UNIVERSITY OF PRETORIA

Port of Durban Container Terminal

Final Project Report

Lothar Schröder

10023306

072 761 1030

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DEPARTEMENT BEDRYFS- EN SISTEEMINGENIEURSWESE
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

FRONT PAGE FOR FINAL PROJECT DOCUMENT (BPJ 420) - 2013)

Information with regards to the mini-dissertation

Title [e.g. A Contingency framework for the after-sales inventory at Xxxxx Part Distribution Centre]	Applying Queueing theory to the Port of Durban Container Terminal
Author [Last name, Initial(s) e.g. Botha, P.J.]	Schröder, L.W.
Student number	10023306
Supervisor/s [Last name, Initial(s) e.g. Botha, P.J.]	Adendorff, K.
Date [(year/month/day) e.g. 2012/10/08]	2013 /08/22
Keywords [Provide keywords from your project (for searching purposes). The first word of two words must always have a capital first letter and the rest of the words following must be lower case. In the event of an abbreviation, use as it is known, e.g. Economic recession, ABSA, ERP, Simulation modelling)]	Queueing theory Simulation modelling Container terminal
Abstract [Provide an abstract of the mini-dissertation. An abstract is a short summary of the contents covered in the item.]	Theory behind- and application of a queueing theory model at a Container terminal
Category [Enter the category in which the project was done. E.g. Operations Research, Simulation, Logistics…]	Probability Modelling

Declaration

1. I understand what plagiarism is and I am aware of the University's policy in this regard.
2. I declare that this is my own original work
3. Where other people's work has been used (either from a printed source, internet or any other source) this has been carefully acknowledged and referenced in accordance with departmental requirements
4. I have not used another student's past work to hand in as my own
5. I have not allowed and will not allow, anyone to copy my work with the intention of handing it in as his/her own work

Signature	

© University of Pretoria

Executive summary

The content of the project report compiled in this document provides the reader with knowledge of operations at a container terminal and how a non-finite queueing theory model has been applied to the Port of Durban Container Terminal.

The document initially discusses the general operations at a container terminal and type of equipment used and what their functions are. The document describes the specific operations at the two piers of the Port of Durban Container Terminal and at the Port of Rotterdam in the Netherlands. The Port of Rotterdam's Container Terminal operations serve as a benchmark to evaluate the Port of Durban Container Terminal operations.

The main section of the report is a discussion on the non-finite queueing model which was created for the container terminal environment. The respective methods used and how the service and arrival rates of the model were established and calculated. The non-finite queueing model makes use of multi-server queueing theory and Jackson's rule to evaluate the models and calculate the total time a container has to wait in a queue for busy equipment, from when the container is unloaded from the sea vessel until it is stored in the stacking area. The aim of the model is to obtain the number of vehicles or equipment needed per quay crane to achieve a balanced system. A balanced system was defined as one where the least delays and congestion occur.

The simulation model created in Simio was used to simulate the container terminal environment of the Port of Durban and the Port of Rotterdam container terminals. The aim of the simulation model was to obtain results from a different perspective. The simulation results are compared to the results of the queueing theory model, which are analysed, discussed and compared to a framework defined by a functionary from the container terminal environment.

The end result was that the queueing theory model provided reliable results. The results for Pier 1 were that four truck-trailer units and four rubber tyre gantries should be assigned to a single quay crane. In the Pier 2 system, four straddle carriers should be assigned to a quay crane.

© University of Pretoria

The advantage of using the most balanced number of vehicles or equipment in the container terminal is that vessels can be processed faster, keeping customers satisfied and generating a greater profit.

© University of Pretoria

Table of Contents

© University of Pretoria

List of Figures

List of Tables

© University of Pretoria

Terms and Abbreviations

TEU - Twenty-foot equivalent unit

FEU - Forty-foot equivalent unit

The rest of the abbreviations used in the project are named and discussed before they are used.

© University of Pretoria

1 Introduction

The popularity of using containerized cargo has grown over the past years, and is expected to become even more popular. This is partly due to the fact that the handling of containerized cargo is much quicker and easier than handling each item individually. The other reason for an increased activity in containerized cargo is that more cargo is transported between more places on earth, as globalisation becomes more and more popular.

The forecast numbers of containers to enter the Port of Durban Container Terminal is estimated to increase from 2.7 million 20 foot-equivalent container units (TEUs) in 2012 to four million TEUs by 2018 and increase even further within the next ten to twenty years. This will create excessive strain on the container terminal and certain changes have to be made.

With this increase in containerized cargo entering the container terminal, the storage of containers, and the equipment used to load and unload vehicles (vessels, road vehicles and trains) need to be done very efficiently, to decrease the time a vehicle stays in the container terminal.

© University of Pretoria

2 Project Aim

The focus of the project has been identified to be an aspect of the horizontal transport from the tandem lift cranes (which remove containers off the ships) to the storage of containers at a stacking area.

The aim of this project is to apply queueing theory to the stacking yard, to analyse the operations and how operations could be done more efficiently.

© University of Pretoria

3 Project Approach

The project approach can be split into a variety of activities. Each activity will have a corresponding deliverable.

- Literature Study: The literature study will be used to investigate which methods and technologies are available to perform the operation at a port. The operation being the horizontal transport and the stacking of containers. The deliverables of this section will be to understand the equipment and processes of a container terminal.

- Conceptual Design: The aim of this section is to discuss and analyse the techniques that will be used to apply queueing theory to the stacking yard at the Port of Durban. The deliverable of this section is to obtain knowledge about the techniques that will be used.

- Data collection: Various data will have to be obtained either manually or extracted from a system. Data sets relevant to the queueing model will be extracted and be used to calculate the variables of the queueing model.

- Model development: Create a queueing model from the data collected. The aim of this activity is to create a model which accurately depicts the processes at the container terminal. The model will be used to optimize the current process and observe how changes influence the system.

- Discussion and Analysis: Using a different industrial engineering approach, namely simulation modelling, results will be obtained to which the queueing theory model results can be compared. This comparison will give a good understanding of the reliability of the results.
  Using the literature study, observe or make conclusions of how different methods or technologies could affect the operations of the port. This will offer a broader understanding of how different methods can be applied and what can be used best.

© University of Pretoria

4 Literature Study

4.1 Introduction

A container terminal can be defined as the link between different modes of transport. It is also a point where different parties who are involved in the carriage of goods interchange containers, information and funds. (Nazari 2005)

The operations at a container terminal are fairly complex and it is of utmost importance that the operations are performed in a perfect manner. One of the main aims of a port is to minimise the time a transport vehicle (vessel, road vehicle or train) spends in a port.

Before the queueing theory model of the project can be discussed, some background knowledge is needed, which will be useful later in the project.

A container terminal consists of various subsystems. The four main subsystems being: Ship to shore, transfer, storage and delivery receipt. Figure 4-1, below, visually depicts the various subsystems and how they interact with each other.

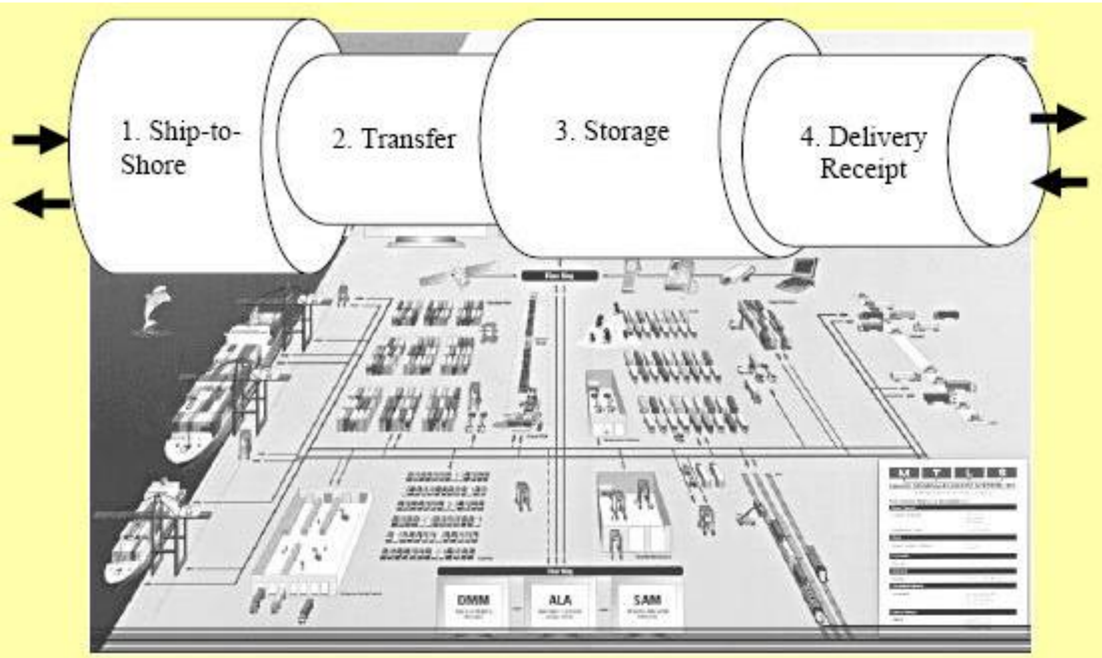

Figure 4-1: Container terminal subsystems

Source: (Henesey 2004)

© University of Pretoria

Ship-to-shore subsystem involves the loading and unloading of vessels at a berth at the port. The vessels are unloaded by making use of tandem lift cranes, otherwise called quay cranes (QC). There are various quay cranes available, each with different characteristics, and therefore different cycle times. Cycle time refers to the time it takes to unload or load a single container. The ship-to-shore subsystem deals with the loading and unloading of vessels.

Transfer subsystem:

The transfer subsystem acts as a link between the ship-to-shore subsystem and the storage subsystem. This transfer subsystem has to operate smoothly with an efficient transfer time. The transfer time being the time it takes the transport equipment to transport a container to the stacking area and to return to the quay cranes (QC). Any downtime in this subsystem can cause a loss in productivity of the entire container terminal, causing customer dissatisfaction and delays. The transfer subsystem is thus very dependent on the right equipment for the right job and enough thought should be placed into the selection of this equipment and how much equipment is needed.

The transfer subsystem is affiliated with both the ship-to-shore and delivery receipt subsystems. The transfer vehicles (otherwise known as horizontal transport) transport container to/from the ship-to-shore and the delivery receipt subsystems respectively. Usually the ports are designed in such a way that the ship-to-shore and delivery receipt subsystems have their own equipment, thus minimising the processing time of a vehicle in the container terminal.

Storage subsystem:

This subsystem acts as a storage depot for containers until they can be taken to their final destination. Containers for import, export and transhipment activities are stored in the container yard (or stacking area). Containers are stacked using various equipment and techniques. The storage subsystem at each port is different, as it depends on a variety of elements which will be discussed later.

© University of Pretoria

Delivery receipt subsystem:

The primary aim of this subsystem is the link between the container terminal and other modes of transport which take the containers to their next destination. These other modes of transport are road vehicles, trains and even barges at certain ports. The delivery receipt subsystem deals with the loading and unloading of containers to/from these transport modes.

As stated in the aim, the focus of this report is on the stacking area and on the horizontal transport. Thus the main focus of the report will be on the transfer and storage subsystems.

4.2 Transfer Subsystem

The transfer subsystem can also be referred to as the horizontal transport at the port. The transfer subsystem that is of interest in this report is the transport between the quay cranes (QC) and the stacking yard. The efficiency of this transport segment is highly dependent on the equipment used, and using the proper equipment yields many advantages. Using more or faster horizontal transport will not necessarily decrease the unloading time of the ship. There is a trend that the more transport vehicles, and the faster they operate the greater the chance of congestion at the QC (quay cranes) and in the stacking yard. While using too few transport vehicles, the quay cranes, and storage subsystem equipment are idle more often, and loading/unloading times increase. The optimal solution at a port is to decrease the congestion, and thus a balance between the number of vehicles or vehicle speed and congestion needs to be reached.

