Record TruckConts[1,3] == 6245 ResetStochasticConts (StochasticConts.InitialValue) Re-fill ContTimes PickUp
		Search Truck Container from TruckConts
	Container1.6245	**PickUpContainersTruck:** *Container.Buffered*? False ReshuffleCheck Wait for RetrieveOK
		ReshuffleCheck: *Is container on top*? True (Container == Container.CurrentStation.Contents.LastItem) Fire: RetrieveContainer
		PickUpContainer_Truck: Set Container.Priority == 2 (turn container in other colour) Delay with SC_TravelTime for 0.03 hours until 720.9895
720.9895	Container1.6245	**PickUpContainers_Truck:** Set NrContBay[3] - 1 (=0) Set Container1.6245.CurrentBay == 0 Batch ContainerMember
	Truck.6600	Add Container1.6245 to batch members of parent entity Truck.600
	Container1.6245	Record value tally statistic DwellTime (=28.3946) Record value tally statistic TurnAroundTime (=0.03) Set NrContRow - 1 (=3)
	Truck.6600	**PlaceBack4High:** *BayToFill > 0*? False
		SelectContainers: Release SC Set SCInRow == False (0)
		NrLeavingContainers + 1 (=223)
		EmptyBufferBay: *NoVehiclesInQueue*? True (Server1.InputBuffer.Contents.NumberWaiting == 0) *NoHousekeeping*? True (HK_Busy == False) *NoSCInRow*? True (SCInRow == False) *BufferBayUsed*? False (BufferBay.Contents > 0)

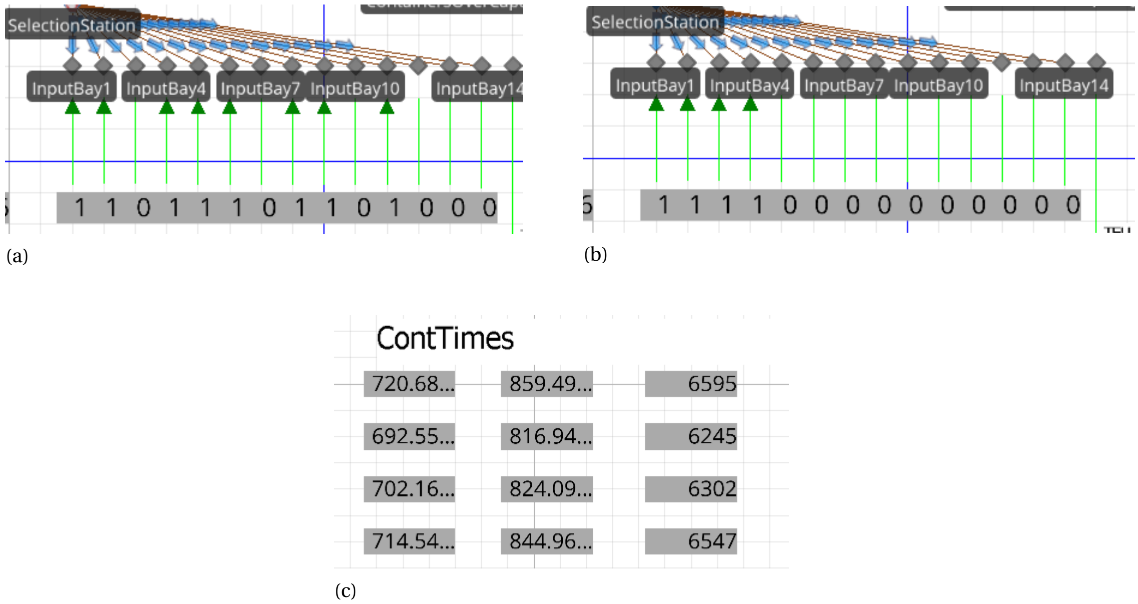

Figure E.7: Screenshot of Simio model trace 1

Screenshots are taken from the model in order to visually verify the description in table E.1. As seen in Figure E.7a, when Container1.6245 arrives in the yard it should be sent to the bay that is 1) closest by and 2) has the least amount of containers in it (bay 3). When Truck.6600 arrives the yard is filled as shown in Figure E.7b. At that moment the matrix ContTimes is filled as shown in Figure E.7c. Therefore the model selects Container1.6245 with the lowest Container.ETD (shown in the second column). Figure E.8 shows Container1.6245 that has turned red (because of a change in priority value) batched to Truck.6600.

