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Subject: **The vertical container terminal: stacking strategies and job dispatching**

A Norwegian company designed an alternative yard storage and handling concept. A concept that is new in the container terminal business. In order for investors to have confidence in the productivity of the new concept, they have made clear to the Norwegian company the productivity of the new concept must be proven via simulation.

The problem is that to determine what the performance of the VCT is in means of TEU per hour and storage capacity, it is important that the design of the VCT is worked out in more detail. Due to the differences of the VCT with conventional terminals, allocating containers and job selection for the equipment in the stack in a conventional way is no longer applicable. Your assignment is to develop the strategies for job dispatching and stacking containers in such a way that the performance of the VCT can be measured and compared with other yard types. Questions that need to be answered are:

- What handling productivity (number of boxes going in and out, per hour) can the new yard concept provide (under different circumstances, e.g. varying the number of equipment of specific types)?
- What handling productivities can the different types of equipment achieve in the new yard concept (scissor lifts, elevators, conveyor belts, rail mounted cranes)?
- What quay crane productivities can be achieved when using the new yard concept (in a given layout, provided by the Norwegian company)?

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

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# Summary

The growth of intercontinental container transport can be found in all facets of container terminal handling. Larger vessels and faster quay cranes require more dense container yards and smarter container stacking due to the increase in number containers handled during the loading and unloading of a vessel. The yard of a container terminal is at the center of all these processes. Almost every container passing through the terminal is stored in the yard for some time. The storage capacity of a storage yard is limited due to the allowed stacking height of containers. The stacking height is influenced by wind loads, yard equipment specifications and the performance in terms of container moves. To overcome this problem the Norwegian company Polotec designed storage yard based on warehouses, the Vertical Container Terminal (VCT). Multiple warehouses(stacks) form the storage yard in the VCT. Each stack consists of a mezzanine floor with several storage floor on top of that. Containers are lifted from the ground onto the mezzanine floor and vice versa by two rail mounted trolley cranes (RMT). The container is moved to the center of the stack by roller beds on the mezzanine floor. An elevator moves the containers to the different storage floors. At each storage floor so called scissor lift trolleys (ScL) move the containers to their final storage position. The VCT allows containers to be stacked more than 12 containers high without losing handling capacity of the yard. Due to the conceptual nature of the design, terminals are not eager to invest in such complex designs if the handling capacities have not first been proven. Simulation is a relatively cheap and fast way to get insight in processes and capacities of such a design. In this research the performance of the VCT is analyzed with simulation and compared with an alternative storage yard. In order to evaluate the performance of the VCT in the simulation model, first a stacking and dispatching strategy are proposed. These strategies are important because without stacking and dispatching strategies, the model would not give a realistic representation of the performance of the VCT.

The stacking strategy and dispatching are considered as two separate parts. The developed stacking strategy is based on stacking strategies applied in conventional storage yards in combination with design specific influences of the VCT. From the analysis of stacking strategies in conventional yards the following conclusions are drawn:

- Due to the lack of information on departure times of import containers, import containers are often stored on lower piles. This minimizes the chance on rehandles.
- Export containers are required at a quay cranes in a specific order based on weight, port of discharge and service. Therefore the export containers are grouped together and stored as close to the loading sequence of the vessel as possible.
- To ensure the quay cranes from a constant flow of containers from the yard, clusters of containers from the same group are stored in different stacks. This spreads the workload over the storage yard.

Analysis of the VCT shows that the bottleneck in container handling process in a VCT stack are the two RMTs responsible for lifting containers into the stack an vice versa. The impact of rehandles on the performance of the VCT is lower than on conventional yards, because the equipment responsible for the rehandles has enough spare capacity to perform the rehandles. A stacking strategy is developed for the VCT with the objective to maximize the performance in terms of container moves but not compromising on storage

capacity. Avoiding rehandles is also an objective because rehandles are unproductive moves. The stacking strategy determines the optimal location for a container based on the following parameters:

- The occupancy of the yard equipment.
- The available storage space.
- Dwell times of a container.
- Containers of the same group already in a stack (export containers).
- The floor a slot is located.

For each container arriving at the terminal, a list of available slots is created and scored based on the presented parameters in combination with a weighting factor for each parameter. This is assumed to result in the optimal storage location for a container. Export containers are grouped together based on their specifications and import containers are stored in slots that can be reached at all time without the need for rehandles.

A simulation model of a terminal with the VCT is developed to determine the influences of the proposed stacking and dispatching strategies and to be able to compare the VCT with an alternative storage yard. The experiments for the stacking strategy show that storing containers based on the current occupancy of the yard equipment and the spread of groups of container over the stacks resulted in the highest performance of the VCT. The proposed dispatching strategy focuses on dispatching rules for each type of handling equipment within a stack. Only the dispatching for the ScLs show an influence on the performance in terms of container moves. Changing the number of orders from the quay cranes that the ScL is allowed to work ahead of the current container a quay crane is loading, influences the number of containers at the mezzanine floor. Working further ahead creates a more constant flow of containers to the stack-out RMT, but also results in a longer retrieval time when a container is picked up at the truck gate. The container then has to wait for containers already prepared for moving to the quay.

The resulting performance is compared with an ASC terminal with the same storage capacity and handling capacity. The ASC yard is chosen as an alternative due to the high storage capacity and the fact that it is also an automated storage yard. The comparison shows that the VCT yard area is almost 38 percent smaller than the ASC yard. However, it takes longer to retrieve a container from the VCT than from the ASC yard.

It is concluded that the stacking and dispatching strategies developed in this research make it possible to compare the VCT with other types of yards. The VCT has only been evaluated in one scenario, so it is recommended to further compare the VCT when an scenario for an actual site can be used. The analysis and experiments conducted in this research have shown possible improvements to the design of the VCT to further increase its performance. Most important improvement is adding an additional place to load and unload containers from the stack, to lower the workload on the RMTs.

# Summary (in Dutch)

De groei van het intercontinentaal container transport kan worden terug gezien in alle facetten van container behandeling op container terminals. Grotere schepen en snellere kadekranen vragen om slimmere strategiën, en opslagruimte voor contianers. Het aantal containers dat per schip moet worden (uit)geladen groeit met het groter worden van de schepen. Bijna elke container die arriveert op de terminal moet door de yard. De capaciteit van de yard is echter beperkt door de maximale stapelhoogte van containers. Windbelasting en de eigenschappen van de werktuigen bepalen deze maximale hoogte. Om dit probleem aan te pakken is het Noorse bedrijf Polotec met een oplossing gekomen. De Vertical Container Terminal (VCT) is een yard bestaande uit warenhuizen (blokken) voor containers. De blokken bestaan uit een mezzinino vloer en verschilende opslag verdiepingen daar bovenop. Containers worden door twee kranen (RMT) op de mezzinino geplaatst, waarna ze via rolbanen naar een lift middenin het blok worden gebracht. De lift brengt de containers vervolgens naar een opslag verdieping. Op de opslag verdieping zorgen 'scissor lift trolleys' (ScL) voor het opslaan van de container. Het aantal opslag verdiepingen bepaalt dus hoe hoog de containers kunnen worden gestapeld. Omdat het ontwerp van de VCT nogal afwijkt van conventionele opslag oplossingen, willen potentiële klanten eerst bewijs zijn van de mogelijkeheden van de VCT voordat ze willen investeren. Om deze mogelijkheden te analyseren is simulatie een goede oplossing. Het is goedkoop in vergelijking met het bouwen van testopstellingen en snel om tot een conclusie te komen. Om resultaten te genereren met het simulatie model is het belangrijk om eerst te bepalen waar welke containers opgeslagen moeten worden en hoe de werktuigen in de VCT aangestuurd kunnen worden. De aansturing van de werktuigen in de VCT en de bepaling van een locatie voor een container worden beschouwd als twee individuele onderdelen. Om te bepalen hoe de beste locatie voor een conainer kan worden bepaald, is eerst gekeken hoe dit op reeds bestaande container terminals gebeurt. Uit de analyse is gebleken dat:

- Door het gebrek aan informatie over de vertrektijden van import containers worden deze vaak geplaatst op lagere stapels. Hierdoor hoeft er minder vaak een container worden uitgegraven.
- Export containers worden in een schip geladen in een bepaalde volgorde, gebaseerd op gewicht en waar de container het schip weer verlaat. Deze containers worden in de yard gegroepeerd zodat een groep in een keer uit de yard kan worden gehaald.
- Om er voor te zorgen dat de kadekranen niet zonder containers komen te zitten terwijl ze een schip aan het laden zijn, worden de groepen vaak verspreid over de verschillende opslag blokken in de yard. Hierdoor wordt de werkdruk verspreid over de werktuigen in de yard.

Analyse van de VCT heeft aangetoon dat de kranen verantwoordelijk voor het uitwisselen van de containers tussen een blok en de shuttle carriers op de terminal, de bottleneck van de processen in de VCT zijn. Het uitgraven van containers heeft niet direct een negatieve invloed op de capaciteit van de VCT, omdat deze opdrachten door werktuigen worden gedaan die meer dan voldoende capaciteit beschikbaar hebben. Met als doel om het aantal oprachten per VCT blok te maximaliseren, zonder daarbij in te leveren op opslag capaciteit, is een opslag strategie bedacht. Omdat het verplaatsen van containers binnen de stack extra tijd kost wanneer er een container wordt gevraagd van een blok, is ook dit

een doel van de opslag strategie. Om de optimale locatie voor een container te bepalen wordt voor elk mogelijke positie een score bepaald op basis van de volgende parameters:

- De drukte van de werktuigen in elk blok.
- Het aantal container dat al opgeslagen is op elke vloer.
- De tijd die de container verwacht wordt door te brengen op de terminal.
- De spreiding van export containers uit de zelfde groep.
- De verdieping waar de positie zich bevindt.

Elke van deze parameters wordt vermenigvuldigt met een gewichtsfactor om zo tot de optimale locatie voor een container te komen. De export containers worden gegroepeerd op basis van hun specificaties en import containers worden in locaties opgeslagen welke altijd bereikbaar zijn zonder dat er containers uit de weg moeten worde gehaald. Om te bepalen wat de instellingen moeten worden voor de bepaling van de optimale locatie van containers en de aansturing van de werktuigen in de stack, is er een simulatie model ontwikkeld. Resultaten van de simulatie worden ook gebruikt om de VCT te vergelijken met een alternatief voor container opslag; een geautomatieerde yard met kranen op rails (ASC), omdat dit alternatief een hoge opslag capaciteit heeft en net als de VCT geautomatiseerd is. De resultaten van de experimenten voor de instellingen van de opslag strategie laten zien dat de beste prestaties worden gehaald wanneer de optimale locatie bepaald wordt door de drukte van de werktuigen in de yard en de spreiding van containers van dezelfde groep over de yard.

Per werktuig in een blok is er gekeken naar wat de beste manier is om deze van opdrachten te voorzien. Omdat de locatie voor een container al grotendeels bepaald welke werktuigen de container moeten verplaatsen, zijn er alleen voor lift in een blok, en de ScLs een keuze welke order ze kunnen beginnen. Simulatie laat zien dat alleen de dispatching regels voor de ScL invloed hebben op de prestatie van de VCT. De opdrachten voor de ScL bestaan voornamelijk uit contianers uit de opslag halen zodat deze in een schip kunnen worden geladen. De hoeveelheid laadopdrachten die een ScL vooruit mag werken bepaalt de drukte op de mezzanine floor. Hoe meer containers de ScL vooruit mag werken hoe kleiner de kans dat de RMT zonder containers komt te zitten. Echter, als er te veel vooruit wordt gewerkt, duurt het erg lang om een container uit de stack te halen wanneer deze door een vrachtwagen wordt opgehaald. De container moet dan eerst wachten tot alle containers voor hem naar de kade zijn. Op basis van de uiteindelijke prestaties van de VCT wordt een ASC terminal ontworpen voor dezelfde capaciteit. De vergelijking tussen de VCT en de ASC yard laat zien dat de VCT veel minder ruimte nodig heeft voor opslag terwijl de prestaties hetzelfde zijn als bij de ASC yard. Het duurt echter wel langer vanaf het moment dat een container wordt gevraagd van de stack totdat deze daadwerkelijk uit de stack is. Dit is van invloed op de wachttijden bij de landzijde van de terminal.

Er wordt geconcludeerd dat de ontworpen opslag en opdacht uitdeel strategieën het mogelijk maken om de VCT te vergelijken met andere opslag alternatieven. De VCT is in dit onderzoek getest onder een specifiek scenario. Als aanbeveling wordt dan ook gegeven om de VCT opnieuw te analyseren wanneer er een echte toepassing voor de VCT is bedacht. Uit de analyse en experimenten in dit ondezoek is gebleken dat er nog meer capaciteit uit de VCT te halen is met enkele aanpassingen aan het ontwerp. De voornaamste aanpassing is het toevoegen van een extra (uit)laad-punt vanuit een blok om zo de werkdruk op de RMTs te verlagen.

## List of abbreviations

**AGV** Automated Guided Vehicle
**ALV** Automated Lifting Vehicle
**ASC** Automated Stacking Crane
**ISO** International Organization for Standardization
**LS** Land Side
**POD** Port of Discharge
**QC** Quay Crane
**RMG** Rail-mounted Gantry
**RMT** Rail-mounted Trolley
**RTG** Rubber-tired Gantry
**SC** Straddle Carrier
**ScL** Scissor Lift trolley
**ShC** Shuttle Carrier
**TEU** Twenty-foot Equivalent Unit
**TOS** Terminal Operating System
**TP** Transfer Point
**VCT** Vertical Container Terminal
**WS** Water Side

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# Chapter 1

# Introduction

The origin of the standard steel shipping container dates from the 1950's. The handling of vessels was becoming a major part of the total cost for transporting freight. Levinson (2006, p. 33) claimed that the cost of cargo transport over sea for one specific case consisted for 37 percent of handling costs. This included not only the labor costs, but also the costs for theft, damage and the time lost in the process. To overcome these problems a solution was presented by Malcolm McLean in 1956. He developed, together with Keith Tantlinger, the first of the modern intermodal container. It was a thick steel box of 2.5 m by 2.5 m by 3.0 m. The container was already equipped with the corner fittings required to secure and lift the container using twist locks. In the following 20 years many different containers systems were used, varying in size as well as the position of the corner fittings. This made it difficult to use the containers on a global scale. With the standards on containers published in 1968 till 1970 by the International Organization for Standardization (ISO) the size and position of the corner fittings were globally standardized.

## 1.1 Containerized transport today

Today the standard container sizes varies from a 20-ft (6.1 m) to a 53-ft (16.2 m) container. To express the container capacity the term 'twenty-foot equivalent units' (TEU) is used. This means that for example a 40-ft container with a length of 40 feet is the same as two TEU. Containers are transported using different modalities such as ship, train and truck. Container terminals are the connection between these different modalities. Figure 1.1 shows a representation of a container terminal. The container arrives by deep sea ship, is unloaded by the quay crane and transported to the storage yard. When the container is then requested for further transport to the hinterland, it is transported from the storage yard to the train or truck gate. It is also possible that the unloaded containers are directly transported to a different ship, skipping the storage yard.

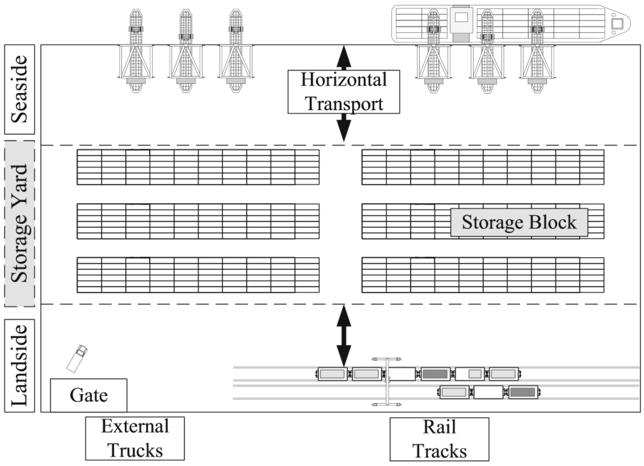



**Figure 1.1: Transport and handling process of a container (Wiese et al., 2011, p. 220).**

The storage yard is the buffer between the water side (WS) and the land side (LS). The storage yard consists of stacks, which are divided in bays, rows and tiers (Figure 1.2). The number of bays, rows and tiers in one stack depends on the handling equipment used. The most common yard handling equipment is the Rubber-tired Gantry (RTG) crane (Figure 1.3a). Wiese et al. (2009) studied 114 container terminals and concluded that 63 percent of the terminals use RTG cranes.

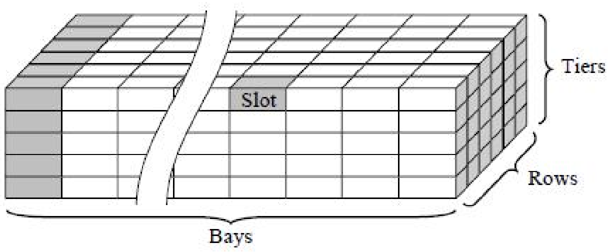



**Figure 1.2: Bays, rows and tiers (Zhen et al., 2013, p. 290).**

The Straddle Carrier (SC), shown in Figure 1.3b, is used in 20 percent of the terminals. The stacks of a storage yard with SCs have a lower density than the stacks with RMTs, because the stacking cannot be higher than three containers. Also extra space is needed in the yard next to each container for the wheels of the SCs.

**(a) Rubber-Tired Gantry crane** **(b) Straddle Carrier**

**Figure 1.3: Container handling equipment. (source: TBA)**

In automated terminals the decision on where the store a container (grounding) and what equipment to dispatch is controlled by the terminal operating system (TOS). The TOS is the primary system for control, planning and monitoring at the terminal. Figure 1.4 shows how the TOS is connected to the processes on the terminal. For example the control of a ShC is presented. An order to store a container arrives at the terminal when for instance a truck arrives at the truck gate, delivering a container. The terminal planning requests a location for the container in the storage yard from the grounding manager. The determination of the location for a container can be done manually or automatic based on a stacking strategy. The stacking strategy describes how the decision on where to store a container is made. The decision on where to store a container in the yard is influenced by many factors, such as specifications of the container (weight, size), destination, handling equipment and yard layout. When the location for a container is determined the origin and destination of a container on the terminal is known and used to dispatch equipment to perform the order. In some cases an extra equipment manager is used to determine for instance a route for the equipment and make sure no collisions occur.

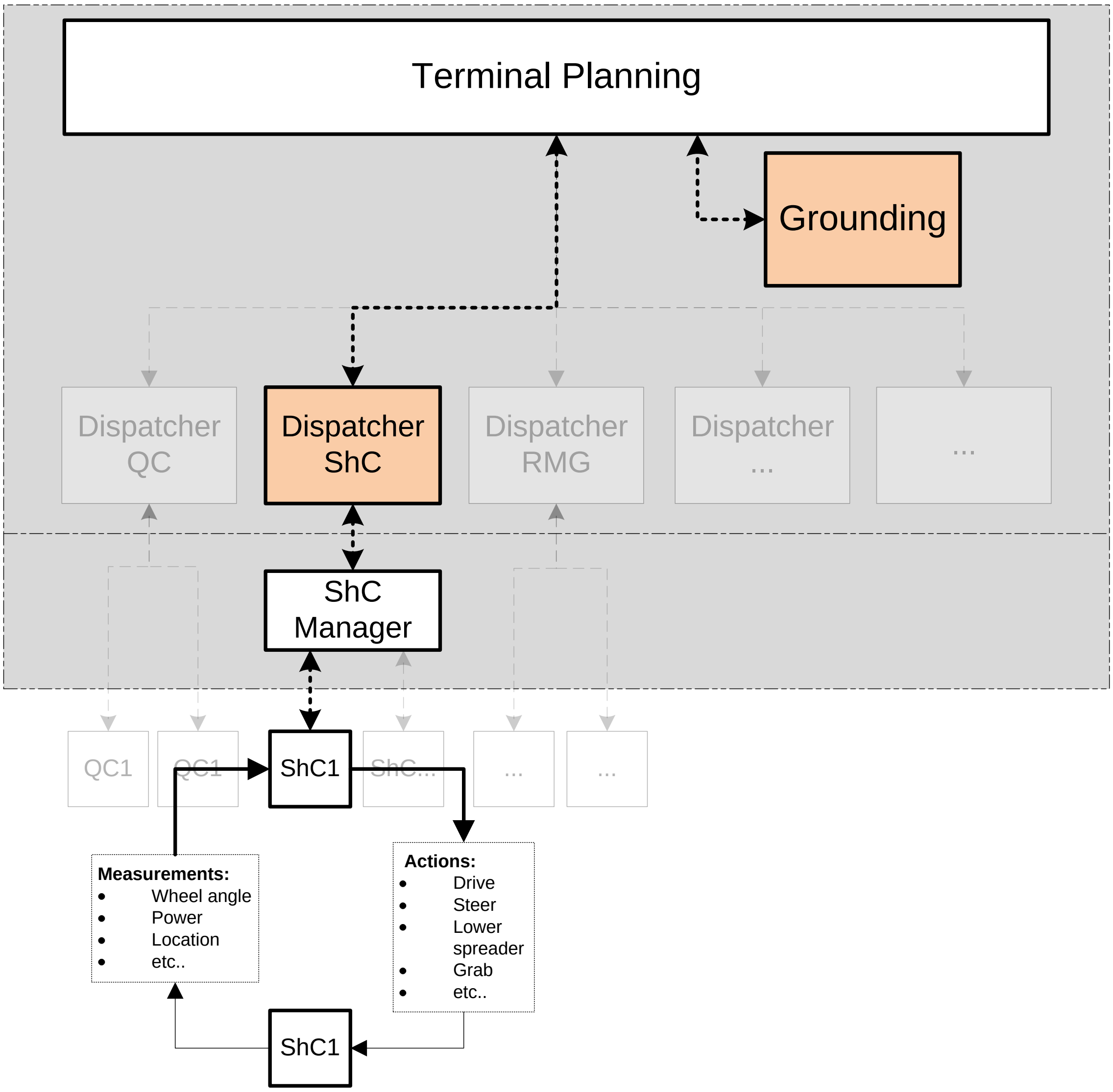



**Figure 1.4: Control of a shuttle carrier by the TOS.**

## 1.2 Trends in containerized transport

In the past decades the demand for containerized transport has increased, as can be seen in Figure 1.5. According to the United Nations Conference on Trade and Development (2013) the increase in demand is for a large part due to the growing demand in developing countries and Asia.

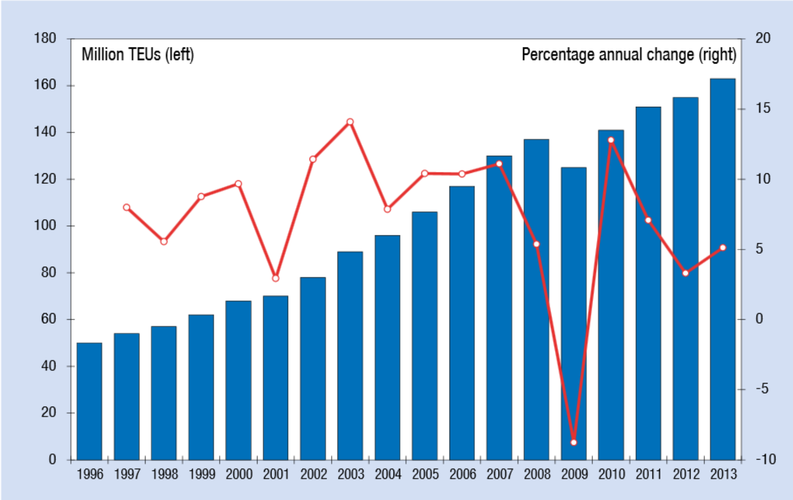



**Figure 1.5: Global container trade, 1996-2013 (UNCTAD 2013, p. 23).**

The trend of increasing containerization can also be seen in the size of the container ships over the years. Table 1.1 shows the development of container ships from the early start of containerized transport until now. Rijsenbrij (2008) presents some of the impacts of the increasing ship sizes and growth in containerization. Besides the larger equipment needed to deal with the dimensions of the ship, larger ships will also influence the call size (container moves per ship). This increases the number of containers to be handled when a ship arrives, requiring faster or more handling equipment and a larger capacity in the storage yard.

**Table 1.1 Size of container ships (Rodrigue et al., 2013).**

| Ship type | Year of introduction | Capacity in TEU |
|---|---|---|
| Early containerships | 1956 | 500-800 TEU |
| Fully Cellular | 1970 | 1.000-2.500 TEU |
| Panamax | 1980 | 3.000-3.400 TEU |
| Panamax Max | 1985 | 3.400-4.500 TEU |
| Post Panamax | 1988 | 4.000-5.000 TEU |
| Post Panamax Plus | 2000 | 6.000-8.000 TEU |
| New Panamax | 2014 | 12.500 TEU |
| Post New Panamax | 2006 | 15.000 TEU |
| Triple E | 2013 | 18.000 TEU |

## 1.3 The Vertical Container Terminal

The requirements of the storage yards of the future are to increase both handling speed of containers and the capacity of the stack. Because the height of the conventional stacks is limited due to the maximum weight that carried by the bottom container of the stack, wind conditions and equipment limitations, new ways of stacking are needed. A Norwegian company called Polotec came up with a concept for a new type of storage yard in which the containers are no longer stacked upon each other, but attached to a steel frame, allowing for higher stacking. The concept can best be compared with warehouses. It is called the 'the vertical container terminal' (VCT) and an impression of a single stack is presented in Figure 1.6.

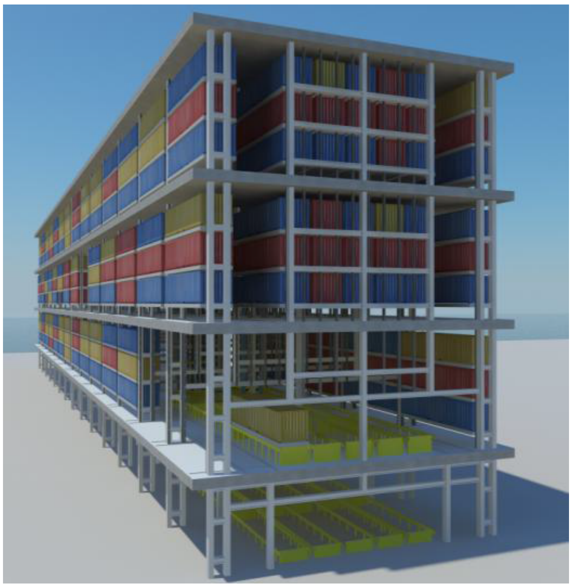


**Figure 1.6: Impression of the warehouse design. (source: Polotec)**

A VCT stack consists of a ground floor where containers are dropped off by shuttle carriers (ShC), a mezzanine floor, and several storage floors. The mezzanine floor moves containers from the front of the stack to the middle, where the elevator to reach the storage floors is located. A storage floor in a VCT stack consist of seven rows of containers and two aisles for the so called Scissor Lifts (ScL) to move through (Figure 1.6). Every container is the stack is placed upon a super skid. A super skid is a steel frame with retractable pins to lock it to the structure of the stack. There are two ways to store a container on a storage floor. In the slots between the two aisles the containers are stored like a normal RMT stack, but upside down. This means that the top middle container is the last container to remove from a bay. In the slots at the outside of the aisles, the containers are loaded sideways into their slot by using roller beds, meaning that every slot in those rows can be reached at all time. The movement of a container trough the VCT stack is represented in Figure 1.7. The different types of equipment that are responsible for the movement of the containers are:

1. A rail mounted trolley (RMT) crane to pick up containers from the ground and to place them on a skid within the structure on a mezzanine floor.
2. Roller beds to move the containers along the mezzanine floor to the middle of the structure.
3. A cargo elevator for lifting the containers to and from the storage floors.
4. ScLs to pick up the container at the cargo elevator and move the container to the designated slot in the stack.

A more detailed description of the VCT stack is presented in Chapter 3.

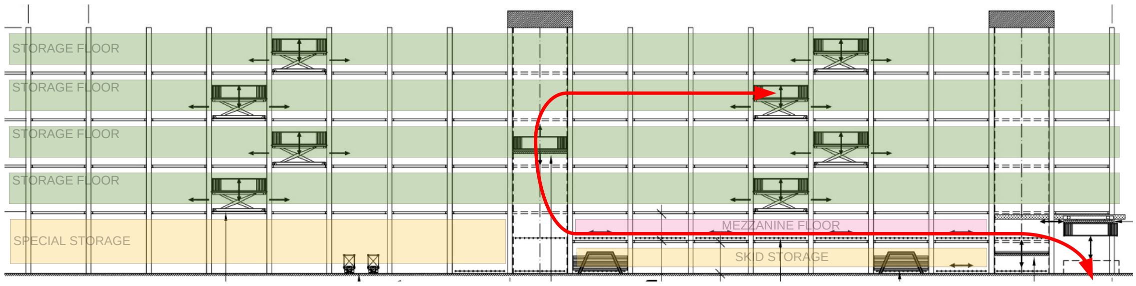



**Figure 1.7: Cross section of a VCT stack.**

## 1.4 Problem Statement

For terminals to invest in such different design for storage yards, it is necessary to prove that the design is worth the investments. Therefore the performance of the VCT in terms of handling and storage capacity needs to be compared to other types of storage yards (e.g. RMT yards, RMG yards). The handling capacity determines the number of containers the stack is able to handle per unit of time. A higher handling capacity means that containers can be delivered to and retrieved from the quay faster , resulting in shorter handling times for vessels (Brinkmann, 2011).

Determining the performance of the VCT in a realistic terminal environment without having to build the actual VCT can be done with simulation. In Robinson (2004) simulation is compared to other modeling approaches such as mathematical programming and heuristic methods. The main advantages of using simulations are:

- *Modeling variability*: Simulation models are able to model variability and the effects. This is either impossible or very complex when using other modeling approaches.
- *Transparency*: Simulation models of complex systems can still represent the processes in a structured manner using animation, increasing the understanding of and confidence in the model.

The performance of a yard does not depend solely on the design of the yard, but also on how the yard is used. For example for RMT yards many studies have been conducted on improving the performance by improving the dispatching of the RMTs or determining the optimal stacking height in the yard. Such studies have not yet been performed for the VCT. Details of the VCT that need to be worked out before the VCTs performance can be compared with other conventional yards are:

- The structure of the VCT stack has a capacity of several normal stacks on top of each other due to the use of different modules. This will have a positive influence on the capacity of the yard in terms of amount of containers stored per ha. The capacity of the stack also depends on the performance in terms of container moves (containers going into and out of the stack). The assumption of the designers is that the equipment within the VCT stack is able to do 60 container moves per hour. This number is only based on the characteristics of the equipment. To determine the capacity in actual operations by taking into account the dynamic nature of terminal operations, strategies for the job dispatching need to be developed.

- The mezzanine floor ensures part of the flexibility in VCT stack. As can be seen from the arrows in Figure 1.8 a container can move in almost every direction trough the mezzanine floor. This generates a large amount of options, for instance on how to use the temporary storage in the middle of the mezzanine floor. To determine the optimal capacity of the VCT stack, the strategy on how to use the mezzanine floor needs to be determined.

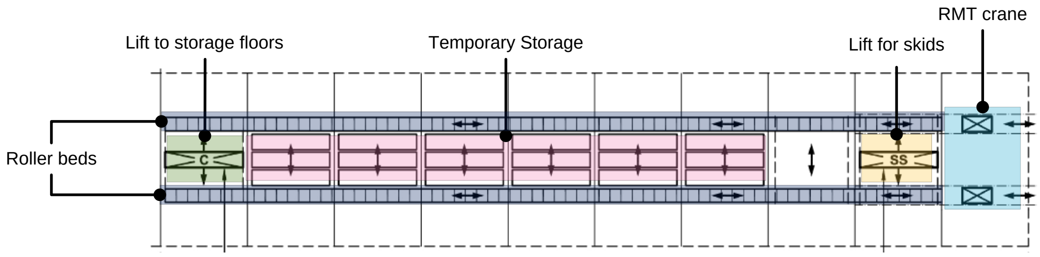



**Figure 1.8: Overview of the mezzanine floor of a VCT stack.**

- As explained in Section 1.3 there are different types of storage slots within the VCT stack. These different types of slots are not comparable with the current stacks on container terminals, leaving the question open on how to use these slots.

- Different problems arise when looking into the layout of the terminal. To be able to reach a high amount of container moves with the stacks it is also important that the terminal equipment is able to keep up with the performance of the stacks. The layout of the terminal plays a big role in this performance. Driving times of equipment as well as space for the maneuvering and possible buffer areas are important factors.

In summary: the problem is that to determine what the performance of the VCT in terms of containers moves per hour and storage capacity, it is important that the design of the VCT is worked out in more detail. Due to the differences of the VCT with conventional terminals, the strategies for dispatching jobs and storing containers need to be designed to fit the specifications of the VCT.

## 1.5 Research Objective

The objective of this research is to develop the strategies for stacking and dispatching in the VCT which can be used in simulation in order to evaluate the performance of the VCT and compare the VCT with alternative storage yards.

## 1.6 Research Question

To meet the objective of this research, the following research question needs to be answered in this research:

*What dispatching and stacking strategies can be used in the VCT to be able to compare the performance of the VCT stacks with other storage yards?* To answer this research question, several sub-questions need to be addressed. The first sub-questions are defined to determine what stacking strategies can be used in the VCT stacks:

- *What are the different stacking strategies used in container terminals?*
- *What are criteria for determining the stacking strategy in container terminals?*

To determine how the dispatching strategy for the equipment in the VCT stacks can be developed, the following sub-questions are defined:

- *What are existing dispatching strategies when using automated equipment?*
- *What criteria need to be considered when developing the dispatching strategy for the VCT stack?*

The final sub-question that needs to be answered is:

- *What are the influences of the combination VCT design and terminal operations on the stacking and dispatching strategies?*

## 1.7 Research Scope

As mentioned in the objective, this research focuses specifically on the storage yard. Therefore the terminal layout and routing of the container handling equipment is not researched in detail.

The ground floor of every VCT stack is dedicated to the storage and delivery of the super skids. The skids are lifted on to the mezzanine floor by a small lift. After the skid is moved sidewards onto the correct position, a container can be placed on it by the RMT. The super skids are vital to the working of a VCT stack, due to the fact that every container needs a skid before it can be stored. The super skid process is not part of this research because when this research was conducted no details on the working of the super skid process were available.

