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Limiting the Performance Loss of an RTG Container Terminal with a Highly Utilized Storage Yard

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by

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TU Delft

Preface

Dear reader,

As I pen down the final words of this master thesis, a sense of achievement and gratitude fills me up. This academic journey has been a challenging yet immensely rewarding experience, and the completion of this work marks a significant milestone. It's been a journey of ups and downs, late nights, and countless cups of coffee. Yet here we are.

For the past 9 months, I have been working on my research looking into the possibilities to mitigate performance loss of RTG container terminals with highly utilized storage yards, ultimately resulting in what feels like a magnum opus—my thesis.

First and foremost, I would like to express my appreciation to Portwise, where I had the privilege of undertaking my graduation internship. The time spent at Portwise has been an invaluable part of my academic and professional growth. I am grateful to Arjen de Waal for his guidance throughout the project. I would also like to express my gratitude to the entire team for their warm welcome and for creating an enjoyable work environment. I appreciate the positive atmosphere and the camaraderie that made working here a truly pleasant experience.

Additionally, I extend my gratitude to my supervisor at the university, Mark Duinkerken, for his unwavering guidance throughout this thesis journey. I appreciate the moments when a gentle nudge turned into a motivating "kick in the ass" that kept me on track. His guidance played a pivotal role in shaping the direction and caliber of this work. I would like to thank Rudy Negenborn, for his valuable insights during the meetings.

To everyone who lent an ear, shared a laugh, or handed me a tissue during the stressful moments, thank you.

In conclusion, I present this thesis, a product of dedication and shared knowledge. May it contribute in its own modest way to the reservoir of academic discourse.

Thank you.

S. Wiersma
Delft, December 2023

Summary

This research addresses the critical role of the Yard Utilization Rate (YUR) in the performance of container terminals, focusing on Rubber-Tyred Gantry (RTG) terminals. The Yard Utilization Rate represents the percentage of the total yard capacity utilized for container storage. While a Yard Utilization Rate of 100% is unfavourable due to the necessity of free space for reshuffling, optimal terminal performance is generally maintained up to a certain Yard Utilization Rate threshold. However, exceeding this threshold results in a significant drop in terminal performance.

Until recently, reaching the Yard Utilization Rate limit was infrequent, but with the increasing size of ships and the popularity of online ordering, especially during peak seasons like the weeks preceding Christmas, container supply increases. Existing literature reveals a gap in studies specifically targeting high Yard Utilization Rates in RTG container terminals.

The performance of the terminal is defined as the container throughput within a certain amount of time and therefore the Key Performance Indicator of focus is the QC productivity. The QC productivity is defined as the average number of lifts at a terminal per QC working hour. The terminal that will be studied is an RTG terminal with remote-controlled RTGs and Terminal Trucks (TTs) and External Trucks (XTs) for container transport. The XTs arrive at the gate. They either are delivering or picking up a container. The XT drives to the right stack where the RTG lifts the container from the truck to place it on a stack, or the RTG places a container from the stack on the truck. So, the XTs provide the transport of the containers between the storage location and the gate. TTs provide the transport of the containers between the quay and the storage location.

In conclusion, this study addresses the significant gap in knowledge regarding high Yard Utilization Rates in container terminals, specifically focusing on RTG terminals. By examining the relationship between the YUR and terminal performance, the research aims to provide valuable insights and solutions to enhance operational efficiency in highly utilized container yards. This leads us to the main research question of this study:

How to reduce QC productivity loss of an RTG container terminal with a highly utilized storage yard?

A Root Cause Analysis (RCA) is done and identifies key factors affecting loading and unloading processes, with a focus on the root causes *Too few TTs deployed*, *Congestion*, and *YUR too high*. Design alternatives are proposed to address these root causes, and three design alternatives are tested through simulation: varying the number of Terminal Trucks (TTs), sacrificing driving lanes for additional storage space, and implementing an alternative shuffle policy with a different bay distribution. Results show a significant influence of the number of TTs on QC productivity, with an optimum at 8 TTs per QC. Sacrificing driving lanes for extra storage space proves counterproductive due to increased congestion. However, the alternative shuffle policy *Multi-bay with Sets Shuffle Policy* with a *Clustered Bay Distribution* shows promise. With an average increase of 0.4 containers per hour and a standard deviation of 0.24 containers per hour, this alternative offers a potential solution to mitigate QC productivity loss in highly utilized RTG terminals.

In conclusion, the study successfully addresses the identified knowledge gap, providing valuable insights and proposing a practical solution for reducing QC productivity loss in RTG terminals with highly utilized storage yards. The suggested approach of *Clustered Bay Distribution* with a *Multi-bay with Sets Shuffle Policy* proves effective in maintaining terminal performance during periods of an increased Yard Utilization Rate.

Samenvatting

Dit onderzoek richt zich op de cruciale rol van de bezettingsgraad van de werf (Yard Utilization Rate) in de prestaties van RTG containerterminals. De bezettingsgraad van de werf van de is gedefinieerd als het percentage van de totale capaciteit van de werf dat wordt gebruikt voor containeropslag. Hoewel een bezettingsgraad van 100% ongunstig is vanwege de noodzaak van vrije ruimte voor "reshuffling", worden optimale terminalprestaties over het algemeen behouden tot een bepaalde bezettingsgraad-drempel. Het overschrijden van deze drempel resulteert echter in een aanzienlijke daling van de terminalprestaties.

Tot voor kort kwam het niet vaak voor dat de limiet voor de bezettingsgraad van de werf werd bereikt, maar met de toenemende omvang van schepen en de populariteit van online bestellen, vooral tijdens piekseizoenen zoals de weken voorafgaand aan Kerstmis, neemt het aanbod van containers toe. Uit bestaande literatuur blijkt dat er een leemte bestaat in onderzoeken die zich specifiek richten op hoge bezettingsgraad van de werf in RTG-containerterminals.

De terminalprestatie wordt gedefinieerd als de containerdoorvoer binnen een bepaalde tijd en daarom is de Key Performance Indicator waar de focus op ligt de productiviteit van de kadekranen. De productiviteit van de kadekranen is gedefinieerd als het gemidddeld aantal verwerkte containers op een terminal per werkuur van de kadekraan. De terminal die onderzocht gaat worden is een RTG-terminal met op afstand bestuurbare RTG's en Terminal Vrachtwagen (TT's) en External Vrachtwagen (XT's) voor containervervoer. De XT's arriveren bij de poort. Ze leveren een container af of halen een container op. De XT rijdt naar de juiste plek op het opslagterrein in de terminal waar de RTG de container van de vrachtwagen tilt om deze op een stapel te plaatsen, of de RTG plaatst een container van de stapel op de vrachtwagen. De XT's verzorgen dus het transport van de containers tussen de opslaglocatie en de toegangspoort. De TT's verzorgen het transport van de containers tussen de kade en de opslaglocatie.

Concluderend richt dit onderzoek zich op de leemte in de kennis met betrekking tot de hoge bezettingsgraad van werf in containerterminals, waarbij de nadruk specifiek ligt op RTG-terminals. Door de relatie tussen de bezettingsgraad van de werf en terminalprestaties te onderzoeken, wil het onderzoek waardevolle inzichten en oplossingen bieden om de operationele efficiëntie op terminals met intensief gebruikte containerwerven te verbeteren. Dit brengt ons bij de hoofdonderzoeksvraag van dit onderzoek:

Hoe kan het productiviteitsverlies van de kadekranen worden verminderd in RTG container terminals met intensief gebruikte opslagterreinen?

Er wordt een Root Cause Analysis (RCA) uitgevoerd, waarbij de belangrijkste factoren worden geïdentificeerd die van invloed zijn op het laad- en losproces van de kadekraan, met de nadruk op de hoofdoorzaken *Te weinig TT's geïmplementeerd*, *Congestie* en *YUR te hoog*. Er worden ontwerpalternatieven voorgesteld om deze hoofdoorzaken aan te pakken, en drie ontwerpalternatieven worden getest door middel van simulatie: het variëren van het aantal Terminal Trucks (TT's), het opofferen van rijbanen voor extra opslagruimte, en het implementeren van een alternatief shuffle-beleid met een andere verdeling van containergroottes binnen een bay. De resultaten laten een significante invloed zien van het aantal Terminal Trucks op de productiviteit van de kadekranen, met een maximum van 8 TT's per kadekraan. Het opofferen van rijbanen voor extra opslagruimte blijkt contraproductief vanwege de toegenomen files. Het alternatieve shuffle-beleid *Multi-bay with Sets Shuffle Policy* met een *Clustered Bay Distribution* is echter veelbelovend. Met een gemiddelde toename van 0,4 containers per uur en een standaardafwijking van 0,24 containers per uur biedt dit alternatief een potentiële oplossing om het productiviteitsverlies van de kadekranen in RTG-terminals met veel opgeslagen containers te beperken.

Concluderend kan worden gesteld dat het onderzoek met succes de geïdentificeerde kenniskloof heeft aangepakt, waardevolle inzichten heeft opgeleverd en een praktische oplossing heeft voorgesteld voor het verminderen van het productiviteitsverlies van kadekranen in RTG container terminals met

intensief gebruikte opslagterreinen. De voorgestelde aanpak van *Geclusterde Bay Distribution* met een *Multi-bay with Sets Shuffle Policy* blijkt effectief bij het handhaven van de terminalprestaties tijdens perioden met een verhoogd gebruik van de werf.

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Abbreviations

Abbreviations

Abbreviation	Definition
AGV	Automated Guided Vehicle
KPI	Key Performance Indicator
POD	Port of Destination
QC	Quay Crane
RCA	Root Cause Analysis
RMG	Rail-Mounted Gantry Crane
RTG	Rubber-Tyred Gantry Crane
TEU	Twenty-foot Equivalent Unit
TT	Terminal Truck
XT	External Truck

Contents

1
Introduction and Problem Definition

This Chapter contains an introduction to the subject of this study. In the first section, the research context and necessary background information will be given (Sec. 1.1). In Section 1.2, the problem will be discussed. Section 1.3 contains literature research on current knowledge about the subject and in Section 1.4 the research gap will be discussed. In Section 1.5, the objective and scope of this study will be given. Section 1.6 contains the main research questions and the subquestions of this study and Section 1.7 discusses the methods that will be used to answer these research questions.

1.1. Research Context

This research is initiated by the company Portwise, which is a consultancy and simulation firm for logistics in ports, terminals and warehouses. They use software called Timesquare for terminal modelling and Trafalquar for berth modelling specifically. As this study is focused on all processes in RTG container terminals Timesquare will be used. More information about Timesquare can be found in Chapter 4.

1.1.1. Background Information

This research focuses on RTG container terminals. An RTG container terminal is a specific type of container terminal. A container terminal in general is a facility that facilitates the transfer of containers between ships and other means of transport. In container terminals, three types of containers are distinguished from each other; import, export and transit containers. Import containers arrive by vessel at the quay of the container terminal and leave by train or truck at the gate. The opposite applies to export containers. They arrive by train or truck at the gate and leave by vessel at the quay of the terminal. Transit containers arrive and leave by vessel at the quay of the terminal. Between arrival and departure, the containers are stored in the storage yard of the container terminal. Figure 1.1 shows a schematic view of a container terminal. The different operations are done with different types of equipment. The loading and unloading of the vessels are done by Quay Cranes (QC), the containers are transported from the quay to the yard and the other way around by yard vehicles, and the containers are lifted onto stacks in the yard by yard cranes. A quay crane is a collective name for different types of cranes operating at the quay. The same applies to yard vehicles and yard cranes, which are operative at the quay and yard, and in the yard respectively.

The most common types of yard cranes are Rubber-Tyred Gantry Cranes (RTGs) and (Automated) Rail-Mounted Gantry Cranes ((A)RMGs). The most common types of yard vehicles are Terminal Trucks (TTs), Automated Guided Vehicles (AGVs), lift-AGVs and Straddle Carriers (SC). This last type of equipment also functions as a crane as it collects the container at the quay, transfers it to the yard and places it on a stack in the yard.

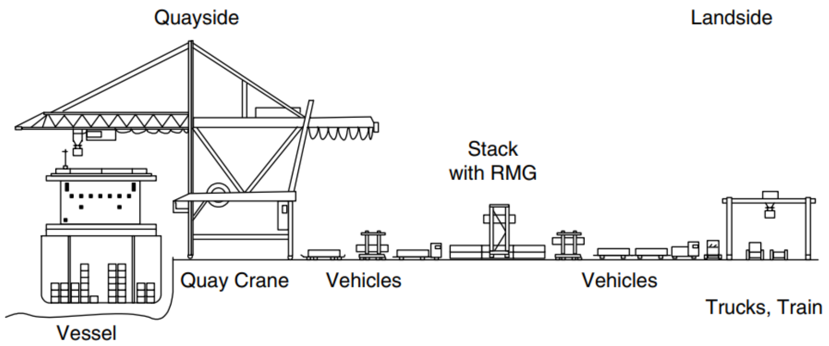


Figure 1.1: A schematic view of a container terminal [34]

A storage yard consists of lanes with *modules* of containers, in Figure 1.2 called a *block*. A module is a collection of containers stacked close to each other and consists of *stacks*, *bays*, *rows* and *tiers* as shown in Figure 1.2. Modules of containers are separated by driving lanes. The number of containers that can be stored in the yard is called the *yard capacity*. The lanes can be perpendicular or parallel to the quay, but this depends on the type of yard crane used. For RTGs, it is conventional to use the parallel layout, for (A)RMGs, it is conventional to use the perpendicular layout [19].

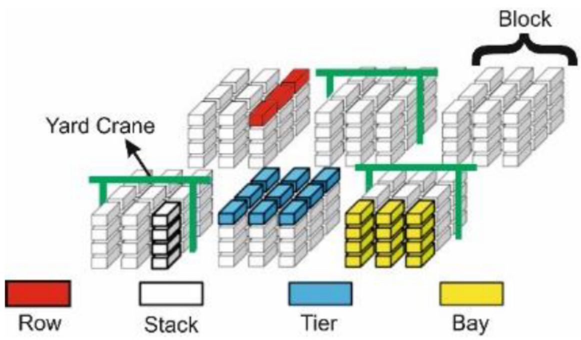


Figure 1.2: A schematic view of the structure of container blocks [33]

The operations in the yard consist of different processes. An arriving container needs to be assigned to a storage location, which is called *container allocation*. The storage location of a container is based on a set of rules, which is called the *stacking strategy*. These rules can be based on different characteristics such as the type, destination, weight or dwell time of the container. However, this stacking can also be completely random. The stacking strategy influences the performance of the container terminal [32]. The right stacking strategy can be different for every terminal and situation.

At a certain moment in time, the stored containers will depart by truck or train and therefore need to be retrieved from the stack. When the desired container is stored underneath one or multiple containers, the containers on top need to be lifted first, before the desired container can be retrieved. The containers on top also need to be placed back in the stack afterwards. These unproductive moves to retrieve the desired container are called *reshuffles*. Reshuffles play an important role in the performance of a container terminal [36] [14]. The performance of the terminal is defined as the throughput of containers in a certain amount of time, but can be measured using different *Key Performance Indicators* (KPIs), which the next section will cover (Sec. 1.1.2).

1.1.2. Terminal Performance

A *Key Performance Indicator* (KPI) is a quantifiable measure that can be used to measure progress towards an intended result and therefore is used to measure the performance of a container terminal.

In table 1.1, all literature found is categorized according to the KPI used.

The main categories are:

- Gross Crane Rate (GCR): The average number of lifts at a terminal per QC working hour [27]. Also described as QC utilization rate [38] or QC productivity [31].
- Time: This can either be the cycle time for a certain type of equipment [2], truck waiting time [20], ship waiting time [20], the service time [6] [22], or the total retrieval time of a container [11] [10].
- Costs: Operating costs for a certain type of equipment [19].

- Number of reshuffles (NoR): Reshuffles are unproductive moves in order to retrieve a container [36]. For example, when two containers are on top of the desired container, the number of reshuffles is four; two unproductive moves to move the containers on top of the desired container, and two moves to put them back.
- Other:
  - Number of times that there is no position available [14] [8]
  - The workload of the automatic stacking cranes (ASC) [2] [8]
  - The occupation of ground locations [2] [14] [8]
  - Stack response time; the average time the ASC uses for 1 move (inbound and outbound) [9]
  - ASC utilization; the percentage of time during which the ASC is active [9]
  - The operation efficiency of automatic quay cranes (AQC) [20]
  - Maximum straddle carrier (SC) utilisation per hour [22]
  - The stack utilization [11]

Author	GCR	Time	Costs	TT	NoR	Other
Balliere et al. [1]	x	x		x		
Borgman [2]		x			x	x
Chen & Lu [5]					x	
Choe et al. [6]		x				
de Castillo & Daganzo [7]					x	
Dekker et al. [8]					x	x
Duinkerken et al. [9]	x	x			x[1]	x
Feng et al. [10]		x				
Gharehgozli & Zaerpour [11]		x				x
Guerra-Olivares et al. [13]					x[1]	
Güven & Eliiyi. [14]					x	x
Jonker [15]	x					
Kang et al. [16]				x		
Kemme [17]	x					
Lan & Kao [18]					x	
Lee & Kim [19]			x			
Li et al. [20]		x				x
Liu et al. [21]	x					
Mutters [22]		x			x	x
Petering [27]	x					
Petering & Murty [28]	x					
Saanen & Dekker [31]	x					
Wiese et al. [36]			x			
Yu & Qi [37]		x				
Yun & Choi [38]	x					x
Total	9	9	2	2	9	8

Table 1.1: Categorisation of papers about performance measures, with the categories Gross Crane Rate (GCR), Time, Costs, Terminal Throughput (TT), Number of Reshuffles (NoR), or an other performance measure

The choice for the KPI depends on where the focus of improvement lies. If the goal is to decrease costs, a cost function should be formulated and used as KPI. If money does not matter, but sustainability

[1] Actually, percentage of containers that need restacking

is important, a suitable KPI would be the energy or fuel consumption of the equipment. In this study, the throughput of the terminal is the point of focus. Therefore, the KPI used is the QC productivity in the number of handled containers per hour. As some KPIs affect other KPIs, multiple KPIs can be taken into consideration. For instance, a certain delay in yard operations results in a longer waiting time for the QC, and in turn, this affects the productivity of the QC. By looking at multiple KPIs the roots of the problem can be identified. Other KPIs that can be relevant for this study are the QC status, RTG status and TT status.

1.2. Problem Statement

The container yard has a maximum storage capacity. The percentage of the total yard capacity used for container storage is called the *Yard Utilization Rate* (YUR). It is unfavourable to have a Yard Utilization Rate of 100% because there always needs to be free space for reshuffles. Up to a certain YUR, the performance of the terminal remains fairly constant, but when that certain percentage is exceeded, the performance of the terminal drops. In the past, it did not occur very often that the limit of the utilization rate was reached. However, it will probably occur more often as ships become bigger and online ordering is more common. Especially the months before Christmas, people all over the world order gifts, which means that container terminals are temporarily busier and the YUR increases. Figure 1.3 shows the YUR of a container terminal over the course of three years [25]. In this terminal, every type of container has its own stacking area. The calculated percentages are therefore the utilized part of the total capacity of the stacking area of that type of container. The cyan line 'Average' is the average of all the stacking areas of the different types of containers. It shows that the YUR of a container terminal fluctuates throughout the year, with high peaks at certain times.

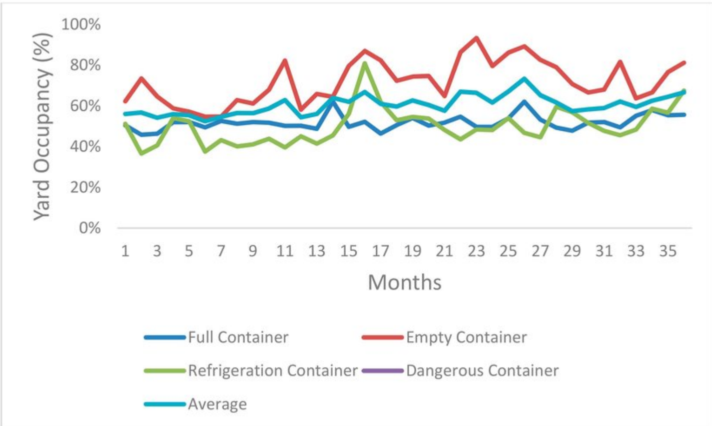


Figure 1.3: Monthly Yard Utilization Rate (YUR) (%) over the course of 3 years (January 2014 - December 2016) [25]

Exploratory research was done to show the drop in performance for higher YURs. Simulations were carried out for three different types of terminals using Portwise's simulation software Timesquare. The first type is an RTG terminal with TTs, the second is an RMG terminal with lift-AGVs and the third is an SC terminal. The total capacities of the storage yard are respectively 44800 TEU, 51000 TEU, and 28200 TEU. For all three scenarios, the same number of 12 QCs operating at the quay is used. The results of the simulations are shown in Figures 1.4a, 1.4b and 1.4c. The QC productivity shown is the average of the total productivity of all 12 QCs.

As can be seen from the Figures 1.4a, 1.4b and 1.4c, the performance deteriorates for an RTG terminal at a utilization rate of 85%. However, for an RMG terminal the performance does not deteriorate until a utilization rate of 95%. Besides, it is not a significant decrease in performance. For an SC terminal, the performance already starts to decrease at a utilization rate of 80%, but is still only half the decrease of the RTG terminal. Therefore, looking into the case of an RMG terminal does not have priority, as it probably will be very difficult to improve the QC productivity with only 1 or 2 boxes per hour. In contrast to the RMG terminal, the RTG terminal does show a significant drop in QC productivity, which is approximately 10 boxes per hour.

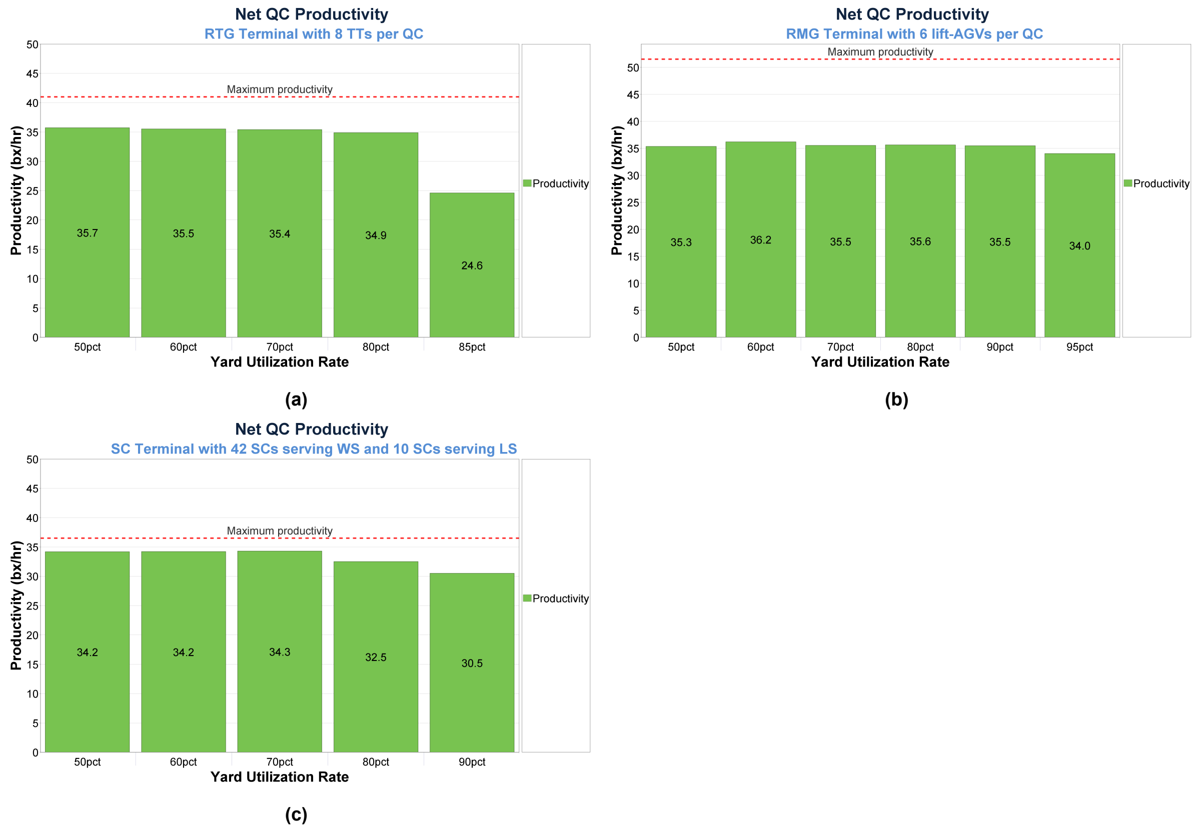


Figure 1.4: Initial YUR vs. QC productivity for an RTG terminal with 6 TTs per QC (a), an RMG terminal with 72 lift-AGVs (b), and an SC terminal with 52 SCs (c)

1.3. Literature

Literature research on this subject resulted in research papers on testing different methods to improve container terminal performance. The focus of these papers could be:

- The stacking strategy used [2] [5] [7] [8] [9] [10] [11] [13] [14] [16] [18] [37]
- The layout of the yard or the design of the storage blocks [19] [28] [27] [21] [36]

In these papers, the YUR was not mentioned and it is therefore assumed that these studies are considered with an average YUR.

Among the studies that explicitly mention the YUR, three categories emerge:

- Papers that solely present the YUR value without relating it to terminal performance [17] [15].
- Papers where the YUR is an output of simulations, yet its impact on performance is not explored [1] [38] [6].
- Papers that did more research into the subject of the YUR [37] [10] [31].

Yu and Qi compared and studied the influence of the container arrival rate, instead of the YUR, of two stacking policies for container allocation of import containers on the performance of an automated RMG terminal [37]. The first policy, the segregation policy, segregates containers according to the batch in which they arrive (by vessel). The second, the non-segregation policy, allows containers of different batches to be stacked together. The results show that for the first policy, higher arrival rates lead to more overflow. Overflow means that there is no available empty slot for an arriving container. This does not happen with the non-segregation policy. This is due to the fact that bays are not being optimally used when the segregating policy is applied. Therefore, the segregating policy is not recommended for high container arrival rates.