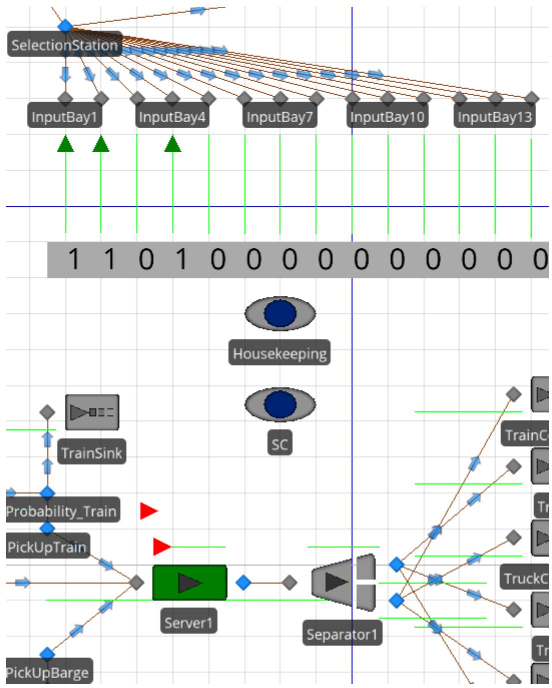

Figure E.8: Screenshot of Simio model trace 1 pickup

In Figure E.9 the row is shown upon arrival of Container1.36568. The row is full, hence the container will be placed in the buffer. Upon retrieval of the container (Figure E.10) an available spot in bay 11 will be created for Container1.37882 to be stored in.