In the design of the VCT, the ScLs are able to move underneath the containers and use the cargo lift as well, which means they can move to every position in the stack. The ScL can also move from one stack to the other to serve a different stack if required. These movements generate a complex routing problem, which is outside the scope of this research. Every VCT stack storage floor is equipped with two ScLs which both serve half of that floor.

A layout for a container terminal using the VCT stacks is defined by Polotec. The layout consists of multiple VCT stacks parallel to the quay. The combination of multiple VCT stacks is taken into account. This resembles the situation in actual operations, making it possible to divide the workload over the different stacks. Figure 1.9 shows the layout of the VCT. The layout also shows the truck gate, but no train station. Container transport by train is not considered in this research.

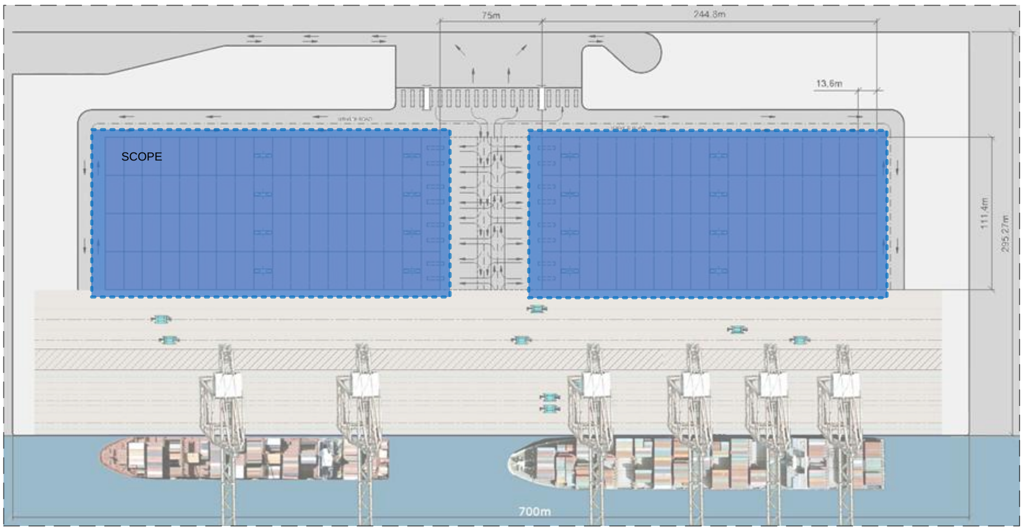



**Figure 1.9: Terminal design with VCT stack and the scope of the research.**

## 1.8 Research Approach

After evaluating the different stacking strategies and dispatching at conventional container terminal the design of the VCT is further analyzed. Based on the literature study and the analysis of the VCT, stacking and dispatching strategies for the VCT are proposed. The dispatching and stacking strategies are considered as two separate steps in the process. First a storage location for a container is determined, followed by the dispatching of the handling equipment. The strategies are evaluated in a simulation model to determine what strategy performs the best in terms of container moves per hour. The developed simulation model is validated and verified before it is used to evaluate the stacking and dispatching strategies. The results of the experiments are used to evaluate optimal performance of the VCT. The results are used to compare the VCT with an alternative type of storage yard. For the comparison an automated storage yard with automated stacking cranes (ASC) is used. A yard with ASCs is like the VCT fully automated and capable of storing a relative high amount of containers per area compared to other conventional storage yards. To make the comparison, an ASC terminal is developed based on assumptions. The developed ASC terminal is evaluated for the same scenario as the VCT. The results of the ASC model are used to compare the ASC terminal with the VCT. A complete overview of the steps in this research process is presented in Figure 1.10.

## 1.9 Structure of the report

Chapter 2 gives an overview of literature on stacking and dispatching strategies and describes the storage processes in conventional storage yards. In Chapter 3 the VCT is explained and analyzed in more detail. In Chapter 4 the literature and design of the VCT are combined to develop dispatching and stacking strategies for the VCT. In Chapter 5 a simulation model is introduced to evaluate the developed strategies and the scenario in which the VCT is evaluated is presented. The chapter also describes the validation and verification of the model. In Chapter 6 different experiments for evaluating the stacking and dispatching strategies are presented and the results of the test discussed. The VCT is compared with an ASC yard in Chapter 7. In the final chapter, Chapter 8, conclusions are drawn and recommendations for further research are done.

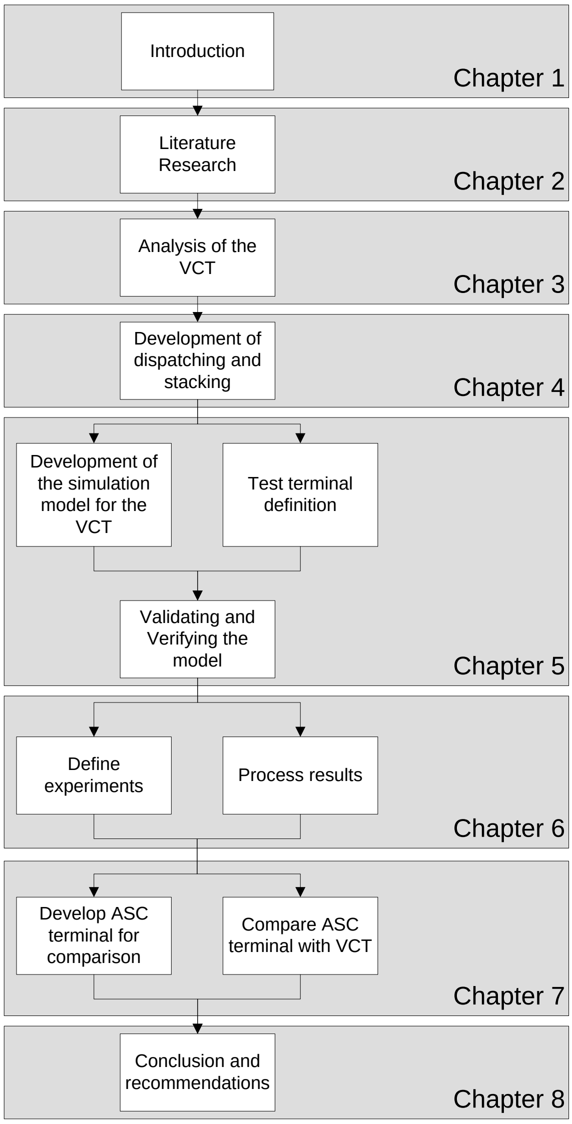



**Figure 1.10: Approach of the research.**

## 1.10 Research Contribution

The design of a stacking strategy and a dispatching strategy in this research will contribute to the understanding of the not yet existing VCT. The research will lead to a simulation model that gives a clear representation of the VCT in actual operation. The model makes it possible to evaluate the VCT's performance. The design of the VCT is unique in comparison with other conventional storage yards, and therefore this research is different from any other research performed on storage yards so far.

# Chapter 2

# Literature review

In this section an overview of storage operations in different types of yards is presented as well as literature on stacking strategies and job dispatching. For literature on storage yard operations in general there can be referred to Carlo et al. (2014). The paper gives an overview of literature on storage yard operations published between 2004 and 2012. The papers are classified based on:

- decision problems: Are the discussed decisions based on for example storage space capacity, dispatching, reshuffling or layout.
- yard layout: what are the layout assumptions in the paper?
- handling equipment: what handling equipment is considered?
- temporal attributes: are the times assumed deterministic or stochastic and is the planning horizon dynamic?
- uncertainty environment: is stochastic optimization used?
- performance measure (to minimize): is the objective function based on e.g. due times, utilization of equipment or storage space?

Carlo et al. (2014) concludes with identifying the gabs in research on yard operations and recommends these as new research avenues.

## 2.1 Review storage yards

### 2.1.1 General container storage

In general the containers on a terminal can be divided in three types based on their origin and destination; import, export and transshipment containers. Of these three types of containers the load can vary. A distinction is made between regular containers, empty containers, refrigerated containers and containers with a special load. Containers of the latter two types are stored at a specific place in the yard.

The containers are stacked upon each other, resulting in rehandles when the bottom container of a pile is needed for handling before the container on top. A major factor in the reshuffling of containers is the lack of data available on the container when it arrives at the terminal. Steenken et al. (2004) state that from only 30-40 percent of the export containers at European terminals, this data is available. For import containers this number is even worse: 10-15 percent. Import containers arrive at the terminal per vessel, which communicates the containers it is going to deliver in a load plan 12 hours in advance of the vessel arrival. Only then the exact containers the vessel is delivering will not change anymore. Export containers arrive at the terminal by truck randomly a few days in advance of the vessel for which the container is destined. The containers are picked up from a terminal at a regular basis, so an estimation can be made on which containers will be picked up by the vessel. The estimated arrival date of a vessel is pre-determined in a so called pro-forma vessel schedule. The pro-forma schedule container the expected arrival date of a vessel. The specific containers the vessel is going to load are unsure until the load plan is determined. Transshipment containers going from one vessel to the next via the terminal have the most complete information. The exact containers delivered and picked-up by a vessel are communicated in the load plan. Table 2.1 gives a summary of the availability of information on arrival and departure times of the different types of containers.

**Table 2.1 Information of arrival and departure times of a container per type of container.**

| Container type | Arrival time of container known in advance [days] | Departure time of container known in advance [days] |
|---|---|---|
| Import container | 0.5 | 0 |
| Export container | 0 | at arrival of the container |
| Transshipment container | 0.5 | at arrival of the container |

When loading a vessel a specific sequence for the containers arriving at the vessel is required (Vis, 2009). The sequence is determined by a load planner with the objective to minimizing the workload on the yard equipment and ensuring the vessels stability (Kim et al., 2000). The heavier containers are placed lower in the vessel and containers for the same POD are grouped together in the vessel. The heavier containers for a bay are often loaded into the ship first to achieve stability of the vessel. Figure 2.1 an example of the loading plan of a single bay in a vessel. This sequence is determined per quay crane working on the vessel. To overcome unnecessary travel for the quay crane (QC), the QC finishes work on a bay in the vessel first before moving on to the next.

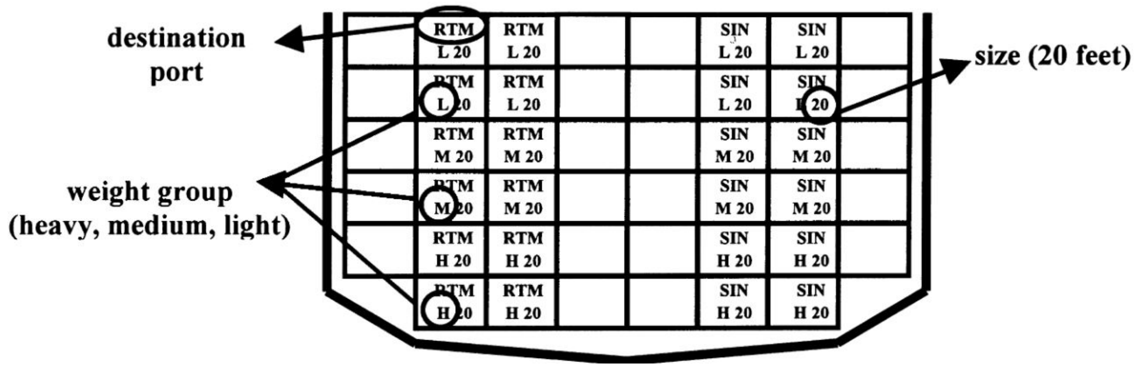



**Figure 2.1: Example of the loading plan of a single bay in a vessel (Kim et al., 2000).**

The storage yards are not all the same. Different handling equipment is used per terminal to store the containers in the yard. Wiese et al. (2009) found that the three most commonly used types storage yards are:

- RMG yard.
- RTG yard.
- Straddle carrier yard.

A representation of the storage in the different types of yards is given in Figure 2.2. In the next sections these different types of storage yards will be described in more detail.

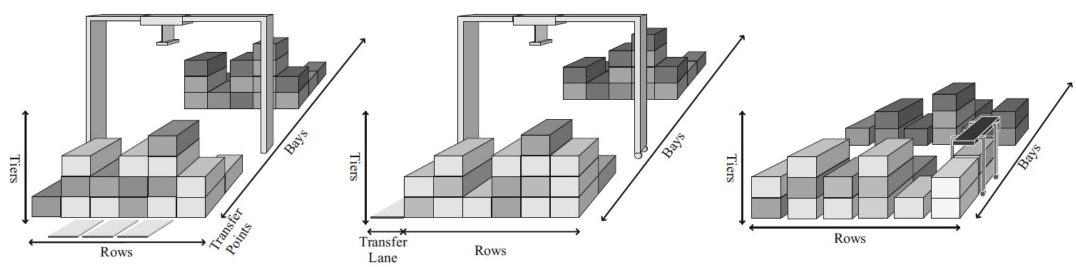



**Figure 2.2: Examples of (from left to right) a RMG stack, a RTG stack and a straddle carrier yard (Wiese et al., 2011).**

### 2.1.2 RTG yard

As mentioned in the introduction in Chapter 1 the RTG is the most commonly used type of yard equipment and is specifically popular on large terminals in Asia (Wiese et al., 2009). A RTG crane is a manually controlled crane, moving on rubber tires. As can be seen from Figure 2.2 the containers are interchanged between the horizontal equipment and the RTGs at the side of each stack. To minimize the travel time of the horizontal equipment between the yard, the LS and WS, the RTG stacks are often orientated parallel to the quay. Multiple RTG cranes are allowed to work on the same stack, depending on the distribution of the workload over the stacks.

According Petering (2013) two different stacking strategies are applied in a RTG yard; re-marshalling and sort and store. With re-marshalling the containers are placed in the yard and moved within the yard when necessary. With sort and store the export containers are grouped together based in five attributes (e.i. container length, height, weight class, service and POD). Grouping the containers based on these attributes complies with the vessel loading plan and thus minimizes the chance on needing to dig out containers from the lower tiers. The piles of the groups are stored in the same bay to avoid additional RTG crane traveling during vessel loading operations. Because of the lack of data on the departure time of import containers, the import containers should not be stacked to high (Dekker et al., 2007). Lower stacks decrease the chance on rehandles.

### 2.1.3 RMG yard

RMG cranes drive on rails instead of tires. In most cases the RMG cranes are fully automated and referred to as automated stacking cranes (ASC). As can be seen from Figure 2.2 the interaction of the RMG with the horizontal takes place at both ends of the stack. Therefore the RMG stacks are in most cases perpendicular to the quay. The landside the yard is often directly connected with the truck gate, making it possible for trucks to deliver and retrieve containers directly from and to the stack. The RMG stacks are in most cases handled with one or two yard cranes, depending on the length of the stack.

For the RMG the containers of the same group are also stored on the same piles, but because the RMG crane travels between the transfer points (TP) and the stack anyway, storing the containers of the same group in the same bay offers no advantage (Park et al., 2011). Since only one RMG crane per stack can serve the TP at the waterside, spreading the workload over the stacks when loading a vessel becomes important (Saanen and Dekker, 2011).

### 2.1.4 Straddle carrier yard

A storage yard with SCs is a low density yard due to the limited stacking height of a SC (maximum 4 containers high) and the space required between the containers for the wheels of the SCs. The SCs are responsible for both the transport and storage of the containers. An example of a straddle carrier yard is the Gioia Tauro Maritime Terminal in Italy. This container terminal serves mainly a transshipment terminal, so most containers arrive and leave per vessel. In this terminal containers are grouped in the yard per service. The containers with a longer dwell time (time a containers spends in the yard) are placed furthest away from the quay to minimize the amount of moves further from the quay and therefor the average handling time of a container (Cordeau et al., 2007).

## 2.2 Literature on stacking strategies

### 2.2.1 Overview

Steenken et al. (2004) describe different stacking strategies used by terminal operators. They distinguish three different types of stacking strategies. With *pre-stowing* the export containers are placed close to the loading place in the stack when the stowage plan for a vessel is available. Because the process of relocating containers is cost extensive due to the extra moves that need to be made, this strategy is only applied when a ship needs to be loaded very fast. With *reservation stacking* the location of the container in the yard is determined ahead of the arrival of the ship, depending on the expected number of import and export containers. The positions for the containers are reserved, so extra stack capacity is occupied. The final strategy is *scattered stacking*. In scattered stacking the different stacks are dedicated to a berthing place. When a ship arrives, the terminal operator selects a position from the stacks assigned to the berthing place of the ship. This strategy results in a higher utilization of the yard since no positions are reserved.

Pre-stowing the containers to minimize travel time of the horizontal equipment is the subject of much research. Chen and Lu (2012) decompose the problem for export containers in two stages. In the first stage, the optimal bays are reserved for containers destined to the same vessel, with the objectives to minimize the driving time between the stack and the berth of the ship and distribute the workload over the yard equipment. In the second stage the containers are allocated to an optimal position in a reserved bay, based on the weight of the container, to avoid rehandles. Zhang et al. (2003) research the problem of finding the best stack to allocate the container. The problem is divided in two mathematical programming models. The first model determines the capacity of the different stacks to balance the workload of the stacks over the time period of a planning horizon. The second decision allocates the container to a stack, given the location of the vessel, with the objective to minimize the travel time of the horizontal transport equipment. Bazzazi et al. (2009) follow up on the first model of that research by extending the problem with the handling of different type of container such as empty and refrigerated containers. A genetic algorithm is used to solve the problem and compared with a branch and bound method. The results from the genetic algorithm showed fast calculation times and a relative gab of 5 percent with the optimum objective function value.

Woo and Kim (2011) research the optimal size of a reservation for the reservation stacking strategy. It is found that the proposed square root arrival rate rule performance the best. The rule determines the size of the reservation based on the square root of the arrival rate of containers of the same group.

In literature on container stacking or allocation, often a distinction is made between online and offline stacking strategies. In the offline stacking strategies, a decision for the optimal location for the container is made before the process of moving the container is actually moved to its destination. In online stacking strategies, the destination of the container is determined along the way of the moving process. This divides the problem in smaller problems with less data, improving the calculation time. It is possible that the solution in the online method does not result in an optimal solution for the total problem. In an offline stacking strategy all data is available at the beginning of the process, making it possible to reach an optimal decision, but increasing the complexity and duration of the calculation of the problem. Kemme (2011) states that the processes in container stacking should be regarded as an online problems, since information on the exact arrival time of a container or the sequence of arrival varies a lot during the handling of the container due to disturbances in the process. An example of an online stacking strategy is presented by Park et al. (2011). They propose an online hierarchical approach consisting of two steps, but for incoming containers only. The first step balances the workload for determining the appropriate stack, while the second step determines the optimal pile based on the efficiency of the storing and retrieving processes of the stacking crane and the storage space usage. They conclude that their online method performs better than the offline methods because of lower computation times and higher flexibility. Van Asperen et al. (2010) evaluate online stacking strategies for an highly automated import terminal by a simulation model. Since only import containers are considered they assume a high uncertainty of the departure time of a container. They conclude that stacking strategies taking into account the workload of the yard cranes outperform those that do not.

## 2.3 Literature on job dispatching

Job dispatching problems are not specific for container terminals. In many logistic systems problems of this nature arise, e.g. manufacturing processes (job-shop problem) and transit operations (vehicle dispatching problems). The literature on dispatching problems in this section is focused on dispatching at container terminals in specific, due to the comparable nature of those problems with the problems in this research.

### 2.3.1 Dispatching of horizontal transport equipment

Literature on dispatching on container terminals mainly focuses on a single type of equipment. Bish et al. (2005) considers the dispatching of the vehicles unloading and loading a vessel. The heuristic algorithm developed in this research aims at minimizing the time it takes to serve the vessel. Many other papers focus on the dispatching of automated guided vehicles (AGV), e.g. Grunow et al. (2004), Cheng et al. (2005), de Koster et al. (2004). Vis (2006) gives a complete overview of papers on dispatching of AGVs. The author concludes that the complex dispatching approaches hardly outperform the simple earlier heuristics. Low computation times for large systems, planning horizons and the interference with other equipment are suggested as avenues for further research.

More recently Nguyen and Kim (2009) presented a study on the dispatching of automated lifting vehicles (ALV) to maximize the efficiency of the Quay Cranes (QC). A mixed-integer programming model is used for optimizing the tasks. The size of the buffers in the process is taken into account and heuristics are used to overcome the large computational time. The results of the heuristics are compared with the optimal results and show that the average of the objective value is a factor of 1.01 higher than the optimum. As further research it is suggested that the performance of the algorithm should be studied in a dynamic environment.

### 2.3.2 Dispatching of storage yard equipment

A complete review of recent literature on storage yard operations is presented by Carlo et al. (2014). The overview includes a section on the dispatching of storage equipment divided per equipment type. Guo et al. (2011) present two algorithms for the dispatching of yard cranes based on A* search algorithm to minimize the waiting times of the vehicles serving the yard crane. Experimental results show that the proposed algorithms perform well, even when arrival times of the vehicles is not accurately predicted. In the research cranes are not allowed to pass each other. A more complex problem is described by Dorndorf and Schneider (2010). They present a dispatching algorithm for three automated stacking cranes serving a single stack. Two of the cranes cannot pass each other and serve an exchange zone in the middle of the stack. The non-passing cranes are not allowed to be in the exchange zone in the same time. The objective is to maximize the cranes productivity while preventing delays at the TPs at both ends of the stack. The proposed algorithm dynamically optimizes the job sequence when a job is done. The proposed heuristics show an increase in productivity of 21,2 percent on average when compared to rules used by terminal operators.

### 2.3.3 Dispatching of quay cranes

Besides the dispatching of horizontal equipment and the yard equipment, the dispatching of QCs is also studied in literature. For an overview of this literature there is referred to the work presented by Bierwirth and Meisel (2010). They consider not only literature on dispatching (or assignment) of the QCs to the vessels, but also on berth allocation, crane scheduling (sequence of tasks per crane) and integrated solutions for these problems.

### 2.3.4 Integrated dispatching problems

In actual operations the equipment mentioned in the previous sections work together on a job. Literature on integrated dispatching problems is not as wide spread as for the problems with only one type of equipment. Chen et al. (2007) propose a solution for the integrated scheduling problem, formulated as a three stages hybrid flow shop problem. In a hybrid flow shop problem every job needs to be handled by the equipment in a specific sequence. Of some equipment types, the equipment works in parallel. A tabu search algorithm is used to find the solution. The objective of the algorithm is to minimize the makespan (total handling time) of the jobs. The arrival of jobs and process times are assumed deterministic, not yet comparable with real operations. Yin et al. (2011) also research an integrated dispatching problem. Their approach is dividing the planning and scheduling over four agents, lowering the computational load by simplifying by distributing the complex problems. The four agents are; a port planning manager, a berth control agent, a shuttle allocation agent and yard storage agent. A case study is performed to test the distributed agent system. Xin et al. (2014) look at the dispatching problem from a different point of view. They propose a hierarchical controller with the objectives to minimize the makespan and energy consumption of the operations. At the highest control level first the makespan for the whole process is minimized after which the process times are maximized subject to the minimal makespan to achieve low energy consumption. For the minimizing of the makespan the problem is again defined as a three stage hybrid flow shop problem.

## 2.4 Conclusion

From the conventional stacking strategies presented in Section 2.1 can be seen what the influences of the type of storage yard is on the stacking strategy used. Avoiding rehandles is in most cases an important objective, since rehandles are no productive moves. Export containers of the same group (based on weight, service and POD) are grouped together in the yard to avoid rehandles. The reservation of bays for the export containers allows for optimizing the loading process of the ship, but influences the stacking capacity in the stack i.e. the reserved bays are not available anymore for other containers. In the RTG yard those containers are also grouped in the same bay to avoid extra driving moves of the RTG crane, while this is not needed in a RMG yard. Besides minimizing travel time of the yard equipment and minimizing rehandles, the stacking strategies also aim at minimizing the driving time of the horizontal equipment by allocating container close to the location where the container is leaving the terminal.

Research on stacking strategies proposes some interesting stacking strategies, but they lack the application in real terminal operations. The literature often proposes strategies that are offline, and assume most of the information of the containers to be available at the start of the process. This does not comply with real terminal operation since this information constantly changes.

At container terminals all operations are interrelated. Due to this complex nature, dispatching is often researched for independent equipment in literature. Studies on integrated problems take into account these interrelations, and are often approached as a flow shop problem. Still the question remains on how these methods for both the single equipment and integrated problems cope when applied on a real terminal, where the situation is more dynamic and the problems are often larger.

# Chapter 3

# Description of the VCT

In the previous chapter storage processes on container terminals in general are presented and an overview of dispatching and stacking strategies on conventional storage yard is given. In this chapter the VCT is presented in more detail. First of all a general description is given, followed by descriptions of the individual parts of a VCT stack. Furthermore hand calculations are presented to evaluate the process times in a VCT stack.

## 3.1 General description

The VCT is a combination of multiple stack modules, together forming the storage yard of a terminal. Each stack consists of a basis; the mezzanine floor, and several storage floors on top. The mezzanine floor forms the buffer between the actual storage of the containers in the stack and the transfer of the containers between the storage yard and the horizontal handling equipment (shuttle carriers). The transfer of containers is performed by two RMTs. Each of these RMTs can move a container from the mezzanine floor to a transfer point on the ground and vice versa. The mezzanine floor is connected to the storage floors by a cargo elevator. Cargo elevators can move a maximum of two TEU per move. Each storage floors consists of 363 2-TEU slots, divided over 3 tiers, 18 bays and 7 rows. Whenever a containers is loaded into a stack, it is placed on a steel frame; a super skid. The super skids are fitted with extractable pins to lock the skid to the structure of a stack. Two ScLs move the containers from and to the different slots on a storage floor. Each storage floor has two aisles for the Scls to move the containers to their storage location. The aisles divide the storage floor in a middle section of five rows and two single rows at each side of the stack (Figure 3.1). The slots in the middle are handled differently than the slots at the side. At the side stacks the containers are stored on roller beds, therefore each container can be reached without having to move another container out of the way. These slots are from now on referred to as the 'free-access slots'. The containers in slots in the middle (the 'middle slots') of the storage floor are hanging in the structure on their super skids. The Scl can drive sideways underneath the middle slots to reach the containers. To reach the top containers, the containers underneath those containers need to be removed first. When moving the container sideways to one of the aisles, the route also needs to be free of containers.

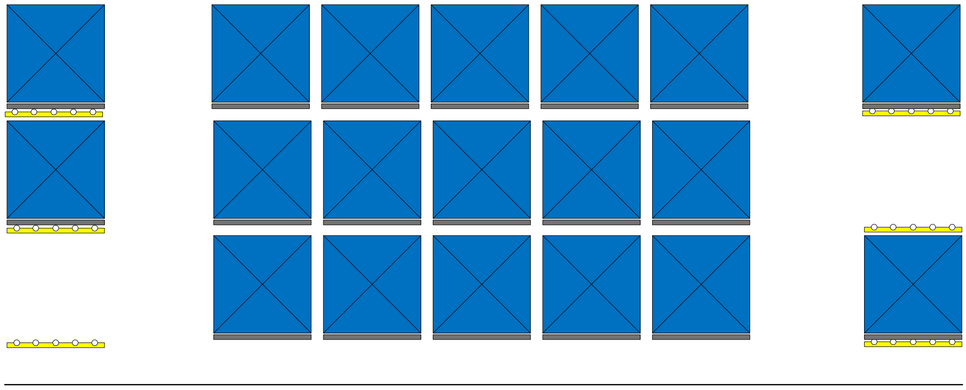


Figure 3.1: Cross section of a storage floor.

In Figure 3.2 the flow of a container through a VCT stack is presented. The container is delivered to the TP on the ground by a shuttle carrier. The container is lifted into the stack on the mezzanine floor an RMT. Roller beds on the mezzanine floor move the container to the cargo elevator in the middle of the stack. The roller beds consist of separate sections which are driven independently, therefore mezzanine floor can also serve as a buffer. The container is picked up at the mezzanine floor by the cargo elevator by rolling the container sideways on the platform of the elevator. The elevator moves the container to a storage floor. At the storage floor the container is moved sideways onto a stack-in buffer that offers space for four 40-ft containers, two at each side of the elevator. An ScL picks up the container at the buffer and stores the container in the stack. Containers moving in the opposite direction are also handled by the same equipment. However, a separate stack-out buffer between the ScLs and the elevator exists. This buffer separates both container flows at the storage floors.

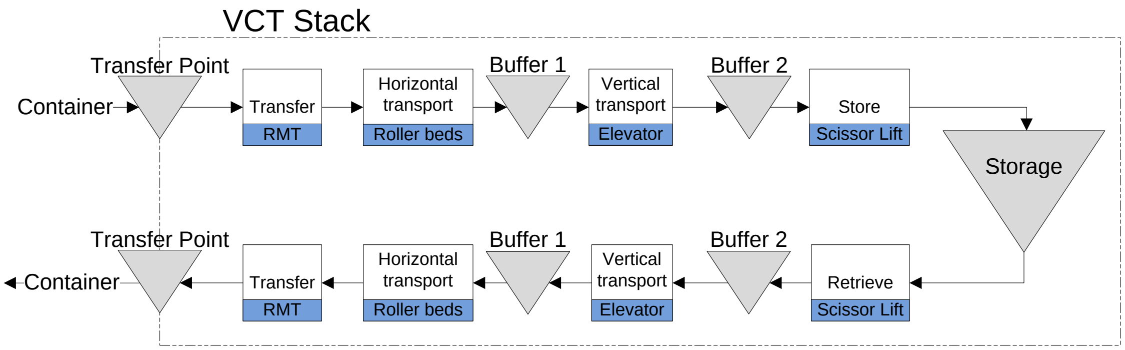



Figure 3.2: Container flow in a VCT stack.

## 3.2 Component description

From the description of a VCT stack in the previous section the following components can be distinguished:

- The RMTs
- The mezzanine floor
- The cargo elevator
- The storage floor buffers
- The ScLs
- The storage floors

In this section each component is discussed in more detail. The velocities and accelerations of the equipment are used to give insight in the process times of the different equipment based only on the specifications presented in this section.

### 3.2.1 Rail mounted trolley cranes

The RMTs lift the containers from the ground floor onto the mezzanine floor or the other way around. The RMTs move along a rail connected to the storage floor above the transfer points. Figure 3.3 shows a side view of a VCT stack at the RMTs.

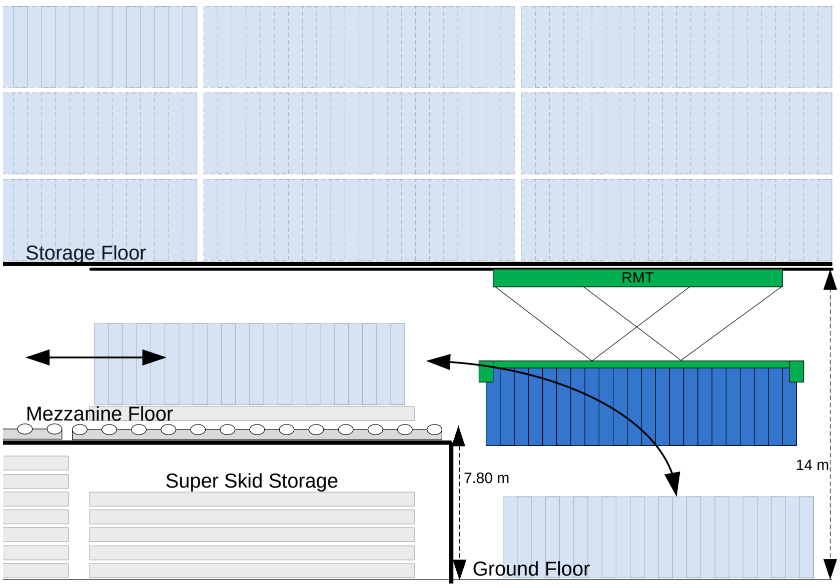



**Figure 3.3: Side view of the RMT.**

The container handling process times of the RMTs can be calculated with the specifications of the RMT presented in Appendix B to give an indication of the possible performance of the RMTs. The specifications lack information on acceleration and deceleration of the hoisting movement. These are assumed to be 0.2 $m/s^2$. The RMT lifts the container from the ground and drops it on the mezzanine floor. The height of the mezzanine floor and the roller beds together is 7.80 meter. The height of the super skid is 0.30 meter.

For moving the container into the stack a clearance above the super skid of 1.3 meters is needed. The container is moved in the direction of the stack over a distance of 15 meter. Table 3.1 presents the process times for a stack-in move. The initial location of the RMT is assumed to be above the mezzanine floor.

**Table 3.1 Result of hand calculation for RMT stack-in move.**

| Movement | Time [s] |
|---|---|
| Move above TP, empty | 22.8 |
| Lower spreader to container, empty | 21.3 |
| Grab container | 10.0 |
| Hoist spreader, loaded | 18.7 |
| Move above mezzanine floor, loaded | 28.0 |
| Lower spreader, loaded | 5.1 |
| Drop container | 6.1 |
| Hoist spreader, empty | 8.0 |
| **Total** | **119.9** |

Because the moves of the stack-in and stack-out RMT are not that different, the presented result is assumed to be also representative for the stack-out move. Assuming RMTs are able to directly start the next move when the current move is completed, the RMTs can perform a maximum of 30 stack-in moves per hour.

### 3.2.2 Mezzanine floor

The mezzanine floor consists of 41 roller beds for transporting the containers between the cargo elevator and the RMTs. The roller beds at the side are able to move to containers sideways as well as in the direction of the stack. The roller beds in the middle can only move containers sideways. Figure 3.4 gives and overview of a mezzanine floor.