Feng et al. compared two stacking strategies, random stacking and smart stacking, under three different YURs (67%, 80%, 85%) for an automated RMG terminal [10]. The smart stacking strategy consists of a non-split and split policy. Within the non-split policy, it is not allowed to split a group of containers over smart and non-smart stacks. In the second policy, this is allowed. Smart stacks are stacks in which no reshuffles are needed when retrieving a container because they are stacked optimally and every time a container needs to be retrieved, it is the container at the top of the stack. They concluded that for higher YURs the random stacking strategy affects the performance of the terminal less than their proposed smart stacking strategy [10]. The container retrieval times increased with the smart stacking strategy for higher utilization rates, while for random stacking they remained the same. That is because eventually, for the smart stacking strategy more reshuffles were necessary in order to retrieve a container.

Saanen and Dekker tried to define a set of rules in order to increase the stacking capacity of the yard without increasing the costs per move and without a decrease in the performance of an RTG transshipment terminal [31]. They compared random stacking to traditional stacking. The most important differences between the two strategies are the fact that for random stacking no space is reserved for containers, and that containers of the same type are distributed as much as possible over the entire yard, while for the traditional strategy, space is reserved for containers and containers of the same type are stored in the same area in the yard. With the type of container is meant containers with the same characteristic(s), such as the port of discharge or vessel. They concluded that the QC productivity decreases for a higher yard utilization for both the random and traditional strategy due to longer RTG gantry times [31]. However, the RTG gantry time per move does not increase as much for the random strategy as for the traditional strategy.

Previous literature research was focused on knowledge about how to improve the performance of a container terminal with a high YUR. However, literature research on the topic of simulations is also necessary to gain more knowledge about what kind of simulations are done and what assumptions they made in order to study similar logistic problems.

1.4. Research Gap

The study by Yu and Qi was done on whether segregating or non-segregating is preferable for high arrival rates [37]. Higher arrival rates lead to higher YURs if the rate at which the containers leave the terminal does not increase. So, there is a relation between those, but the study of Yu and Qi is not specifically focused on container terminals with high YURs.

The study by Feng et al. was done on proposing a new stacking strategy (smart stacking) for automated container terminals. They studied this new stacking strategy for three utilization rates, of which one was a high YUR of 85% [10]. However, the focus of the study was the new stacking strategy and they did not recommend specific measures for highly utilized container yards.

The only study found on specifically container terminals with high YURs is the study of Saanen and Dekker [31]. The research was focused on an RTG transshipment terminal, so all containers arrive and leave by vessel, and on finding the factors that are affected most by the higher YUR. They did not focus on finding solutions on how to ensure the performance of the terminal does not decrease or does decrease less.

It can be concluded that there is a lack of knowledge on the topic of high YURs in container terminals. As Figure 1.4a and the study of Saanen and Dekker show, the QC productivity of an RTG container terminal deteriorates with an increasing YUR. However, there is no research done on how to reduce the loss of performance on an RTG terminal. This states the research gap.

1.5. Research Objective and Scope

As described in Section 1.4, the YUR is an interesting topic for research, as there is still little knowledge on this subject. As the first simulations have shown, the RMG terminal does not show a significant drop in performance for a higher YUR, and therefore little improvement can be made there. A more interesting scenario would be the RTG terminal, as the performance does decrease significantly for a higher YUR (Fig. 1.4). However, it can be useful to analyse the scenario of the RMG terminal and use this as a reference for the RTG terminal. Saanen and Dekker already showed in their study which factors are of influence on the decrease in performance of an RTG terminal[31], but for a pure transshipment terminal. Therefore, a comparable study can be done for a terminal at which import containers are transported to the hinterland by trucks, and export containers arrive by trucks. Besides, it can be attempted to find solutions such that the performance does not decrease or decrease less at higher YURs. So, the goal of this study is to properly show the relationship between the YUR and the performance of an RTG container terminal and to find solutions for the decreasing performance at higher utilization rates. A more detailed explanation of the methodology can be found in Section 1.7.

This study aims to show the influence of the YUR on different processes in the terminal, and in turn, show how these processes affect the performance of the container terminal. The performance of the terminal is defined as the container throughput within a certain amount of time and therefore the KPI of focus is the QC productivity. Performance in terms of costs, or in terms of sustainability is out of the scope of this study.
The terminal that will be studied is an RTG terminal. The yard cranes operating in the yard are remote-controlled RTGs. This means there is a central point from which the RTGs are controlled, and the RTGs are thus not manned. The advantage is that every RTG can be moved in a couple of seconds, instead of an employee that needs to go to the RTG and enter it, before it can be moved. The containers are transferred with Terminal Trucks (TTs) and External Trucks (XTs). The XTs arrive at the gate. They either are delivering or picking up a container. The XT drives to the right stack where the RTG lifts the container from the truck to place it on a stack, or the RTG places a container from the stack on the truck. So, the XTs provide the transport of the containers between the storage location and the gate. TTs provide the transport of the containers between the quay and the storage location. Only 20-foot and 40-foot standard dry containers and empty containers are considered. Reefers and hazmat containers are left out of consideration for the sake of simplicity, and because these types of containers have their own storage location in the yard that only makes up about 15% of overall yard capacity and therefore the contribution to the overall utilization rate of the yard is negligible [27].

The system is defined as everything between the gate at the landside and the quay at the water-side. Figure 1.5 shows a schematic side view of a container terminal with the rectangle as the system boundary and within the rectangle the system. This means that containers enter and leave the system either at the gate, or at the moment they are loaded on the vessel.

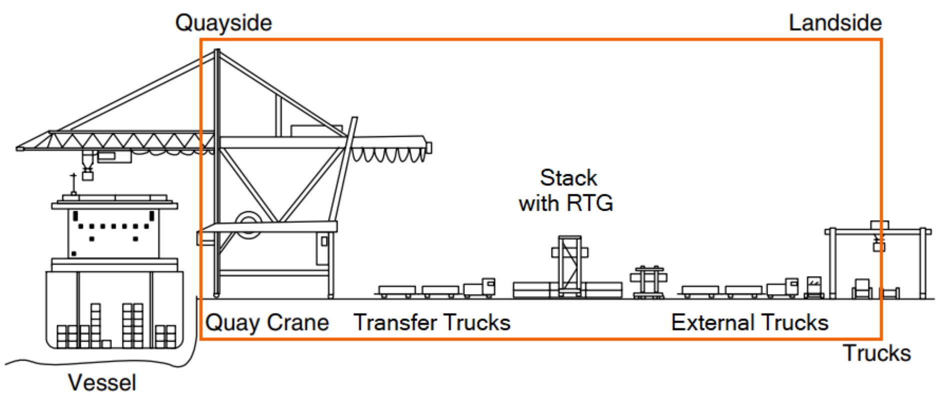


Figure 1.5: Side view of a container terminal with the system boundary

1.6. Research Questions

The main research question of this study is:

How to reduce QC productivity loss of an RTG container terminal with a highly utilized storage yard?

The following subquestions are formulated in order to be able to answer the main research question:

1. *What is an RTG container terminal?*
2. *What is the QC productivity in an RTG container terminal and how do processes within the terminal affect this?*
3. *What possible solutions can be found such that the processes that affect the QC productivity, are not influenced or less influenced by a high Yard Utilization Rate?*
4. *How to model the relation between the Yard Utilization Rate and the QC productivity in RTG container terminals?*
5. *Which processes of an RTG container terminal are affected most by a high utilization rate of the storage yard?*
6. *Which of the possible solutions of subquestion 3 ensure that the QC productivity is not affected or less affected by a high Yard Utilization Rate?*

1.7. Methodology

In this section, methods are discussed on how to approach each of the research questions.

1. *What is an RTG container terminal?*
   Goals:

   - Describe the processes that take place within RTG terminals.

   Methods: Literature study.

2. *What is the QC productivity in an RTG container terminal and how do processes within the terminal affect this?*
   Goals:

   - Describe what QC productivity is.
   - Describe how QC productivity is connected to the processes in an RTG terminal.

   Methods: Literature study and expert interviews.

3. *What possible solutions can be found such that the processes that affect the QC productivity, are not influenced or less influenced by a high Yard Utilization Rate?*
   Goals:

   - Find possible solutions to reduce the influence of the Yard Utilization Rate on the QC productivity.

   Methods: Literature study and expert interviews.

4. *How to model the relation between the Yard Utilization Rate and the QC productivity in RTG container terminals?*
   Goals:

   - Describe all requirements to obtain a model of an RTG terminal which shows the relation between the Yard Utilization Rate and the QC productivity.

   Methods: Literature study and expert interviews.

5. *Which processes of an RTG container terminal are affected most by a high Yard Utilization Rate of the storage yard?*
   Goals:

   - Describe how the utilization rate of the yard is connected to the processes in an RTG terminal.

   Methods: Simulation.

6. *Which of the possible solutions of subquestion 3 ensure that the QC productivity is not affected or less affected by a high Yard Utilization Rate?*
   Goals:

   - Test if the possible solutions have the intended results on the QC productivity.

   Methods: Simulation.

2
RTG Container Terminal

In Section 1.1, background information is given about container terminals in general. This chapter focuses on the RTG terminal specifically. In this chapter, subquestions 1 and 2 are addressed.

1. *What is an RTG container terminal?*

2. *What is the QC productivity in an RTG container terminal and how do processes within the terminal affect this?*

Literature study will be used to answer these subquestions.

This chapter is divided into four sections. Section 2.1 describes the path a container follows in an RTG container terminal from arrival to departure and is divided into three sections. Each section represents a part of the RTG terminal, as is shown in Figure 2.1.

To ensure the logistics process runs smoothly, all operations need to be adequately planned and controlled. Section 2.2 describes the processes in an RTG container terminal belonging to planning and control. Section 2.3 describes the QC productivity and the processes that are connected to the process of loading and unloading of vessels by QCs. In the last section, the two subquestions are answered (Sec. 2.4).

2.1. Logistics: Container flow

A container terminal can be divided into three parts as is shown in Figure 2.1. The gate is the entrance of the terminal at which trucks and trains arrive. The quay is where ships arrive. Containers can enter and leave the terminal on both sides. Import containers arrive by vessel at the quay and leave by truck or train, for export containers this is reversed. Between arrival and departure, the containers are stored in the storage yard. Figure 2.2 shows the container flow in an RTG container terminal.

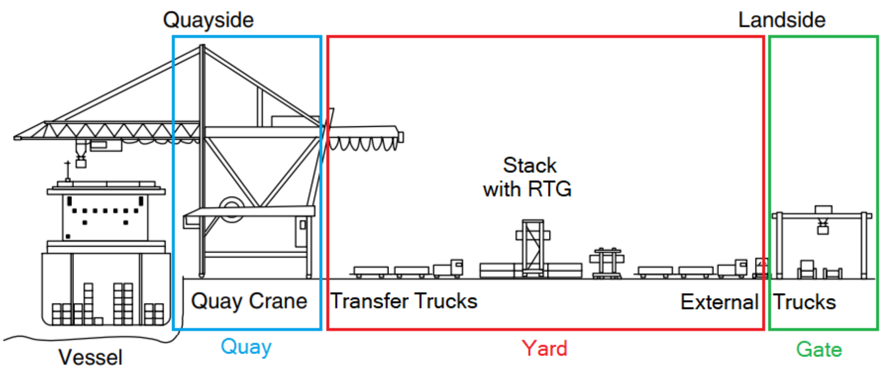


Figure 2.1: The three main parts of an RTG container terminal.

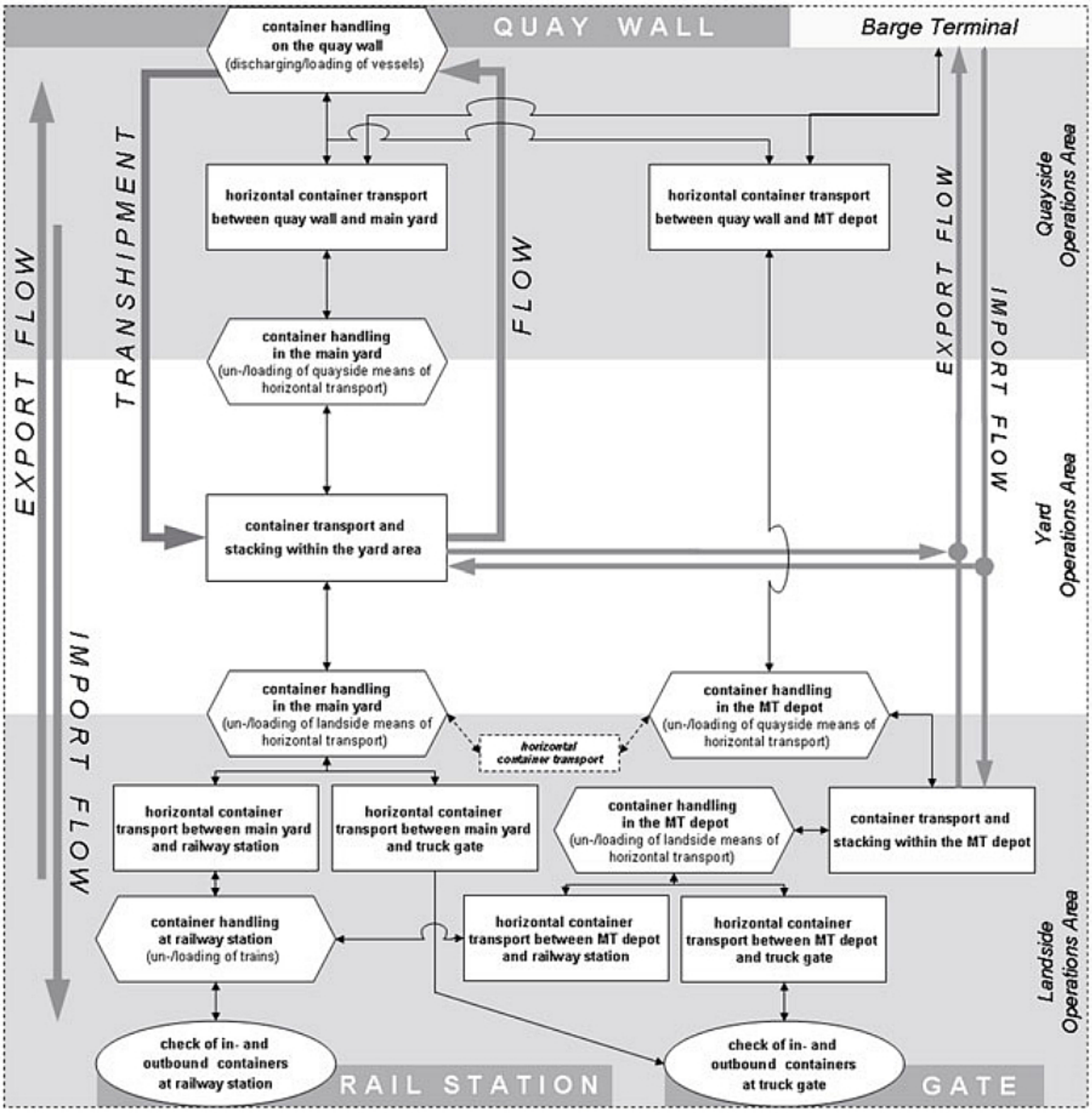


Figure 2.2: Logistics and main container flow in an RTG container terminal [3]

2.1.1. Gate and Rail Station

The gate is the entrance of the container terminal. At this point, External Trucks (XTs) arrive either to deliver an export container or to collect an import container (or multiple). The XT carries either a 20-foot container, two 20-foot containers or a 40-foot container. Security and administrative checks are done at the gate before the XT can enter the terminal. Trains arrive at the rail station. Trains can carry both 20-foot and 40-foot containers. As defined in Section 1.5, the scope of my study does not contain the gate and the rail station and therefore will not be elaborated further.

2.1.2. Storage Yard

Once the XT has entered the terminal, it drives to the correct stack in the storage yard. As already mentioned in the Introduction (Subsec. 1.1.1), a container terminal's storage yard is where containers are temporarily stored between arrival and departure.

In the case of an export container, the RTG lifts the container of the chassis of the XT and places it on the stack. The XT then drives either to the gate, to leave the terminal, goes to the parking spot to wait on a container to pick up, or immediately drives to the right stack to collect a container. When arrived at the stack, the RTG lifts the container from the stack and places it on the chassis of the truck. Then the XT drives to the gate and leaves the terminal. Sometimes it happens that the desired container is not at the top of the stack, but another container has to be removed first before the desired container can be retrieved. These unproductive moves necessary in order to retrieve the desired container are called *reshuffles*.

The container that is delivered by the XT is stored in the container yard and eventually will be shipped. When the container is ready for shipping, it is collected by a Terminal Truck (TT). These Terminal Trucks are internal trucks and operate in the yard and the quay area, but do not leave the terminal.

The storage yard consists of multiple blocks with containers, each block orientated parallel to the quay (Fig. 2.3). The blocks are placed in such a way that there is enough space for the wheels of the RTG on one side of the block, while there is also a transfer lane and passing lane on the other side. The transfer lane lies between the side of the block and the wheels of the RTG, such that the container can be placed on top of the truck (or the other way around). The passing lane is a normal drive lane that can be used for trucks to pass by.

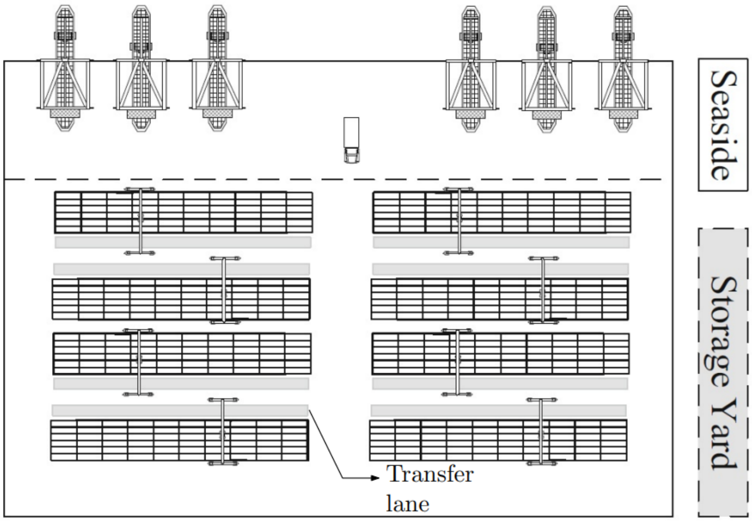


Figure 2.3: The parallel yard layout of RTG container terminals [30]

In the storage yard, 20-foot, 40-foot and 45-foot containers are stacked together. MT containers, short for empty containers, are stored separately. The same applies to reefers (refrigerated containers). These containers need a power supply in order to remain cool. As these power outlets take up space and the containers need free space to dissipate their heat, the storage area for reefers is separated from the other containers. Lastly, the hazmat containers are also stored separately. Hazmat stands for Hazardous Material and these containers are thus containers that contain dangerous goods. Reefers and hazmat containers are left out of scope for the sake of simplicity.

2.1.3. Quay

Quay Cranes (QCs) operate at the quay. These cranes load and unload the vessels. The containers are delivered to and collected from the QCs by TTs. QCs can operate in different configurations but need different types of spreaders for each operation. With the single lift operation, the QC lifts a single 20-foot or 40-foot container (Fig. 2.4). With the twin lift operation, the QC can lift two 20-foot containers end-to-end (Fig. 2.5). With the tandem lift operation, the QC can lift two 20-foot containers, two 40-foot containers, or four 20-foot containers (Fig. 2.6).

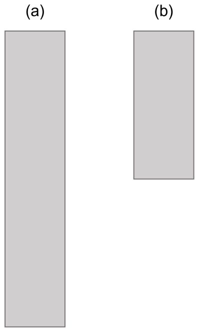


Figure 2.4: Single lift

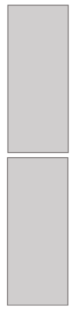


Figure 2.5: Twin lift

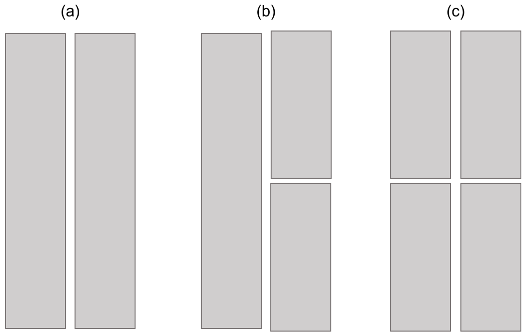


Figure 2.6: Tandem lift

The type of QC most commonly used in RTG terminals is the single-trolley QC. The single trolley crane has a single trolley, as is shown in Figure 2.7a. A second type of QC is the dual trolley crane, as is shown in Figure 2.7b. This crane has besides the boom girder a second girder a bit below the boom girder. The main trolley drives on the boom girder, and the second trolley, the portal trolley, on the lower girder. When a container is lifted from a ship, the main spreader and trolley place the container on a pinning platform (called 'buffer' in Fig. 2.7b). The portal spreader and trolley lift the container from the platform onto the yard vehicle. This dual trolley crane is often used with automated vehicles, and therefore less often used in RTG terminals. The reason why these dual trolley cranes are not often used with TTs is that the pinning platform adds another step in the (un)loading process, which leads to a longer cycle time. The containers are secured with twist locks on the ship and the containers are secured on the TTs with twist locks too. Therefore, the twist locks do not to be removed. At the quay, the twist locks are handled manually to secure the container to the TT. However, with an automated vehicle, the twist lock handling is often automated. Therefore, the twist locks used on the ship have to be removed. As it is safer for humans not to interact with these automated vehicles, the twist locks can already be removed on the pinning platform, where the personnel do not come into contact with the automated vehicles.

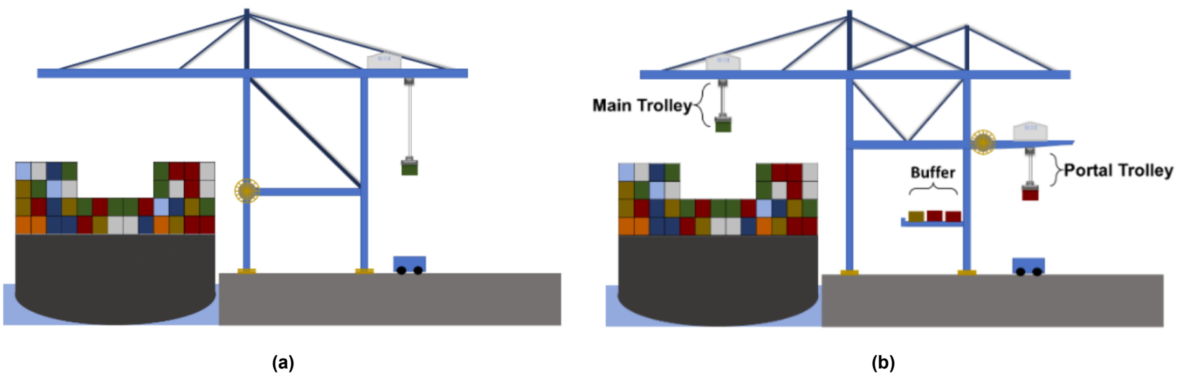


Figure 2.7: QC with a single trolley system (a) versus a QC with a dual trolley system (b) [23]

2.2. Terminal Processes

In the previous section, the path a container follows from the moment it enters the terminal to the moment it leaves the terminal is globally described. However, much more complex processes are involved in the transfer of containers. In this section, all processes belonging to planning and control that take place in an RTG container terminal are discussed in more detail.

2.2.1. Berth Planning

Berth planning, also often called *berth allocation*, is the process that assigns berths to vessels. The arrival information of small vessels is known a few days in advance and for large overseas vessels even months in advance [34]. The berth planning is made the moment arrival information is known and is continuously updated. The berth planning takes into account the size of the ship and the length of the berths when assigning a berth. However, other factors taken into account are the berthing time, future vessel arrivals within this time window, and availability of equipment and staff.

2.2.2. Stowage Planning

Stowage planning is the process that plans when each container is loaded onto the ship. This is connected to the processes in the yard, as the containers that will be loaded onto the ship first, also need to be collected from the yard first. The stowage planning is made a few hours before the vessel arrives at the terminal [4]. The stowage planning is based on the *stowage instruction* and the *bayplans* provided by the shipping line [34]. The stowage instruction contains information about the positions where export containers need to be located and the bayplan is a cross-sectional view of every bay that shows all containers and their data currently on the ship.

2.2.3. Container Allocation

Container allocation is the process that makes a decision on where to store a container in the storage yard. This decision depends on several factors, such as where import and export containers are stored, the shipping company of the container, the port of destination (POD), the weight of the container and whether this information is known in advance. Arrival information of import containers is often known in advance, as the arrival information of the vessel also is known in advance. However, arrival information for export containers is known the moment the XT arrives at the terminal. Therefore, a decision on the storage location of an export container is made the moment the container arrives at the terminal. Container allocation is often called *yard planning* because all containers present in the yard have to be taken into account when making the decision on the storage location of a single container [4].

2.2.4. Stacking Strategy

A *stacking strategy* is a set of rules on which the location of the container to be stored is based [22]. These rules can be based on different characteristics such as destination, weight or dwell time of the container, or the stacking can be done completely randomly. Besides, a stacking strategy is a method to make the container retrieval process as efficient as possible.

2.2.5. Equipment Allocation

Equipment allocation is the process that plans the equipment in the yard and at the quay. The decision on how many RTGs are necessary at each block, when the RTGs are moved to another block to help out, how many TTs are necessary in the yard, which TTs serve which QC, how many TTs serve each QC, which routes the TTs take, and what the exact number of QCs is that work simultaneously on one ship.

2.2.6. Housekeeping

Housekeeping is an operation that is planned during less busy moments in the yard. With housekeeping containers in the yard are rearranged, such that fewer reshuffles are required when retrieving those containers in the future. The decisions made are which containers need to be relocated and which RTGs will perform these operations.

2.3. QC Productivity

QC productivity is a measure of how productive a QC is. It is defined as the average number of lifts at a terminal per QC working hour [27]. As it shows how many containers move in and out of the terminal, it is considered an indicator to measure the performance of a container terminal.

If the QC and the ship together are considered as a separate system, higher productivity ensures faster loading or unloading of the ship. This productivity then solely depends on the maximum trolley and hoist speed of the QC. However, loading and unloading operations are dependent on the TTs that deliver or collect the containers.