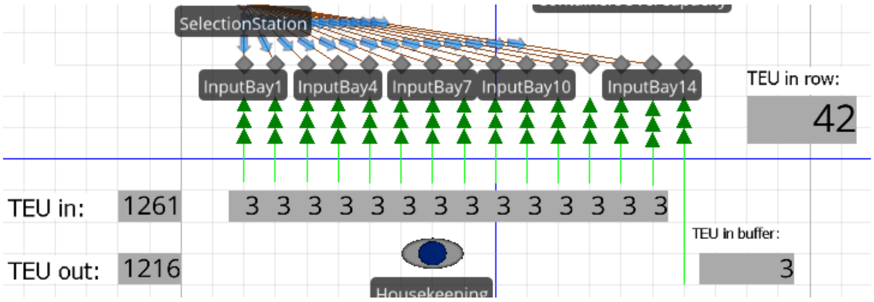

Figure E.9: Screenshot of Simio model trace 2 upon container arrival

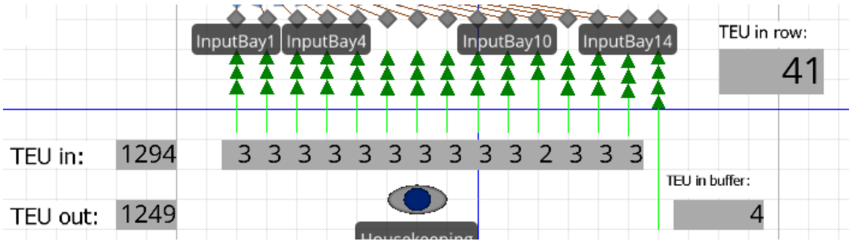

Figure E.10: Screenshot of Simio model trace 2 pickup

Table E.2: Trace of Container1.36568

Runtime (hours)	**Entity**	**Process Description**
4041.1673	Container_Generator	Create Entities
	Container1.36568	SelectionStation Entered: Execute SelectBay
		SelectBay: *NoSCInRow?*: True (SCInRow == False) *RowNotFull?*: False (NrContRow < 42) SetNode: InputBuffer
		Set NrIncomingContainers + 1 (= 1262)
		BufferBayentered
		StoreInBuffer: Container1.36568.CurrentBay == 15 Set NrContBay[15] + 1 (= 4) Set Container1.36568.Buffered == True (1) Set SCInRow == True (1) Delay with SC_TravelTime for 0.015 hours until 4041.1861
4041.1861	Container1.36568	Find Empty Row ContTimes Record ATA: ContTimes[ContainerIndex, 1] & Container1.36568.ATA == 4041.1861 Record ETD: ContTimes[ContainerIndex, 2] & Container1.36568.ETD == 4081.8025 Record ID: ContTimes[ContainerIndex, 3] == 36568 Set SCInRow == False (0)
4043.195	Truck.36593	After picking-up container1.35011, EmptyBufferBay: *NoVehiclesInQueue*? True (Server1.InputBuffer.Contents.NumberWaiting == 0) *NoHousekeeping*? True (HK_Busy == False) *NoSCInRow*? True (SCInRow == False) *BufferBayUsed*? True (BufferBay.Contents > 0) *SpacesFree*? True (NrContRow < 42 AND NrContBay [1] + ... + NrContBay[14] < 42) Search container in buffer (BufferBay.Contents): Container1.36568 found
	Container1.36568	**Emptybufferbay:** Set SCInRow == True (1) Seize SC Execute Reshuffle
		Reshuffle: *BayUpExists*? False (Container.CurrentBay + ChangeBay <= 14) *BayDownExists*? True (Container.CurrentBay - ChangeBay >= 1) *BayDown*? False (NrContBay[Container.CurrentBay - ChangeBay < 3]) Set ChangeBay == ChangeBay + 1 (=2) ... Set ChangeBay == ChangeBay + 1 (=4) *BayDown*? True (NrContBay[Container.CurrentBay - ChangeBay < 3]) Set Container1.36568.BaysToMove == 4 Delay with SC_TravelTime for 0.026667 hours until 4043.2221

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Table E.2 – *Continued from previous page*

<table>
<tr><th>Runtime</th><th>Entity</th><th>Process Description</th></tr>
<tr><td rowspan="3">4043.2221</td><td rowspan="3">Container1.36568</td><td>Reshuffle:
Relocate container to InputBay11
Set NrContBay[15] - 1 (= 3)
Set NrContRow + 1 (= 42)
Fire ReshuffleComplete
Set Container1.36568.Reshuffled == True (1)
Set NrReshuffles + 1 (= 385)
Reset ChangeBay to ChangeBay.InitalValue (= 1)</td></tr>
<tr><td>EmptyBufferBay:
Release SC
Set SCInRow == False (0)</td></tr>
<tr><td>StoreInBay11:
Set Container1.36568.CurrentBay == 11
Set Container1.36568.Buffered == False (0)</td></tr>
<tr><td rowspan="4">4146.9570</td><td>Truck_Generator</td><td>Create Entities</td></tr>
<tr><td rowspan="3">Truck.37899</td><td>Input@Server1 Entered: TAT_Truck</td></tr>
<tr><td>TAT_Truck: Truck.ATA == 4146.9585</td></tr>
<tr><td>SelectContainers:
NoSCInRow? True (SCInRow == False)
Set SCInRow == True (1)
Seize SC
Truck?: True (EntityType == Truck)
Find LowestETD (min(ContTimes[ContainerIndex,2]))
ContainerInYard?: True (ContTimes[ContainerIndex,2] is not InitialValue)
Record StochasticConts[1,1] == 4041.1861
Record StochasticConts[1,2] == 4081.8025
Record StochasticConts[1,3] == 36568
Record StochasticConts[1,4] == 1
ResetContTimes (ContTimes.InitialValue)
Enough containers in row for stochasticity? True (NrContRow >= StochLevel)
StochLevel? False (Stoch_Nr == StochLevel)
Set StochNr + 1 (= 2)
Find LowestETD (min(ContTimes[ContainerIndex,2]))
ContainerInYard?: True (ContTimes[ContainerIndex,2] is not InitialValue)
Record StochasticConts[2,1] == 4021.7927
Record StochasticConts[2,2] == 4096.8743
Record StochasticConts[2,3] == 36495
Record StochasticConts[2,4] == 1
ResetContTimes (ContTimes.InitialValue)
...
Record StochasticConts[3,1] == 3980.5360
Record StochasticConts[3,2] == 4100.6861
Record StochasticConts[3,3] == 36418
Record StochasticConts[3,4] == 5
...
Record StochasticConts[4,1] == 3986.8094
Record StochasticConts[4,2] == 4105.5199
Record StochasticConts[4,3] == 36446
Record StochasticConts[4,4] == 3
...</td></tr>
</table>

