MASTER

Improving yard deployment efficiency at APM Terminals Rotterdam

van Putten, M.P.

Award date:
2005

TECHNISCHE UNIVERSITEIT EINDHOVEN
Department of Mathematics and Computer Science

MASTER'S THESIS

Improving yard deployment efficiency at APM Terminals Rotterdam

by

M.P. van Putten

Eindhoven, August 2005

Supervisors: Dr. ir. I.J.B.F. Adan
Dr. ir. C.A.J. Hurkens
Ir. R.J.G. van de Weijer

Acknowledgements

I have been very lucky with the people who supported me during this project and I will try to name all of them, starting with my company supervisor. I think he did a great job by always being there for answering questions, brainstorming with me, or looking critically at my work. Roel, the rest of the evaluation will follow by e-mail...

Second, but not second best, are my university supervisors, Ivo and Cor. Yes, I am in the luxurious position to have two of them and they complement each other very well, which ensured me of a thorough academic supervision.

Then, without Simone, Stef, and Jan this project would not even have been carried out by me.

Furthermore I want to thank the people who provided me with the data or the operational knowledge I needed: Danny, Frans, Eddo, Yasmien, Guido, and Dong.

Finally, I want to name Ronny, who made starting my new life in Rotterdam a lot easier and a lot more fun than if I had to do it on my own.

Summary

The yard lay-out should support high production

The number of container moves over the quay determines the production of APM Terminals Rotterdam. Therefore, all processes aim at (un)loading vessels as fast as possible. The yard lay-out influences the production, because the stacking position of a container determines its transportation distance to or from the quay. The longer this distance, the longer (un)loading takes, the lower the production.

The yard lay-out has to support a high production. Thus, a yard lay-out is optimal when the total time it takes to get containers to and from the quay is minimal. The current yard lay-out has been determined based on experience and it was not known if the current lay-out is the optimal one. A mathematical model of the yard can determine the optimal lay-out.

A mathematical model determines optimal stacking positions

We developed a mathematical model which determines the stacking position of each containergroup entering the yard in one week. The containergroups are based on incoming and outgoing modality or service, so, for example, export entering by truck and leaving by AE1 could be considered one containergroup. The number of containers, the average dwell time, and the arrival or departure time of each containergroup are input to the model. The model determines those stacking positions which result in the lowest total transportation distance of the containers to and from the quay. Distances to and from other interchange zones are also taken into account, but considered less important than distances to and from the quay.

A data analysis provides an overview of the weekly cargo flow

A detailed overview of the cargo flow is needed for determining the optimal yard lay-out. This overview was not available at APM Terminals Rotterdam, so we created an overview of the average weekly cargo flow of January 2005. For each containergroup entering the terminal during one week we calculated the average number of containers in the containergroup and the average dwell time. These two figures together determine what capacity is needed at what day.

Small changes in cargo flow do not affect the yard lay-out

The model is applied to the basic cargo flow of January 2005 and to changed versions of this cargo flow. Some examples of changes are adding an extra service, adding more housekeep capacity, and higher stacking. The resulting changes in stacking positions are not that large that a different stacking strategy is required. Therefore, we present one stacking strategy, which is still valid in case of small cargo flow or yard configuration changes.

Stacking guidelines

For the current situation, the recommended yard lay-out is given in Figure 1.

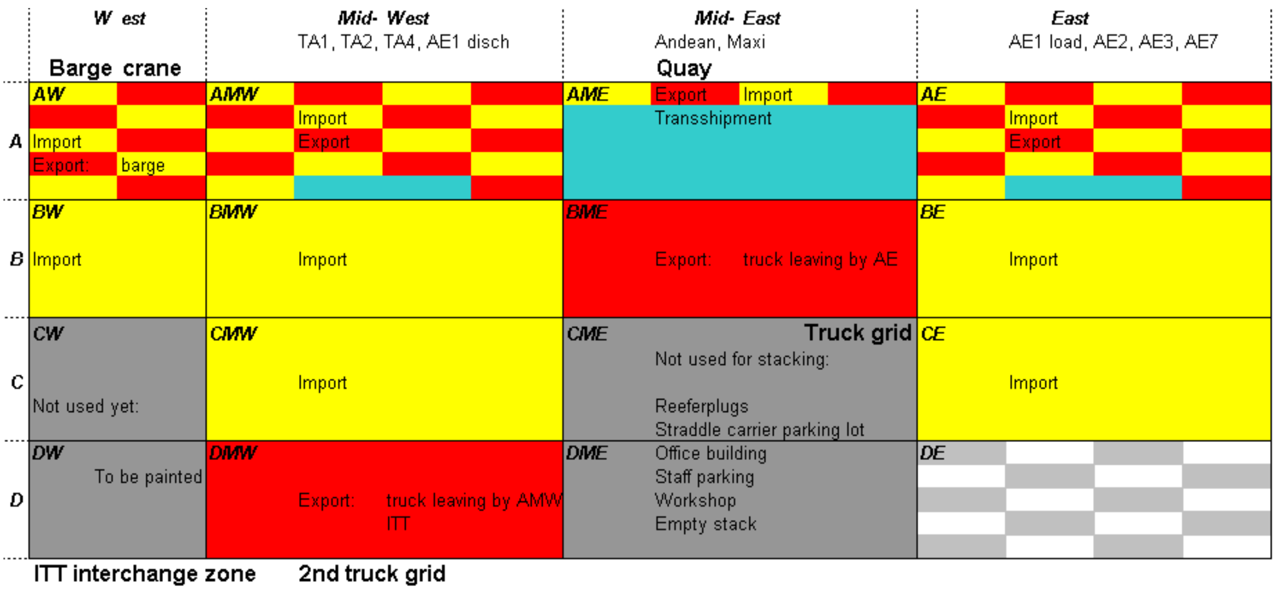

Figure 1: Recommended yard lay out

- A is used by as many import, export, and transshipment containers as possible, because it is close to the quay. Therefore, most import containers are dumped in A and removed after a few days and almost all export containers are moved to A the last one or two days before arrival.
- B and C are used as additional import areas. B is not too far from the quay, so usable for dumping if A is full. B and C are both located centrally, with a reasonable distance to all interchange zones. This keeps the expected driving distances for import containers with an unknown outgoing modality low.
- Export is "dumped" near its incoming interchange zone and moved to A one or two days before departure.

Contents

Chapter 1

Introduction

Over the past decades, container transportation has been a quickly growing industry. In early times the way containers were handled could be planned with 'gut feeling'. Currently, however, sophisticated systems are needed for streamlining the processes at container terminals, where thousands of containers a week are transferred.

APM Terminals Rotterdam uses such a system for determining the exact position of individual containers, but the global lay-out of the terminal is determined on the basis of common sense. APM Terminals Rotterdam wondered if the current lay-out supports the most efficient (un)loading of vessels or if a better lay-out exists. Answers to this question and related questions are provided in this report, supported by mathematical models.

This project has been carried out in the Terminal Development department of APM Terminals Rotterdam, which takes care of improvements and expansion projects. It is the final project of the two-year postgraduate program Mathematics for Industry (Technische Universiteit Eindhoven), as well as a master's thesis for Applied Mathematics (at the same university).

As this report is intended for readers with various backgrounds and knowledge, we provide some guidelines for reading the report. The next paragraph gives an overview of the chapters with background information and studies. The last paragraph gives an overview of the chapters which describe the modelling.

Chapter 2 contains necessary background information on container handling, especially for people who are not familiar with container terminals. Chapter 3 gives the initial (global) problem description of the project, which is useful for all people involved in this project. The specific research questions handled during this project are presented in Chapter 6. Before determining these research questions, two studies have been performed: a literature study (Chapter 4) and an analysis of the cargo flows at APM Terminals Rotterdam (Chapter 5). The former is useful in case one wants to perform further investigations into container terminal processes. The latter gives an overview of the current processes at APM Terminals Rotterdam, useful for yard managers and supervisors, or for development projects.

The research questions in Chapter 6 have been investigated with help of the mathematical models described in Chapter 7. This chapter is accessible for all interested readers. The mathematical formulation of the models is presented in Appendix C. The cases we investigated with the models are presented in Chapter 8 and the corresponding results in Chapter 9. Chapter 10 contains guidelines for determining the yard lay-out, which can be derived from these results.

Chapter 2

Background

In this chapter we explain container handling at APM Terminals Rotterdam, starting from a very basic level and finishing with quite specific information. For more general background on container terminals, see (in increasing order of detail) Murty et al. [22], Vis and De Koster [29], and Steenken et al. [27]. If the meaning of a word or abbreviation (anywhere in this report) is not clear, we refer to the glossary (Appendix A).

2.1 Introduction to the company: APM Terminals Rotterdam

APM Terminals Rotterdam is a container terminal at the Maasvlakte. It is part of the A.P.Moller-Maersk Group, a company which deploys a wide range of activities like shipping, oil and gas exploration, and aviation. One of the activities is transporting containers. APM Terminals serves the vessels from Maersk Sealand (another part of A.P.Moller-Maersk) and has other customers. Approximately 350 people work at APM Terminals Rotterdam. The terminal runs continuously: 24 hours a day, seven days a week.

2.2 Container classification

Containers are classified by the physical characteristics given in Section 2.2.1, 2.2.2, and 2.2.3.

2.2.1 Size

The length of most containers equals 20, 40 or 45 feet. *TEU* (Twenty feet Equivalent Unit) is used as a measuring unit. The *TEU factor* gives the ratio between the number of TEU and the number of containers. When we have one 20 feet container and one 40 feet container, for example, the TEU factor is $\frac{1+2}{2} = 1.5$ The width is standardized (8 ft) and the height can be 8.6 or 9.6 ft.

2.2.2 Weight

APM Terminals Rotterdam distinguishes three weight classes, namely 1-10 tons, 10-20 tons and 20-30 tons.

2.2.3 Contents

The following contents types are distinguished:

- *Dry vans* are regular containers;
- *Reefer containers* have to stay cool. When they are stored, they need a special installation which provides them with the energy for cooling;
- *Empty containers*;
- *IMO containers* are used for transporting dangerous goods.

2.3 Modalities

APM Terminals Rotterdam takes care of temporary storage and moving containers to and from *modalities* (modes of transportation): deep sea vessels, barges, trucks, and *ITT* (Inter Terminal Transport).

2.3.1 Vessel

Vessels transport containers over the oceans. The largest vessels can nowadays carry up to 9,000 TEU. Most vessels follow a *service*, a planned recurring route with fixed arrival and departure times, port of destination, and cargo. Services can be compared to a metro service: different ships are sailing the same route at the same time. The same service arrives at a terminal every week at the same day (and time). A vessel calls on several ports in one voyage.

A *feeder* is a deep sea vessel which only sails relatively short distances, e.g. Rotterdam - Southampton. Feeders transport cargo to the larger vessels ("feed" them).

2.3.2 Barge

Barges transport containers over inland waterways (rivers). They are smaller than vessels and transport between ten and several hundreds of containers.

2.3.3 Truck

Trucks can transport one or two containers at a time.

2.3.4 Inter Terminal Transport (ITT) and rail

ITT is carried out with small train-like vehicles (*MTS*, Multi Trailer Systems) which can transport approximately 10 containers at a time. APM Terminals Rotterdam does not have its own railway. It transports the containers to the neighbouring terminal, ECT, by ITT. The containers are put on a train there. Therefore rail moves and other ITT moves are not distinguished.

2.4 Equipment

2.4.1 Quay cranes

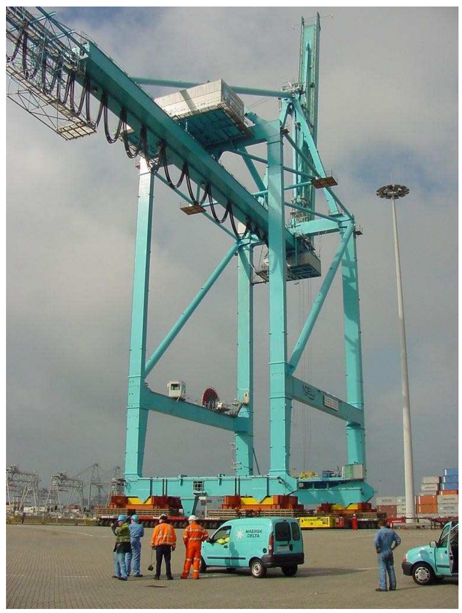

Figure 2.1: Quay crane

The containers are moved to and removed from vessels by quay cranes (Figure 2.1) which can move alongside the quay on rails. The super post panamax cranes have a boom of 60 meters, which gives the possibility to handle 22 rows-wide vessels. Several cranes can (and will, if possible,) work simultaneously on one vessel. A vessel is, along its long axis, divided into several *bays*. For technical reasons, two cranes cannot work on adjacent bays at the same time. Also, no three cranes can work next to each other with only one bay between each pair of them. If this is done, vehicles bringing the containers to or fetching them from the cranes have to drive underneath one of the side cranes to reach the middle one. This would be too dangerous.

Currently, there are eight deep sea cranes and one barge crane. The number of cranes will be extended to 11 in 2006. APM Terminals Rotterdam cranes are capable of lifting two 20 ft containers at the same time (*twin-lifting*). This gives the advantage of a double productivity.

There is a buffer under the crane in which up to five containers can be stacked. When the buffer is full, the crane cannot unload more containers.

2.4.2 Straddle Carriers

Figure 2.2: Straddle Carrier

Straddle Carriers (SCs) (Figure 2.2) are vehicles which transport a container over the yard. They pick up a container by driving in the space on both sides of it and then lifting the container underneath them. The SCs are approximately 13 meters high, to be able to handle containers from a pile of maximal four containers. Some SCs can only handle three-high stacks, depending on their height. As expected, four-high SCs are a bit more expensive than three-high ones.

SCs also have the possibility to lift twins, but sometimes cannot because of too much weight. (Their maximum capacity is ± 42 tons.) Twin-lifting reduces total driving distances significantly. SCs drive at a maximum speed of 25 km/h.

2.4.3 Empty handlers

Most empty containers are stacked densely. In a *dense stack* there is no space between the containers and usually it is quite high (up to eight containers). Because of this, SCs are not able to serve a dense stack. Therefore other equipment is used, an *empty handler*, which does not drive over a pile of containers but picks them from aside.

2.4.4 Equipment used at other terminals

Dense stacking can also be done by *gantry cranes*, large cranes which can move over a stack of approximately seven containers wide. They are not used by APM Terminals Rotterdam, but they are used by some other terminals. If the benefits outweigh the costs, the operation type might be changed in the future by using dense stacking everywhere and replacing the SCs by gantry cranes. However, in this project we focus on the current SC operation.

2.5 Yard lay-out

In this section we discuss the current lay-out of the yard and the way of deploying it on basis of the schematic map in Figure 2.3. We also mention some considerations which have lead to the current practice. The map is not completely up to date, but it gives a good idea of the lay-out. This lay-out is tried to be kept as flexible as possible and updated whenever necessary.

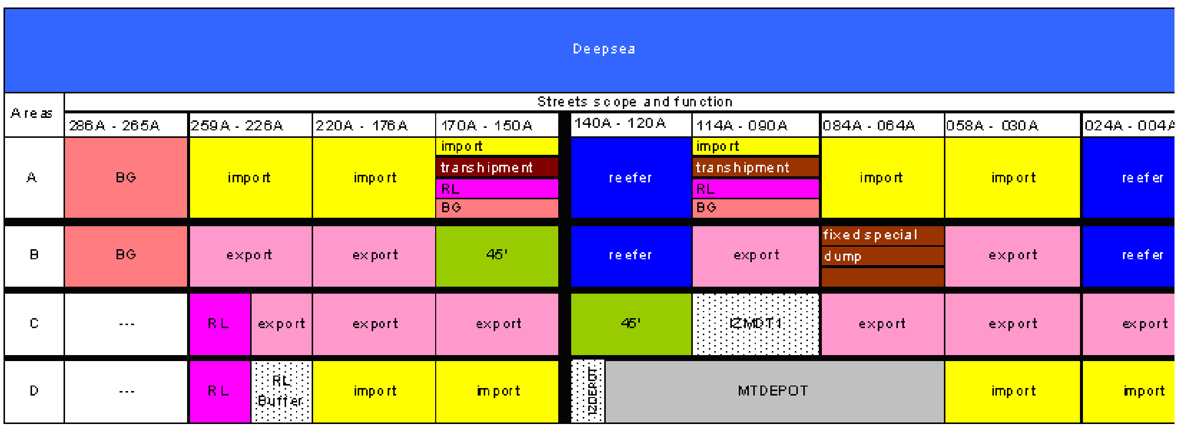

Figure 2.3: Current yard lay-out

The yard is divided into four main areas, A, B, C, and D, A being closest to the quay and D the furthest from the quay. 286 streets have been constructed perpendicular to the quay. (In Figure 2.3 they are numbered from east to west.) Between the areas A, B, C, and D and between blocks of several streets are lanes where straddle carriers can drive (the black lines in the figure). A street is divided into several 40 ft slots, in which one 40 ft or two 20 ft containers can be put. However, the policy is not stacking 20 and 40 ft containers in the same street. The streets in the A-block are seven slots long and in the other blocks six. Up to three or four containers are stacked on one ground slot. 45 ft containers have their own block (streets 120C to 140C).

The yard will be expanded, but the operation type and the lay-out of the new area have not been determined yet. There are several growth scenarios, so we cannot use *the* expected growth in our research.

Containers from the Asia services (code: TA) are stacked on the west side (left side in Figure 2.3) of the terminal and all containers from the America services (code: AE) on the east side.

2.5.1 Interchange zones

The areas where the containers are moved to and from land transportation are called *interchange zones*:

- IZMDT1 is the main truck parking area for delivery of export and pick-up of import;
- IZDEPOT is the truck parking area for delivery and pick-up up of empty containers;
- RL Buffer is the multi-trailer parking area for ITT transportation.