To minimise the congestions, different strategies to allocate vehicles to cranes have been created. The two main strategies are single-cycle and dual-cycle modes. Single-cycle modes or gang structure is where a vehicle serves only one QC at a time. The operations of the vehicle depend on the operations of the QC, e.g. if the QC is unloading a ship then the vehicles transport container to the stacking yard and vice versa. In a dual-cycle mode or pooling, a single vehicle serves multiple QCs (given that the cranes are operating), so the vehicle transports both export and import containers.

Horizontal transport vehicles which are used between the QC and the stocking yard at various ports around the world vary hugely. The horizontal transport vehicles can however be split up into four main categories: SCs (straddle carriers), AGVs (automated-guided vehicles), TTUs

© University of Pretoria

(truck-trailer units) and MTSs (multi-trailer systems). Examples of these four types of vehicles are given in figure 4-2.

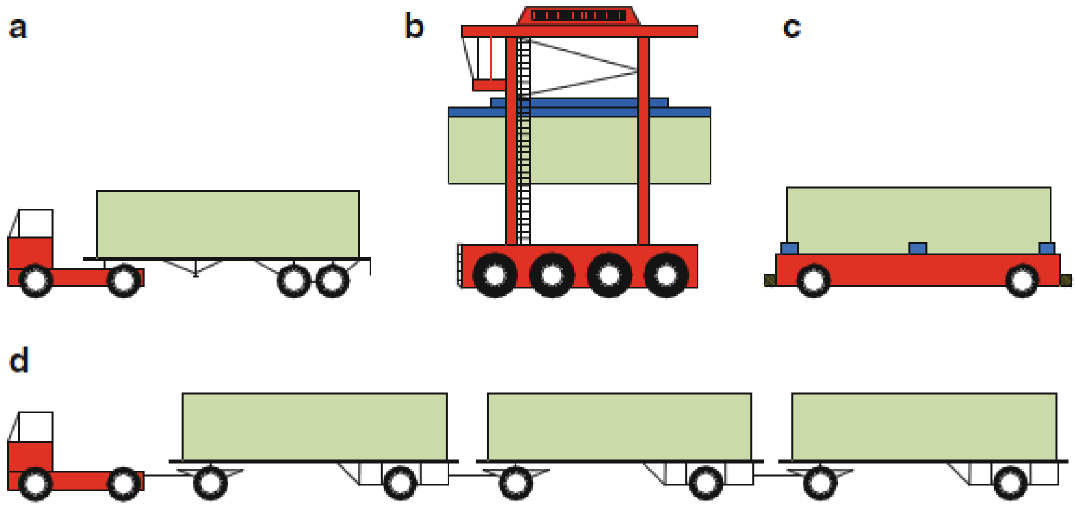

Figure 4-2: Horizontal-transport vehicles: a) TTU, b) SC, c) AGV and d) MTS

Source: (Kemme 2013)

The horizontal transport vehicles can either be passive (the vehicle is not able to lift a container) or active (the vehicle is able to lift a container). Passive vehicles rely on lifting equipment to place and remove containers where active vehicles can perform all the actions themselves, resulting in less equipment and labour required. TTUs, AGVs and MTSs belong to the passive vehicle class and SCs belong to the active vehicle class.

TTUs and MTSs are quite similar to each other, and therefore they can be discussed together. The average speed that one of these vehicles travels in the container terminal is 11 km/h (Nazari 2005). The only main difference between the two vehicles is the number of containers that they transport at a time. A TTU transports a single container and an MTS transports anything more than two containers to a maximum of five containers. MTSs have a greater capacity than TTUs as they can transport more than one container at a time therefore they can visit multiple stacking yards in a single trip. TTUs are however, more flexible and logistically simpler than MTSs and less planning has to be done for the route (only one pick-up and drop-off location).

© University of Pretoria

The success of an SC is due to the fact that it is an active vehicle. The SC is based on an inverted U-shaped metal frame. This metal frame helps the SC to pick up containers and then drive between one-TEU-wide container rows (figure 4-7, page 17) and place the container on the stack. The SC can also remove containers from the stack and place them on trucks or trains. SCs can transport a single or two TEUs or a single forty-foot equivalent unit. SCs can stack up to three containers high. This makes the SC completely independent from any other equipment. This is hugely advantageous, as it saves on labour and equipment costs. The disadvantage is that SCs require skilled operators to operate the complex machines, where a TTU requires a less trained employee. An SC is more expensive than other horizontal transport (excluding AGVs) and the SCs have a tendency to fall over in corners if drivers are negligent, due to their high centre of gravity. SCs can stack up to three containers high. The typical lifespan of an SC is 10 years. Technical data for an SC can be obtained from Table 1 below. With the dawn of technology, some modifications have been made. Firstly, are the automated SCs otherwise known as ALVs (Automated Lifting Vehicles). ALVs have the same functions as SCs. The other modifications are shuttle carriers which are the same SCs but can only stack two containers high. These shuttle cars are faster than SCs and have a lower centre of gravity, so there is less of a chance for them to tip over.

Table 1: Straddle Carrier Technical Data

SC	
	Speed (km/h)
Max Loaded Speed	12
Max Unloaded Speed	16
Speed Inside a Bay	7
	Time (seconds)
Time to Load/Unload a container from the floor	μ=30, ∂=10
Time to Enter and Exit a bay	μ=5, ∂=2
	Key: μ: Mean time ∂: Standard Deviation
Source: (Soriguera, Espinet & Robuste 2006)	

© University of Pretoria

AGVs or automated guided vehicles are unmanned robotic transport vehicles which work with sensors and radio transponders in the floor of the container terminal. AGVs are able to carry a load of up to 60 tons which is equal to two twenty-foot equivalent units (TEU) or a single 40-foot equivalent unit. An AGV is in essence the same as a TTU, it is just automated. The AGV is a highly technological vehicle with infrared sensors to detect collisions and obstacles. AGVs are also easy to track due to the network of transponders they communicate with on a constant basis. The setback with an AGV is the high investment cost. The cost of a single AGV is equivalent to the cost of purchasing four TTUs. AGVs are advantageous in countries where labour costs are very high, and TTUs are preferred in countries where the labour cost is low. For more information of an AGV, refer to Table 2.

Table 2: Automated Guided Vehicle Technical Data

AGV – Gottwald Port Technology	
	Speed (m/s)
Average Vehicle Speed	4.6
Source: (Kim, Jeon & Ryu 2006)	

4.3 Storage Subsystem

The storage subsystem is arguably the most important subsystem as it forms the link between the landside container transportation and the waterside container transportation logistics network. As the amount of containerized cargo is increasing, space in the container terminal and more specifically in the stacking yard becomes less and less. This fact leads to the suggestion that the storage subsystem is the most important.

The stacking yard is commonly separated into different areas. The different containers are allocated to imported and exported containers, reefer containers (containers which act like a refrigerator) and containers containing dangerous and hazardous materials, damaged containers and empty containers. A stacking decision or a storage planning system which is implemented at ports around the world is used to decide where the container will be stored in the stacking yard.

There are two common strategies to stack containers in a container terminal. Each strategy is however, adjusted to be ideal for each port's needs. In the first strategy, areas or slots in a

© University of Pretoria

stack area are allocated to vessels prior to their arrival, according to the number of import and export containers expected for that vessel. For import containers slots in the stack area are allocated where these containers will be stored. If more information (departure date or final location) is available the containers are stacked accordingly. Due to the yard and storage planning being a stochastic process, it is difficult to plan accurately. Due to this fact another stacking strategy, scattered stacking, was created. Scattered stacking has no slots assigned to a specific vessel. When a vessel arrives at the port, it is given an unloading berth. Once the vessel has been assigned a berth, the planning system assigns a suitable stacking location close to the berth. Import containers with the same characteristics (weight, length, type) are piled one onto another. Containers from a ship are scattered over various stacks which results in higher yard utilization (due to no slot being assigned to a vessel).

In general, there are two main ways of storing containerized cargo. The first option is to store the containers on chassis. This option allows each container to be directly accessed, making this option very convenient. The downside of this model is that a very large area of space is needed. Chassis storage is shown in figure 4-3 (below).

Figure 4-3: Chassis container storage

Source: (Paul M. Griffin and H. Donald Ratliff 1991)

© University of Pretoria

The other method of storing containers is stacking, where containers are stored on the ground and containers are placed on top of each other. This model is popular due to the fact that many more containers can be stored in an area when compared with chassis stacking method. The negative of this method is that each container is not directly accessible and in order to obtain containers which are stored under other containers, the above containers need to be moved and assigned to another location. This is known as reshuffling. Reshuffling is considered wasted time and should be minimised. One of the main reasons why reshuffles occur for import containers is because the data of the stacked containers is wrong, incorrect or incomplete.

International container terminals make use of the stacking method due to space constraints. Different stacking equipment is used to store and remove containers from the stacking yard. The most common types of stacking equipment are reachstackers (Figure 4-4: a), forklifts (Figure 4-4: b), SCs (straddle carriers) (Figure 4-2: b) and different variations of yard cranes (Figure 4-4: c). Figure 4-4 can be found on the following page.

© University of Pretoria

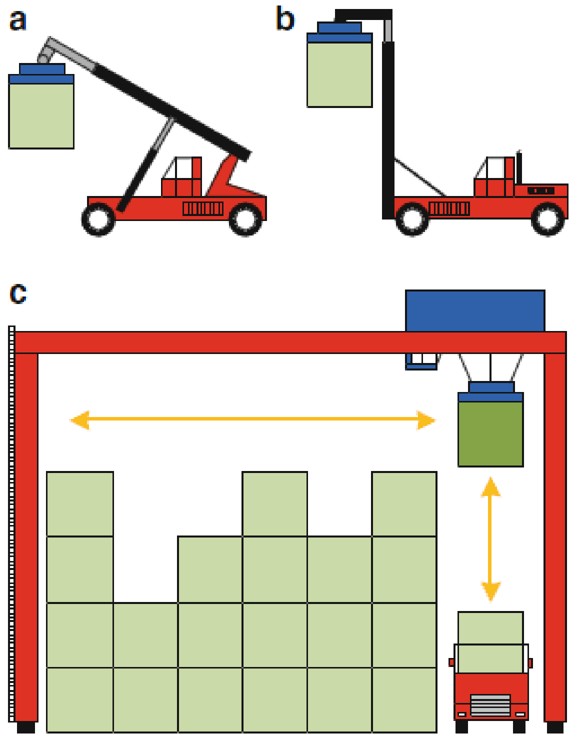

Figure 4-4: Stacking Equipment: a) Reachstacker, b) Forklift, c) Yard Crane

Source: (Kemme 2013)

Reachstackers and forklifts are fairly similar in appearance and functions. Both vehicles are operated by operators in the vehicle and have rubber tyres. These two vehicles are mainly used in smaller ports that do not have a high throughput of containers. These vehicles are also used in larger ports to store empty, lighter or special containers. Both of these vehicles are flexible in their operations and can move efficiently between stacking areas in the stacking yard. Forklifts and reachstackers are active vehicles, and in smaller ports they are also used as horizontal transport. With these two vehicles being so similar there are however, a few huge differences. Firstly, is the lifting gear. The Reachstacker makes use of a telescopic arm which extends forwards and upwards while the mast on the forklift extends upwards only. The mast is the vertical assembly which allows the forklift to move the container or load up or down. The telescopic arm allows the reachstacker to store or retrieve containers on the inside of the stack where the forklift needs to reshuffle the outside containers to get to the containers on the inside of the stack. Secondly, the reachstacker has better forward visibility than a forklift,

© University of Pretoria

due to the absence of a mast. The third advantage is that due to the absence of a mast, which reduces the vehicle height, a reachstacker can move containers into a warehouse more easily than a forklift.

SCs were discussed earlier in section 4.2 of this report.

The most common stacking equipment found at large ports around the world are yard/gantry cranes. A yard crane is by far the most expensive type of stacking equipment available. However, this high investment cost comes with its own advantages. Yard cranes allow for high-density stacking (block stacking) at the stacking yards and the machine is very productive. There are several variations of yard cranes available, and each variation has its own characteristics. The main types of yard cranes are: rubber tyred gantry (RTG) and rail mounted gantry (RMG) (Figure 4-4: c).