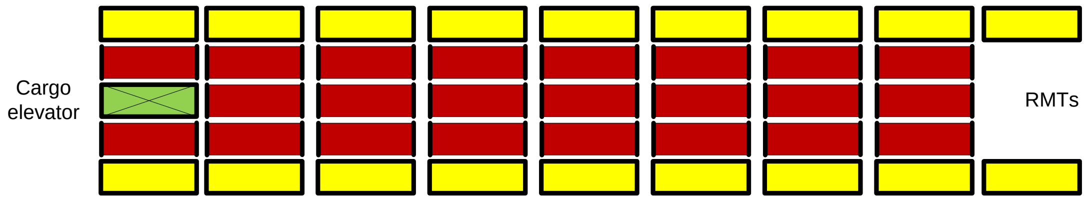



**Figure 3.4: Overview of the mezzanine floor.**

The length of a roller bed is 13.6 meters and with a speed of 0.35 $m/s$ it can move a 40-ft container in the longitudinal direction in 38.9 seconds. The width of a roller bed is 2.8 meters, which results in eight seconds for moving a container sideways. Changing direction of the movement of a roller bed takes an additional five seconds. Moving a container in the longitudinal direction with changing direction of movement of a roller bed twice takes the longest. Therefore the slowest roller bed is able to do 73.7 container moves per hour. This number only represents the capacity of moving containers along one side of the mezzanine floor, for example from the elevator to the stack-out RMT. In the opposite direction the same capacity can be reached. Moving a container directly from the elevator to the RMTs takes 362 seconds.

### 3.2.3 Cargo elevator

The cargo elevator moves the containers from and to the different floors in a VCT stack. It has an capacity of one 40-ft container. To load and unload containers from the elevator, the elevator is equipped with rollers. The elevator retrieves or drops the containers from two different buffers at each floor. Figure 3.5 shows a cross section of a stack at the elevator. The containers are stored in the stack are dropped at the highest buffer of each floor and the containers that are retrieved from the stack are delivered to the elevator from the lowest buffer at each floor. The speed of the cargo elevator varies when loaded or empty as can be seen from Table 3.2.

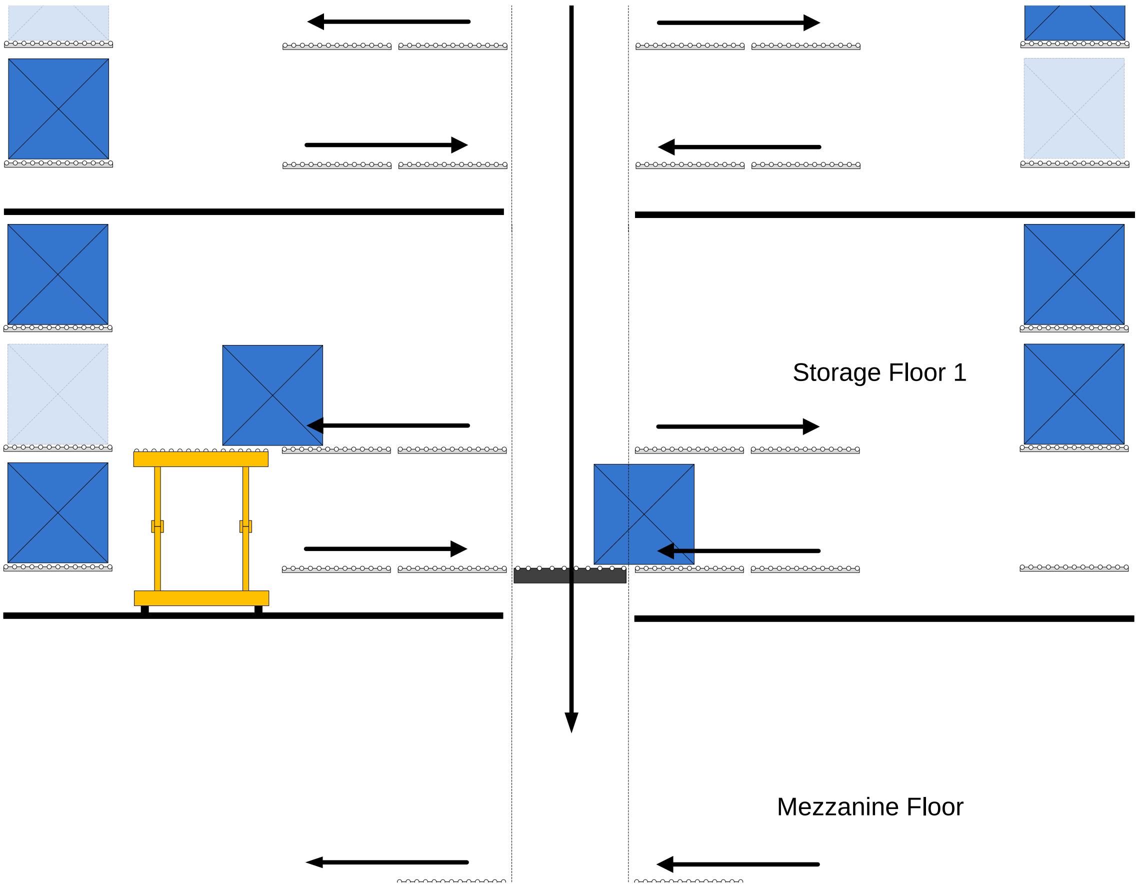



**Figure 3.5: Cross section VCT stack at the cargo elevator.**

**Table 3.2 Specifications of the cargo elevator.**

| Movement | Value | Unit |
|---|---|---|
| Acceleration | 0.2 | $m/s^2$ |
| Deceleration | 0.2 | $m/s^2$ |
| Max speed loaded | 1 | $m/s$ |
| Max speed empty | 1.2 | $m/s$ |

In table 3.3 the distances from the mezzanine floor to the buffer positions on the different storage floors are presented. The distances are used to gain some insight in the process times of the cargo elevator. Column four and five show the travel time to a specific buffer, calculated from the distance, velocities and accelerations. Loading or unloading the elevator takes eight seconds. Combining an empty move, a loaded move and the loading and unloading time of the elevator results in the total time per move presented in Column six.

**Table 3.3 Travel times and distances of the cargo elevator.**

| Floor | Buffer type | Distance [m] | Time [s] | | Total time per move [s] |
|---|---|---|---|---|---|
| | | | empty | loaded | |
| 1st floor | stack-out buffer | 7.50 | 11.3 | 12.5 | 39.8 |
| 1st floor | stack-in buffer | 10.74 | 14.0 | 15.7 | 45.7 |
| 2nd floor | stack-out buffer | 18.50 | 20.4 | 23.5 | 59.9 |
| 2nd floor | stack-in buffer | 21.74 | 23.1 | 26.7 | 65.9 |
| 3th floor | stack-out buffer | 29.50 | 29.6 | 34.5 | 80.1 |
| 3th floor | stack-in buffer | 32.74 | 32.3 | 37.7 | 86.0 |
| 4th floor | stack-out buffer | 40.50 | 38.8 | 45.5 | 100.3 |
| 4th floor | stack-in buffer | 43.74 | 41.5 | 48.7 | 106.2 |

Assuming that every move is performed exactly the same number of times the average time to perform a move can be calculated. The average time for an elevator move is 73 seconds, which comes down to 49.3 moves per hour. However, the travel time of the elevator can decrease when elevator starts the stack-out move at the end point of the stack in-move. The elevator would in that case perform less unproductive (empty) moves.

### 3.2.4 Storage floor buffers

As can be seen from Figure 3.5, every storage floor has four buffer positions for containers loaded into the stack and four buffer positions for containers unloaded from the stack. The buffers consist of the same roller beds as on the mezzanine floor, they move a container sideways in 8 seconds.

### 3.2.5 Scissor lift trolleys

The ScLs move the container between the storage floor buffer and the container slots in the stack. Figure 3.6 shows the ScLs lifting a container on a super skid. The ScLs working area is restricted to half a storage floor. The working areas of two ScLs only overlap in the middle row of a stack. The ScLs can drive and change the height of the platform at the same time to minimize process times, although this is only possible when the weight of the container is less than 30 tons. For heavier containers lifting and driving needs to be performed in series. The ScL either moves a container from or to a free-access slot or from or to a slot in the middle of the stack. The process of a ScL storing a container is presented in Figures 3.7 and in Figure 3.8 the process of retrieving the container is described. In both figures the container is assumed to weigh less than 30 tons, so driving and lifting at the same time is allowed.

**Figure 3.6: Impression of the a ScL. (source: Polotec)**

In Table 3.4 the distances of the movements of the ScLs are presented. The distances of the different slots are the differences between the height of the ScL (1.2 meter) and the height of the slot. The specification of the ScLs presented in Appendix B are used to calculate an estimation of the process times of the ScL. In the estimation is assumed that every slot is visited once for a retrieval order and once for a storage order.

**Table 3.4 Distances of the movements of the ScLs.**

| Locations | Distance [m] |
|---|---|
| Distance from bay to next bay | 13.6 |
| Distance from row to adjacent row | 2.8 |
| Distance to 1st (lowest) slot | 0.7 |
| Distance to 2nd slot | 3.9 |
| Distance to 3th slot (highest) | 7.2 |

Two cases are distinguished; the interaction with a free-access slot and the interaction with a middle slot. For each of these cases the average travel distance alongside the stack can be calculated. This is different for the two cases, since there are also free-access slots opposite the elevator. With the distances the travel time for moving an empty and a regular (20 tons) container. The average lifting movement to or from the location of the container in the stack is the distance from the normal height of the ScL platform to the height of the second tier. Grabbing or dropping a container at a free-access slot takes eight second and five seconds to align the platform with the roller bed before the container can be transferred. Locking or unlocking the super skid to/from the structure of the stack at a middle slot takes 7.5 seconds. Moving underneath the container slots is only necessary trying to reach the middle slots. The length of this movement is on average the width of two rows; 5.6 meter. Table 3.5 shows the results of the described calculation for the average process times of an ScL. Assuming that the distribution of moves to free-access slots to moves to middle slots is equal to the ratio in terms of available slots, the total average process time is 99.8 seconds, resulting in 36.1 container moves per hour per ScL.

**Table 3.5 Results from hand calculations on ScL specifications.**

| Move | Distance [m] | Time (free-access slot) [s] | Time (middle slot) [s] |
|---|---|---|---|
| Avarage distance to bay (free-access slot) | 61.2 | 36.9 | - |
| Avarage distance to bay (middle slot) | 64.8 | - | 38.0 |
| Grabbing/dropping container at elevator | | 13.0 | 13.0 |
| Grabbing/dropping container at stack | | 13.0 | 7.5 |
| Exchange wheel direction (2x) | | - | 10.0 |
| Driving underneath container slot | 5.6 | - | 16.2 |
| Lifting/lowering platform at slot location | | 21.3 | 21.3 |
| Total | | 84.2 | 106.0 |

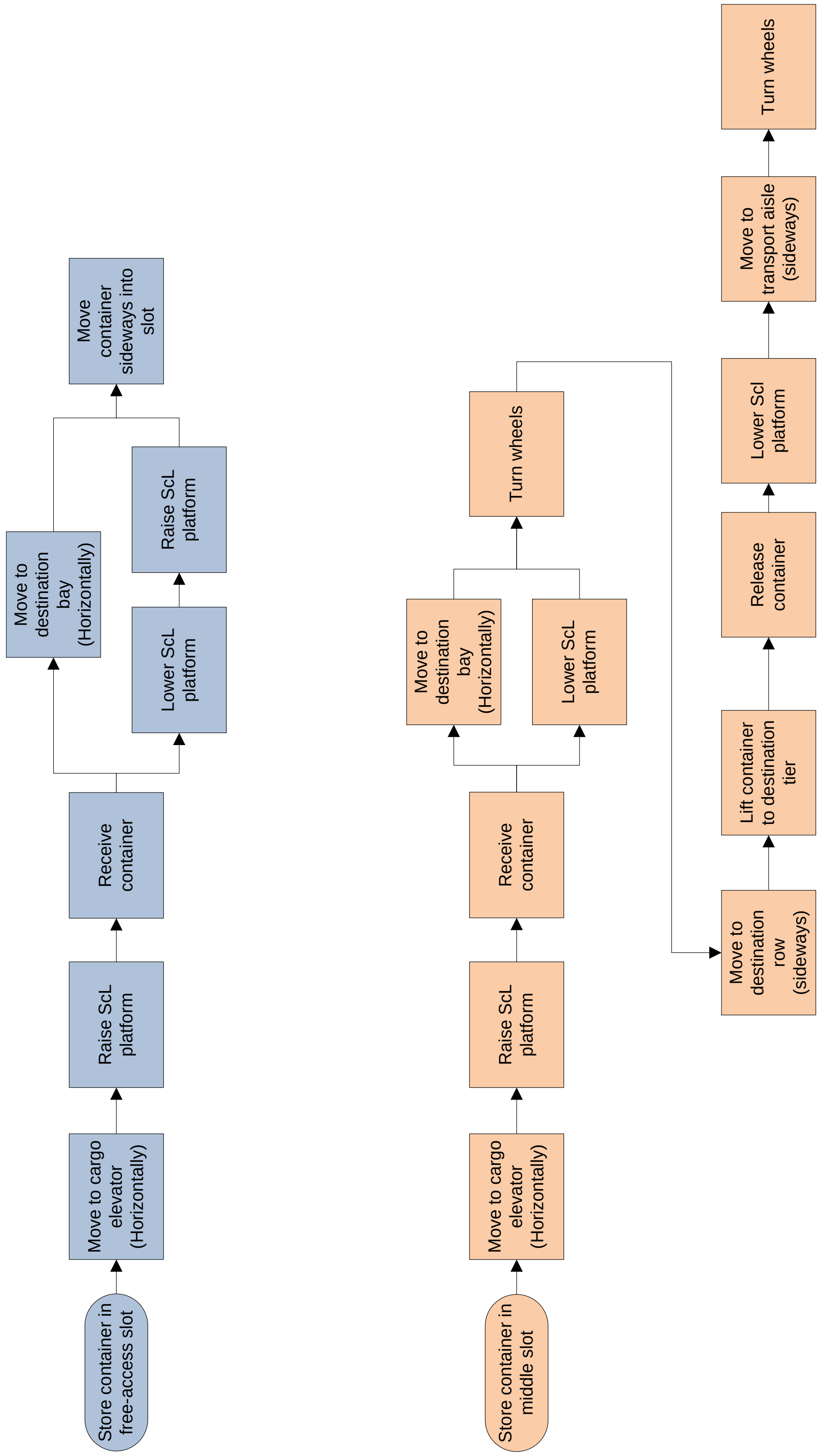



**Figure 3.7: Process description storing a container in a free-access slot (blue), and a middle slot (orange).**

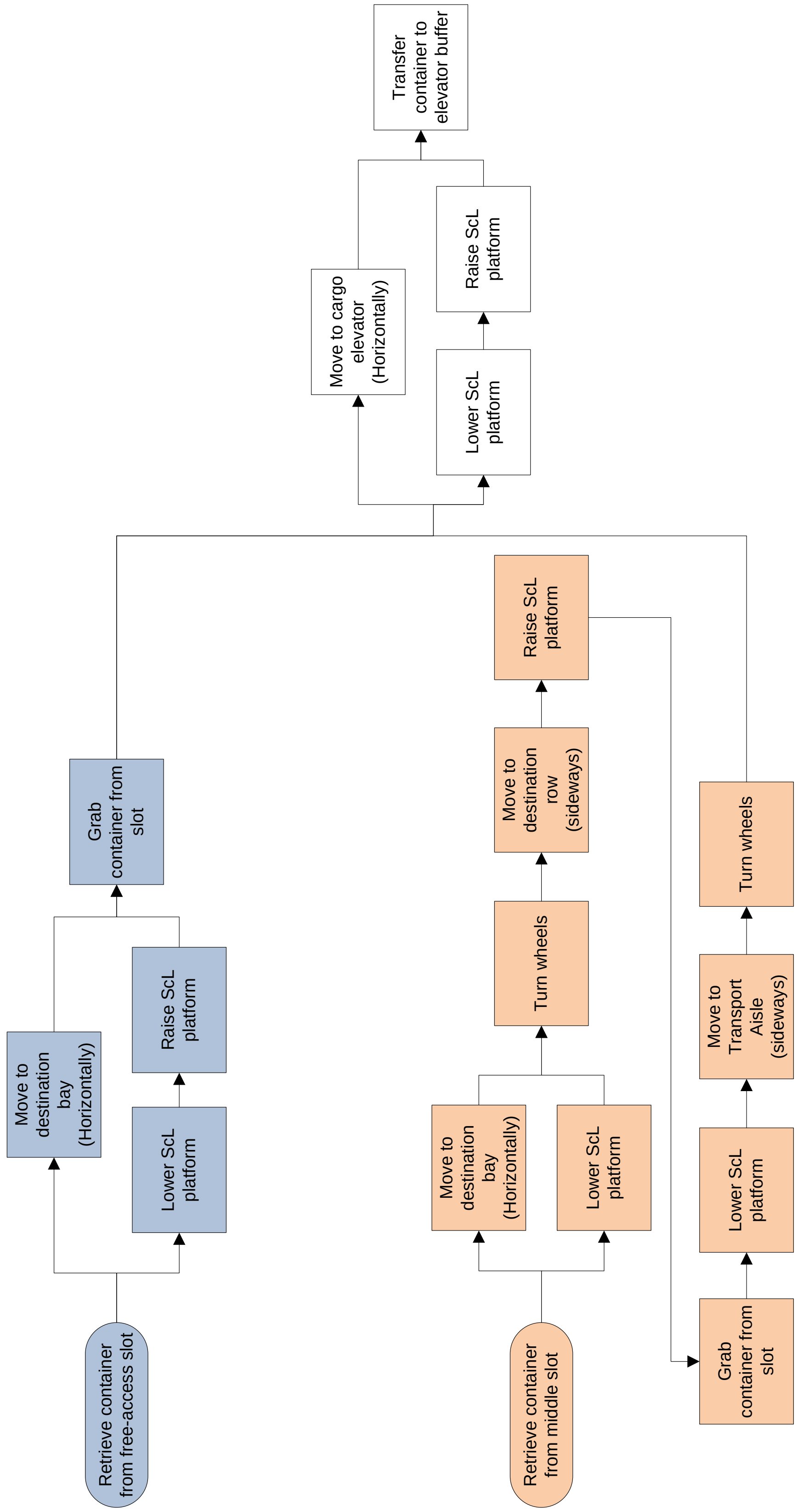
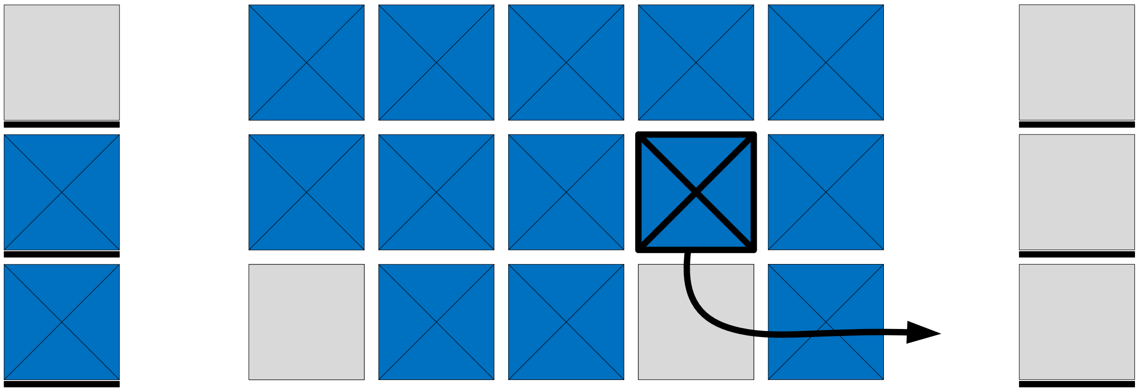


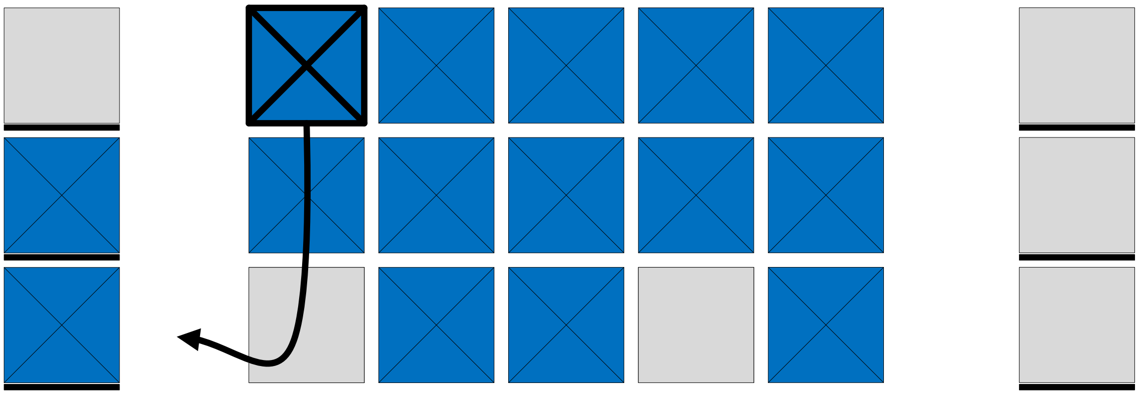

**Figure 3.8: Process description of retrieving a container from a free-access slot (blue), and a middle slot (orange).**

### 3.2.6 Storage floors

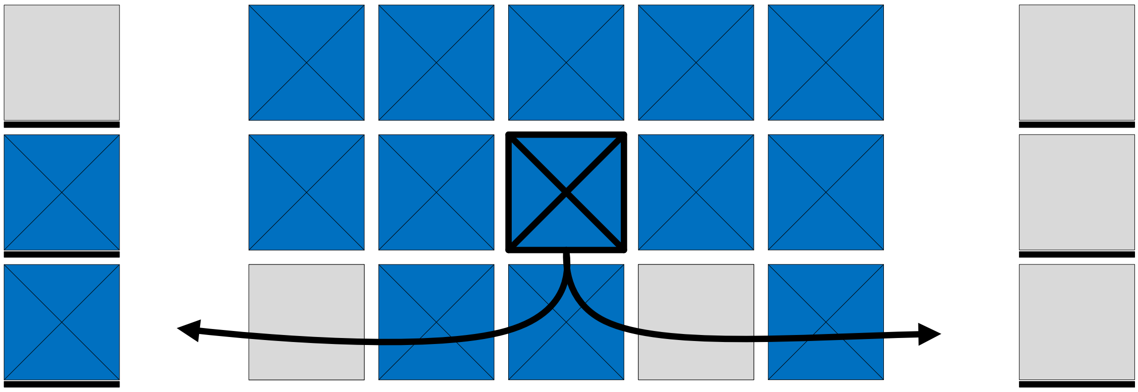
As mentioned in the general description of the VCT in Section 3.1, a storage floor in a VCT stack consists of different types of slots. The free-access slots can be reached without having to move another container out of the way. For the middle slots this process is different. Since the container in the middle of the stack can only be released from the stack by approaching the container with the ScL from below, any container underneath that container needs to be moved out of the way (rehandled). This is also the case when a ScL with container needs to move from one of the middle rows of the stack to the aisles. Since a loaded ScL cannot pass underneath the other containers stored in the lowest position, these container need to be moved out of the way. Figure 3.9 presents cross sections of a VCT stack for different situations where rehandles are required. In the first situation (Figure 3.9a) a container needs to be moved out of the stack but is blocked when the container is moved sideways to the aisle. In the second situation (Figure 3.9b) the container cannot be reached by the ScL from the bottom because another container is in the way. In the third situation (Figure 3.9c) a container can be moved to both sides, because it is located in the only row that can be reached by both ScLs. However, the container is blocked from the underneath and also when it is moved sideways to an aisle.



(a) Situation 1: container sideways movement blocked.



(b) Situation 2: container grab blocked.



(c) Situation 3: Container blocked both sides.

Figure 3.9: Different situations when reshuffles occur.

## 3.3 Conclusion

In this chapter the VCT was described in detail. Basic calculations have been done and assumptions are made to get insight in the process times of the different equipment in a VCT stack and show the capacities of the equipment based only on their specifications. Table 3.6 gives a summary of the calculated process times. The table also shows the amount of equipment of each type per stack, assuming a stack consists of four storage floors.

**Table 3.6 Cycle times for the handling equipment in the VCT stack.**

| Equipment | Number per stack | Average cycle times [s] | Container moves per hour |
|---|---|---|---|
| RMT | 2 | 119.8 | 30.1 |
| Mezzanine floor* | - | 48.9 | 73.6 |
| Cargo elevator | 1 | 73.0 | 49.3 |
| ScL | 8 | 99.8 | 36.1 |

* The capacity of the mezzanine floor only represents the process for containers moving out of the stack. Moving containers into the stack can be done in parallel with the same capacity.

Based on the analysis of the VCT stack the following conclusions can be drawn:

- The bottlenecks in the storage and retrieval processes in the VCT stacks are the RMTs and the cargo elevator. For the elevator some improvement is still possible by combining stack-in and stack-out moves.
- Rehandles in the VCT are different than in conventional stacks, because containers can also be blocked from the side. The rehandles are performed by the ScLs, which do not directly influence the performance of the VCT due to the number of ScLs per stack.
- Different types of slots make it possible for a limited number of containers to be retrieved without the need for rehandles.

In the next chapter the analysis in this chapter is used for the development of stacking and job dispatching strategies for the VCT.

# Chapter 4

# Stacking and dispatching in the VCT

In the Chapter 2 an overview of the stacking and dispatching in conventional terminals was presented and in the Chapter 3 the design of the VCT was evaluated and explained in more detail. In this chapter stacking and dispatching strategies for the VCT are proposed based on stacking strategies on conventional storage yards and the design of the VCT. In Section 4.1 the proposed stacking strategy is described and in Section 4.2 the dispatching is discussed.

## 4.1 VCT Stacking strategy

According to Dekker et al. (2007) the three main objectives of stacking strategies are:

- Efficient and timely transportation from quay to stack, to further destinations and vice versa.
- Avoidance unproductive moves.
- Efficient use of storage space.

Timely transportation of the container means that containers need to arrive at their destination at the requested time. The destination can be the storage yard, truck gate or QCs. As described in Chapter 2, containers going to the QC are bound to a specific sequence once the loading process has started, so containers arriving too late delay the loading process of the vessel. Import containers which need to be transported to the truck gate are not influenced by each other, but the trucker does not want to wait forever for a container. Therefore timely transportation also applies to the import containers. When a container is moved to the storage yard, the arrival time at the stack is not important, but since at the gate and at the QCs only a limited amount of space is available, the containers need to be moved out of the way on time. Storing the container randomly to move it out of the way influences the performance and is not efficient on the long term when containers need to be retrieved from the stack again.

Unproductive moves directly influences the productivity when using yard cranes, because the yard cranes are responsible for the rehandles and delivering the containers at the TPs of the stack. In the VCT rehandles are of less influence on the performance because they are performed by the ScLs. There are two ScLs per floor. According to the hand calculations in Chapter 3, there is enough capacity available to keep up with the speed of the elevator and the mezzanine floor. Since each stack consists of multiple storage floors, ScLs are able to perform rehandles without influencing the performance of the stack in terms of container moves. However, rehandling containers when a truck has requested a container from the yard influences the timely transport of the container. Unproductive moves are also not energy efficient and thus they should be avoided if possible.

Efficient use of storage space is not an objective on its own, but more a limiting condition for the other objectives. In conventional stacks rehandles can for example be avoided by simply stacking the containers only a single container high, only this would go against the objective to efficiently use the storage space.

Based on these objectives a stacking strategy for the VCT is developed. The structure of the stacking strategy is the same for all types of containers. First of all a selection of possible locations for the container is made. For every slot in the selection a penalty is determined based on characteristics (e.g. stack occupancy, equipment occupancy, etc.) of the location of the slot. The slot with the lowest penalty is assumed to result in the optimal location for the container. The location for the container in terms of bay, row, tier and module is determined in one step, while in literature (Park et al., 2011; Zhang et al., 2003; Chen and Lu, 2012) often an hierarchical approach consisting of several steps is chosen. For example, the steps consist of first allocating a container to a stack by spreading the workload over the different stacks, followed by the allocation to an actual slot. The approach in this research combines these steps and makes it possible to evaluate all slots at once, therefore no slot is excluded in earlier steps.

### 4.1.1 Import containers

Due to the lack of information on the departure time of import containers, there is a large chance of rehandles when the container is stored somewhere in the middle of the stack. Having to dig out a container influences the timely delivery of a container to the truck gate. This problem is already addressed in the conventional RTG stacks. Import containers are often stored on low piles or on top of the piles to ensure the container can be retrieved with minimal rehandles needed. In the VCT stack the special free-access slots at the side of the stack can be used for this purpose.

The ScLs have relatively large capacity compared to the other equipment in the VCT stacks, due to the amount of ScLs per stack. Therefore the distance a container needs to travel on the storage floor is not taken into account when determining the optimal location for a container.

The optimal storage location for an import container is determined once the container is picked up at the quay by a shuttle carrier. This is the last moment that optimal location for a container can be determined, resulting in a decision based on the most recent information. All available free-access slots are taken into account when selecting a slot. Determining the optimal location for a container is based on several factors:

- Occupancy of the stack: Dividing the containers over the different stack is assumed to have a positive influence on the workload later on, when the containers are picked up again. This results in a lower chance of delays during the retrieval process of the containers.
- Occupancy of the equipment: The arrival of the container might be at a busy moment at the terminal. The occupancy of the equipment gives an indication on how busy every stack is at the current moment.

Based on these factors the stacking strategy for an import container can be described as follows:

- **Step 1**: List all empty free-access slots, and for every slot determine the floor and stack it is located. The slots that are already reserved for containers underway are left out.
- **Step 2**: For every slot in the list determine the occupancy of the stack-in RMT, by taking the number of containers going to each stack. The number of containers is multiplied by a weighting factor. Slots located in stacks where many containers are already moving towards get the highest penalty.
- **Step 3**: For every slot determine the occupancy of the free-access slots per floor and multiply this with a weighting factor. Slots located on floor with a lower occupancy receive a lower penalty. The penalty is added to the result of step 2.
- **Step 4**: Sort the slots based on the penalty. The slot with the lowest penalty is the optimal slot for a container.

The equation for determining the penalty ($P_i$) for every import slot ($i$) consists of two parts. The first part determines the penalty for the occupancy of the stack where slot $i$ is located by multiplying the number of containers moving to the stack ($R_i$) with weighting factor $W_{Ro}$. The second part determines the penalty for the occupancy of the import container slots by multiplying the occupancy ($C_i$) with weighting factor $W_{So}$. The complete equation is shown in equation 4.1.1. An overview of the parameters in the equation is given in Table 4.1.

$$P_i = (R_i * W_{Ro}) + (C_i * W_{So}) \tag{4.1.1}$$

**Table 4.1 Parameters for import container equations.**

| Parameter | Influence | Unit |
|---|---|---|
| $R_i$ | the number of containers moving to the same stack as the location of the slot $i$. | containers |
| $W_{Ro}$ | the weighting factor for the occupancy of a RMTs. | – |
| $C_i$ | the occupancy of the floor the slot $i$ is located on. | percentage |
| $W_{So}$ | the weighting factor of the floor occupancy. | – |

To be able to determine what the optimal location for a container is, two weighting factors have to be determined ($W_{Ro}$ and $W_{So}$). With simulations these weighting factors can be varied to obtain the optimal values. The results of the simulations are presented in Chapter 6. In Figure 4.1 an overview of the decision process for the allocation of import containers is presented.

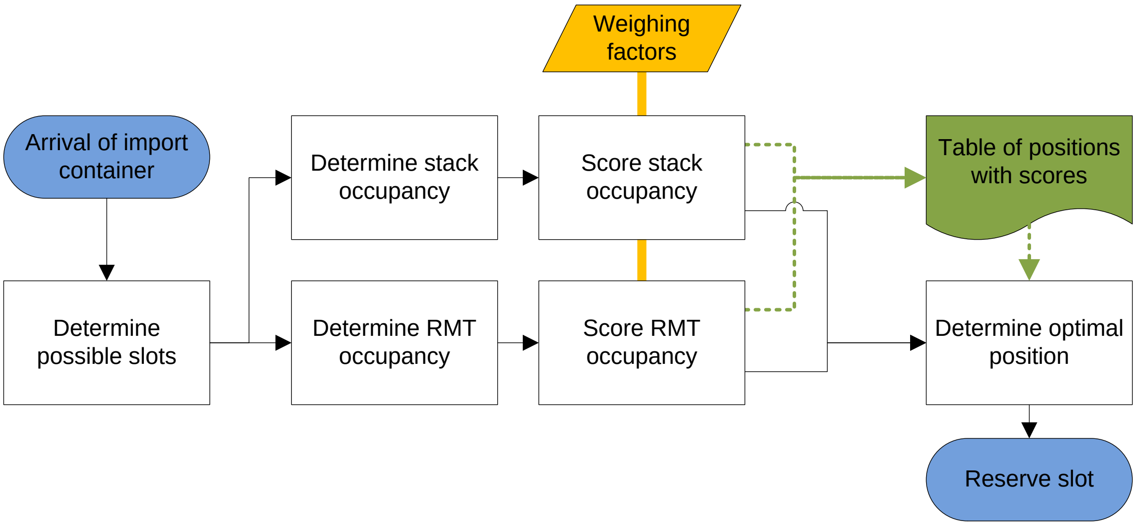



**Figure 4.1: Representation of the process of determining an optimal location for import containers.**

### 4.1.2 Export containers

Export containers arrive at a terminal several days before arrival of a vessel. When a container arrives at the terminal, the pro-forma vessel schedule gives an indication for the date of departure of the container. The ratio of import and export containers and the PODs for the export containers can be estimated from earlier vessels and sometimes this information is part of the contract with the shipping company. In Chapter 2 is explained that the heavier containers are loaded into the vessel first due to the weight distribution in the vessel. Therefore these containers are also the first to leave the stack.

#### 4.1.2.1 Reservations

To minimize the rehandles when loading a vessel the containers need to be placed in the stack in the reversed order as they are expected to leave the stack. As mentioned in Chapter 2, the containers are loaded into the vessel in batches of the same POD, meaning that these containers need to be grouped together. On the other hand, an average cycle time for a dual-hoist QC is around 100 seconds, meaning that a container is requested at least every 50 seconds. For this reason the containers for the same POD need to be divided over the different stacks. Because containers of the same group will not arrive at the stack at the same time, slots need to be reserved to ensure that the groups are stacked together and can be unloaded in the right sequence.