2.5.2 Reefer racks

Reefer containers have their own blocks, because a special installation is needed for energy supply. Also because of this installation, the 20 and 40 ft reefers are not mixed and the reefers are only stacked up to three-high. However, in the future this might be changed to four-high, because of the high cost of a ground slot.

In Figure 2.3 you find four reefer blocks, but at the moment of writing this text, extra reefer plugs are being built in the C and D area in streets 152 to 170.

2.5.3 IMO streets

For safety reasons, IMO containers are stacked at the sides of the blocks, close to the lanes.

2.5.4 Empty depot

The non-Maersk empty containers are treated as normal containers, but the empty containers from Maersk are stacked in the empty depot in the D-area (MTDEPOT). Only if they need to be transshipped, they are tried to be stacked in the A-area. Before use, empty containers are moved by an empty-handler from the empty depot to so-called *M-streets* or directly to a truck. From the M-streets they are moved with a straddle carrier, like all other containers.

2.5.5 Dry vans

We have pointed out the interchange zones and areas for containers with ”special” (including no) contents and the interchange zones. The rest of the yard is occupied by dry vans, which are globally split into *import*, *export*, and *transshipment*.

Transshipment

Transshipment containers arrive by vessel and leave by vessel. In order to reduce transportation distance over the yard, they are stacked near the quay (in the A-area).

Import

Import containers arrive but do not leave by deep sea vessel. When they arrive, mostly the departure time is not known yet and often also the departure modality is not known yet. To be able to serve a vessel quickly, all import containers are *dumped* (unloaded and stacked randomly) in the A-area, close to the berthing position of the vessel. (This excludes reefers and IMOs, as they need special care which cannot be facilitated in the dumping area.) Dumping saves some time, because of the stacking location close to the quay. If there is no hurry, the containers are stacked in the right place in the yard right away.

This "right place" is based on the outgoing modality of the container, if it is known. There are special blocks for barge (BG), close to the berthing place for barges, and rail (RL), in the back of the yard, for fast transportation by ITT. Truck containers and containers with unknown future modality are stacked in the yellow blocks in the D-area. New ("hot") containers are stacked on top of old ("cold") ones. At first, import containers are stacked two-high. If more space is needed, three-high is also allowed.

Except for the speed, another advantage of dumping in the A-area is that the D-area is kept relatively "clean". This means that the number of shifters needed before being able to fetch a container from the D-area is low, which implies short waiting times for trucks. A *shifter* is a container move needed because the container to be fetched is inaccessible. Shifted containers are, if possible, always moved to another position in the same street. This is a setting in the software system which supports the operation (discussed in Section 2.6) and can easily be changed.

Despite the dumping, rail and barge (and transshipment) containers are filtered right away if possible. If the vessel has moored on the east side of the quay, barge and rail containers are firstly dumped in the two middle blocks of the A-area. If the vessel has moored on the west side of the quay, barge and rail containers are stacked in their dedicated blocks at once. The other containers are dumped in the yellow blocks in the A-area.

Stacking locations for those containers are also determined by the probable mooring location of the vessel. Depending on this location, certain boundaries are set inside which the container should be stacked. These boundaries are changeable. Stacking is started from a "center point" inside the boundaries. Containers are stacked as close as possible to the center point.

When more space is needed or in less demanding periods, dumped containers are removed from the A-area (except for the barge containers, because the dumping area is close to the barge berthing place) and stacked in the yard (so called *housekeeping*). This is not always necessary, because approximately half of the containers is picked up within a few days after arrival. The moves of the containers during housekeeping are the *unpaid* moves, in contrast to the moves to and from a vessel, truck or train. Generally there is enough capacity (man-power and SCs) to do all necessary housekeeping.

Export

Export containers leave by deep sea vessel. They are classified by the following characteristics:

- outgoing service;
- length;
- height;
- weight class;
- port of discharge.

Containers with (nearly) equal characteristics are tried to be stacked on top of each other. The same boundary system as used for the dumped import containers is used for the export containers.

Starting from this summer, export containers might be stacked by *ETD* (Estimated Time of Departure). This means that export containers with an ETD in the near future are stacked on top of export containers with a later ETD.

Containers with totally equal characteristics are preferably stacked together in the same street. Such streets are called *fixed specials*. A tool is used which determines the number of containers with each combination of characteristics. If this number is high for a certain combination, this combination is remembered by the planning software and containers of this type are stacked in a fixed special street. Such a street is reserved as soon as the first container of this type arrives (if there is space, of course). Fixed specials are created in the B area (046B - 084B and 190B - 259B) and in at most 30 streets in the A area. If there is no space in a special street and no new one can be constructed, the special container is planned manually or planned as if it is a normal container.

If a street contains containers for just one vessel, the containers are stacked three high, otherwise only two high. The reason for this is the possibility that a container is needed which is located in the middle of a mixed street (with containers for different vessels). If the street is three high, the container can only be reached by dismantling the street starting from one end, because three-high SCs cannot move a container *over* a pile of three others.

Sometimes sticking to the schedule is more important for the vessels than taking all containers with them. In this case, if a vessel is expected to leave late, it just leaves without the full number of planned containers. This action is called "cut-and-run". It can result in, for example, 300 containers which, in contrast to the planning, have not been loaded and should be stacked somewhere in the yard. In principle, each container leaves with the first arriving vessel of the service it should attend.

2.6 Terminal Operating System and container handling on operational level

APM Terminals Rotterdam uses software, a Terminal Operating System (*TOS*) called COSMOS, to support operational decisions. The functions of this system and the way operational decisions are made are described in the remainder of this section.

2.6.1 Berth planning

The first thing to be planned is the berthing position of the vessels, given their arrival times and cargo to be (un)loaded. The duration of a berthing can last up to approximately 24 hours, depending on the number of containers to be (un)loaded. The berth planning is done by hand. There is a proforma berth planning, which also gives the number of in and out moves for each vessel. This planning is changed a few times a week, when new information about arrival times and containers to be (un)loaded becomes available. Soon, *BAS*, a Berth Allocation System, will be introduced.

2.6.2 Vessel planning

The allocation of containers on board of a vessel (vessel planning) is outlined by a central (inter-terminal) planner. The allocation cannot be determined freely by one terminal, because most vessels have to (un)load at more than one terminal. After each terminal visit, the cargo in a ship should still satisfy certain criteria. The weight should be balanced, for example, in order to guarantee stability of the vessel. Also, the containers should be spread over the vessel such that they can be unloaded efficiently.

Therefore, the loading of a vessel has to be done in a strict order. The container type that has to be put in each slot is given by the central planner. The exact order of the containers to be taken from the yard and put in the vessel is determined by the Marine Planning department with help of SHIPS, a part of COSMOS. This order depends on the locations of the containers in the yard.

When the vessel is ready for loading, Marine Planning provides the tower, from where the operation is managed, with an ordered list of containers to be moved. The tower communicates with the SC drivers. This is generally automated.

Instead of first to be totally unloaded and then to be totally loaded, bays are sometimes loaded and unloaded at the same time. This is called double cycling. This process is always used for trucks: SCs serving trucks take a container from a truck, stack it in the yard, fetch a container from the yard, put it on another truck, etc.

2.6.3 Yard stacking

While the loading order of a vessel is fully planned, *un*loading is not done in a strict order. The SC-driver communicates to the tower what container he (I have not seen any female SC drivers yet.) has picked from underneath the crane and then he is informed where to stack it. The stacking positions of those containers are determined by the Yard department. This is done with support of SPACE, another part of COSMOS. SPACE can be set to two-high or three-high stacking, according to the wishes of the user.

When determining where to stack a certain container, a container of the same service, size, destination, and weight is localised and the new container is put on top of it. If no such container is found, the new one is put in an empty ground slot.

If there are no free ground slots anymore, the container is planned manually. For manual planning certain guidelines are used, for example, "heavy on light": In a vessel, light containers are generally stacked on top of heavy ones, so in the yard it is done the other way around. This keeps the number of shifters low. Sometimes a container arrives which was not mentioned on the discharge list. This causes trouble for the planning. Often these containers are planned manually.

2.6.4 Dispatching

The landside, seaside and empty stack are managed separately. Each SC is appointed to one of those three by a dispatcher. The SCs on the seaside are appointed to a specific crane (or two specific cranes and have to serve the busiest). If SCs turn out to be a bottleneck in the operation, the total number of SCs can be increased on the long run. However, if too many SCs are working in one area, their production decreases because of congestion. This implies that just increasing the number of SCs does not solve all problems. There is congestion near the *truck grid* (place where trucks are (un)loaded), for example, when the number of container moves per hour to and from the grid is approximately larger than 80.

Chapter 3

Problem description

The current strategy for deploying the yard of APM Terminals is based on several years of experience. Since the initial set-up of the yard, trial and error have led to many improvements. However, there are still indications that improving the efficiency might be possible. There seem to be too many shifters and driving distances of the straddle carriers seem unnecessarily long, which could lead to a sub-optimal performance of the yard. An improved efficiency leads to an improved terminal performance (or production, more moves of containers to and from vessels). This will become even more important in view of the foreseen extension of the yard and increasing volumes.

Another factor which leads to a sub-optimal terminal performance is the unreliability of cargo flows: modality, amounts, departure times, etc. Data reliability is not taken into account in the current yard deployment strategy. Often, unreliable data delays the process.

The main goal of this project is the development of a well-grounded yard strategy which improves the productivity of the terminal by maximizing the efficiency. This efficiency will be expressed by one or more Key Performance Indicators (to be determined during the project), e.g., average amount of shifters and transportation time per paid move.

Chapter 4

Literature review

Over the past few decades, a lot of literature has been written on container terminals. There are several non-straightforward questions in container terminals, like the amount of equipment to use, how to use it, the lay-out of the yard, the berthing position of the vessels etc. Most of those influence each other. The decisions to be made on how to carry out the processes are often split into decisions on the berthing, the yard lay-out, and the interchange zones for truck, rail, and *ITT* (Inter Terminal Transport). Only an integral approach to all decisions could lead to an optimal container terminal deployment strategy. Some papers try handling a whole terminal and all processes at once, but always split the questions somehow. The reason for this is the complexity and the uncertainty of the processes.

The decisions at a terminal can also be split in another way, into three levels: the strategic level (*How much space do we need for our import containers?*), the tactical level (*How many cranes do we use on a ship?*), and the operational level (*What is the shortest route to the stacking location?*). Most papers written during the past decade discuss the processes on a tactical or operational level and assume that a global yard lay-out exists, for example, the locations of the import and export blocks have already been fixed. In this project we will not investigate the operational level, but try to find strategic (and tactical) stacking guidelines. In this literature review we focus on papers which are specifically useful in the context of the yard efficiency or for other current developments at APM Terminals Rotterdam. Each subsection discusses one of the relevant topics.

4.1 Overview

Vis and De Koster [29] and Meersmans and Dekker [21] both give a literature overview of container transfer at a terminal and corresponding decision problems. Steenken et al. [27] present a more detailed introduction to the container business as well as an extensive literature overview. They state that the need for operations research in container terminals has increased in recent years. The reason is the level of complexity of the logistic processes (especially in large terminals). Further improvements would require scientific methods. They conclude that operations research methods are used more and more in real terminals.

4.2 Number of rehandles

Many papers state that processing times of containers are very dependent on the number of *rehandles* (moves of containers from one position in the yard to another one). Kim et al. have done quite some research into this topic:

- Kim [11] presents both a probability (slow) and a regression (fast) model for estimating the expected number of rehandles needed to pick up an arbitrary container. Some of their assumptions do not coincide with the practice at APM Terminals Rotterdam, but adjusting their method to make it suitable for this specific terminal might be possible.
- Kim and Kim [13] introduce a mathematical programming model which estimates the stacking height for import containers that minimises the number of rehandles. This could be considered a strategic or tactical model. They consider, among others, a cyclic arrival pattern (like at APM Terminals Rotterdam). They suggest a solution method based on Lagrangian relaxation. They stick to a segregation strategy, which requires that newly arrived containers are not allowed to be stacked on top of containers that arrived earlier.
- Kim et al. [16] present a dynamic programming model to determine storage locations for individual export containers in a pre-determined area such that the number of rehandles is minimised. This is an operational problem. They only distinguish containers based on weight (class). They present a recursive solution method and a faster decision tree for real-time solutions.
- Kim and Kim [14] present a deterministic model for calculating, for a given lay-out, the terminal operation cost due to rehandles and travelling time over the yard.

The methods presented in the four papers mentioned above ([11], [13], [16], and [14]) are not directly useful for APM Terminals Rotterdam, because each of them has been developed for yards with an RTG (yard stacking crane) operation. However, adapting them to a Straddle Carrier operation might be possible.

4.3 Export dumping

Taleb-Ibrahimi et al. [28] investigate (on a tactical level) ”pre-stacking” strategies for export containers: Containers are dumped at arrival and at a certain moment space is reserved in the ”permanent stack” for all containers of a certain type. For very simple arrival patterns they determine the optimal moment for permanent stacking and for general arrival patterns they present a heuristic.

Their first strategy focuses on minimising the amount of space used. This implies that the containers are pre-stacked as long as possible. (The sizes of the dumping area and the permanent stack are fixed, so some containers cannot be dumped due to the limited amount of space.) Their second strategy minimizes the amount of rehandles and as such tries to minimize the number of containers which are pre-stacked.

A pre-stacking strategy might be very useful for APM Terminals Rotterdam, but the ones presented by Taleb-Ibrahimi et al. use too many assumptions which are not applicable to APM Terminals Rotterdam. They assume, for example, that they know the exact delivery patterns per vessel, which, as we will see later, is not the case at APM Terminals Rotterdam. One of their conclusions states that without pre-stacking, the maximum yard utilisation is only 50%.

4.4 Space allocation

As already stated in the introduction, most papers handle space allocation on an operational or tactical level. In this section we name the papers which handle the tactical level.

Kozan [17] presents a network model for minimising the handling time by determining the optimal amount of equipment used and the optimal stacking positions. He uses this model to investigate the sensitivity of the handling time to the amount of equipment. It might as well be used for determining stacking positions at APM terminals Rotterdam, but this would require several adjustments to the model.

Goetschalckx and Ratliff [5] consider a general warehousing system and describe some shared storage policies. Their proposed methods assume ideal situations and are therefore not (directly) applicable in a container terminal. However, they conclude that there is potential for reducing travel times by a shared storage policy based on duration of stay.

Kim and Park [15] formulate a Mixed Integer Programming model for space allocation for groups of export containers. They use a rolling horizon. One of their two heuristics for solving the model is based on duration-of-stay of the containers, the other on sub-gradient optimisation. The results found with both techniques do not differ much.

Kozan and Preston [18] and Preston and Kozan [24] formulate a Mixed Integer Programming model for determining storage positions for individual export containers such that handling times are reduced. This problem is known to be NP-hard, so they determine an approximate solution with a genetic algorithm. They discuss different storage policies and conclude, among others, that fixed (planned) stacking is better than random stacking and that the optimal stacking height is three containers. However, the occupation rates used in their case study are much lower than at APM Terminals Rotterdam, so the last conclusion might not hold here.

Also Bruzzone and Signorile [2] use genetic algorithms. They develop one for determining the order in which space is reserved for containers of each ship. Another genetic algorithm is used for actually determining the stacking area for the containers of each ship. This is done ship-wise, following the order determined with the first genetic algorithm. They take into account occupied and reserved space, but do not take into account future ships from which the containers have not been planned yet. The algorithms are used in a simulation model. Bruzzone and Signorile conclude that this is a good first step in developing software tools for shipyard planning, but that more research should be done.

Zhang et al. [33] use a rolling horizon and consider a yard with stacking cranes. For each planning period, the container allocation problem is decomposed into two levels and each level is formulated as an Integer Linear Programming model. The solution to the first level determines the number of containers to be stored in different blocks such that the workload is spread. (This is not necessary at APM Terminals Rotterdam.) Given the numbers determined in the first level, the solution to the second level gives the number of containers from each vessel to be stacked in each block, such that the transportation distances of containers from the vessel to the block are minimised. Import, export, and transshipment containers may be mixed. Upon arrival, containers are placed directly in their final stacking position.

The model is applied to a terminal in Hong Kong. CPLEX is used for finding a feasible solution to the model. Zhang et al. only discuss the performance of the first-level model, which is not useful for APM Terminals Rotterdam.

4.5 Housekeeping

Cao and Uebe [3] consider housekeeping on a tactical level: The input of their model is the number of streets they want to empty at a certain moment, the collection of streets which may be emptied (to choose from), and the streets to which the containers may be moved. The solution to their model, a capacitated multi-commodity p-median transportation model, states what containers are moved where, minimising transportation cost plus some fixed cost per street. They use lagrangian relaxation and a heuristic (consisting of a sub-gradient method and branch-and-bound) for approaching the optimum. They conclude that their heuristic seems to be an efficient alternative for solving difficult capacitated multi-commodity p-median transportation problems.

4.6 Berth allocation

Imai et al. have written several papers on berth allocation (see, for example, [10]). Also see Legato and Mazza [20]. If needed for further studies on berth allocation, more papers can be found. Several are mentioned in the references of Imai et al. [10]. As we take the berthing as given in this project, we do not describe those papers.

4.7 Simulation

Yun and Choi [32] present an object oriented simulation model for analysis of a container terminal operation. In case we choose to perform a simulation, their modelling methods might be useful for the case of APM Terminals Rotterdam. Parola and Sciomachen [23] describe simulation models for evaluating the effect of possible future growth of container flows on landside transportation and interchange zone congestion. This is not useful for the current project on yard lay-out, but could be useful for other projects at APM Terminals Rotterdam.