An RTG and an RMG are in essence the exact same crane. The main difference that exists between the two is that an RTG uses rubber tyres and where an RMG operates on modified train rails. The lifting gear of a gantry crane is attached to a container in order to move the container. The lifting gear of the gantry crane is connected to the trolley, which moves horizontally on the beam of the gantry crane. Gantry cranes usually stack in the vicinity of 8-12 rows wide and 4-10 rows high enabling them to have a very high stacking density. RTGs have the advantage that they can travel from one stacking area to another, this makes them extremely flexible. The RTGs also have the ability to be used for landside operations (for loading of train and road trucks). The negative aspect of an RTG is that reinforced concrete floors are needed for the RTG to travel on and reinforced concrete with steel pads is required for the vehicle to turn on. This makes the construction of the container terminal complex and expensive. The average RTG can perform 10.14 moves per hour (VYCON 2012).

RMGs can be viewed as the bigger brother to RTGs. An RMG has the ability to stack wider, higher and faster than an RTG. RMGs are also more durable and reliable. RMGs have lower running costs and operating costs than RTGs. The negative of this bigger and better gantry crane is that it comes with a higher price tag than an RTG. The higher price tag is due to the fact that the RMG is heavier than an RTG and thus requires a more stable and solid surface to travel on. This leads to higher costs to reinforce the container terminal floor. The installation of train tracks adds to the installation cost of RMGs. Having implemented RMGs, changing

© University of Pretoria

the layout of the yard becomes difficult due to the tracks which were installed. Having listed all the negatives, the other huge positive of an RMG is that it is easier to automate than an RTG. An automated RMG is called an ASC (automatic stacking crane) and it has roughly the same capability as an RMG. On average an ASC can perform in the vicinity of 16 to 18 moves/hour (Cargo Systems 2007). This easier to automate option is definitely a positive for the RMG system, as labour prices are on the rise and human error equates to large sums of money over the long period. An RMG also has a five year longer life span than an RTG.

Table 3 contains technical data of the various gantry cranes discussed previously. The various speeds in Table 3 can be described by referring back to figure 4-4: C. Gantry speed refers to the speed at which the respective gantry crane can move along the stacking area. In figure 4-4: C, the gantry speed is the speed at which a crane moves in and out of the page. Trolley speed refers to the speed at which the trolley can move horizontally along the beam of the gantry crane (in figure 4-4: C, trolley speed is the horizontal yellow arrow). Finally, the hoisting speed refers to the speed at which the respective gantry crane can move its lifting gear vertically (this is displayed in figure 4-4: C, by the vertical yellow arrow).

Table 3: Gantry/Yard Crane Technical Data

<table>
<tr><th colspan="4">Gantry Crane Technical Data</th></tr>
<tr><td></td><td colspan="3">Speed (m/min)</td></tr>
<tr><td></td><td>RTG - Konecrane</td><td>RMG - Konecrane</td><td>ASC - Gottwald Port Technology</td></tr>
<tr><td>Gantry speed – Full</td><td>90</td><td>140</td><td rowspan="2">240</td></tr>
<tr><td>Gantry speed - Empty</td><td>135</td><td>150</td></tr>
<tr><td>Trolley speed</td><td>70</td><td>70</td><td>60</td></tr>
<tr><td>Hoisting speed - Full</td><td>31</td><td>45</td><td>39</td></tr>
<tr><td>Hoisting speed - Empty</td><td>62</td><td>90</td><td>72</td></tr>
<tr><td>Source</td><td>(Konecranes 2013)</td><td>(Konecranes 2013)</td><td>(Gottwald Port Technology GmbH 2013)</td></tr>
</table>

© University of Pretoria

Two gantry cranes usually operate at a single stacking area; this increases the productivity and reliability (in case of technical problems) of the stacking area. A common practice is that one gantry crane is used for import and the other for export containers. In practise the same types of gantry crane is employed at a stacking area. Containers that need to be transported from one side of the block to the other side have to be removed by the one gantry crane and placed in a transition area for the other gantry crane to take to the other side. The transition area is also commonly known as the handshake area. A new development in rail mounted gantry cranes is the double-RMG system (shown in figure 4-5). This system consists of two RMGs with different heights and widths which enables one RMG to travel under the other. This system avoids the handshake area, and each crane has access to the entire yard without disruption of the productivity of the other RMG.

Figure 4-5: Double-RMG system

Source: (D. Steenken et al. 2004)

When taking the stacking of containers on top of each other, there are various other options of the layout of the stacking yard. The layout options are: block stacking, linear stacking, a combination of block and linear stacking and high bay racking.

© University of Pretoria

Block stacking is when the stacking area is compact and there is minimal space between the containers. An aerial example of block stacking is shown in figure 4-6. Gantry cranes are used to remove the containers from the horizontal transport and then stack the containers in the stacking yard.

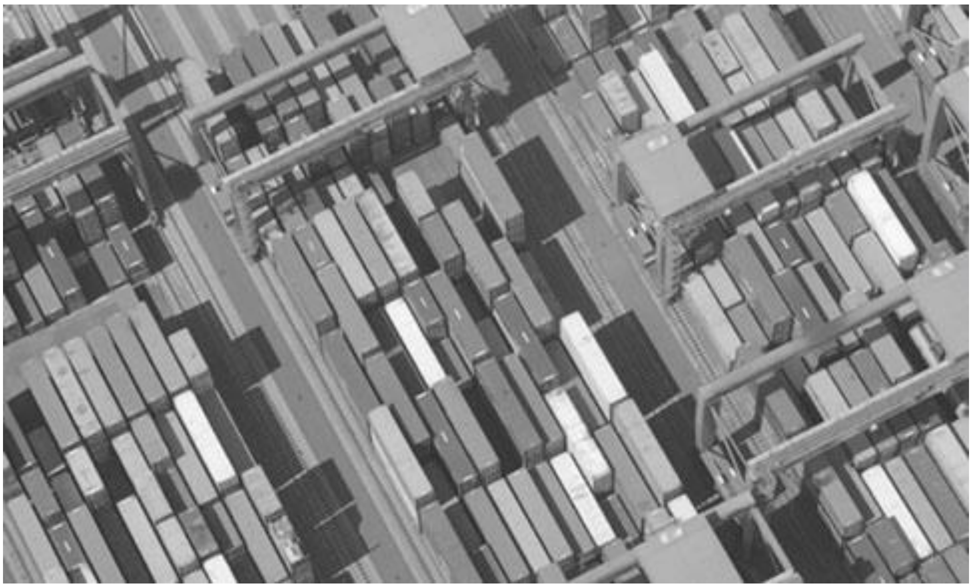

Figure 4-6: Block stacking

Source: (Brinkmann 2011)

The second option of stacking is linear stacking. In this layout option spacing is left between container rows and relatively wide terminal roads are also a prerequisite. This spacing between the rows is because the containers are stacked by making use of SCs (or straddle carriers). To recapitulate from section 4.2, the SCs can drive between these linear rows and stack containers above one-another. Figure 4-7 visualizes the linear stacking method. The block and linear stacking methods are very popular and used widely around the world.

© University of Pretoria

© University of Pretoria

4.4 Methods of operations

4.4.1 Port of Durban

The Port of Durban Container Terminal is separated into two separate piers which operate independently from each other and have different operating methods.

The analysis of Pier 1 is as follows:

At Pier 1, containers are off-loaded from the ship by quay cranes (QCs). The quay cranes unload the containers from the ship and place them on horizontal transport. The horizontal transport used at Pier 1 are TTUs (refer to section 4.2). The TTU transports the containers to the stacking area where an RTG (rubber tyre gantry) stores the containers in the respective stacking area. Refer to the figure below, as well as the text which follows, for greater detail on the pier layout.

A stacking area is referred to as a bay (the light grey square) which consists of rows of containers, which are known as bay-rows. This is used for illustration purposes later on.

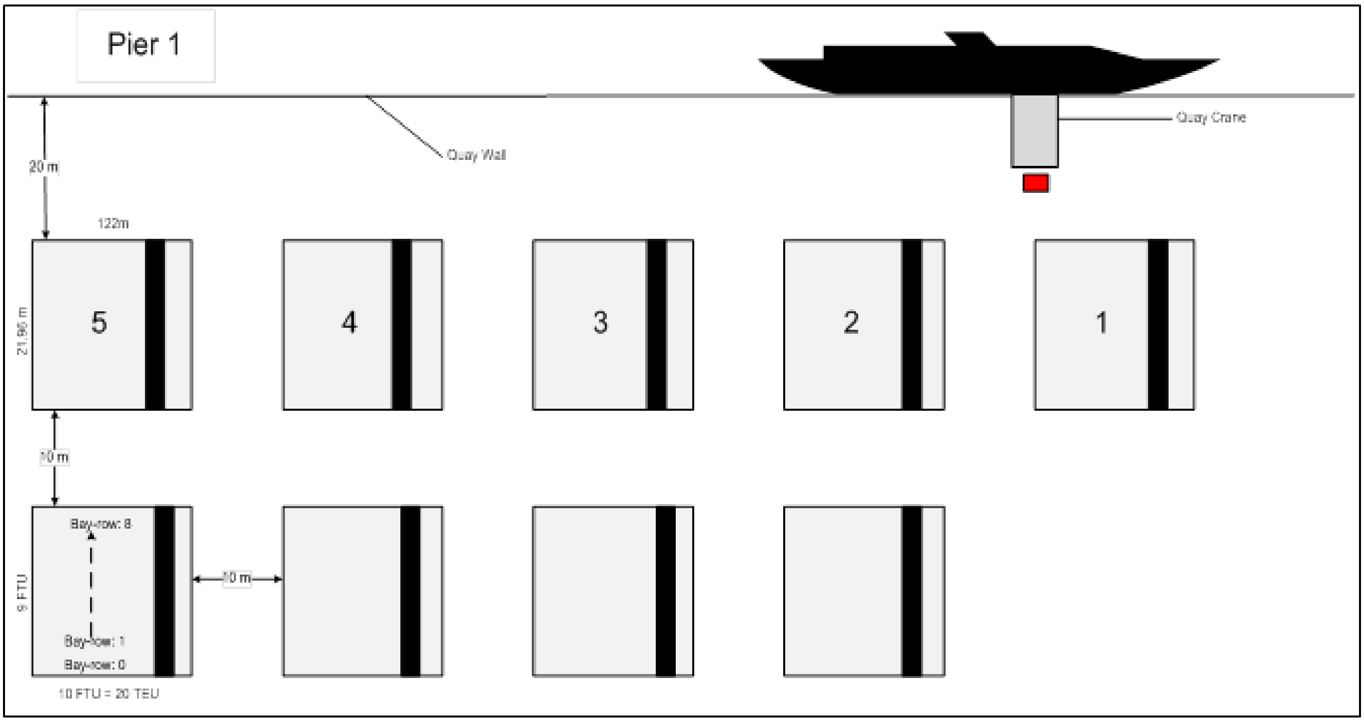

Figure 4-9: Pier 1 Layout

© University of Pretoria

- **Number of bays:** There are a total of nine bays which were considered for this project.
- **Bay specifications:** Each bay has nine bay-rows and each bay-row is ten FEU containers long (twenty TEU containers). Containers are however, only stored in eight bay-rows (bay-row 1-8) and the first bay-row (bay-row 0) is where the TTUs drive into the bay, so that the overhead RTG can remove the containers from the TTU and store them. The TTU then returns to the QC to fetch another container.
- **Bay roads:** All the roads between the bays are 10m wide.
- The area between the quay wall and the first bay is 20m wide.
- **Stacking Method:** Due to space constraints, Pier 1 makes use of the stacking method of storing the containers, and not the chassis method. The containers are stacked using the block stacking method (Figure 4.6, page 16)

The operations at Pier 2 are slightly different than those performed at Pier 1. Quay cranes unload the container from the vessel and place them on the terminal floor. Straddle carriers remove the containers from the floor and subsequently transport and store the containers in the desired location. Refer to the figure and text below for the details of the pier layout.