Therefore, it can be said that the QC productivity depends on internal factors and external factors. Table 2.1 shows the causes for a loss of QC productivity. The figures that are mentioned in the table are tree diagrams and are a result of a Root Cause Analysis based on expert opinions. A Root Cause Analysis (RCA) is the process of discovering the root causes of a problem in order to identify appropriate solutions [29]. The idea is to eliminate these root causes and thereby solve the problem. Figure 2.8 contains a tree diagram that shows the most common causes of why a QC is waiting for a container to load. Figure 2.9 contains a tree diagram that shows the most common causes of why a QC is waiting to unload a container from a ship. The orange blocks at the end of all the 'branches' are considered the root causes of the problem.

	Internal	**External**
Loading	Failure or breakdown QC	Figure 2.8
Unloading	Failure or breakdown QC	Figure 2.9

Table 2.1: Causes of QC productivity loss

If the QC has to wait for the delivery of a container to load it on a vessel, its productivity decreases. The same applies to unloading operations. If the QC has to wait for a TT with an empty chassis to arrive, its productivity also decreases. Important to mention is that the block "*TT left transfer lane yard module too late*" in Figure 2.9, concerns the previous order. In the RTG terminal, a group of TTs is serving a particular QC. The best 'option' is chosen out of these TTs. When the TT is not available at the QC, this block "*TT left transfer lane yard module too late*" is only the case if there are no other TTs with a better starting position than the chosen one. Therefore, it is essential that TTs arrive on time at the quayside in order to keep the QC productivity high.

In turn, whether the TTs arrive on time at the quay depends on other processes within the terminal. One of them is the transfer from the yard block to the quay. If it is busy in the yard, congestion may occur, which leads to a delay in travel time and possibly a delay in waiting time at the blocks too. Another process on which the TT arrival time depends is the RTG operation. It can occur that an RTG breaks down. The other RTGs need to take over the tasks of the RTG that has broken down, which gives a higher workload for these RTGs, who might not be able to keep up. This leads to either less productivity because the RTGs have to travel longer distances, or this leads to longer handling time. A longer handling time would not necessarily lead to less QC productivity, as it only takes more time to load the ship. In this case, the QC productivity does not sufficiently reflect the terminal's performance, as the QC productivity only reflects the terminal throughput over a more extended period of time. In that case, it would be necessary to use a second KPI to measure the performance of the terminal accurately.

Either way, it can be useful to look at several KPIs. That is, after all, a way of finding out where things go wrong in the terminal when things get stuck at the QCs.

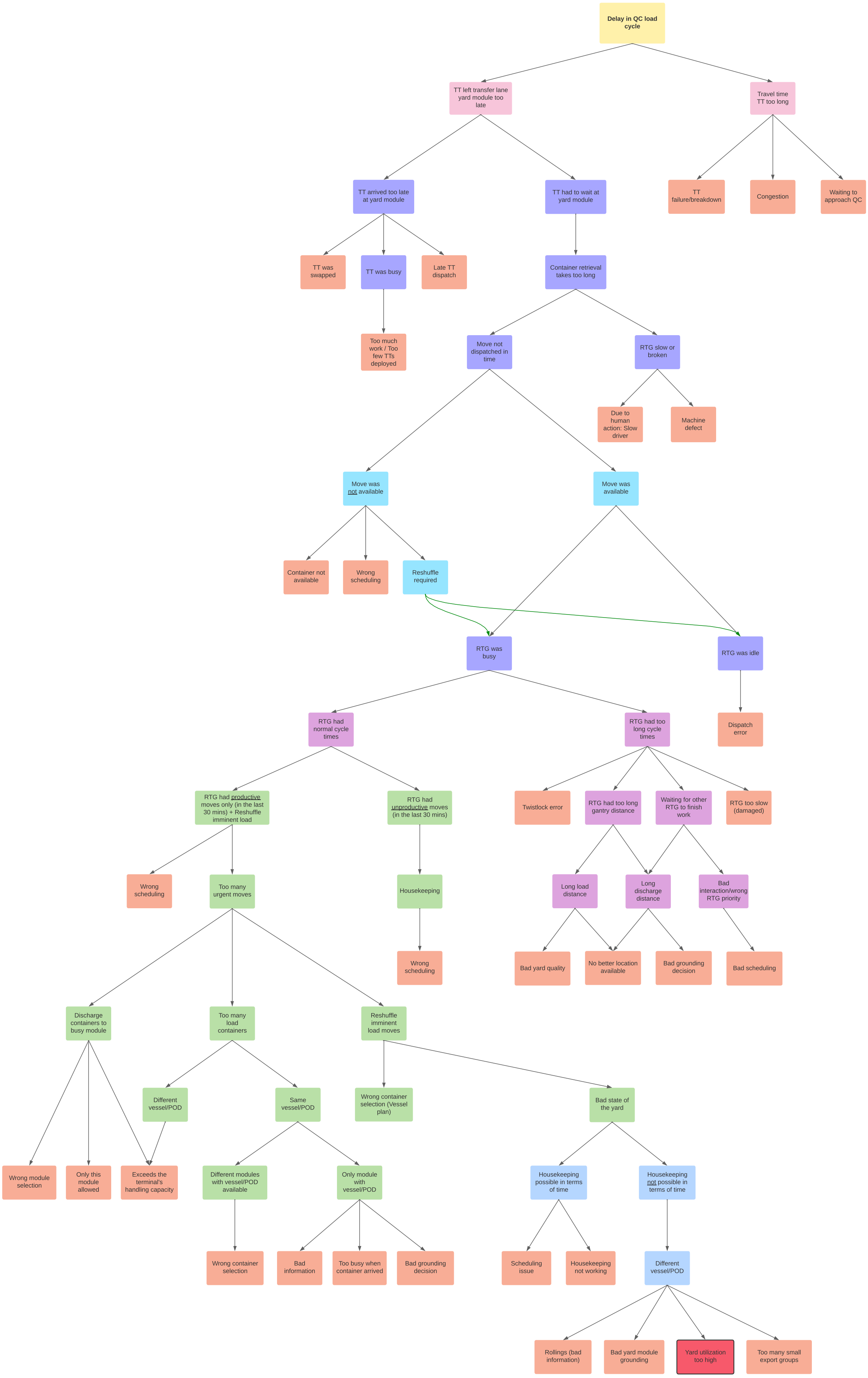


Figure 2.8: Root Cause Analysis: tree diagram of why a QC is waiting to load a container

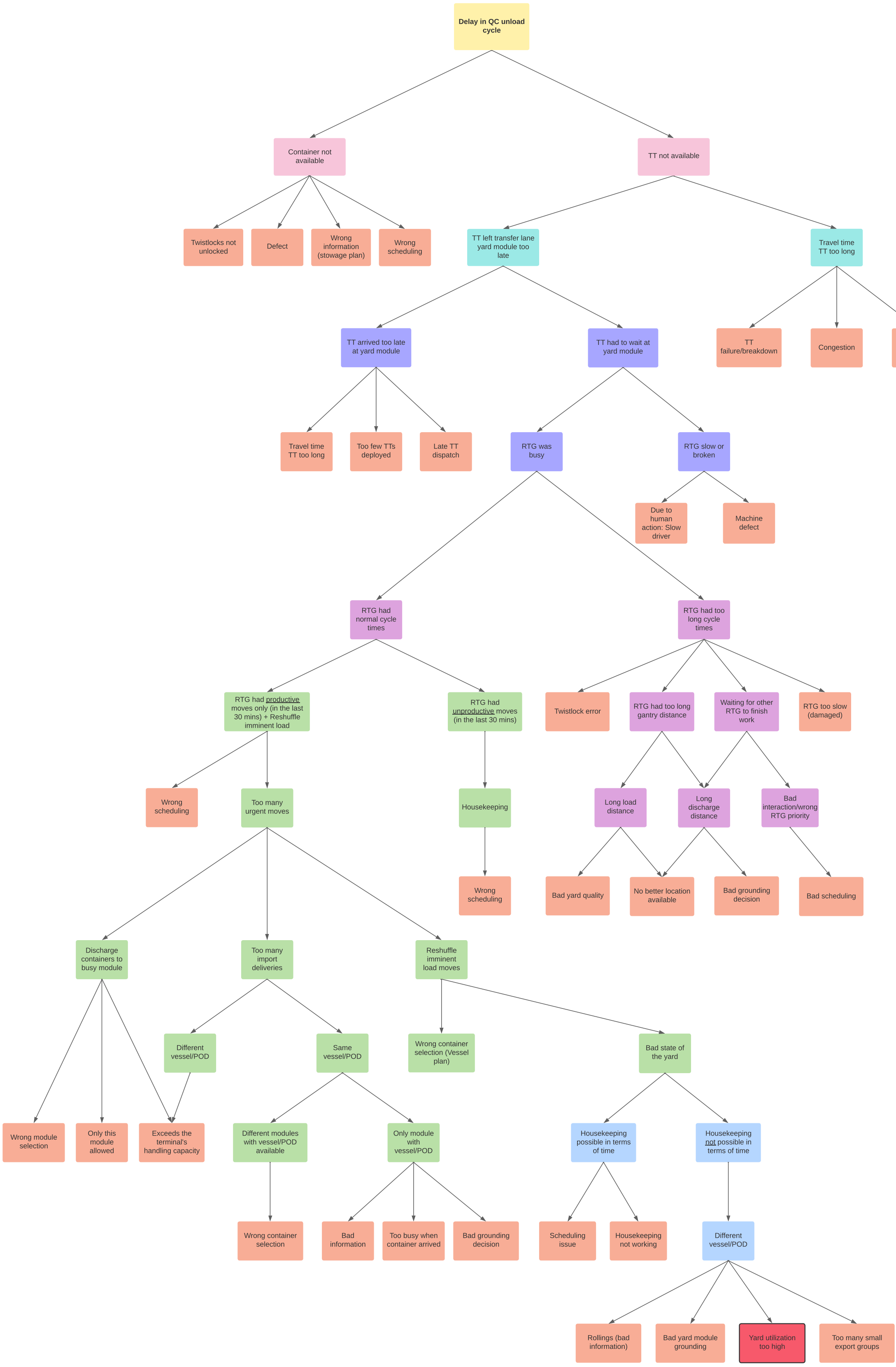


Figure 2.9: Root Cause Analysis: tree diagram of why a QC is waiting to unload a container

2.4. Conclusion

This chapter provides a general description of an RTG container terminal and the processes that take place within the terminal. A description of the path a container follows from arrival to departure is given and subquestions 1 and 2 have been answered.

1. *What is an RTG container terminal?*

   A container terminal is a facility that facilitates the transfer of containers between ships and other means of transport. Since containers cannot be directly transferred to another means of transport, the terminal has a storage yard where the containers can be temporarily stored. An RTG container terminal is a container terminal where the cranes used in the storage yard are Rubber-Tyred Gantry Cranes (RTGs).

2. *What is the QC productivity in an RTG container terminal and how do processes within the terminal affect this?*

   QC productivity is defined as the average number of lifts at a terminal per Quay Crane (QC) working hour [27].

   Since the goal is to improve the QC productivity, the focus lies on which processes affect the QC productivity in a negative way. Figures 2.8 and 2.9 are tree diagrams that show what causes can be the reason for the delay in the load or unload cycle of the QC. These diagrams have been set up using a Root Cause Analysis (RCA). For both processes, i.e. unload cycle and load cycle, it was investigated which other processes have a negative effect on these cycles. The orange blocks show which things can be the 'root causes'.

   When a QC is waiting on a container to load, it is either because of a delay in the travel time of the TT or because of a delay in picking up the container at the storage yard. A delay in travel time can be because of failure of the TT, congestion in the yard, or because of queues near the quayside. However, container retrieval in the yard is a much more complex process than the transfer of the container, and therefore there are many reasons why the delay could have occurred.
   When a QC is waiting for a container to unload, that is either because there is no TT available yet to pick up the container, or because the container is not available. The container must be on the ship. In that case, wrong information is given about the location of the container on the ship, the twist locks are not unlocked yet, or there is a defect. In the case of no available TT, the two reasons are the same as described above. It is either because of a delay in the travel time of the TT, or because of a delay in picking up the container at the storage yard.

   Not surprisingly, a high Yard Utilization Rate (YUR) may be one of the causes of a delay in the QC cycle in an RTG terminal in general. The main topic of this thesis is to look at what solutions are possible to ensure that QC productivity is influenced as little as possible by a high YUR. So, it was already known that a high YUR plays a part in this. The idea of an RCA is that the problem is tackled by removing the root causes. This will automatically solve the problem. Taking away the root cause "Too high YUR", sounds like circular reasoning because it is logical that if the QC productivity deteriorates at a high YUR, it is due to this high YUR. However, there are options to tackle this high YUR, more about that in the next chapter. Therefore, "Too high YUR" is still considered as a root cause. All other root causes can not be taken away because they rely on the planning, gathering of information or human actions, which are out of the scope of this study.

3 Design Alternatives

In this chapter subquestion 3 is addressed.

3. *What possible design alternatives can be found such that the processes that affect the QC productivity, are not influenced or less influenced by a high Yard Utilization Rate?*

Literature study and expert interviews are used to answer this subquestion.

3.1. QC Loading and Unloading Process

As mentioned in Section 2.4, a delay in the load process of the QC is either caused by a delay in the travel time of the TT or by the fact that the TT left the yard too late. The focus will be on the latter, which can be caused by the fact that the TT arrived at the yard too late, or because the TT had to wait at the yard. The first can be because of a late dispatch of the order, because the TT was swapped with another, or because it was busy. A solution for this last cause mentioned can be to deploy more TTs, which is therefore one of the design alternatives (Sec. 3.2.2). The other two causes are planning and control-related and therefore out of the scope of this study.

The reason why the TT has to wait at the yard is because the container retrieval takes too long. Several causes can be at the root of this problem. It can be caused by, among other things, wrong scheduling, a defect of the RTG, an error in dispatching the order, a twist-lock error, wrong or incomplete information, and a too-high utilization of the yard. The utilization rate of the yard can be decreased by increasing the yard capacity. Design alternatives 4, 5 and 6 focus on increasing the yard capacity (Sec. 3.2.4, 3.2.5, 3.2.6).

For the unloading process, either the container is not available or the TT is not available. The availability of the container is out of the scope of this study. Hence, the focus is on the other branch *TT not available* of the diagram. There are several possibilities of causes why the TT is not available. The two main reasons, which can each be divided into multiple other reasons, are the same as for the load process. It is either caused by a delay in the travel time of the TT or by the fact that the TT left the yard too late during its previous task. Therefore, the design alternatives and alternative shuffle policies can be applied to the unloading process as well.

3.2. Design Alternatives

In the following sections, design alternatives for the storage yard are discussed that could possibly lead to a smaller decrease in QC productivity. These design alternatives are based on previous studies on the topic of optimizing container terminal performance and on expert interviews. For each design alternative, it is determined whether the design alternative can be a realistic solution and whether it is worth testing with a simulation.

3.2.1. Design Alternative 1: Block Width

Extensive literature research on methods used to improve the performance of highly utilized storage yards has shown that several studies have been done on the topic of the influence of block width on the performance of a container terminal. For instance, the study of Petering shows that the optimal block width for an RTG container terminal ranges from 6 to 12 rows, but is dependent on numerous factors [27]. However, these studies do not consider a highly utilized storage yard. Therefore, it is all the more interesting to study the influence of block width on the performance of a container terminal. However, this design alternative is solely based on the research studies found in the literature. The RCA done in Chapter 2 does not show a root cause that can be eliminated by changing the width of blocks in the yard. Besides, the block width depends on the size of the RTGs used. Increasing the width of the blocks would mean that new RTGs have to be purchased which is an expensive solution.

3.2.2. Design Alternative 2: Number of Equipment

As mentioned above, the study of Petering showed the optimal block width for RTG container terminals [27]. This study also showed that the optimal block width decreases when more RTGs are deployed in the storage yard. As the block width is a fixed number, the number of deployed RTGs can be varied. Besides, the tree diagrams 2.8 and 2.9 show that too few deployed TTs as well as congestion can be causes why the performance of the QCs decreases. There is a possibility that there is an optimal number of deployed TTs for which the performance of the QCs is highest.

3.2.3. Design Alternative 3: Storage Yard Shape

Petering's study showed in addition that the overall performance of the terminal increases if the shape of the yard becomes more square-shaped, instead of rectangular. However, changing the shape of the storage yard is difficult to realize. The dimensions of the terminal are already defined before the terminal is built. If the terminal has a rectangular shape, it can be decided to not use certain parts of the terminal for storage, such that the storage yard is square. However, by making this decision the capacity of the storage yard decreases, while more capacity for storage is desirable at peak times in the year.

3.2.4. Design Alternative 4: Sacrificing Driving Lanes

This design alternative consists of sacrificing driving lanes for storage space. A higher utilization of the yard leads to more reshuffles. Reshuffles increase the retrieval time of containers and in turn, can affect the QC productivity. This is not necessarily always the case, as the planning and control can be adjusted such that it will not lead to a delay in the transfer of the container from the yard to the quay. However, planning and control is out of the scope of this thesis study and therefore the focus will lie on the physical adjustments in the storage yard design. Therefore, the utilization rate of the yard can be brought down by increasing the yard capacity.

The solution of sacrificing driving lanes has already been studied by Wiese et al. [36]. They studied the optimal positions and the number of driving lanes within a rectangular-shaped yard. The objective of this study is to minimize the handling costs, which consist of costs depending on the length of the blocks, and therefore on the number of driving lanes. Costs depending on the block length are costs for the yard crane to perform reshuffles and costs for truck travelling. Not very surprisingly, it was concluded the optimal number of driving lanes differs for different yard lengths. Their recommendation for further research is to measure the impact of the yard layout on the overall performance of the container terminal using simulation.

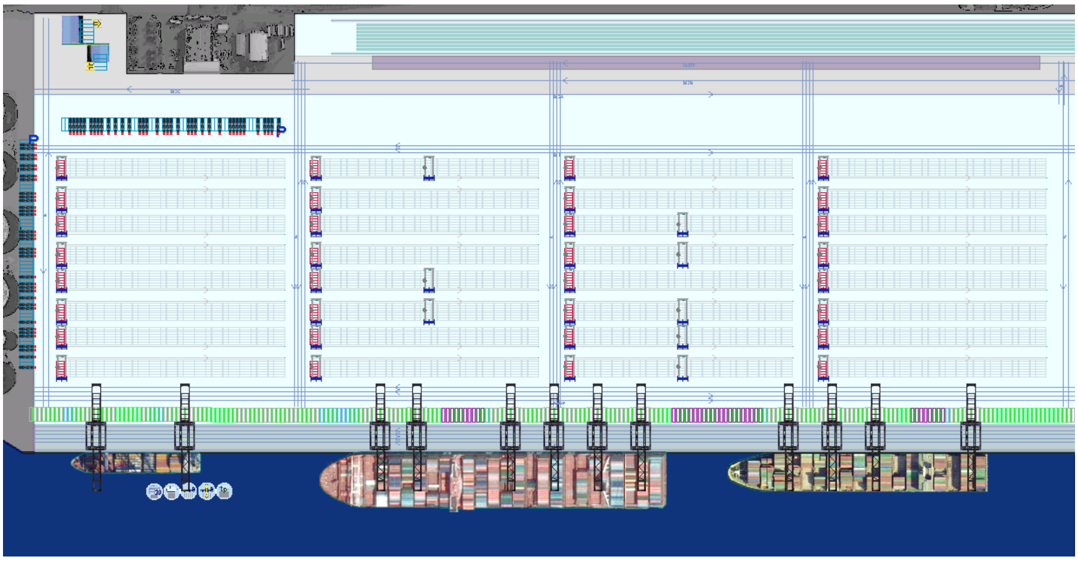


Figure 3.1: RTG Terminal with a storage yard consisting of 4 blocks, with between the blocks driving lanes from landside to quayside

Between every two adjacent blocks in the storage yard is a driving lane across the depth of the terminal (from landside to quayside) as is shown in Figure 3.1. These driving lanes can be sacrificed by making the blocks longer by adding more bays to the block. This way the two adjacent blocks become one big block. The downside of this is that the Terminal Trucks (TTs) have to drive a longer route around the block when going to the quayside (and back). Simulation will show whether longer driving routes and more storage space versus less storage space but shorter routes is more beneficial for the QC productivity. This design alternative came about through discussions and interviews with an expert in this field.

3.2.5. Design Alternative 5: Stack Height

Another way of increasing the yard capacity is by increasing the stack height. Stacks can be a certain height, depending on the size of the yard crane. Therefore the increase in stack height is limited to only one container because otherwise new equipment must be purchased. Purchasing bigger RTGs is not desirable, for the same reasons as mentioned in Section 3.2.1. In a bay, a couple of container slots need to stay unoccupied in order to make reshuffles. There is no space for reshuffles next to the bay, as there is a transfer lane where trucks are positioned to receive the container. The number of available spots for shuffles depends on the maximum height of the stacks, as this number is the maximum height minus one. The maximum height refers to the height of the stacks at which the RTG is still able to lift a container over the stacks. With increasing the stack height, it has to be taken into account that when a certain stack is increased to the maximum height plus one, there is no possibility anymore to lift a container over this stack. Therefore, only the outermost stack row, the row farthest from the transfer lane, can be made one container higher. However, it must be taken into account that when the bottom container of that stack has to be retrieved, the containers on top of it must be moved. In this case, this is one container more than the other stacks, so there must be one extra reshuffle slot available in the bay.

3.2.6. Design Alternative 6: Alternative Shuffle Policies

The idea of an alternative shuffle policy also arises from increasing the yard capacity. First, it will be explained what a shuffle policy entails.

A shuffle policy consists of two parts. First, it consists of rules on which the decision on where to store a container is based. Second, it consists of rules on where to move a container to that needs to be shuffled. Currently, a shuffle policy is used that will be called from now on the *One-bay Shuffle Policy*. This means that only one bay is considered. When a container arrives at the yard, the desired bay is checked on available slots. There is a certain number of slots that must remain open in order to perform shuffles; the shuffle slots. This number of slots per bay is the maximum height of containers minus one. In the case of a 1 over 5 RTG, which means that the RTG can lift one container over five containers stacked on top of each other, four slots have to remain free for shuffles. Secondly, if a container needs to be retrieved and therefore other containers on top need to be shuffled, it happens within the bay.

To create extra storage space, it is possible to divide the shuffle slots over two adjacent bays. This means that four storage slots are created, as only four shuffle slots must be available over two adjacent bays. A downside of this idea is that driving with a container takes more time than relocating a container in the same bay. This shuffle policy will be called the *Two-bay Shuffle Policy*.

A second option is to take three bays together and ensure that those three bays together have enough shuffle slots. The middle bay of those three bays is the bay where the container is located that needs to be retrieved, and therefore the containers to be reshuffled can be moved to the bays on either side of the bay where the desired container is located. In this case, the driving distance of the RTG is still limited to one bay. This shuffle policy will be called the *Multi-bay Shuffle Policy*.

Literature research has shown that no previous research has been conducted into alternative shuffle policies.

3.3. Conclusion

Several design alternatives are found which could ensure that the processes that affect the QC productivity are less influenced by a high Yard Utilization Rate (YUR). Design alternatives *1: Block Width*, *3: Storage Yard Shape* and *5: Stack Height* will not be tested in simulation, as these solutions are not realistic. Design alternatives *2: Number of Equipment*, *4: Driving Lanes* and *6: Alternative Shuffle Policies* and will be tested in simulation. The design alternatives will be explained in more detail in Chapter 5. Below, the reasoning behind the decision on whether an alternative will or will not be tested with simulation is given.

3.3.1. Design Alternative 1: Block Width

This design alternative consists of varying the width of the storage blocks. However, the block width is dependent on the size of the RTG used. Often, the blocks are as wide as the blocks can be. The only way to increase the block width is to use bigger RTGs. However, it is a very expensive solution if all the RTGs need to be replaced by bigger ones. Besides, the larger RTGs are only useful at the peak moments of the year. At other times of the year, the normal RTG will suffice. Therefore, this design alternative will not be tested with simulation, because it is simply not a realistic solution.

3.3.2. Design Alternative 2: Number of Equipment

This design alternative consists of varying the number of equipment. Varying the number of used RTGs is not a realistic solution. In this case, extra RTGs have to be purchased for use during short moments during a year when it is busy in the terminal and the YUR is increased. RTGs are quite expensive and therefore the design alternative of increasing the number of RTGs will not be tested with simulation.

Increasing the number of deployed TTs can be a possible solution and will be tested with simulation. The number of TTs will be varied between 6 en 10 TTs per QC. This range of number of TTs is based on expert opinions. For this solution, extra TTs have to be purchased, but they are less expensive than RTGs and therefore this is a more realistic option.

3.3.3. Design Alternative 3: Storage Yard Shape

The design alternative of making the yard square-shaped is not a realistic solution. The dimensions of the terminal are already defined before the terminal is built. Making the yard square-shaped, leads to a part of the existing storage area not being used. This is contradictory to what is desirable when the yard is highly occupied. Therefore, this design alternative will not be tested with simulation.

3.3.4. Design Alternative 4: Sacrificing Driving Lanes

This design alternative consists of sacrificing driving lanes in the yard for extra storage space. An expert opinion stated that it is an idea that needs to be further studied, as it is beforehand unknown if longer travelling distances for the trucks in combination with a lower YUR leads to a better performance than shorter travelling distances in combination with a higher YUR. Therefore, this design alternative will be tested with simulation.

3.3.5. Design Alternative 5: Stack Height

This design alternative consists of increasing the stack height of the outermost stack. By increasing the stack height an extra shuffle slot is necessary, which results in the same amount of storage slots as without this extra container on the outermost stack. The conclusion is that the number of containers that can be placed in the bay remains the same, and this alternative always leads to an extra shuffle because of the fact that a container cannot be lifted over the outermost stack when this stack is six containers high, this design alternative will not be tested with simulation.

3.3.6. Design Alternative 6: Alternative Shuffle Policies

Literature research shows a gap in research into alternative shuffle policies in RTG terminals. With the Two-bay Shuffle Policy, four extra 1-TEU storage slots are created for each two bays. With the Multi-bay Shuffle Policy, eight extra 1-TEU storage slots are created for each three bays.