Kozan [19] compares two analytical models, one of which is a batch-arrival multi-server queueing system, and a simulation model. The models determine the expected turnaround time of a ship under certain parameter settings (arrival rates, service times, etc.). He concludes that the analytical model can take the place of the simulation model. However, he gives several good reasons why implementation of this model is still far away, so we will not use it for APM Terminals Rotterdam.

4.8 Decision Support Systems

A few papers discuss Decision Support Systems for container terminals (Van Hee and Wijbrands [7], Van Hee et al. [6], and, much more recent, Murty et al. [22]). The applications vary from terminal design and choice of equipment to management of day to day operations. None of the papers found discusses the yard lay-out in terms of global guidelines for positioning the containers. However, Van Hee and Wijbrands [7] introduce stochastic models for determining transportation times over the yard and the mean and variance of the storage space utilisation. To solve the latter, some assumptions on arrival rates need to be made (Poisson, for example).

4.9 Conclusion

The papers found are not directly useful for the current project at APM Terminals Rotterdam, but some of the papers found might be useful for other developments at APM Terminals Rotterdam, like the introduction of *BAS* (Berth Allocation System), which helps in determining the berthing position of the vessels.

Chapter 5

Cargo flow analysis

At APM Terminals Rotterdam a lot of monitoring data has been stored in the databases. The amount of data extracted from those databases increases, to serve various development projects. Also, a lot of implicit knowledge is present because of the experience of the employees. However, a global overview of the cargo flow and its characteristics is not available. Such an overview provides insight into the bottlenecks in the current situation and into the possibilities for improving it. Also, the information is needed as input when (a part of the processes at) the terminal is modelled. Therefore, the first phase of the project consists of making a cargo flow overview.

The next section describes the data used. The other sections discuss performance measures. The results presented in this chapter are a summary. The tables with the most relevant results are presented in Appendix D. The most extensive version of the results, as well as the data, are provided on a cd-rom with excel files.

Not each presented performance measure is investigated thoroughly, because the data was not available in time. We discuss these performance measures anyway, because a future investigation might still be useful (and in the respective section we state why).

The values of the performance measures are determined for containergroups, not for individual containers. We define a *containergroup* as a number of containers with similar characteristics. We choose characteristics which are expected to influence the "behaviour" (like dwell times and data quality) of the containers:

- Incoming modality
- Outgoing modality
- Incoming service (if applicable)
- Outgoing service (if applicable)
- Incoming voyage (direction) (if applicable)
- Outgoing voyage (direction) (if applicable)

- Length
- Height
- Weight (class)
- ISO code
- Port of discharge

Different levels of detail can be observed. We can consider, for example, all containers which entered by vessel or we can consider all 40 ft, weight class II, 9.6 ft high reefer containers which entered by vessel and left by truck. The amount of output data increases quickly with the level of detail. Therefore the analysis starts with a low level of detail (a high level of aggregation); only the incoming and outgoing modality and the contents type are distinguished. So one containergroup consists, for example, of all full dry containers which have entered by vessel and will leave by truck. Depending on the performance measure, other levels of detail are studied as well. Generally splitting dry vans again according to length, weight and POD is too detailed. This does not contribute to the global lay-out of the yard. It is useful, however, during operations, for example, for decisions on fixed special streets.

5.1 Data

The data used for the cargo flow analysis is derived from a database which stores information about past moves and is linked to the central database, CTCS. All out-moves (moves of a container from the terminal to an outgoing modality) are collected and the corresponding in-move (of the same container) is linked to it. The exact information logged for each container which left the terminal is given in Appendix B.

Data is collected for October 2004 up to and including February 2005. Each month is analysed separately, to be able to keep track of seasonal differences. Generally we assume that results for different months can differ because of seasonal effects, but that variations *within* one month are not due to seasonal effects (so we do not expect, for example, structural differences between weeks). Therefore we have chosen to consider time intervals of one month. For each performance measure the average value is calculated over all containers (of a certain containergroup) which left the terminal in a month.

It would be interesting to know if our hypothesis on seasonal effects is correct, but a few years of data would be needed to perform an extensive statistical analysis. This takes too much memory and storage space and in the past few years so much has changed in the cargo flow, that such a long history would still not be useful for the current operation. Therefore we mainly stick to calculating averages.

Additional to the data on past moves, an extra data set has been constructed for January: a daily yard overview. This shows all containers which were stacked in the yard each day at 8am.

5.2 Flow counts

The *flow counts* give for each containergroup the number of containers transferred. Flow counts are used to estimate the impact of each containergroup on the terminal performance. If, for example, two containers stay at the terminal for a few weeks, it is not important, but in case the number of containers is 200, it is important.

For this performance measure different services are distinguished, in addition to higher levels of aggregation such as import, export, transshipment, and, of course, the total number of containers. We present some aggregated results in Table 5.1. More (detailed) results are presented in Appendix D.1. As expected, most moves are vessel moves, then truck, then barge and then ITT (Inter Terminal transport). Approximately 40% import, 30% export, 20% transshipment, and 10% other containers visit the terminal. In total approximately 56000 containers leave the terminal in a month. (Over the five investigated months the standard deviation was approximately 2500).

	Full dry	Reefer	Empty	IMO	Total
Import	19289	2730	1889	244	24152
Export	12790	1396	2883	790	17859
Transshipment	7411	1411	1526	249	10597
Other	90	12	3754	3	3859
Total	39580	5549	10052	1286	56467

Table 5.1: Total number of containers transferred in January 2005

For validation of the results, the calculated number of out-moves per service in one week have been compared with the figures in the *KPI* (Key Performance Indicators, calculated weekly) file. No significant differences between the KPI and our results have been observed. The differences can be explained by things like ITT moves which are counted twice by APM Terminals Rotterdam and moves which have not been activated in the system and are therefore not counted by us.

5.3 Dwell times

The *dwell time* of a container is the time which elapses between entering and leaving the terminal. The dwell times are used to determine the occupation of a certain area. A container with a long dwell time might preferably not be put near the quay, because you want to use the slots near the quay as frequently as possible.

For the dwell time calculation, the same containergroups are used as for the flow counts. The average dwell times are calculated in two ways. The first method calculates the time difference between the in-move and the out-move and takes the average over one month.

The second method is only applied to January 2005. Each day a snapshot of the yard is taken. For each of these days, the number of import, export and transshipment containers are determined. Within these containergroups, dry vans, reefers, IMO's and empties are distinguished, so we get three times four is twelve containergroup. Now the dwell times per containergroup are determined by the dividing the average number of containers in the yard (of the considered containergroup) by the average number of out moves (of the considered containergroup) per day. This calculation is also known as Little's formula. The exact computation is presented in Appendix C. Note that its results are only trustworthy if a long period is considered in which the average number of out-moves (approximately) equals the number of in-moves. This is the case for a month, but not for a week.

Comparison of the results for the two methods generally shows small differences (+/- 5%). However, also larger differences are found. An explanation of this is the different definition of *import* which is used in each of both methods. Generally throughout this report, we define import as containers which enter by vessel and do *not* leave by vessel. In the first method this number of containers can be determined, but in the second method, the outgoing modality of many containers on the terminal is not known yet.

In the second method we assumed all containers which entered by vessel and with unknown outgoing modality to be import. In reality, they might turn into transshipment. This imposes a bias on the results. Luckily, containers with unknown information on arrival which turn into transshipment are usually empty. (See Appendix D.6.1 for an argumentation.) This means that the comparison is meaningless for empty containers, but useful for full ones.

Because of the bias caused by unknown outgoing modality we stick to the first calculation method. All results presented from now on are calculated this way. We only use the second method for validating the results of the first one (except for the empty containers).

An overview of the most important results is presented in Appendix D.3. In Table 5.2 we present the aggregate dwell times (in days) for January 2005:

	Full dry	Reefer	Empty	Total (days)
Import	5.0	1.8	10.9	5.1
Export	6.4	4.4	9.6	6.2
Transshipment	5.3	4.6	16	6.8
Total (days)	5.5	3.2	9.8	6.1

Table 5.2: Dwell times for January 2005

If we divide import and export moves in truck, barge and ITT (rail) moves, we see that barge dwell times are the lowest. A comparison of the dwell time of one containergroup in different months showed a difference of approximately 10% between the highest and the lowest dwell time.

The results in Table 5.2 can be explained as follows: The dwell time for reefer containers is shorter than for full dry ones, because reefers contain perishable goods. Also, the goods have a relatively high value and reefers have higher storage cost than dry containers. Because of these three reasons they have to be transported quickly. Empty containers have a longer dwell time than full ones, because they do not have any load which has to be transported somewhere.

(Full) import has a shorter dwell time than (full) export. This might partly be due to the *cargo cutoff*: *export* containers have to be ready at the terminal at least 24 hours before arrival of the vessel. On the other hand, sometimes trucks are already waiting at the terminal for *import* containers when the vessel has not even arrived.

5.4 Delivery and pickup times

The *delivery pattern* shows how many days before arrival (or departure) of a vessel each export container is delivered. The *pickup pattern* shows how many days after departure (or arrival) of a vessel each import container is picked up. Both give information on the yard usage by a certain service and thus of the amount of space to reserve for this service. In an ideal case, if two services have complementary yard usage, many containers in the yard for one service imply only a few for the other. Then the containers for both services can be stacked together in the same area. Sometimes more slots are used for one service, sometimes more for the other.

Knowledge of delivery patterns is also useful for planning fixed special streets. However, on such a detailed level (vessel, ISO code, size, weight, and POD distinguished), no general delivery pattern can be found. One week there are 80 containers for fixed special streets a week before arrival of the vessel and another week 20 containers for a fixed special street three days before arrival. Even if all containers of a service are taken together, delivery patterns vary a lot between weeks (see Appendix D.4). Therefore we can only compare different services and say that in general, containers for one service are brought earlier than for another one.

In Figure 5.1 delivery patterns for the Asia services (AE1, AE2, AE3, AE7) and America (TA1, TA2, TA4, ANDEAN) services are compared. The average is calculated over the vessels of these services which visited the terminal in January 2005. We observe that deliveries for AE services are concentrated in the last week before arrival of the vessel, while containers for the TA services are more often brought early: 25% of the AE containers is already present in the yard more than one week before vessel arrival and 34% of the TA containers. This is also reflected in the respective dwell times, which are 6.3 and 6.7 days.

One might notice that these dwell times are both higher than the overall export dwell time. This is the case because here we only considered the large vessels, excluding feeders, for which the dwell time is usually shorter than the average.

Soon, the delivery date of export containers might be restricted to seven days before departure of the vessel. If shipping companies follow up on this restriction, delivery patterns will change drastically, because now still approximately a quarter of the containers is delivered early. 8% is even delivered more than two weeks in advance and 2% more than a month. The delivery pattern for all full containers which left the terminal in January is presented in Figure 5.2. On the horizontal axis you see the number of days before arrival, on the vertical one the percentage of the total number of containers to be delivered present in the yard a certain number of days before arrival. Note that the percentages are again averages over all vessels within January 2005.

We also determined how many containers *per service* arrive early (more than seven days before departure). The values are provided on the cd-rom. Dumping these containers (four-high)

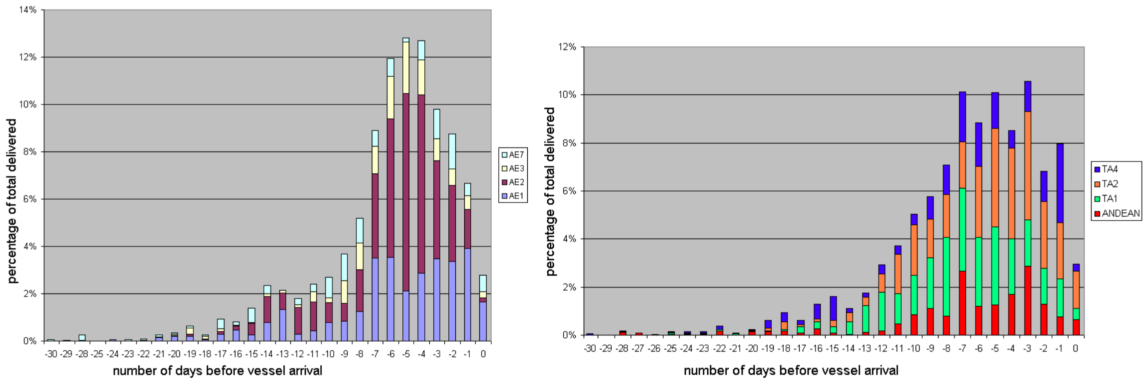

Figure 5.1: Comparison arrival patterns Asia and America services

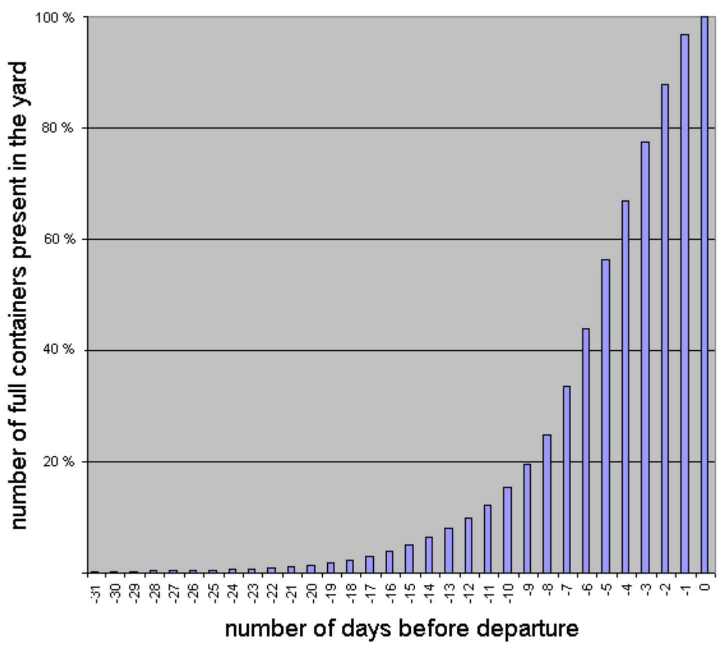

Figure 5.2: Full export delivery

somewhere in the far end ("a dark corner") of the yard and stacking them in the right position later might positively influence the free yard capacity. We determined what containergroups to housekeep each day, keeping the number of housekeeping moves constant (around 230) over the days.

What we can learn from a delivery pattern comparison based on modality, is that in general export containers being delivered by ITT arrive earlier than the ones by truck and the ones by truck earlier than the ones by barge. This is also reflected in the dwell times (see Appendix D.3.1).

Van Hee and Wijbrands [7] have already shown that newly arrived containers have a higher probability to be picked up soon than older ones. This also holds at APM Terminals Rotterdam and implies that putting new ones on top of old ones leads to fewer reshuffles than the other way around. Therefore import containers need to be spread as much as possible: First all ground slots have to be occupied, then the next layer can be started. Generally it is already done this way in the D block.

We do not have sufficient data to investigate the full *pickup patterns* for one month, but we have done the following investigation.

We can look at the vessels which left the terminal in January. Usually this is four per service. We know the most about the first of the four, because we have information about all departures until almost a month after arrival of this first one. The results give an indication of the pickup pattern, but only for one vessel. This is probably not representative; in our discussion on the delivery patterns we already stated that the patterns vary too much to draw detailed conclusions from them.

5.5 Operational stacking height

The operational stacking height highly influences yard capacity and production, so it is an important performance measure. Stacking high saves space, but causes more shifters in case of low data quality. If later on we want to determine the optimal stacking height, the current stacking height is useful information.

Data on the current operational stacking height is only available on a very global level. The maximum average height is set for different container types. If all containers of one type are stacked at their maximum height, the yard density is considered to be 100%. We present the maximum heights and the densities realised in 2003 (copied from the expansion document [30]):

ISO code	Max stacking height	Realised density
Dry van	2.5	78%
Reefer	3	71%
Empty	7	68%

Table 5.3: Operational stacking heights and realised densities

A rough guess from the yard manager tells us that the yard contains on average 12000 containers. In the current situation, if too many containers are stacked three high, the process does not run smoothly anymore. Then there are too many shifters and manual planners. According to the yard supervisor this becomes a problem above 80% yard utilisation. Around 70/75% the process still runs smoothly.

However, from the expansion document [30] we learn that APM Terminals Rotterdam does not consider any of the current yard densities to be the maximum yard density possible. Therefore, the present yard capacity has not been reached yet. APM Terminals Rotterdam believes that reaching the yard densities in Table 5.4 is possible, based on the present operation setup and productivity.

ISO code	Density
Dry van	85%
Reefer	85%
Empty	70%

Table 5.4: Yard densities expected to be reachable

5.6 Data quality

The *data quality* shows the number of changes of information about a container after it has entered the yard. This could be information regarding the outgoing modality, outgoing time, etc. First, it was supposed to leave by train, for example, but its future modality is suddenly changed into truck. If this happens often, high stacking could result in many shifters or housekeeping moves (yard moves). So if the number of yard moves is to be kept low, the data quality should be taken into account when determining the stacking height. Knowing that export containers for a certain service usually experience many information changes (also called *rollings*), stacking them two-high might be better than three-high.

We split the data quality in the data quality for containers with known outgoing modality on arrival and the number of containers with unknown outgoing modality on arrival. Data on both is not available yet, so we have analysed the *snapshots* (overview of the containers on the yard at one moment in time) of the yard of January. For those snapshots, the outgoing modality of on average 43% of the import containers at the terminal was unknown. (Only pure import was considered, so no transshipment.) This implies that stacking import containers high probably causes many shifters.

According to Steenken et al. [27], at European terminals 30% to 40% of the export containers arriving at the terminal lack accurate data for the respective vessel, for example, port of discharge (POD) or weight. For import containers the situation is even worse: the outgoing modality is known for at most 10% to 15% percent of all containers at the moment they are being unloaded from a vessel.