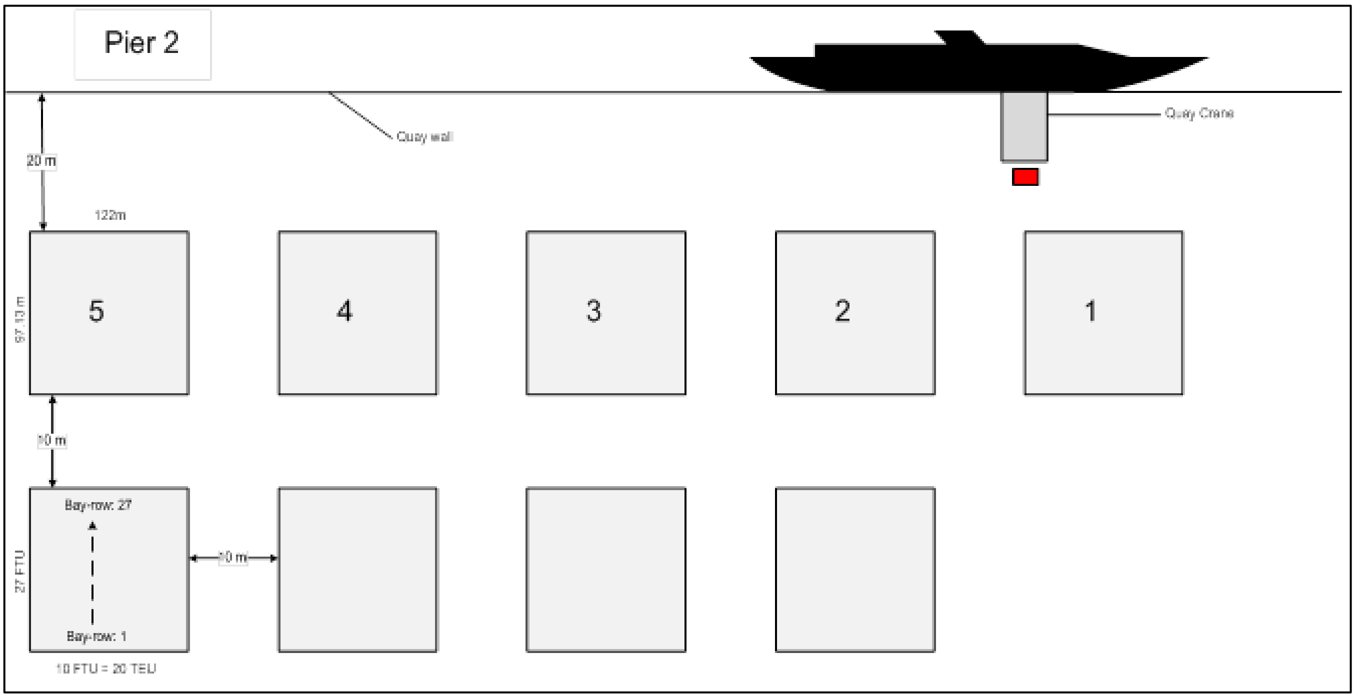

Figure 4-10: Pier 2 Layout

© University of Pretoria

- **Number of bays:** There are a total of nine bays which were considered for this project**.**
- **Bay specifications:** Each bay has twenty-seven bay-rows and each bay-row is ten FEU containers long. Each bay-row is separated to allow the straddle carrier to drive between the bays (Refer to figure 4-7, page 17).
- **Bay roads:** All the roads between the bays are 10m wide.
- The area between the quay wall and the first bay is 20m wide.
- **Stacking Method:** Similar to Pier 1, Pier 2 does not use the chassis method, but uses the stacking method of storing containers. With straddle carriers operating at Pier 2, the containers are stacked using the linear stacking method (figure 4-7, page 17)

The Port of Durban Container Terminal consists of the two piers and the related equipment operating at each pier, as discussed above. There is however, other equipment that operates at the container terminal that was not discussed above. Forklifts and reachstackers operate at the container terminals which are used to store the empty containers and transport damaged containers. MTSs (multi-trailer systems) are not used at the Port of Durban Container Terminal.

The container terminal operates 24 hours a day. When shift and driver changes are considered, the net effective working time is 21.83 hours per day (specified by **TRANSNET** National Ports Authorities). This is taken into consideration later on.

© University of Pretoria

4.4.2 Port of Rotterdam

The Port of Rotterdam in the Netherlands has one of the largest container terminals in the world, and it has the most advanced operations to manage the number of containers. The Port of Rotterdam will be used as a benchmark when considering the Port of Durban Container Terminal operations.

The Port of Rotterdam follows the same basic principle of storing containers as the operations at Pier 1. To recapitulate, this operation involves unloading containers from the ship, placing them on horizontal transport which then transports the containers to the stacking area where yard gantry cranes store the containers. The main difference between the operation at Pier 1 and those of the Port of Rotterdam are that at Rotterdam, the horizontal transport and yard gantry cranes are all automated. At Rotterdam, AGVs are used instead of TTUs and ASCs are used instead of RMGs. This automation system is more efficient mainly due to the fact that it removes human error and human fatigue elements from the system.

The container terminal at the Port of Rotterdam operates 24 hours a day, and the effective working time per day is close to 24 hours. This is due to the fact that almost the entire process is automated therefore shift and driver changes are not necessary.

© University of Pretoria

5 Model Design

The equipment described previously in section 4-2 and 4-3, is the most commonly used equipment and methods applied in large ports around the world. The equipment plays an important role in the port productivity, and thus the best applicable equipment is essential. The Queueing Theory that will be applied in this project is directly influenced by this equipment. Having an understanding of what the equipment is, and how it operates makes the model background easier to understand.

The original plan of the project was to create a finite queueing model for the extension of the Port of Durban Container Terminal. After discussions with **TRANSNET,** the focus area of the project was defined and the model had to be reviewed. After further research, it became clear that a finite queueing model could not be used. This is because the population size (number of the containers arriving at the stacking area) is not finite since there are always containers continually entering the stacking area. Due to this fact, the finite queueing model was replaced with a non-finite queueing model, which will be discussed shortly.

As discussed in the previous sections, the correct quantity and types of equipment are needed for a container terminal to operate efficiently. Having too many horizontal transport vehicles causes congestion at the stacking area and having too few causes the system to be too idle. Due to this fact, a model has to be created which will assist in determining the number of vehicles and the type of vehicles which would create the most efficient system for the container terminal.

The aim of the queueing model is to investigate and calculate the time that a customer or a container spends in the queue while waiting to be served. This will be done for the operations at Pier 1, Pier 2 and at Rotterdam. The results will be compared and verified using simulation modelling.

During the research period no queueing model, which addresses the stacking yard of the container terminal in the desired manner, was found. Due to this, an adequate queueing model had to be adapted to the stacking yard.

A report by authors Mrnjavac & Zenzerovic (Mrnjavac & Zenzerovic 2000), describes how a container terminal can be modelled by making use of queueing theory. The report states that a

© University of Pretoria

container terminal can be defined as a queueing system where ships have an arrival rate and the port has a service rate. In their report, the authors define an M/M/S/∞/FCFS queueing system using the Kendall-Lee notation. The first and second letter refers to the arrival and service rates respectively. The letter S refers to the number of servers, in this example the number of servers are the number of berths at a port. The ∞ sign refers to the maximum number of allowable vessels in the system (waiting in line and being serviced). The model proposed by Mrnjavac & Zenzerovic (Mrnjavac & Zenzerovic 2000) also addresses the cost associated with ships queueing at the port and the cost of an idle berth (an unoccupied berth). To eliminate or greatly diminish the waiting time for vessels at the port, a large number of berths would have to be available. The trade-off with this suggestion is that a large number of those berths would be idle during off peak times, thus resulting in high labour costs.

The above model was taken as a guide line for the definition of a queueing model for the stacking yard of a container terminal. The model created for this project is one where containers arrive at the container terminal on a ship. Quay cranes unload the containers from the ship, and the unloading rate (containers per time period) defines the arrival rate (λ). The arrival rate varies with the type of quay crane used. The horizontal transport and stacking equipment operate in the model at their own service rate of μ1 and μ2 respectively. μ has the same units as λ, which are containers per time period. The service rate varies depending on the type of system and the type of equipment used. The service rate will be revisited at a later stage. The model will also be based on an M/M/S/∞/FCFS (Kendall-Lee notation) queueing model.

The cost calculations determined in the report of Mrnjavac & Zenzerovic can also be adapted to the model which can be applicable to this project. The cost of a horizontal transport vehicle standing idle in the queue and the cost of the stacking equipment at the stacking area being idle are two costs that would be of interest.

Before the model can be accepted, the model must be justified. To justify the model, another similar model, but from a different environment was studied. The model in question was a queueing theory model used for high-speed robotic palletizing (Li & Masood 2008). The authors of the journal article create a one job-two machine model which can be described by the following queueing model format: M/M/2/∞/FCFS. The high-speed robotic palletizing

© University of Pretoria

operation has cartons which arrive from a packaging line. The two robotic palletizers stack the products into pallets which are then stored. The model is in essence the same as the model proposed for this project where cartons or containers arrive at the palletiser or the container terminal and are stored. The main difference between the two models is the S value, which is defined in the palletizing model as being 2. The theory behind the queueing model for the high-speed robotic palletizing is similar to the proposed theory of the stacking yard queueing model, therefore the theory for the stacking yard queueing model has merit and should be able to work. However, once in practice, some changes might have to be made to accommodate variables not yet known.

The literature in section 4.2 and 4.3 discusses the various types of horizontal transport [AGVs (automated-guided vehicles), TTUs (truck-trailer units) and MTSs (multi-trailer systems)] and stacking equipment [Reachstackers, forklifts and different variations of yard cranes]. The horizontal transport and stacking equipment will each have their own service rate (μ) which will be used with the arrival rate of containers to create the queueing theory model. To model the scenario, a multi-server queueing theory model will be used. The horizontal transport transports the containers to the stacking equipment at a certain service rate and lastly the stacking equipment stores the containers at a calculated service rate.

The only vehicle that was not addressed in the above paragraph was the straddle carrier. The straddle carrier (SC) is unique in its own way as it is an active vehicle. Therefore for the SC model, containers arrive at an arrival rate of λ from the quay cranes. SCs fetch the container and store it in the stacking area at a service rate of μ.

© University of Pretoria

6 Model Development

To create the queueing model various variables had to be calculated and assumptions had to be made for the model to be successful.

The first was to calculate the arrival rates and service rates for the model. The arrival rate, which is defined as the amount or number of containers unloaded from the vessel by the quay cranes, was fixed for all models as being twenty-seven containers per hour. Although there are various cranes at Pier 1 and Pier 2 and at Rotterdam, the arrival rate was fixed, so the effect of the different storage and transport equipment in the container terminal could be analysed.

The service rate for the straddle carriers and the service rate for the horizontal transport (TTUs and AGVs) were calculated as the distance (in metres) travelled multiplied by the velocity (the velocity depended on various aspects which will be discussed separately for each model). The service rate of the yard gantry cranes will be discussed later.

The arrival rate of twenty-seven containers per hour already includes shift changes. Therefore, when calculating the service rates (containers per hour), the calculated service rate had to consider shift changes.

The container intensity can be measured by dividing the arrival rate by the number of servers multiplied by the service rate. The number of servers refers to the number of respective yard's equipment in each model. The container intensity is a measure used in the queueing theory model calculations.

The following assumptions were made in general for each model:

- The position of the quay crane in all the models remained the same so that the results could be compared and discrepancies would not arise. The red square indicates the point where the quay crane unloaded the containers (refer to figure 6.1 and 6.2 on the following pages).
- It takes a yard gantry crane (RTG and RMG) or a quay crane 15 seconds to line up with a container and an additional 50 seconds to remove the container from the vessel or horizontal transport. This equates to 65 seconds for placing or removing a container from a vessel or horizontal transport vehicle. (Nazari 2005)

© University of Pretoria

- In the model, the effects of traffic were not considered since only one quay crane was considered. More than one quay crane may be considered in the model; however, that would only increase the arrival rates.
- The furthest container is situated 750m from the quay cranes which was observed in this model. The mean distance between the quay crane and the furthest container was calculated and is the average distance from the reference point from which a container had to be retrieved from. The reference point was identified as bay 4 (Figure 6.1 and Figure 6.2)
- The models make use of the scattered stacking method of storing containers in the stacking area(s).
- Horizontal transport vehicles are allocated to QCs using a single-cycle strategy.

In the model, specific notation was used. Below is a description of the notation.

W_q (1x) - the number 1 refers to state 1. The letter ‘x’ refers to the scenario (x can take any letter from a to h).