3.3.7. Summary

This chapter gives design alternatives as possible solutions to decrease the influence of the YUR on the QC productivity, as well as Subquestion 3 has been answered.

3. *What possible design alternatives can be found such that the processes that affect the QC productivity, are not influenced or less influenced by a high Yard Utilization Rate?*

The possible design alternatives that can be found are several, some more realistic than others. After weighing the advantages and disadvantages, it was decided to simulate three solutions. The design alternative of varying the number of TTs, of sacrificing driving lanes and of applying an alternative shuffle policy will be tested with simulation. The first one is based on the root causes *"Too few TTs deployed"* and *"Congestion"*. The other two alternatives create extra storage space to decrease the YUR.

4
Modelling

In this chapter subquestion 4 is addressed.

4. *How to model the relation between the yard utilization rate and the QC productivity in RTG container terminals?*

Literature study is used to answer this subquestion.

4.1. Model Objective

The main goal of this study is to reduce the QC productivity loss, that occurs because of an increasing utilization rate of the container storage yard. The aim of the model is to show the relation between the QC productivity and the Yard Utilization Rate (YUR) for the different design alternatives. Figure 4.1 shows a simplified representation of the simulation model. In the following sections, the four components of the simplified representation will be elaborated. Besides, the assumptions made, and the verification and the validation of the model will be discussed.

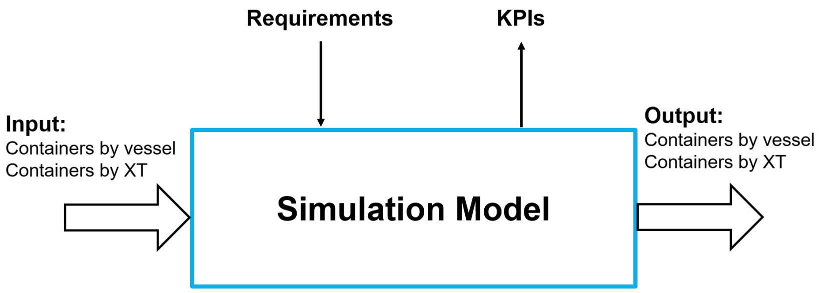


Figure 4.1: Simplified representation of the simulation model

4.2. Model Input and Output

The system is demarcated by the edges of the terminal. The system is 'open' at two locations, the gate and the quay. At the gate, external trucks (XTs) enter and leave the terminal with or without containers. At the quay, vessels arrive and containers enter and leave the terminal as well.

The arrival pattern of the external trucks, as well as the vessel arrival pattern, is given in Section 5.1. The containers that arrive by XT at the gate are shortly afterwards stored in the yard. The containers that are exported and leave the terminal by vessel, are not the same containers that have arrived that day by truck. The same applies to import containers. All containers have a certain dwell time. The dwell time of a container is defined as the time the container is stored in the yard between arrival and departure. The dwell time is on average more than two days. Since the simulation will only last 28 hours (Subsec. 4.7.1), the containers that arrive in this simulation will not leave the terminal in this same simulation.

4.3. Key Performance Indicators

Other outputs of the model are the Key Performance Indicators. Since the model aims to show the relation between the QC productivity and the yard utilization rate, the *QC productivity* is one of the KPIs. The QC productivity is measured in boxes per hour handled by the QC. Therefore, for each individual QC, the productivity must be captured. This way, when one specific QC is decreasing in productivity it can be tracked down. As discussed in Section 2.3, Figures 2.8 and 2.9 show which causes can affect the QC cycle. Therefore, besides QC productivity, other KPIs are:

- the status of the TTs for each hour
- the status of the QCs for each hour
- the status of the RTGs for each hour

4.4. Requirements

The model must meet the following requirements to be able to represent an RTG terminal in a realistic way:

- The model must be able to measure the KPIs:
  - QC productivity
  - the status of the TTs for each hour
  - the status of the QCs for each hour
  - the status of the RTGs for each hour
- It must be possible to change the utilization rate of the yard.
- It must be possible to change the layout of the yard.
- It must be possible to apply specific shuffle policies.
- It must be possible to change the number of equipment.
- The model must capture the operations of the RTGs, TTs and QCs.
- The model must be able to record the handling times of the ships.

4.5. Assumptions

Model assumptions are specifications, and sometimes simplifications, of the model that make modelling easier, or in some cases even possible.

- The terminal consists of three parts; a gate, a storage yard and a quay.
- Export containers arrive by External Truck (XT) at the gate, and import containers leave the terminal at the gate by XT.
- Export containers leave the terminal at the quay by vessel, and import containers arrive at the terminal by vessel.
- At the gate, one XT can enter and one XT can leave the terminal at the same time.
- The quay is considered continuous and is 1200 meters long.
- The storage yard is divided into four blocks, each block containing 8 modules.
- A module consists of 7 rows, 40 bays and 5 tiers.
- Import and export containers are stored separately as much as possible.
- Import containers are stored in the modules at the land side and export containers most to the quayside of the storage yard.
- External Trucks (XT) transfer containers from the gate to the storage yard and vice versa.
- Terminal Trucks (TT) transfer containers from the storage yard to the quay and vice versa.
- Rubber Tyred Gantry Cranes (RTG) transfer containers from the XT or TT to a storage slot in the stack and vice versa.
- Quay Cranes (QC) transfer containers from a TT to a vessel and vice versa.
- Only standard dry and empty 20-foot and 40-foot containers are considered. Reefers, IMO containers, 45-foot and all other types of containers are left out of scope.

- The distribution of which percentage of the total TEU arrives by deepsea vessel, feeder or truck is determined. This is called the *modal split*.
- Al containers have the same average dwell time.
- Only single and twin lifts are taken into consideration for QC lifting operations. Tandem lift is left out of scope since tandem lifts are not convenient to perform with Terminal Trucks. An extra step in the (un)loading process is necessary, which takes time and is unfavourable.
- The following grounding rules apply:
  - Import containers are separated from export containers as much as possible.
  - Empty containers are also stored in their own area.
  - Separating empty containers has a higher priority than separating imports and exports.
  - Containers with the same POD are stored as much together as possible.

4.6. Model Description

Figure 4.2 shows the RTG terminal as shown in the simulation model Timesquare. In the left upper corner is the gate where the XTs arrive. The XT drives via the driving lanes to the yard and the correct stack in the yard, where the RTG lifts the container from the chassis of the XT and places it in the yard for storage, or the other way around. The XT drives back to the gate and leaves the terminal. The RTGs move horizontally along the modules. Active RTGs are green and non-active RTGs are grey. At the left side of the Figure between module 4 and 5, a RTG is switching modules. In that case, the RTG is orange. The red icon at each left side of a module is a button to enter the environment with information of that module.

The vessels can be seen at the bottom of the Figure. The left vessel is a feeder with two QCs working on it. The middle vessel is an ULCV with six QCs working on it and the last vessel is a Panamax with four QCs working on it. The TTs transport the containers from the yard to the quay. The two types of trucks can be distinguished by the colour of the cabin. The XTs have a blue cabin and the TTs have a red cabin.

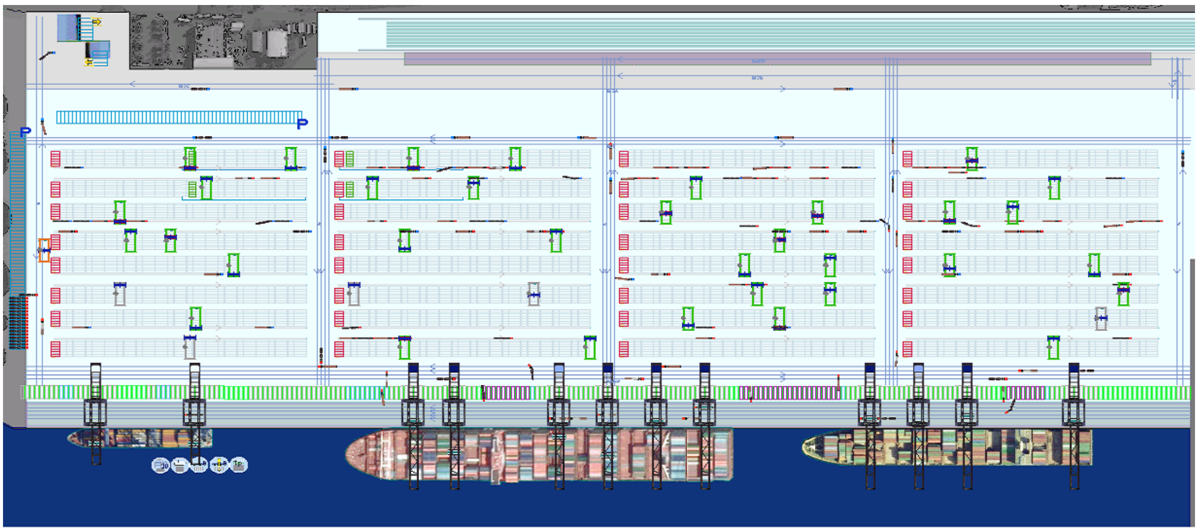


Figure 4.2: Overview of the RTG terminal in Timesquare

4.7. Verification and Validation

Verification of the model is a necessary step in the process of modelling. This step answers the question if the model is implemented according to the specifications.

The software used to create the model has been in use for several years by Portwise, formerly TBA. Parameter settings must be entered in order to create the desired model. Verification of the model is done by a visual check. For example, the number of vessels should match the entered value, as well as the number of QCs, RTGs and TTs. Different types of containers have different colours. Containers with the same colours should be stored together if the settings require it.

Besides, the most important requirement of the model is that it should capture the performance of the terminal by measuring the QC productivity when a certain yard utilization rate is applied. Test runs were done to ensure this was the case. This also brings us to the validation of the model.

The step of validating the model answers the question if the model gives an accurate representation of the real system. Portwise knows from previous studies what the graph of QC productivity versus the YUR should look like. The figures presented in the Problem Statement, Section 1.2, serve as validation of the model (Figs. 1.4a, 1.4b and 1.4c). Experts from Portwise can confirm that the model works as it should because these figures show results that correspond to reality. A comparison of the simulation results with results from reality cannot be given here, as this conflicts with the contract concluded between the customer and the company at the time.

4.7.1. Length of simulation

The length of the simulation is 28 hours. The simulation starts at midnight and ends the day after at 4 a.m. The goal is to simulate a full day, but to ensure that the ships are completely handled the simulation length has been extended by 4 hours. The reason behind this is that only data is logged when ships have been completely handled.

4.7.2. Number of replications

In simulation, several replications have to be done in order to generate sufficient results. Without sufficient results, the drawn conclusion can be incorrect. To determine how many replications have to be done to obtain enough results, the standard deviation for each scenario simulated has to be determined. The standard deviation is calculated with the formula

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{4.1}$$

In which N is the number of replications done of a scenario, x_i is the QC productivity for replication i and $\overline{x}$ is the average QC productivity of all replications for this specific scenario.

Portwise applies a standard deviation for the QC productivity of a maximum of half a move per hour with a 95% confidence interval. This means that it must be for 95% sure that the deviation of the QC productivity will be equal to or less than 0.5 moves per hour. To ensure this, a two-tailed Student's t-test is done. For each replication, the QC productivity μ may deviate $\frac{ts}{\sqrt{N}}$ from the average $\overline{x}$.

$$\mu = \overline{x} \pm \frac{ts}{\sqrt{N}} = \overline{x} \pm d_N \tag{4.2}$$

$$d_N = \frac{ts}{\sqrt{N}} \leq 0.5 \tag{4.3}$$

This calculation is done for each time new results are available until the condition given in 4.3 is met. This algorithm, which repeats itself for each replication, is shown below (Alg.1). t is calculated using a *t-table* or the *t.inv* function in Excel [35].

Algorithm 1 Calculating the required number of replications

```
1:  N = 4
2:  Run N replications of the model
3:  Calculate s (Eq. 4.1)
4:  Determine value of t
5:  Calculate d_N
6:  if d_N ≤ 0.5 then
7:      N_required = N
8:  else if d_N > 0.5 then
9:      N = N + 1
10:     Run an extra replication of the model
11:     Go back to step 3 and repeat
12: end if
```

4.8. Conclusion

The subquestion asked at the beginning of this chapter was

4. *How to model the relation between the yard utilization rate and the QC productivity in RTG container terminals?*

The relation between the yard utilization rate and the QC productivity can be modelled with a simulation model of an RTG container terminal, in which containers arrive and depart by truck or vessel, and containers are stored in the storage yard. The number of QC moves per hour has to be captured and the data has to be stored. Several repetitions of a simulation have to be done in order to have a representative outcome of the productivity of the QCs, since the standard deviation must remain below a certain value.

5

Experimental Plan

In this chapter, the experimental plan is discussed. In Section 5.1 the simulation inputs are presented. In Section 5.2, the configuration parameters are given. Thereafter, in Sections 5.3, 5.4 and 5.5, the experimental plans for the design alternatives are given. From here on, the design alternatives have a different numbering than mentioned in Chapter 3 In Section 5.6, an overview will be given of all experiments that will be conducted. The subquestions related to this chapter are subquestions 5 and 6, but will only be answered in Chapter 6 where the results of the experiments will be presented.

5. *Which processes of an RTG container terminal are affected most by a high utilization rate of the storage yard?*
6. *Which of the possible solutions of subquestion 3 ensure that the QC productivity is not affected or less affected by a high yard utilization rate?*

5.1. Simulation Input

As described in Section 4.2, the input of the simulation model will be containers. These containers either arrive by External Truck (XT) at the gate or by vessel at the quay. In the following three sections, the input parameters, the vessel arrival pattern and the truck arrival pattern will be given. These parameter settings will be used for all experiments, so only one scenario will be used for the simulation of the different design alternatives.

5.1.1. Input Parameters

- The model contains four vessels; two feeders, a Panamax and a ULCV.
- 25.5% of the containers are transported by truck and 74.5% by vessel.
- The TEU factor is 1.6. This means that 40 % of the total number of containers are 20-foot containers and 60 % are 40-foot containers.
- The container type distribution per modal flow is shown in Table 5.1.
- The call size, ETA and length of each vessel are given in Table 5.2. The vessel arrival pattern is discussed in Section 5.1.2.
- The land side truck arrival pattern is a multiple normal distribution shown in Figure 5.1 and is further explained in Section 5.1.3.
- The External Trucks (XTs) are divided into three groups; delivery only, pickup only and both delivery and pickup. The ratio between these three types of External Trucks is 40-30-30.
- External Trucks have a 2 TEU capacity.

	Train	Vessel
Full dry 20-foot	7,7 %	22,4 %
Full dry 40-foot	11,5 %	33,5 %
MT 20-foot	2,5 %	7,4 %
MT 40-foot	3,8 %	11,2 %
Modal split	25,5 %	74,5 %

Table 5.1: Container type distribution as a percentage of total container transport

5.1.2. Vessel Arrival Pattern

Four vessels are being handled over the course of a day; two feeders, one Panamax and one Ultra Large Container Vessel (ULCV). The ULCV already arrived before the start of the simulation, and the last containers are being handled during the simulation. The Panamax arrives at 2 a.m., the first feeder at 5 a.m. and the second feeder at 3 p.m. The arrival times are, along with other specifications of the vessels, shown in Table 5.2.

	Vessel 1	Vessel 2	Vessel 3	Vessel 4
Size	Small	Middle	Big	Small
Category	Small feeder	Panamax	ULCV	Small feeder
Length	140 m	290 m	400 m	140 m
Breadth	21,8 m	32 m	58,6 m	21,8 m
Capacity in TEU	600	4.200	20.160	600
Call size in TEU	300	1.680	9.072	300
Modal split	1,5 %	11,6 %	61,4 %	1,5 %
ETA	05:00	02:00	Previous day	15:00

Table 5.2: Vessel specifications

5.1.3. External Truck Arrival Pattern

Research on opening times of terminals in the Netherlands pointed out that big terminals are opened 24/7 for trucks, and smaller terminals have opening times that vary from 5 to 8 a.m. to 7 to 10 p.m.[26] [24]

The following paper shows a truck arrival pattern for each day during the week.[12] This terminal is open 24/7, but shows a peak in the morning and a peak in the afternoon. The increase in the morning towards the first peak is faster than the decline after the second peak in the afternoon. This was taken into account while creating the truck arrival pattern for the simulation. The created truck arrival pattern is a combination of two normal distributions, which is shown in Figure 5.1.

The truck arrival pattern shows what percentage of the total number of trucks arriving that day, arrive within a certain hour. The inter-arrival time of the trucks is defined as the time between the arrival of two trucks. This inter-arrival time in seconds is calculated by dividing 3600 seconds by the number of trucks that will arrive in that hour.

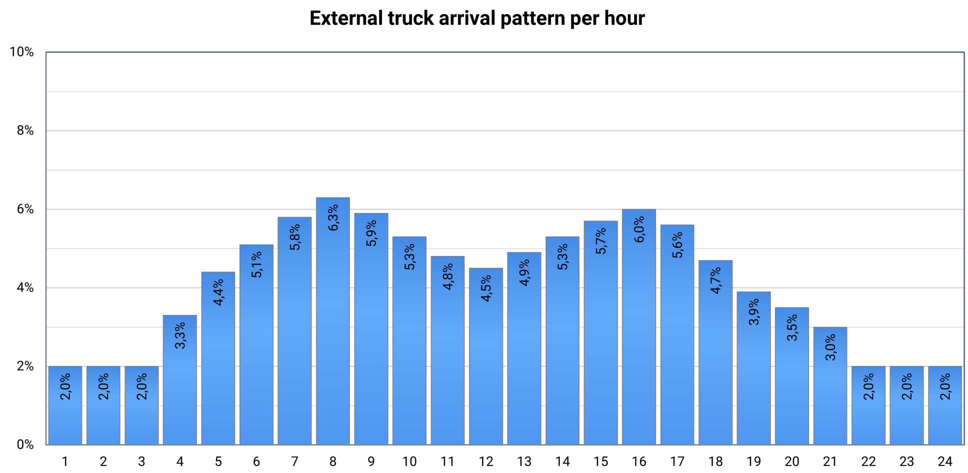


Figure 5.1: External truck arrival pattern with a total of 3200 external trucks in a day and a peak value of 200 trucks

5.2. Configuration Parameters

Configuration parameters are specified settings for a certain configuration of the simulation. These settings can vary for different configurations. Below, the specifications are given that will be used in each experiment, including the benchmark.

- The terminal is equipped with 12 QCs, 40 RTGs and 72 TTs.
- The number of gate moves per hour at peak hours is 200 moves per hour.
- The main operating specifications of the RTG are given in Appendix E. These are not special settings but are standard for this type of equipment.
- The main operating specifications of the QC are given in Appendix F. These are not special settings but are standard for this type of equipment.
- The initial yard utilization rate is considered 83% of the total yard capacity occupied.
- The specifications of the yard are given in Table 5.3.

For clarification: In Section 1.1.1, a block or module was defined as a collection of containers stacked close to each other and separated by driving lanes. In Table 5.3, the terms *block* and *module* have different definitions. With *module* is meant the collection of containers as mentioned in Section 1.1.1. With *block* is meant a collection of *modules*. A block is in this case one module wide and several modules long, as is also shown in Figure 5.2. From now on these two terms will be used with the definition as mentioned here.

Benchmark specifications	
№ of blocks	4
№ of modules per block	8
Total № of modules	32
№ of bays per module	40
№ of rows per module	7
Stack height	5
Ground slots	8.960 TEU
Total yard capacity	44.800 TEU
Quay length	1.200 m

Table 5.3: Specifications of the storage yard

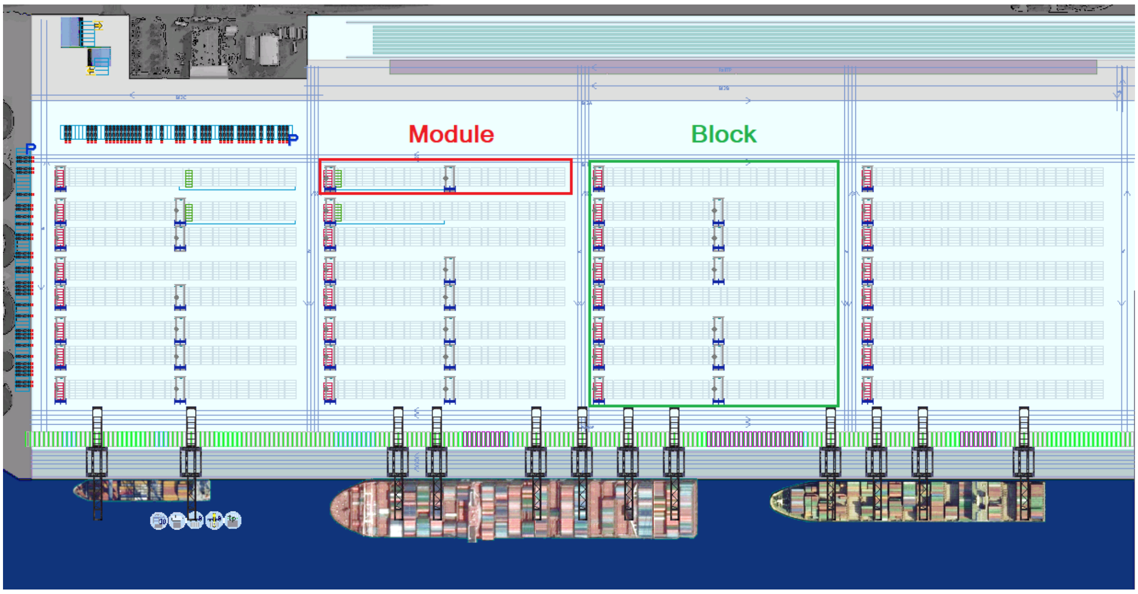


Figure 5.2: Benchmark terminal layout

5.3. Design Alternative 1: Number of TTs

For this design alternativessss, the number of deployed TTs will be varied. As mentioned in 3.2.2, too few deployed TTs as well as congestion can be causes of a decrease in the performance of the QCs. Congestion can be a result of too many deployed TTs. Therefore, there probably will be a tipping point at which the performance of the QCs goes from increasing performance to decreasing performance. This tipping point will be at the optimum number of TTs deployed.

The number of TTs serving each QC will be varied from 6 TTs per QC to 10 TTs per QC. This means with 12 QCs deployed, there will be respectively, 72, 84, 96, 108 and 120 TTs in total deployed.

5.4. Design Alternative 2: Sacrificing Driving Lanes

For this design alternative, three different yard layouts are tested. The default layout consists of four blocks. This is the reference case. The three other layouts consist of three blocks, two blocks and one block.

In the layout with three blocks, the two blocks in the middle are merged and therefore one driving lane is sacrificed (Fig. 5.4). In the layout with two blocks, the first two blocks and the other two blocks are merged, resulting in a sacrifice of two driving lanes (Fig. 5.5). In the last layout, of one block, all blocks are merged and therefore only driving lanes around the block still exist (Fig. 5.6). In Table 5.4, the number of extra container storage space created is given, as well as the decrease in yard utilization rate that comes with creating extra storage space.

	4 blocks[1]	**3 blocks**	**2 blocks**	**1 block**
№ of bays per module	40	2*40+1*85	85	175
№ of rows per module	7	7	7	7
Maximum stack height	5	5	5	5
Grounding slots in TEU	8.960	9.240	9.520	9.800
Total yard capacity in TEU	44.800	46.200	47.600	49.000
Total yard capacity in № of containers[2]	28.000	28.875	29.750	30.625
Yard utilization rate	83%	80%	78%	76%

Table 5.4: Specifications of the different design alternatives for the yard layout simulated.