However, these figures can differ a lot between terminals, because usually more is known about export and transshipment containers than about import. If a terminal has, for example, relatively much import, there are relatively many containers with unknown information. Moreover, a lot is done to increase the number of containers with correct information.

Data on information changes is not available yet at APM Terminals, so we cannot give the actual data quality. However, the figures given above might be useful when import with unknown outgoing modality arrives. From Section 5.2 we know what percentage of the import eventually leaves with each modality. So for each incoming vessel the expected number of containers to leave with each modality can be calculated. We also know the outgoing modality for some of the import containers and we know what containers already left. With those three variables the number of import containers with unknown outgoing modality which is expected to leave with each modality can easily be calculated. We give an example, say:

25% of the containers arriving by vessel also leave by vessel.

500 containers arrived by vessel, 200 of which have unknown outgoing modality.
No containers have left yet.
100 of the 500 (20%) containers are known to be transshipment.
We know that eventually it is expected to be 25%.
25% of 500 equals 125 containers.
So 125-100=25 of the containers with unknown outgoing modality are expected to leave by vessel.

We do not know which 25 containers we should consider, but we know that it is only 25/200=12,5 percent of the total number with unknown outgoing modality. This implies that stacking the whole containergroup close to the deep sea cranes is probably not useful.

5.7 Yard usage

As production over the quay is the most important, the area near the quay should be used most efficiently. There we probably (to be determined later in this report) want to have the highest throughput. We define the *throughput* as the number of different containers which have occupied a slot (or an area) in a certain time frame. We would like to calculate the throughput per block for January 2005.

We consider two different ways of calculating the throughput. One is looking at all moves in January and counting for each block the number of times a container is moved in(to) this block. By taking a snapshot at the beginning of the month, also the slots which were occupied during the whole month (so did not experience any moves) are incorporated.

The second method uses all (daily) snapshots of one month with container ID and location of the container. With those snapshots the number of different containers which have occupied each block can be counted. This is currently done by Danny Holthuysen (APM Terminals Rotterdam). The first method would be the most accurate of both, but the necessary data is not available yet.

With the snapshots, the average number of containers in the yard (in January) were calculated. The results are presented in Table 5.5.

	Full dry	Reefer	Empty	IMO	Total
Import	3248	167	1175	118	4708
Export	2513	198	216	170	3097
Transshipment	1240	210	141	95	1686
Other	41	4	1294	6	1345
Total	7042	579	2825	389	10835

Table 5.5: Average number of containers in the yard in January 2005

5.8 Move distances

The *move distance* is the sum of the Manhattan distances between each pair of consecutive positions of a container. We split this into the distance from the incoming modality to the first yard stacking position, the distance from the last yard stacking position to the outgoing modality, and distances between each pair of consecutive yard positions. The last distances are bridged during shifters or housekeeping. Containergroups with relatively high average distances need extra attention: there might be a better stacking location. Data on move distances is not available yet.

5.9 Yard moves

The number of *yard moves* gives the average number of times a container of a certain containergroup has been moved inside the yard between entering and leaving. If possible, housekeeping moves and shifters should be distinguished. Attention needs to be paid to containergroups with relatively high move counts: high move counts indicate a possibility for improving the stacking strategy (height, position, etc). No data on yard moves is available yet.

5.10 Total handling time

An estimate of the *total handling time* of a container can be derived from the two former sections. From measurements from practice we know that the average speed during a yard move is three m/s, including picking up and putting down the container. If we also know the (average) time a yard move takes, the driving time and the yard move time can be added to get the total handling time. Considering this total handling time is more important in finding out what containergroup need most attention than considering only one of its components.

Chapter 6

Research questions

The problem description stated in Chapter 3 is quite general. Therefore we started with a literature study to find out what already has been investigated in this field and a data analysis to get an overview of the current processes at APM Terminals Rotterdam. The results of both investigations have led to a more specific project definition and research questions, which are formulated in this chapter. These questions are investigated with help of the mathematical models described in Chapter 7.

6.1 Project definition

Production (i.e. number of moves over the quay while a vessel is moored) is the most important issue at the terminal. We will not use production as a performance measure, because production depends on many factors and incorporating all those factors in a model is impossible. In this project we only consider yard lay-out issues which may influence the production.

The following Key Performance Indicators (*KPIs*) are chosen: the number of shifters and the transportation distances over the yard. These are selected because we believe that the production increases (or at least does not decrease) by minimising them and both can be measured. To be able to compare them, we express both in the amount of time they take. The answer to each research question in chosen such that the total handling time is minimised.

We assume containers are always transported along the shortest route from one place to another. We only focus on those container transportation distances, not on the actual straddle carriers routes. Also we do not take into account congestion in the yard - which is highly related to straddle carrier deployment - because measuring this is difficult and it depends on too many factors.

We only consider positioning containergroups, not individual containers. A containergroup was defined as a number of containers with equal characteristics. We choose characteristics which are expected to influence the "behaviour" (like dwell times and data quality) of the containers. To start with, we choose these characteristics to be the incoming and outgoing modality of a container. So one containergroup consists, for example, of all containers which have entered by vessel and will leave by truck. The incoming service is as added as an extra characteristic later. This results in smaller containergroups.

We only consider dry vans, for the following reasons. Most empty containers are stacked in their designated area (empty depot), reefer containers have to be connected to the immobile reefer plugs, and IMO containers are only stacked in certain streets near the border of a block of containers. This implies that we cannot make large improvements to the stacking locations of these containers, because they can only be moved within their designated areas. These areas are relatively small compared to the full dry ("normal containers") stack, because only two percent of the total number of containers is IMO, ten percent is reefer, and the eighteen percent empties are stacked densely and high. Therefore large improvements are only possible for the full dry containers.

Note that up to a certain level quay crane deployment highly influences the number of moves over the quay. However, quay crane deployment is not a lay-out issue. We assume we cannot influence it and take it as given. According to Steenken et al. [27] the quay cranes are faster than the stacking and transportation equipment.

6.2 Static yard lay-out

In case there is no housekeep capacity, all containers have to be stacked in their final position on arrival and stay there until they leave the terminal again. We want to determine the optimal allocation of containergroups in the terminal:

What is the optimal stacking position for each group of containers if they can only be stacked in one position during their stay?

A reduction of the driving time to the cranes can be expected by optimizing the use of the slots at the quay side. Therefore those slots have to be used many times, which implies that the dwell times of the containers in those slots should be low. Also the impact on the landside should be considered, but this is of secondary importance.

6.3 Dynamic yard lay-out

If changing the stacking positions during the week is allowed, the capacity can be used more efficiently. If the lay-out is changed, containers might have to be moved (housekept) within the yard. Currently, APM terminals Rotterdam has enough manpower and straddle carriers to do some housekeeping, so we want to know where to stack the containers if a maximum of one housekeep move per container is allowed. The basic question is the same as the one in Section 6.2, but for each day of the week we add a maximum total number of housekeeping moves which can be carried out.

In what area(s) is each group of containers stacked on each day of the week, when a maximum of one yard move per container is allowed?

6.4 Stacking height

By stacking higher, the driving distances and the amount of space used decrease, but the number of shifters may increase. An optimum should be found between stacking high and spreading the containers. Currently spreading out is preferred (except for fixed specials). The data reliability influences the number of shifters. If it happens too often that information about a container changes, the probability of having to move many containers before being able to pick the right one is high.

What is the optimal stacking height for each group of containers?

6.5 Pre-stacking

Some export containers arrive many days before they leave. If they are put in the export streets at the moment of arrival, they take up valuable slots which might better be used by containers which leave earlier. This can be prevented by *pre-stacking* the early export containers "somewhere in a dark corner" until more containers of the same group have arrived.

Should all export containers be stacked in their final position when they enter the terminal or should some be pre-stacked?

What is the right time to move pre-stacked export containers forward (if at all)?

Note that both questions are very interesting, but a few months ago a new rule has been introduced: export containers may not be brought more than seven days before arrival of the vessel. If customers actually obey this rule, most of the current problems with early arrivals might be solved.

6.6 Back-stacking

Back-stacking is defined in this context as moving dumped containers from the A-area to another area. A lot of time, man-power, and money is invested in back-stacking. Back-stacking is applied because the slots in the A-area are needed for newly arrived containers. Often the departure time of a dumped container is unknown, so sometimes a container is back-stacked and picked up an hour later. In this case back-stacking was only a good choice if the freed slot in the A-area was needed instantaneously. Otherwise, the "natural" removal from the A-area would have been better, because this would have cost one less yard move of the container. In this section the question is if, given the information we have on the containers, we can determine the best time for back-stacking:

When (for what containers at what time) should we apply back-stacking?

If both back-stacking and pre-stacking are applied, the operation speed might increase a lot by back-stacking one container, then picking a pre-stacked one from the back, stacking it in the export area, picking up a dumped container for back-stacking etc. This reduces the total empty (without a container) driving distances of the straddle carriers.

6.7 Non-handled research questions

The reader might miss certain questions in the presented list. Therefore we also state other questions which have crossed our mind, with the reasons for not investigating them.

Should you start stacking high or start spreading (or something in between)?

If an optimal stacking height is given, still the way to build the stack has not been determined. There are two extremes: starting with stacking high or starting with spreading. When you start with stacking high, one pile or street is filled up to its optimal level before a new ground slot is occupied. When you start with spreading, first the ground layer is filled and then the next layer is put on top of it. One might feel that there exist compromises between those two extremes as well. The answer to this question will probably be very useful. However, it was not a core question in this project and unfortunately we do not have enough time to do additional investigations on it.

When is dumping import better than stacking in the right place at once?

This is outside the scope of this project, because crane productivity plays a large role in this question. Also, Roel van de Weijer (APM Terminals Rotterdam) has already worked on this question.

If there are free slots available for containergroup, in what order do we fill these slots? Do we start stacking in the middle of a block or in the far end or somewhere else?

This is related to the question whether to start with stacking high or with spreading. However, when this strategic question has been answered, the physical order of stacking the containers is an operational decision.

Should we stack export randomly or per service?

An advantage of random stacking is a decrease of straddle carrier congestion. The hypothesis that planned stacking is better than random stacking has already been proven in literature (and probably by experience of some terminals as well).

When is a buffer system (like in Kingston) useful?

In a buffer system, one straddle carrier transports containers between the buffer and the crane and others transport containers between the buffer and the stack. We will not research buffering, because bottlenecks in the operation cannot be determined due to lack of measurements. Knowledge of the bottlenecks is necessary for determining the added value of a buffer system.

Chapter 7

Models for determining yard lay-out

In this chapter we describe the mathematical models which have been developed to answer the research questions. The mathematical formulation of the models is presented in Appendix E. We develop separate models for the stacking height and the stacking location (or lay-out). The stacking height model determines the relation between the stacking height and the average handling time of a container due to shifters. (It answers the research question from Section 6.4.) We can include this relation in the stacking location model as follows. When determining the stacking location, we take the stacking height as given (input parameter), but the stacking location model adds the handling time due to the specific stacking height to the handling time due to the transportation distance.

Firstly, a Linear Programming model for determining the stacking location is described. Depending on the values of the input parameters, it answers the research question from Section 6.2 or in one run the research questions from Section 6.3, 6.5, and 6.6.

7.1 Lay-out model

This model takes into account the capacity which is available for housekeeping in each night (this capacity can differ between the nights). The model determines if and, if so, when containers of each containergroup are housekept. One containergroup does not necessarily have to be housekept at once.

7.1.1 Assumptions

- The container flows follow a cyclic pattern (typically of one week); in the models we only consider one cycle and the solutions are repeated periodically.
- All containers in one containergroup are stacked at the same height.
- All containers of a containergroup arrive and leave at the same day. The time spent in the yard is given by the average dwell time of this containergroup (determined in the cargo flow analysis).

- During its stay in the yard, each container is stacked at maximally two different positions.
- The location of a vessel of a certain service at the quay is given and does not change over the weeks.

7.1.2 Input parameters

- Cycle length (in days)

Areas in the yard:

- Number of ground slots
- Distances to interchange zones
- Transportation speed over the yard

Containergroups:

- Stacking height
- Arrival day
- Average dwell time
- Number of containers of this containergroup entering the terminal during one cycle

Days of the week:

- Maximum capacity available for housekeeping

The yard size and the locations of the interchange zones are fixed. Also the berthing is taken as given. Therefore the distances each containergroup has to cover from their incoming modality to a certain stacking position and from this stacking position to their outgoing modality can be determined.

This total distance can be calculated in several ways: One can only consider the distance to and from the quay, but one can also include distances to and from other modalities. If both distances are not considered equally important, they can be weighted. When considering the distance to and from the quay, also different values can be used: A simple one is the shortest distance (perpendicular to the quay), another one is the distance to the middle of the quay. If it is known, the actual distance to the berthing location of the vessel can be used.

7.1.3 Decision variables

The model determines the first and an optional second stacking area for each group of containers, as well as the day on which the containers are housekept from the first to the second area. Containers of one group do not have to be stacked together in one area. The also do not have to be housekept at the same time.

7.1.4 Constraints

Not each yard configuration is possible. We need to include constraints in the model which make sure that each container gets a position assigned and that the capacity of the areas is not exceeded. Also the housekeep capacity may not be exceeded.

7.1.5 Objective

The objective is minimising the total transportation distance (from the quay) to the first stacking position plus the total transportation distance from the last stacking position (to the quay). The total transportation distance can be a weighted total, if one distance is considered more important than another one. The weight for the distance to the quay can, for example, be taken higher than the weight for the distance to other interchange zones. The influence of different weights is investigated in Chapter 8. Housekeeping distances can be added if this is wanted.

7.1.6 Extra model features: Total handling time, occupation, throughput, long standings

As we already stated in the introduction to this chapter, we want to calculate the total handling time of a container. This total handling time consists of the time spent on transportation and the time spent on shifters. The total time spent on transportation can be derived from the total transportation distance by multiplying it by the average transportation speed, which has been measured to be 3 m/s (including picking up and putting down thee container). The total time spent on shifters depends on the stacking height. The model which determines the expected number of shifters per container for a certain stacking height is presented in Section 7.2. Multiplying this figure by the number of containers and the time spent on one shifter (estimated by the yard supervisor to be three minutes) gives the total time spent on shifters. The average handling time per container can of course be calculated by dividing the total handling time by the number of containers.

From the ground slot reservations made, the yard occupation per day of each containergroup can easily be calculated, as well as the throughput of each area. The *throughput* is defined as the number of different containers which visits an area during one week.

Some import containers are not picked up within a week, or even two weeks, or a month. They are called *long standings*. Unfortunately we do not know in advance what containers will be picked up within a week and what are the long standings. This is only recognised at the moment they have been in the yard for too long. APM Terminals would like to have a separate policy for handling long standings, for example, moving them to a 'dark corner' after they have resided in the yard for more than a week. In the next paragraph we describe how to incorporate the possibility for a separate strategy in the model.

We split the group of import containers in one with a short (average) dwell time (let's say four days) and one with a long (average) dwell time (say ten days). A few extra constraints make sure that the two groups are treated as if it is one group during the days both are still at the terminal.

7.1.7 Discussion

In this section we discuss the advantages and disadvantages of the presented model. The model can determine on a very detailed level what containers to stack when in what area. In order to get detailed output which is useful, the input needs to be detailed and very accurate as well. Collecting data for producing this input and the production of the input itself take too much time to do it weekly.

7.2 Stacking height model

The stacking height model shows the influence of the stacking height on the number of shifters and therefore on the time spent on those shifters. We first describe some approaches found in literature:

7.2.1 Literature

Abacoumkin and Ballis [1] give a formula for the probability of having to reshuffle in a dense stack. Without adjustments, this formula cannot be used for a straddle carrier operation. Moreover, they assume that all containers in a stack are equally likely to have to be picked up first. At APM Terminals the stack is organised in such a way that the container on top is picked up first, unless the information about one of the containers in the stack changes. This information quality is not taken into account by Abacoumkin and Ballis.

Also Van Hee and Wijbrands assume that they pick up a random container from the stack when investigating the relationship between stacking height, width and handling time. As far as it is described, also this method seems not to be useful in the case of APM Terminals Rotterdam. Under the same assumption, Kozan [17] concludes that the expected number of moves per containers is the average of the maximum stack height and the minimum stack height.

Other papers found which assume random pickup from a dense stack are written by Kim and Kim [13], [14]. The assumptions in all papers found differ too much from the situation at APM Terminals Rotterdam to be useful at this moment. Therefore we develop another method.

7.2.2 Model functionality

In Chapter 6 we stated that we wanted to develop a model which finds the optimum between time spent on driving further due to spreading the containers and time spent on shifters. However, the total driving distance does not only depend on the stacking height, but also highly depends on the yard lay-out. Therefore we wanted to develop a model which estimates the amount of time spent on shifters, given a certain stacking height and information quality. This time is added to the total time spent on transportation determined with the lay-out model. If the stacking height (input for the lay-out model) is changed, the lay-out model determines a new lay-out which minimises the driving distance and again the new time spent on shifters is added. By varying the stacking height, the different total handling times can be compared.

In order for the stacking height model to be useful, the information on the data quality of the containers should be accurate. Unfortunately, the only data we got were rough estimates. Therefore we did not implement this model, because with inaccurate input it might give wrong results. We describe two models, an analytical one and a simulation model. They can be used as soon as the right data becomes available.

The analytical model presented is aimed for export and transshipment containers, because shifters for those influence the production much more than shifters for import containers. Such a model could also be developed for import containers, by using extra knowledge on stacking methods and behaviour of import. At the moment this information is partially available. As it is not enough for full development and implementation of more refined models, we do not describe them here.