W_q (2x) – the number 2 refers to state 2. The letter ‘x’ refers to the scenario (x can take any letter from a to h).

W_q (x) - The letter ‘x’ refers to the scenario (x can take any letter from a to h).

Refer to Appendix B, for the Excel spread sheets created for calculating the queueing theory models discussed in section 6.1 - 6.3.

© University of Pretoria

6.1 Pier 1 Model

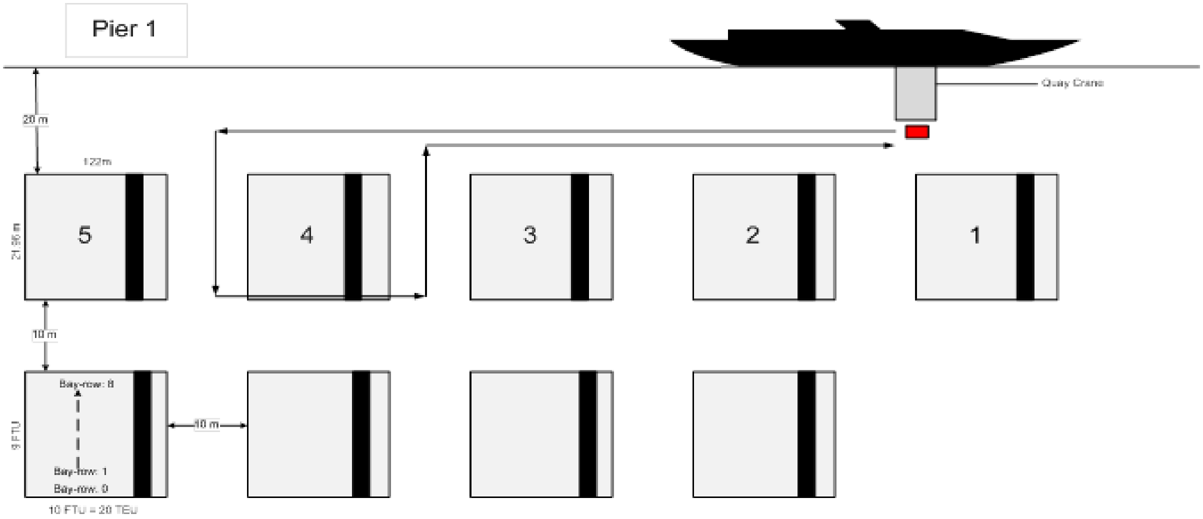

Figure 6-1: Pier 1 Model Design

The arrival rate λ was previously defined as being 27 containers per hour.

The service rate was calculated by taking the distance which the arrows in figure 6.1 represent. The arrows give a visual representation of the path that the TTUs travel. The distance was multiplied with the average velocity or speed of the TTU. This velocity is 11 km/h (this is an average velocity and applies whether the vehicle is loaded or empty). This yielded the time in seconds it takes the TTU to travel from the quay crane to the RTG in the stacking yard and return to the quay crane. This time value was converted to a rate and after considering shift changes, the service rate 1 (μ_1) for the model was determined.

μ_1=8 containers/hour

Following this calculation, a service rate for the RTG had to be calculated. The easiest way to calculate the service rate was to use the moves/hour that an average RTG can perform. From the literature in section 4.3, the moves/hour value is 10.14 (moves/hour equates to containers/hour). This value had to be converted to a 24 hour working day (which incorporates shift change), therefore;

μ_2=9.22 containers/hour

© University of Pretoria

Two separate calculations are used to calculate the waiting time for two different scenarios (These two scenarios each having a different number of horizontal and stacking equipment).

The first two scenarios (a and b) are calculated using Jackson's rule.

The two service rates were used together with the arrival rate to calculate the expected time that a container will spend waiting to be serviced. This was calculated by using Jackson's Rule. Jackson's rule states that if $\lambda < s_i \mu_i$ then the i^{th} state may be analysed using an $M/M/s_i/\infty/FCFS$ queueing theory model (Winston 2004).

Considering scenario a; for state 1 (TTUs) to abide by Jackson's rule, the number of servers or the S value had to be equal to 4. For state 2, the s-value had to be equal to 3 which yielded a value of 32 for state 1and 27.66 for state 2. Both of these values are greater than 27, and therefore Jackson's rule is applicable.

Using Jacksons rule the following results were calculated for each state:

- W_q (1a) = 8.28 min
- W_q (2a) = 38 min
- W_q (a) = 46.28 min

Scenario b is where the S value of the TTU and RTG had to be altered from 4 to 5 and from 3 to 4 respectively generated the following results for each state;

- W_q (1b) = 3.8 min
- W_q (2b) = 2.6 min
- W_q (b) = 6.4 min
- W_q (1x) refers to the time (per hour) that a quay crane has to wait for a TTU to collect a container.
- W_q (2x) refers to the time (per hour) that a TTU has to wait at a bay for the RTG to remove its container.
- W_q (x) refers to the total time a container waits in line to be serviced. [W_q (x) = W_q (1x) + W_q (2x)]

© University of Pretoria

The second calculation (for scenarios c and d) will use a normal M/M/S/∞/FCFS queueing theory model. The operations at Pier 1 are separated into two different calculations which will be used together to obtain the waiting time of a container in the system. The first calculation will be a queueing model for the quay crane unloading the containers from the vessel and placing them on the TTU which then takes the container to the stacking area. The second calculation will encompass the TTUs bringing containers to the stacking area where RTGs stack the containers.

The first calculation of scenario c is evaluated by;

λ = 27 containers

The service rate for the calculation will be the service rate of the TTUs, which is;

μ=8 containers/hour

The S-value for the model was taken to be the same as the S-value specified for the TTUs in the Jackson model, which was 4.

Using the above information the expected time (per hour) that a quay crane has to wait for a TTU to collect a container is;

- W_q (1c) = 8.28 min

The second calculation follows;

The arrival rate of containers in this model is the service rate of the TTUs in the model above, which is λ =8 containers/hour, however, in the previous model there were 4 TTUs used in the system. The arrival rate of the second model is the same as the service rate of the first model, and thus the service rate needs to be multiplied by 4.

λ =32 containers/hour

The service rate is the number of moves per hour that an RTG can perform. This information can be obtained from the previous page;

μ=9.22 containers/hour

© University of Pretoria

The S-value for the number of RTGs had to be such, that Sµ>= 32. If S=3, W_q (2d) = "no solution" since Sµ<32. Due to this fact, the S value was calculated to be 4.

Using the above information, the time (per hour) that a TTU has to wait at a bay for the RTG to remove its container can be evaluated:

- W_q (2c) = 8.5 min

The total time that a container has to wait from when it is unloaded from the vessel until it is stored in the stacking area is denoted by W_q (c).

- W_q (c) = 16.78 min

Scenario d was where three RTGs where used in a model to calculate W_q (2d) which returned an answer of 'no solution'.

© University of Pretoria

6.2 Port of Rotterdam Model

In keeping a constant arrival rate throughout the whole model, the service rate for this model is;

λ = 27 containers per hour

The Port of Rotterdam model is identical to the model constructed for Pier 1. The service rate calculation is based on exactly the same method as that of the TTU for the Pier 1 Model. The only difference is the average velocity. The average velocity was found to be approximately 4.6 metres per second (Table 2, page 9).

μ_1 = 11.4 containers per hour

The service rate of a typical ASC is to be between 16 and 18 moves per hour (section 4.3, page 14). The idea was to take an average of these two figures which resulted in a service rate of 17 moves per hour.

μ_2 = 17 containers per hour

To calculate the average time a container spends in the queue waiting for service (W_q (x)), the above service rates with their corresponding number of servers need to adhere to Jackson's rule. To meet Jackson's rule, a minimum of 3 AGVs and 2 ASCs are needed.

Using Jackson's rule, the W_q value calculated for states 1 and 2 are: (scenario e)

- W_q (1e) = 5.8 min
- W_q (2e) = 3.6 min
- W_q (e) = 9.4 min

Increasing the S value to 4 AGVs and 3 ASCs yields the following results for each state; (scenario f)

- W_q (1f) = 2.2 min
- W_q (2f) = 1 min
- W_q (f) = 3.2 min

© University of Pretoria

- W_q (1x) refers to the time (per hour) a quay crane has to wait for an AGV to collect a container.
- W_q (2x) refers to the time (per hour) that an AGV has to wait at a bay, for the ASC to remove its container.
- W_q (x) refers to the entire time a container waits in line to be serviced. [W_q (x) = W_q (1x) + W_q (2x)]

© University of Pretoria

6.3 Pier 2 Model

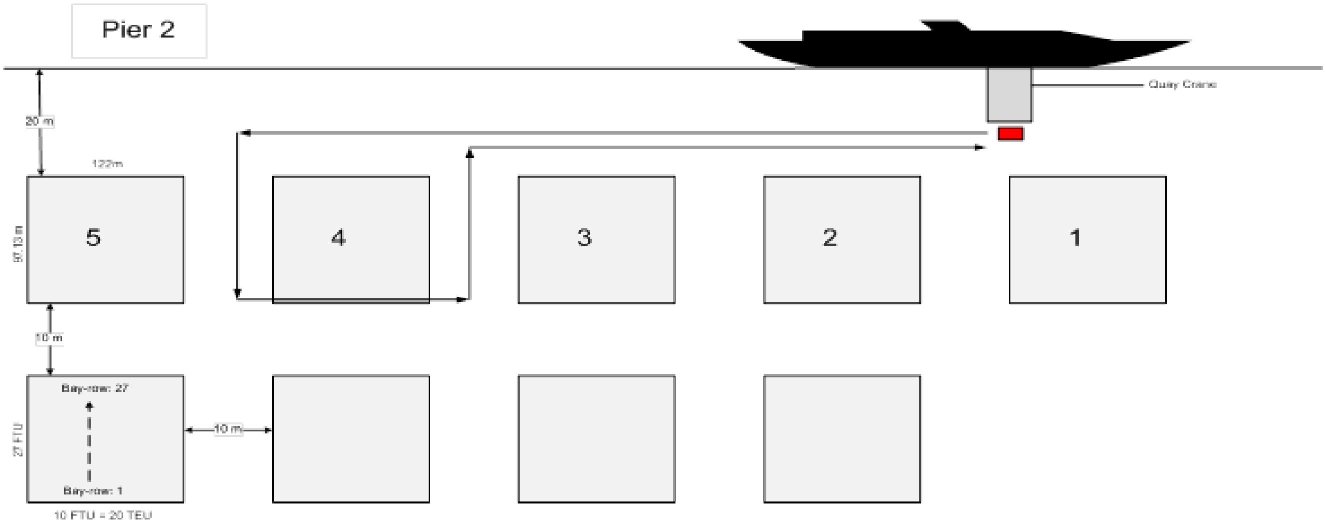

Figure 6-2: Pier 2 Model Design

As in section 6.1 above, the arrival rate of container has remained the same.

λ=27 containers/hour

The service rate of the straddle carrier was calculated using the same principle as was used to calculate the service rate for a TTU in section 5.1. The distance travelled (which can be seen in figure 6.2 above) multiplied by the various corresponding vehicle velocities (refer to Table 1 on page 8) to calculate the service rate. The time taken for an SC to enter the bay and the time taken to load and unload a container (Table 1, page 8) was also included in the calculation. After shift changes are considered, the calculated service rate is;

μ=7.55 containers/hour

The arrival rate and service rate where used in a simple M/M/S/∞/FCFS queueing model to calculate W_q. The S value in the model refers to the number of servers or SCs operating in the system. The S value can be adjusted in the model to obtain an understanding of what effect the number of SCs will have on the system.

© University of Pretoria

Using various values for the S value, the corresponding W_q (x) value for each S values was calculated.

- If: S=4 then W_q (g) = 10.3 min
- If: S=5 then W_q (h) = 3min

The W_q (x) value refers to the time (per hour) that a quay crane has to wait for an SC to remove the current container from the unloading point on the container floor.

© University of Pretoria

7 Simulation Model

The simulation models for the container terminal were created using Simio. The variables for the model were obtained from section 6 and converted to a time value per container. Two separate simulation models where created, for Pier 1 and Pier 2. The variables of the Pier 1 model where altered to obtain results for the Port of Rotterdam model. Refer to Appendix C for screenshots of the model.