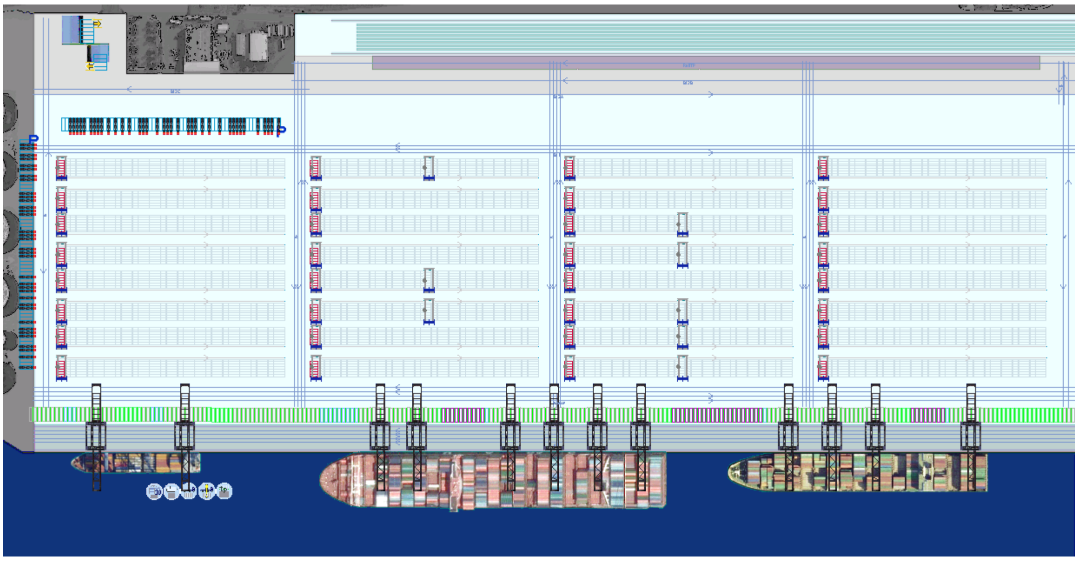


Figure 5.3: Default yard layout consisting of four blocks

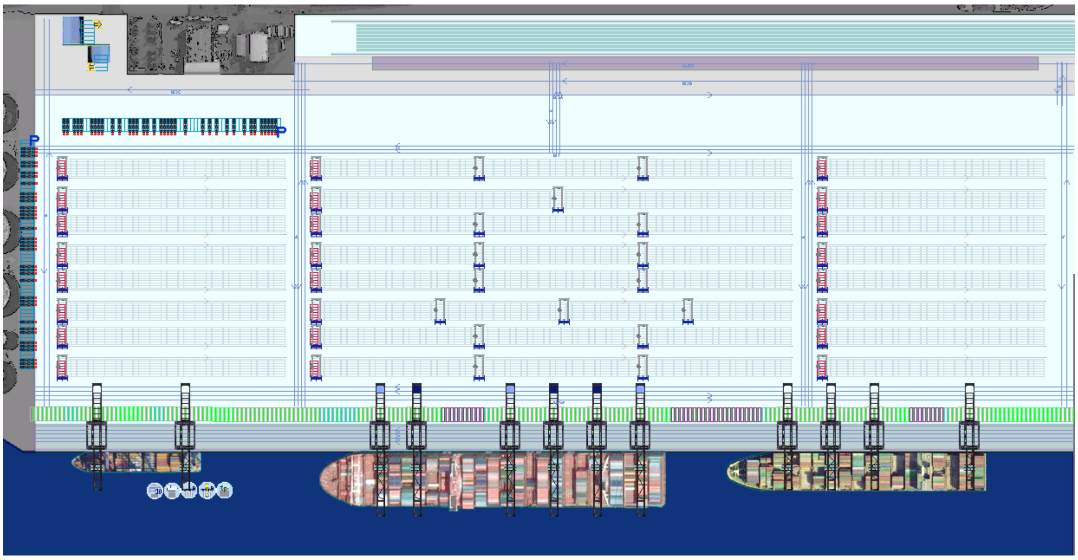


Figure 5.4: Sacrificing one driving lane for additional storage space, resulting in a layout of three blocks

[1]Default layout
[2]With a TEU-factor of 1.6

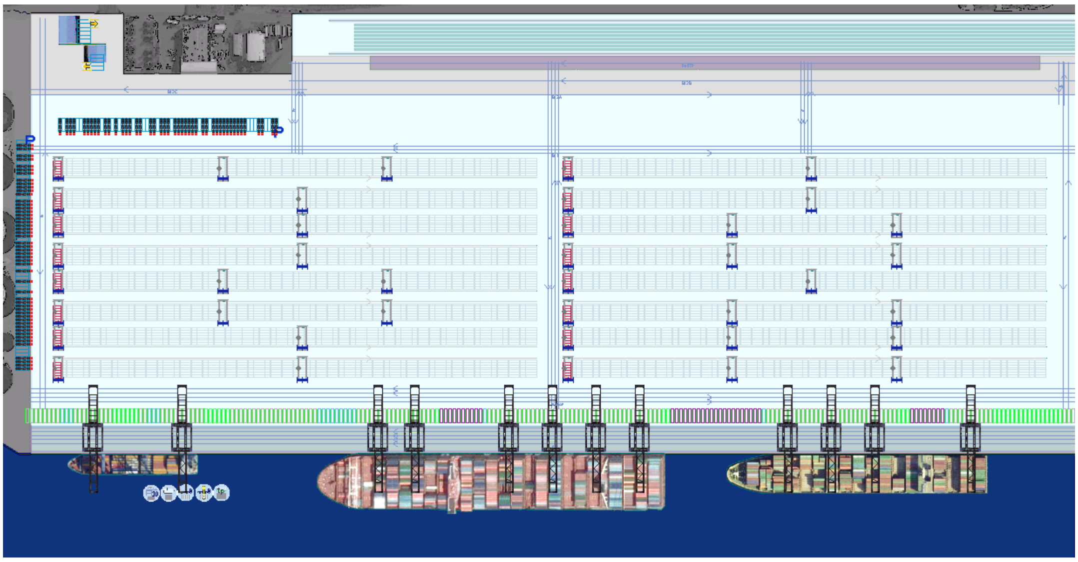


Figure 5.5: Sacrificing two driving lanes for additional storage space, resulting in a layout of two blocks

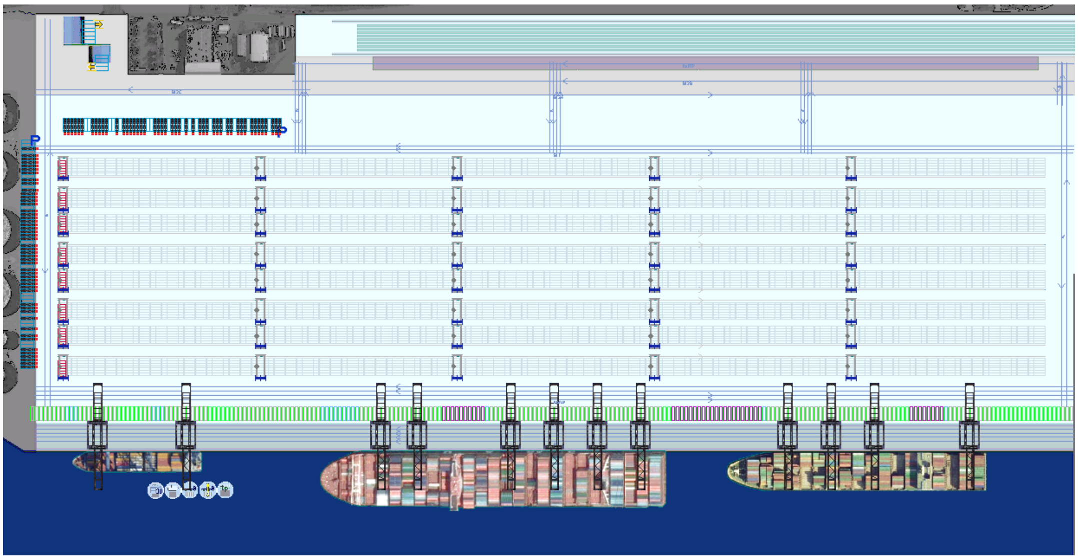


Figure 5.6: Sacrificing three driving lanes for additional storage space, resulting in a layout of one big block

5.5. Design Alternative 3: Alternative Shuffle Policies

In Section 3.2.6, two main ideas for alternative shuffle policies were described. These two ideas are further developed and are described in this section. Besides the two alternative shuffle policies, an alternative bay distribution is developed. Different combinations between the bay distributions and the alternative shuffle policies are made. These combinations are shown in Table 5.5.

There are two aspects that change when applying an alternative shuffle policy. In the default situation, the number of available slots in the desired bay is checked when a container arrives. This number of available slots must be a minimum of five, as a maximum of four containers have to be moved when the bottom container of a stack needs to be retrieved. Besides, shuffles take place within the bay the container is stored in.

With an alternative shuffle policy, the number of available slots of the desired bay together with the bay-friend must be a minimum of five. In that case, it is possible that one of these bays is completely full. Therefore, shuffles can also take place outside of the bay the container is stored in, and can be moved to the bay-friend. The fact that multiple bays are coupled ensures that there is more storage space for containers in the module.

The algorithm for finding a storage space for an arriving container in the default situation:

1. Check if the container is 20-foot or 40-foot.
2. Check if the container is import or export and if export, check POD.
3. Make a decision in which bay n to store the container.
4. Look for an available slot within bay n by checking if available slots $x_n > 4$.
   Slot found? Store container in bay n.
   No slot found? Find another bay.

The algorithm for finding a storage space for an arriving container in the situation where an alternative shuffle policy is applied:

1. Check if the container is 20-foot or 40-foot.
2. Check if the container is import or export and if export, check POD.
3. Make a decision in which bay n to store the container.
4. Look for an available slot within bay n by checking if available slots $x_n > 0$ and $x_n + x_{bay-friend} > 4$.
   Slot found? Store container in bay n.
   No slot found? Go to the next step.
5. Check if $x_{bay-friend} > 0$ and $x_n + x_{bay-friend} > 4$.
   Slot found? Store container in bay *bay-friend*.
   No slot found? Find another bay.

Shuffling containers in the default situation always takes place within the bay.

The algorithm of shuffling containers in the situation where an alternative shuffle policy is applied:

1. Are there free shuffle slots in the current bay? Yes? Shuffle within bay.
   No? Shuffle to bay-friend.
2. Check if the container is import or export and if export, check POD.
3. Make a decision in which bay n to store the container.
4. Look for an available slot within bay n by checking if available slots $x_n > 0$ and $x_n + x_{bay-friend} > 4$.
   Slot found? Store container in bay n.
   No slot found? Go to the next step.
5. Check if $x_{bay-friend} > 0$ and $x_n + x_{bay-friend} > 4$.
   Slot found? Store container in bay *bay-friend*.
   No slot found? Find another bay.

	Bay Distribution	**Shuffle Policy**
Combination 1	Default	Two-bay
Combination 2	Default	Multi-bay
Combination 3	Clustered	Multi-bay
Combination 4	Clustered	Multi-bay with sets

Table 5.5: Overview of the experiments regarding alternative shuffle policies and bay distributions

5.5.1. Current Situation

In a module, 20-foot and 40-foot containers are often stored together. Since the TEU-factor is often above 1.5, 40-foot containers account for a larger share of the yard utilization than 20-foot containers. In the case of a TEU-factor of 1.6, a yard module is arranged such that no 20-foot bays are adjacent, as is shown in Figure 5.7. This bay distribution will be called the *Default Bay Distribution*. Shuffles take place within the bay. This will be called a *One-bay Shuffle Policy*. The combination of the Default Bay Distribution with the Default Shuffle Policy creates the reference case.

5.5.2. Combination 1: Default Bay Distribution and Two-bay Shuffle Policy

This experiment consists of the Default Bay Distribution with the Two-bay Shuffle Policy. The general idea of the Two-bay Shuffle Policy is that two neighbouring bays form a couple. The shuffles are performed within these two bays, and when an arriving container needs to be stored, both bays are checked on the minimum available shuffle slots. For the 40-foot containers, there is one set with three containers instead of two, as the number of 40-foot container bays is odd. Appendix A contains the shuffle matrix of Combination 1, showing which bay pairs are created.

5.5.3. Combination 2: Default Bay Distribution and Multi-bay Shuffle Policy

This experiment consists of the Default Bay Distribution with the Multi-bay Shuffle Policy. The general idea of the Multi-bay Shuffle Policy is that shuffles can be moved to the neighbouring at each side of the current bay n. When an arriving container needs to be stored, these three bays are checked on the minimum available shuffle slots. Appendix B contains the shuffle matrix of Combination 2, showing which bay pairs are created.

5.5.4. Combination 3: Clustered Bay Distribution and Multi-bay Shuffle Policy

This experiment consists of a Custered Bay Distribution with the Multi-bay Shuffle Policy. The Custered Bay Distribution is designed to minimise the travel distance of the RTG. Still, the Multi-bay Shuffle Policy allows the container in a bay n to be shuffled to the neighbouring bays of the same container size at each side of bay n, but because of the Custered Bay Distribution, the RTG travel distance will probably be less than for the Default Bay Distribution with the Multi-bay Shuffle Policy. The Custered Bay Distribution is shown in Figure 5.8. Appendix C contains the shuffle matrix of Combination 3, showing which bay pairs are created.

5.5.5. Combination 4: Clustered Bay Distribution and Multi-bay with Sets Shuffle Policy

This configuration consists of a Custered Bay Distribution with the Multi-bay with Sets Shuffle Policy. The difference with the Multi-bay Shuffle Policy is that in this new policy sets of bays are made. In Combination 3, it can occur that the container has to be moved a couple of bays, as for example, two 20-foot bays can be between bay n and a bay-friend. With this new policy sets are made such that the bay-friends are always adjacent. Appendix D contains the shuffle matrix of Combination 4, showing which bay pairs are created.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
40		20	40		20	40		40		20	40		20	40		40		20	40		20	40		40		20	40		20	40		40		20	40		20	40	

Figure 5.7: Default Bay Distribution with a TEU-factor of 1.6

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
40		40		40		20	20	40		40		20	20	40		40		40		20	20	40		40		20	20	40		40		40		20	20	40		40	

Figure 5.8: Custered Bay Distribution with a TEU-factor of 1.6

5.6. Experiments

In Sections 5.3, 5.4 and 5.5 is explained what the experimental plan for the three design alternatives will be. A total of 12 experiments will be conducted. All experiments are shown in the overview below (Tab 5.6). The first experiments that will be carried out are the experiments in which the number of deployed TTs will be varied. After these five experiments, the optimal number of TTs will be chosen for the next set of experiments in which the driving lanes will be sacrificed for container storage. This is marked in the Table with a *. For the last set of experiments, in which the alternative shuffles policies in combination with two bay distributions will be tested, the optimal number of TTs (*) and the optimal number of blocks (**) will be used. This is done with the idea that testing all different possible combinations, which are 100 combinations and thus 100 experiments, will take too much time.

		№ of TTs	**№ of blocks**	**Bay Distribution**	**Shuffle Policy**
DA 1	Exp. 1	6	4	Default	Default
	Exp. 2	7	4	Default	Default
	Exp. 3	8	4	Default	Default
	Exp. 4	9	4	Default	Default
	Exp. 5	10	4	Default	Default
DA 2	Exp. 6	*	1	Default	Default
	Exp. 7	*	2	Default	Default
	Exp. 8	*	3	Default	Default
DA 3	Exp. 9	*	**	Default	Two-bay
	Exp. 10	*	**	Default	Multi-bay
	Exp. 11	*	**	Clustered	Multi-bay
	Exp. 12	*	**	Clustered	Multi-bay with sets

Table 5.6: Overview of the experiments

6
Results

This chapter is divided into multiple parts. The first part, Section 6.1, shows the results of the design alternative of varying the number of TTs deployed. These results will give an optimal number of deployed TTs. Hereafter, only results are shown with this certain number of TTs. The second part, Section 6.2, shows the results of the design alternative of sacrificing driving lanes for additional storage space The third part, Section 6.3, shows the results of the alternative shuffle policies. In the fourth part, Section 6.4, subquestions 5 and 6 will be answered.

5. *Which processes of an RTG container terminal are affected most by a high utilization rate of the storage yard?*
6. *Which of the possible solutions of subquestion 3 ensure that the QC productivity is not affected or less affected by a high yard utilization rate?*

6.1. Results Design Alternative 1: Number of TTs

This experiment consists of testing the design alternative of varying the number of TTs. The TTs deliver the containers from the yard to the QCs and the other way around. The TTs are therefore in direct connection with the QCs. Five different configurations were simulated, namely with 6 TTs, 7 TTs, 8 TTs, 9 TTs and 10 TTs serving each QC. This gives a total of 72, 84, 96, 108 and 120 TTs deployed respectively.

The results of the simulations of the five configurations are presented in Figures 6.1, 6.2 and 6.3 and are discussed below.[1]

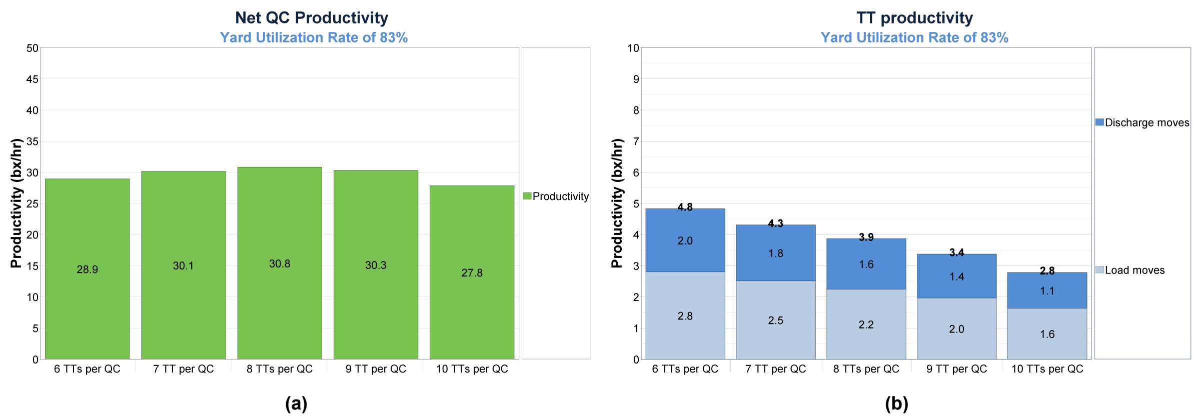
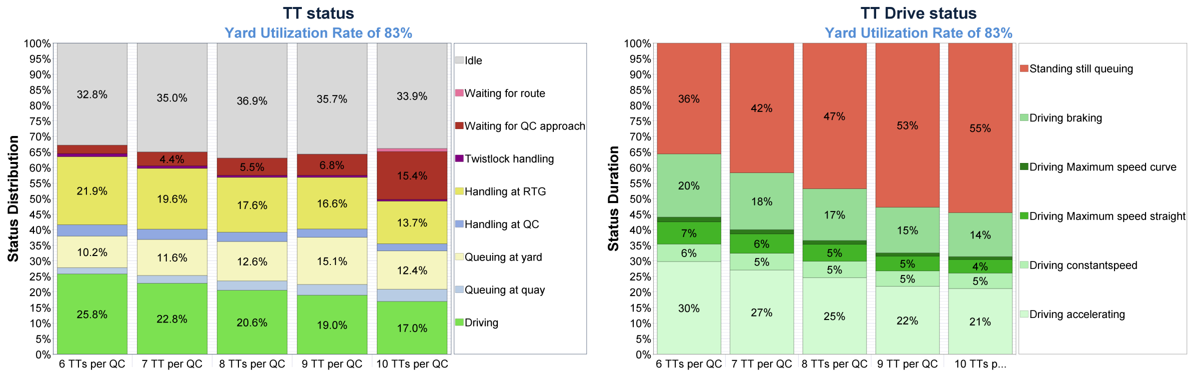


Figure 6.1: QC productivity (a), and the TT productivity (b) for an RTG terminal with a yard utilization rate of 83% for a different number of TTs serving each QC.

[1] It was ensured that the standard deviation calculated over all replications was a maximum of 0.5 boxes per hour. This number is too small to be visibly indicated in the graphs and is therefore mentioned this way.



(a) (b)

Figure 6.2: The TT status (a), and the TT drive status (b) for an RTG terminal with a yard utilization rate of 83% for a different number of TTs serving each QC.

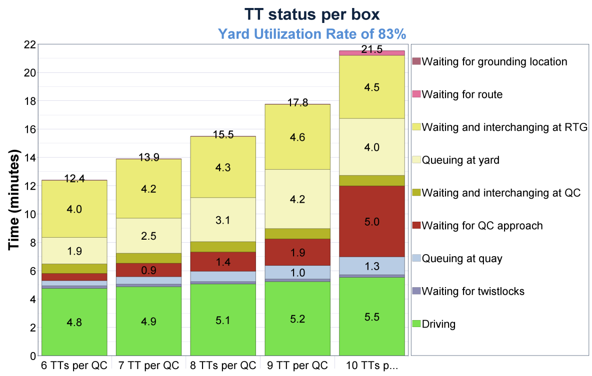


Figure 6.3: The TT status per box for an RTG terminal with a yard utilization rate of 83% for a different number of TTs serving each QC.

Figure 6.1a shows the QC productivity for each of the configurations regarding the number of TTs deployed. The Figure shows that the QC productivity is the highest with 8 TTs deployed per QC. Figure 6.1b shows that the TT productivity decreases as more TTs are deployed. Figure 6.2a shows that the idle time doesn't increase for more deployed TTs. However, *Waiting for QC approach* increases. Besides, the overall time the TTs are productive (not being idle) decreases as more TTs are deployed. Figure 6.2b shows that the TTs are *Standing still queuing* more often instead of driving, which means there is more congestion on the driving lanes in the terminal as the number of TTs deployed increases. Figure 6.3 shows that the average time it takes to handle a container increases as the number of TTs deployed increases. The factors that contribute the largest share to this increase are *Queuing at the quay* and *Waiting for QC approach*. *Queuing at quay* means that the TT is in a traffic jam on the driving lanes near the quay. *Waiting for QC approach* means that the TT has to park at a parking spot near the QCs as it is not their turn yet to approach the QC. There is a certain planning in which order the containers have to be delivered at the QC. The reason why *Queuing at quay* increases for more TTs deployed is because more TTs lead to more traffic on the driving lanes, and thus a greater chance of congestion. The reason why a TT has to wait longer to approach a QC can be that the container that has to be delivered prior to this container is stuck in traffic in the terminal.

Above results and explanation shows that a number of 9 TTs or 10 TTs deployed in this certain configuration is too much. As 8 TTs give the optimal QC productivity, this number of TTs deployed is chosen for the upcoming experiments.

6.2. Results Design Alternative 2: Sacrificing Driving Lanes

This experiment consists of testing the design alternative of sacrificing driving lanes for extra storage space. Four different scenarios were simulated, namely a 4-blocks, a 3-blocks, a 2-blocks and a 1-block scenario. The last one mentioned is the default. These scenarios are shown in Figures 5.3, 5.4, 5.5 and 5.6 respectively.

The results of the simulations of the four scenarios are presented in Figures 6.4, 6.5 and 6.6 and are discussed below.[2]

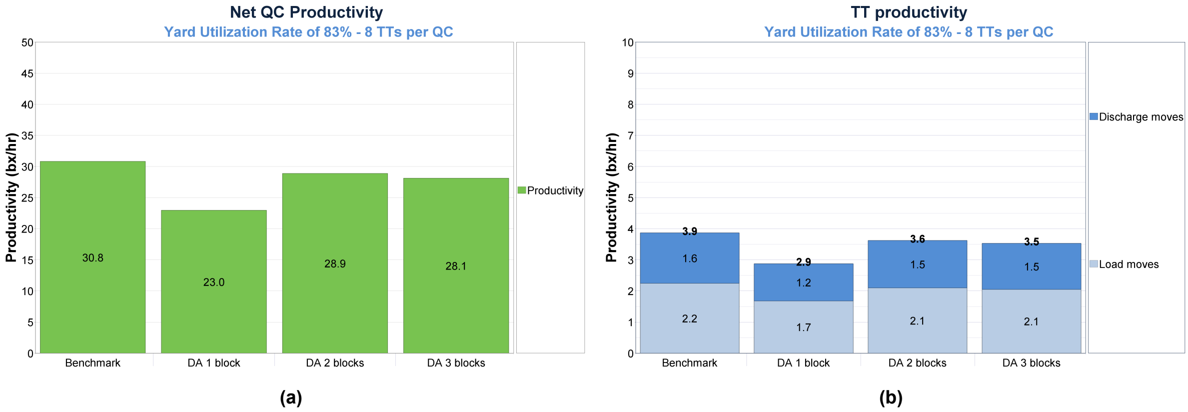


Figure 6.4: The QC productivity (a), and the TT productivity (b) for an RTG terminal with a yard utilization rate of 83% for the different yard configurations.

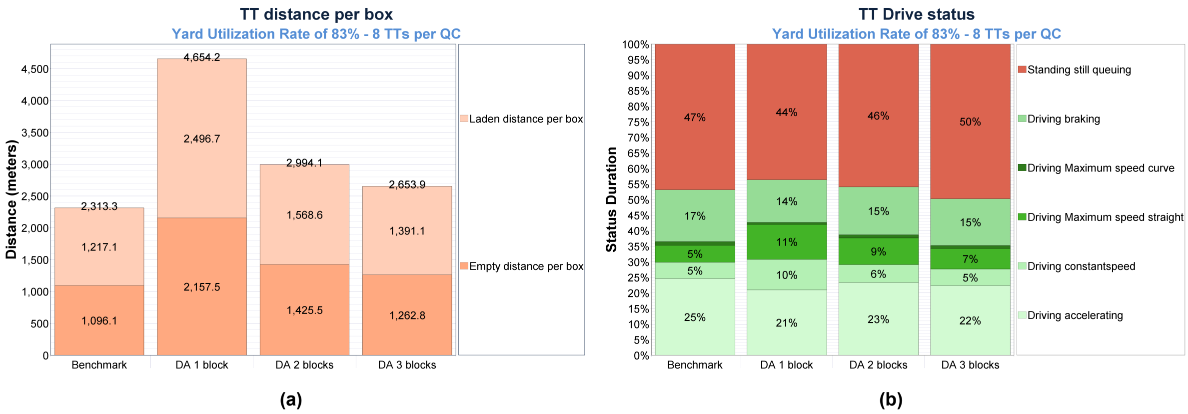


Figure 6.5: The TT average driven distance per box (a), and the TT drive status (b) for an RTG terminal with a yard utilization rate of 83% for the different yard configurations.

Figure 6.4a shows that the QC productivity for the layout with 1 block shows a significant decrease compared to the benchmark. Figure 6.5a shows that the distance a TT travels on average per box doubles for the scenario with only 1 block compared to the benchmark. This is easy to explain. The TT has to drive around the entire block, as there are no longer any roads in between to get from the landside to the waterside. Figure 6.5b shows that the TTs are less queuing on average. It also shows that the TTs drive for a longer period of time at full speed. This probably is because of longer straights and fewer bends on their way from the yard to the quay and the other way around. The amount of time the TTs can drive at full speed in the scenario of 1 block is twice the amount of time as for the benchmark. This in combination with less braking can partly compensate for the fact that the TTs have to travel a greater distance in this scenario compared to the benchmark. However, the longer distance outweighs the benefit of extra storage space, less braking, longer straights and fewer bends, and this

[2]It was ensured that the standard deviation calculated over all replications was a maximum of 0.5 boxes per hour. This number is too small to be visibly indicated in the graphs and is therefore mentioned this way.

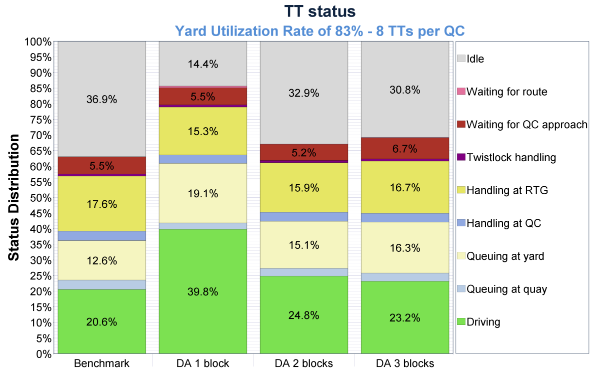


Figure 6.6: The TT status for an RTG terminal with a yard utilization rate of 83% for the different yard configurations and 8 TTs serving each QC.