A simulation model can handle a larger variety of stacking policies than an analytical model can. Therefore we also describe how the time spent on shifters could be determined by a simulation model. Again, because of lack of accurate input data, we have not implemented this model. If this is done, it can be used to validate the analytical model.

7.2.3 Assumptions

- The total area is large enough to stack all containers at each height.
- Each container of a certain containergroup has the same probability of getting an information change. The probabilities for different containers are independent.
- Export containers in one pile leave at the same time.
- An info change for an export container always results in a later departure. If there are containers underneath the one with the rolling, this one needs to be removed (shifted).
- Each shifter costs the same amount of time/effort/money (3 minutes, according to a yard supervisor).

- There is enough straddle carrier capacity to carry out the necessary shifters: We only take shifter time into account, no waiting time.
- The information changes occur (or are at least handled) when a stack is totally filled, i.e. stacked at its maximum height and when no containers have been removed yet.
- There are SCs available which are high enough to lift a container over another stack. This means that we do not consider interaction of containers in a street, but only consider separate piles of containers. This assumption can be made, because full containers at APM Terminals are (up till now) never stacked four high and there are enough four high straddle carriers.

7.2.4 Input parameters

The following figure is given:

- Probability of an information change for one container

7.2.5 Decision variables

The stacking height can be set at any desired number.

7.2.6 Output variables

The model gives the expected number of shifters for export containers with a certain stacking height. The calculation method can be found in Appendix E.

7.2.7 Simulation model

By building a simulation model, many of the assumptions presented in Section 7.2.3 can be dropped. The analytical model presented assumes a static situation, in which information changes only occur when the stack has totally been built. A simulation model can handle information changes during building or taking down the stack. The way of building the stack should be included in such a model and can be made as detailed as one likes. Also, a simulation model is able to handle variation in pickup or delivery patterns. A drawback of developing a simulation model is the amount of work it takes before it gives realistic results and the accuracy of the input data needed.

7.2.8 Discussion

We assume that enough space is available to spread the containers as much as necessary for minimising the handling time. Of course this is not true in reality, but in the end the space needed for the optimal solution can be compared with the available space. If not enough space is available, the decision either to create more space or to use a sub-optimal stacking strategy is up to APM Terminals Rotterdam.

7.3 Implementation in AIMMS

Linear Programs are quickly too large to solve by hand, so software is needed for solving them. AIMMS is software developed for solving Mathematical Programming models. It has several possibilities for user-friendly data entry, model solving and developing a user interface. Therefore the lay-out models are implemented in AIMMS.

Chapter 8

Test cases

In this chapter we present some of the test case which are used as input for the lay-out model (Chapter 7). We start with some global cases, in which we use a rough division in container groups and yard areas. Those are used to get a general overview of the stacking policy. Then we present a case which represents the cargo flow of January 2005. The last section of this chapter describes cases which are nearly the same as the case from January 2005, but deviate at specific points. The results of those cases are useful in deciding what to do when the cargo flow changes.

The values of the variables in the test cases are derived in several ways: some are results from the cargo flow analysis, some are derived from literature, KPI documents, or earlier studies performed at APM Terminals (Rotterdam), and some were provided by the yard manager or supervisor. In order not to go into too much detail, not all values are presented in this chapter. For the precise values we refer to Appendix F.

8.1 Global test cases

The test cases in this section are described in increasing order of detail.

8.1.1 Division in import/export and A/B

We start with a test on a very global level, only splitting import and export and dividing the yard into two areas: one on the seaside (A) and one on the landside (B). We choose small values for all parameters (see Appendix F.1.1), because using larger values is just scaling and will give the same results. Because of the rough division of the area and the containers, this case is not a very realistic one. It is mainly developed for investigating the behaviour of the model and checking if it produces logical results.

8.1.2 Division in import/export/transsshipment and A/B/C/D

At the next level we split import, export, and transshipment. We divide the yard into four areas, A, B, C, and D, the way it is currently done at APM Terminals Rotterdam (A closest to the quay and D furthest from the quay). This time more realistic input parameter values are used. The specific input values can be found in Appendix F.1.2.

8.1.3 Division per modality

On the third level we also split the groups of containers per modality. In the first two levels we rated distances to and from the quay equally important to distances to and from other interchange zones. However, production over the quay is the most important performance measure at a container terminal, so we want our tests to reflect this. We developed three different test cases in which we varied the importance of the distances to the inland interchange zones (so all interchange zones except for the quay):

1. Distances to all interchange zones are equally important.
2. Only distances to and from the quay are important.
3. Distances to and from the quay are x times more important than distances to and from other interchange zones. (In this case we take x to be 100.)

In all cases discussed in the remainder of this chapter the distances are determined according to the third method.

In the cases discussed up till now we assumed that we knew with what modality the import containers were leaving. This knowledge was a result of the cargo flow analysis. This analysis was based on historical data. In general we do not know in advance what group of import containers is leaving with what modality. Therefore we developed a test case with import for which we do not know the departure modality per container, only the relative modality split: 40% barge, 20% ITT, and 40% truck. This knowledge is incorporated in the distance calculation.

In the cases discussed up till now we used the average dwell time and did not consider long standings separately. In order to see what stacking method the model suggests for long standings, we create an example with long standings by splitting the group of truck import containers in the following way (according to the cargo flow in January 2005):

Containergroup	Number of containers	Arrival day	Dwell time	Stacking height
Vessel-Truck	1600	Thursday	4	2
Vessel-Truck long	300	Thursday	10	2

This year a rule was implemented which stated that export cannot be brought more than seven days before departure of the vessel. Following up on this rule results in a lower export dwell time. We developed one case with a lower export dwell time, to find out how this influences the yard lay-out. The average truck export dwell time in this case is taken to be six days instead of seven.

8.2 January 2005

The test case described in this section is (a simplified version of) the cargo flow in January 2005. In this test case we do not only distinguish modalities, but also services. We included the ten largest services and feeders. As different services berth at different positions at the quay and as ITT and barge interchange zones are situated at one side of the terminal, we divide the terminal also "horizontally" in pieces. Now the container positions are not only based on their distance to the quay, but also on an east-west orientation. We split each area (A,B,C,D) into four pieces: W (West), MW (Middle West-side), ME (Middle-East), and E (East). The pro forma berthing shows that with this division each vessel (or barge) moors at one of the four parts of the quay.

As the straddle carrier parking lot, the office building, and the workshop take up a piece of the yard and we do not take the reefers into account, the total number of stacking areas is 4x4-3=12, each with a different number of ground slots available. The determination of the number of ground-slots available is given in Appendix F.3.

8.3 Deviations from January 2005

In order to find out what happens to the lay-out of the terminal if the cargo flows change, we perform a sensitivity analysis. This means that the input of the model is varied and changes in corresponding output are investigated. The cargo flow of January 2005 is taken as a starting point. We call this input data case the *basic* case. Several parameters in this case are changed (one by one) and the resulting changes in yard lay-out are described in Chapter 9. An overview of the changed parameters is given in Table 8.1. If additional explanation is needed for a test, it is given in the subsection which we refer to in the table. The cases are derived from APM Terminals Rotterdam practice.

For most changes we do not investigate interactions, because we would get too many test cases and we assume most changes not to interact significantly. The only interaction we investigated is the one between the stacking height and the data quality. If small input changes result in small output changes, we can conclude that the model is robust to changes in the investigated input parameter.

8.3.1 Fewer different areas

We start with a case in which the A, B, C, and D areas are not subdivided.

Section	Parameter	Basic case	Changed case
8.3.1	Area division	12	4
8.3.2	Services	10	AE8 added
8.3.3	Berthing schedule	January 2005	AE1 load call two days delayed
8.3.4	Number of barge moves	January 2005	10% extra
8.3.5	Housekeep capacity	basic	100 extra per day
	Housekeep capacity	basic	None
8.3.6	Transshipment dwell time	January 2005	plus one week for one group
8.3.7	Dense stack in the back	no	yes: in DE
	All over stacking height	3	4
8.3.8	Import stacking height	3	2
8.3.9	Export rollings	5%	10%
8.3.9	Export rollings and stacking height	5%, 3	10%, 2

Table 8.1: Test cases

8.3.2 Extra service

Sometimes new services start visiting APM Terminals Rotterdam. Here we investigate a case with the new AE8, which adds 1400 container to the total number of containers transferred in one week. As there was no data on the modality split of the AE8 containers, we assumed it was the same as for the AE7.

8.3.3 Delayed vessel

If a large load vessel is delayed, the yard gets overfull. Two days is a realistic figure.

8.3.4 Extra barge moves

An increasing trend in the number of barge moves (containers entering or leaving by barge) has been noticed and an increase of 10% over the next few years is expected.

8.3.5 Extra housekeep capacity

The housekeep capacity is used in the basic case is given in Table 8.2. In this test case we add 100 moves per day to this capacity.

8.3.6 Longer dwell time for one group of transshipment

Sometimes a whole group of transshipment containers is re-planned to the vessel which leaves one week later. In this case it is the group which enters by AE1 and leaves by TA4.

Day	basic	test
Monday	400	500
Tuesday	400	500
Wednesday	400	500
Thursday	400	500
Friday	400	500
Saturday	400	500
Sunday	1400	1500

Table 8.2: Housekeep capacity (number of moves)

8.3.7 Dense stack in the back of the yard

By giving some model parameters a specific value, we can include a high density stack in the back of the yard in our model. In a *high density stack*, containers are stacked on average six high without spaces between them. (This implies that they cannot be stacked by straddle carriers, other equipment is needed.)

Because the stacking height is containergroup-dependent and not area-dependent, we use a trick to formulate a dense stack in the back of the yard in terms of the model: The actual number of ground slots in the area in which we want to put a high density stack is multiplied by two. In reality, to make the assigned container group fit, it should be stacked two times higher than in the other areas.

A high density stack suffers from more shifters than a low stack. Therefore the extra time spent per container because of shifters is included in the transportation time: The transportation distances to and from the dense stack area are risen artificially such that the extra time spent on shifters is included in the transportation time.

8.3.8 Lower import stacking

Dumped import is stacked three high and import in the back of the yard two high. In our global models we stacked all import two high and in the basic model we stacked it three high. We want to see the difference between stacking two high and stacking three high.

8.3.9 More export rollings

A *rolling* is an (export) container in the yard which is booked onto a later vessel than originally planned. This often results in a shifter. The exact number of rollings is not known, but in the basic case it is taken to be 5% of all export containers. We want to investigate what happens to the total handling time of the containers if this is actually 10%. We also want to investigate the change in this handling time if we stack the "unreliable" export containers two-high.

Chapter 9

Results

In this chapter we describe the most important results of the test cases described in Chapter 8. Our main goal is finding out how the suggested yard lay-out depends on the cargo flow and how it changes if the cargo flow changes. We do this partially based on a number of lay-out characteristics:

- Throughput per area
- Number containers per area of a certain containergroup, e.g., import and export

We also investigate absolute values and/or changes in the performance measures like the driving distance and the handling time.

This chapter has the same structure as Chapter 8, so we start with the global test cases. We will check if the stacking strategy suggested by their results suggest corresponds to the strategy the results of the more detailed cases suggest.

9.1 Global test cases

9.1.1 Division in import/export and A/B

In Figure 9.1 you see some results of our simplest test case. It is a schematic representation of the most efficient yard lay-out, which illustrates how the model works. We observe that import (two containers per week) is put in A on arrival (on Monday) and export (five containers per week) is put in B on arrival (Thursday). Export was chosen to have a dwell time of eight days, so on Thursday there are two export groups: One in B which has just arrived and one in A which is almost going to leave. The capacity of one housekeeping move a day is used to move export forward and import backwards. This result is logical, because the total incoming and outgoing driving distance was minimised. This means that on arrival and departure, containers have to be as close to their interchange zones as possible.

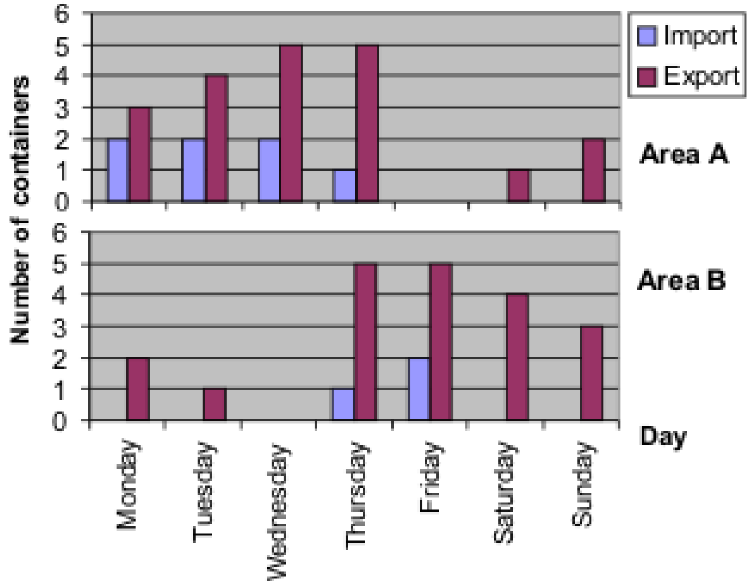

Figure 9.1: Simple test case

9.1.2 Division in import/export/transshipment and A/B/C/D

The yard lay-out for the case in which we distinguished import, export, and transshipment as well as the four areas A, B, C, and D is given in Figure 9.2.

These results support the ones from the first test case. We make the following observations:

- *Transshipment* is stacked close to the quay and stays there during the total dwell time (five days). This is a results one would expect, because it enters and leaves over the quay, so it is stacked as close as possible.
- Most *export* is put in D on arrival (in this case closest to its incoming modality) and moved forward to A before it leaves. This is again done to minimize the total distance to and from the interchange zones. The housekeep distance is not minimized, so moving the containers during their stay in the yard is not "punished" by the model.
- Most of the *import* is on arrival already stacked in B, while A is closest to the quay. This can be explained in the following way: The model does not only take into account the distance to the quay, but also the distance to the other interchange zones, most of which are located in the back of the yard. In this case there is not enough housekeep capacity to first dump the import in A and then move it towards the back. This can only be done with a small part of the import.
- Export gets priority over import for being stacked in A. The reason for this is the difference in stacking height: In this case import is stacked two-high and export three high. This implies that one ground-slot is used more efficiently by export than by import. In order to keep the total driving distance as low as possible, the ground-slots

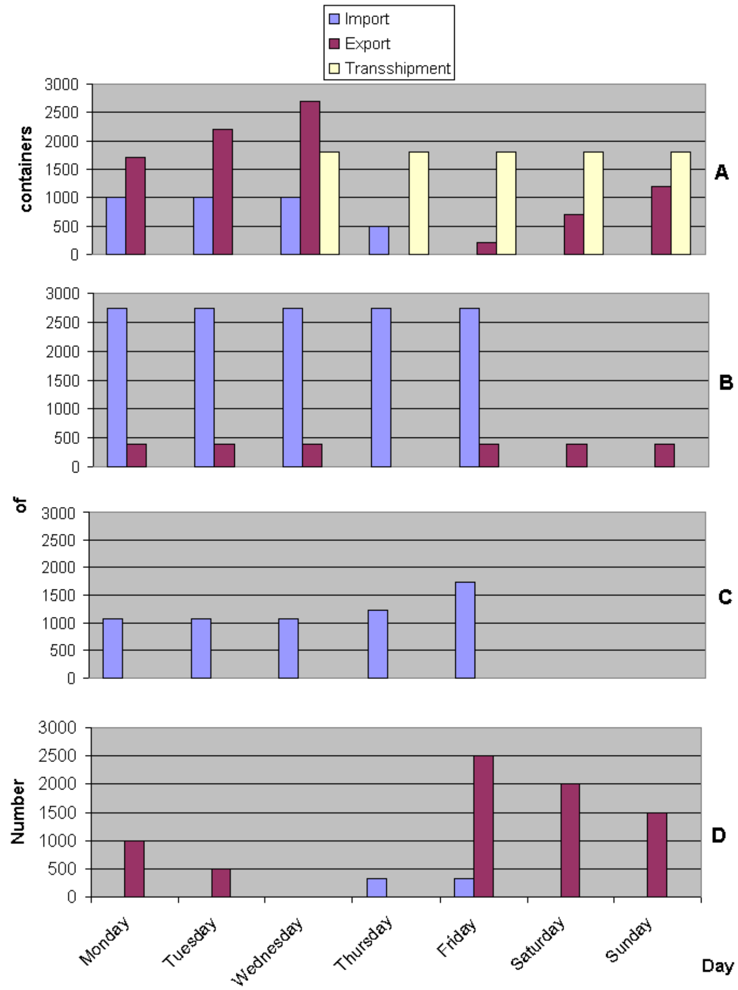

Figure 9.2: Global case with realistic values

near the quay should be used as efficiently as possible, in this case by stacking export on them.

- Most housekeeping is done from A to D or from D to A. Containers stacked in B or C on arrival stay there until they leave. This shows that each housekeeping move is used as efficiently as possible, to get the largest possible driving distance reduction.

9.1.3 Division per modality

The first three cases in this section are used to investigate what happens if we vary the importance of the distances to the landside interchange zones (including barge). We are especially interested in the throughput of each area (Table 9.1). We distinguish Case 1 (all distances equally important), Case 2 (only distance to and from the quay important), Case 3 (distance to and from the quay 100 times more important than distance to and from other interchange zones). The number 7647 means that 7647 containers have visited area A during

	Case 1	Case 2	Case 3
A	7647	8567	8567
B	2353	3633	2233
C	1500	900	1300
D	1900	300	1300

Table 9.1: Throughput with weighed distances

one week. We observe that in the first case the throughput close to the quay is lower than in the other cases, so A is used less efficiently than in the other cases. The throughput in A is generally higher than in the other areas, because all containers enter and/or leave over the quay. The throughput in C and D in case 2 is very low, because the model does not try at all to reduce driving distances to, e.g., truck interchange zones in the back of the yard. Some containers are transported to B on arrival, even if they will be housekept to A a few days later. In this case it would be better to unload the truck and ITT containers first into C and D, instead of in B. This is what the higher throughput of B and C in Case 3 reflects. In all tests discussed from now on the method of case 3 is used for determining the distances.