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Table E.2 – *Continued from previous page*

Runtime	Entity	Process Description
	Truck.37899	Record StochasticConts[5,1] == 3977.5068 Record StochasticConts[5,2] == 4106.6238 Record StochasticConts[5,3] == 36392 Record StochasticConts[5,4] == 3 ResetContTimes (ContTimes.InitialValue) StochLevel? True (Stoch_Nr == StochLevel) SelectContainers (min(StochasticConts[Stoch_Nr, 4]) Record TruckConts[1,1] == 4041.1861 Record TruckConts[1,2] == 4081.8025 Record TruckConts[1,3] == 36568 ResetStochasticConts (StochasticConts.InitialValue) Re-fill ContTimes PickUp
		Search Truck Container from TruckConts
	Container1.36568	**PickUpContainersTruck:** *Container.Buffered*? False ReshuffleCheck Wait for RetrieveOK
		ReshuffleCheck: *Is container on top*? True (Container == Container.CurrentStation.Contents.LastItem) Fire: RetrieveContainer
		PickUpContainer_Truck: Set Container.Priority == 2 (turn container in other colour) Delay with SC_TravelTime for 0.03 hours until 4146.9885
4146.9885	Container1.36568	**PickUpContainers_Truck:** Set NrContBay[11] - 1 (= 2) Set Container1.36568.CurrentBay == 0 Batch ContainerMember
	Truck.37899	Add Container1.36568 to batch members of parent entity Truck.37899
	Container1.36568	Record value tally statistic DwellTime (= 105.7608) Record value tally statistic TurnAroundTime (= 0.0299) Set NrContRow - 1 (= 41)
	Truck.37899	**PlaceBack4High:** *BayToFill > 0*? False
		SelectContainers: Release SC Set SCInRow == False (0)
		NrLeavingContainers + 1 (= 1249)
		EmptyBufferBay: *NoVehiclesInQueue*? True (Server1.InputBuffer.Contents.NumberWaiting == 0) *NoHousekeeping*? True (HK_Busy == False) *NoSCInRow*? True (SCInRow == False) *BufferBayUsed*? True (BufferBay.Contents > 0) *SpacesFree*? True (NrContRow < 42 AND NrContBay [1] + ... + NrContBay[14] < 42) Search container in buffer (BufferBay.Contents): Container1.37882 found

E.3. Extreme conditions testing

As the name already indicates, in extreme conditions testing one of the input parameters is set to extreme conditions and model behaviour is observed.

Table E.3: Extreme Conditions

Input parameter	Modification	Observed behaviour
Arrival rate containers	Very high	Row is filled to maximum capacity and buffer is extensively used. Since the high arrival rate, other model activities (such as EmptyBufferBay) will be blocked since a new container is already waiting at the node SelectionBay.
Arrival rate containers	Very low	Number of reshuffles decreases since the yard is relatively empty, hence requested containers are less often stacked below others.
Bay travel time SCs	Very high	High truck service times and high dwell times of containers, even when the row is not full.
Travel time SCs	Very low	Slightly smaller truck service time of trucks, since this is already relatively small in the current model.

F

Experimental Design

In this appendix the reasoning behind the main model settings for experiments are discussed. These settings are warm-up period, run length and number of replications.