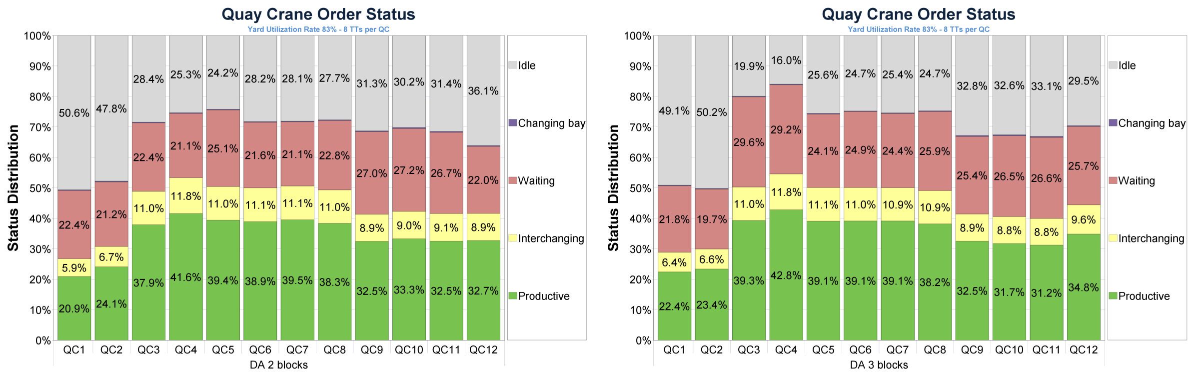
is reflected in lower productivity for both the QCs and the TTs.

The QC productivity of the 2- and 3-block scenarios show a decrease compared to the benchmark (Fig. 6.4a). The average TT distance per box for the scenario of 2 blocks is less than the 1-block scenario, and the one with 3 blocks is less than the one with 2 blocks (Fig. 6.5a). Both scenarios have a greater average TT travel distance per box than the benchmark, as those scenarios have fewer driveways from landside to waterside than the benchmark. The TT Drive Status (Fig. 6.5b) shows that for both the 2- and 3-block scenarios the amount of time the TTs can drive at full speed is greater than for the benchmark. This is for the same reason as for the 1-block scenario. In contrast to the 1-block scenario, the TT productivity of the 2- and 3-block scenarios do not differ much from the TT productivity of the benchmark (Fig. 6.4b).

Remarkably is the fact that the QC productivity for the scenario with 3 blocks is less than the QC productivity for the scenario with 2 blocks (Fig. 6.4a).

The first thing that stands out is that there is more queuing for the 3-block scenario than for the benchmark, while the 1-block and 2-block scenarios have less queuing (Fig. 6.5b). This can imply that there is more congestion in the yard for the 3-blocks scenario. Figure 6.6 confirms this. It shows more queuing in the yard for the 3-block scenario than the 2-block scenario, while this should be descending from the 1-block scenario to the 4-block scenario. Besides, the figure shows that the 3-block scenario has longer waiting times to approach the QC than all the other three scenarios. This can imply that there is more congestion in the yard for 3 blocks than for 2 blocks, even though the 3-block scenario has one more driving lane from landside to waterside than the 2-block scenario. An explanation can be that for the 2-block scenario, the driving lane from the landside to the waterside is in the middle of the yard. The driving lane ends in the middle of the second berth, where the ULCV is berthed. Left from the driving lane are five QCs and right from the driving lane are six QCs. One QC is exactly at the spot where the driving lane ends (Fig. 5.5). In the scenario of three blocks, the driving lanes are positioned such that two QCs are left from the first driving lane, three QCs are right from the second driving lane and seven QCs are in between (Fig. 5.4). In the 2-block scenario, the truck traffic is more distributed over both halves of the terminal than in the case of the 3-block scenario. Figure 6.7 shows that this indeed is the case, as the TTs on average have to wait longer for QCs 3 till 9 in the 3-blocks scenario than for the same QCs in the 2-blocks scenario.

Since this experiment shows that the default layout with 4 blocks gives the best results, the next experiment that tests alternate shuffle policies will be done with the 4-block layout.



(a) **(b)**

Figure 6.7: The QC order status for the scenario with 2 blocks (a), and the scenario with 3 blocks (b) for an RTG terminal with a yard utilization rate of 83% and 8 TTs serving each QC.

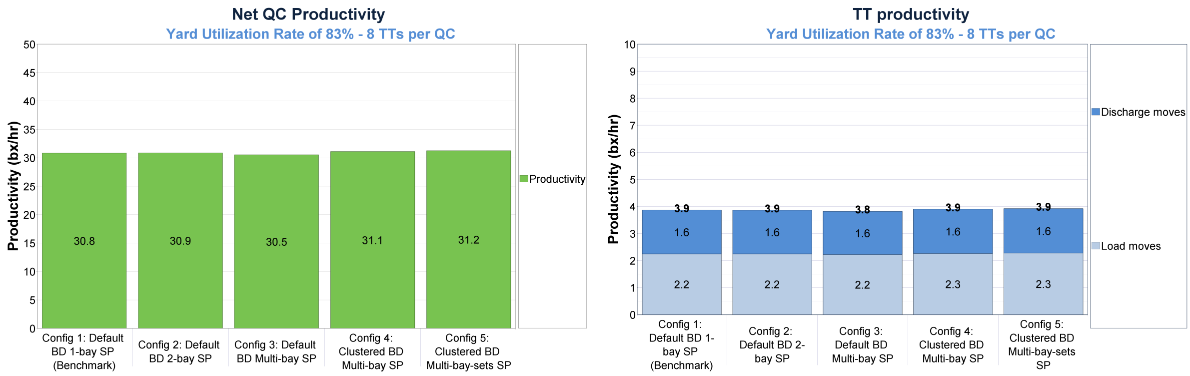
6.3. Results Design Alternative 3: Alternative Shuffle Policies

This experiment consists of testing three different shuffle policies in combination with two different bay distributions. Four different combinations were made and simulated, as is shown in Table 6.1.

The results of the simulations of the four combinations are presented in Figures 6.8, 6.9 and 6.10 and are discussed below.[3]

	Bay Distribution	Shuffle Policy
Combination 1	Default	Two-bay
Combination 2	Default	Multi-bay
Combination 3	Clustered	Multi-bay
Combination 4	Clustered	Multi-bay with sets

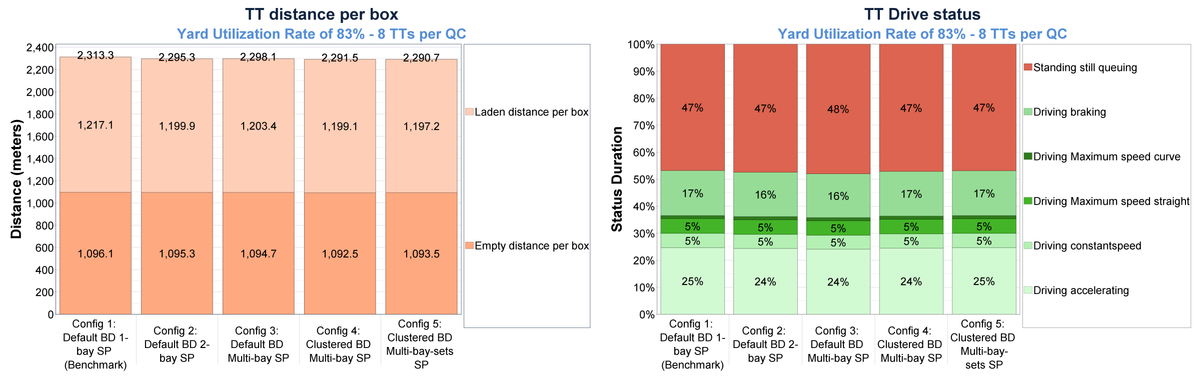
Table 6.1: Overview of the experiments regarding alternative shuffle policies and bay distributions



(a) **(b)**

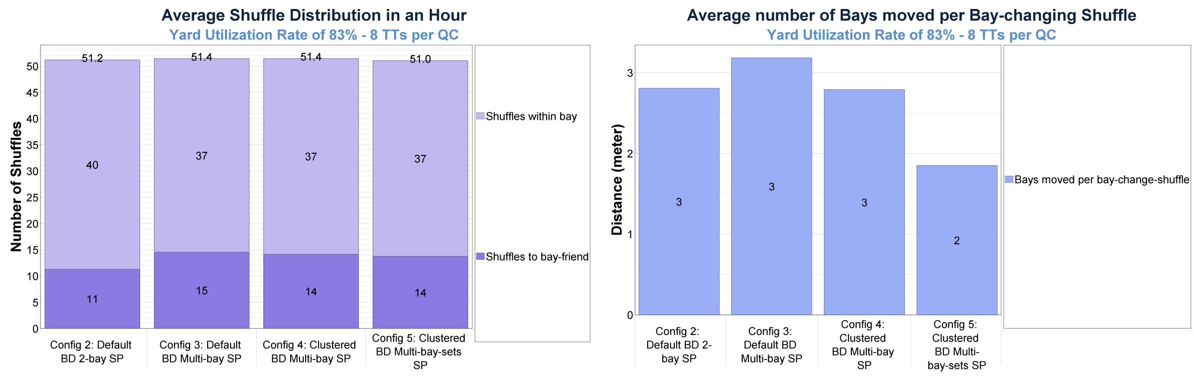
Figure 6.8: QC productivity (a), and the TT productivity (b) for an RTG terminal with a yard utilization rate of 83% and 8 TTs per QC for the different combinations of Shuffle Policies and Bay Distributions.

[3]It was ensured that the standard deviation calculated over all replications was a maximum of 0.5 boxes per hour. This number is too small to be visibly indicated in the graphs and is therefore mentioned this way.



(a) (b)

Figure 6.9: The TT average driven distance per box (a), and the TT drive status (b) for an RTG terminal with a yard utilization rate of 83% and 8 TTs per QC for the different combinations of Shuffle Policies and Bay Distributions.



(a) (b)

Figure 6.10: The average distribution of shuffles in an hour (a), and the average number of bays moved per bay-changing shuffle (b) for an RTG terminal with a yard utilization rate of 83% and 8 TTs per QC for the different combinations of Shuffle Policies and Bay Distributions.

Figure 6.8a shows the QC productivity of the five experiments. The combination of the default bay distribution with the multi-bay shuffle policy (Combi. 2 in Tab. 6.1) performs worse than the reference case. The other three combinations show an increase in QC productivity. The reason for the decrease in QC productivity for Combination 2 is probably that the RTGs have to drive a greater distance for the shuffles to the bay-friend than for the other combinations. Figure 6.10b shows the average number of bays the RTG has to move the container that has to be shuffled outside of the bay, thus to the bay-friend. For Combination 2, this number is a bit higher than for the other combinations.

The TT productivity remains the same for all experiments (Fig. 6.8b). Also, the average driven distance per box for the TTs and the TT Drive states are for one combination not significantly different than for the others (Fig. 6.9).

Figure 6.10a shows that the number of shuffles done is fairly equal for all experiments. The number of shuffles that take place to the bay-friend is for Combination 1 less than for the other three combinations. Apparently, it was more often the case for this combination that there was still space in the current bay for a shuffle and the container did not have to be moved to the bay-friend than for the other combinations.

Combination 4, the Clustered Bay Distribution with the Multi-bay with Sets Shuffle Policy, shows the best performance in terms of QC productivity. The increase in average QC productivity compared to the benchmark is 0.4 containers per hour.

6.4. Conclusion

This chapter gave the results of the experiments done. Subquestion 5 and 6 have been answered as well.

5. *Which processes of an RTG container terminal are affected most by a high utilization rate of the storage yard?*

   The QCs depend on the TTs. As long as they are on time, the QCs will simply run at their maximum productivity (internal failures of the QC not taken into account). The TTs are not on time if it is busy in the yard or if there are not enough TTs deployed. The first could be due to more XTs and more TTs in the terminal, the second logically due to too few TTs. As a terminal, you have control over the deployment of TTs. Over XTs as well, as you can decide to allow a maximum number per time unit. If you assume that the number of XTs does not increase over time, then the only process affected by the high YUR is the retrieval of a container by the RTGs. The containers will be stored less logically and conveniently, as there is no space for that, which will require more shuffles. This explanation is based on the tree diagrams in Chapter 2 (Fig. 2.8 and 2.9). The results of the simulations confirm this line of thinking, as the number of shuffles (in green) done by an RTG on average in an hour increases as the YUR also increases (Fig. 6.11).

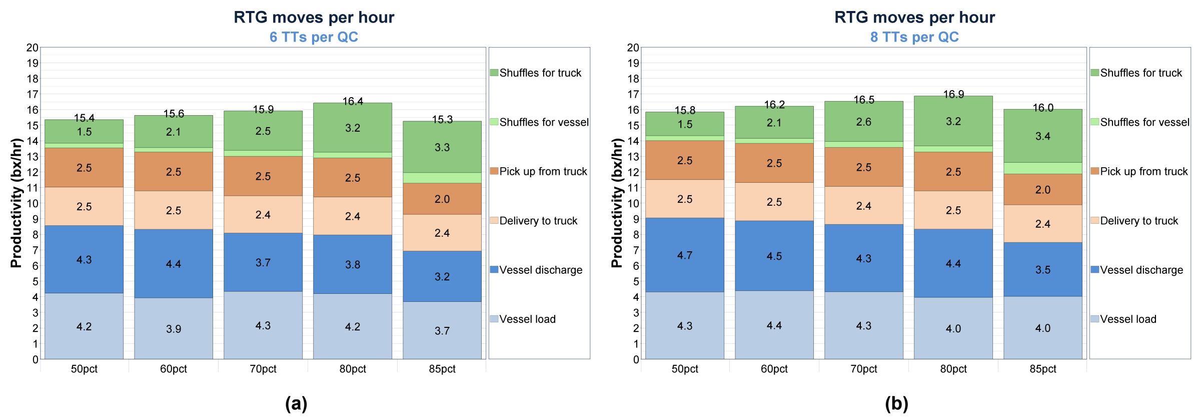


Figure 6.11: The average distribution of moves done by an RTG in an hour for an RTG terminal with different Yard Utilization Rates and 6 TTs per QC (a) or 8 TTs per QC (b).

6. *Which of the possible solutions of subquestion 3 ensure that the QC productivity is not affected or less affected by a high yard utilization rate?*

   Figures 2.8 and 2.9 in Chapter 2 showed the reasons causing a delay in the load or unload cycle of a QC. The focus has been on the TTs. One of the root causes was *Too few TTs deployed*. However, another root cause was *Congestion*. The experiment of deploying extra TTs shows the relation between those two, as more TTs means more traffic, which can eventually lead to congestion if too many TTs are deployed. Figure 6.1a shows an increase till 8 TTs per QC and from then on decreases. This means that 8 TTs per QC is the perfect balance between not too few TTs deployed, but also not too many causing congestion. Therefore, increasing the number of TTs deployed can be a solution for RTG terminals where a high Yard Utilization Rate affects the QC productivity, provided that 8 TTs have not already been deployed. You could say this is not a specific solution for RTG terminals with a high Yard Utilization Rate, but for RTG terminals in general.

   The design alternative of sacrificing driving lanes for extra storage space is not a solution that ensures that the QC productivity is not affected or less affected by a high YUR. The opposite is the case; sacrificing driving lanes for extra storage space causes a decrease in QC productivity. The benefits of having extra storage space do not outweigh the fact that fewer driving lanes mean more traffic and congestion.

Changing the bay distribution and shuffle policy is a solution. These alternative shuffle policies respond to the fact that the bays can become full with a high YUR. Three combinations show an increase in QC productivity compared to the benchmark and one combination shows a decrease. The clustered bay distribution with the multi-bay with sets shuffle policy (Exp. 12) shows the greatest increase in average QC productivity, which is 0.4 containers per hour compared to the benchmark.

Table 6.2 and Figure 6.12 give an overview of all experiments and their QC productivity.

		№ of TTs	№ of blocks	Bay Distr.	Shuffle Policy	QC Prod.	Std. Dev.
DA 1	Exp. 1	6	4	Default	Default	28.9 bxs/h	0.18 bxs/h
	Exp. 2	7	4	Default	Default	30.1 bxs/h	0.31 bxs/h
	Exp. 3	8	4	Default	Default	30.8 bxs/h	0.30 bxs/h
	Exp. 4	9	4	Default	Default	30.3 bxs/h	0.38 bxs/h
	Exp. 5	10	4	Default	Default	27.8 bxs/h	0.39 bxs/h
DA 2	Exp. 6	8	1	Default	Default	23.0 bxs/h	0.24 bxs/h
	Exp. 7	8	2	Default	Default	28.9 bxs/h	0.41 bxs/h
	Exp. 8	8	3	Default	Default	28.1 bxs/h	0.49 bxs/h
DA 3	Exp. 9	8	4	Default	Two-bay	30.9 bxs/h	0.31 bxs/h
	Exp. 10	8	4	Default	Multi-bay	30.5 bxs/h	0.36 bxs/h
	Exp. 11	8	4	Clustered	Multi-bay	31.1 bxs/h	0.29 bxs/h
	Exp. 12	8	4	Clustered	Multi-bay with sets	31.2 bxs/h	0.24 bxs/h

Table 6.2: Overview of the experiments and their average QC productivity

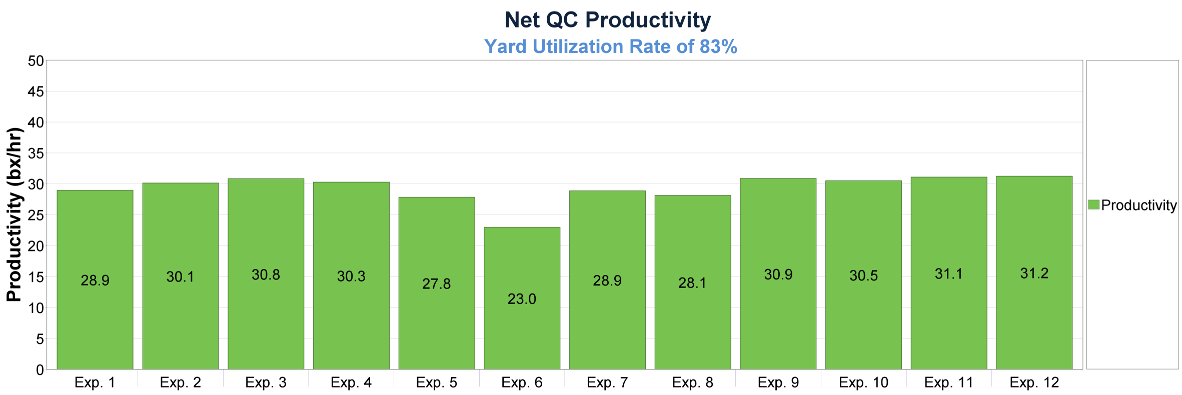


Figure 6.12: Overview of the QC productivity for an RTG terminal with a yard utilization rate of 83% for all experiments.

7 Conclusion

The container shipping industry is witnessing a significant increase in vessel sizes, resulting in a substantial growth in the supply of containers to container yards. Consequently, the yards must contend with a higher demand for storage space, particularly during peak periods such as the months leading up to Christmas when global online ordering intensifies.

The Yard Utilization Rate (YUR), representing the percentage of the total yard capacity utilized for container storage, plays a crucial role in the performance of container terminals. While a YUR below a certain threshold allows for optimal terminal performance, exceeding this threshold leads to a decline in terminal performance. In the past, it did not occur very often that the limit of the Yard Utilization Rate was reached. However, it will occur more often, especially in the months before Christmas when people all over the world order gifts.

This thesis aims to find solutions to reduce the decrease in terminal performance during this temporary increase in YUR for RTG terminals specifically. An RTG container terminal is a container terminal where the cranes used in the storage yard are Rubber-Tyred Gantry Cranes (RTGs). Exploratory research showed that the decrease in terminal performance for RTG terminals was greater than the decrease in performance for two other types of terminals.

The terminal performance is measured by the QC productivity. QC productivity is defined as the average number of lifts at a terminal per Quay Crane (QC) working hour [27]. In Chapter 2, a Root Cause Analysis (RCA) was done in order to understand all processes in the terminal that are involved in loading and unloading vessels and to find out which root causes disrupt the loading and unloading process of vessels by the QCs. The RCA led to the tree diagrams in Figures 2.8 and 2.9. It was decided for all root causes whether they were outside the scope of this study or not. The root causes that were the focus of this study were *"Too few TTs deployed"*, *"Congestion"* and *"YUR too high"*.

In Chapter 3, several alternatives were devised to address these causes. It was then decided which alternatives would be tested with simulation, by determining whether all the design alternatives were realistic or not. The three design alternatives that were simulated are

1. Varying the number of terminal trucks (TTs)
2. Sacrificing driving lanes for additional storage space
3. Applying an alternative shuffle policy in combination with an alternative bay distribution

The first mentioned alternative responds to the root causes *"Too few TTs deployed"*, *"Congestion"*. The other two alternatives address the root cause *"YUR too high"*.

The simulation model is described in Chapter 4. The model consists of an RTG container terminal in which containers arrive and depart by truck or vessel, and containers are stored in the storage yard. The number of QC moves per hour has to be captured and the data has to be stored in order to show the relation between the yard utilization rate and the QC productivity. In Chapter 5, the experimental plan is set up.

After running 12 experiments, the results of these experiments are shown in Chapter 6. The design alternative of varying the number of TTs showed that there is a relationship between the number of TTs deployed and the QC productivity. With too few trucks, the QCs are waiting and not working continuously. As a result, they cannot achieve their optimal productivity. As the number of trucks increases, the QC productivity also increases. Up to a certain point, when it becomes too busy in the yard and the number of TTs causes congestion. This has a negative effect on the QC productivity. With the tested scenario, it turns out that 8 TTs per QC, so a total of 96 TTs, appears to be the optimal number. However, you could say this is not a specific solution for RTG terminals with a high YUR, but for RTG terminals in general.

The design alternative of sacrificing lanes for additional storage space did not appear to be a solution that ensures that QC productivity is not or less affected by a high YUR. The opposite is the case; sacrificing driving lanes for additional storage space reduces the QC productivity. The benefits of extra storage space do not outweigh the fact that fewer driving lanes mean more traffic and congestion.

The design alternative of applying an alternative shuffle policy with an alternative bay distribution is a solution. Three of the four configurations show an increase in QC productivity compared to the current situation. The Clustered Bay Distribution with the Multi-bay with Sets Shuffle Policy (Exp. 12) shows the greatest increase in average QC productivity. This combination shows that the RTG has to drive on average the least of the four combinations. Apparently, the benefits of having additional storage space outweigh the disadvantage of the time it takes to shuffle to other bays. Although the increase is 0.4 containers per hour, the standard deviation of 0.24 containers per hour for this alternative, and a standard deviation of 0.3 containers per hour for the benchmark, indicate that the results are not very significant. If the benchmark has the maximum deviation upwards and the alternative of the Multi-Bay with Sets Shuffle Policy and the Clustered Bay Distribution has the maximum deviation downwards, the QC productivity of the alternative even turns out to be lower than the QC productivity of the benchmark.

Despite the results not showing significant improvements, there is something else positive to take from this research. Due to the alternative for shuffle policy and bay distribution, it is now possible to utilize the terminal more fully than before. In a module, each bay should have 4 spots left empty, it means 31 of the 35 spots per bay can be used. This applies to every bay in every module, so 31/35 = 0.885. Hence, a maximum of 88.5% can be occupied. However, this implies that some containers need to be removed before adding new ones. Import and export are often separated, limiting the maximum average over these two parts to 88.5%. In reality, this means that the maximum Yard Utilization Rate (YUR) for operational feasibility is even lower than 88%.

Now, with the new Two-bay Shuffle Policy, four shuffle spots need to remain vacant over two bays. This implies (31+35)/(35+35) = 66/70 = 0.942. Consequently, 94% is the new maximum YUR where the terminal can still function. This is nearly 6 percent higher than before. With the Multi-bay with Sets Shuffle Policy in combination with the Clustered Bay Distribution this percentage is even 95.0%.

The main research question of this study has been answered:

How to reduce QC productivity loss of an RTG container terminal with a highly utilized storage yard?

A possible solution to reduce the QC productivity loss of an RTG container terminal with a highly utilized storage yard is to apply an alternative shuffle policy in combination with an alternative bay distribution. Specifically applying a Clustered Bay Distribution in combination with a Multi-bay Shuffle Policy in which sets of bays are made has showed that the QC productivity loss can be reduced by an average of 0.4 boxes per hour.

8 Recommendations

The results of this study are of a very specific case or scenario. Only one scenario is tested that has a specific External Truck (XT) arrival pattern and specific vessel arrival times. All simulations were done with the same load/unload plan. This means that for every replication the same bays were handled in the same order. For future research, multiple scenarios could be tested. For this specific case, certain design alternatives were a solution. But it is possible that for different scenarios different design alternatives show better results.

Due to the limited amount of time for this study, it was decided that the best configuration of a design alternative would be a setting for the next design alternative. That led to the different yard layouts in the design alternative of sacrificing driving lanes for additional storage space only being tested with 8 TTs per QC. Results showed that for the 1-block layout, congestion occurred due to all the trucks (XTs and TTs) driving the same route. Future research could be done for example to see if fewer trucks affects the QC productivity in this layout less and leads to better performance. So, different combinations between the number of TTs deployed and the number of blocks in the yard could be made to see if there are configurations that show an even better terminal performance in terms of QC productivity than this study has shown.

Section 3.3 describes for each solution how realistic it is and whether it is worth testing with simulation, which led to an elimination of several design alternatives. It has become apparent that the combination of a *Clustered Bay Distribution* with the *Multi-bay with Sets Shuffle Policy* achieves the best results. However, in reality, it is very difficult to have a Clustered Bay Distribution. It is not possible to suddenly use a different bay distribution when the terminal is fully functional, because then all containers have to be moved. Therefore, follow-up research is necessary. Does this Clustered Bay Distribution also achieve desired results with the current 'default' shuffle policy, the One-bay Shuffle Policy, and with an average YUR? If that is the case, the Clustered Bay Distribution could be introduced from the start in terminals that do not yet exist and are being built. In addition, it could be tested whether the combination of the Clustered Bay Distribution with the Multi-bay with Sets Shuffle Policy also works well at an average YUR. In that case, this shuffle policy can be implemented from the start.

However. the greatest challenge lies with already existing terminals that face a greater container supply in the weeks before Christmas, causing the YUR to increase. It is not realistic to implement the Clustered Bay Distribution at these terminals. This means that the Default Bay Distribution has to be combined with one of the alternative shuffle policies. The Default Bay Distribution combined with the Multi-bay Shuffle Policy shows a lower QC productivity than the benchmark. The Default Bay Distribution in combination with the Two-bay Shuffle Policy shows a slightly higher QC productivity than the benchmark. However, this increase is only 0.1 box/h on average. Therefore, further research should be conducted into whether this shuffle policy actually shows better results than the current situation, also in other scenarios.