In the next test case the outgoing modality of the import was not known in advance. The resulting yard lay-out is given in Appendix G, Figure G.1. We make the following observations:

- All *transshipment* is stacked in A.
- 85% of the *export* is stacked in A at once and stays there until departure. The remaining 15% consist of truck and ITT export.
- The ITT export which is not stacked in A at once, is stacked in D, close to the ITT interchange zone, and moved to A the last day before departure.
- The truck export which is not stacked in A at once, is stacked in B. Area C would have been closer to the truck interchange zone, but C was full (with import).
- If there is enough space left, *import* is dumped in A and moved to C as soon as housekeep capacity is available.
- Area B is used as an overflow area for import which does not fit in A on arrival or in C when housekeeping.
- Once import is stacked in B, it stays there until it leaves the terminal.

The results from the test case with the long standings can be found in the appendix in Figure G.2. The long standings are dumped in A, but moved to C the next day. 94% of the other truck import stays in A, probably because it has a short dwell time; moving it backwards is a waste of energy, because it will be picked up soon anyway.

The results for the test case with the shorter truck export dwell time do not differ much from the original results. Nothing changes, except for one thing: In the original case (G.1) the truck export which was not stacked directly in A (113 containers), was stacked in B, because there was not enough space to dump it in C near the truck grid. In the changed version, the truck export arrives one day later. This time there is enough space in C, so the same 113 containers are dumped in C (and moved forward later, just like in the original case).

9.2 January 2005

In this test case we distinguish 82 groups of containers and 12 areas. In the resulting yard lay-out we see that at one day containers of ten different groups can be stacked in one area. This is too many to give a good overview, therefore we aggregate the results before presenting them. A global map of the yard lay-out suggested by the model is presented in Figure 9.3.

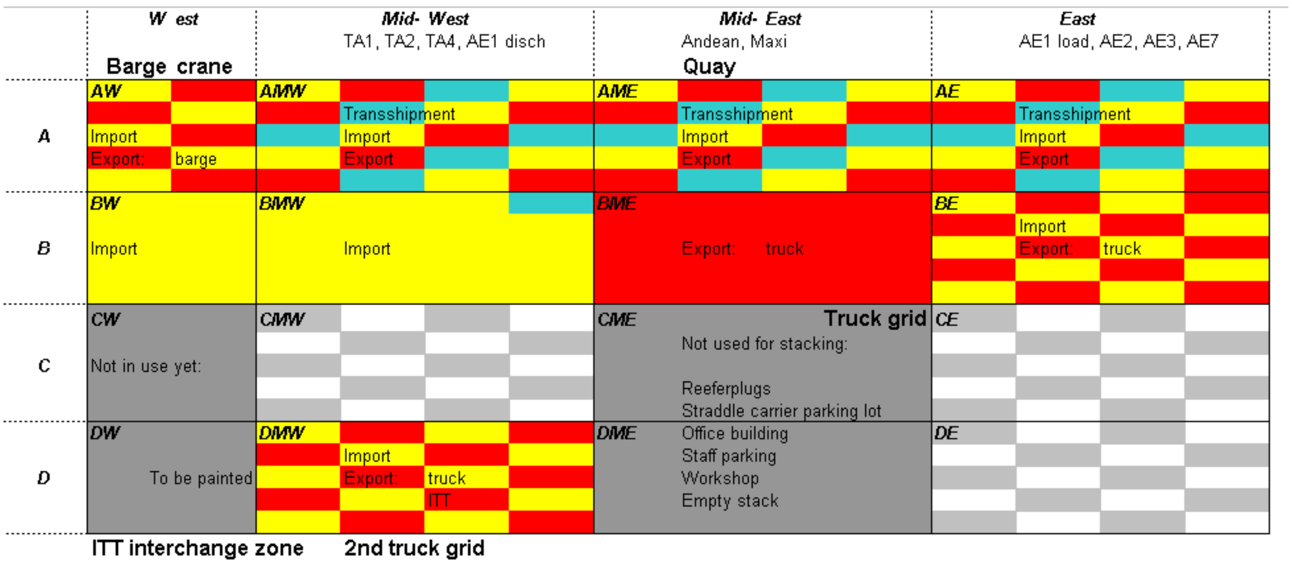

Figure 9.3: Yard lay out for January 2005

We make the following observations on transshipment :

- All transshipment is stacked in A, except for groups with an average dwell time of ten days or higher, being TA1-AE1, PLATE-TA4, and TA4-AE7, they are stacked in BMW.
- The containers are unloaded as close as possible from the berthing position of the incoming vessel and loaded from a stacking position as close as possible to the outgoing vessel, so often housekeeping is necessary.

We make the following observations on export:

- Most export is dumped near its incoming modality and moved forward one or two days before departure.
- One exception is truck-AE1 export, which is dumped in BE and stays there until arrival.

- The second exception is export leaving via AME; this is stacked there at once and stays during all its stay at the terminal. The reason for this is that AME is a very quiet area.
- ITT export is dumped in DMW.
- Long standing truck export is dumped in BME and moved to the area closest to its departing vessel after six days. This accounts for truck-AE2, with a dwell time of eight days, and for 67% of truck-TA1, with a dwell time of nine days.
- Truck-AE1 export has a dwell time of only six days and is therefore stacked in AE during its total stay. The same accounts for 31% of truck-PLATE export. The other 69% enters via BMW and stays there until two days before departure, when it is moved to AE.
- All truck export for the AE3, AE7, TA2, and TA4 is dumped in DMW. For AE3 and AE7 this is illogical, because it is further from the berthing position than BME, where the other truck grid is located. This illogicality can be explained by the model, which does not take the housekeeping distance into account.

We make the following observations on import:

- If dump does not fit in the area right in front of the vessel, it is stacked further towards the back of the yard, not in another A-area.
- The larger part AE2 and AE7 import (around 500 containers of both) is dumped in AE and the rest in BE. The part stacked in BE stays there until departure. Half of the part stacked in AE is housekept to BW and BMW.
- Import which enters via vessels berthing at AME (being Andean and Maxi), are unloaded at AME and stay there during their total stay in the yard.
- AE3 import is stacked in AE on arrival and stays there until departure. A combination factors can give the explanation: AE3 import consists of only 90 containers and has a dwell time of only five days. 50% of those 90 containers leave by truck and one of the truck grids is close to AE.
- 40% of AE1 import is dumped in AMW and 60% in BMW and is not moved backwards, because 50% of all AE1 import leaves by barge.
- In contrast to AE2, AE3, and AE7 export, TA export is unloaded in AMW. This is a less busy area than AE, where the AE services (except for the AE1 discharge call) moor. Therefore TA1 and TA4 export are stacked in AMW during all their stay. They have 60% and 70% of truck import, respectively, and AMW is close to a tuck grid.
- TA2 has 50% of barge import and is therefore 24% is unloaded in AMW immediately and 70% is dumped in AE. 20% is housekept from the dumping area to BW later and 26% to AW.

General observations:

- The moment of housekeeping depends on the difference in popularity of the first and the second area (within the boundaries given by the housekeep capacity). The throughput per ground slot (column "basic" in Table 9.3) indicates how popular an area is. For example, as AME is much less popular than the other two areas used for transshipment, containers are stacked as long as possible in AME. If transshipment containers have to leave via AME, they are immediately after dumping moved to AME. If they enter and do not leave via AME, they stay as long as possible in AME and are moved to their final area the last day before departure.
- The southeastern corner of the terminal is not used at all. You might wonder why all areas are used now, but not in the result of the test. In the test all containers are stacked up to its maximum height, while in reality this height is often not reached. However, the same number of containers has to be stacked, if this is not done high, more space has to be used. Results of cases with lower maximum height are discussed in Section 8.3.8.

9.3 Deviations from January 2005

9.3.1 Fewer different areas

In this case the yard is only split in area A, B, C, and D and these are not subdivided. We observe the following:

- All transshipment is stacked in A, except for the Plate-TA4. Plate-TA4 is stacked in B, because its dwell time is 16 days (the highest after that one is ten days). This strategy is almost the same as with the more detailed area division in the basic case, but in that case also transshipment with a dwell time of ten days is stacked in B.
- All truck export is dumped in C and moved to A approximately the last day before departure. Only TA1 and TA2 truck export is partially dumped in B, because they have a relatively long dwell time of nine and eight days, respectively. They would occupy the popular space in C too long, so overflow area B is used.
- ITT export is dumped in D and moved to A the last day before departure. Only TA1 and TA2 ITT export is stacked in A immediately after arrival and stays there until departure. This can be explained by the relatively short ITT export dwell time for TA1 and TA2, six and five days respectively.
- Most barge export is stacked directly in A, except for AE3, AE7, and TA4, because they have a dwell time larger than or equal to seven. In order for them not to take up too much capacity in A, they are stacked in B first and moved forward later.
- Import is dumped in A and moved backwards when space is needed for export or earlier, when housekeep capacity is available.

The resulting yard lay out is summarised in Figure 9.4. We see some differences with the detailed area division, for example, B is used mainly for export now, while in the detailed

Area	# Ground slots	Throughput	Throughput per ground slot
A	1500	8593	5.7
B	1000	416	0.4
C	750	2736	3.6
D	750	681	0.9

Table 9.2: Throughput with January 2005 cargo flow and four yard areas

case it is also used for import. This shows that investigations at this global level do not tell us everything we need to know. Therefore the remaining tests are done with a yard with 12 stacking areas.

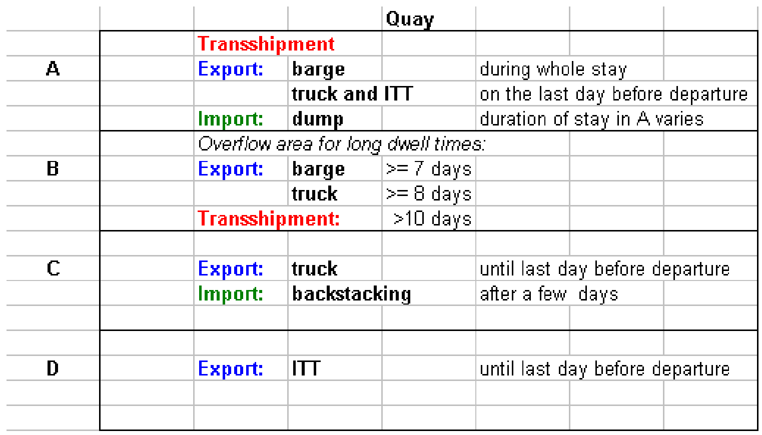

Figure 9.4: Yard lay out with four areas

The throughput (per ground slot) for each area is presented in Table 9.2.

9.3.2 Extra service

AE8 transshipment and IT containers behave like containers from the other AE services. Therefore, when the AE8 service is added, other containers have to make room for the new ones: a part of the AE2 containers is stacked further backwards, especially the ones with a longer dwell time than others. AE3 containers are not moved, as there are not many of them. Some AE7 containers is stacked a bit more and/or earlier backwards.

Half of the AE8 import is dumped in AE and housekept immediately to CMW. The other half is stacked in BE (the ”overflow” area for AE) and stays there until it leaves the terminal again.

Area	Basic	10% additional barge moves
AW	4.1	4.6
AMW	5.7	5.7
AME	2.4	2.4
AE	8.2	8.2
BW	4.2	4.1
BMW	2.5	2.5
BME	3.0	3.0
BE	2.6	3.0
CMW	0	0.4
CE	0	0
DMW	3.8	3.6
DE	0	0

Table 9.3: Throughput per ground slot for the basic case and with 10% extra barge moves

9.3.3 Delayed vessel

We simulate a delay of two days for the AE1 load call. In our test case this means that 504 containers stay in the yard for two more days. As in the basic case there was some spare space in the back of the yard, this space is used now: we see that the AE1 load containers stay longer in the back. They are moved forward on the last day. Some container groups undergo a small shift in stacking location, but the global lay-out of the terminal is not changed by the delayed vessel. For example, one group of transshipment (TA4-AE1) is during its last days stacked in BE instead of AE, because its dwell time increases to nine days by the delay.

9.3.4 Extra barge moves

We compare the throughput for each area of the basic case and with 10% extra barge moves (Table 9.3).

- AW is the area closest to the barge interchange zone. Most of the barge containers are unloaded into or loaded from this area. The increased throughput shows that some of the extra containers still fit in this area. When we take a look at the specific groups stacked in AW (AE1-barge and TA2-barge), we see that the shares stacked in AW increase. This can be explained by the increased relative number of barge containers in those groups.
- Containers arriving by barge and with a dwell time smaller than six days are stacked in their final position at once.
- A large part of the AE2 and AE7 import is dumped in BE. Both carry more than 40% barge containers, so when the number of barge moves increases and the stacking position is not changed, the throughput in this area increases.

Area	Basic	Extra housekeep
AW	4.1	5.7
AMW	5.7	5.9
AME	2.4	2.5
AE	8.2	9.0
BW	4.2	4.4
BMW	2.5	1.9
BME	3.0	3.0
BE	2.6	1.6
CMW	0	1.2
CE	0	0
DMW	3.8	3.8
DE	0	0

Table 9.4: Throughput per ground slot for the basic case and with extra housekeep capacity

9.3.5 Extra housekeep capacity

When 100 extra housekeeping moves a day are available, they are used for removing more import from the A area and moving more export to the A area. More transshipment is moved inside the A area to make sure it is unloaded and loaded as close to the vessels as possible. This results in a higher throughput of the A area. The comparison is made in Table 9.4. We also observe that some areas which are not used in the basic case, are used now. These areas are far from interchange zones, but with the extra capacity containers can be moved closer later on.

9.3.6 No housekeep capacity

The suggested yard lay-out when no housekeep capacity is available is given in Figure 9.5. In Table 9.5 we compare the relative amounts of import, export, and transshipment in A, B, C, and D with those in the basic case (with housekeeping). We observe that without housekeeping capacity, generally more import is stacked close to the quay than export. When stacking export in the back, the berthing position of the serving vessel is taken into account, so most AE export is stacked in an E area (DE, CE, ...) and most TA export is stacked in an MW area.

When we compare the yard lay-outs for the basic case (Figure 9.3) and the case without housekeep capacity (Figure 9.5), we see that the areas which are not used in the latter case have something in common: Those were the areas which, when you do have housekeep capacity, were used for temporary stacking of containers near their landside (including barge) interchange zones. AW and BW were used for barge, DMW for ITT and truck, and BME for truck. Most of the containers stacked in one of those areas in the basis case were in transit; they were not stacked there during all their stay, but (un)loaded near the vessel.

In Table 9.6 we present the (relative) throughput per area split in import, export, and trans-

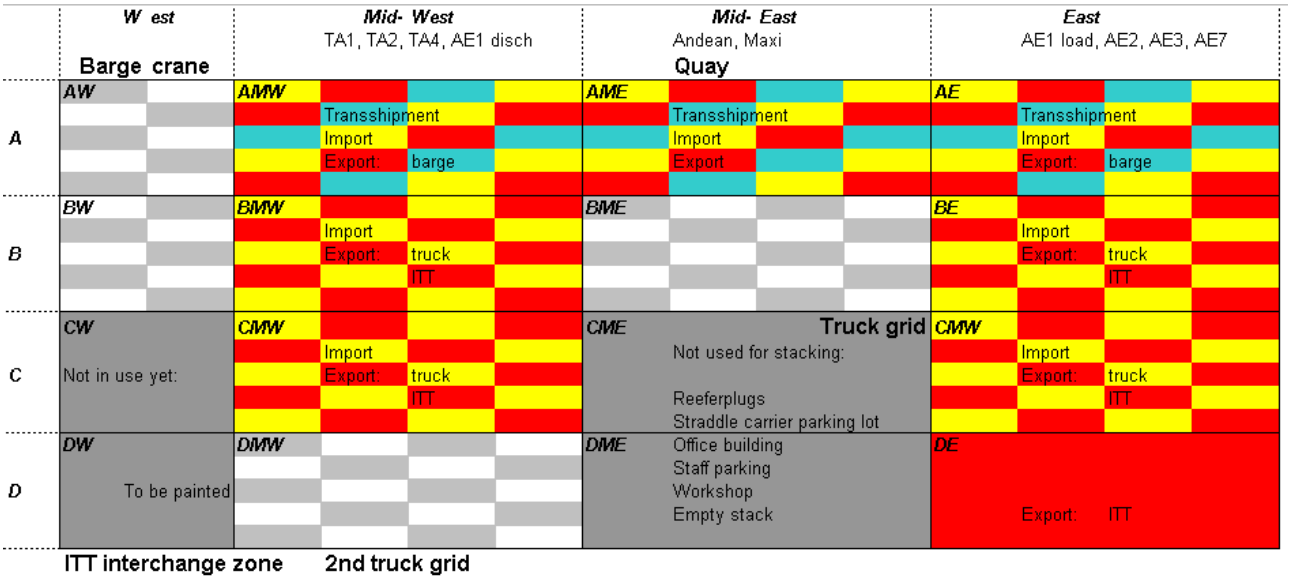

Figure 9.5: Yard lay out without housekeeping possibilities

shipment. This does not mean that exactly this percentage of ground slots should be reserved for the respective containergroup, because the number of ground slots needed during one week also depends on the dwell time. As most dwell times are around six days, however, the throughput does give an indication of the number of ground slots needed.