F.1. Warm-up period

Different warm-up periods have been tested and compared based on the number of reshuffles per retrieval. The goal of the warm-up period is to initiate collecting statistics when the model has reached a steady state, i.e. that the empty starting conditions of the model will no longer affect the model outputs to a large extent. Since the model starts as an empty row, it is expected that the number of reshuffles per retrieval increases when the warm-up period increases, as no reshuffles are needed in the beginning of a model run. Some testing of warm-up periods is needed to determine which period renders accurate results. The warm-up periods have been tested over a run length of 40 weeks and 40 replications. The results are shown in Table F.1. As shown in Table F.1, the number of reshuffles per retrieval stays the same when the warm-up period increases and the confidence interval broadens as the warm-up period increases. Boxplots of the spread around mean values are given in Figure F.1 for warm-up periods of 0, 7, 14, 21, 28, 70 and 140 days. As can be seen in the boxplots, when choosing a warm-up period of 140 days, 2 replication results are identified as outliers. It seems that when the warm-up period will be too large, the system results show more variance in the amount of reshuffles per retrieval. Also following the idea retrieved from Figure E.1, a warm-up period of less than 1 month would be sufficient to reach a stable system. Hence, a warm-up period of 28 days is chosen.

Table F.1: Warm-up period tests

Warm-up period (days)	**Mean number of reshuffles per retrieval ± 95% confidence interval**
0	0.95 ± 0.0057
7	0.95 ± 0.0057
14	0.95 ± 0.0059
21	0.95 ± 0.0060
28	0.95 ± 0.0060
70	0.95 ± 0.0069
140	0.95 ± 0.0078

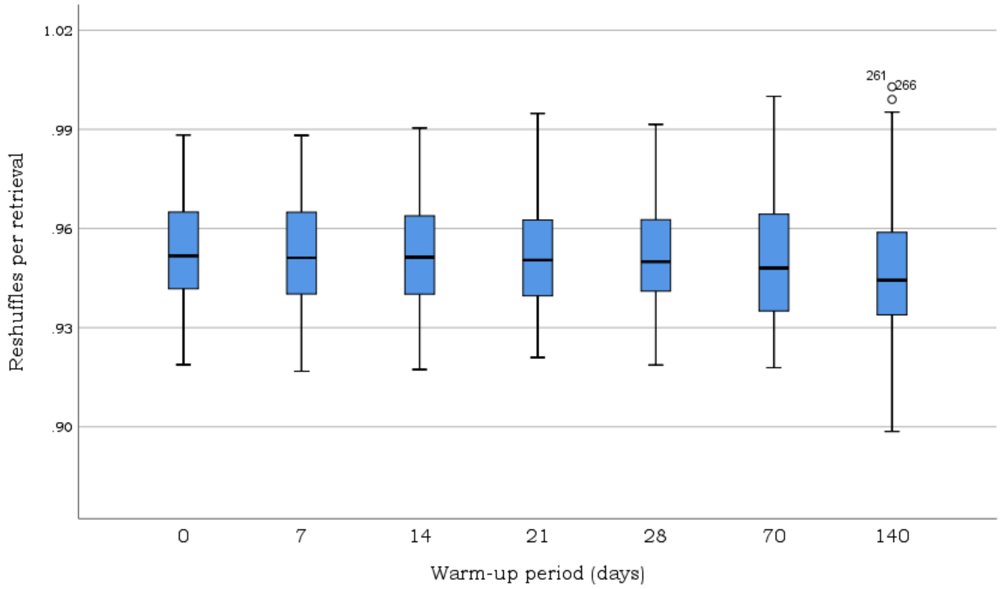

Figure F.1: Number of reshuffles per retrieval for different warm-up periods

F.2. Run length

Different run lengths are tested based on the effect on the number of reshuffles per retrieval. The run length should be large enough to capture the dynamics of arrivals and retrievals of containers, but short enough to facilitate an acceptable run completion time. The run lengths have been tested with model settings of a warm-up period of 28 days and 40 replications. Similar as with the warm-up period, when increasing the run lengths the number of reshuffles per retrievals reaches a stable value of 0.95 (see Table F.2). The number of reshuffles per retrieval will be low when the row is empty and higher when the row becomes full. Therefore it is expected that with a longer run, the number of reshuffles per retrieval is expected to average out. Figure F.2 shows the box plots of amount of reshuffles per retrieval for the the different run lengths. As can be seen when the run length is short, since the boxes are larger and outliers are present, the data for reshuffles per retrieval shows more variance. When the run length increases to 60 weeks, again, outliers are visible which represents a larger variance in the data. A run length of 50 weeks is chosen for the experimental setup, as this run length reaches a stable average number of reshuffles per retrieval and the variance in the data is acceptable.