The operations of Pier 1 where modelled for scenario a and b as defined in section 6.1. Once the model was created the effects of changing the number of TTUs and RTGs were recorded and analysed. The results that were obtained from the simulation of Pier 1 (Table 4) and Rotterdam (Table 5) are shown below.

Table 4: Pier 1 Simulation Results

Equipment	Scheduled utilization %							
	Scenario							
	2	3	4	5	6	7	8	9
TTU-1	62.99	64.31667	73.61389	76.56944	62.99444	59.60278	59.60278	55.37778
TTU-2	65.29	56.39167	75.89444	66.68333	65.28611	58.63889	58.63889	54.99722
TTU-3	52	65.74444	78.82778	76.30556	52.00833	46.85556	46.85556	61.73611
TTU-4	40.74			62.53333	40.73889	36.49444	36.49444	
TTU-5					0	0		
Average TTU	55.255	62.15093	76.11204	70.52292	44.20556	40.31833	50.39792	57.37037
RTG-1	60.11111111	48.03333	54.38056	73.07222	60.11111	48.75	48.75	47.51389
RTG-2	59.58	64.21389	78.73056	78.41944	59.58333	54.16667	54.16667	37.91667
RTG-3	56.63	54.16667			56.63333	26.88611	26.88611	48.75
RTG-4						48.75	48.75	37.91667
Average RTG	58.7737037	55.4713	66.55556	75.74583	58.77593	44.63819	44.63819	43.02431
QC	67.5	62.55556	51.8	59.2	67.5	67.5	67.5	64.7
# containers processed	32	29	24	27	32	32	32	31

© University of Pretoria

Table 5: Rotterdam Simulation Results

Equipment	Scheduled utilization %					
	Scenario					
	1	2	3	4	5	6
AGV-1	72.27222222	71.05278	71.05278	81.50833	81.8	81.13056
AGV-2	64.06944444	59.24167	59.24167	88.98056	73.02222	73.96667
AGV-3		59	59		65.85278	68.73889
AGV-4			0			61.14722
Average AGV	68.17083333	63.09815	47.32361	85.24444	73.55833	71.24583
ASC-1	54.92222222	61.04444	61.04444			
ASC-2	67.69166667	59.58333	59.58333	63.71667	79.35278	79.35278
ASC-3	37.91666667	57.56667	57.56667	61.78056	78.53611	80.47778
Average ASC	53.51018519	59.39815	59.39815	62.74861	78.94444	79.91528
QC	59.7	67.5	67.5	48.1	60.52778	62.9
# containers processed	29	32	32	22	28	28

The results of Table 4 and 5 show the % utilization of each equipment after changes were made to the simulation. The Tables can be read as following:

In Table 4, scenario 2, there were four TTUs and three RTGs operating in the system. The results of the simulation where that the average utilization of a TTU of the system was 55.3% and of an RTG was 58.8%. The quay crane had a utilization of 67.5% and in total thirty-two containers were processed during the 2 hour simulation of the system. Another example is given in Table 5, scenario 3, where four AGVs and two ASCs were operating on the system. The reason for the 0% utilization of AGV 4 will be addressed shortly.

When analysing the results from Table 4 certain values need to be addressed. The utilization of the quay crane in both Table 4 and Table 5 never goes above 67.5%. This is correct since the remaining 32.5% of the time the quay crane loads containers onto the TTU or AGVs (which takes a further 65 seconds per container). With the quay crane operating at maximum

© University of Pretoria

capacity (67.5%) the maximum number of containers that can pass through the system in a two hour time period is equal to 32.

In both Tables 4 and 5, when the quay crane is operated at 67.5% the number of containers passing through the system remained constant, and the average % utilization of each piece of equipment (TTU and RTG or AGV and ASC) remained constant. This is due to the fact that no matter which changes were made to increase the numbers of equipment in the system, no more containers would be processed since the quay crane was operating at maximum capacity.

There is a change in the utilization of the quay crane when considering scenarios 2 and 3 of Table 4. The change that was made to the model was to remove a TTU from the system. This change caused an average utilization of the TTUs to increase as there were less TTUs in the system, and each would have less idle time. At this point, it should be defined that the idle time of the simulation was defined as when the TTU waits in line at the quay crane to be serviced with a container. The rest of the time can be classified as utilization time of the TTU. This increased utilization refers to the fact that the TTUs spend more time waiting at the RTGs to be serviced. The utilization of the RTGs also decreased and this referred to the fact that less containers passed through the system.

When comparing scenario 3 and 4 (change in the number of RTGs) with scenario 4 and 5(change in the number of TTUs) it can be seen that the number of RTGs have a greater influence on the number of containers processed by the system than the number of TTUs. This calculation proves that the RTGs have a greater influence on the operations at Pier 1.

When comparing scenarios of equal numbers of equipment from Table 4 to those of Table 5 certain conclusions can also be made. For example, when comparing Table 4 scenario 4 with Table 5 scenario 5, it can be established that the operations at the Port of Rotterdam are performed more efficiently and rapidly than those of Pier 1. This conclusion is made by considering the number of containers processed per 2 hour period.

The conclusion made above about the Port of Rotterdam can be verified when comparing Table 4 scenario 3 with Table 5 scenario 1. The results show that Rotterdam needs one less AGV to reach the same throughput as that of Pier 1.

© University of Pretoria

The area of the simulation which could have been altered to make it more realistic would be to change the processing time of the quay crane. Having the opportunity to spend more time at the Container Terminal in Durban and performing time studies to obtain a different or more realistic service rate would have had an influence on the outcome of the simulation. Due to the time and distance constraints, spending more time at the container terminal to perform time studies and obtain information was not possible. Therefore the service rate of the quay crane was adapted from the arrival rate of the queueing theory model (which was 27 containers per hour, as defined by **TRANSNET**)

In concluding the analysis of the results of the Pier 1 and Rotterdam models, the following scenarios can be identified as being the best.

For the Pier 1 operations, scenario 2 is defined as being the best combination of equipment needed to operate at Pier 1. This conclusion was made since this system processes the maximum number of containers and it uses the least numbers of equipment (less labour costs and initial investment than the other scenarios with the same throughput), and therefore makes it most desirable.

The Port of Rotterdam simulation, scenario 2 is seen as the best possible combination for Rotterdam. This was once again concluded on the grounds of maximum throughput (of thirty-two containers) with the least equipment.

The simulation results for Pier 2 operations are shown below in table 6.

Table 6: Pier 2 Simulation Results

Equipment	Utilization %	
	Scenario	
	1	2
SC-1	50.83514631	50.83515
SC-2	49.63768409	49.63768
SC-3	49.67515297	49.67515
SC-4	48.64960815	48.64961
SC-5		0
Average SC	49.69939788	39.75952
QC	100	100
# containers processed	51	51

© University of Pretoria

From the results of the simulation of Pier 2 the first item that needs addressing is the fact that the utilization of the quay crane is 100%. This is due to that fact that the QCs can place a container on the container terminal floor from where the SCs can fetch and store the respective container. This eliminates extra loading time that the QC has to spend to load a TTU or an AGV. The other aspect to consider is that the utilization of the 5th SC in scenario 2 is zero. This is due to the fact that there is enough capacity with respect to SC service in the system to process the containers in the given circumstances.

From the simulation results, scenario 1 (Table 6) seems that the ideal number of SCs needed to operate at Pier 2. Scenario 1 was chosen over Scenario 2 since the extra SC of scenario 2 makes no difference. Scenario 1 employs one less SC which saves significant initial capital investment and labour expenses.

© University of Pretoria

8 Model Discussion

In an article written by Birgitt Brinkmann (Brinkmann 2011), the author describes typical numbers of yard equipment assigned to each quay crane. According to the article four to five TTUs and two to three RTGs are typically allocated to each quay crane. Each quay crane is allocated four to five SCs. These numbers vary with distances but do give a good indication of the accuracy of the model.

<u>Pier 1 Model:</u>

A brief summary of the results for the Pier 1 models:

- W_q (1a) = 8.28 min
- W_q (2a) = 38 min
- W_q (1b) = 3.8 min
- W_q (2b) = 2.6 min
- W_q (1c) = 8.28 min
- W_q (2c) = 8.5 min
- W_q (2d) = "no solution"
- (refer to section 6.1 for details of each calculation)

The first aspect to discuss is the W_q (2a) value. To have a total waiting time of 38 min for the four TTUs at the RTG is a serious aspect to consider. When increasing the number of RTGs from three to four, the waiting time of the TTUs drops from 38 min to 2.6 min. A reason for this high value of 38 min could be the fact that the distance that the TTUs travel from the quay crane to the RTG is small, and thus the service rate of the TTUs increases (due to the decrease in the distance the TTUs need to travel). This reason is admissible due to the fact that W_q (2d) gives an answer of "no solution". This refers to the fact that with three RTGs and a service rate of 9.22 containers/hour per RTG, there exists no steady state (the container intensity is bigger than 1, and thus the queue becomes unconstrained). This is a good explanation of the high waiting time of TTUs at the RTG of the Jackson model. The Jackson model gives an answer for W_q (2a) since it uses a different approach to the normal queueing theory model used in the second calculation (scenario c and d).

© University of Pretoria

The analysis of the simulation model discussed in section 7 established that the RTGs had a greater influence on the number of containers processed by the system than the number of TTUs, consequently the RTGs formed a greater bottleneck in the system than the TTUs. This verifies the conclusion made above that the RTGs, and an extra RTG will have a considerable influence on the operations and throughput of the container terminal.

W_q (2b) and W_q (2c) both use four RTGs but there is a difference in the waiting times of the TTUs at the RTGs. The difference is due to the differing approach that the two queueing models use. The more accurate of the 2 calculations would be the W_q (2c) as it takes the arrival rate of the containers on the TTU into account. The W_q (2b) (which used Jackson's method) completely ignored the TTUs in the calculation and only focused on the unloading rate of the quay crane, even if the unloading rate of the quay crane had no direct impact on the RTG.

The queueing model provides a good indication of the number of TTUs and RTG assigned to each quay crane at the Pier 1 operations. The optimum number was four TTUs and four RTGs, the TTU number falls into the category defined by Birgitt Brinkmann and the number of RTGs is close to the parameters of two to three RTGs per quay crane but varied due to the distance element. From this comparison the results of the model are reasonable.

When comparing the numbers of equipment of the ideal scenario of section 7 for Pier 1, the ideal scenario was to implement four TTUs and three RTGs. This range of equipment also falls into the range defined by Birgitt Brinkmann. The difference in the two conclusions for the Pier 1 operations is interesting, as the queueing theory model needed four RTGs where simulation only needed three RTGs to operate. This difference could be influenced by the quay crane and how the models calculate the service rate differently. If the quay crane could have processed more containers in the simulation (by increasing its utilization) the simulation may have returned the same results as the queueing theory model. This can be proven by referring to scenario 2 and scenario 4 of Table 4. The difference in these two simulations is the utilization percentage of the quay crane. To increase the utilization from scenario 4 to scenario 2, an additional RTG is needed.

© University of Pretoria

This same phenomenon would have occurred if the utilization of the quay cranes was increased to above 67.5% thus giving rise to a large possibility that the simulation model and the queueing theory model would return the same results.

Port of Rotterdam Model:

An overview of the results for the Port of Rotterdam models:

- W_q (1e) = 5.8 min
- W_q (2e) = 3.6 min
- W_q (e) = 9.4 min
- W_q (1f) = 2.2 min
- W_q (2f) = 1 min
- W_q (f) = 3.2 min

The expected result of the model was that the operation of the Port of Rotterdam is done much more efficiently and with less queue time than those of Pier 1 (Rotterdam has a lower W_q time for both states 1 and 2). This was proved by the model and it was expected due to the fact that Rotterdam uses newer and more improved technology. An 8.28 min queue time for the quay crane using four TTUs in the operation and 2.2 min waiting time for the quay cranes using four AGVs in operation. Considering that the AGVs operate at a higher speed than the TTUs, it can be said that the operations of the TTUs are very efficient.