On a more detailed level we observed the following:

- *Transshipment* is stacked in the middle of the quay, in AME. There are a few exceptions: Transshipment entering and leaving via AMW is stacked in AMW and transshipment entering and leaving via AE is stacked in AE. We expected groups with a shorter dwell time to be stacked closer to the quay side. However,
- All containers entering and
  or leaving by the *ANDEAN or MAXI* service are stacked in AME.
- All containers entering by *barge* and leaving via the eastern part of the quay are stacked in AE on arrival. Containers leaving via the mid-western part of the quay are stacked in AMW on arrival.
- *Truck export* is stacked in BE, CE, CMW, or BMW, depending on the berthing position of the vessel it leaves with.
- Most *ITT export* is stacked in C and D, E or MW again depending on the berthing position of the vessel.
- Also *import* is stacked on the mid-west side of the terminal if its vessel unloads there and on the east side if the berthing position of its vessel is on the east side of the quay.
- Contrary to what was expected, not all groups (import or export) with a short dwell time are stacked consequently close to the quay. The stacking position also depends on

Area	Containergroup	with housekeep	without housekeep
A	Import	45%	54%
	Export	42%	30%
	Transshipment	13%	16%
B	Import	77%	72%
	Export	21%	28%
	Transshipment	1%	0%
C	Import	0%	50%
	Export	0%	50%
	Transshipment	0%	0%
D	Import	20%	0%
	Export	80%	100%
	Transshipment	0%	0%

Table 9.5: Relative throughput comparison: with and without housekeep

	Import	Export	Transshipment
AE	602	416	84
	55%	38%	7%
AME	195	312	467
	20%	32%	48%
AMW	1498	571	123
	68%	26%	6%
BE	577	323	0
	64%	36%	0%
BMW	982	293	0
	77%	23%	0%
CE	709	371	0
	34%	66%	0%
CMW	144	493	0
	23%	77%	0%
DE	0	374	0
	0%	100%	0%

Table 9.6: Detailed throughput per area without housekeeping

the arrival date of the vessel, because this determines if there is enough space at the right time.

9.3.7 Longer dwell time for one group of transshipment

If AE1-TA4 transshipment stays one extra week, the average dwell time of this group becomes nine days. However, the group (of 60 containers) is still stacked in A, during all of its stay. Some other groups make room by being housekept to the back earlier. For example, 40 AE1 import containers are moved earlier, 10 TA2, and 10 TA4. The first two are moved to BW or BMW, close to the barge crane, because most of those import containers leave by barge (50%). The TA4 containers are stacked closer to the truck grid, in CMW, as 70% of the TA4 import leaves by truck.

9.3.8 Dense stack in the back of the yard

We choose to put a dense stack in DE. Unfortunately, DE was not used in the basic case, so it is also not used in this case. The driving distance is minimal when nothing is stacked in DE. Being able to stack densely does not change this. However, the rest of the yard utilisation differed a bit from the basic case. This shows that there are more solutions which have the same minimal driving distance. The solutions do not differ that much that they advise a different yard lay-out.

The largest differences between the basic and the "dense stack" case can be found in the import and truck export groups. In this model it does not matter if truck export enters by one or the other truck grid, as long as it is moved close to the departing vessel later. In reality one would choose the truck grid which results in the shortest housekeeping distance. The housekeeping distance is not taken into account in the model. The departure modality of a lot of import is not known on arrival. Therefore there is not one certain best stacking position. This explains the ambiguity of the model results for the import stacking position.

9.3.9 Four-high stacking

The throughput per ground slot for each area is given in Table 9.7. We compare this throughput for the basic case and for the case in which we stack everything four-high. As we stack higher, we can stack more containers on one ground slot. Thus we can stack more containers in their preferred area and have less "overflow" to neighbouring areas (especially B). This is reflected by an increased throughput in the popular areas (AMW, AE, and DMW) and a decreased throughput in the overflow areas (AW, BW, BMW, BME, BE). The relatively large throughput decrease in BW, BMW, and BE confirms that those areas were mainly used for overflow. AW is also used for barge cargo and BME for containers entering or leaving via the truck grid nearby.

Area	Basic	4-high
AW	4.1	3.8
AMW	5.7	6.3
AME	2.4	2.4
AE	8.2	9.8
BW	4.2	1.4
BMW	2.5	1.3
BME	3.0	2.0
BE	2.6	0.5
CMW	0	0
CE	0	0
DMW	3.8	5.1
DE	0	0

Table 9.7: Throughput per ground slot for the basic case and for four-high stacking

9.3.10 Lower import stacking

At APM Terminals Rotterdam, dumped import is stacked three-high, but import in the back is stacked two high. As in reality never all containers are stacked three high (even when dumping), the case in which we stack all import two high is closer to reality than the case in which we stack all import three high.

In Figure 9.6 the yard lay-out with two-high import is presented. We observe from the detailed figures (which give the number of containers of each group stacked in each area on each day and are not presented because of the large amount of numbers) that the main changes w.r.t. three high import are containers which are stacked further backwards or sidewards than desired. CMW and CE are used as extra import areas. There is one exception (or, actually two): ITT export with a dwell time of nine days (IT-AE7 and IT-TA4) are on arrival stacked in CMW. (They are moved forward (to A) one or two days before departure. BE has become an import only area.

With Table G.1 in Appendix G we can investigate how the throughput per area is split in import, export, and transshipment. When we compare the basic case (three-high import) and the case with two-high import we observe the following: The percentage of import containers in A decreases by five, but the percentage of ground slots needed for those containers increases by five. This means that in case of two-high stacking fewer containers are stacked in A, but more ground slots in A are occupied by import containers, so less space is available for export. This is contrary to what we expected, that the percentage of ground slots to be used by export containers would increase. This is a trend we find throughout all results for two-high import stacking: More import containers are stacked further backwards, but the general yard strategy does not change drastically.

Table 9.8 compares the throughput per ground slot for different stacking heights: The basic case has an all over stacking height of three, in one case we lowered the import stacking height to two and in the other the export stacking height. We make some observations:

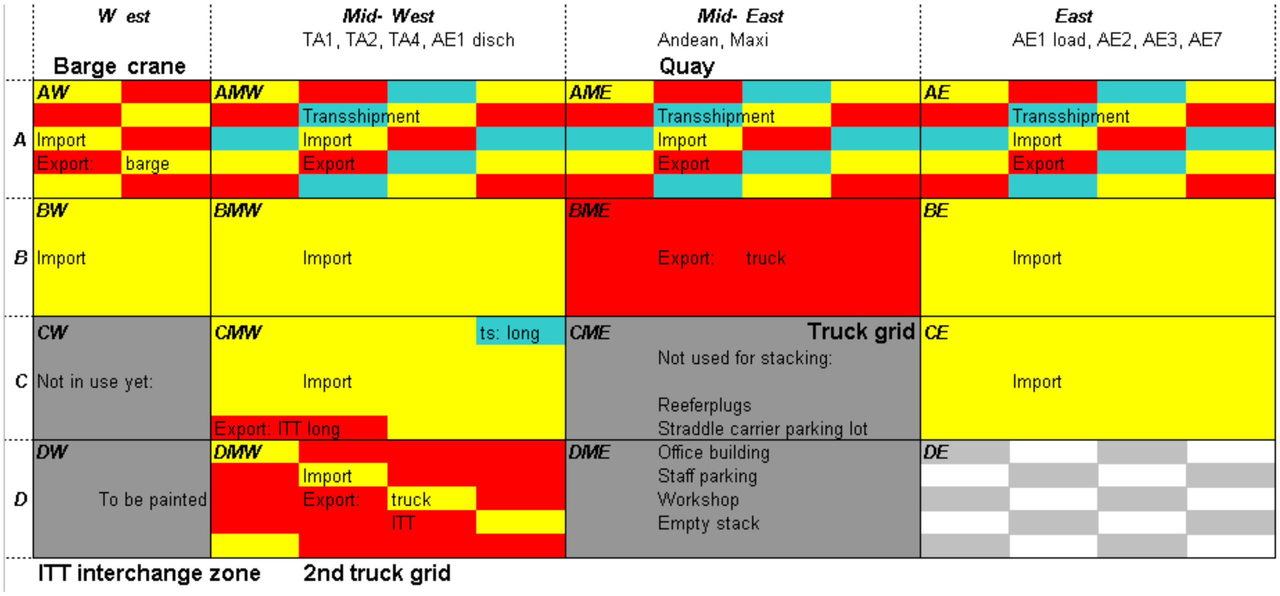

Figure 9.6: Yard lay out with two-high import stacking

- In both cases more areas are used than in the basic case, because more space is needed when stacking lower.
- AMW and AE are areas with a lot of import and export. A lower stacking height for one of those results in a lower throughput, because still a large number of the lower stacked containers is stacked on those areas.
- BME is an export area. When the export stacking height is lowered, it is still only used for export, but fewer containers fit. This is reflected in the lower throughput. The same reasoning can be used for the import areas BW and BMW.
- Also another reasoning holds for import areas BW and BMW. When the export stacking height is lowered, less import fits in other areas, so it needs to be stacked partially in BW and BMW.

9.3.11 More export rollings

We compared the total handling times for different probabilities of an information change in export containers (shortly before departure). This resulted in different total handling times. (Note that the total handling time for all containers cannot be compared to realistic values, because we used unrealistically small driving distances to and from landside interchange zones, including the barge crane.) In Table 9.9 we present the results of the three cases we compared.

We see that the increase in information change probability hardly has an effect on the total handling time, which decreases by 3.6%. The shifter time saved by lowering the stacking height is offset by the much longer extra time spent on driving. We conclude that for an

Area	Import 2-high	Basic	Export 2-high
AW	3.1	4.1	4.1
AMW	5.4	5.7	5.3
AME	2.4	2.4	2.7
AE	7.1	8.2	7.7
BW	3.4	4.2	4.3
BMW	2.0	2.5	2.7
BME	3.0	3.0	2.0
BE	2.0	2.6	3.0
CMW	2.1	0	1.2
CE	1.6	0	0.2
DMW	3.4	3.8	3.0
DE		0	0

Table 9.8: Throughput per ground slot for the basic case and for lower stacking heights

Exp. stacking height	Info change prob.	Handling time (min)
3	0.05	6456
3	0.10	6466
2	0.10	6715

Table 9.9: Handling time depending on info quality and stacking height

information change probability of 0.1, under the current circumstances at APM Terminals Rotterdam, stacking three high is better than stacking two high.

9.4 Conclusion

The results presented above provide us with insight into the optimal yard lay-out under several circumstances. This insight will be summarised in the next chapter by providing guidelines for planning the yard lay-out at APM Terminals Rotterdam.

Chapter 10

Conclusions and recommendations

10.1 Cargo flow analysis

We have performed a cargo flow analysis for January 2005. The result of this analysis is knowledge of the average number of containers per containergroup which is transferred per week, as well as their respective dwell times. We investigated four other months and concluded that January's cargo flow is representative, as long as the investigated containergroups are large enough.

The difference with existing analyses performed at APM Terminals Rotterdam was the link between the in-move and the out-move of the container. Up till now those moves have been analysed separately. We linked the moves, to investigate the modality split per vessel. This knowledge is very useful for determining a yard lay-out, the main objective of this project. Therefore we recommend using the results of the cargo flow analysis for the yard planning and to recalculate them when the cargo flow changes significantly.

In relation to the cargo flow analysis, we recommend standardising calculations which have to be performed more than once. During data collection and processing we noticed that some figures are calculated by several people at APM Terminals independently. By storing calculation methods and its resulting figures centrally (on the X-drive?), everyone uses the same values for the same performance measures.

One of those performance measures is the dwell time. We recommend using the Little's formula (Appendix C.1) for calculating the mean dwell time, because this is simple and accurate and reflects the situation better than the "snapshot method" formerly used at APM Terminals Rotterdam.

10.2 Model for determining the optimal yard lay-out

We have developed a model which determines the optimal stacking location(s) for each containergroup. We assumed that, during its stay in the yard, each container may be stacked at a maximum of two different positions. The model determines if the number of stacking positions is one or two and, if applicable, when the container is moved to the second position. With the determined stacking positions, the total transportation distance of containers from their stacking position to the quay and from the quay to their stacking position is minimal. The results of the cargo flow analysis of January 2005 have been used as basic input for this model.

We made changes to the basic input, for example, by adding an extra vessel and investigated the resulting changes in model output. It turned out that these changes in model output lead to minor changes in yard lay-out. This means that the model results are robust to small changes in input parameters. In practice, this implies that small changes in the cargo flow or the available stacking positions at APM Terminals Rotterdam do not require changes in the stacking strategy. In Section 10.3 we present a slightly adapted version of the stacking strategy suggested by the model. We adapted the strategy a bit to make it easier to implement and work with in practice.

10.3 Yard deployment guidelines

In Figure 10.1 we present the recommended yard lay-out for the current terminal size and configuration. We discuss the functionality of each area and the first and optional second stacking position of the containergroups. We also discuss the principles on which these functionalities and stacking positions are based. Those principles can be used for determining the lay-out of the expanded yard.

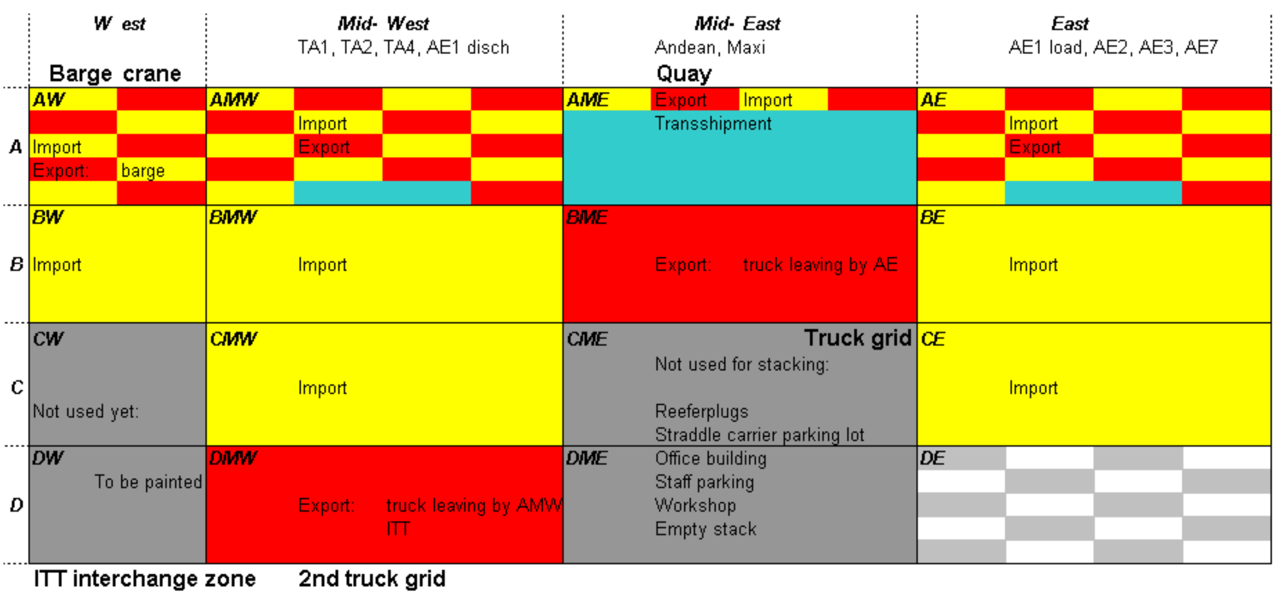

Figure 10.1: Recommended yard lay out for the current yard

10.3.1 Mixed stacking in A

The most remarkable change with respect to the current situation is the mixed A-area. AMW and AE are used for dumping import, which is removed after a few days, as soon as space is needed and housekeep capacity is available. AMW and AE are also used for preparing export one or two days before departure. Stacking import and export at different distances from the quay is not logical, because the speed of serving a vessel depends as much on its load containers as on its discharge containers.

Transshipment which enters and leaves via the same part of the quay is stacked in the area adjacent to this part of the quay during its total stay. Transshipment which enters via AMW and leaves via AE or the other way around is stacked in AME during its total stay. Also all containers which enter or leave via AME are stacked in AME during its total stay. This is possible, because AME is not a very busy area, in the sense that it is not close to a busy interchange zone. (We also consider each part of the quay as an interchange zone.) The *throughput* per ground slot (Table 9.8) indicates how busy an area is.

AW is purely a barge area. Barge import is dumped first and moved to AW as soon as possible. Barge export is dumped in AW and moved to the area via which it leaves as late as possible. Barge export gets stacking priority for AW above import, so if there is not enough space in AW, some of the barge import is stacked in BW.

10.3.2 Housekeeping

The moment of housekeeping the containers is determined by a number of factors:

1. The first is the available space in the second stacking area. Only containers for which there is space in their second stacking area can be housekept.

2. If enough space is available, we look at the second criterion. This is the departure time of the container. Export containers which leave in one or two days have to be moved to the area adjacent to which their vessel moors.

3. If no export containers which leave in one one or two days need to be housekept, we look at the throughput of the areas. If a container has to be housekept from one area to another, we compare the throughput of both areas to determine the moment of housekeeping. If the originating area has a higher throughput than the destination area, the containers need to be housekept as early as possible. If it is the other way around, the containers have to be housekept as late as possible. Give priority to removing containers from the busiest area (i.e. with the highest throughput). In practice these are areas near the quay via which many containers enter or leave, in this case AE and AMW.

10.3.3 Import stacking in B and C

Not all import is dumped in A. Area B is generally used as an overflow area for import dump. Import which is stacked in B stays there until departure.

BW is an overflow area for AW. It only used for import leaving by barge which does not fit in AW. Barge import is always dumped first and moved to AW or BW later. If one wants to save on housekeeping moves, import entering via AMW and known to leave by barge can be stacked directly in AW (or BW). This just results in a somewhat higher driving distance, which takes more time during unloading.