Table F.2: Run length tests

Run length (weeks)	**Mean number of reshuffles per retrieval ± 95% confidence interval**
10	0.95 ± 0.022
20	0.96 ± 0.0097
30	0.96 ± 0.0066
40	0.95 ± 0.0060
50	0.95 ± 0.0052
60	0.95 ± 0.0045

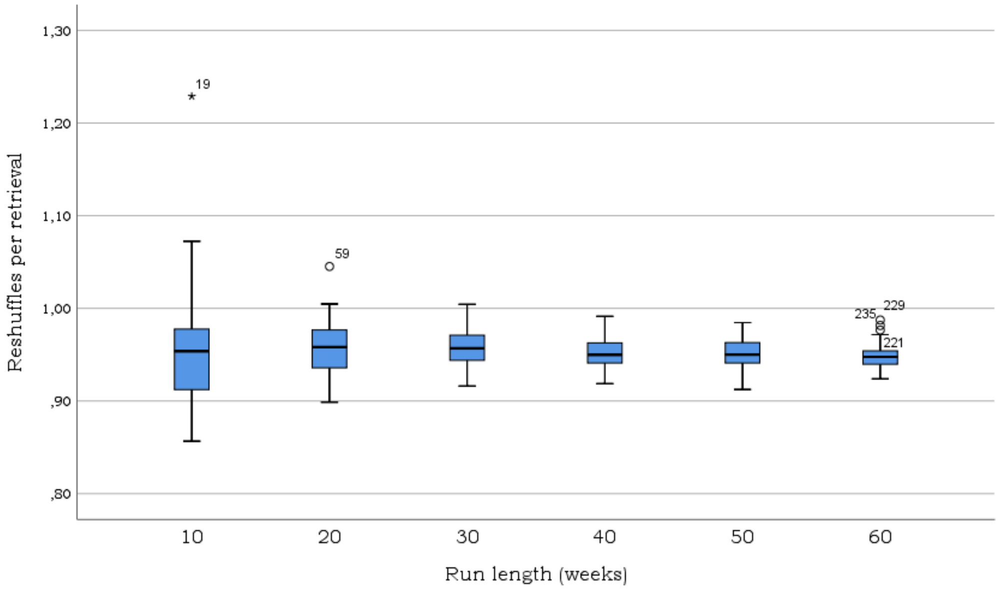

Figure F.2: Number of reshuffles per retrieval for different run lengths

F.3. Number of replications

To determine the adequate number of replications, a similar process is performed as in determining the warm-up period and run length. The expectation is that the higher the number of replications will be, the more narrow the confidence interval is. Since a too large number of replications will hinder an acceptable run completion time, a trade-off should be made. As can be seen in Table F.3, the number of reshuffles per retrieval is again 0.95 for different number of replications. Figure F.3 shows that the mean number of reshuffles per retrieval either increases or decreases slightly when 10 more replications are done. The run completion time with 50 replication is still acceptable and the fluctuation in mean number of reshuffles per retrieval seems to become less when more replications are done. Hence, 50 replications are chosen.

Table F.3: Number of replications

Number of replications	Mean number of reshuffles per retrieval ± 95% confidence interval
20	0.95 ± 0.0076
30	0.95 ± 0.0060
40	0.95 ± 0.0052
50	0.95 ± 0.0053
60	0.95 ± 0.0049
70	0.95 ± 0.0046