The number of reservation for the same group per stack depends on the decision of the size of the reservation and the number of containers in each group. In literature this problem is often approached as an optimization problem by setting the objective to minimize travel time between the bays and quay, as well as spreading the workload. Since in this study routing the horizontal equipment is outside the scope, it is assumed that the travel times do not play a role in these decisions. From the layout of the VCT can be seen that the difference in distance to the quay for the different stacks is relatively small (assuming a travel speed of 30 km/h, the maximum difference in travel time between the stacks is only 12 seconds). Since a reservation occupies slots, the size of the reservation will influence the occupancy of the stacks over time. To achieve a high occupancy of the stack, the number of reserved slots over time should be minimized.

Two different situations can be distinguished when determining where to create a new reservation for a container group. The first situation is when containers arrive by truck, spread over the week in advance of the arrival of destination vessel. In that case the arrival time of the different containers is very unpredictable, as well as container information. The second situation occurs when unloading a vessel with transshipment containers. Containers with the same POD and destination vessel will arrive in a shorter time span, and the information on all containers unloaded is available at the start of the unloading process. The size of the reservation can be determined based on with what modality the container is arriving. When a container is arriving by truck a reservation for six slots is made, to minimize the number of reserved slots over time. The transshipment containers are placed in reservations of either six or nine slots, because the number containers of the same group unloaded from a vessel is known beforehand. By applying these rules, the number of empty slots in the stacks due to reservations is minimized. The optimal location for a reservation depends partly on the same factors as for the import containers. Because the dwell time of an arriving export container can be estimated based on the vessel arrival schedule, containers with a longer dwell time can be placed higher in the stack. This means that fewer moves to the higher floors are required from the cargo elevator, decreasing average cycle times of the elevators.

The steps for determining a location for a new reservation can be described as follows:

- **Step 1**: Determine the size of the reservation. When a container arrives by truck a reservation of six slots is made. When a container is delivered by a vessel, the size of the reservation can be determined beforehand, based on the number of containers of the same group unloaded by the vessel.
- **Step 2**: Determine the maximum number of reservations of the same group per stack, based on the expected number of containers for the group.
- **Step 3**: List all possible locations for new reservations of the size specified in step 1.
- **Step 4**: Determine the occupancy of the stack-in RMTs for every location in the list by determining the number of container going to the stack. The number of containers is multiplied by a weighting factor. Slots located in stacks where many containers are already located to get the highest penalty.
- **Step 5**: Determine the occupancy of the middle slots on the floor of the locations and multiply this with a weighting factor. Locations on a floor with a lower occupancy get a lower penalty. The penalty is added to the result of step 4.

- **Step 6**: Determine the number of slots reserved and occupied by containers for the same group for every location and subtract the number of slots of the same group allowed per stack. This step ensures that containers of the same group are divided over the different stacks. Multiply the difference with a weighting factor and add the result to the result of step 5.

- **Step 7**: Multiply the floor of each location with a weighting factor and and the expected dwell time of the container. If the expected dwell time is relatively long, a higher location in the stack might be preferable to minimize the number of moves to the higher floor. Add the result of this step to the result of step 6.

- **Step 8**: Sort the locations based on the penalties. The location with the lowest penalty is the optimal location for a new reservation.

The equation for determining the penalty for every possible reservation locations ($r$) can be compared with formula 4.1.1, but with addition of factors for the number of slots for a group per stack ($G_r$) and the dwell time ($D$). The full equation for determining the optimal location for a new reservation is presented in equation 4.1.2. In Table 4.2 an overview of the parameters in the equation is presented.

$$P_r = (R_r * W_{Ro}) + (C_r * W_{So}) + (G_r * W_g) + (F_r * D * W_d) \tag{4.1.2}$$

**Table 4.2 Parameters for reservation equations.**

| Parameter | Influence | Unit |
|---|---|---|
| $R_r$ | the number of containers moving to the same stack as the possible location $r$. | containers |
| $W_{Ro}$ | the weighting factor for the occupancy of a RMTs. | – |
| $C_r$ | the occupancy of the floor the possible location $r$ is located on. | percentage |
| $W_{So}$ | the weighting factor of the floor occupancy. | – |
| $G_r$ | number of containers of the same group in stack(planned) minus slots allowed per group (negative value) | containers |
| $W_g$ | the weighting factor for the number of slots of a group still available per stack | – |
| $F_r$ | the floor the possible location is located on. | floor |
| $D$ | the estimated dwell time. | days |
| $W_d$ | the weighting factor for the dwell time of the container. | – |

Figure 4.2 represents the process of determining the best location for a new reservation.

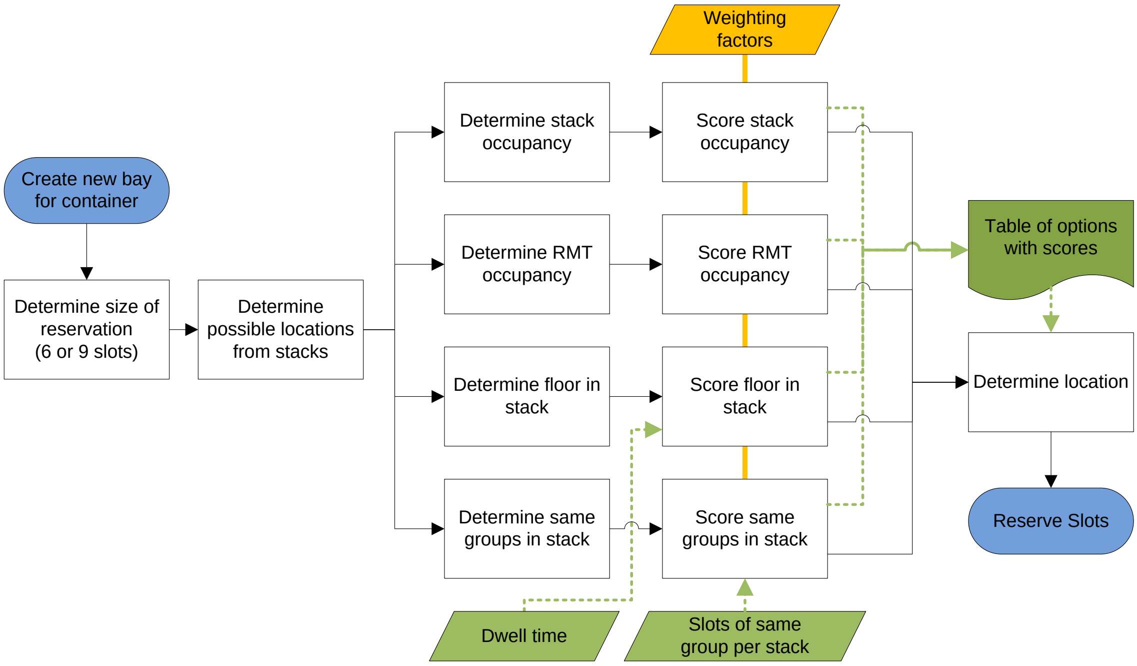



**Figure 4.2: Representation of the process of determining an optimal location for new reservations.**

#### 4.1.2.2 Export container allocation

In Section 4.1.2.1 is shown how the location for containers of the same group can be found. In this section the steps to locate an export container to one of the slots within a reservation are described. The allocation of an export container arriving at the terminal can be described in the following steps:

- **Step 1**: Check if there are already reserved slots for the group of the container. If slots for the groups of the container are available, proceed to step 2, else start a new bay according the steps in Section 4.1.2.1.
- **Step 2**: Check for every reservation if the reservation contains slots for the weight class of the container. If none of the reservation contains the right slot for the weight class of the container exists, make a new reservation for the group, else proceed to step 3.
- **Step 3**: Make a list of all possible slots.
- **Step 4**: Determine the occupancy of RMT for each slot, and add this to the penalty of the slot.
- **Step 5**: Multiply the floor a slot is located with a weighting factor and the expected dwell time of the container. If the expected dwell time is relatively long, a higher location in the stack might be preferable to minimize the amount of moves to the higher floor. Add the result of this step to the result of step 4.
- **Step 6**: Select the slot with the lowest penalty.

Figure 4.3 gives a graphical presentation of the process described in the previous steps.

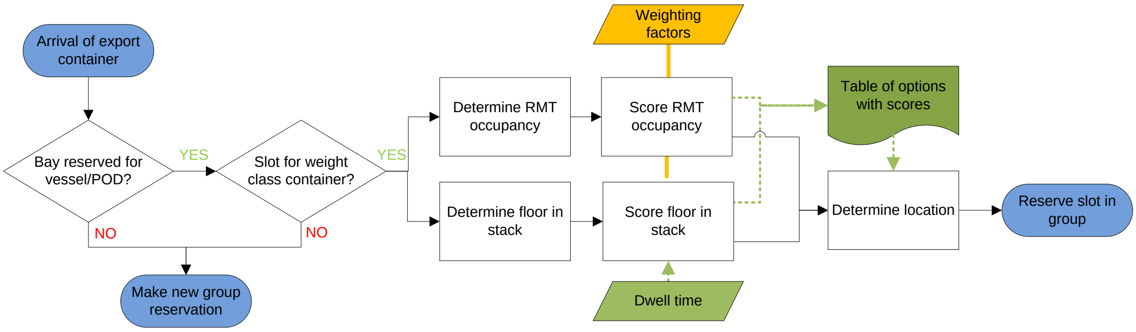



**Figure 4.3: Representation of the process of determining an optimal location for import containers.**

#### 4.1.2.3 Pre-Positioning

Export containers arriving by truck are not per definition in the order as they need to be loaded into a vessel. The heaviest containers are the first to go into a vessel's bay, but containers do not arrive at the terminal in exactly that sequence. To avoid rehandles when loading a vessel, the containers can be pre-positioned somewhere else near the final location as long as no lighter containers are yet available. Figure 4.4 represents the working area of an ScL. The six slots in the middle are reserved for the group of the container that needs to be stored. If the container is heavy it should go into slot *M-Slot 1*, but placing it there would block the access to slots *M-Slot 4* and *M-Slot 5*. To overcome this problem, the container can be temporary stored at *FA-Slot 2*. This should also be taken into account when reserving a new bay for a group. A free-access slot should be available nearby. To determine if the container is a heavy or a light container the container weights are divided in five different categories. The weight of a typical 40-ft container varies between 4 ton (empty) and 35 ton. The size of the categories depends on the distribution of the container weights at the terminal.

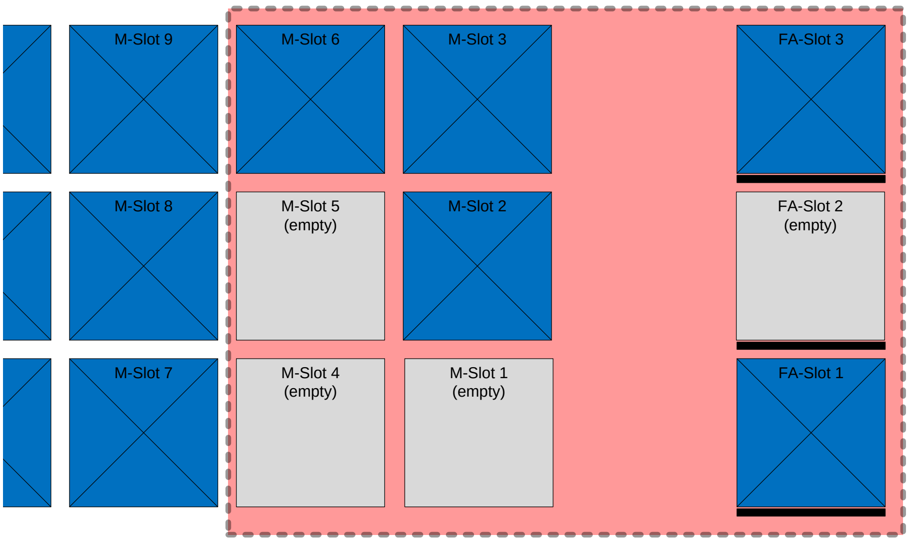



**Figure 4.4: Reservation for an export container arriving per truck.**

Due to the availability of enough ScL capacity, the pre-positioning is not taking into account when allocating a container. If less ShLs were used in the VCT stack their performance becomes more crucial, and by that also the time it takes to perform a pre-position move. In that case the pre-positioning can be added to the equation by adding a variable (one for 'true', zero for 'false') and a weighting factor.

### 4.1.3 Empty containers

The number of empty containers moving through a terminal depends on the location of the terminal. For example in the port of Rotterdam the number of empty containers loaded onto the vessels is around 25 percent of the containers, while only 2 percent of the unloaded containers is empty. In general empty containers stay longer on the terminal because they contain no valuable goods. Because of the light weight of the containers, the empty containers are stored in the top floor of a VCT stack. This minimizes the number of long moves for the elevator due to the longer dwell time, as well as the influence of the container weight on the stability of a VCT stack.

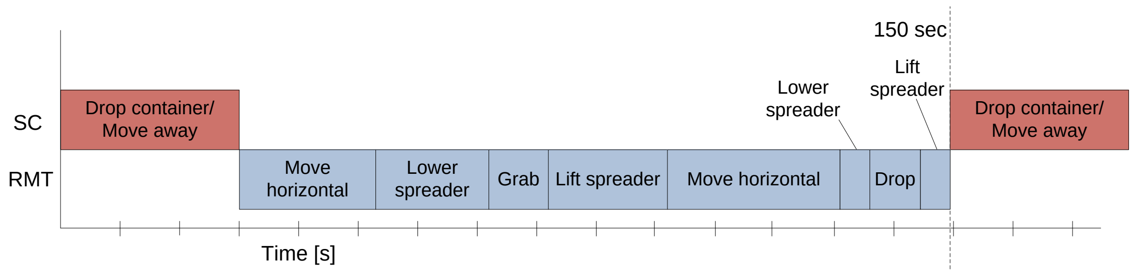
## 4.2 VCT Dispatching strategy

In the previous section a stacking strategy for the VCT are developed. With the stacking strategy the destination for each container arriving at the storage yard is already determined. In conventional terminals this leaves open the question which specific equipment is going to perform the handling of the container. When dispatching orders to specific vehicles often the goal is to minimize travel time of the equipment or limit the handling time of a vessel. To reach these goals, the dispatching of for instance horizontal equipment (Vis, 2006) or yard cranes (e.g. Gharehgozli et al., 2014) is researched. Since the scope of this research is the storage yard, the dispatching of the horizontal equipment is not part of this research. On first sight research on dispatching of yard cranes seems to be closest related to the dispatching problem in this research. However, there are some design differences between conventional stacks with yard cranes and a VCT stack. First of all different types of equipment are used in the stack. A yard crane performs the all storage and retrieval processes, but in the VCT stack the processes are split up between different handling equipment. Secondly, yard cranes can often drop or retrieve a container from multiple transfer points at both ends or alongside the stack, while in the VCT only two transfer points are available, minimizing the flexibility in choosing containers to pick-up or drop at a transfer point.

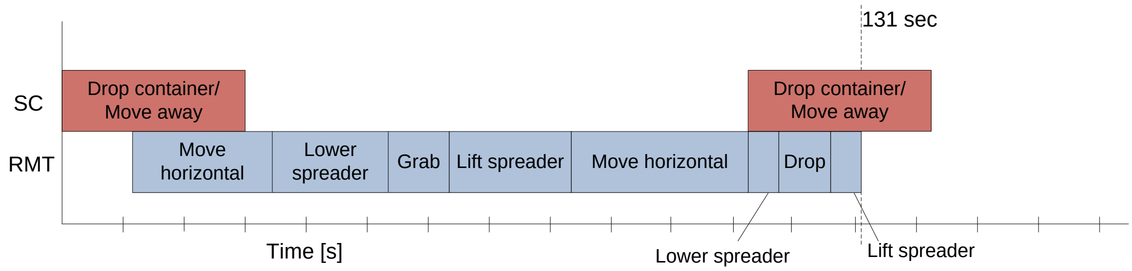
Due to the limited number of transfer points and the fact that the allocation of the containers already determines the equipment needed to handle a container, the dispatching in the VCT stacks consist for the larger part of timing the interchanges between the equipment to ensure a high capacity of the stacks. In this section the dispatching for each type of equipment in the VCT is discussed and optimizations are proposed. The objective of the dispatching is to maximize the capacity in terms of container moves each stack is able to perform.

### 4.2.1 RMT

In Chapter 3 is shown that the RMTs are potential bottlenecks in the processes of the VCT, but the process of unloading a container from the stack becomes even slower when the interaction with its surroundings is taken into account. The RMTs interact with the shuttle carriers on one side and the mezzanine on the other side. A shuttle carrier occupies a TP for around 30 seconds at the time (based on 10 seconds driving onto TP, 10 seconds grabbing or dropping a container and 10 seconds for leaving the TP). In this time period the RMT is not allowed at the TP. At the mezzanine side a container is delivered or moved away from the interchange point every 39 seconds (see Chapter 3). If the RMT is empty, the spreader can wait above the interchange point, which is the case for the stack-in RMT. However, if the RMT is loaded the RMT has to wait before moving over the TP. Figure 4.5 shows what the improving the timing between the stack-out RMT and shuttle carrier could mean in theory to the process time of the RMT. The proposed improvement, results in a decrease in process time of 13 percent.




(a) Process time without improved timing.




(b) Process time with improved timing.

**Figure 4.5: Effects on the RMT process time when improving the timing of the RMT.**

### 4.2.2 Cargo elevator

For the elevator the order it can perform depends on the containers available for pick-up. Figure 3.5 shows that the elevator can choose from the containers standing ready at the different buffer positions. These buffers are shown in the figure with the arrows pointing towards the elevator. In a stack of four storage floors this means that the elevator can select orders from from one point at the mezzanine floor and from two points per storage floor: making a total of nine orders.

The elevator can choose orders and therefore influence the sequence of the container unloaded from the stack. By choosing either a loading or unloading container, the elevator also influences the number of container on the mezzanine floor. The elevator is close to being the bottleneck in the process therefore the cycle times of the elevator need to be taken into account. Basically there are three factors that can influence the order selection of the elevator:

- Overcome the flooding of the mezzanine floor with containers by balancing stack-in and stack-out moves, but keeping the RMTs occupied.
- Ensuring that the containers are delivered to the QCs closest to the required sequence.
- Keeping the cycle time of the elevator low.

These factors and possible solutions will be discussed in the Sections 4.2.2.1, 4.2.2.2 and 4.2.2.3, followed by the complete dispatching strategy for the elevator in Section 4.2.2.4.

#### 4.2.2.1 Mezzanine floor flooding

As can was concluded from the hand calculations in Chapter 3 the performance of the stack depends for a major part on the occupancy of the RMTs. The stack-in RMT is not influenced by the dispatching of the cargo elevator, but the stack-out RMT is. The dispatching of the elevator should aim at having a container available for the stack-out RMT at all time. In the ideal situation (without any delays in the process) this would mean that a container must be dropped at the mezzanine floor at least every two minutes (the average cycle time of the RTMs is slightly longer). The average cycle time of the cargo elevator is almost one minute. To ensure the steady flow of containers to the RMT the decision of the cargo elevator for picking up a specific container depends on the amount of containers waiting on the mezzanine floor to be handled by the RMT. If the amount of containers waiting for the RMT is less than a predetermined limit, the elevator should prefer handling stack-out containers, on the other hand when the amount of containers waiting for the elevator to go into the stack is more than a certain limit these containers should be handled.

#### 4.2.2.2 Container Sequence

The containers moving to the QCs are bound to a certain sequence. The elevator influences the sequence of container unloaded from the stack. It might occur that from some floors only containers that are not immediately necessary at the QCs are available. These containers are dropped at the elevator by the ScLs. To make sure that containers that are expected earlier at the QCs are handled first, these containers need to be preferred when dispatching an order to the elevator.

#### 4.2.2.3 Elevator cycle time

The elevator is not the bottleneck in the current design of the VCT. However, when the design of the RMTs is improved, the capacity of the elevator of only one container can become the new bottleneck in the process. Therefore the cycle still needs improvement.

The cycle time of the elevator can be improved when the elevator is forced to perform dual cycle moves. Dual cycle can be enforced when the elevator alternates between stack-out and stack-in orders. Simply alternating between the different order types does not always result in the optimal solution. When for example a stack-in container is dropped at the first floor, and the only available stack-out container is from the top floor, getting another stack-in container is faster.

#### 4.2.2.4 Elevator dispatching

The first factor, which prevents the RMTs from going idle and balances the stack-in and stack-out orders on the mezzanine floor, is the most important for the performance of the stacks. The sequence is the second most important. Minimizing the cycle time of the elevator is only important if changes are made to the VCT stacks. Therefore the type (stack-in or stack-out) of order to be performed is determined first and if multiple stack-out orders are still possible, the sequence of the QCs determines which order to perform first.

The two steps for choosing an order for the elevator are:

- Determine which type of order is preferred using the amount of containers on the mezzanine floor. It is assumed that in the ideal situation at least 5 containers are waiting for the RMT to be unloaded from the stack, and no more than five containers wait for the elevator to be moved to a floor. For each type of containers the difference with the ideal scenario is determined resulting in a score for both types of containers. If the stack-out have the highest score, step two is performed, else the stack-in order is selected.
- The stack-out orders are sorted based on their expected time of arrival at the QC. The first order is the most urgent and is selected.

### 4.2.3 Scissor lift

There are three types of orders for the ScLs:

- Stack-in orders waiting at the elevator with a maximum of one at the time.
- Stack-out orders from the working area of the ScL.
- Rehandle orders in the working area of the ScL.

The amount of stack-in orders is limited to one because the buffer between the ScLs and the elevator can only supply one container at the time. The number of stack-out orders is determined by the containers requested by the QCs and the trucks. Rehandle orders depend on those requests. If containers are in the way when reaching for another container, those containers need to be rehandled.

Because the productivity of the ScLs is low compared to the other equipment in the stack, there is always time to do rehandles without delaying the process and influencing the performance of the stack. Stack-out orders are influenced by the same factors as presented in Section 4.2.2.2. Since the ScLs are at the beginning of the sequence for loading containers, the order selection by the ScL determines the sequence in which the containers arrive at either the QCs or trucks (if no delays occur). Therefore the ScLs also select the orders based on the requested arrival time at the destination. The orders for the QCs are known more in advance then orders for the trucks. Because of that the ScL can work far ahead QC loading schedule. To prevent the ScL from working too far ahead and by that flooding the stack-out route with containers for the vessel, leaving no space for incidental containers going to a truck, the ScL is not allowed to work more than 20 order ahead of the QC. With six QCs and eight stacks this means that if the containers are spread evenly over the different stacks, from every stack at least 15 containers are requested at any moment minus the ones already transported by the SCs.

## 4.3 Conclusion

In this chapter stacking and dispatching strategies for the VCT have been proposed. The stacking strategies handle import and export containers differently. The optimal location for each container is assumed to be based on:

- The occupancy of the yard equipment.
- The occupancy of the storage floor.
- The dwell time of the container.
- The floor of the location
- The number of containers of the same group already in the stack (export containers).

Each of these parameters is multiplied with a weighting factor to determine the optimal location for a container. The size of the weighting factors need to be determined. This will be done with the simulation model presented in the next chapter. The results of the experiments on the stacking strategies are presented in Chapter 6.

The dispatching of the equipment in the VCT is for the larger part determined by the location for container determined by the stacking strategy. For the elevator there is still the possibility select an order from available containers. The selection of the job that the elevator needs to perform is based on the balance of containers on the mezzanine floor and the sequence of containers moving to the QCs. With simulation the influence of the elevator dispatching on the performance of the yard is evaluated.

The ScLs are the first equipment to handle a retrieval order. The ScLs generally select orders based on the sequence the containers are loaded into the vessels. The dispatching of the ScLs depends on the number of orders for the QCs the ScLs are allowed to work ahead. It is assumed that working 20 orders ahead balances the occupancy of the stack-out RMT and the time it takes to serve the incidental truck order. Simulation will be used to evaluate different values for the number of orders the ScLs are allowed to ahead.

# Chapter 5

# Simulation model description

In the previous chapter stacking and dispatching strategies have been proposed. These strategies are evaluated in a simulation model. The objectives of the model are to evaluate the influences of the developed strategies on the performance of the VCT and compare the performance of the VCT to other more conventional storage yards. The simulation model is developed in eM-Plant software from Tecnomatix. eM-Plant is event based discrete simulation software based on on the scripting language simple++. An extensive library within eM-Plant developed by TBA contains many components used to model container terminals in general and is used as a basis for the simulation model of the VCT. The library also makes it possible to quickly generate a simple simulation model of alternatives storage yards to compare the VCT with. The structure of the simulation model of the VCT is presented in Figure 5.1. The input of the model consists of a scenario under which the VCT is evaluated (Section 5.1) and the simulation settings in which the used stacking and dispatching strategies are described. The model itself consists of the planning (Section 5.2.2 on the terminal (e.g. job scheduling, dispatching, routing, etc.) and the execution (Section 5.2.3) of the planning by the equipment. The output of the model is written to a database and exists of hourly data of the equipment such as number of performed moves and execution time.

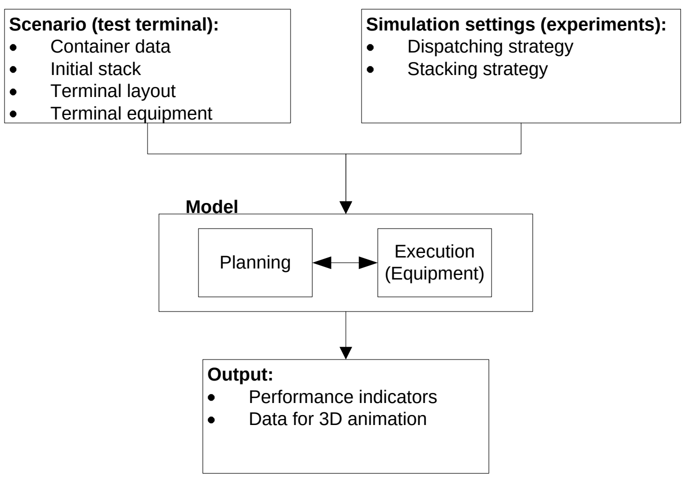



**Figure 5.1: Structure of the simulation of the VCT.**

To evaluate the performance of the VCT with a different storage yard, also simple model of an terminal with an automated RMG yard is developed. This model will be discussed in Section 5.3.

## 5.1 Test terminal

### 5.1.1 General description

To evaluate the performance of the stack a test terminal is designed. A layout of what a VCT terminal could look like is designed by Polotec and this layout will also be used in the simulation. The layout consists of six QCs, eight stacks of four storage floors (three for regular container and one storage floor for empty containers) each and a truck gate. The total storage capacity of the yard is 23.232 TEU. To leave enough extra space for performing rehandles the maximum density of each stack is 80 percent or 18.586 TEU. The dwell time of containers differs per terminal, but often an average dwell time of around five days is assumed. However there is a difference in dwell time between empty and regular containers. Due to the fact there is normally no rush to pick up empty containers their average dwell time might be twice as long as for a regular container. Assuming 15percent of the containers arriving at the terminal are empty with a dwell time of 9 days and the other 85 percent are regular with a dwell time of 4.5 days, the average dwell time is 5.2 days. In the storage yard this means that 26 percent of all the containers in the yard are empty, resulting in the storage floors for empty container being slightly more dense than the storage floors for regular containers.

The transshipment ratio determines the ratio between the number of import containers and export containers arriving per vessel. The transshipment ratio depends on the type of terminal. Container terminals can serve as hub with a transshipment ratio above 40 percent up to even 90 percent (Huang et al., 2008) for transport over water or as import/export terminal serving the hinterland. For the test terminal the transshipment ratio is assumed to be 55 percent, which results in 31 percent of the containers is the storage yard being import containers and 69 percent export containers.

With the presented settings for the test terminal the total annual number of container moves over the quay can be calculated. This number represents the size of the terminal so it can be compared with terminals of the same capacity. The transshipment flow of 55 percent means that in total 72.5 percent of the number of containers going over the quay goes through the stack, because transshipment containers go over the quay twice while only once trough the storage yard. As a rule of thumb the peak density of the yard is 1.3 times the average density, therefore the average number of TEU in the stack is 14.296 TEU. The average dwell time of 5.2 days gives an arrival rate of container in the yard of 2.762 containers per day, which is 72.5 percent of the total number of containers going over the quay. The total annual throughput of the designed terminal is 1.39 million TEU per year. In Figure 5.2 the container flows over the terminal are presented.

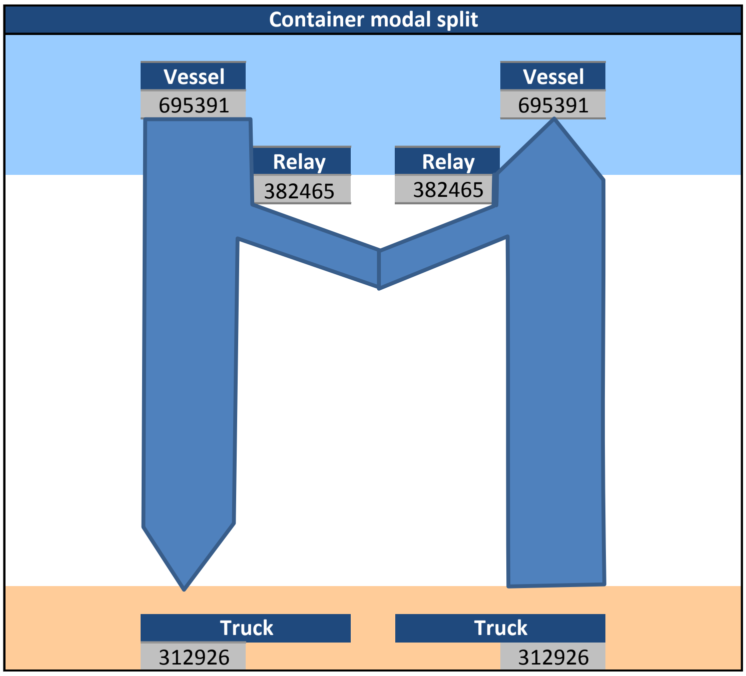



**Figure 5.2: Modal split in TEU for the test scenario.**

Because the goal is to evaluate the performance of the yard and not the terminal in total, the influence of the processes of the horizontal equipment, truck gate, and the QCs is minimized by making sure enough capacity is available. 120 trucks per hour arrive at the gate to either deliver or pick-up a container. The speeds of the QCs are set slightly higher than what is possible in actual operations. The QCs are able to perform over 50 moves per hour at least. In total this generates a constant flow of containers of 420 moves per hour trough the yard. Therefore each stack needs to perform 53 moves in order to keep up with the requirements. Based on the possible productivity from the calculations in Chapter 3 this performance is assumed to be too high for the stacks to ever reach. After each simulation the idle time of the QCs and the horizontal equipment is monitored to ensure the performance is not influenced by these equipments. There are 35 shuttle carriers available for performing the moves.

This concludes the general description of the test terminal used to evaluate the performance of the VCT under different settings for the stacking and dispatching strategies. In the next section the distributions of the parameters are discussed in more detail.

### 5.1.2 Detailed description

#### 5.1.2.1 Container dwell times

In the previous section the average dwell time of a container is stated to be 5.2 days. The distribution of the dwell time is based on experts experience of the arrival pattern of containers at the terminal. To generate a realistic dwell time for every container an

Erlang distribution is used to determine the dwell time per container. The asymmetrical shape of the Erlang distribution (Figure 5.3) compares with the arrival of the containers.

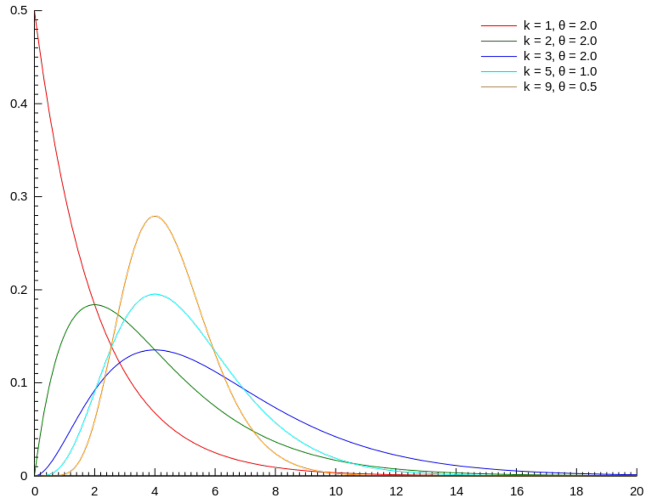



**Figure 5.3: Example of an Erlang distribution.**

#### 5.1.2.2 Container weights

The weight of a 40-ft container ranges from 4 tons for an empty container up to 35 tons for a loaded container. The weight distribution is based on average weight distributions provided by TBA. The weight distribution of containers is presented in figure 5.4. Only the weight distribution of 40-ft containers is presented because no 20-ft containers are used in the model.

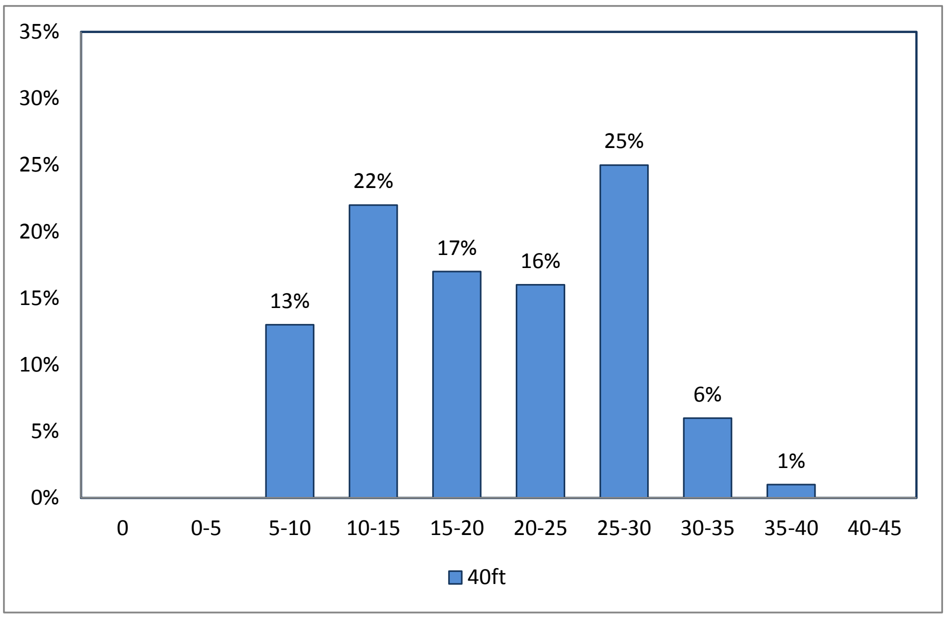



**Figure 5.4: Weight distribution of the containers.**

#### 5.1.2.3 Container services

A container terminal is often visited by several shipping companies (services) spread over the week. Containers arriving at the terminal are linked to a shipping company. The amount of services handled on a terminal is specific for a terminal. For the scenario an assumption is done for the amount of services. Since the scenario defines a throughput of 1.39 million TEU over the quay, this can be used to estimate the amount of vessels arriving in a week using a call size of on average 3.500 TEU per vessel. 1.39 million divided by 52 weeks results in 27.000 TEU per week, which divided by 3.500 results in around eight vessels per week. Assuming that vessels arrive periodically once a week, the amount of services visiting the terminal is also eight. The simulation will simulate only 8 hours during the week, which means that for the vessels about to arrive or arriving, more containers will be in the yard, while the containers arriving at the terminal during those 8 hours will be from other services arriving later that week. Figure 5.5 gives an example of the amount of containers of the different services during the week.