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A
Scientific Research Paper

Limiting the Performance Loss of an RTG Container Terminal with a Highly Utilized Storage Yard

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***Abstract*—This research addresses the critical role of the Yard Utilization Rate (YUR) in the performance of container terminals, focusing on Rubber-Tyred Gantry (RTG) terminals. Existing literature reveals a gap in studies specifically targeting high YURs in RTG container terminals. The primary research question is, "How to reduce Quay Crane (QC) productivity loss in RTG container terminals with highly utilized storage yards?" A Root Cause Analysis (RCA) identifies key factors affecting loading and unloading processes, with a focus on the root causes *Too few TTs deployed*, *Congestion*, and *YUR too high*. Design alternatives are proposed to address these root causes, and three design alternatives are tested through simulation: varying the number of Terminal Trucks (TTs), sacrificing driving lanes for additional storage space, and implementing an alternative shuffle policy with a different bay distribution. Results show a significant influence of the number of TTs on QC productivity, with an optimum at 8 TTs per QC. Sacrificing driving lanes for extra storage space proves counterproductive due to increased congestion. However, the alternative shuffle policy *Multi-bay with Sets Shuffle Policy* with a *Clustered Bay Distribution* shows promise, offering a potential solution to mitigate QC productivity loss in highly utilized RTG terminals, with an average increase of 0.4 boxes per hour. In conclusion, the study successfully addresses the identified knowledge gap, providing valuable insights and proposing a practical solution for reducing QC productivity loss in RTG terminals with highly utilized storage yards. The suggested approach of *Clustered Bay Distribution* with a *Multi-bay with Sets Shuffle Policy* proves effective in maintaining terminal performance during periods of an increased YUR.**

***Index Terms*—Container Terminal Performance, Quay Crane Productivity, Rubber-Tyred Gantry Crane (RTG), Shuffle Policy, Yard Utilization Rate**

I. INTRODUCTION

The container yard's utilization rate (YUR) is crucial for the performance of container terminals. The YUR represents the percentage of the total yard capacity utilized for container storage. While a YUR of 100% is unfavourable due to the necessity of free space for reshuffling, optimal terminal performance is generally maintained up to a certain YUR threshold. However, exceeding this threshold results in a significant drop in terminal performance. Until recently, reaching the YUR limit was infrequent, but with the increasing size of ships and the popularity of online ordering, especially during peak seasons like the weeks preceding Christmas, container supply increases.

A. Literature Overview

Existing studies on high YURs in container terminals were explored, revealing a gap in knowledge. While some studies, like Yu and Qi's, explored the relationship between arrival rates and YUR and studied stacking methods for high container arrival rates, none specifically addressed solutions for maintaining performance in highly utilized container yards [8]. The only study focused on high YURs was conducted by Saanen and Dekker, centered on an RTG transshipment terminal [7]. However, their emphasis was on identifying factors affected by a higher YUR rather than proposing performance-enhancing measures. This research aims to bridge this gap by focusing on RTG terminals, where performance significantly declines at higher YURs.

The literature on container terminal performance enhancement reveals a predominant focus on testing various strategies, such as stacking policies and yard layout designs. Notably, several studies investigate the stacking strategy and yard layout, assuming an average Yard Utilization Rate (YUR) in their considerations.

Among the studies that explicitly mention the YUR, three categories emerge:

- Papers that solely present the YUR value without relating it to terminal performance [5] [4].
- Papers where the YUR is an output of simulations, yet its impact on performance is not explored [1] [9] [2].
- Papers that did more research into the subject of the YUR [8] [3] [7].

For instance, Yu and Qi explored the influence of container arrival rates, rather than YUR, on the performance of an automated RMG terminal [8].

Feng et al. compared random stacking with smart stacking under different YURs for an automated RMG terminal [3]. They found that, for higher YURs, the random stacking strategy had a lesser impact on terminal performance than their proposed smart stacking strategy. The latter resulted in increased container retrieval times due to the need for more reshuffles.

Saanen and Dekker aimed to enhance stacking capacity without increasing costs or compromising performance in an RTG transshipment terminal [7]. Their comparison of random stacking to traditional stacking revealed that QC productivity decreases with higher yard utilization for both strategies. However, the increase in RTG gantry time per move is less pronounced for random stacking.

B. Objective

The study's objective is to show the influence of the YUR on different processes in the terminal, and in turn, show how these processes affect the performance of the container terminal. The performance of the terminal is defined as the container throughput within a certain amount of time and therefore the KPI of focus is the QC productivity.

The terminal that will be studied is an RTG terminal with remote-controlled RTGs and Terminal Trucks (TTs) and External Trucks (XTs) for container transport. The XTs arrive at the gate. They either are delivering or picking up a container. The XT drives to the right stack where the RTG lifts the container from the truck to place it on a stack, or the RTG places a container from the stack on the truck. So, the XTs provide the transport of the containers between the storage location and the gate. TTs provide the transport of the containers between the quay and the storage location. Only 20-foot and 40-foot standard dry containers and empty containers are considered for simplicity, excluding reefers and hazmat containers, which have a negligible contribution to the Yard Utilization Rate [6].

In conclusion, this study addresses the significant gap in knowledge regarding high YURs in container terminals, specifically focusing on RTG terminals. By examining the relationship between the YUR and terminal performance, the research aims to provide valuable insights and solutions to enhance operational efficiency in highly utilized container yards. This leads us to the main research question of this study:

How to reduce QC productivity loss of an RTG container terminal with a highly utilized storage yard?

This paper has the following structure. Section II-A provides a description of the analysis of the unloading and loading process of the QC. Section II-B, gives a description of the RTG container terminal used in this simulation study and a description of the simulation model. In Section II-C, the experiments are discussed. Section II-D provides an overview of all experiments done. Section III shows the results of the study and Section IV discusses these results.

II. METHODOLOGY

In order to answer the main research question, the relationship between the Yard Utilization Rate (YUR) and the QC productivity of the terminal must be identified. Therefore, first, the process of loading and unloading vessels by Quay Cranes (QCs) is analyzed in Section II-A. Thereafter, solutions are devised to ensure that the loading and unloading processes are less negatively affected. It is then determined what the model should look like in order to test the solutions devised (Sec. II-B). As a final step, the experimental plan is set up to test the solutions devised (Sec. II-C).

A. Process Analysis

A Root Cause Analysis (RCA) is the process of discovering the root causes of a problem in order to identify appropriate solutions. The idea is to eliminate these root causes and thereby solve the problem. In this study, the problem is a decreasing QC productivity for higher Yard Utilization Rates (YURs). Therefore, first, the QC loading and unloading process in an RTG terminal without a high YUR were analyzed. In Appendix VI, Figures 7 and 8 show the tree diagrams created of the QC unloading and loading process, respectively. These diagrams show common causes for delays in loading and unloading containers by Quay Cranes (QCs). The orange blocks at the end of each branch represent the root causes.

The main causes for a delay in the QC (un)loading process are either because of internal, for example a defect in the QC, or external factors. One of these external factors is that QCs are directly dependent on the Terminal Trucks (TTs). When a QC waits for container delivery for loading or for a Terminal Truck (TT) with an empty chassis for unloading, its productivity decreases. Notably, timely arrival of TTs at the quayside is crucial for maintaining high QC productivity. Reasons why a TT can arrive too late at the quay can either be because a delay in the travel time of the TT or because the TT left the yard too late. There are three root causes for a too long travel time of the TT. One of them in *Congestion*. The root causes for why the TT left the yard too late are many more. This side of the tree diagram is more complex. The root cause that will be the focused on is *Too few TTs deployed*. All other root causes are considered out of the scope of this study, because they are planning and control-related, or are dependent on external parties.

The reason why the TT has to wait at the yard is because the container retrieval takes too long. Several causes can be at the root of this problem. It can be caused by, among other things, a too-high YUR. The utilization rate of the yard can be decreased by increasing the yard capacity. Design alternatives 2 and 3 focus on increasing the yard capacity. Design alternative 1 varies the number of TTs and thus seeks a balance between *Congestion*, because of too many TTs deployed, and *Too few TTs deployed*.

The devised design alternatives will be explained in more detail in Section II-C.

B. Modelling

The main goal of this study is to reduce the QC productivity loss, that occurs because of an increasing utilization rate of the container storage yard (YUR). The aim of the model is to show the relation between the QC productivity and the YUR for the different design alternatives. Figure 1 shows a simplified representation of the simulation model.

1) Model Input and Output: The system is demarcated by the edges of the terminal. The system is 'open' at two locations, the gate and the quay. At the gate, external trucks (XTs) enter and leave the terminal with or without containers.

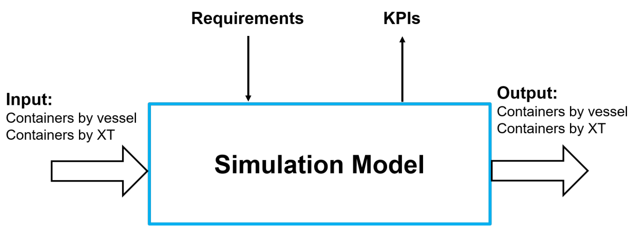

Fig. 1. Simplified representation of the simulation model

At the quay, vessels arrive and containers enter and leave the terminal as well.

2) Key Performance Indicators: Other outputs of the model are the Key Performance Indicators. Since the model aims to show the relation between the QC productivity and the YUR the *QC productivity* is one of the KPIs. The QC productivity is measured in boxes per hour handled by the QC. Therefore, for each individual QC, the productivity must be captured. This way, when one specific QC is decreasing in productivity it can be tracked down. As mentioned in Section II-A, other causes can affect the QC cycle. Therefore, besides QC productivity, the other KPIs are:

- the status of the TTs for each hour
- the status of the QCs for each hour
- the status of the RTGs for each hour

3) Requirements: The model must meet the following requirements to be able to represent an RTG terminal in a realistic way:

- The model must be able to measure the KPIs.
- It must be possible to change the utilization rate of the yard.
- It must be possible to change the layout of the yard.
- It must be possible to apply specific shuffle policies.
- It must be possible to change the number of equipment.
- The model must capture the operations of the RTGs, TTs and QCs.
- The model must be able to record the handling times of the ships.

4) Model Description: Figure 2 shows the RTG terminal as shown in the simulation model Timesquare. In the left upper corner is the gate where the XTs arrive. The XT drives via the driving lanes to the yard and the correct stack in the yard, where the RTG lifts the container from the chassis of the XT and places it in the yard for storage, or the other way around. The XT drives back to the gate and leaves the terminal. The RTGs move horizontally along the modules. Active RTGs are green and non-active RTGs are grey. At the left side of the Figure between module 4 and 5, a RTG is switching modules. In that case, the RTG is orange. The red icon at each left side of a module is a button to enter the environment with information of that module.

The vessels can be seen at the bottom of the Figure. The left vessel is a feeder with two QCs working on it. The middle vessel is an ULCV with six QCs working on it and the last vessel is a Panamax with four QCs working on it. The TTs transport the containers from the yard to the quay. The two types of trucks can be distinguished by the colour of the cabin. The XTs have a blue cabin and the TTs have a red cabin.

C. Experiments

For all experiments the same scenario was used, which will be detailed shortly. This scenario served as the basis for testing various design alternatives, and Table V provides an overview of all experiments.

1) Scenario: As described in Section II-B, the input of the simulation model will be containers. These containers either arrive by External Truck (XT) at the gate or by vessel at the quay. Below, the input parameters are given.

- The model contains four vessels; two feeders, a Panamax and a ULCV.
- 25.5% of the containers are transported by truck and 74.5% by vessel.
- The TEU factor is 1.6. This means that 40 % of the total number of containers are 20-foot containers and 60 % are 40-foot containers.
- The container type distribution per modal flow is shown in Table I.
- The call size, ETA and length of each vessel are given in Table II.
- The land side truck arrival pattern is a multiple normal distribution shown in Figure 3.
- The External Trucks (XTs) are divided into three groups; delivery only, pickup only and both delivery and pickup. The ratio between these three types of External Trucks is 40-30-30.
- External Trucks have a 2 TEU capacity.

	Train	**Vessel**
Full dry 20-foot	7,7 %	22,4 %
Full dry 40-foot	11,5 %	33,5 %
MT 20-foot	2,5 %	7,4 %
MT 40-foot	3,8 %	11,2 %
Modal split	**25,5 %**	**74,5 %**

TABLE I
CONTAINER TYPE DISTRIBUTION AS A PERCENTAGE OF TOTAL CONTAINER TRANSPORT

Additional settings are:

- Beside, the terminal is equipped with 12 QCs, 40 RTGs and 72 TTs.
- The number of gate moves per hour at peak hours is 200 moves per hour.
- The initial yard utilization rate is considered 83% of the total yard capacity occupied.
- The specifications of the yard are given in Table III.

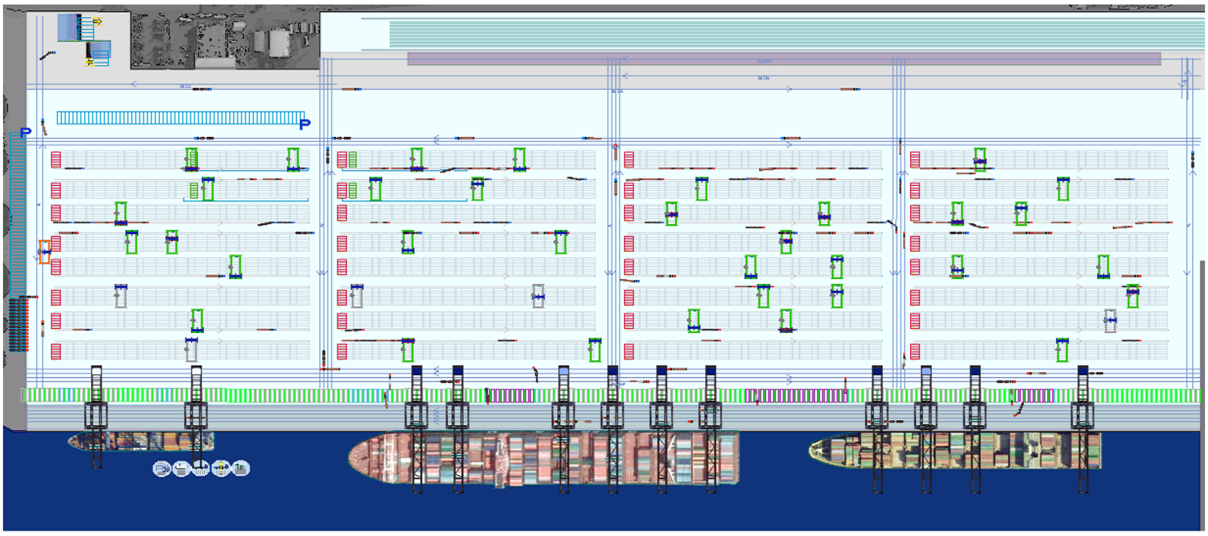

Fig. 2. Overview of the RTG terminal in Timesquare

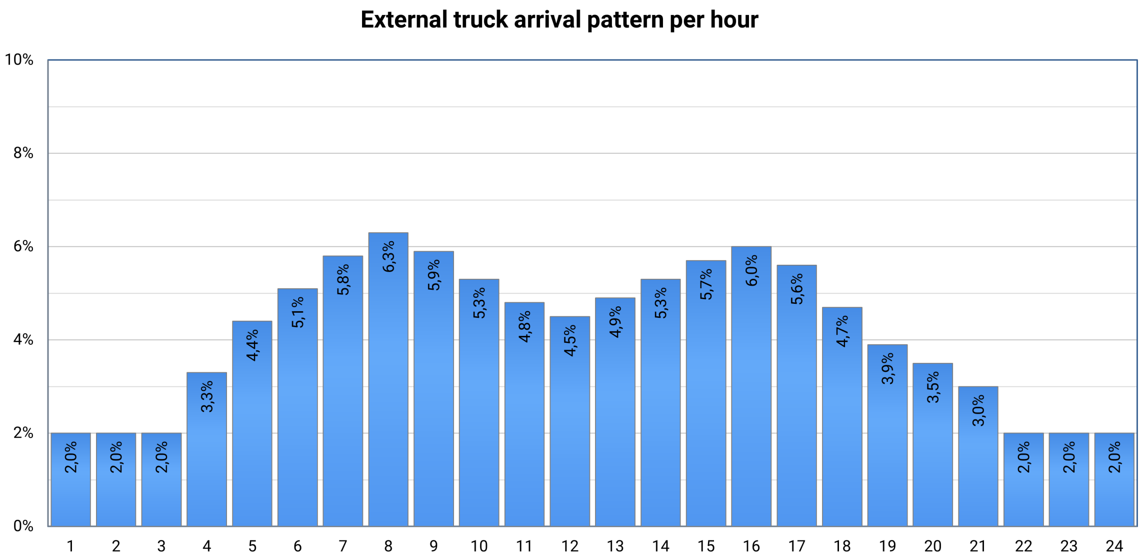

Fig. 3. External truck arrival pattern with a total of 3200 external trucks in a day and a peak value of 200 trucks

	Vessel 1	**Vessel 2**	**Vessel 3**	**Vessel 4**
Size	Small	Middle	Big	Small
Category	Small feeder	Panamax	ULCV	Small feeder
Length	140 m	290 m	400 m	140 m
Breadth	21,8 m	32 m	58,6 m	21,8 m
Capacity in TEU	600	4.200	20.160	600
Call size in TEU	300	1.680	9.072	300
Modal split	1,5 %	11,6 %	61,4 %	1,5 %
ETA	05:00	02:00	Previous day	15:00

TABLE II
VESSEL SPECIFICATIONS

Storage yard specifications	
№ of blocks	4
№ of modules per block	8
Total № of modules	32
№ of bays per module	40
№ of rows per module	7
Stack height	5
Ground slots	8.960 TEU
Total yard capacity	44.800 TEU
Quay length	1.200 m

TABLE III
SPECIFICATIONS OF THE STORAGE YARD OF THE REFERENCE CASE

2) Design Alternative 1 - Varying Number of TTs: For this design alternative, the number of deployed TTs will be varied. As mentioned in Section II-A, *Too few deployed TTs* as well as *Congestion* can be causes of a decrease in the performance of the QCs. Congestion can be a result of too many deployed TTs. Therefore, there probably will be a tipping point at which the performance of the QCs goes from increasing performance to decreasing performance. This tipping point will be at the optimum number of TTs deployed. The number of TTs serving each QC will be varied from 6 TTs per QC to 10 TTs per QC. This means with 12 QCs deployed, there will be respectively, 72, 84, 96, 108 and 120 TTs in total deployed.

3) Design Alternative 2 - Sacrificing Driving Lanes: For this design alternative, three different yard layouts are tested. The default layout consists of four blocks. This is the reference case. The three other layouts consist of three blocks, two blocks and one block.

In the layout with three blocks, the two blocks in the middle are merged and therefore one driving lane is sacrificed (Fig. 10). In the layout with two blocks, the first two blocks and the other two blocks are merged, resulting in a sacrifice of two driving lanes (Fig. 11). In the last layout, of one block, all blocks are merged and therefore only driving lanes around the block still exist (Fig. 12). By sacrificing driving lanes, additional storage space is created. Respectively, 1.400 TEU, 2.800 TEU and 4.200 TEU additional storage space is created compared to the reference case.

4) Design Alternative 3 - Alternative Shuffle Policies: A shuffle policy consists of two parts. First, it consists of rules on which the decision on where to store a container is based. Second, it consists of rules on where to move a container to that needs to be shuffled. Currently, a shuffle policy is used that will be called from now on the *One-bay Shuffle Policy*. This means that only one bay is considered. When a container arrives at the yard, the desired bay is checked on available slots. There is a certain number of slots that must remain open in order to perform shuffles; the shuffle slots. This number of slots per bay is the maximum height of containers minus one. In the case of a 1 over 5 RTG, which means that the RTG can lift one container over five containers stacked on top of each other, four slots have to remain free for shuffles. Secondly, if a container needs to be retrieved and therefore other containers on top need to be shuffled, it happens within the bay.

To create extra storage space, it is possible to divide the shuffle slots over two adjacent bays. This means that four storage slots are created, as only four shuffle slots must be available over two adjacent bays. A downside of this idea is that driving with a container takes more time than relocating a container in the same bay. This shuffle policy will be called the *Two-bay Shuffle Policy*.

A second option is to take three bays together and ensure that those three bays together have enough shuffle slots. The middle bay of those three bays is the bay where the container is located that needs to be retrieved, and therefore the containers to be reshuffled can be moved to the bays on either side of the bay where the desired container is located. In this case, the driving distance of the RTG is still limited to one bay. This shuffle policy will be called the *Multi-bay Shuffle Policy*.

Besides the alternative shuffle policies, also an alternative bay distribution is devised. In a module, 20-foot and 40-foot containers are often stored together. Since the TEU-factor is often above 1.5, 40-foot containers account for a larger share of the yard utilization than 20-foot containers. In the case of a TEU-factor of 1.6, a yard module is arranged such that no 20-foot bays are adjacent, as is shown in Figure 4. This bay distribution will be called the *Default Bay Distribution*.

The *Clustered Bay Distribution* is designed to minimise the travel distance of the RTG in the case the Multi-bay Shuffle Policy is applied. The Clustered Bay Distribution is shown in Figure 5. Since the combination of the Clustered Bay Distribution with the Multi-bay Shuffle Policy still can lead to a great travel distance of the RTG, for example if a 20-foot container in bay 8 needs to be shuffled to bay 13, a last shuffle policy is created. This shuffle policy allows, just as the Multi-bay Shuffle Policy, containers to be shuffled to bays at both sides of the current bay. But the difference with the Multi-bay shuffle Policy is that in this new policy sets of bays are made such that the bays that form a set are always adjacent. This shuffle policy will be called the *Multi-bay with Sets Shuffle Policy*.

For each combination of bay distribution and shuffle policy, a matrix was created indicating which bays are linked together. If there is a 'true' in the matrix, it is allowed to shuffle to this bay. The matrices are given in Appendix VI, Figures 13 to 16, for each combination.

	Bay Distribution	**Shuffle Policy**
Combination 1	Default	Two-bay
Combination 2	Default	Multi-bay
Combination 3	Clustered	Multi-bay
Combination 4	Clustered	Multi-bay with sets

TABLE IV
OVERVIEW OF THE EXPERIMENTS REGARDING ALTERNATIVE SHUFFLE POLICIES AND BAY DISTRIBUTIONS

D. Experiment Overview

A total of 12 experiments will be conducted. All experiments are shown in the overview in Table V. The first experiments that will be carried out are the experiments in which the number of deployed TTs will be varied. After these five experiments, the optimal number of TTs will be chosen for the next set of experiments in which the driving lanes will be sacrificed for container storage. This is marked in the Table with a *. For the last set of experiments, in which the alternative shuffles policies in combination with two bay distributions will be tested, the optimal number of TTs (*) and the optimal number of blocks (**) will be used. This is done with the idea that testing all different possible combinations, which are 100 combinations and thus 100 experiments, will take too much time.

		№ of TTs	№ of blocks	Bay Distribution	Shuffle Policy
DA 1	Exp. 1	6	4	Default	Default
	Exp. 2	7	4	Default	Default
	Exp. 3	8	4	Default	Default
	Exp. 4	9	4	Default	Default
	Exp. 5	10	4	Default	Default
DA 2	Exp. 6	*	1	Default	Default
	Exp. 7	*	2	Default	Default
	Exp. 8	*	3	Default	Default
DA 3	Exp. 9	*	**	Default	Two-bay
	Exp. 10	*	**	Default	Multi-bay
	Exp. 11	*	**	Clustered	Multi-bay
	Exp. 12	*	**	Clustered	Multi-bay with sets

TABLE V
OVERVIEW OF THE EXPERIMENTS

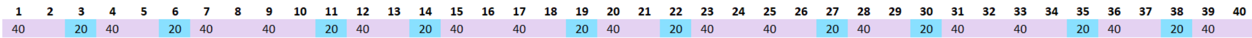

Fig. 4. Default bay distribution with a TEU-factor of 1.6

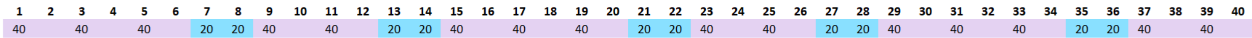

Fig. 5. Clustered Bay Distribution with a TEU-factor of 1.6

III. Results

Experiments 1, 2, 3, 4, & 5

The first experiments conducted were based on finding if there is an optimum in the number of TTs deployed. The root causes *Too few TTs deployed* and *Congestion* were the reason for this solution approach. The experiment of deploying a different number of TTs shows the relation between those two, as more TTs means more traffic, which can eventually lead to congestion if too many TTs are deployed. Figure 6 shows an increase till 8 TTs per QC and from then on decreases. This means that 8 TTs per QC is the perfect balance between not too few TTs deployed, but also not too many causing congestion. Therefore, increasing the number of TTs deployed can be a solution for RTG terminals where a high Yard Utilization Rate affects the QC productivity, provided that 8 TTs have not already been deployed. You could say this is not a specific solution for RTG terminals with a high Yard Utilization Rate, but for RTG terminals in general.

Experiments 6, 7 & 8

The design alternative of sacrificing driving lanes for extra storage space is not a solution that ensures that the QC productivity is not affected or less affected by a high YUR. The opposite is the case; sacrificing driving lanes for extra storage space causes a decrease in QC productivity, see Figure 6. The benefits of having extra storage space do not outweigh the fact that fewer driving lanes mean more traffic and congestion.

Experiments 9, 10, 11 & 12

Changing the bay distribution and shuffle policy is a solution. These alternative shuffle policies respond to the fact that the bays can become full with a high YUR. Three configurations show an increase in QC productivity compared to the benchmark and one configuration shows a decrease (Fig. 6). The *Clustered Bay Distribution* with the *Multi-bay with Sets Shuffle Policy* (Exp. 12) shows the greatest increase in average QC productivity, which is 0.4 containers per hour compared to the benchmark.