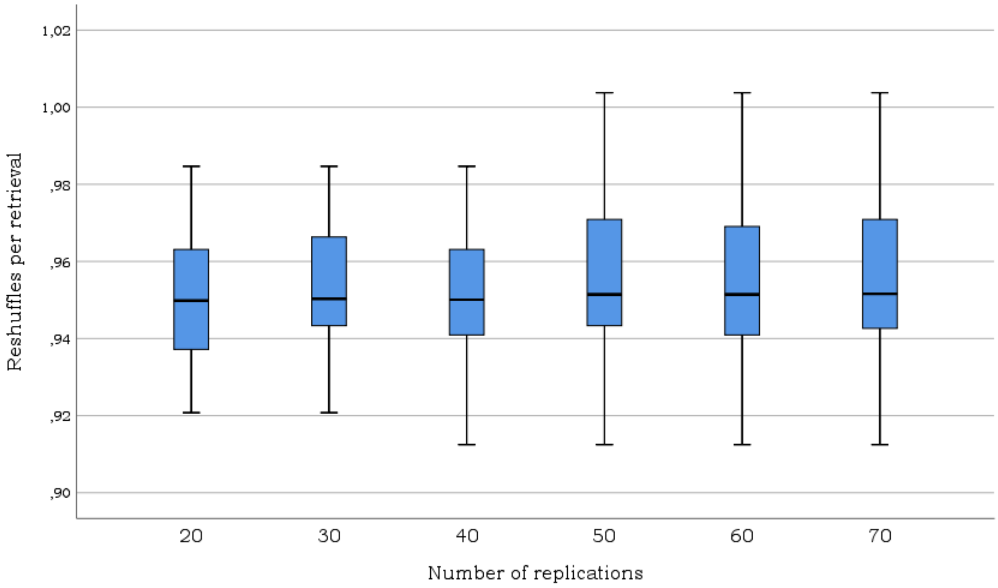

Figure F.3: Reshuffles per retrieval for different number of replications

G
Additional results from experiments

Table G.1: Stoch_5 (4) compared to Stoch_5_control experiment (3)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	8.374	0.005	-196.738	0.000	-63.6%
Nr of HK shifts	103.349	0.000	983.890	0.000	-
Truck service time (min)	0.026	0.872	-125.099	0.000	-23.9%
Max SC utilisation	0.000	0.986	-9.709	0.000	-29.8%
Total SC working hours	19.680	0.000	303.016	0.000	131.2%

Table G.2: Stoch_10 (6) compared to Stoch_10_control experiment (5)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	6.302	0.014	-142.029	0.000	-52.1%
Nr of HK shifts	75.473	0.000	978.923	0.000	-
Truck service time (min)	0.039	0.844	-91.894	0.000	-19.2%
Max SC utilisation	0.052	0.819	-8.028	0.000	-25.7%
Total SC working hours	11.205	0.001	239.844	0.000	127.1%

Table G.3: Stoch_15 (8) compared to Stoch_15_control experiment (7)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	3.999	0.048	-102.851	0.000	-40.0%
Nr of HK shifts	131.400	0.000	786.831	0.000	-
Truck service time (min)	0.742	0.391	-65.342	0.000	-13.9%
Max SC utilisation	8.491	0.004	-8.675	0.000	-25.3%
Total SC working hours	6.891	0.010	246.701	0.000	125.2%

Table G.4: Stoch_20 (10) compared to Stoch_20_control experiment (9)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	4.390	0.039	-77.617	0.000	-29.7%
Nr of HK shifts	109.446	0.000	891.118	0.000	-
Truck service time (min)	0.270	0.605	-43.639	0.000	-9.8%
Max SC utilisation	2.702	0.103	-5.598	0.000	-18.9%
Total SC working hours	12.019	0.001	280.515	0.000	123.7%

Table G.5: Stoch_25 (12) compared to Stoch_25_control experiment (11)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	1.121	0.292	-45.824	0.000	-18.6%
Nr of HK shifts	127.020	0.000	789.690	0.000	-
Truck service time (min)	1.033	0.312	-20.842	0.000	-4.7%
Max SC utilisation	5.375	0.023	-3.776	0.000	-11.8%
Total SC working hours	16.778	0.000	251.103	0.000	124.5%