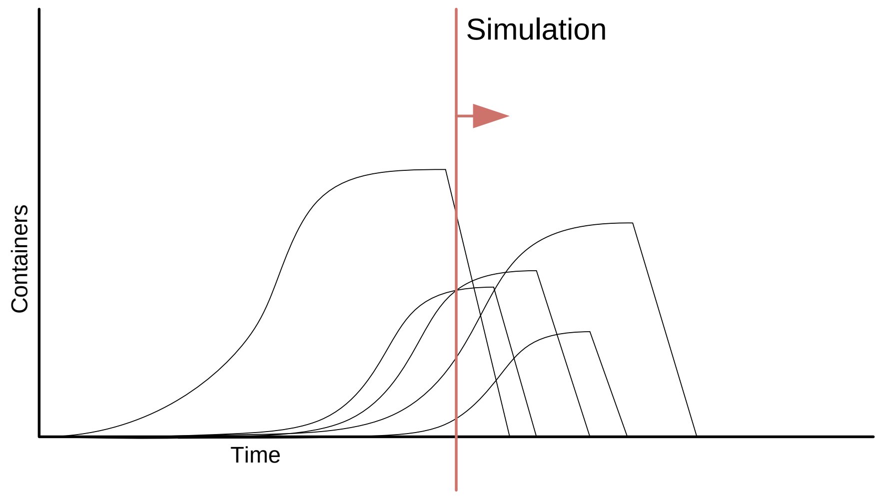



**Figure 5.5: Example of the distribution of containers in the yard during a specific moment in time.**

To take into account these two different situations, two distributions are assumed for the creation of new containers. The distribution of the services of the containers is presented in Table 5.1. In column two the distribution from the initial build is presented and in column three the distribution during the simulation. The vessels for the first three services are assumed to be loaded or unloaded during the simulation or arrive soon.

**Table 5.1 Services for containers**

| Service | Containers at initial stack build | Containers arriving during the run |
|---|---|---|
| Service 1 | 25% | 10% |
| Service 2 | 20% | 5% |
| Service 3 | 20% | 8% |
| Service 4 | 7% | 10% |
| Service 5 | 7% | 15% |
| Service 6 | 7% | 16% |
| Service 7 | 7% | 16% |
| Service 8 | 7% | 20% |

The expected dwell time of the export containers can in real operation be determined from the vessel plan. In Figure 5.6 a vessel plan for the eight arriving vessels is presented. This vessel plan is based on average vessel sizes and handling time per vessel. The vessel plan can be used to estimate the dwell times for the containers. During the simulation only vessel S1 and S2 will be loaded or unloaded, but the arrival times of the other vessels will also be used to allocate incoming containers to the yard.

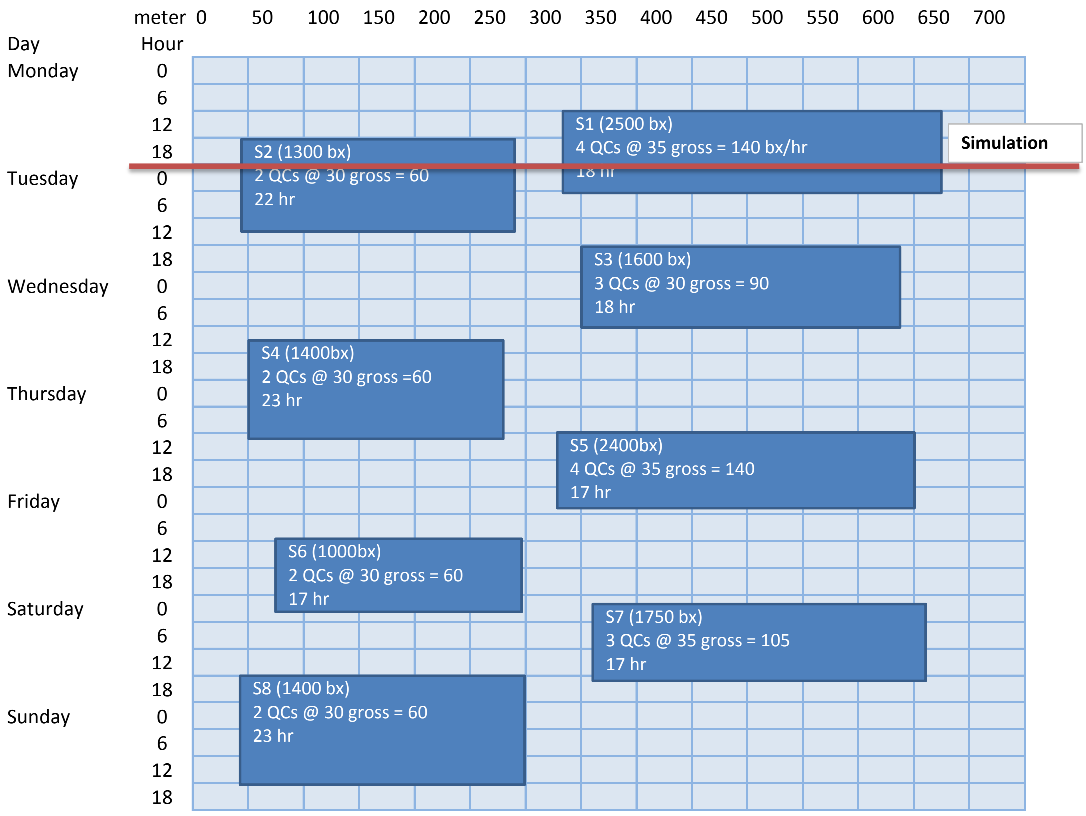



**Figure 5.6: The vessel plan for the test scenario.**

#### 5.1.2.4 Port of discharge

Different vessels visit different ports. For every container the port of discharge is also determined. Depending on the service of the container, the container is destined for one of three ports visited by that specific service. These ports can partially be the same for the different services.

### 5.1.3 Initial stack

Before the start of the simulation, all containers are created and allocated to a slot one by one. Since the containers have arrived at different moments in time, and thus have a different dwell time, first a list of containers is generated. The specifications of each container are determined by the distributions of weight, origin, destination, type and import/export presented in the previous sections. In Table 5.2 presents the distribution of containers in the initial stack.

**Table 5.2 Distribution of containers in the initial stack.**

| | Export | Import | T/S | Sum |
|---|---|---|---|---|
| regular | 23% | 23% | 28% | 74% |
| empty | 8% | 8% | 10% | 26% |
| Sum | 31% | 31% | 38% | 100% |

In the second step the time of arrival is determined by generating a dwell time for the container based on the distributions presented in Section 5.1.2.1. The dwell time is subtracted from the expected arrival of the vessel from the vessel plan. This process is presented in Figure 5.7.

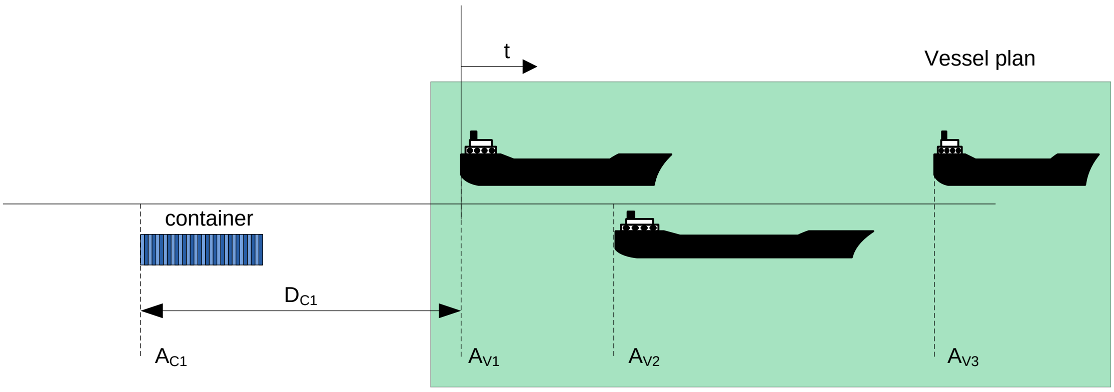



**Figure 5.7: Determination of arrival time ($A_{c1}$) of a container for vessel 1 by using the dwell time ($D_{c1}$) and the arrival ($V_{a1}$) of the vessel.**

In the final step, before the actual simulation run, the container is allocated to a specific location in the yard. The sequence of this allocation is determined by the arrival time of the container. Since no realistic information on the occupancy of the equipment and occupation of stacks is available before the start of the simulation, this information is randomly generated when a new container is created. This is assumed to result in a realistic layout of the stacks.

## 5.2 VCT simulation model

In the previous section a test terminal to evaluate the performance of the VCT is presented. The test terminal is the first part of the input of the simulation model. The second part of the input for the simulation model are the experiment settings, which are presented in Section 6. In this section the working of the developed simulation model is discussed. Figure 5.1 shows that the model consists of the planning and the execution by the equipment. In Section 5.2.1 is explained how orders are created in the simulation model. In Section 5.2.2 the planning in the model is discussed and in Section 5.2.3 the execution of the orders by the equipment is discussed.

### 5.2.1 Order creation

The job creation in the simulation model uses the input data as specified in Section 5.1. Three types of orders can be distinguished at the terminal; orders from the vessel, orders from the truck gate and rehandle orders in the stack.

The orders from the vessel are either unload or load orders. The containers that need to be loaded into the vessel are selected by the QCs. Based on the current vessel at the berth the QC selects containers from the yard. This is done by randomly selecting a container from the same service as the vessel. The containers of the same group that are in the same pile of the selected container are also added to the load plan. This is repeated until 75 containers are selected. The 75 containers represent the number of containers moving into a single bay in the vessel. When the 75 containers are almost loaded into the vessel, the whole process starts over again to select containers for the next bay. The 75 randomly selected containers are sorted on their weight class to simulate a normal loading sequence. For containers of the same weight class the sequence is changed to prevent sequential orders from the same stack. This distributes the workload over the stacks as much as possible. Orders to unload a container from the vessel are also generated by the QCs. The containers that need to be unloaded are created based on the distributions of container specifications presented in the test terminal description. Again the orders are created in batches of 75 orders. The total numbers of orders created depends on the unloading speeds of the QCs.

The number of orders from the truck gate depends on the number of truck arrivals per hour specified in the scenario. A container to be picked up by truck is randomly selected from the import containers in the yard. An container arriving per truck is created based on the distribution of container specifications.

### 5.2.2 Planning

As mentioned in the introduction of this chapter, the planning on the terminal performs the tasks normally handled by the TOS on existing terminals. The tasks of the TOS are the job dispatching of terminal equipment and the routing of the equipment. Figure 5.8

shows a representation of the planning in the simulation model and how the planning interacts with the execution of the orders. In the figure the following modules can be distinguished:

- Central planning and scheduling: The central planning collects the orders that need to be performed by the terminal. The orders are sorted based on execution time and the sequence of the yard equipment that needs to handle the orders is determined.
- Grounding: The grounding determines the location for each container arriving at the terminal. To do so the grounding makes used of the stacking strategy described in Chapter 4.
- TP management: TP management keeps track of all containers waiting for pickup by yard equipment.
- Equipment dispatchers: The dispatchers control the equipment. If an order needs to be performed by the equipment, the dispatcher determines which vehicle is going to perform the job, end sends the jobs to the execution part of the model.

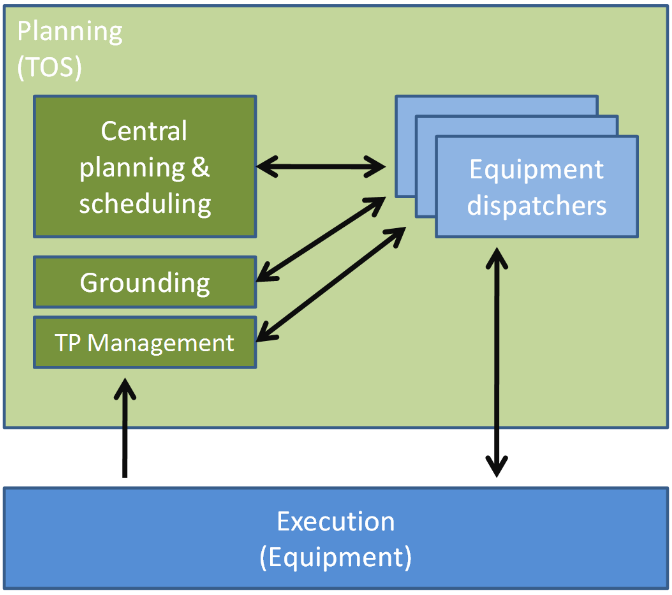



**Figure 5.8: Representation of the TOS in the simulation model. (source: TBA)**

#### 5.2.2.1 Job dispatching

The central planning collects all the orders on the terminal. The scheduling determines the sequence of equipment for handling each order. When for instance a truck arrives at the terminal, the following equipments are involved: shuttle carrier, RMT, mezzanine floor, cargo elevator and ScL. The central planning informs the dispatchers of the equipment of the orders that need to be handled. The dispatchers determine which vehicle or crane is going to perform the order and sends the order to the equipment manager.

#### 5.2.2.2 Rehandles

The rehandles are performed by the ScLs on every floor. To determine if rehandles are needed, a selection is made of each container that is scheduled to leave the stack. Per container the number of containers blocking the route of the container out of the stack is determined. For every blocking container the expected retrieval time is compared with the retrieval time of the container for which the rehandles are determined. If the blocking containers are expected to be retrieved earlier, nothing happens; else the rehandle orders are planned.

The second step is to determine a new location for the container that is blocking another container. The new location of the container depends on the current location of a container due to the limited working area of the scissor lifts. If the container is not in the exact middle of the stack the destination for the container can only be in the working area of an ScL where it is already located. The allocation of the container is then performed in two steps:

- Step 1: Check the vicinity of current location, maximum four bays from current position.
- Step 2: Check for a new location on the total floor.

### 5.2.3 Execution

The execution of the orders is done by the actual terminal equipment. Figure 5.9 shows a representation of the execution of orders in the model. The following modules can be distinguished in the execution:

- The equipment managers: The equipment managers form the link between the planning and the physical equipment. The equipment manager receives jobs from the planning via a dispatcher. The managers split the order in to job-steps to be performed by the equipment. Example of a job-step is: drive from coordinate $[x_1, y_1]$ to $[x_2, y_2]$. It uses the infrastructure to determine the route for the equipment. The managers keep track of the movements of the equipment to avoid collisions and deadlocks.
- The equipment: The equipment is the actual equipment on the terminal. The equipment is modeled with their own kinematic properties to simulate their behavior close to reality. The equipment receives job-steps from the manager and reports back its progress to the manager.
- The inter-change (IC) manager: The IC manager arranges the interchange of containers between the different equipment. Equipment often only knows a location to drop or pick-up a container, but not with what equipment an interchange is performed. Therefore the IC manager facilitates this interchange.

The handling equipment responsible for the execution of the orders in the VCT are:

- QCs
- Shuttle Carriers
- RMTs
- Mezzanine floor
- Cargo elevator
- ScLs

The processes of the handling equipment in the model are explained in the next sections.

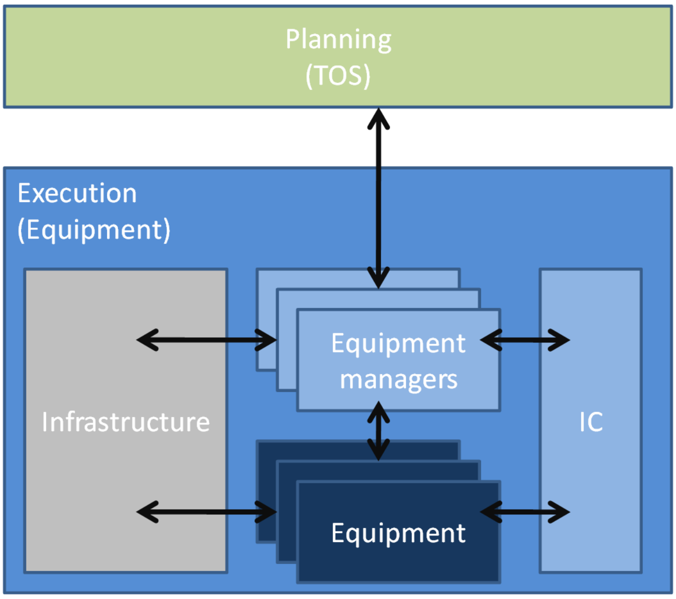



**Figure 5.9: Representation of the execution in the simulation model. (source: TBA)**

#### 5.2.3.1 QCs

The QCs are modeled by TBA and used in the VCT to generate the orders from the WS. The generation of orders is discussed in Section 5.2.1. The different components of the QC (e.g. trolley, spreader, etc.) are modeled separately and work together to perform the moves of the QC. The model uses the distances of the moves in combination with the specifications of the QC and weight of the loads to determine the time each movement takes.

#### 5.2.3.2 Shuttle Carriers

The model for the shuttle carriers is also an already existing model which is used in the VCT. The shuttle carriers are modeled close to how it should behave in reality. Due to the fact that a shuttle carrier is a manned vehicle, the model does not take into account collision avoidance.

#### 5.2.3.3 RMTs

An RMT has two directions of movement; moving in the length direction of the stack and lowering or hoisting the spreader. Figure 5.10 shows the basic process of the RMT. The RMT receives the job-steps defined by the RMT manager. The manager checks if a container is available at the TP on the ground for the stack-in RMT or on the mezzanine floor for the stack-out RMT. It does this whenever the RMT has finished an order. Because it is possible that no container is available for pick-up at that moment, the dispatcher checks for containers again when the RMT is still idle and the manager receives a signal from the planning that the previous equipment is done. The steps shown in the figure are also the job-steps that the RMT equipment receives from its manager. The steps consist of locations and pre-conditions. The pre-conditions determine when each job-step can be performed. For instance the lowering of the spreader has as pre-condition that the move in the direction of the stack is finished. The previous equipment is either the mezzanine floor or a shuttle carrier. In some cases it is possible that the RMT already picks up a container before the location where it needs to drop the container is free from other containers or shuttle carriers. Therefore the RMT has as pre-condition for the movement in the direction of the stack that the drop-off location must be free.

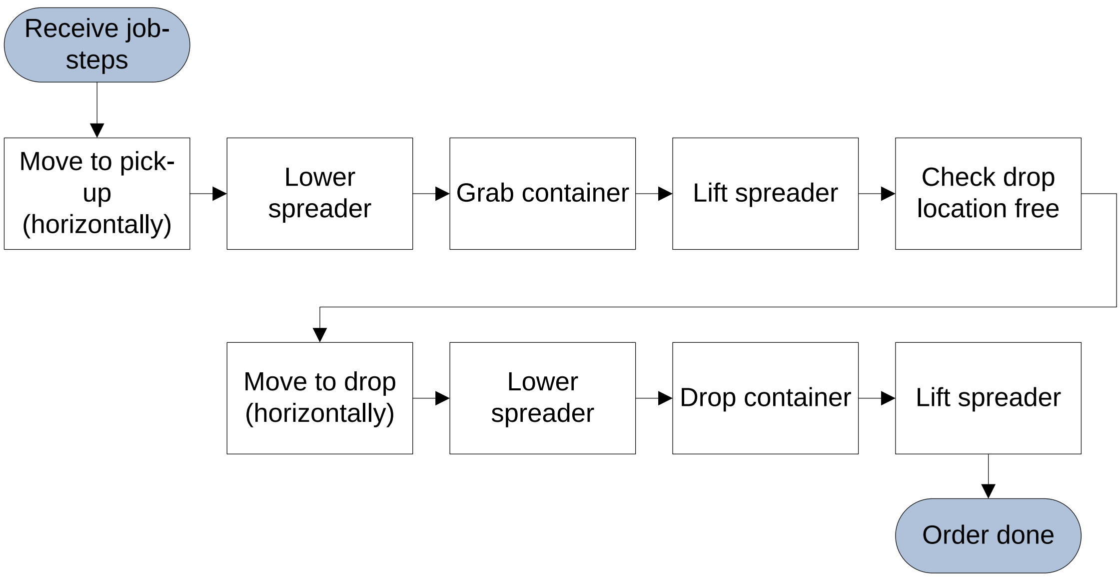



**Figure 5.10: Representation of the RMT process in the simulation model.**

As presented in Chapter 4, the RMT can increase it efficiency by preparing for the next move. The preparation of the moves is modeled by adding an extra job-step after the steps presented in the Figure. For the stack-out RMT the first four job-steps, moving to the pick-up location and grabbing a container, are added after the current final job-step. The stack-in RMT is allowed to move horizontally above the TP on the ground right after it has finished a stack-in order.

#### 5.2.3.4 Mezzanine floor

The mezzanine floor receives the containers from the RMTs and the elevator. When a container is dropped at the mezzanine floor, the mezzanine floor receives a notification which container has been dropped. The mezzanine floor requests a route from its mezzanine manager. The route consists of a list of roller beds the container needs to be moved by. Before the container is moved to the next roller bed, the mezzanine floor checks if the next roller bed is empty. If this is the case, the process is repeated until the container reaches its final destination on the mezzanine floor. If a container has to wait for another container, it is added to a waiting list. Each time a container is moved to the next roller bed or removed from the mezzanine floor by a RMT or the elevator, this list is checked. The movement of the container over the mezzanine floor is initiated again. Figure 5.11 shows how the mezzanine floor process is modeled.

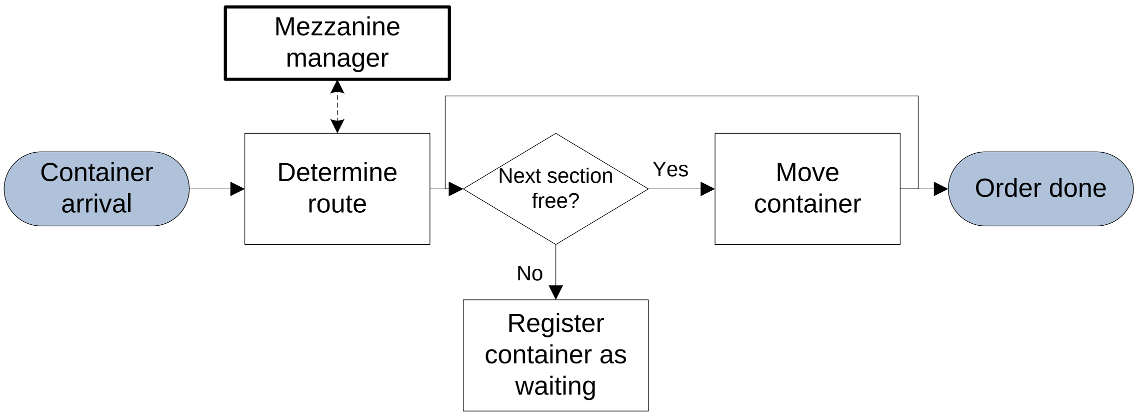



**Figure 5.11: Representation of the mezzanine process in the simulation model.**

#### 5.2.3.5 Cargo elevator

The cargo elevator receives containers from the mezzanine floor and the storage floor buffers. The elevator dispatcher in the planning part of the model keeps a list of orders for the elevators. The dispatcher starts selecting an order for the elevator if the elevator is idle and a container is available. If multiple containers are available the in Chapter 4 defined rules for job dispatching are used to select an order. The elevator manager splits the order up into job steps for the elevator. The process of the elevator is presented in Figure 5.12.

#### 5.2.3.6 ScLs

In Chapter 3 the job-steps of the ScLs have been explained. These job-steps are defined by the ScL manager. The ScL dispathcer has a list of order for retrieving containers from the stack for loading the vessel. Orders from the truck gate are added to this list whenever a truck arrives at the terminal to pick up a container. Orders for storing containers in the stack are added to the list once the containers arrive at the storage floor. Orders for rehandling containers are also in the list. In Section 5.2.2.2 the process of determining rehandles has been explained. Whenever an ScL is idle, the ScL dispatcher determines

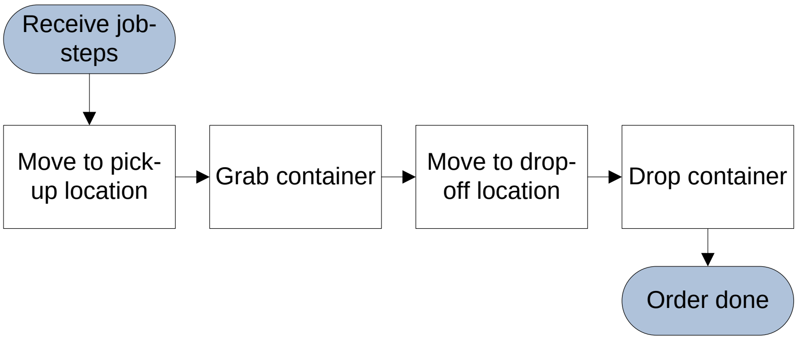



**Figure 5.12: Representation of the cargo elevator process in the simulation model.**

what orders the ScL can perform. Possible orders for an ScL are orders that are in the working area of the ScL. Based on the dispatching rules defined in Chapter 4 an order is selected to be performed by the ScL.

### 5.2.4 Simplifications in the VCT model

Although the RMTs are capable of moving containers both stack in and stack out, the model is simplified by setting a dedicated RMT for each type of move. By this simplification the routing of containers on the mezzanine floor becomes less complex. The slow speeds of the roller beds are assumed to result in losses of productivity when RMTs constantly switch between loading and unloading containers.

## 5.3 ASC simulation model

In Chapter 7 the VCT is compared with an ASC yard. To evaluate the performance of the ASC in the scenario presented in Section 5.1, a simulation model of the same structure as the VCT simulation model is developed. The structure of planning and execution in the model is the same as presented in Section 5.2. The differences with the VCT model are the used stacking strategy and the type of yard equipment. In this section those differences are explained.

### 5.3.1 Yard cranes

In the ASC simulation model the yard is served by automated RMG cranes. Per stack two of these cranes are available. The cranes are not allowed to pass each other. One crane is serving the WS and the other crane the LS. The specifications of the cranes are chosen to match the average ASC (Kemme, 2013). Table 5.3 presents the specifications of the ASCs used in the simulation model.

**Table 5.3 Specifications of the ASC cranes in the simulation model.**

| | Export |
|---|---|
| Gantry speed | 4.5 $m/s$ |
| Gantry acceleration/deceleration | 0.3 $m/s^2$ |
| Trolley speed | 1.0 $m/s$ |
| Trolley acceleration/deceleration | 0.3 $m/s^2$ |
| Spreader hoisting/lowering speed | 0.5 - 1.0 $m/s$ |
| Spreader acceleration/deceleration | 0.35 $m/s^2$ |

### 5.3.2 Stacking strategy

The stacking strategy applied in the simulation model of the ASC is based on the stacking strategies used on conventional terminals described in Chapter 2. The stacking strategy determines the optimal location for a container in two steps. In the first step the stack is determined. In the second step the final location for the container within the stack is determined. The first decision is made when the container is dropped at the quay by a QC or a truck delivering a container has arrived. The following factors are considered when finding a stack for the container:

- Distance from the location of the container to each stack.
- The expected next destination (e.g. vessel or truck).
- The availability of piles of containers of the same group (for export containers).
- The density of each stack.
- The workload of the yard cranes.
- The workload of the shuttle carriers.

When the optimal stack for the container is determined, the shuttle carrier transports the container to the stack. When the container is dropped on the TP of the stack, the location in the stack is determined. The optimal location in the stack for a container is determined based on the specification of the container. Export containers are preferred to be located in piles of the same group. Import containers are stacked close to the landslide when the workload of the yard cranes is not to high.

## 5.4 Assumptions and Simplifications

In the previous sections the simulation models for the VCT and ASC yards are explained and a test terminal is defined to evaluate the performances of the storage yards. The test terminal already contains assumptions on the container flows over the terminal. In this section other assumptions and simplifications of the simulation models are discussed.

The simplifications made for both simulation models are:

- The simulation models do not take into account breakdowns of equipment.
- Only 40-ft containers are used in the simulation, because the VCT does not contain a system for moving 20-ft containers together on one super skid.

## 5.5 Validation and Verification

In the previous section simulation models are developed for the VCT and a terminal with an ASC yard. In this section the validation and verification of the simulation models is discussed to determine if the model is right (verification) and if it is the right model (validation).

### 5.5.1 Verification

The simulation is based on the eM-plant library from TBA, TIMSQUARE (Tecnomatix, 2014), which has already been used in many projects so basic equipment in the VCT has already been verified during these projects. Verification of the added VCT model is done in several ways. First of all the code is constantly checked during the development of the simulation. Figure 5.13 presents the development environment of eM-plant. At the bottom of the screen events and possible errors are printed and the graphical interface in the middle of the screen is used to detect problems such as idle equipment or equipment moving the wrong way. To evaluate the processes in more detail the eM-plants line by line trace function is used.

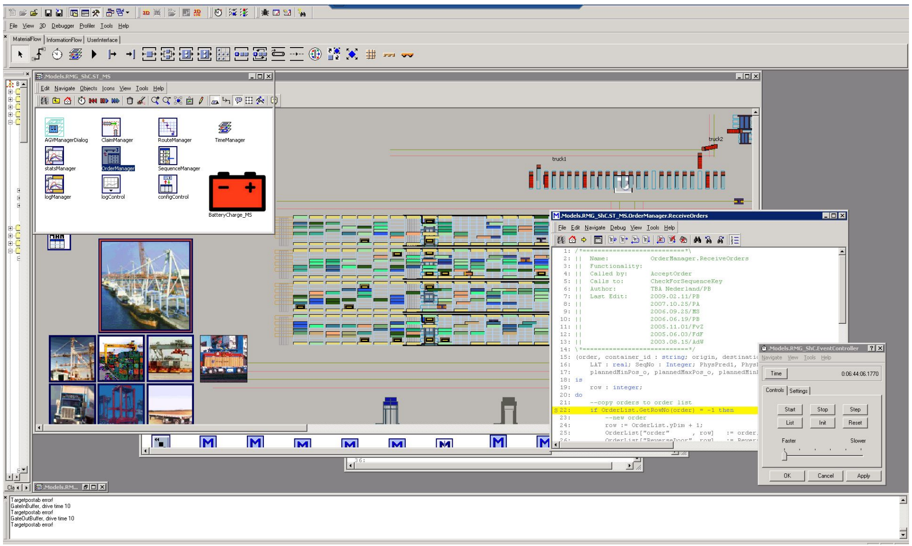


**Figure 5.13: An overview of the modeling environment in eM-plant.**

Results from the simulation are also loaded in a 3D replay environment to determine if the movement of the equipment and containers is fluent and realistic. Figure 5.14 shows two examples of the 3D animation.


**(a) Container handling by RMTs.** **(b) Scissor lift, buffer interaction.**

**Figure 5.14: Captures from the 3D animation.**

Furthermore the results of the simulation are constantly compared with the hand calculations presented in Chapter 3.

### 5.5.2 Validation

Validation of the model is often done by comparing the results of the model with real live data. In case of the VCT, no real live data is available since the VCT stack has not been built yet. Therefore the validation of the model is performed by evaluating the model with the designers by use of the 3D animation and by comparing their expectations of the results of the model with the outcome of the model. The model has been accepted by the designers of the VCT stack as the right model for the simulation of the VCT.

## 5.6 Conclusion

In this chapter simulation models for the VCT and an ASC terminal are developed to evaluate the performance of the VCT under different settings for the stacking and dispatching strategies and compare the VCT and ASC yard. The models have been verified and validated.

# Chapter 6

# Experiments & Results

In Chapter 4 stacking and dispatching strategies for the VCT are developed. The simulation model defined in Chapter 5 is used to evaluate the performance of the VCT under the influence of the different weighting factors of the stacking strategy and settings for the dispatching strategy. Each experiment is performed multiple times with different randomly generated containers. The performed experiments consist of runs of eight hours. The first hour is assumed to start up the simulation and thus removed from the results. For each result at least 100 hours of experimental data is collected. In this chapter experiments to evaluate the VCT are defined. The experiments are structured as following:

- Experiments for determining optimal weighting factors of for the stacking strategy (Section 6.1).
- Experiments for evaluating the different settings for the dispatching in the VCT (Section 6.2).
- Experiments to determine the performance of the VCT based on the best results from the other experiments (Section 6.3).

Conclusions on the performed experiments are presented in Section 6.4.

## 6.1 Stacking strategy

### 6.1.1 Experiments

The three basic equations from Chapter 4 consist of different weighting factors that influence the stacking strategy. For determining the optimal location for import containers the following weighting factors are involved:

- $(R_i * W_{Ro})$: $R_i$ is the number of containers moving to the stack. $W_{Ro}$ can be varied. A relative high value for $W_{Ro}$ puts the focus on the current situation in the stack, balancing the workload at the moment the location for a container is determined.
- $(C_i * W_{So})$: $C_i$ expresses the occupancy of the stack in terms of containers in a value between zero and one. A high value for weighting factor $W_{So}$ means that containers

are distributed over the stacks evenly, which might result in a better distribution of workload in when a containers are being retrieved from the stack again.