Referring to the discussion and comparison on the Pier 1 and Rotterdam simulation it also concluded that Rotterdam performs the operations more rapidly than Pier 1. Once again this is due to the quicker and more efficient equipment Rotterdam employs. The simulation model proved that the queueing theory model returned reliable results.

Comparing the queueing time of containers when using the four RTGs of Pier 1 (W_q (2a)) with the three ASCs (or automated RMG) of Rotterdam (W_q (2f)), it can be seen, from the difference of 37 minutes in expected queue time (in favour of the ASC) that the operations and capabilities of the ASC are much better than that of the RTG. This is partly due to the fact that the ASC has a higher gantry and hoisting and trolley speeds than a RTG (refer to Table 3, page 14).

© University of Pretoria

Pier 2 Model:

The only way to compare the model of Pier 2 with the models of Pier 1 and Rotterdam is to take the W_q (x) value of Pier 1 and of Rotterdam and compare it with the W_q (x) value of the Pier 2 model.

Below are the W_q (x) values from the models;

- W_q (a) = 46.28 min
- W_q (b) = 6.4 min
- W_q (c) = 16.78 min
- W_q (e) = 9.4 min
- W_q (f) = 3.2 min
- W_q (g) = 10.3 min
- W_q (h) = 3 min

From the above data, it can be seen clearly that the Rotterdam operations are the most efficient (e and f). The equipment is used in such a way that highest productivity is obtained from each piece of equipment. This is largely due to an automation factor.

The waiting time in g is close to the waiting time in e. This is highly possible, due to the fact that less equipment is used in g and this equates to less hand-over points (the SC does all the work itself, instead of an AGV transporting and an ASC stacking). The operations at g are also better than those of a, and h is much better than that of b. This is once again due to the same factor mentioned earlier, the hand-over points. The Pier 2 operation also has the advantage that it requires fewer operators than the Pier 1 operation. The disadvantage with the SC system is that the number of containers stored per area in the stacking area is considerably less when using a SC than using an RTG or ASC. The RTG or ASC can also restack more efficiently and retrieving containers is easier.

© University of Pretoria

The queueing model of Pier 2 used four and five straddle carriers respectively, for g and h, which fit into the guidelines defined by Birgitt Brinkmann. The simulation agreed with using four SCs for the Pier 2 operations. The SCs in the simulation also had to wait for the quay crane to unload containers, just as the SCs also had to wait in the queueing theory model. This agreement between the simulation and the queueing theory model proved that the queueing theory model returned a feasible solution.

© University of Pretoria

9 Conclusion

Having the correct equipment and using it in the most efficient manner can have many advantages for a port. Although capital is needed at the outset, the capital can soon be regenerated, as vehicles (vessels, road vehicles and trains) can be processed much quicker.

The theory from the literature study provided a good foundation and base knowledge from where the queueing theory model could be created and optimised.

Having discussed and compared the results of the queueing theory model with the simulation model, the results obtained from both where fairly similar (refer to section 8). The difference between the results of the models can be due to the different approach which the two methods use. Having analysed and understood the results, the final conclusion was that the results were fairly similar and share the same concepts. With the framework set by Birgitt Brinkmann (Brinkmann 2011) it can be concluded that the queueing theory model for the Container Terminal of the Port of Durban returned reliable results. The queueing theory model and the simulation model are a framework which affords future academic efforts.

Ultimately each of the systems (the TTU and RTG system, the SC system and the automated system) have their own advantages and disadvantages. From the results it seems as if the SC system is the most economically feasible since it requires less equipment and employees (which is a huge positive), however, container reshuffling takes much more time and effort than the two other systems. This is due to the fact that the RTG and ASC are dedicated to storing containers, and the storage and retrieval of containers is much easier and quicker.

The TTU and RTG system has the advantage of being easy to implement and operate. However, the negative of this aspect is that, as was seen from the results of the project, it requires the most time or equipment to process the same number of containers as the SC or automated systems. The advantage of this system is that it is not as difficult to implement as the automated system, it is much less complex and it requires a much smaller initial investment.

© University of Pretoria

With the current labour unrest and the demand for higher wages, opportunities arise for automated systems to enter the market. The operations at the Port of Durban Container Terminal would not in the near future be automated, as it will cause many individuals to lose their jobs, thus adding to the already huge unemployment rate of the country. Secondly, in South Africa the general hourly wage of employees is considered to be low with comparison to other European countries.

In conclusion, the operations of the Port of Durban Container Terminal should remain the same with regard to operations. The operations at Pier 1 should continue to operate with TTUs and an RTG where Pier 2 should operate with SCs. This setup in operations is highly advantageous as the container terminal can employ various methods and see which work well. It allows **TRANSNET** to make use of the latest technological developments of both systems without major container terminal restructuring costs.

This project sets out guidelines for the numbers of equipment assigned to each quay crane at the two piers. It was established that with the current parameters defined in the project, four TTUs and four RTGs are needed for the best overall operations at Pier 1. Four straddle carriers per quay crane would be the best option for the operations at Pier 2.

The guidelines from the queueing theory models give a good representation of the numbers of equipment needed for each operation. Having too many stacking areas assigned to a single quay crane causes the container terminal to become large and spread out, thus decreasing the service rate of the horizontal transport (fewer containers can be transported per horizontal transport vehicle per time period). Having too many TTUs or SCs in the system causes congestion in the container terminal, and having too few causes the quay cranes and stacking equipment to be idle for longer than usual, which decreases the productivity of the container terminal. The guidelines aim to achieve the best balance between the numbers of equipment to ensure vessels are processed in the quickest possible time thus increasing the container throughput at the Port of Durban Container Terminal, one of the largest container terminals in Africa.

© University of Pretoria

10 Bibliography

Brinkmann, B 2011, 'Operations Systems of Container Terminals', in JW Böse (ed.), *Handbook of Terminal Planning*, XXIII edn, Springer, Hamburg.

Cargo Systems 2007, *TBA uploads*, viewed 12 August 2013, <www.tba.nl/uploads/files/picking_the_right_crane.pdf>.

D. Steenken et al. 2004, 'Container terminal operation and operations', Thesis, Institute of Information Systems, University of Hamburg, 10.1007/s00291-003-0157-z, Springer-Verlag, Hamburg.

Gottwald Port Technology GmbH 2013, *Gottwald port technology*, viewed 29 April 2013, <www.gottwald.com>.

Henesey, LE 2004, 'Enhancing Container Terminal Performance:', Thesis, Department of Systems and Software Engineering, BLEKINGE INSTITUTE OF TECHNOLOGY, 91-7295-040-4, Blekinge Institute of Technology, Karlshann, Sweden.

Kemme, N 2013, 'Chapter 2', in PD Knut (ed.), *Design and Operation of Automated Container Storage Systems*, XX edn, Physica-Verlag HD, Heidelberg.

Kim, KH, Jeon, SM & Ryu, KR 2006, *SpringerLink*, viewed 12 August 2013, <http://link.springer.com/static-content/lookinside/179/art%253A10.1007%252Fs00291-006-0055-2/000.png>.

Konecranes 2013, *Konecranes: POrt Cranes: Container Handling*, viewed 30 April 2013, <www.konecranes>.

Li, J & Masood, SH 2008, 'Modelling robotic palletising process', *Journal of Achievements in Materials and Manufacturing Engineering*, vol 31, no. 2, pp. 526-530.

Mohseni, NS 2011, 'Developing a Tool for Designing a Container Terminal Yard', Master Thesis, Hydraulic Engineering, Delft University of Technology, oai:tudelft.nl:uuid:020efc36-c130-4429-a1b6-7028235400ab, Delft University of Technology, Delft.

© University of Pretoria

Mrnjavac, E & Zenzerovic, Z 2000, 'Modelling of port container terminal using the queuing theory', Report, Maritime Studies, University of Rijeka, 1825-3997, EUT Edizioni Università di Trieste, Rijeka.

Nazari, D 2005, 'Evaluating container yard layout', MSc Thesis, Maritime Economics and Logistics, Erasmus University Rotterdam, 66452627, Erasmus University, 2005, Rotterdam.

Paul M. Griffin and H. Donald Ratliff 1991, 'Material Handling and Storage Strategies for a Containerized', Document, School of Industrial and Systems Engineering, Georgia Institute of Technology, 30332-0204, Georgia Institute of Technology, Atlanta.

Soriguera, F, Espinet, D & Robuste, F 2006, 'A Simulation Model For Straddle Carriers Operational Assessment in a Marine Container Terminal', *Journal of Maritime Research*, vol III, no. 2, pp. 19-34.

Transnet 2013, *Transnet port terminals*, viewed 18 February 2013, <http://www.transnet.net/Divisions/PortTerminals.aspx>.

VYCON 2012, *VYCON flywheel energy*, viewed 09 August 2013, <www.vyconenergy.com/pages/pdfs/REGEN_White_Paper_4_8_08.pdf>.

Winston, WL 2004, 'Queuing Theory', in A Day (ed.), *Introduction to Probability Model*, 4th edn, Curt Hinrichs, Indiana University.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

11 Appendix A: Industry Sponsorship Form

Department of Industrial & Systems Engineering
Final Year Projects
Identification and Responsibility of Project Sponsors

All Final Year Projects are published by the University of Pretoria on *UPSpace* and thus freely available on the Internet. These publications portray the quality of education at the University and have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide the best guidance to the student on the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

Project Sponsor Details:

Company:	TRANSNET (PLANNING AND INTEGRAT
Project Description:	Applying Queueing theory to the Port of Durban Container Terminal
Student Name:	L. W. Schröder
Student number:	10023306
Student Signature:	[signature]
Sponsor Name:	H. W. ITTMANN
Designation:	SENIOR MANAGER: MODELLING AND SIMU
E-mail:	HANS.ITTMANN@TRANSNET.NET
Tel No:	011 - 239 6230
Cell No:	082 451 1691
Fax No:	—
Sponsor Signature:	[signature]

© University of Pretoria

12 Appendix B: Excel Model

12.1 Pier 1 Model

40 TEU containers			TTU specs					3.6036		RTG and QC		
length	12.2		speed	11	km/h	3.0525	m/s			loading/unloading	65	sec
width	2.44											
height	2.6						Yard Specs - TTU					
							Bay length		122			
							Bay width		19.52			
							Spacing vertically		10			
			only for column >=2				spacing horizontally		10			
container location		column	4				quay-stack dist		20			
		row	1									
		bay-row	1									
	y=	59.04										
	x=	797										
	distance for TTU:											
		410.44	sec									
		6.8406	min									
	for a single vehicle				type	number						
	μ1	8	containers/hr		TTU	4						
	μ2	9.22	containers/hr		RTG	3						
	λ	27	containers/hr		QC	1						
	Calculation 1 & 2									**Calculation 3 & 4**		
	β1	0.8438								TTU	8	4
	β2	0.9761								RTG	9.22	4
1	P	0.69								β	0.8677	
	Wq(1)	0.138	8.28	min						P	0.69	
	Wq(1a)	8.28	min							Wq(1c)	0.138	
2	P	0.42								Wq(1c)	8.28	min
	Wq(2)	0.6364	38.182	min						Wq(2c)	0.1414	
	Wq(2a)	2.56	min							Wq(2c)	8.5	min
	Wq(a)	46.462	min							Wq(c)	16.78	min

Figure 12-1: Queueing model - Pier 1

© University of Pretoria

12.2 Rotterdam Model

40 TEU containers			TTU specs					3.6036		RTG and QC		
length	12.2		speed	11	km/h	4.6	m/s			loading/unloading	65	sec
width	2.44											
height	2.6						Yard Specs - TTU					
							Bay length		122			
							Bay width		19.52			
							Spacing vertically		10			
			only for column >=2				spacing horizontally		10			
container location		column	4				quay-stack dist		20			
		row	1									
		bay-row	1									
	y=	59.04										
	x=	797		856.04			401					
	distance for TTU:							402.12				
		316.1	sec									
		5.2683	min									
	for a single vehicle				type	number						
	μ1	11.389	containers/hr		AGV	3						
	μ2	17	containers/hr		ASC	2						
	λ	27	containers/hr		QC	1						
	β1	0.7902										
	β2	0.7941										
1	P	0.69										
	Wq(1c)	0.0963										
	Wq(1c)	5.8	min									
2	P	0.42										
	Wq(2c)	0.06										
	Wq(2c)	3.6	min									
	Wq(c)	9.3766	min									

Figure 12-2: Queueing model - Rotterdam

© University of Pretoria

12.3 Pier 2 Model

Stacking yard specs - SC	
Bay length	122
Bay width	97.13
Spacing vertically	10
spacing horizontally	10
quay-stack dist	20

SC specs				
Unloaded	16	km/h	4.44	m/s
Loaded	12	km/h	3.33	m/s
Inside bay	7	km/h	1.94	m/s
Loading/unloading	30	sec		
entering and exiting	5	sec		

			only for column >=2
container location	column	4	
	row	1	
	bay-row	1	

y=	103.44		
x=			
distance	433.51	sec	
	7.2251	min	
μ	7.55	containers/hour	8.3044
λ	27	containers/hour	
M/M/S/infinite			
S=	4		
β(row)	0.894		
π0	0.014		
P	0.55		
Wq	0.1719		
Lq			
Wq	10.313	min	

Figure 12-3: Queueing model - Pier 2

© University of Pretoria

13 Appendix C: Simio Model

The figures in this appendix are screenshot of the Simio simulation models created for the container terminals.