Table G.6: Stoch_30 (14) compared to Stoch_30_control experiment (13)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	1.947	0.166	-35.949	0.000	-14.2%
Nr of HK shifts	74.324	0.000	857.984	0.000	-
Truck service time (min)	6.730	0.011	-13.209	0.000	-2.8%
Max SC utilisation	13.106	0.000	-4.093	0.000	-14.8%
Total SC working hours	26.243	0.000	239.473	0.000	128.2%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Conts	Between Groups	331.246	13	25.480	.849	.608
	Within Groups	20558.576	685	30.013		
	Total	20889.823	698			
ContRow	Between Groups	.780	13	.060	1.161	.304
	Within Groups	35.382	685	.052		
	Total	36.162	698			
TruckG	Between Groups	2144.901	13	164.992	.300	.992
	Within Groups	376679.694	685	549.897		
	Total	378824.595	698			
TrainG	Between Groups	1912.692	13	147.130	.689	.775
	Within Groups	146251.568	685	213.506		
	Total	148164.260	698			
BargeG	Between Groups	4007.755	13	308.289	.649	.813
	Within Groups	325362.248	685	474.981		
	Total	329370.003	698			
DwellTime	Between Groups	7.211	13	.555	1.169	.298
	Within Groups	324.947	685	.474		
	Total	332.158	698			

Figure G.1: ANOVA test for handled container volume and dwell time for all 14 experiments

Table G.7: Base case experiment (1) compared to Stoch_5_control experiment (3)

KPI	**F-value**	**Sig.**	**t-value**	**Sig.**	**Difference**
Reshuffles per retrieval	0.001	0.969	1.422	0.158	-0.5%
Truck service time (min)	0.459	0.500	0.971	0.334	-0.2%
Max SC utilisation	0.066	0.798	2.203	0.030	-6.5%

Table G.8: Base case experiment (1) compared to Stoch_10_control experiment (5)

KPI	**F-value**	**Sig.**	**t-value**	**Sig.**	**Difference**
Reshuffles per retrieval	0.236	0.628	0.361	0.719	-0.2%
Truck service time (min)	2.461	0.120	-0.116	0.908	0.0%
Max SC utilisation	0.499	0.482	0.578	0.565	-1.8%

Table G.9: Base case experiment (1) compared to Stoch_15_control experiment (7)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.334	0.565	2.494	0.014	-1.0%
Truck service time (min)	0.271	0.604	3.209	0.002	-0.6%
Max SC utilisation	1.929	0.168	0.921	0.359	-2.9%

Table G.10: Base case experiment (1) compared to Stoch_20_control experiment (9)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.345	0.558	3.450	0.001	-1.4%
Truck service time (min)	3.404	0.068	3.181	0.002	-0.6%
Max SC utilisation	3.806	0.054	1.163	0.248	-3.7%

Table G.11: Base case experiment (1) compared to Stoch_25_control experiment (11)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.096	0.757	8.486	0.000	-3.5%
Truck service time (min)	0.501	0.481	8.493	0.000	-1.6%
Max SC utilisation	0.964	0.329	2.423	0.017	-7.7%

Table G.12: Base case experiment (1) compared to Stoch_30_control experiment (13)

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.885	0.349	13.158	0.000	-4.8%
Truck service time (min)	0.043	0.836	12.693	0.000	-2.3%
Max SC utilisation	8.057	0.006	0.580	0.563	-2.2%

Table G.13: Base case compared to Housekeeping experiment for $\frac{2}{3}$ of the container volume

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	21.374	0.000	147.410	0.000	-77.0%
Nr of HK shifts	104.504	0.000	-563.791	0.000	-
Truck service time (min)	4.467	0.037	118.420	0.000	-23.2%
Max SC utilisation per hour	4.540	0.036	13.022	0.000	-27.6%
Total SC working hours	51.177	0.000	-206.146	0.000	108.1%

Table G.14: Stoch_20_control compared to Stoch_20 experiment for $\frac{2}{3}$ of the container volume

KPI	F-value	Sig.	t-value	Sig.	Difference
Reshuffles per retrieval	0.085	0.771	23.763	0.000	-16.2%
Nr of HK shifts	81.991	0.000	-415.440	0.000	-
Truck service time (min)	0.011	0.917	12.711	0.000	-3.1%
Max SC utilisation per hour	0.273	0.602	1.620	0.109	-4.2%
Total SC working hours	63.112	0.000	-185.843	0.000	106.0%