The equation for determining the optimal location for a reservation for an export container group uses partly the same weighting factors as for import containers. The additional weighting factors are:

- $G_l * W_g$ : $G_l$ is the number of containers and reserved slots of the same group already in the stack. Weighting factor $W_g$ determines how important spreading the containers of the same groups over the different stacks is. A relative higher value is expected to result in a low distribution of containers of the same group. This can result in delays in the loading process of a vessel because to many containers need to be retrieved from the same stack in a short amount of time.
- $F_r * D * W_d$ : $D$ is the expected dwell time of a container. Weighting factor $W_d$ determines how important the dwell time of a container is for the allocation of a container and $F_r$ is the floor where the reservation can be made.

Table 6.1 summarizes the weighting factors for the dispatching strategy. For each weighting factor the expected influence is shown. Because the weighting factors are multiplied with variables that are different in size, the average value of the variables is shown.

**Table 6.1 Weighting factors of the stacking strategy for import containers.**

| Weighting factor | Expected effect of factor | Unit variable | Value variable |
|---|---|---|---|
| $W_{Ro}$ | With a high value the workload at current moment is distributed evenly. | orders | (0-5) |
| $W_{So}$ | With a high value the workload in the future is expected to be distributed evenly. | occupancy | (0-1) |
| $W_g$ | With a high value the groups need to be spread over the different stacks, resulting in a better distribution of the workload when loading a vessel. | slots | (0-200) |
| $W_d$ | With a high value the a higher floor is preferred when the dwell time is long. | dwell time | (1-14) |

To determine the influence of the different weighting factors, the weighting factors are applied one by one in different experiments. In each of the experiments, the weighting factor is set equal to one and the rest to zero. Therefore, if none of the other weighting factors are applied, only the weighting factor with value zero determines where a container is allocated to. For each experiment, the performance of the stacks in terms of container moves is discussed. Each experiment is performed with the settings of the test terminal presented in Chapter 5. The different experiments and expectations are defined as following:

- Experiment 1.1: Determine the performance of the stack when no weighting factors are applied, to serve as a baseline for comparing the rest of settings.

- Experiment 1.2: The weighting factor for RMT occupancy is applied. It is expected that the containers going into the stack are spread over stacks, distributing the workload over the different RMTs and increasing performance for the stack-in handling of the containers.
- Experiment 1.3: The weighting factor of the groups is applied, spreading the containers from the same groups over the stacks. This experiment is expected to result in a higher performance of the stack-out moves, due the spread of the workload of vessel loading orders.
- Experiment 1.4: The weighting factor for the dwell time is applied. Containers with longer dwell times are placed higher in the stack. The expected result is a shorter average cycle time for the elevator. This might not directly influence the performance of the stack if the elevator is not the bottleneck in the process.
- Experiment 1.5: The weighting factor for the stack occupancy is applied. Applying this weighting factor results in the containers being evenly spread over the terminal, but not taking into account how busy the equipment in the stacks are. The expected influence of this weighting factor is the spread of the workload from container going stack-out.

In table 6.2 the settings for the experiments are summarized.

**Table 6.2 Overview of experiments for determining influence of weighting factors.**

| Experiment | Description | $W_{Ro}$ | $W_{So}$ | $W_d$ | $W_g$ |
|---|---|---|---|---|---|
| 1.1 | Random stacking | 0 | 0 | 0 | 0 |
| 1.2 | Stacking based on RMT occupancy | 1 | 0 | 0 | 0 |
| 1.3 | Stacking based on groups distribution | 0 | 0 | 0 | 1 |
| 1.4 | Stacking based on container dwell time | 0 | 0 | 1 | 0 |
| 1.5 | Stacking based on stack occupancy | 0 | 1 | 0 | 0 |

From the first set of experiments, experiment 1.2 and experiment 1.3 showed an increase the performance of the VCT (see Section 6.1.2 for more details). Therefore the weighting factors of those experiments are further evaluated in a second set of experiments. The second set of experiments aims to find a balance between both weighting factors by testing five different situations. The second sets of experiments consists of the following experiments

- Experiment 2.1: equal weight for both factors. The weighting factor for occupancy RMT is multiplied with the amount of containers moving to the stack, which is assumed to be 3 containers. The weighting factor for the distribution of containers of the same group is multiplied by the number of containers of the same group already in the stack. In the tested scenario these groups consist of 50 to 500 containers, spread over eight stacks. This results in a ratio 10:1 for $W_{Ro}$:$W_g$.
- Experiment 2.2: slightly larger influence for the occupancy of the RMT. The preference for each container is be to allocated based in occupancy of the RMT, but if the spread of group containers is very unbalanced the container is allocated based on the group weighting factor.

- Experiment 2.3: the influence of the RMT occupancy is leading. As long as there is a difference in penalty between the stacks based on the RMT occupancy, the other weighting factor is of no influence. If more slots are optimal based on the RMT occupancy, the slot with the lowest penalty on group distribution from those slots is the best location.
- Experiment 2.4: slightly larger influence of the group distribution.
- Experiment 2.5: the influence of the group distribution determines the optimal location. If multiple slots are optimal based on the group distribution the RMT occupancy determines the best location from those slots.

In table 6.3 the the settings for the experiments are summarized.

**Table 6.3 Overview of experiments for determining the optimal value for the weighting factors.**

| Experiment | Description | $W_{Ro}$ | $W_g$ |
|---|---|---|---|
| 2.1 | Equal influence | 10 | 1 |
| 2.2 | RMT occupancy $>$ Group distribution | 20 | 1 |
| 2.3 | RMT occupancy $>>$ Group distribution | 100 | 1 |
| 2.4 | RMT occupancy $<$ Group distribution | 10 | 3 |
| 2.5 | RMT occupancy $<<$ Group distribution | 1 | 100 |

The experiments on the stacking strategy in the VCT are performed with the following dispatching rules:

- The ScLs are allowed to work 20 containers ahead of the current container loaded into the vessel.
- The elevator performs the order based on the time the container becomes available for pick-up by the elevator.
- The RMTs use the optimized job dispatching presented in Section 4.2.1.

### 6.1.2 Results

In the next sections the results of the experiments on the weighting factors for the stacking strategy are presented. In the Section 6.1.2.1 the results on the performance of each of the weighting factors are presented. In Section 6.1.2.2 the result for determining the optimal value for two of the weighting factors is presented.

#### 6.1.2.1 Influence of the weighting factors

To get an overview of the results Figure 6.1 presents the result for the experiments in one graph. The results are expressed in the average number of RMT moves per hour per stack. The RMTs are the first and last equipment of a stack to handle a container and give therefore a clear representation of the performance of the stacks in terms of container moves.

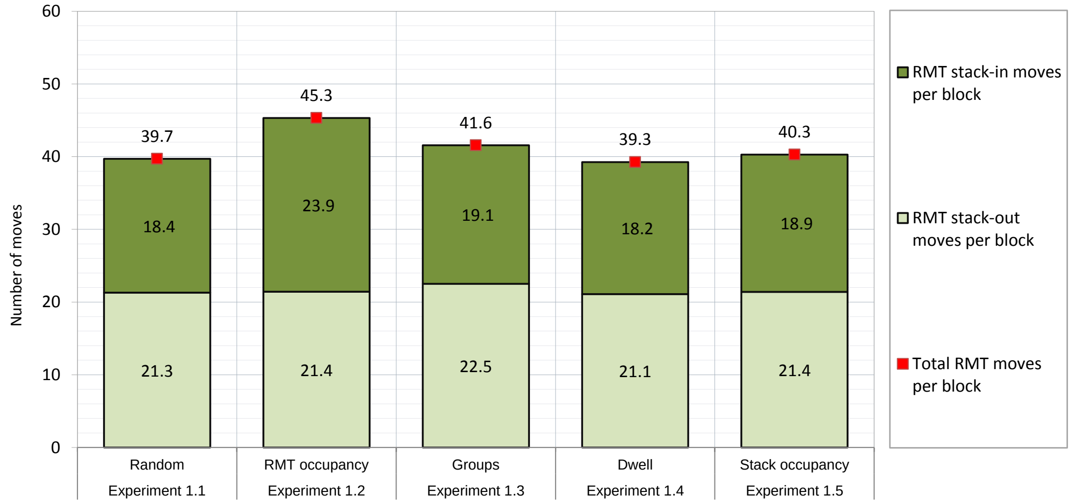



**Figure 6.1: The average number of container moves per stack per hour.**

**Experiment 1.1: Random** For the baseline experiment no stacking strategy is used. The import containers are still placed in the free-access slots and the export containers are grouped in the middle of the stack, but selecting one of these slots is done totally random. To determine what limits the performance in this case, the occupancy of the equipment is evaluated.

Figure 6.2 shows the idle time of the RMTs over a set of 7 hours for both the stack-in and stack-out RMT per stack. From the figure can be seen that the workload is not divided evenly over the different stack. While some RMTs have almost no idle time left, other RMTs are not working at all. The differences in idle time are larger for the stack-in RMTs then for the stack-out RMTs resulting in an average idle time of 61 percent for the stack-in RMT and 22 percent for the stack-out RMT.

| Hour | Stack 1 | Stack 2 | Stack 3 | Stack 4 | Stack 5 | Stack 6 | Stack 7 | Stack 8 |
|---|---|---|---|---|---|---|---|---|
| 2 | 7% | 46% | 86% | 69% | 17% | 72% | 60% | 50% |
| 3 | 8% | 85% | 88% | 77% | 61% | 86% | 92% | 89% |
| 4 | 8% | 82% | 41% | 78% | 30% | 46% | 69% | 82% |
| 5 | 68% | 57% | 58% | 68% | 6% | 82% | 72% | 75% |
| 6 | 76% | 65% | 67% | 85% | 4% | 86% | 73% | 82% |
| 7 | 33% | 81% | 82% | 82% | 4% | 82% | 72% | 75% |
| 8 | 8% | 66% | 68% | 54% | 39% | 78% | 78% | 75% |

**(a) Idle time stack-in RMT.**

| Hour | Stack 1 | Stack 2 | Stack 3 | Stack 4 | Stack 5 | Stack 6 | Stack 7 | Stack 8 |
|---|---|---|---|---|---|---|---|---|
| 2 | 13% | 42% | 20% | 29% | 29% | 22% | 30% | 23% |
| 3 | 9% | 23% | 22% | 27% | 10% | 10% | 9% | 15% |
| 4 | 25% | 49% | 19% | 11% | 9% | 38% | 10% | 44% |
| 5 | 15% | 10% | 18% | 14% | 8% | 8% | 37% | 9% |
| 6 | 35% | 7% | 32% | 43% | 16% | 52% | 27% | 22% |
| 7 | 11% | 11% | 18% | 20% | 24% | 17% | 8% | 28% |
| 8 | 14% | 8% | 45% | 27% | 42% | 28% | 8% | 37% |

**(b) Idle time stack-out RMT.**

**Figure 6.2: Idle times of the RMTs per stack per hour with random stacking strategy.**

**Experiment 1.2: RMT occupancy** Figure 6.1 shows an increase in number of moves per hour by the stack-out RMT. This result was to be expected because the allocation of the containers is only based on the spread of workload over the different modules. This effects only the stack-in moves as can be seen from figure 6.3. The average idle time of the stack-in RMT is decreased to 13 percent for this specific simulation run, which is a trend that is seen throughout all experiments.

| Hour | Stack 1 | Stack 2 | Stack 3 | Stack 4 | Stack 5 | Stack 6 | Stack 7 | Stack 8 |
|---|---|---|---|---|---|---|---|---|
| 2 | 6% | 12% | 8% | 12% | 5% | 21% | 11% | 12% |
| 3 | 11% | 14% | 16% | 14% | 7% | 15% | 17% | 20% |
| 4 | 7% | 10% | 14% | 13% | 4% | 15% | 15% | 9% |
| 5 | 12% | 10% | 10% | 9% | 3% | 15% | 14% | 12% |
| 6 | 10% | 11% | 11% | 8% | 18% | 14% | 8% | 11% |
| 7 | 11% | 19% | 13% | 9% | 10% | 13% | 17% | 12% |
| 8 | 26% | 24% | 27% | 12% | 12% | 22% | 8% | 10% |

**(a) Idle time stack-in RMT.**

| Hour | Stack 1 | Stack 2 | Stack 3 | Stack 4 | Stack 5 | Stack 6 | Stack 7 | Stack 8 |
|---|---|---|---|---|---|---|---|---|
| 2 | 25% | 18% | 36% | 30% | 8% | 34% | 9% | 15% |
| 3 | 5% | 7% | 29% | 5% | 22% | 13% | 5% | 10% |
| 4 | 11% | 16% | 38% | 8% | 19% | 28% | 45% | 10% |
| 5 | 32% | 39% | 34% | 8% | 30% | 31% | 15% | 16% |
| 6 | 24% | 13% | 9% | 19% | 16% | 18% | 15% | 9% |
| 7 | 19% | 50% | 8% | 12% | 7% | 20% | 39% | 25% |
| 8 | 12% | 59% | 23% | 10% | 8% | 29% | 20% | 13% |

**(b) Idle time stack-out RMT.**

**Figure 6.3: Idle times of the RMTs per stack per hour with RMT occupancy weighting factor in stacking strategy.**

**Experiment 1.3: Groups** The influence of the group weighting factor is seen in an increase in the stack-out moves. Spreading containers of the same group over the different stack is only of direct influence on the export containers, since the import containers are not stored as groups. Figure 6.4 shows the average number of moves per hour per QC. Comparing experiment 1.3 with the other results, experiment 1.3 reaches the highest number of container moves into the vessel. The stack-in moves also show an increase in moves per hour in comparison to experiment 1.1. The group weighting factor distributes containers from the same group over the stacks, therefore also the workload distribution is influenced.

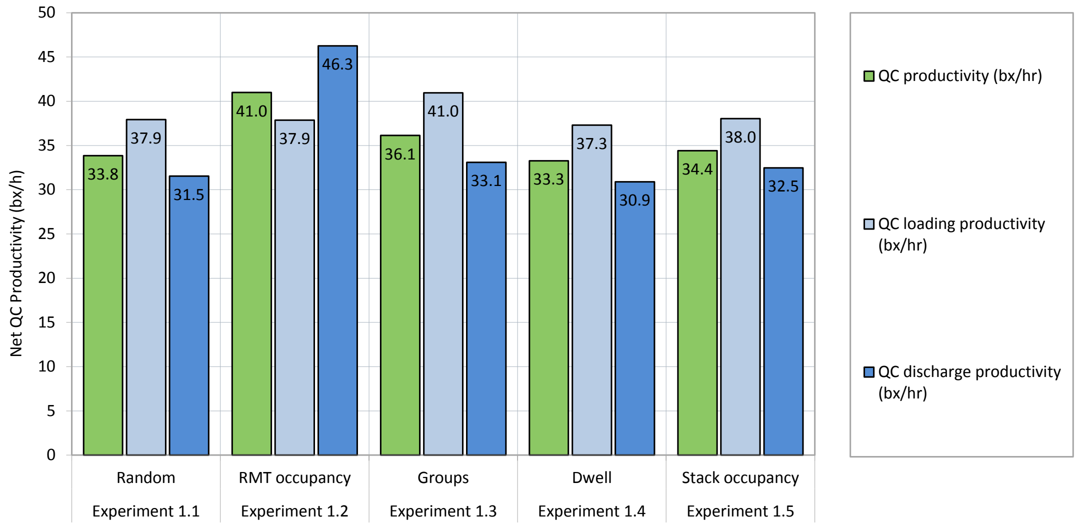



**Figure 6.4: The average number of container moves per QC per hour.**

**Experiment 1.4: Dwell time** The results from the experiment 1.4 show no significant difference in performance with the experiment 1.1. This was also expected since the addition of the dwell time to the stacking strategy only influences the average length elevator moves. From the occupancy of the RMTs in Figures 6.2 and 6.3 can be seen that the RMTs are currently the bottleneck in the process so an improvement in the elevator does not directly result in a higher performance of the stacks. In Figure 6.5 the average number of moves per hour per elevator is presented. The graphs show a slight increase in the possible productivity of the stack, meaning that the moves of the elevator are indeed shorter on average. The results show that only allocating containers based on their dwell time does not improve the performance of the stack, but it does have a slight effect on the elevator performance.

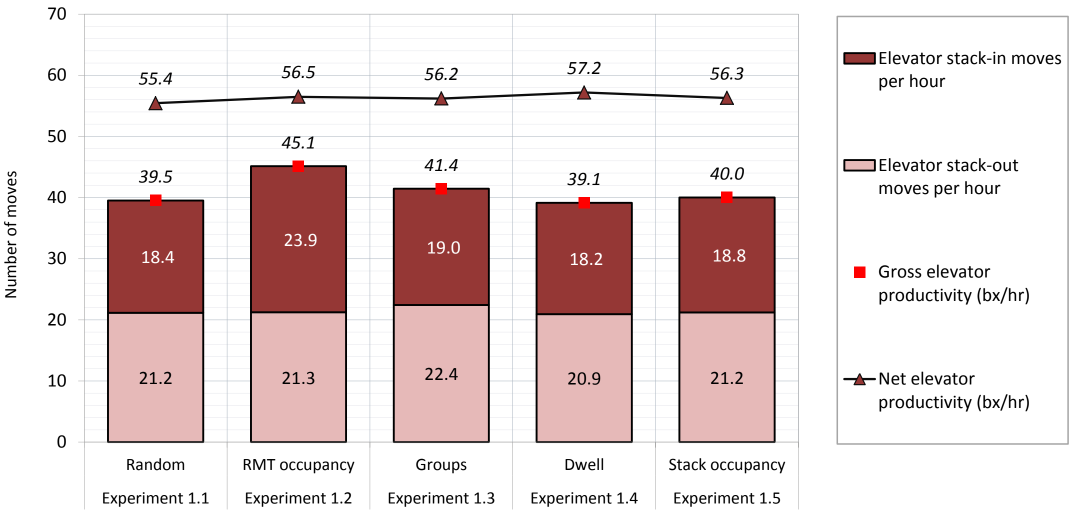



**Figure 6.5: The average number of container moves per elevator per hour.**

**Experiment 1.5: Stack occupancy** Experiment 1.5 shows an improvement of stack-in moves compared to the results of the experiment 1.1. This can be explained by the fact that each container is allocated based on the distribution of containers over the stacks. If a container is allocated to a stack, the occupancy of that stack increases, making that stack less favorable for the next container to be allocated.

#### 6.1.2.2 Value for weighting factors

From result on the influence of each of the weighting factors can be concluded that the weighting factors resulting in a more constant flow of containers to the RMT have the largest influence on the performance of the VCT. Weighting factor $W_{Ro}$ for the occupancy of the RMT has the largest influence on the stack-in RMT. Weighting factors $W_{So}$ for stack occupancy and $W_d$ for dwell times, result in no direct improvement of the performance of the stacks. The influence of weighting factor $W_g$ for the distribution of containers from the same group is the only weighting factor that shows an improvement for the performance of the stack-out RMT. Because weighting factors $W_{Ro}$ and $W_g$ have shown the larges improvement in performance, those weighting factors are used for determining the optimal performance of the stack.

Figure 6.6 shows the results of the experiments for finding the optimal values for the weighting factors $W_{Ro}$ and $W_g$. The results show a slight increase in stack out-moves when the value for the grouping weighting factors is relatively large compared to the RMT occupancy weighting factor.

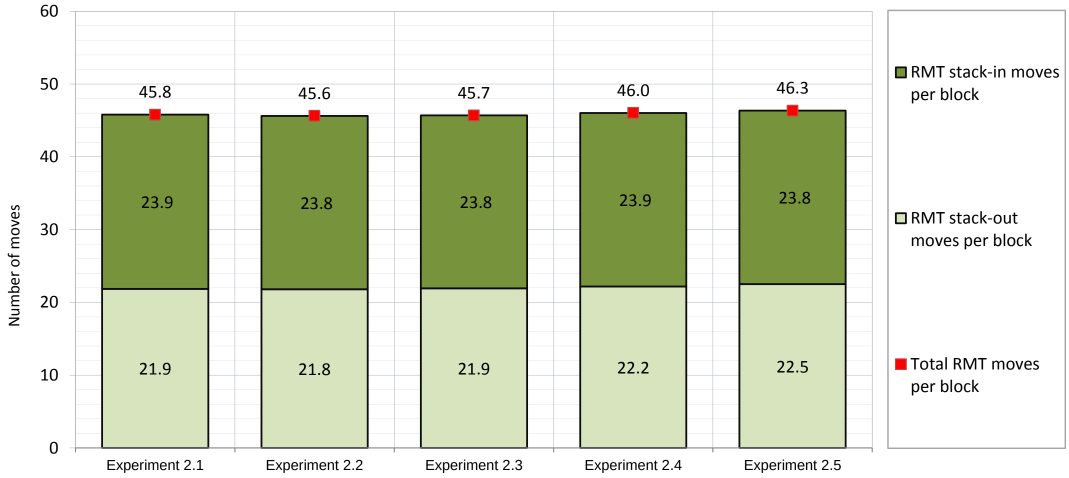



**Figure 6.6: The average number of container moves per stack per hour.**

The increase of weighting factor $W_{Ro}$ compared to $W_g$ does not show significant difference in the results. Even if the weighting factor $W_g$ is relatively large compared to $W_{Ro}$, the influence of $W_{Ro}$ can still determine the location for a container in some cases. When multiple slots in already existing reservations are available for the container, the container is allocated based only on RMT occupancy. For import containers this is also the case, because those are not stored in groups at all. Moreover, the stack-in RMT only is idle for 10 percent of its time during the different experiments, therefore almost not performance can be gained. Experiment 2.5 shows the highest number of stack-out moves, since those are mainly influenced by how the containers of the same group are spread over the storage yard.

### 6.1.3 Discussion

The results of the experiments show that the stack-out RMT is not able to perform the same as the stack-in RMT. Of influence on the results for the stack-out RMT is the selection procedure of containers to be loaded into the vessel in the model. In Chapter 5 is described how the QCs generate the loading orders of the vessel. The generation of loading orders does only try to balance the workload for orders of a single QC. The loading sequence of the QCs together might still be unfavorable for the workload distribution over the yard. In conventional terminals the determination of the vessel loading plan is also based on what gives the best performance from the terminals point of view.

## 6.2 Dispatching strategy

In the previous section the optimal values for the weighting factors of the stacking strategy are found. In this section the influence of different dispatching rules on the performance of a VCT stack is evaluated.

### 6.2.1 Experiments

The experiments are based on experiment 2.4 from the previous section. So the weighting factors $W_{Ro}$ and $W_g$ are respectively 10 and 3. In Chapter 4 several improvements to the dispatching in the VCT are proposed. The experiments for evaluating these improvements are described per equipment type.

#### 6.2.1.1 Cargo elevator

In Section 4.2.2 two rules for improving the performance stack by applying dispatching rules are proposed; determining if a stack-in or stack-out order is preferred based on the number of containers on the mezzanine floor, and determining the preferred stack-out order based on the requested arrival time at the QC or truck gate.

To evaluate the dispatching rules, the scenario with best result of Chapter 6 is extended with both rules in two steps. The results are compared with the result of the simulation without the dispatching rules. The two experiments that are performed and the expectation of the results are:

- **Experiment 3.1**: the cargo elevator selects orders based on requested time at destination. It is expected that by applying this dispatching rule, the containers arrive in an improved sequence at the QC and trucks, minimizing delays QC resulting from QCs waiting for the last container of the vessel bay handled by the QC.
- **Experiment 3.2**: the cargo elevator also determines which order is preferred based on the amount of containers on the mezzanine floor. It is expected that this dispatching rule results in a higher occupancy of the stack-out RMT by keeping the flow of the containers constant, increasing the performance of the stack.

#### 6.2.1.2 Scissor lifts

In Section 4.2.3 the dispatching of the ScLs is explained. Changing the number of moves the ScL is allowed to work ahead influences the performance of the stacks. A higher value results in a more constant flow of containers, but if an incidental container is picked up by a truck, the retrieval process takes longer due to the number of containers already waiting to go out of the stack. A lower value results is possible gabs in the stream of containers moving stack-out, however when a container is required incidentally, less containers to be handled are in front of that container, increasing the retrieval times.

To evaluate the different influences of the working ahead variable, five experiments are performed:

- **Experiment 4.1**: ScLs are allowed to work ahead 5 orders.
- **Experiment 4.2**: ScLs are allowed to work ahead 10 orders.
- **Experiment 4.3**: ScLs are allowed to work ahead 20 orders.
- **Experiment 4.4**: ScLs are allowed to work ahead 30 orders.
- **Experiment 4.5**: ScLs are allowed to work ahead 35 orders.

### 6.2.2 Results

#### 6.2.2.1 Results of elevator dispatching experiments

Figure 6.7 shows the results of the elevator dispatching experiments compared with the a baseline run. The presented results for the dispatching of the elevator only show no increase in total performance of the stack.


**Figure 6.7: The average number of container moves per stack per hour under different settings for elevator dispatching.**

#### 6.2.2.2 Results of ScL dispatching experiments

Figure 6.8 shows the results from the experiments on the optimal value of the amount of orders the ScLs are allowed to work ahead. From the amount of container moves per stack can be seen that the Experiment 4.1 and experiment 4.2 perform less than the other experiments. Experiment 4.3 performs the best.

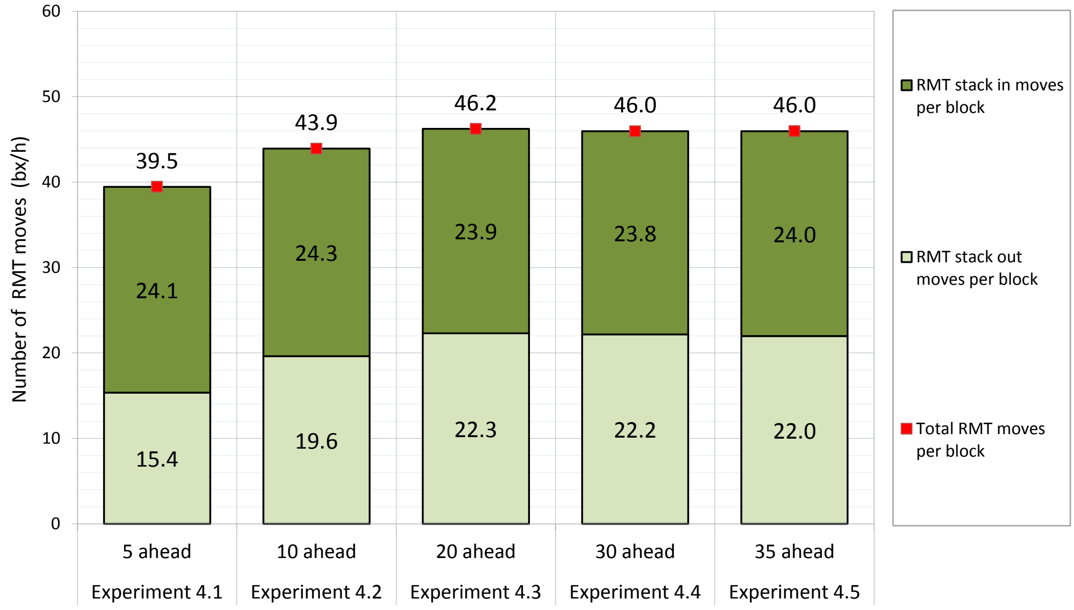



**Figure 6.8: The average number of container moves per stack per hour under different settings for ScL dispathcing.**

### 6.2.3 Discussion

In Section 6.1 it has already been explained that for further increasing the performance of the stack-out RMT, the model needs to select an even number of containers from each stack. The results for the dispatching of the ScLs show that Experiment 4.1 results in the lowest performance. This was already expected. In Figure 6.9 shows the average number of truck moves performed per hour. Experiment 4.1 is able to reach the maximum amount of truck moves defined in the scenario. This effect was also predicted in Section 4.2.3.

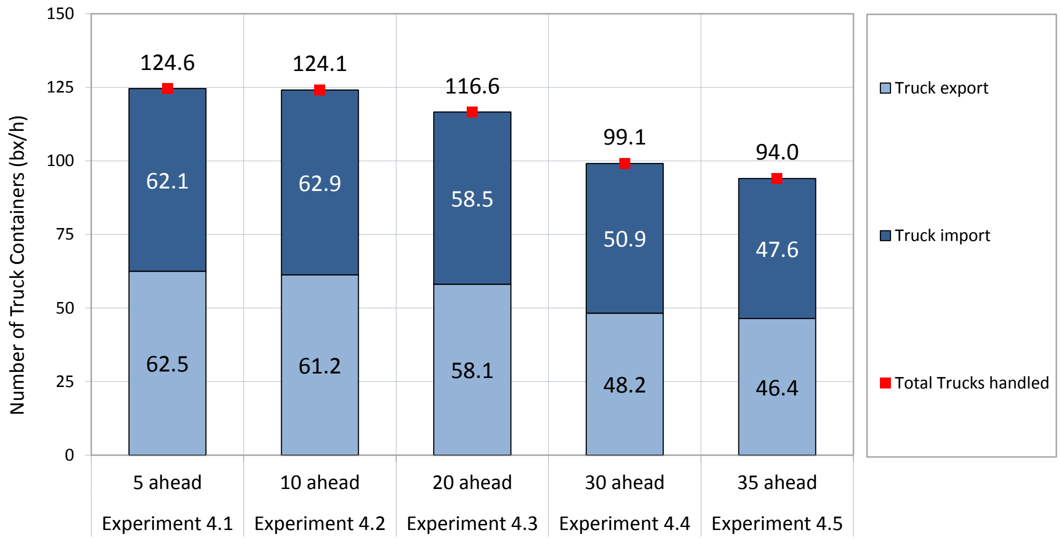



**Figure 6.9: Results ScL dispatching in average number of truck moves per hour at the gate.**

## 6.3 Performance of the VCT

### 6.3.1 Experiment

In the previous sections experiments with different settings for the dispatching and stacking strategies have been performed. To determine what the performance of the VCT is, the dispatching and stacking strategies are combined into a single result which can be used for comparison with an ASC yard in Chapter 7. In the previous sections the dispatching for the elevator and the Scl is presented. The results of the elevator dispatching experiments do not show a large difference with the baseline. The dispatching of the ScL results in the highest performance when the ScL is allowed to work 20 orders ahead. This setting is also preferred because of the ratio of containers to truck and containers to QCs is close to the performance defined by the scenario. For the stacking strategy, the results of experiment 2.5 are used. The experiment settings to determine the performance of the VCT are presented in Table 6.4.

**Table 6.4 Experiment settings for the combination of stacking and dispatching strategies.**

| Parameter | Setting |
|---|---|
| Weighting factor $W_{Ro}$ (RMT occupancy) | 1 |
| Weighting factor $W_{So}$ (Stack occupancy) | 0 |
| Weighting factor $W_d$ (Dwell time) | 0 |
| Weighting factor $W_g$ (Group distribution) | 100 |
| Dispatching ScL | *The ScL performs orders based on their requested time at the destination. The ScLs are allowed to work 20 orders from the QCs ahead.* |
| Dispatching strategy elevator | *Elevator performs orders based on requested arrival time at the destination. It determines to perform a stack-out or stack-in order based on the occupancy of the mezzanine floor.* |

### 6.3.2 Results

The results of the experiment show the performance of the VCT in terms of stack moves, and the occupancy of the equipment in the VCT. The total performance of the VCT is, like in the previous experiments, expressed in number of moves performed by the RMTs. Table 6.5 shows the performance of the VCT.

**Table 6.5 Results from the experiment with the combination of stacking and dispatching strategies.**

| Parameter | Result |
|---|---|
| Stack-in moves per hour per stack | 23.8 |
| Stack-out moves per hour per stack | 22.5 |
| Total moves per hour per stack | 46.3 |
| Truck moves per hour | 114.8 |
| QC moves per hour (6 cranes) | 256.2 |

Figure 6.10 shows the frequency distribution of RMT moves per stack. In Figure 6.11 the frequency distribution of the elevators is presented and in Figure 6.12 the frequency distribution of the ScL moves. These figures can be used to evaluate possible gain in performance.