Table VI and Figure 6 give an overview of all experiments and their QC productivity.

IV. Discussion

This section provides the discussion and conclusion of the conducted study. In Section IV-A, the key findings are discussed and the main research question is answered. Section IV-B provides recommendations for future research.

A. Key Findings

The study addresses the challenges posed by the increasing Yard Utilization Rate (YUR) in container terminals, particularly during periods when the container supply increases like pre-Christmas online ordering. Focusing on Rubber-Tyred Gantry Crane (RTG) terminals, the study aims to find solutions to mitigate the decrease in terminal performance associated with a temporary increase in YUR.

The analysis, centered on RTG terminals, reveals a greater performance decline compared to other terminal types. Terminal performance is measured by Quay Crane (QC) productivity, defined as the average number of lifts per QC working hour. A Root Cause Analysis (RCA) identifies key factors affecting loading and unloading processes. With a focus on the root causes *Too few TTs deployed*, *Congestion* and *YUR too high*, several design alternatives were proposed to address these root causes. Through simulation, three alternatives

		№ of TTs	№ of blocks	Bay Distr.	Shuffle Policy	QC Prod.
DA 1	Exp. 1	6	4	Default	Default	28.9 bxs/h
	Exp. 2	7	4	Default	Default	30.1 bxs/h
	Exp. 3	8	4	Default	Default	30.8 bxs/h
	Exp. 4	9	4	Default	Default	30.3 bxs/h
	Exp. 5	10	4	Default	Default	27.8 bxs/h
DA 2	Exp. 6	8	1	Default	Default	23.0 bxs/h
	Exp. 7	8	2	Default	Default	28.9 bxs/h
	Exp. 8	8	3	Default	Default	28.1 bxs/h
DA 3	Exp. 9	8	4	Default	Two-bay	30.9 bxs/h
	Exp. 10	8	4	Default	Multi-bay	30.5 bxs/h
	Exp. 11	8	4	Clustered	Multi-bay	31.1 bxs/h
	Exp. 12	8	4	Clustered	Multi-bay with sets	31.2 bxs/h

TABLE VI
OVERVIEW OF THE EXPERIMENTS AND THEIR AVERAGE QC PRODUCTIVITY

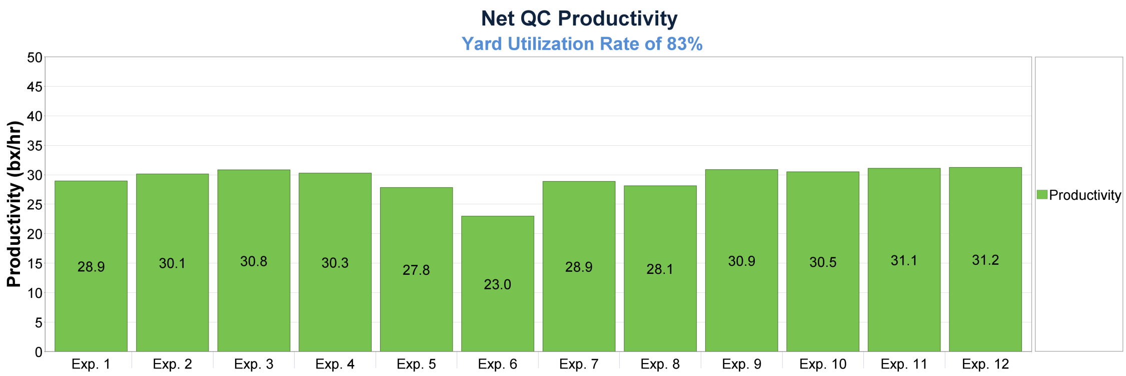

Fig. 6. Overview of the QC productivity for an RTG terminal with a yard utilization rate of 83% for all experiments.

were tested: varying the number of Terminal Trucks (TTs), sacrificing driving lanes for additional storage space, and implementing an alternative shuffle policy with a different bay distribution.

Results indicate that the number of TTs deployed significantly influences QC productivity, reaching an optimum at 8 TTs per QC for this specific scenario. Sacrificing driving lanes for extra storage space, however, proves counterproductive, reducing QC productivity due to increased congestion. The alternative shuffle policy *Multi-bay with Sets Shuffle Policy* with a *Clustered Bay Distribution* demonstrates promise, showing an average increase of 0.4 boxes per hour in QC productivity, offering a potential solution to mitigate performance loss in highly utilized RTG terminals.

In conclusion, the study answers the main research question

How to reduce QC productivity loss of an RTG container terminal with a highly utilized storage yard?

and suggests that applying a *Clustered Bay Distribution* with a *Multi-bay with Sets Shuffle Policy* can effectively reduce QC productivity loss in RTG terminals with highly utilized storage yards.

B. *Recommendations*

The results of this study are of a very specific case or scenario. Only one scenario is tested that has a specific External Truck (XT) arrival pattern and specific vessel arrival times. All simulations were done with the same load/unload plan. This means that for every replication the same bays were handled in the same order. For future research, multiple scenarios could be tested. For this specific case, certain design alternatives were a solution. But it is possible that for different scenarios different design alternatives show better results.

Due to the limited amount of time for this study, it was decided that the best configuration of a design alternative would be a setting for the next design alternative. That led to the different yard layouts in the design alternative of sacrificing driving lanes for additional storage space only being tested with 8 TTs per QC. Results showed that for the 1-block layout, congestion occurred due to all the trucks (XTs and TTs) driving the same route. Future research could be done for example to see if fewer trucks affects the QC productivity in this layout less and leads to better performance. So, different combinations between the number of TTs deployed and the number of blocks in the yard could be made to see if there are configurations that show an even better terminal performance in terms of QC productivity than this study has shown.

It has become apparent that the configuration of a *Clustered Bay Distribution* with the *Multi-bay with Sets Shuffle Policy* achieves the best results. However, in reality, it is very difficult to have a Clustered Bay Distribution. It is not possible to suddenly use a different bay distribution when the terminal is fully functional, because then all containers have to be moved. Therefore, follow-up research is necessary. Does this Clustered Bay Distribution also achieve desired results with the current 'default' shuffle policy, the One-bay Shuffle Policy, and with an average YUR? If that is the case, the Clustered Bay Distribution could be introduced from the start in terminals that do not yet exist and are being built. In addition, it could be tested whether the combination of the Clustered Bay Distribution with the Multi-bay with Sets Shuffle Policy also works well at an average YUR. In that case, this shuffle policy can be implemented from the start.

However, the greatest challenge lies with already existing terminals that face a greater container supply in the weeks before Christmas, causing the YUR to increase. It is not realistic to implement the Clustered Bay Distribution at these terminals. This means that the Default Bay Distribution has to be combined with one of the alternative shuffle policies. The Default Bay Distribution combined with the Multi-bay Shuffle Policy shows a lower QC productivity than the benchmark. The Default Bay Distribution in combination with the Two-bay Shuffle Policy shows a slightly higher QC productivity than the benchmark. However, this increase is only 0.1 box/h on average. Therefore, further research should be conducted into whether this shuffle policy actually shows better results than the current situation, also in other scenarios.

V. Abbreviations

KPI: Key Performance Indicator; QC: Quay Crane; RCA: Root Cause Analysis; RTG: Rubber-Tyred Gantry Crane; TEU: Twenty-foot Equivalent Unit; TT: Terminal Truck; XT: External Truck

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VI. Appendix

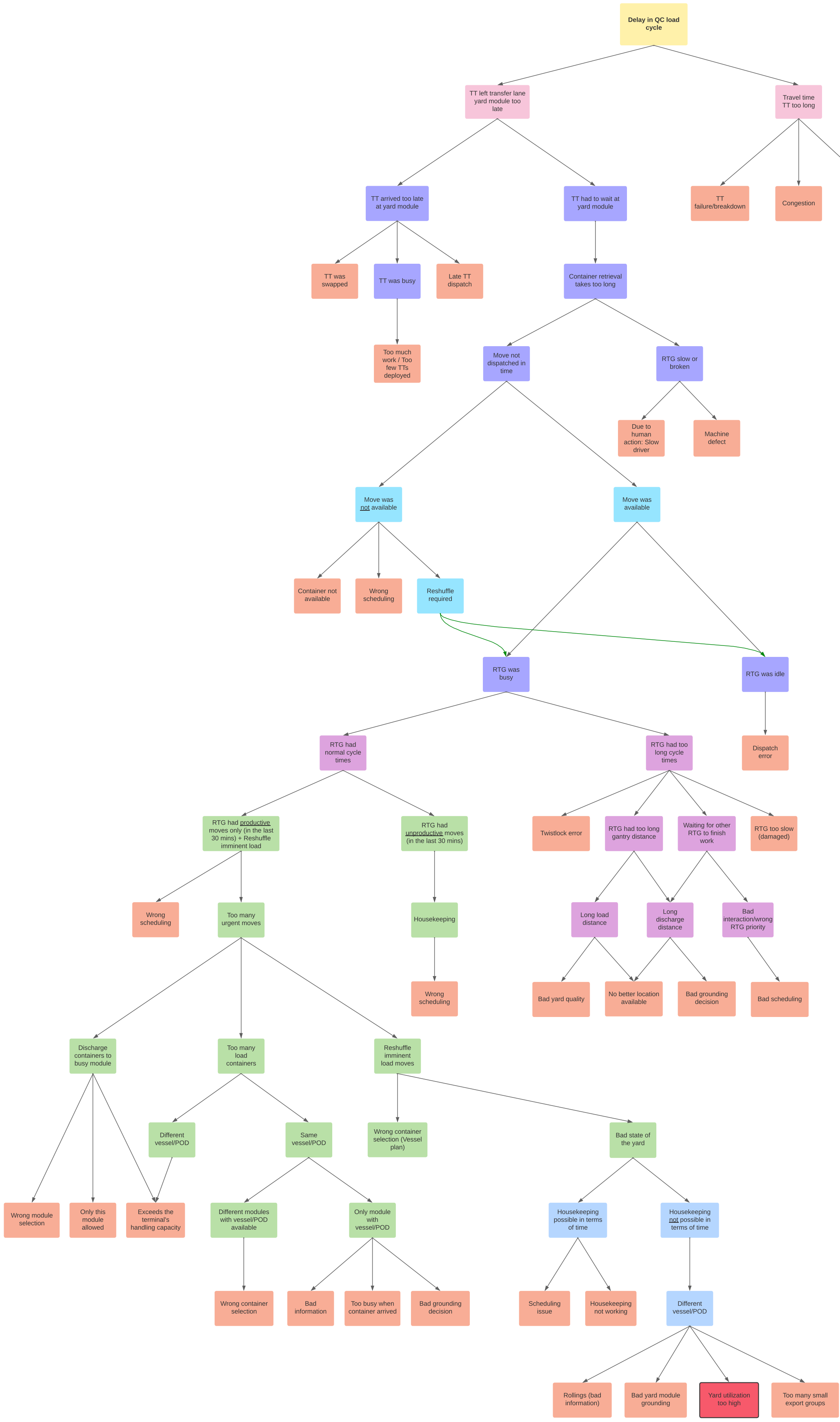

Fig. 7. Root Cause Analysis: tree diagram of why a QC is waiting to load a container

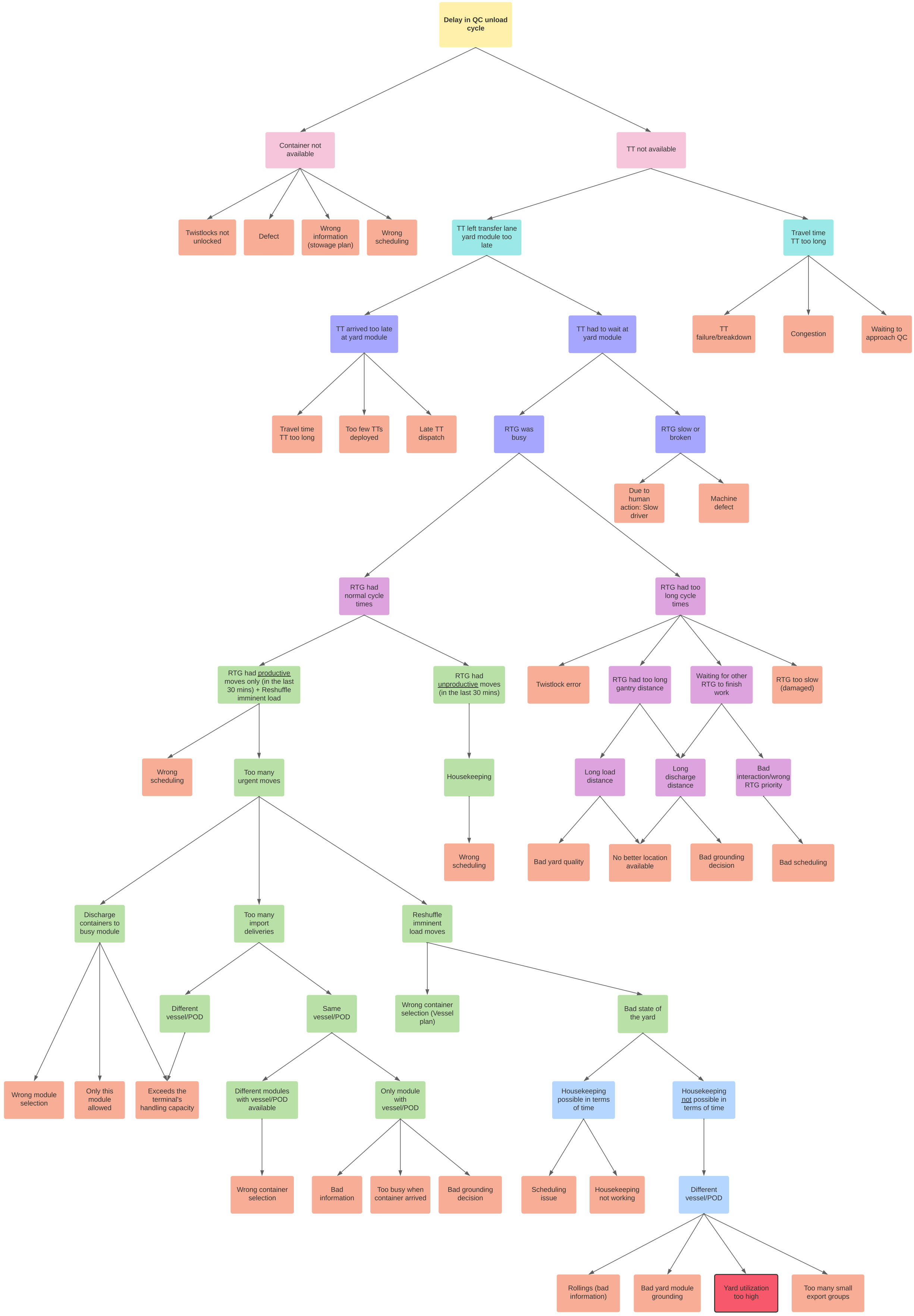

Fig. 8. Root Cause Analysis: tree diagram of why a QC is waiting to unload a container

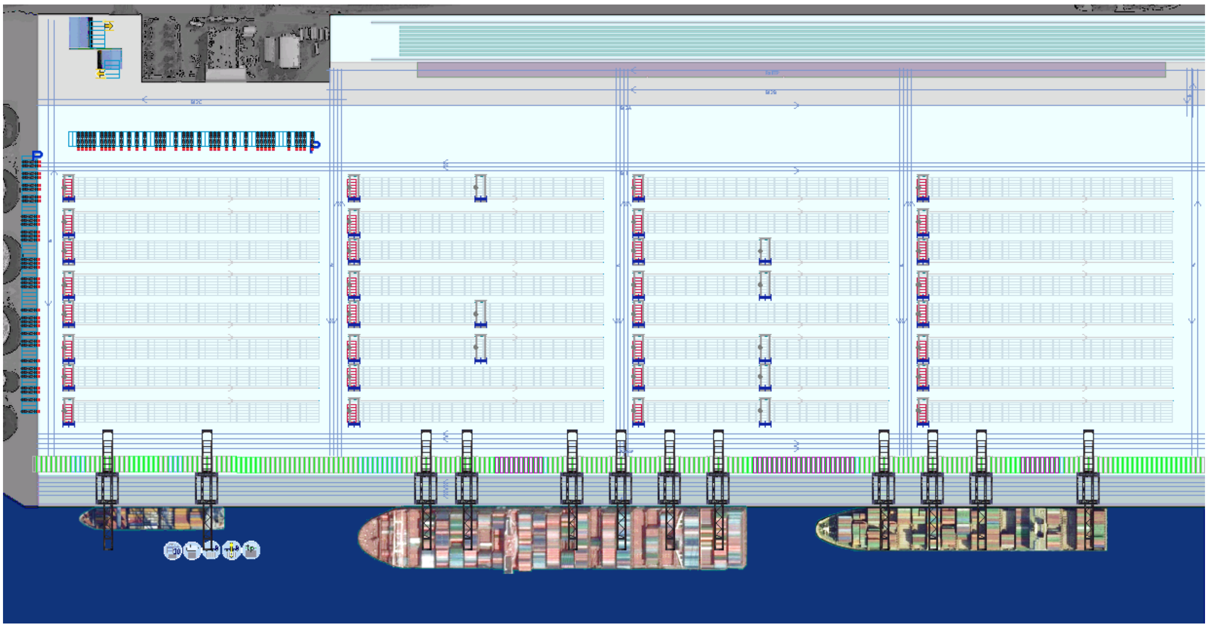

Fig. 9. Default yard layout consisting of four blocks

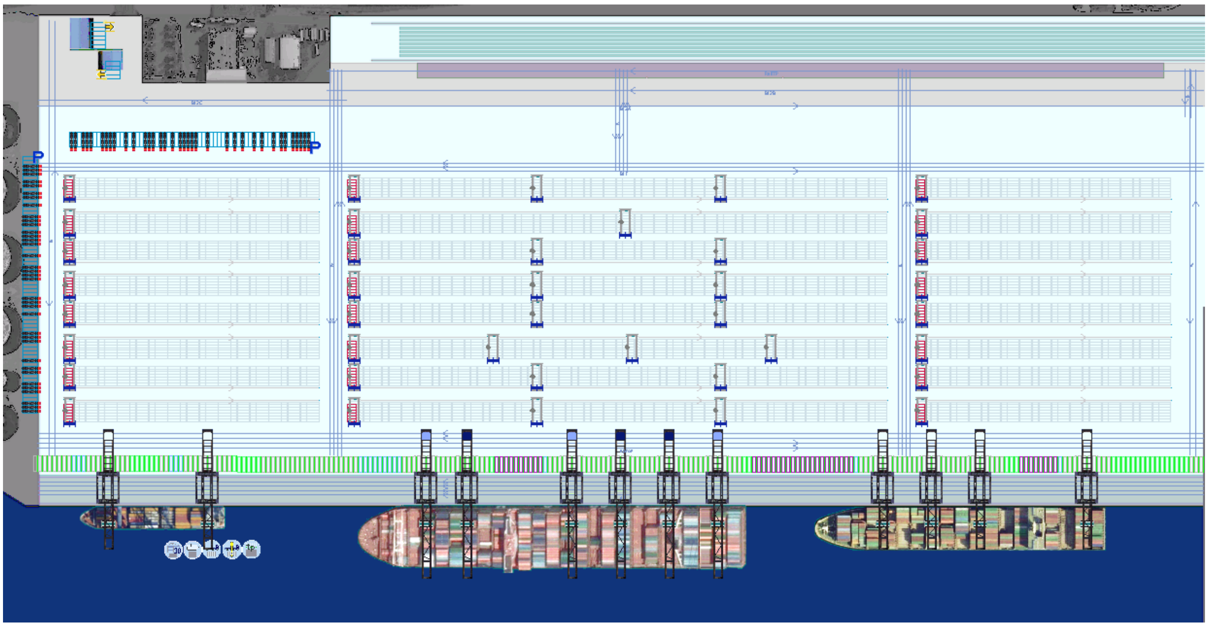

Fig. 10. Sacrificing one driving lane for additional storage space, resulting in a layout of three blocks

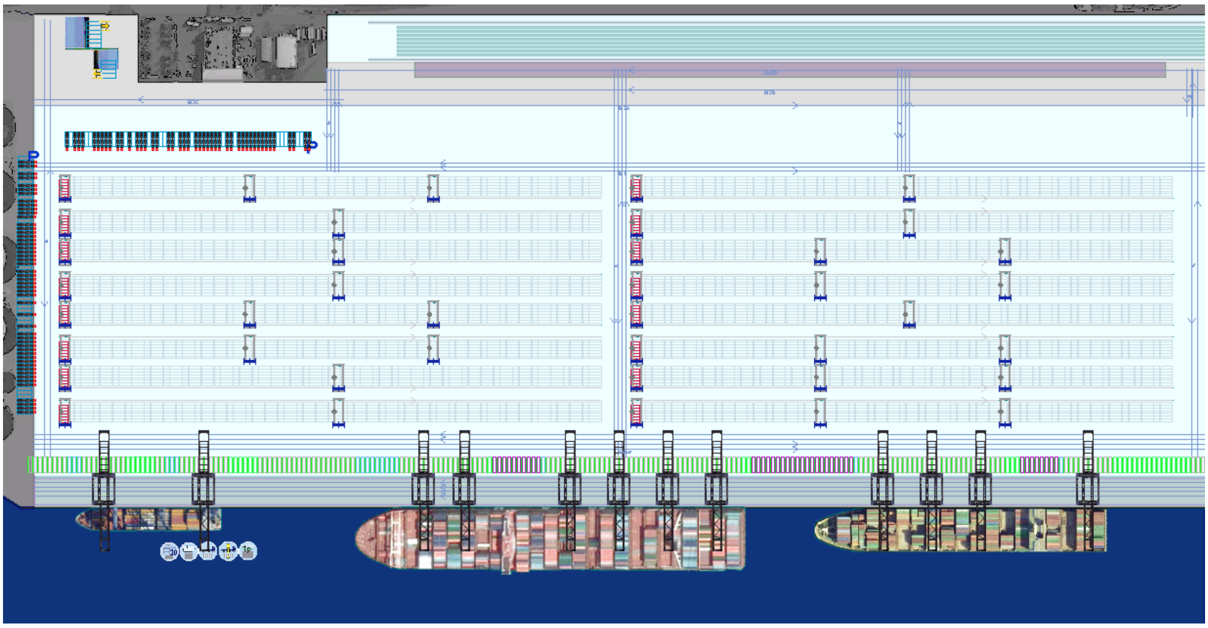

Fig. 11. Sacrificing two driving lanes for additional storage space, resulting in a layout of two blocks

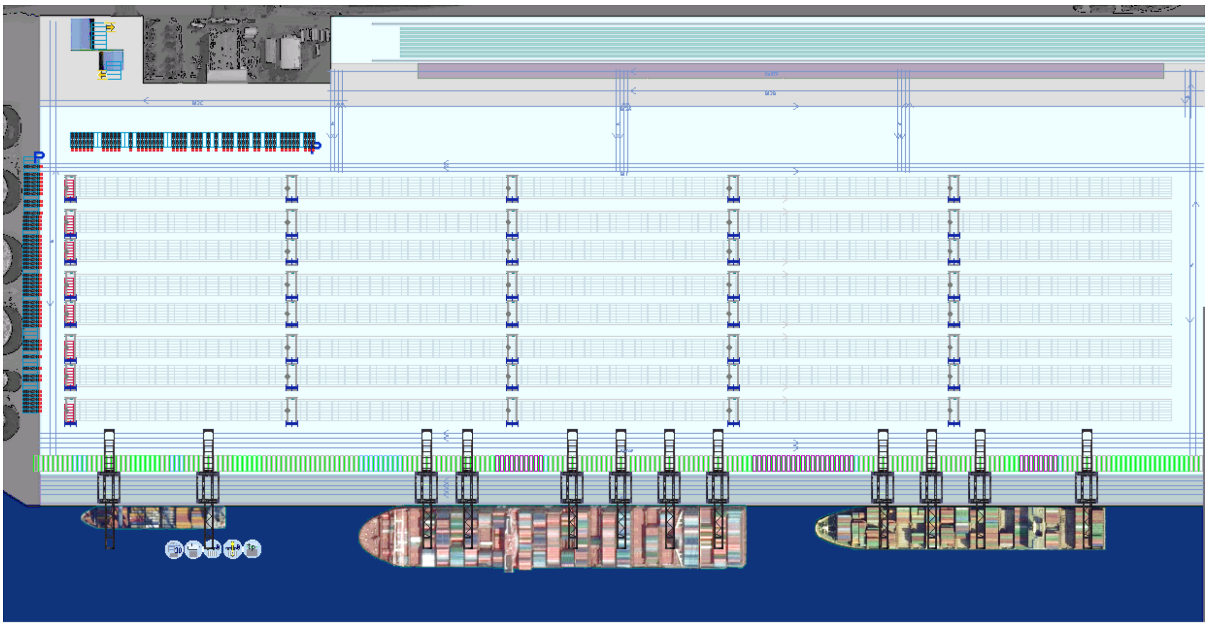

Fig. 12. Sacrificing three driving lanes for additional storage space, resulting in a layout of one big block

Bay	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
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Fig. 13. Shuffle Matrix Combination 1

Bay	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
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Fig. 14. Shuffle Matrix Combination 2

Bay	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
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Fig. 15. Shuffle Matrix Combination 3

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Fig. 16. Shuffle Matrix Combination 4

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Shuffle Matrix Combination 2

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Shuffle Matrix Combination 3

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Shuffle Matrix Combination 4

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F
RTG specifications

RTG operating specifications	
Gantry speed	1.5 m/s
Gantry acceleration	0.3 m/s^2
Gantry deceleration	-0.3 m/s^2
Trolley speed	1.16 m/s
Trolley acceleration	0.3 m/s^2
Trolley deceleration	-0.3 m/s^2
Spreader hoist speed	Table F.2
Spreader hoist acceleration	0.35 m/s^2
Spreader hoist deceleration	-0.35 m/s^2

Table F.1: Operating specifications of the RTG

Spreader speed specifications	
Load in tonnes	**Spreader hoist speed**
0	50 m/min
2	50 m/min
5	50 m/min
10	50 m/min
15	50 m/min
20	45 m/min
25	40 m/min
30	35 m/min
35	28 m/min
40	22 m/min
50	22 m/min

Table F.2: Specifications of the spreader speed