The figures refer back to Table 4 in section 7. Figure 13-1 depicts scenario 2 and figure 13-2 is the model for scenario 7.

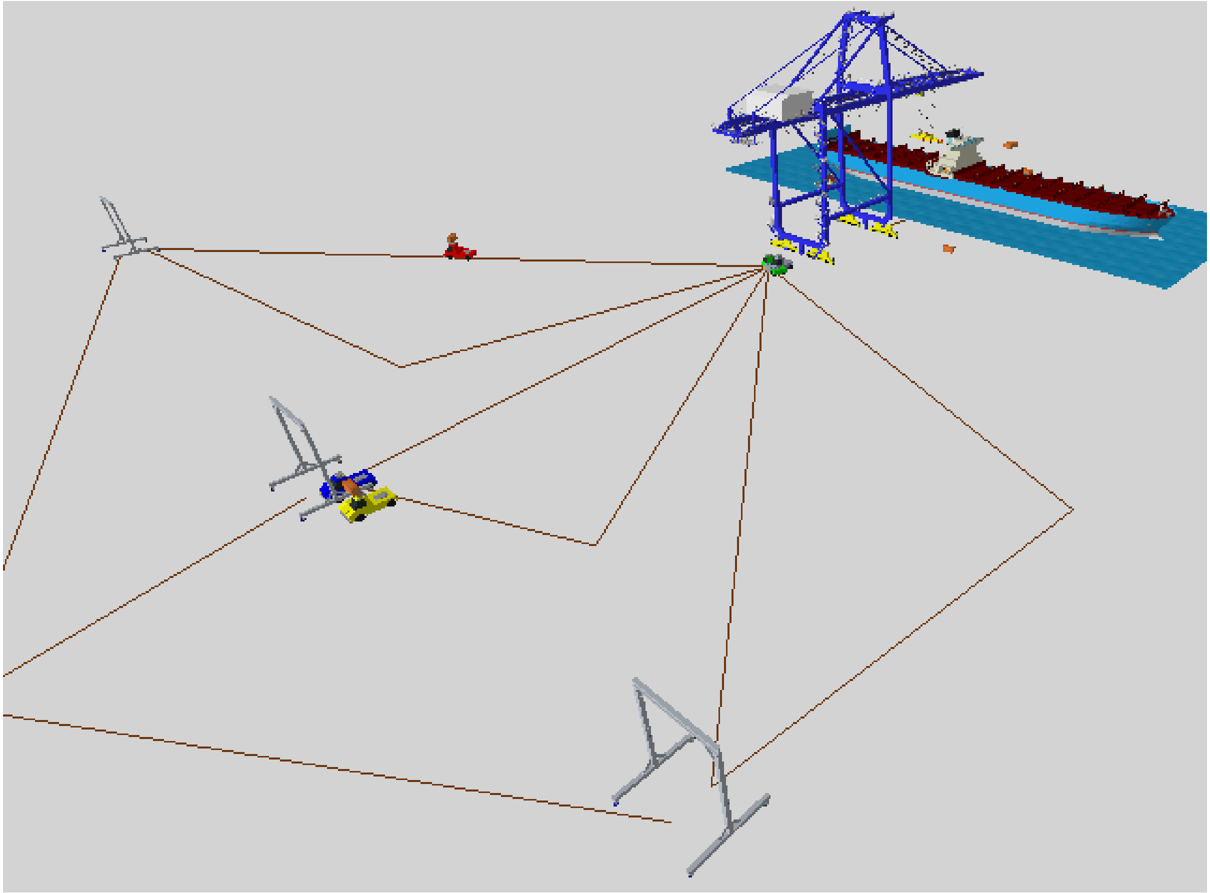

Figure 13-1: Simio Model

© University of Pretoria

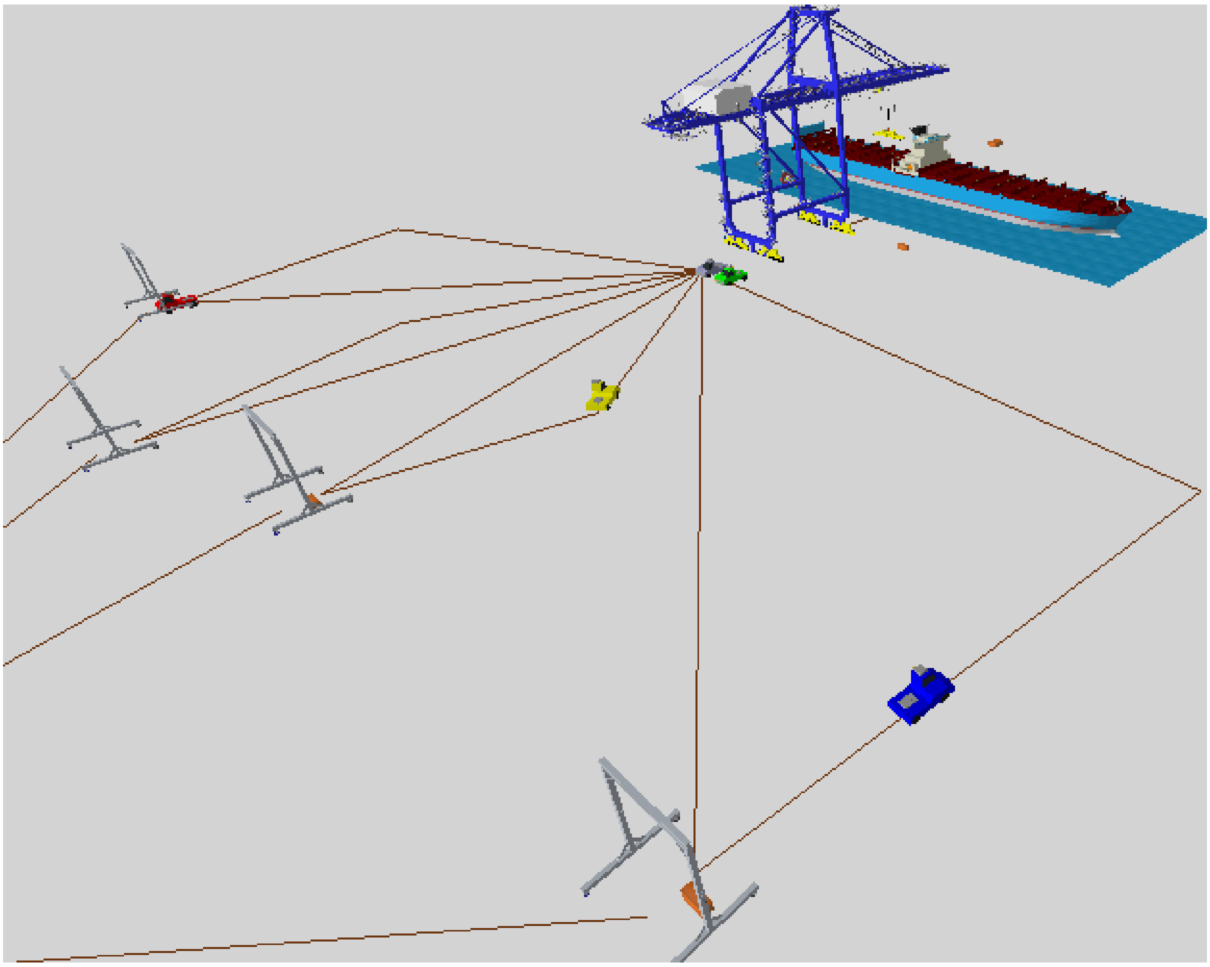

Figure 13-2: Simio Model

Figure 13-3 is the Simio model of Pier 3.

When referring to the CD attached to this report, the Simio models can be obtained. Please note however, that the Simio models on the CD differ from the models which are seen in the figures in this appendix. This difference is due to financial constraints, as the full version of Simio could not be obtained. The Simio models on the CD however still show the thought and logic behind the model.

© University of Pretoria

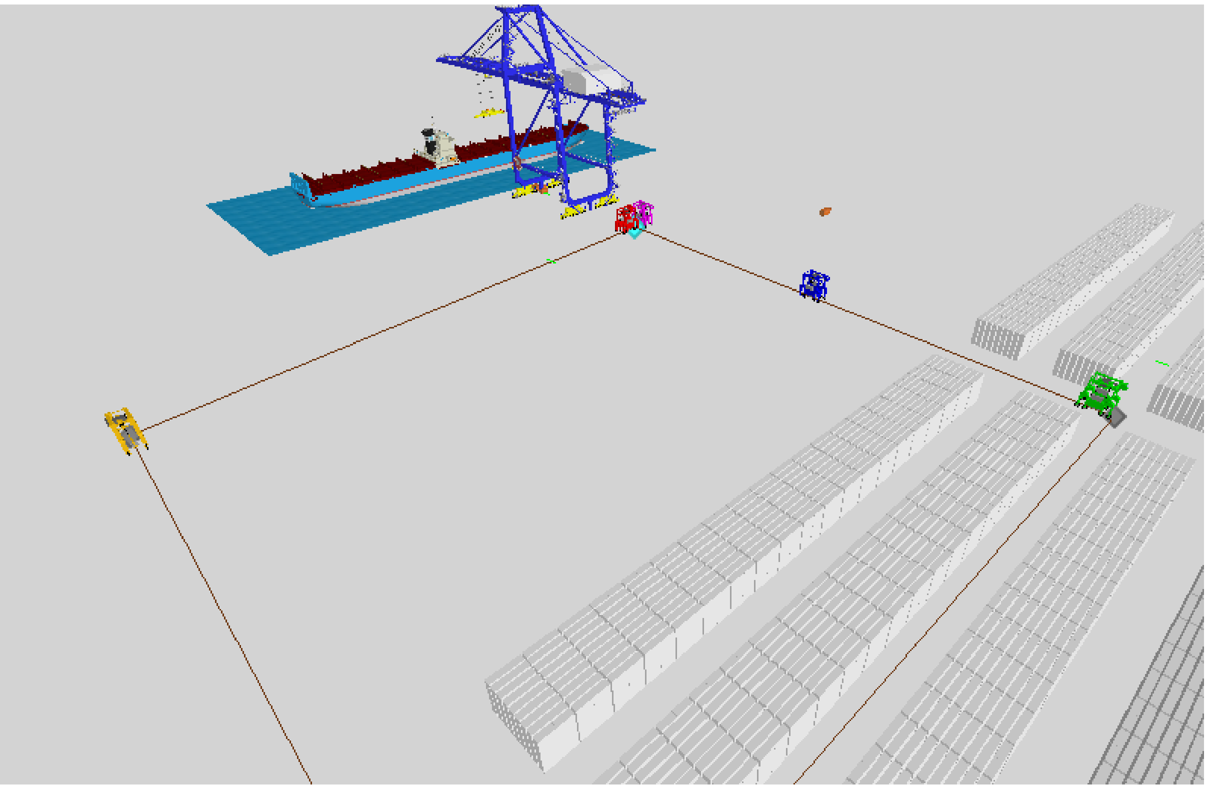

Figure 13-3: Simio Model

© University of Pretoria