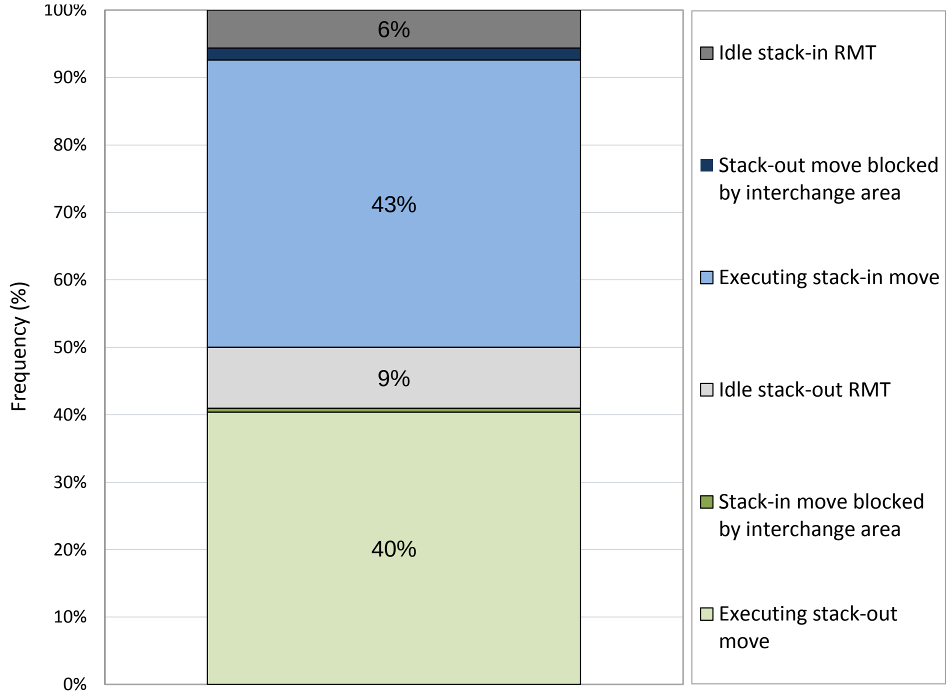



**Figure 6.10: Frequency distribution of the RMTs.**

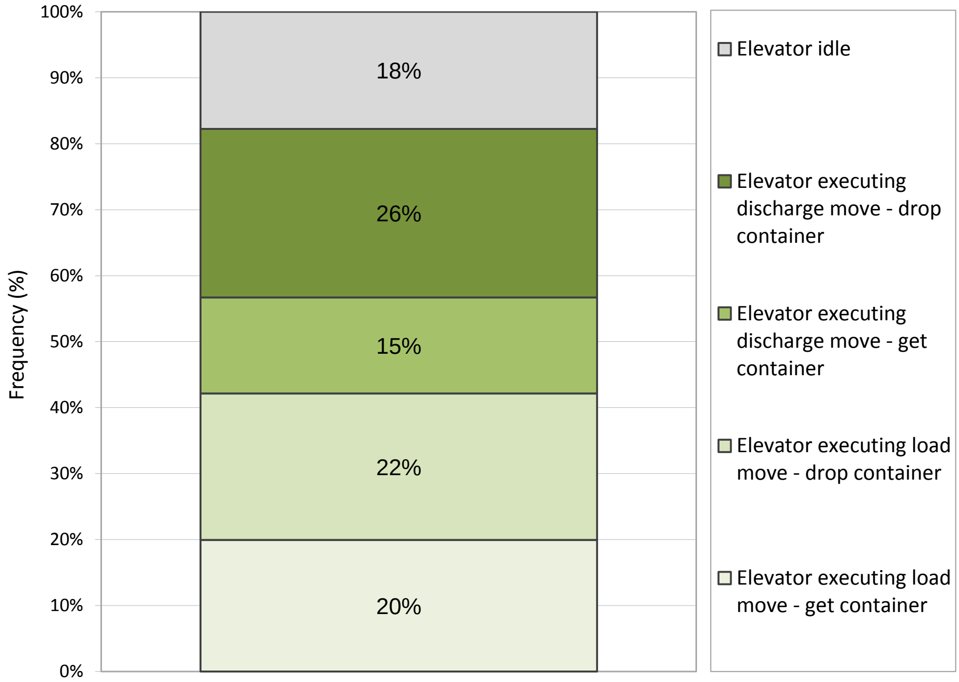



**Figure 6.11: Frequency distribution of the elevators.**

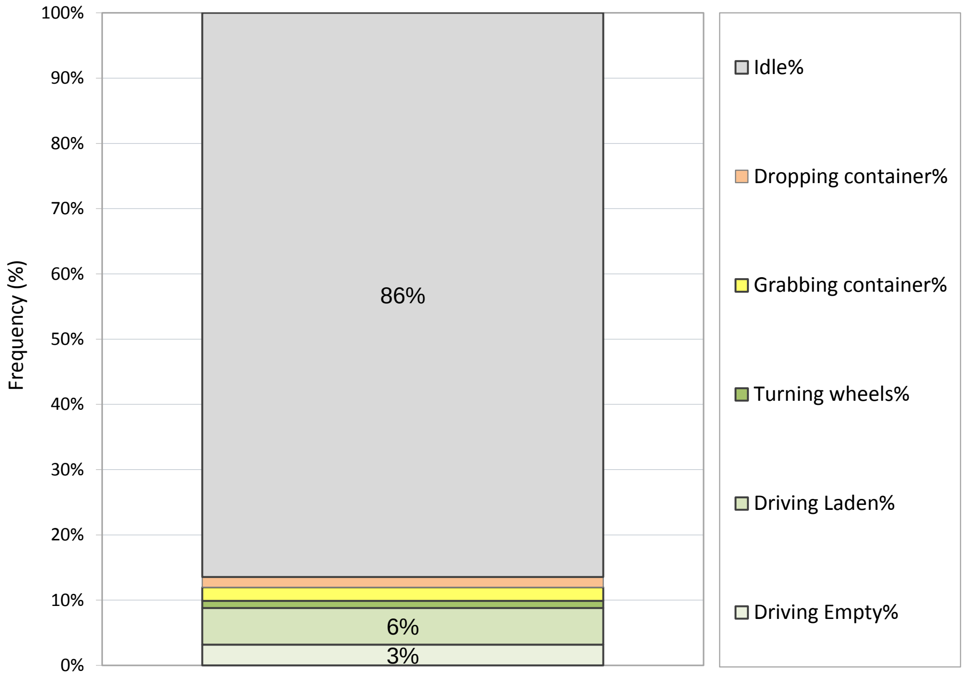



**Figure 6.12: Frequency distribution of the ScLs.**

### 6.3.3 Discussion

In this section the performance of the VCT has been determined to be able to compare the VCT with an alternative storage yard. The results of the performance with the combination of the optimal settings for the stacking and dispatching strategy do not show an improvement compared to experiment 2.5 in Section 6.1. This is because the only difference with that experiment is the dispatching of the elevator which, as has been shown in Section 6.2, does not influence the performance in terms of container moves. Figure 6.10 shows that the idle time of the stack-out RMT is high compared to the stack-in RMT. The elevator still has some spare capacity in the current settings, as shown in Figure 6.11.

## 6.4 Conclusion

The experiments presented in this chapter show the influence of the weighting factors on the performance of the stack. In the current design of the VCT only weighting factors influencing the flow of containers to the RMT result in a higher performance of the VCT. Other weighting factors show improvements for the elevator and not for the VCT as a whole.

The experiments have only been performed under a specific scenario and setup of the stacks to test the possible performance of the VCT. Designing the stacking strategy for different distribution of container flows can change the influences on the stacking strategy. For example; less empty containers slows down average speed of movements and less transshipment containers means more space is needed for import containers. If those import containers were also to be stacked in the middle of the stack, load increases on the ScLs because of an increase in rehandles. Also the setup of the VCT stack itself influences the stacking strategy. In the experiments the VCT is assumed to have four floors. Increasing the number of floors increases the load on the elevator, possibly making the weighting factor for dwell time more important.

Overall the presented stacking strategies result in a high performance in terms of container moves with only an idle time of on average 15 percent for the RMTs. Part of this idle time can be explained by the selection procedure of orders by the QC.

The proposed dispatching rules in Chapter 4 result only in a slight performance increase in terms of container moves compared to no improved dispatching. This can be partly explained because the experiments where no specific dispatching was applied, still used some basic dispatching in order to generate results for the experiments. This basic dispatching means that orders are dispatched in the sequence they arrive. The dispatching of the elevator does not directly influence the performance of the stacks due to the fact that the elevator is currently not the bottleneck in the process. The dispatching of the ScLs which focuses on the number of containers the ScLs are allowed to work ahead result in an increase of performance when they are allowed to work further ahead, however this results in a slower retrieval of import containers. In the model it is assumed that the containers move directly from the elevator to the stack-out RMT. The VCTs mezzanine floor offers the possibility of storing the containers temporarily in the middle, allowing the stack to work ahead but still keep the route from the elevator to the RMT free for other orders.

From the results can be concluded that specifically for the stack-out RMT there is still some performance left for improvement. As explained in Section 6.1 the performance of the stacks can be increase by improving the distribution of containers being unloaded from the stacks. The number of truck moves per hour is slightly below the in Chapter 5 described 125 trucks moves per hour. Combining the use of the mezzanine floors temporary storage and the ScLs working ahead more can balance the performance to the trucks and the QCs.

# Chapter 7

# VCT versus ASC yard

In Chapter 6 the performance of the VCT has been evaluated. In this chapter that performances is used to compare the VCT with an alternative storage yard. In Chapter 1 three other types of stacking yards are mentioned; a shuttle carrier yard, RTG yard and an ASC yard. The automated ASC (ASC) yard is found to be the most usable for a comparison with the VCT, because it is like the VCT stack also a high capacity fully automated stacking yard. For comparison an ASC storage yard is designed based on the test terminal described in Section 5.1. In Section 7.1 a layout for the ASC yard is developed. In Section 7.2 the designed ASC yard is evaluated with simulation. In Section 7.3 the VCT and ASC yard are compared.

## 7.1 ASC yard design

The requirements and boundaries for the ASC yard are presented in Table 7.1. The storage capacity of the stack should be the same as the storage capacity of the VCT. As presented in Chapter 5.1 number of containers in the yard is 18.586 TEU. ASC yards have a typical density of 85 percent, resulting in a required storage capacity of 21.866 TEU. The width of the yard is 500 meters, leaving an additional 200 meters of area for other purposes such as parking and maintenance buildings. The capacity of the stack in terms of container moves is defined as the WS and LS requirements from Chapter 5.

**Table 7.1 Requirements of the design of the ASC yard.**

| Requirement | Value | Unit |
|---|---|---|
| Width of the storage yard | 500 | $m$ |
| WS moves | 240 | $moves/h$ |
| LS moves | 125 | $moves/h$ |
| Total storage capacity | 21.866 | $TEU$ |

To determine the actual layout of the ASC yard, some assumptions are made and presented in Table 7.2. If two yard cranes are used, a rule of thumb based on experience states that a single stack is capable of producing 10 LS and 16 WS moves per hour. The typical density of an ASC stack is 85 percent. In the VCT, an area between the opposing stack is reserved for the movements of the shuttle carriers.

**Table 7.2 Assumptions for the design of the ASC yard.**

| Requirement | Value | Unit |
|---|---|---|
| Width of an ASC stack | 33 | *m* |
| Moves LS per stack | 10 | *moves/h* |
| Moves WS per stack | 16 | *moves/h* |
| Stack density of a RTG stack | 0.85 | |

Combining the requirements and the assumptions the following ASC yard layout is determined and presented in Figure 7.1. In Appendix C the calculations for the layout are presented in more detail. The results of the calculations are presented in Table 7.3.

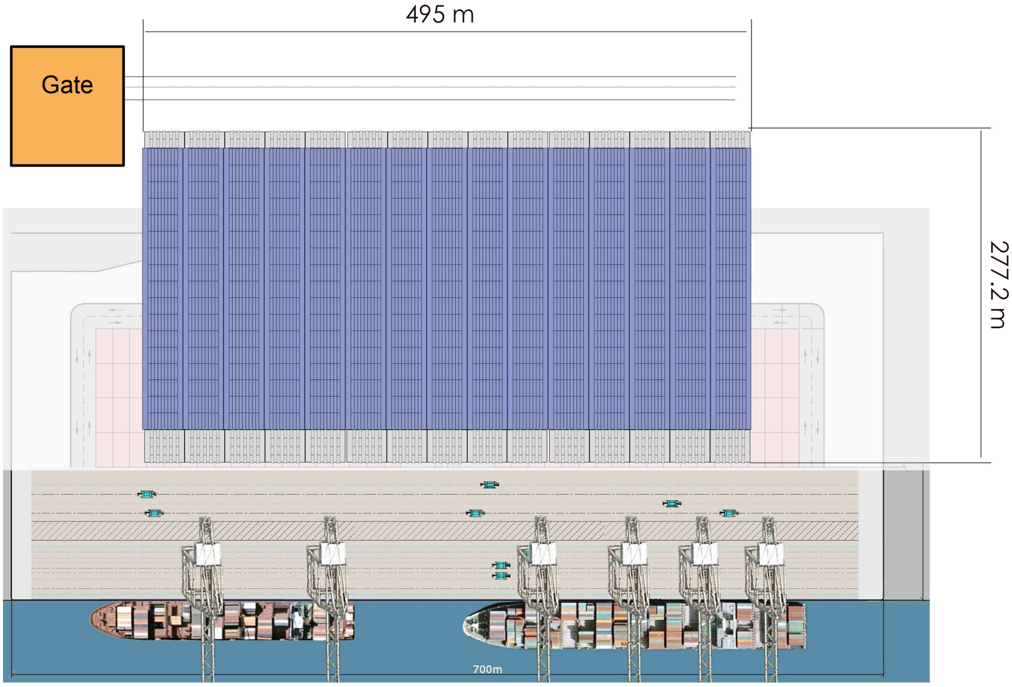



**Figure 7.1: Layout of the designed ASC terminal.**

**Table 7.3 Results from calculations on the ASC yard design.**

| Requirement | Value | Unit |
|---|---|---|
| LS capacity | 150 | *moves/h* |
| WS capacity | 240 | *moves/h* |
| Number of stacks | 15 | *stacks* |
| Stack width | 9 | *containers* |
| Stack length | 34 | *TEU* |
| Yard peak capacity | 22.950 | *TEU* |

## 7.2 ASC terminal simulation

In the previous section an ASC terminal with comparable performance to the VCT in terms of stack capacity and performance in terms of container moves has been designed. In this section the designed terminal is simulated to evaluate the performance of the ASC terminal. The performance is evaluated to determine if the designed yard is comparable with the VCT. The key performance indicators that are evaluated in this section are:

- Stack performance in terms of moves is assumed to result in the calculated performance of the stack, however this still needs to be proven.
- Yard equipment occupancy shows if the stack is performing at full capacity.
- Truck handling times gives insight in how long it takes to retrieve a container at peak load. Although the stacking and dispatching in the VCT are not developed to optimize truck handling times, for the comparison this performance indicator is evaluated.

### 7.2.1 Experiments

For the experiments again at least 100 hours of simulation are used to generate the results. The results are presented for different number of shuttle carriers to show that the shuttle carriers are not the bottleneck in the process. The experiments are performed with respectively 16, 20 and 24 shuttle carriers.

### 7.2.2 Results

The number of yard moves per container shows if the assumptions on the container moves per stack are correct. Figure 7.2 presents the different stack moves per stack performed by the LS and WS ASC.

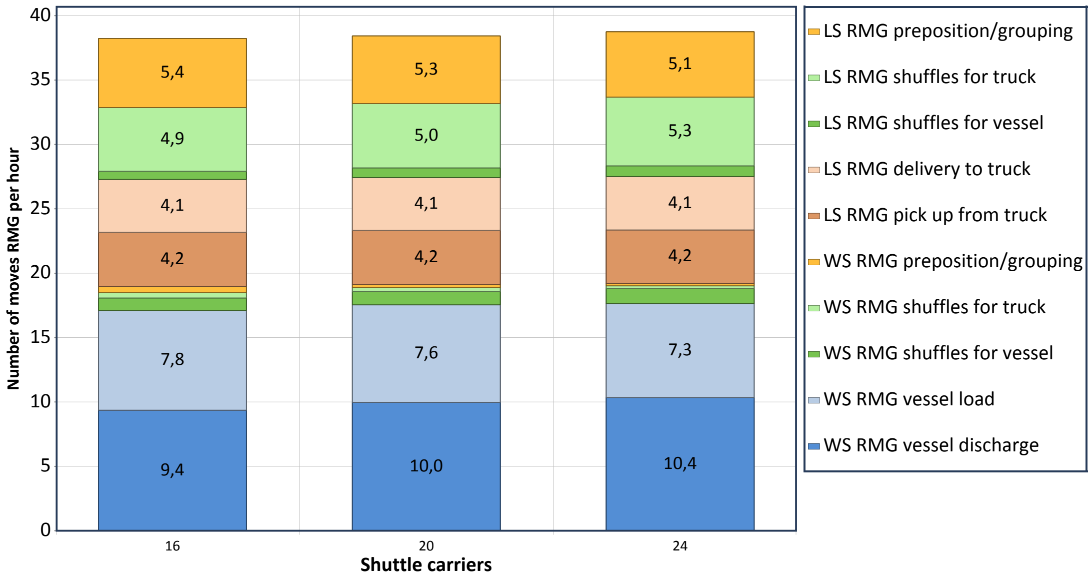
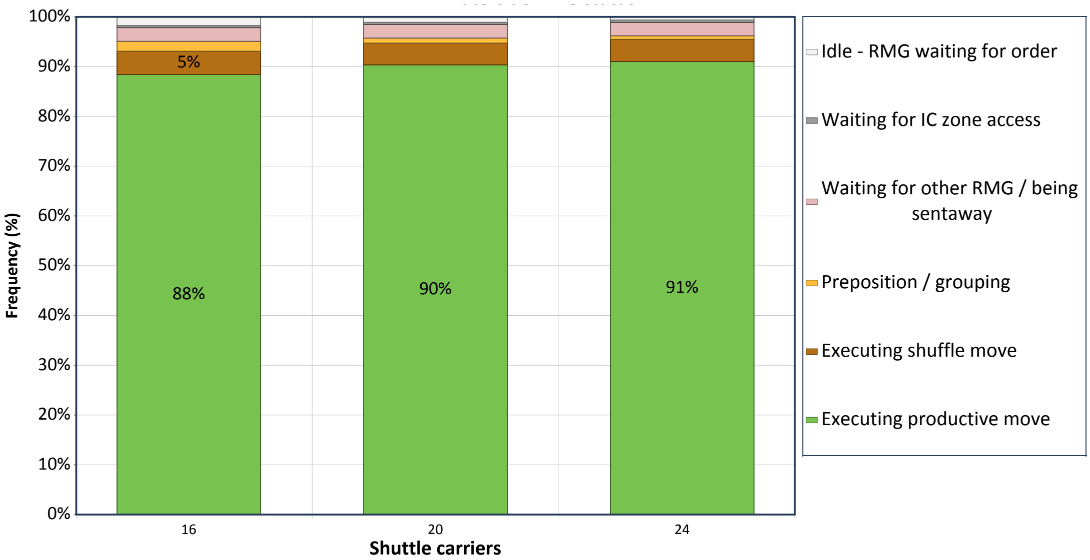
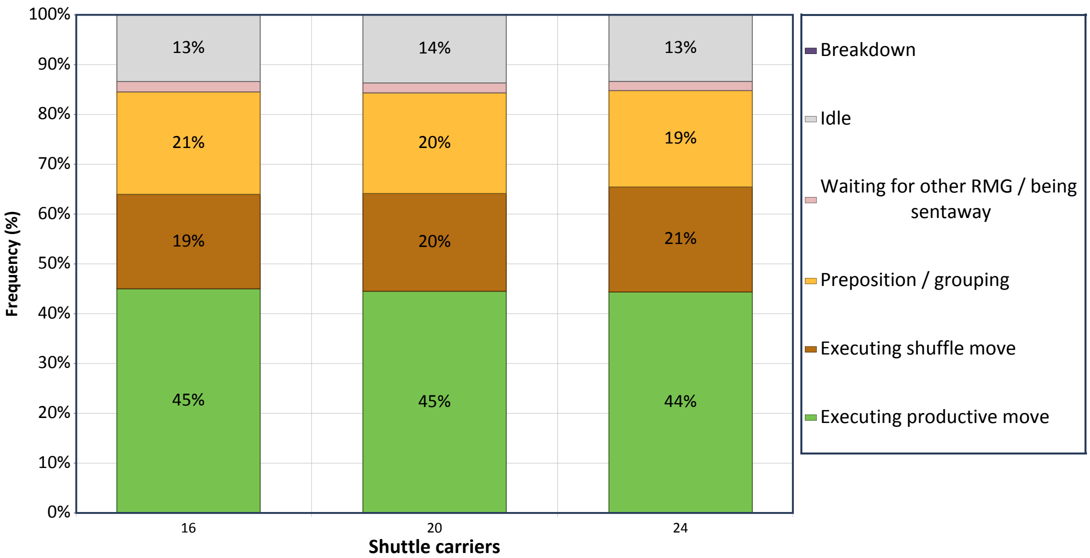



**Figure 7.2: Moves performed by the yard cranes in the ASC stacks.**

To determine if the presented number of containers moves per stack is the maximum productivity of the ASC stacks, the occupancies of the LS and WS ASC are used. Figure 7.3 presents the productivity of the WS and LS yard cranes.




(a) **Waterside yard crane productivity.**




(b) **Landside yard crane productivity.**

**Figure 7.3: Productivity of the ASCs.**

In the ASC yard the trucks are handled directly by the LS yard crane, so no extra transport between the truck and yard exists. The truck handling time of the ASC yard is presented in Figure 7.4, and represents the average time it takes to fulfill a truck pick-up or drop-off order. The truck handling time is the time between the arrival of the container at the stack and the time it leaves the TP again.

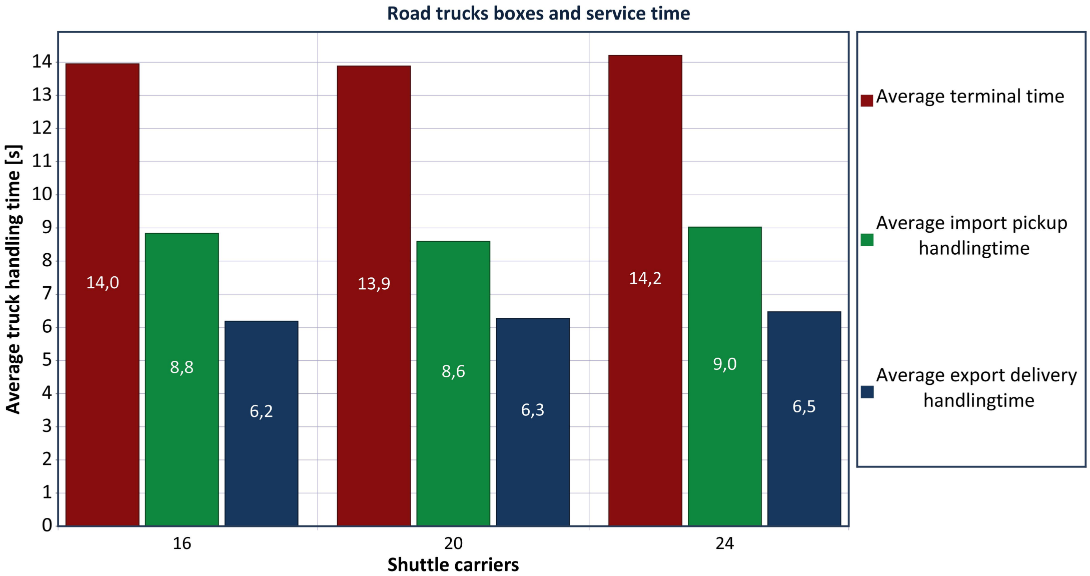



**Figure 7.4: Handling times of trucks in the ASC yard.**

### 7.2.3 Discussion

The WS yard cranes are at maximum capacity as concluded from the lack of idle time in Figure 7.3a. The LS yard crane presented in Figure 7.3b shows on average 13 percent idle time. At full productivity this would result in 9.5 moves per hour, which is close to the assumed 10 moves per hour. From the figure can be seen that the number of WS moves per hour is higher than assumed; almost 18 container moves per hour instead of 16 moves per hour. On the other hand the number of LS moves is lower than expected (8 moves per hour instead of 10 moves per hour). This difference can be explained by the demand on the LS. 125 Trucks per hour are divided over 15 stacks results in only 8.33 trucks per stack. In general the performance of the ASC yard in terms of container moves is close enough to the expected productivity to be able to make a fair comparison between the VCT and the ASC.

## 7.3 VCT and ASC comparison

The results in the previous section show that the performance of the ASC stack is as expected. Therefore the ASC yard can be compared with the VCT. The previous sections have already shown that the handling capacity and storage capacity of both yards is equal. The comparison of both stack types is done by comparing the following parameters:

- Containers per area
- Truck handling times

Since the presented results are only based on a single scenario some influences on the performances of both yards are also discussed in this section.

### 7.3.1 Yard area

To compare the size of the yard area the yard area first is defined. The area of the ASC yard is already presented in Figure 7.1. For the VCT stack the transfer zone between the shuttle carriers and the trucks is also defined as part of the yard area, since the trucks in the ASC yard interchange directly with the stack. In Figure 7.5 the area defined as the yard area is marked. In Table 7.4 the sizes of the yards are presented.

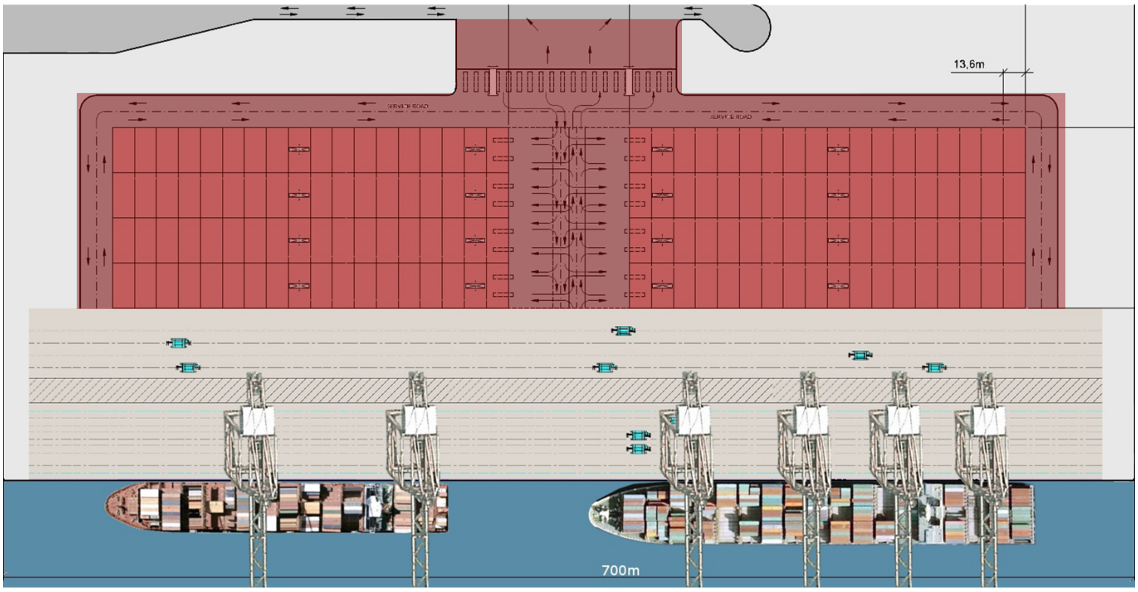



**Figure 7.5: Layout of a VCT terminal.**

**Table 7.4 Yard area comparison.**

| | VCT | ASC |
|---|---|---|
| Yard area [m] | 85.203 | 137.214 |
| TEU per ha | 2.253 | 1.422 |

The VCT yard is 38 percent smaller than a conventional ASC yard with the same capacity.

### 7.3.2 Truck handling times

The truck handling times in the ASC yards are presented in Figure 7.4. If the container is parked at the LS end of the ASC stack, it takes nine minutes to pick-up a container and six minutes to drop-off a container. In the VCT there is a large difference in handling time of drop-off and pick-up container because of the handling equipment. A container is considered to be picked up as soon as a shuttle carrier lifts the container from the truck. As long as enough shuttle carriers are available for picking up containers from trucks this process starts as soon as the truck has arrived at the transfer point. Therefore the drop-off time of a container by truck is not directly related to the stack and cannot be compared. The time it takes to pick-up a container by truck is related to the yard. In the VCT stack this process is longer, because a container passing through the mezzanine floor already takes more six minutes. Because it is possible for the VCT to work ahead, the truck order is send to the stack at the moment the truck enters the terminal. The average handling time of a truck picking up a container in the VCT stack is around 17 minutes, which is relatively long compared to the ASC stack.

### 7.3.3 Other influences

#### 7.3.3.1 Import/export ratio

The scenario under which the performance of both stacks is determined is developed to be able to test the maximum performance of the stack. The modal split determines the share of import and export containers moving through the stack. If the share of export container is larger than the assumed 55 percent the VCT stacks can store those containers also in the free access slots. If the share of import container increases, the import containers might need to be stored in the middle of the stack, increasing the chance on reshuffles. In the current design, with two ScLs per floor, the extra reshuffles do not pose a direct problem for the performance of the VCT. In the ASC stack the export containers are stacked lower to not lose performance due to reshuffles.

#### 7.3.3.2 TEU factor

Throughout this research the VCT has been tested only by using 40-ft (two TEU) containers. In general the TEU factor can lie anywhere between one and two. For the ASC stack the 20-ft container can be handled like 40-ft containers and two 20-ft containers fit on the same slot as one 40-ft container. In the VCT different problems arise when the TEU factor changes. To minimize the effect on the performance of the stack, the single 20-ft containers could be place super skid. This will result in less capacity in terms of slot because the 20-ft container would still occupy a 40-ft slot. Another solution is to store 2 20-ft containers on a single skid, but then if the containers do not arrive or depart at the same time, extra movements are required to combine or split two containers. This might influence the performance of the stack.

## 7.4 Conclusion

In this chapter a simple layout for an ASC stack is developed to compare the VCT and ASC yards. The assumptions on which the ASC yard is designed are tested with simulation to ensure a fair comparison. Since the performance in terms of container moves and storage capacity are equal for both yards, the yards are compared on; the space required for the terminal, the number of container moves and the truck handling times. The VCT occupies the least amount of space (38 percent less than a ASC yard). The ASC is faster in retrieving containers from the stack when requested from the truck gate.

# Chapter 8

# Conclusion and Recommendations

## 8.1 Conclusions

The main research question of this research is defined as; *What dispatching and stacking strategies can be used in the VCT to be able to compare the performance of the VCT stacks with other stacking yards?*. In order to answer this question literature on stacking and dispatching strategies is reviewed. The influences of the design of the VCT on stacking and dispatching are determined by analysis of the design of the VCT. Based on the findings in these steps, a stacking and dispatching strategy for the VCT are developed. A simulation model of the VCT is built to evaluate the performance of the VCT under different settings for the stacking and dispatching strategies. Finally the best results from the experiments are used to compare the VCT with an alternative storage yard, an ASC yard.

The performed literature study showed that literature on storage yard operations often assumes ideal settings or situations in which only one type of container or equipment is concerned. From literature on stacking strategies on conventional storage yards is concluded that the design of the stacking strategy depends partly on the type of storage yard and partly on processes outside the storage yard.

Analysis of the design of the VCT resulted in the following conclusions:

- The free-access slots offer the possibility to reach containers without reshuffling.
- The RMT is the bottleneck in the storage processes of the VCT, keeping the RMT productive directly influences the stack performance.
- Rehandles in the VCT can be compared with rehandles on conventional stacks, only containers in the VCT can also be blocked sideways. The ScLs are responsible for the rehandles, but with 2 ScLs per floor, performing rehandles does not directly influence the performance of the stack.

The ScLs show a productivity of only 15 percent, therefore is might be interesting to evaluate the performance when less ScLs are used. The design of the VCT even offers the possibility to move ScLs between the different floors and stack, letting them work wherever the workload is high.

The objective of the stacking strategy is to maximize the number of container moves per hour, but not compromising on stack density. The developed strategy assumes separate slots for the import and export containers. Import containers are stored in the free-access slots due to the lack of data on their departure time while export containers are stored in the middle slots. The allocation of the container starts by selecting all possible slots for an arriving container. Each slot is rated based on the parameters factors:

- Floor the slot is located.
- Occupancy of the RMT the slot is located.
- Occupancy of the floor the slot is located.
- Groups of containers (export containers).

Export containers are often loaded into a vessel in groups based on port of discharge and weight. To minimize rehandles which cost extra empty slots in a stack, these containers are like in conventional terminals grouped together in groups of six or nine containers in one bay. Locations for the groups of containers are reserved to ensure no other containers are mixed with the group. Containers of the same group are spread over the different stacks. This ensures the spread of workload over the different stacks when loading a vessel.

Each of the presented parameters is multiplied with a weighting factor to balance the influence of each parameter. A simulation model is developed to determine the influence of different values for the weighting factors. It is concluded that the weighting factors for spreading the workload over the stacks results in the highest performance. The two weighing factors that are used to do this are:

1. The occupancy of the RMT. Containers going into the stack are spread over the different stacks to increase the performance of the stack-in RMT.
2. Spread of the group containers. Since containers of the same group are requested by the QC to be loaded into the vessel in a relatively short time, the spreading of containers of the same group over the stacks results in an increase in performance of the stack-out RMT.

The RMT is in the current design of the VCT the bottleneck in the process. The productivity of the RMT is based on the fact that every container is moved away or dropped as soon as required by the RMTs, by letting the shuttle carriers already drive to and pre-position near the stacks before the RMT has finished its previous move. This costs extra shuttle carriers and space for maneuvering. During the research several options have been proposed to improve the design of the VCT. One of the improvements consists of adding extra TPs from the stack near the elevator. This improvement releases the pressure on the performance of the RMTs. However, the increase in performance might be limited due to the performance of the elevator. The experiments have shown that the stacking strategy is able to increase the performance of the elevator by storing containers with a longer expected dwell time higher in the stack, minimizing the number of moves to the higher floors.

Since the containers are already allocated to a location in the stack, the jobs for the yard handling equipment is for the larger part already decided. The elevator in the each stack can choose which order to perform (from what floor). It is proposed to let the elevator choose its order based on the occupancy of the mezzanine floor to ensure a continues flow of containers to the stack-out RMT. If the elevator is to become the new bottleneck in the stack due to improvements to the design of the VCT, the dispatching of the elevator can also improve the performance of the elevator by selecting orders based on the distance from the current position of the elevator, resulting in more dual-cycle moves.

The scissor lifts are allowed to work a certain number of moves ahead. It is found that the performance of the stack increases with the number of orders for the QCs the Scl works ahead, but this also results in a lower performance to only the truck gate. This can be explained by the fact that when a truck comes to pick up a container the mezzanine floor is already flooded with containers that are prepared to be unloaded from the stack. In the VCT the temporary storage on the mezzanine floor could be used to move prepared containers aside from the regular flow of containers over the mezzanine floor.

The results of the experiments show a limited productivity of the stack-out RMT of 80 percent. The containers moved by the stack-out RMT consist mainly of containers moving to the vessels at the quay. The model selects containers from the stack to be loaded into the vessel per QC, not taking into account the workload on the stacks already created by the other QCs. It is expected that the performance of the stack-out RMT can be further increased when the distribution of containers over the stack to be loaded into the vessel is determined for all QCs at once.

To compare the VCT with an ASC yard the best result of the experiments on the dispatching and stacking strategies is used. The comparison of the VCT and the ASC yard showed that the area required for the ASC yard is significantly larger than that of the VCT, while the performance in terms of container moves and storage capacity is about the same. It must be noted that the retrieval time of containers from VCT is much longer than from the ASC yard because of the slow mezzanine floor.

Overall the proposed strategies for dispatching and stacking made it possible to evaluate the performance of the VCT in the simulation model. The strategies have shown what the important factors are that influence the performance. The research has shown that the performance of the VCT can be compared with the performance of an ASC yard. Because this research shows that the performance of the VCT is comparable with alternative yards, this research is an important step for the future of the VCT.

## 8.2 Recommendations

This research did not only provide the possibility of comparing the VCT stack. It also resulted in improvements to the stack and recommendations for further research. The following recommendations can be made:

- Since the workload on the RMTs is for a large part responsible for the performance of the stacks, adding extra locations for loading and unloading the stack could increase the performance. Adding these extra transfer points near the elevator at the mezzanine floor should be further investigated.
- The routing of the horizontal shuttle carriers was outside the scope of this research. However, for a terminal to operate properly, the routing of the vehicles is important

to prevent delays during the transport. Therefore it is proposed to further research the the routing of the horizontal transport equipment.

- This research only considered 40-ft containers. To create a more realistic situation it is important to determine how to handle 20-ft containers in the stack. Since storing a single 20-ft container in a 40-ft slot is to space consuming, a process and possible improvement for the VCT stack needs to be researched to store two 20-ft container in a 40-ft slot.
- The mezzanine floor has in this research only been used for transporting containers between the RMTs and the elevator. Determining container routing and temporary storage on the mezzanine floor offers an interesting option to prepare containers for the vessel loading process.
- The performed tests in this research are all based on the same assumptions for the container flows. It is recommended to further evaluate the performance of the VCT in a situation where the VCT can actually can be applied.
- This research has focused on the stacking and dispatching strategy in the VCT assuming a certain load plan for the vessels. The load plan in the simulation model does not take into account the workload created in the stacks by all processes taking place at the same moment. A load plan often is based on getting the optimal performance from both the QCs and the yard. Therefore optimizing the load plan for the VCT as storage yard may result in a better performance from the yard.

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# Appendices

# Appendix A

# Scientific research paper

# Comparing container storage yards: VCT versus ASC yard

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***Abstract*—As the volume of container transport increases so do the requirements on handling of containers at terminals. As almost every container on the terminal passes through a storage yard, the storage yard is also forced to increase its performance and storage space. To meet the increasing requirements on the storage yard a company called Polotec designed a warehouse for container storage, the vertical container terminal (VCT). The concept of the VCT aims at storing the containers in a steel structure, therefore the stacking heights is no longer be limited to the maximum height of container stacking nowadays. In this paper the performance of the VCT is evaluated and compared to the performance of an alternative storage yard; a yard with automated stacking cranes (ASC). The results of the experiments show that, although the performance of the used ASC terminal is slightly better than the performance of the VCT, the VCT requires almost 38 percent less space. It is recommended to further research the VCT in different scenarios that more closely resemble the situation on a site where the VCT can actually be applied.**

## I. Introduction

Over the past few decades the demand for containerized transport has increased. Container vessels become increasingly larger in size, not only requiring larger equipment to handle the vessel, but also demanding more from the container terminals. Larger vessels result in large call sizes, requiring faster and more handling equipment and larger capacity in the storage yard [1]. The storage yard capacity is limited by the yard equipment, maximum stacking heights and requirements on the performance of the yard in terms of container moves. To overcome these problems the Norwegian company, Polotec designed warehouse for storing containers (Figure 1). Since containers are stored in a steel structure, the containers can be stored higher than currently possible in conventional storage yards. Therefore less space is needed to store the same amount of containers. However, storage capacity is not the only performance indicator for a storage yard. The storage yards should also be able to meet the requirements of the terminal in terms of performance [2]. While a vessel is being loaded or unloaded, the yard should be able to deliver or store containers at a constant flow, to minimize idle time of the quay cranes (QC). The containers have different destinations in terms of modality. Some containers are leaving the terminal per vessel (export) while others leave per truck or train (import). In this paper the performance of the VCT in terms of container moves is investigated by discrete event simulation. The VCT is then compared with an alternative storage yard; an ASC yard with the same storage capacity. The question that is answered in this paper is: *How does the VCT compare to a ASC yard in terms of storage capacity and handling capacity?* In Section II the design of the VCT is explained in more detail. To evaluate the performance of the VCT, stacking and dispatching strategies are proposed in Section III. In Section IV the characteristics of a typical ASC terminal are described. The ASC terminal is used to compare its performance with the performance of the VCT. The ASC terminal and VCT are compared in the same scenario. The scenario and the results of the experiments are presented in Section V. In Section VI the conclusions of the paper are presented and recommendations for further research are done.

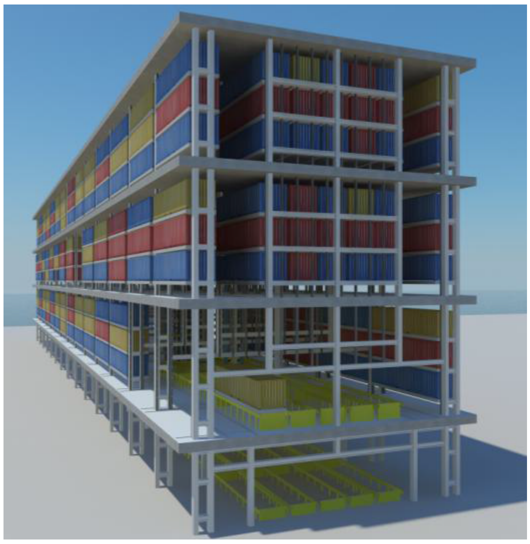
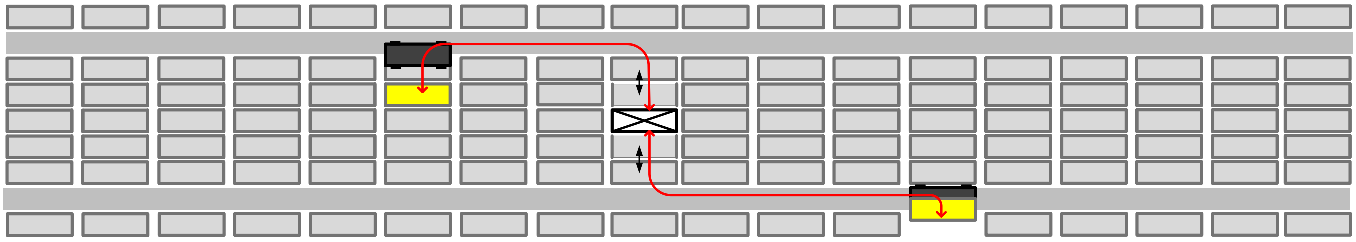


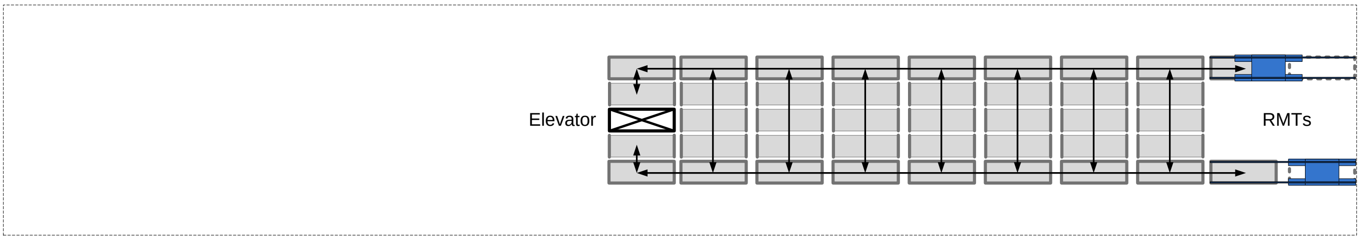
Fig. 1. Impression of a VCT stack. (source: Polotec)

## II. VCT terminal characteristics

The VCT storage yard consists of multiple stacks. Each stack consists of several *storage floors* and a *mezzanine floor* at the base. When storing a container in a stack, the container is lifted from the ground onto the mezzanine floor by two *rail mounted trolley cranes* (RMT). The container is moved over the mezzanine floor by the use of roller beds to an elevator in the middle of the stack. The mezzanine floor is presented in Figure 2b. At the left side of the mezzanine floor some unused space is located. This area does not have a specific use, but might be used for storing containers that require special handling. The mezzanine floor does not only move containers from and to the elevator, but also offers the possibility to



(a) Storage floor




(b) Mezzanine floor

Fig. 2. Top view of a storage floor (a) and a mezzanine floor (b).

temporarily store containers. The arrows in the figure show the direction of movement of the roller beds. The elevator picks-up the container and moves it to a storage floor. At the storage floors so called *scissor lift trolleys* (ScL) store the container in a slot on the storage floor. Each storage floor has a capacity of 363 40ft containers, which are stored in 18 40ft bays, seven rows and three tiers. The storage floors have two aisles for the ScLs to move along the bays, as can be seen in Figure 2a. To store the container in the VCT the containers need to be locked to the structure of the stack. This is done by placing the container on the so called *super skids*. These steel frames have retractable pins to lock the skid to the frame of the stack. The super skids are able to carry a single 40ft or two 20ft containers, although the stack currently does not support the process of combining two 20ft containers on the same skid. When a container is stored in the middle, the ScL moves sideways under the containers. When the ScL underneath the correct position of the container, the ScL lifts its platform to either store or retrieve a container from a slot. When a container is stored at the outside of the aisle, the super skid is not locked to the structure, but placed upon a roller bed. Loading and unloading the ScL from these slots is performed by shifting the container sideways onto or from the platform of the ScL. An example of handling a container from both types of slots is also shown in Figure 2a

## III. VCT Stacking & dispatching strategies

The determination of the optimal location for a container and the job dispatching for the vehicles are considered as two separate parts in the VCT. First the location for a container is determined when a container arrives at the terminal. The dispatching of jobs to the equipment of the VCT depends for the larger part on where the container is located in the yard or where it needs to be stored.

### A. Stacking strategy

In general the objectives of stacking strategies are [3]:

- Efficient and timely transportation from quay to stack and further destination and vice versa.
- Avoidance of unproductive moves.
- Efficient use of storage space.

In contrast to conventional stacks where the yard crane is responsible for all the moves including rehandles, rehandles do not directly influence the performance of the stack in the VCT. A four floor high VCT stack already contains eight ScLs, which have enough idle time to perform the rehandle moves. Therefore the objective of the stacking strategy for the VCT is to maximize the number of container moves per hour, without compromising on storage capacity. To achieve this, first a basic structure for the stacking strategy is defined after which the optimal location of the container is determined based on weighting factors. Two types of containers are distinguished in the stacking strategy; import and export containers. Import containers arrive per vessel and leave the terminal per truck. The exact time of a container pickup at the truck gate is not known beforehand. These containers are always stacked in the free access slots, so no containers ever have to be moved out of the way before the import container can be reached. The export containers arrive either by vessel or truck and leave per vessel. Based on stacking strategies in conventional terminals the export containers are grouped together in the stacks based on weight of the container, service and port of discharge [4]. The containers are placed in a bay in such a way that the heavier containers (going in the vessel first) are the first containers to reach by the ScLs. Containers of the same group arrive randomly over the days before the vessel arrives. Therefore, as soon as a container is stored in a bay, the surrounding slots are reserved for other containers of the same group. Because the containers stored in the exact middle row in a bay can only be retrieved when there is no container at the lowest position in the two adjacent bays, a reservation for a group of containers consists always of six or nine slots.

Following the basic structure, the exact location for a container is determined when it is unloaded at the QC or delivered at the truck gate. Spreading the workload over the different stacks when loading a vessel is important in RMG yards since only one crane per stack serves the interchange of containers with the horizontal equipment at the waterside [5]. For the VCT this is even more important since the flow of import containers moving stack-out is also handled by the same crane (stack-out RMT). When an *import container* arrives, the following steps are taken:

- **Step 1**: Get a list of all empty free-access slots, and store this list together with the information on the location of every slot in terms of floor and stack. The slots that are already reserved for containers under way are left out.
- **Step 2**: Determine the occupancy of the RMTs for every slot in the list by considering the number of containers going to each RMT. The number of containers is multiplied by a weighting factor so that the slots located in stacks with a large number of orders get the highest penalty.
- **Step 3**: Determine the occupancy of the free-access slots per floor of each slot in the list and multiply this with a weighting factor. Slots in floor with a lower occupancy receive a lower penalty. The penalty is added to the result of step 2.
- **Step 4**: Sort the slots based on the penalty. The slot with the lowest penalty is the best slot for this container.

When an *export container* arrives, it is first determined if there is already a suitable location for the container in an already existing reservation for containers of the same group. A suitable location means that there is a slot reserved for the same group and also specifically for the weight class of the container. If multiple suitable locations are found, then the following steps are taken:

- **Step 1**: Determine for every slot the occupancy of RMT, and add this to the penalty of that slot.
- **Step 2**: For every location multiply the floor it is located with a weighting factor and the expected dwell time of the container. If the expected dwell time is relatively long, a higher location in the stack might be preferable to minimize the amount of moves to the higher floor. Add the result of this step to the result of step 1.
- **Step 3**: Select the slot with the lowest penalty.

If no suitable locations exist, a new reservation has to be made. The location of the new reservation is again determined by rating the different options for a new reservation based on different parameters. For determining the optimal location for a new reservation, the following steps are taken:

- **Step 1**: Determine what the size of the reservation should be. When a container is delivered per truck a reservation of six slots is made. When the container is delivered per vessel the size of the reservation can be determined on forehand, based on the number of containers of the same group unloaded by the vessel.
- **Step 2**: Determine the maximum number of reservations of the same group per stack, based on the expected number of containers for the group.
- **Step 3**: Make a list of the possible locations for new reservations of the size specified in step 1 is made.
- **Step 4**: Determine for every slot the occupancy of RMT, and add this to the penalty of that slot. slots located in stacks with a large number of orders get the highest penalty.
- **Step 5**: For every location determine the number of slots reserved and occupied by containers for the same group and subtract the number of slots of the same group allowed per stack. This step makes sure that containers of the same group are divided over the different stacks. Multiply the difference with a weighting factor and add this value to the result of step 4.
- **Step 6**: For every location multiply the floor it is located with a weighting factor and the expected dwell time of the container. If the expected dwell time is relatively long, a higher location in the stack might be preferable to minimize the number of moves to the higher floor. Add the result of this step to the result of step 5.
- **Step 7**: Sort the locations based on the penalties. The location with the lowest penalty is the best locations for the new group.

### B. Dispatching

Dispatching is determining for the equipment what orders they need to perform. For the RMTs the container to be handled is already determined by the sequence in which the containers arrive over the mezzanine floor or are dropped at the transfer point on the ground. The elevator can select orders from the storage floor or the mezzanine floor. The dispatching of the elevator is selecting either a stack-in or stack-out order based on the number of containers on the mezzanine floor. Balancing the stack-in and stack-out containers on the mezzanine floor generate a constant flow of containers to the stack-out RMT without flooding the mezzanine floor. The ScLs determine the sequence in which the containers are delivered to the QCs and the truck gate. The ScLs dispatching aims at keeping a constant floor of containers to the stack-out RMT. At any moment in time all containers that need to be loaded into a vessel are known. However, when the ScL keeps moving containers for the vessel, the incidental orders to the truck gate are delayed due to the number of export containers already waiting to move to the vessels. The ScLs are therefore allowed to work only 20 orders ahead.

## IV. Typical ASC terminal characteristics

An ASC yard is a high density fully automated storage yard. A typical ASC yard consists of multiple stacks perpendicular to the quay. Each stack is served by one, two or in some cases even three automated rail mounted gantry cranes. These cranes can either be passing or non-passing [6]. The typical stacking height of a yard crane is five containers high and the span of the crane can be 8 to 12 containers wide [7].

TABLE I. SPECIFICATIONS OF A TYPICAL ASC CRANE.

| Parameter | Value |
|---|---|
| Gantry speed | 4.5 $m/s$ |
| Gantry acceleration/deceleration | 0.3 $m/s^2$ |
| Trolley speed | 1.0 $m/s$ |
| Trolley acceleration/deceleration | 0.3 $m/s^2$ |
| Spreader hoisting/lowering speed | 0.5 - 1.0 $m/s$ |
| Spreader acceleration/deceleration | 0.35 $m/s^2$ |

The layout of an ASC yard depends on the requirements of the terminal. In general two factors play an important role when designing a layout:

- The required storage capacity of the yard.
- The required handling capacity of the yard to the water side and the land side.

As a rule of thumb a single stack in a ASC yard is able to perform 16 moves per hour to the water side and 10 moves per hour to the land side, assuming that each stack is equipped with two non-passing ASC cranes. The specifications of a typical yard crane are presented in Table I. These specifications are used when simulating the ASC yard.

## V. EXPERIMENTS

The experiments are conducted in two separate models of container terminals; One for the ASC yard and one for the VCT. The basic structure for each of the models is the same. The only differences between the two models is the type of storage yard, and the stacking and dispatching strategy.

### A. Simulation Model

To compare the performance of the VCT and the ASC a discrete event simulation model is developed in eM-plant [8] by the use of the TIMESQUARE library [9]. The performed experiments test the performance of the storage yards under peak conditions, which means that there is always a vessel for each of the QCs and that a constant flow of trucks arrive at the truck gate. The orders are generated randomly. The vessel selects containers from the yard that are destined for the service of the vessel. Other unload orders and load orders from the truck gate are randomly generated. The transport over both terminals is handled by shuttle carriers. The routing and collision avoidance is not taken into account, so each vehicle drives the shortest route without taking into account other vehicles. The number of vehicles is set high enough to ensure the performance of the yards is not influenced by the performance of the shuttle carriers. Each experiment runs for eight hours. The first hour is assumed the warm-up hour and deleted from the results. The simulation randomly generates the containers to fill the yard before the start of the simulation. Each container is generated with random values based on the described scenario. After the containers are generated they are allocated based on the stacking strategy described later in this section. This concludes the initial build of the yard.

The TIMESQUARE library contains the basic objects for a container terminal (e.g. QCs, terminal operating system (TOS), containers, etc.) and is used as a basis for the simulation models. For the ASC model no extra objects needed to be added to the library. For the VCT the following objects are added to the library: Mezzanine floors, RMTs, ScLs and Elevators. The TOS handles the dispatching of all terminal equipment, order handling and storage strategies for the containers. For the ASC yard, conventional stacking and dispatching rules are used in the simulation. Containers are allocated based on their weight, location, group, destination, etc. For the VCT, the in Section III developed strategies are used. The ASC model has already proven to be a valid model based on the numerous projects it has already been used in. The validity of the VCT is tested by reviewing 3D data resulting from the simulation with the designers of the VCT and comparing the results with their expectations.

The following simplifications are made in the simulation models:

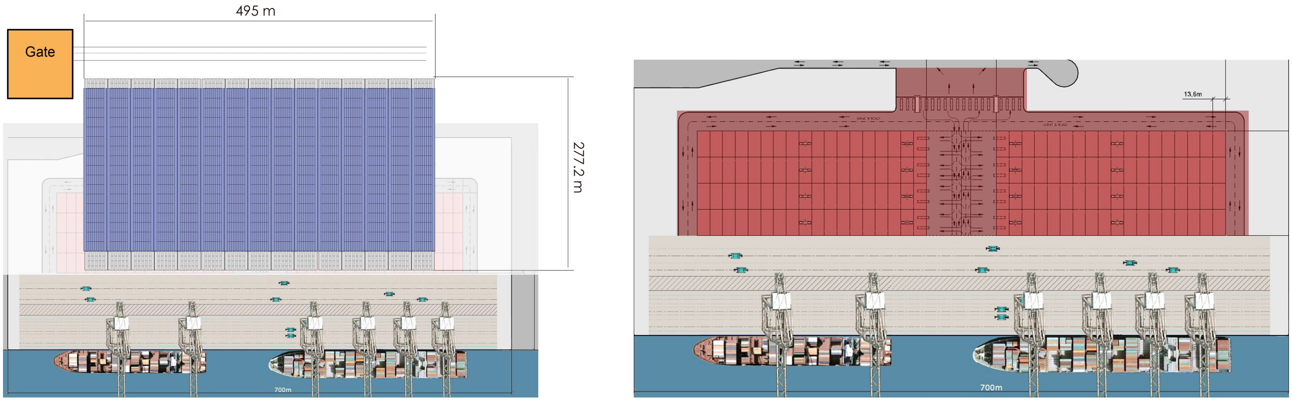
- In the VCT the temporary storage on the mezzanine floor is not used, the containers are only moving over the mezzanine floor between the elevator and the RMTs.
- The simulation models only handle 40ft containers, because the process of handling two 20ft containers on one super skid has not yet been designed for the VCT. It is possible to replace all 40ft containers by a single 20ft container, but this will impact the storage capacity of the yard.
- The model of the VCT does not take into account the delivery of the super skids. The super skids are assumed to be available when a containers is lifted into the stack by the RMT. When the container is discharged from the stack, the super skid is removed again.

### B. Scenario

The two models have exactly the same scenario as input for the simulation. The developed scenario is a balance between what can be assumed as an average terminal and where the VCT could be applied. The influences of changes to scenario are discussed in the conclusions. The basis for the simulation is an 1.4 million TEU per annual terminal with six QCs. The performance of the QCs is set high compared to reality to evaluate what performance the yards can reach. Each QC is capable of performing 50 moves per hour. At the truck gate 125 trucks per hour arrive either picking-up or delivering a container. The transsshipment ratio is 55 percent, and 15 percent of the arriving containers is empty. These settings result in an ideal distribution of types of container in the VCT yard, so no exceptions need to be made when allocating a container. For example storing an import container in one of the slots in the middle of a stack. A summary of the scenario is presented

TABLE II. SUMMERY OF SCENARIO

| Parameter | Value |
|---|---|
| Ratio import/export container flow | 9:11 |
| Ratio regular/empty container flow | 17:3 |
| Dwell time empty container | 9 days |
| Dwell time regular container | 4.5 days |
| Maximum container moves quay | 300 m/h |
| Maximum container moves truck gate | 125 m/h |




(a) ASC yard

(b) VCT yard

Fig. 3. Layout of an ASC yard (a) and a VCT yard (b).

TABLE III. RESULTS PERFORMANCE OF THE VCT.

| Parameter | Value |
|---|---|
| Storage capacity | 18.585 TEU |
| Maximum capacity land side | 116.6 moves/hour |
| Maximum capacity water side | 253.8 moves/hour |
| Total area of storage yard | 85.203 $m^2$ |

in Table II. Based on the scenario, layouts for the VCT yard and the ASC yard are developed. The results of both layouts are presented in Figure 3. The ASC yard consists of stacks of nine container wide and five containers high. The length of each stack is 34 TEU.

### C. Results

Table III shows the results of the experiment on the performance of the VCT. Table IV shows what percentage of the stacks capacity is used to give an insight into what performance might be possible in the future. Table V shows the result of the experiment for the ASC yard.

The results from the experiments on the VCT show that the VCT is capable of reaching the performance defined in the scenario. The idle times of the equipment in the VCT show that the ScLs have a high percentage of idle time. This can be explained by the fact that there are eight ScLs in a stack with four storage floors, while the stack is equiped with only elevator and two RMTs. The difference between the idle time of the stack-in RMT and the stack-out RMT can be explained by the selection of orders for the QCs. Containers arriving at the terminal allocated to a location in the stack based on the stacking strategy and thus sent to stacks with the lowest occupancy for the stack-in RMT. The orders that are performed by the stack-out RMT are orders loading orders for

TABLE IV. IDLE TIME OF THE EQUIPMENT IN THE VCT.

| Parameter | Value |
|---|---|
| Average idle time ScL | 86% |
| Average idle time Elevator | 17% |
| Average idle time stack-in RMT | 11% |
| Average idle time stack-out RMT | 19% |

TABLE V. RESULTS PERFORMANCE OF THE ASC YARD.

| Parameter | Value |
|---|---|
| Storage capacity | 19.508 TEU |
| Maximum capacity land side | 150 moves/hour |
| Maximum capacity water side | 270 moves/hour |
| Total area of storage yard | 137.214 $m^2$ |

trucks or vessels. The loading orders for the QCs are selected per QC. In the model the sequence of the stack-out orders is only optimized for workload distribution per crane. Often multiple QCs are loading vessels and require containers from the same stack, increasing the workload in one stack while in another stack the workload is fairly low. The elevator does also not have much spare productivity, but the dispatching of the elevator in the model only focuses on the number of containers on the mezzanine floor. If the dispatching of the elevator forces the elevator to perform more dual-cycle moves if possible, then the performance of the elevator can increase.

The results from the experiments with the ASC yard are presented in Table V.

In Figure 4 the handling capacity of the VCT and the ASC yard is compared. The ASC yard performs slightly better for the number of LS and WS moves. Figure 5 shows the area required for both storage yards. As can be seen from the figure, the storage yard of the VCT is 38 percent smaller than the ASC yard. The calculation for the total area of the yard also takes into account the lanes around the stack and the area between the yard and the truck gate.

## VI. CONCLUSIONS & FUTURE RESEARCH

In this research the performance of the VCT has been evaluated. The results show that the number of ScLs per stack can be lowered without losing performance of the stack. The bottlenecks in the storage processes are the RMTs. The performance of the stack-in RMT is expected to increase if the spread of workload is taken into account when planning the containers that need to be loaded into vessels by the QCs.

This research has shown that the VCT can be compared with an ASC storage yard in terms of storage and handling

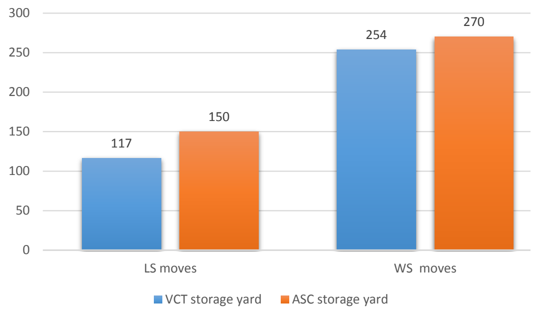



Fig. 4. Resulting performance from simulation experiments

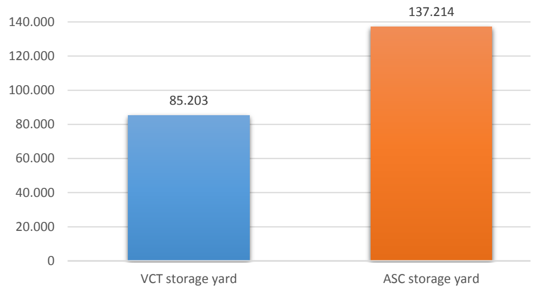



Fig. 5. Area required for the presented storage yards.

capacity. The required space for the storage yard is significantly smaller for the VCT yard.

It is important to notice that the performance has only been tested in a single scenario. Changes to the scenario might influence the performance of the storage yards. A different ratio between import and transshipment containers creates more rehandles in the VCT when import containers also need to be stored in the middle of a storage floor. However in the design of the VCT, with two ScLs per storage floor, these extra rehandles do no directly influence the performance of the stack. The fact that only 40ft containers are used in this comparison means that the VCT loses no capacity. When also 20ft containers need to be handled, a system must be developed in the VCT to combine and split containers on one super skid. It is also possible to place a single 20ft container on one super skid, but this influences the storage capacity of the yard. In the ASC yard two 20ft containers can be placed together in a 40ft slot, so the storage capacity of the ASC yard is not influenced. The following recommendations are done for further research:

- The VCT has currently only been evaluated for 40ft containers. However, in real terminals also 20ft containers are used. To prevent losing storage space when handling 20ft containers the design of the VCT must be changed to be able to combine and split two 20ft containers on a single super skid.
- The workload on the RMTs currently determines the performance in a VCT stack. To improve the performance of the VCT, extra locations for loading and unloading the stacks can be added near the elevator at the mezzanine floor. This improvement needs to be further investigated.
- In this research the mezzanine floor has only been used to transfer containers from the RMTs to the elevator. The use of the mezzanine floor as temporary storage has not been evaluated yet. Depending on the requirements of stack it is also possible to use both RMTs for only loading or unloading. The problem of how to route the containers over the mezzanine floor in combination with temporary storage is recommended for future research.
- The VCT has only been tested in a single scenario. The simulation model could be used for future research when an actual possible site for the VCT is determined. It is recommended that the VCT is tested in an environment where it can be used. An actual site for a terminal might give a different layout and container flow, influencing the decision for one storage yard or the other.

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# Appendix B

# Equipment specifications

In this appendix the specifications of the different equipment in the VCT stack, as provided by Polotec, are presented.

- Tabel B.1: Rail mounted trolley specifications.
- Tabel B.2: Scissor lift specifications.
- Tabel B.3: Cargo elevator specifications.
- Tabel B.4: Roller beds specifications.

**Table B.1 Specifications of the rail mounted trolleys.**

| | Direction | m/s m/s2 | sec | Notes |
|---|---|---|---|---|
| Longitudinal speed, loaded | h | 0.6 | | |
| Acceleration | h | 0.2 | | |
| Deceleration | h | 0.2 | | |
| Lowering speed, loaded | v | 0.5 | | |
| Hoisting speed, loaded | v | 0.6 | | |
| Spreader engage | | | 10 | |
| Spreader disengage | | | 6 | |
| Longitudinal speed, empty | h | 0.8 | | |

**Table B.2 Specifications of the scissor lifts.**

| | Direction | m/s m/s2 | sec | Notes |
|---|---|---|---|---|
| Lashing in Elevator posit | h-long | | 5 | Low level:export, Upper lev.:import |
| Lashing in all positions where SLT shift loads on roller conveyors | h-long | | 5 | |
| Acceleration loaded; 40t | h-long | 0.4 | | Parallel v+h drive |
| Acceleration loaded; 20t | h-long | 0.5 | | Parallel v+h drive |
| Deceleration loaded:40t | h-long | 0.5 | | Parallel v+h drive |
| Max speed loaded:40t | h-long | 3 | | Parallel v+h drive |
| Max speed loaded:20t | h-long | 4 | | Parallel v+h drive |
| Max speed, empty | h-long | 6 | | Parallel v+h drive |
| Max acceleration, empty | h-long | 2 | | Parallel v+h drive |
| Speed transverse; 40t | h-transv | 0.5 | | Single drive |
| Speed transverse; 20t | h-transv | 0.5 | | Parallel v+h drive |
| Speed transverse; empty | h-transv | 0.5 | | Parallel v+h drive |
| Exchange wheel direction,all | h | | 5 | |
| Acceleration, loaded;40t | v | 0.1 | | Single drive |
| Acceleration, loaded;20t | v | 0.1 | | Parallel v+h drive |
| Acceleration, empty | v | 0.3 | | Parallel v+h drive |
| Deceleration, loaded;40t | v | 0.1 | | Single drive |
| Deceleration, loaded;20t | v | 0.1 | | Parallel v+h drive |
| Deceleration, empty | v | 0.3 | | Parallel v+h drive |
| Hoisting speed, loaded;40t | v | 0.5 | | Single drive |
| Hoisting speed, loaded;20t | v | 0.5 | | Parallel v+h drive |
| Lowering speed, Loaded;40t | v | 0.5 | | Single drive |
| Lowering speed, Loaded;20t | v | 0.5 | | Parallel v+h drive |
| Hoisting speed empty | v | 0.6 | | Parallel v+h drive |
| Lowering speed empty | v | 0.6 | | Parallel v+h drive |
| SS-final positioning-lashing to column | h/v | | 10 | |
| SS-release from rack | h/v | | 5 | |

**Table B.3 Specifications of the cargo elevator.**

| | Direction | m/s m/s2 | sec | Notes |
|---|---|---|---|---|
| Acceleration | v | 0.2 | | |
| Deceleration | v | 0.2 | | |
| Max speed loaded | v | 1 | | |
| Max speed empty | v | 1.2 | | |
| Time to load/unload elevator | h | | 8 | |

**Table B.4 Specifications of the roller beds.**

| | Direction | m/s m/s2 | sec | Notes |
|---|---|---|---|---|
| Speed longitudinal drive, all | h | 0.35 | | |
| Speed transverse drive, all | h | 0.35 | | |
| Exchange time in crossings | h | | 5 | |

# Appendix C

# Calculations: design of an ASC layout

In this appendix the calculations for the design of the ASC terminal are presented. In Section C.1 the requirements on the yard design are presented. In Section C.2 the size of the yard in terms of slots and stack is determined. In Section C.3 the dimensions of the storage yard are determined.

## C.1 Requirements

The designed ASC terminal is designed to fit the same requirements as the VCT terminal. The requirements on the ASC terminal are:

- The storage capacity of the ASC yard must be equal to the capacity of the VTC. Therefore the yard must be able to store 18.586 TEU.
- The requirements from the WS and LS of the terminal are respectively 240 moves per hour and 125 moves per hour.
- The maximum width of the storage yard is equal to the width of the VCT; 500 meter.

## C.2 Storage & handling capacity

First of all the total number of required slots are calculated. An ASC terminal has a maximum density of 85% under which the yard is assumed to still be able to deliver the required performance. The total required number of slots is the peak capacity divided by the maximum density. The ASC yard needs a storage capacity of 21.866 TEU. The number of stacks is determined by the number of moves on each side of the stack. As a rule of thumb it is assumed that an ASC stack with two yard cranes is able to perform 10 container moves per hour at the LS and 16 moves per hour on the WS. Considering the requirements at least 15 stacks are required to reach the performance of 240 moves at the WS.

The number of stacks and the storage capacity are determined and can be used to determine the layout of each. Per stack a storage capacity of 1.458 TEU is required. The width of a stack with ASCs ranges from 8-10 containers and containers can be stored up to 5 containers high. If stacks of 9 containers wide and of 5 containers high are used, each stack must be at least 33 TEU long. Since only 40-ft containers are considered the 34 TEU is assumed for the length of the stack.

## C.3 Dimensions

The ASC stacks are perpendicular to the quay. To determine if the designed stacks fit within the required 500 meter, the width of each stack in meters must be determined. The new APM terminal on the Maasvlakte 2 APM Terminals (2014) uses ASCs. The average width of a stack on the APM terminal, including space for the rails of the yard cranes and service aisles, comes down to around 33 meters per stack. Assuming this width to be representative for the average width of an ASC stack, the 15 stacks have a total width of 495 meters. The length of the stacks in meters can be calculated width the length of a slot. A 20-ft container is 6.10 meters. Considering some space between the containers, the length of 1 TEU is 6.60 meters. Multiplying the length of a slot with the total number of slots, the length of the storage is 224.4 meters. Part of the storage yard are also the TPs at each side of the stack. On the WS and LS the TP has a capacity of 4 TEU per row, adding an extra 26.4 meter to each side of the yard. The total length of the yard is 277.2 meters.