The (second) import stacking position highly depends on the outgoing modality, if this is known. BMW is located approximately equally close to the barge, ITT, and truck interchange zones and the quay. This location makes it perfect for dumping import entering via AMW, with an unknown outgoing modality, and for which also historical data does not clearly point out the outgoing modality. Using this guideline saves unnecessary housekeeping of containers whose outgoing modality is not known. This housekeeping capacity can better be used for moving export containers, which surely leave by vessel, to A.

We give an example: 70% of the TA4 import is known to leave by truck. Therefore its best stacking position is close to a truck grid, in this case in CMW. 50% of AE1 import leaves by barge and the other 50% leaves by truck or ITT, but for most individual containers the outgoing modality is not known on arrival. Therefore all AE1 discharge containers with unknown outgoing modality are stacked in BMW.

Keep blocks with import containers with unknown departure information as low as possible. First spread the containers and only start a next layer when all ground slots are occupied. This strategy keeps the number of shifters low, because containers which entered the terminal later have a higher probability to be picked up first.

BE and CE are used as dump overflow areas for AE. Import containers with unknown outgoing modality entering via AE are dumped in BE or CE, in case of no space in BE, and stay there until they leave the terminal again. An example is AE7 import, 40% of which leaves by truck, 20% by ITT and 40% by barge. On arrival for the greater part of the containers the outgoing modality is not known yet. This part is stacked in BE.

All ITT import is dumped as close to its vessel as possible and moved to CMW after a few days. Also import known to leave by truck and entering via AMW is dumped first and moved to CMW after a few days. In case there is not space for dumping import with unknown outgoing modality entering via AMW in BMW, CMW is even sometimes used for dumping this import.

10.3.4 Export stacking in DMW and BME

Areas DMW and BME are purely used for export. All ITT export is dumped in DMW and moved forward one or two days before departure. Most truck export leaving via AMW enters via DMW and is moved forward later. Most truck export leaving AE enters via BME and is moved forward later. There are a few exceptions:

- Truck export with a relatively short dwell time of six days (or shorter) leaving via AE is already stacked in AE on arrival. This saves housekeeping. Note that if AE gets busier, for example, by adding an extra service which moors at AE, this guideline has to be reconsidered. In that case the boundary might be set at a dwell time of five days instead of six.
- If export entering via DMW arrives more than eight days before departure of the vessel, it can be dumped in CMW instead of DMW, in order for those export containers not to occupy DMW too long. This is an option and for simplicity we did not include it in the map of the terminal (Figure 10.1).

10.3.5 Stacking height

Based on our investigations on the balance between time spent on shifters due to high stacking and time spent on transportation due to low stacking, we would recommend stacking everything three high, instead of stacking some containergroups lower. However, this investigation is based on rough estimates. Also the yard planning strategy does not depend highly on the stacking height. Therefore the suggested yard planning strategy may also be adopted with the current stacking heights. As soon as additional data on shifters is available and new stacking height investigations have proven our results, higher stacking can be implemented.

10.3.6 Major yard configuration changes

In the presented lay-out, we take the locations of the interchange zones and the stacking areas as given. In case changing these locations is possible, we add some recommendations:

- In our results area DE is not used at all, because it is far from all interchange zones. Move the ITT interchange zone (back) to DE, to make DMW less crowded.
- The southeastern corner of the terminal is not used for stacking, because it is located too decentralized. Move the empty stack, workshop, office building, parking lots, etc. there in order to make more space for containers in the middle of the yard.
- When expanding the yard, move the ITT interchange zone further from the truck grid. Currently in the optimal lay-out one area (DMW) is used for dumping truck and ITT export. This makes the area too crowded.

10.3.7 Application of the guidelines

The model produces more detailed output than the results presented in this chapter. In order to get detailed and accurate results, it is essential that the model input is detailed and accurate as well. Collecting correct data needed for the model input and developing this model input is very time-consuming. Also, this data is not always available. The number of containers to transfer, for example, is hardly ever exactly known in advance. These are obstacles which need to be overcome before the model can be used for detailed yard planning.

Therefore we recommend to start with using the global guidelines. As soon as the guidelines have proven to be useful for increasing the production at APM Terminals Rotterdam, we recommend including them in SPACE (yard planning system), if this is technically possible.

Even when using the presented global guidelines, accurate information on arrival and departure times, dwell times, and numbers of containers which will be transferred in the future are very useful for efficient yard planning. We recommend to improve the information exchange with Maersk Sealand, in order to use move forecasts which are as accurate as possible.

10.4 Recommendations for further research

Perform the parts of the cargo flow analysis mentioned in chapter 5 which have not been performed yet. Doing those analyses and the ones we performed for January 2005 on a regular basis would even be better, in order to get more insight into the performance of the yard. When performance measures like the average handling time of the containers are monitored, changes in stacking strategy can be evaluated by, for example, investigating the resulting handling time.

Monitoring the number of rollings and the resulting number of shifters should lead to a better understanding of the relation between the two. If this relation is known, also the the number of shifters per container for a certain stacking height can be determined more accurately. If the time spent per shifter is known, also the total time spent on shifters, given a certain stacking height, can be determined. Our model determines the time spent on transportation within the yard. If the stack is higher, the transportation time is lower, but the shifter time is higher. Additional knowledge on shifters can be used for weighing shifter time against transportation time and eventually determining the optimal stacking height, taking both components of the container handling time into account.

In our model we assumed that the number of containers to be transferred was known. In reality this number is not exactly known. Besides trying to get more accurate predictions from the customers, as we recommended in Section 10.3, finding a way to deal with the unpredictability of container numbers also helps. Develop, for example, forecasts with historical data and validate them with real container numbers to see how accurate they are. If the developed forecasts are accurate enough, they can be of great help for the yard-planning.

Some of the research questions in Section 6.7 were not investigated because they lay outside the scope of this project or because not enough data was available. In other projects or when enough data is available, investigating those non-handled research questions could be very useful for APM Terminals Rotterdam.

Bibliography

[1] Constantinos Abacoumkin, Athanasios Ballis, *Development of an expert system for the evaluation of conventional and innovative technologies in the intermodal transport area*, European Journal of Operational Research 152 (410-419), 2004.

[2] Agostino Bruzzone, Robert Signorile, *Simulation and genetic algorithms for ship planning and shipyard lay-out*, Simulation 71: 2 (7483), 1998.

[3] Buyang Cao, Gotz Uebe, *An algorithm for solving capacitated multicommodity p-median transportation problems*, The Journal of the Operational Research Society 44: 3 (259-269), 1993.

[4] Bernardo de Castillo, Carlos F. Daganzo, *Handling strategies for import containers at marine terminals*, Transportation Research Part B 27: 2 (151-166), 1993.

[5] Marc P. Goetschalckx, H. Donald Ratliff, *Shared storage policies based on the duration of stay*, Management Science 36:9 (11201132), 1990.

[6] K.M. van Hee, B. Huitink, D.K. Leegwater, *Portplan, decision support system for port terminals*, European Journal of Operational Research 34, 1988.

[7] K.M. van Hee, R.J. Wijbrands, *Decision support system for container terminal planning*, European Journal of Operational Research 34: 3 (262-272), 1988.

[8] Simone Hilkens, *Truck Turn Times*, internal report, APM Terminals Rotterdam, May 2004.

[9] Akio Imai, Kazuya Sasaki, Etsuko Nishimura, Stratos Papadimitriou, *Multi-objective simultaneous stowage and load planning for a container ship with container rehandle in yard stacks*, European Journal of Operational Research (in press), 2004.

[10] Akio Imai, Xin Sun, Etsuko Nishimura, Stratos Papadimitriou, *Berth allocation in a container port: using a continuous location space approach*, Transportation Research Part B 39 (199-221), 2005.

[11] Kap Hwan Kim, *Evaluation of the number of rehandles in container yards*, Computers & Industrial Engineering 32: 4 (701-711), 1997.

[12] Kap Hwan Kim, Jong Wook Bae, *Re-marshaling export containers in port container terminals*, Computers & Industrial Engineering 35: 3-4 (655-658), 1998.

[13] Kap Hwan Kim, Hong Bae Kim, *Segregating space allocation methods for container inventories in port container terminals*, International Journal of Production Economics 59 (415-423), 1999.

[14] Kap Hwan Kim, Hong Bae Kim, *The optimal sizing of the storage space and handling facilities for import containers*, Transportation Research Part B 36 (821-835), 2002.

[15] Kap Hwan Kim, Kang Tae Park *A note on a dynamic space-allocation method for outbound containers*, European Journal of Operational research 148 (92-101), 2003.

[16] Kap Hwan Kim, Young Man Park, Kwang-Ryul Ryu, *Deriving decision rules to locate export containers in container yards*, European Journal of Operational Research 124 (89-101), 2000.

[17] Erhan Kozan, *Optimising container transfers at multimodal terminals*, Mathematical and Computer Modelling 31 (235-243), 2000.

[18] Erhan Kozan, Peter Preston, *Genetic algorithms to schedule container transfers at multimodal terminals*, International Transactions in Operational Research 6 (311-329), 1999.

[19] Erhan Kozan, *Comparison of analytical and simulation planning models of seaport container terminals*, Transportation Planning and Technology 20: 3 (235248), 1997b.

[20] Pasquale Legato, Rina M. Mazza, *Berth planning and resources optimisation a a container terminal via discrete event simulation*, European Journal of Operational Research 133 (537-547), 2001.

[21] Patrick J.M. Meersmans, Rommert Dekker, *Operations Research Supports Container Handling*, Report EI 2001-22, Econometric Institute, Erasmus University, Rotterdam, 2001.

[22] Katta G. Murty, Jiyin Liu, Yat-wah Wan, Richard Linn, *A decision support system for operations in a container terminal*, Decision Support Systems 39 (309-332), 2005.

[23] Francesco Parola, Anna Sciomachen, *Intermodal container flows in a port system network: Analysis of possible growths via simulation models*, International Journal of Production Economics (in press), 2004.

[24] Peter Preston, Erhan Kozan, *An approach to determine storage locations of containers at seaport terminals*, Computers & Operations Research 28 (983-995), 2001.

[25] Yvo A. Saanen, *An approach for designing robotized marine container terminals*, PhD thesis, TU Delft, 2004.

[26] D. Sculli, C.F. Hui, *Three dimensional stacking of containers*, Omega 16: 6 (585594), 1988.

[27] Dirk Steenken, Stefan Voss, Robert Stahlbock, *Container terminal operation and operations research - a classification and literature review*, OR Spectrum 26 (3-49), 2004.

[28] Mounira Taleb-Ibrahimi, Bernardo de Castilho, Carlos F. Daganzo, *Storage space vs handling work in container terminals*, Transportation Research Part B 27: 1 (13-32), 1993.

[29] Iris F.A. Vis, René de Koster, *Transshipment of containers at a container terminal: An overview*, European Journal of Operational Research 147 (1-16), 2003. Also see www.ikj.nl/container (last checked in january 2005).

[30] *Expansion document*, Internal report, APM Terminals Rotterdam, 2004.

[31] Roel van de Weijer, *Yard Enhancement*, Internal report, APM Terminals Rotterdam, 2004.

[32] Won Young Yun, Yong Seok Choi, *A simulation model for a container-terminal operation analysis using an object-oriented approach*, International Journal of Production Economics 59 (221-230), 1999.

[33] Chuqian Zhang, Jiyin Liu, Yat-way Wan, Katta G. Murty, Richard J. Linn, *Storage space allocation in container terminals*, Transportation Research Part B 37 (883-903), 2003.

Appendix A

Glossary

Not all terminology in this glossary is used in this report. However, all of it is used in literature about container terminals, so this glossary is also useful for studying this literature.

AGV	Automatic Guided Vehicles
AS/RS	Automated Storage and Retrieval Systems
Back-stacking	Moving dumped containers from the A-area to the D-area
BAS	Berth Allocation System
Bay	Part of a ship (split along its long axis) in which containers are stacked
Containergroup	Number of containers with similar characteristics
CTCS	Information system used at APM Terminals Rotterdam
Dense stack	Containers stacked in one block instead of in streets
DGPS	Digital Global Positioning System
DOS	Duration Of Stay
Dry van	Regular container
ED	Expert Decking
EDI	Electronic Data Interchange
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
Export	Containers which leave by vessel but did not enter by vessel
Fixed special	Street with containers with equal characteristics
Free flow	Random (dense) stacking
Grid	Truck interchange zone
Hatch	See "Bay"
Hold	See "Bay"
HDS	High Density Stack: (High) stack without space between the containers
IMO	Container used for transporting dangerous goods
Import	Containers which enter by vessel but do not leave by vessel
Interchange zone	Area where containers are moved to and from their mode of transportation
ITT	Inter Terminal Transport
KPI	Key Performance Indicator

Long standing	A container which has been standing in the yard for too long
Modality	Transportation mode (deep sea, barge, train, truck or ITT)
Move	One relocation of a container, picking it up once and putting it down once
M-street	Street where empty containers are stacked
MT	Empty container
MTH	Empty container Handler
MTS	Multi Trailer System
OOG	Out Of Gauge, with a differing size
Paid move	Container move into or out of the yard
PM	Prime Mover
POD	Port Of Discharge
QC	Quay Crane
Rehandle	Container move from one position in the yard to another one
RMG	Rail Mounted Gantry crane
Rolling	Stacked container which is booked onto a later vessel than originally planned
RTG	Rubber Tired Gantry crane
Service	Planned recurring route of a vessel
Shifter	Getting a container which is blocked by another one
Space	The yard planning system APM Terminals Rotterdam uses
Straddle carrier	Vehicle which can pick up a container from a stack and transport it
TEU	Twenty feet Equivalent Unit
TEU factor	Ratio between the number of TEU and the number of containers
TGS	Terminal Ground Slot
TOS	Terminal Operating System
TPR	Terminal Performance Report
TR	Truck
Truck grid	Place where trucks are (un)loaded
t/s	Transshipment
Unpaid move	Container move within the yard

Appendix B

Cargo flow analysis data

This appendix gives an overview of the data used for the cargo flow analysis. One (Excel) data sheet of extracted data contains information about each container which has left the terminal in a certain month. Data from a longer period does not fit, because in one month more than 55000 containers are transferred and an excel sheet contains 60000 lines.

For each container the following information is logged (if applicable):

- Reference (unique ID of a move)
- Container ID
- Line
- Length
- Height
- Type (=Iso code: dry van, IMO, empty, or reefer)
- Load status (full or empty)
- Weight
- IMO code (=blank if it does not have dangerous contents)
- TS/RS (indicates if a container is TransShipment or *ReStow* (unloaded and reloaded, because it blocks another container))
- OR (yes/no, indicates if a container is an Operational Reefer)
- Incoming modality
- Incoming service
- Incoming vessel
- Incoming voyage

- Incoming date
- Incoming time
- Outgoing modality
- Outgoing service
- Outgoing vessel
- Outgoing voyage
- Outgoing date
- Outgoing time
- Port of discharge

This data needs some processing before the needed information can be derived from it. ITT moves, for example, are logged twice: once when a container is loaded from the terminal onto an MTS and once when the container is loaded from the MTS onto a train (or the other way around). These two logged moves together represent one out-move, so one of the logged moves should be deleted.

The daily yard overview data file contains records with the same information as for the moves. However, not all information on out moves is available yet at the moment a container is still present in the yard, so some fields are blank.

Appendix C

Mathematical calculations

C.1 Dwell time calculation with Little

The dwell times per containergroup are determined by the dividing the average number of containers in the yard (of the considered containergroup) by the average number of out moves (of the considered containergroup) per day. This calculation is also known as Little's formula.

Meaning of the indices:

t: containergroup

i: day of the month, $i = 1, ..., I$

Measured:

n_i^t: number of containers of containergroup t in the yard on day i

m^t: number of containers of containergroup t that left the terminal in one month

I: number of days in the month

Now the average dwell time of containers of containergroup t is given by

$$\frac{\sum_i n_i^t / I}{m^t / I} = \frac{\sum_i n_i^t}{m^t} \tag{C.1}$$

Appendix D

Cargo flow analysis results

As we have most data for January 2005 (move counts as well as yard overviews), we mainly present in this chapter results for this month. The results for October, November, December, and February can be found in the Excel files on the cd-rom, as well as more detailed results (per service). The total number of containers handled in the investigated months is given in Table D.1.

Month	Number
Okt	56184
Nov	54931
Dec	52978
Jan	56454
Feb	59771

Table D.1: Total number of containers transferred per month

Note that some small unexpected value differences between results may occur due to errors or blank fields in the data.

D.1 Flow counts for January 2005

D.1.1 All containers

	Barge	ITT	Truck	Vessel	Total
Barge	662	234	402	5340	6638
ITT	137	62	83	4390	4672
Truck	852	181	1234	8128	10395
Vessel	9328	4216	10608	10597	34749
Total	10979	4693	12327	28455	56454

D.1.2 Full dry

	Barge	ITT	Truck	Vessel	Total
Barge	0	6	18	3818	3842
ITT	1	9	11	3816	3837
Truck	0	11	27	5155	5193
Vessel	8050	3627	7612	7411	26700
Total	8051	3653	7668	20200	39572

D.1.3 Empty

	Barge	ITT	Truck	Vessel	Total
Barge	662	228	384	1181	2455
ITT	134	51	72	225	482
Truck	852	169	1197	1477	3695
Vessel	802	532	555	1526	3415
Total	2450	980	2208	4409	10047

D.1.4 Reefer

	Barge	ITT	Truck	Vessel	Total
Barge	0	0	0	97	97
ITT	0	2	0	67	69
Truck	0	1	9	1193	1203
Vessel	275	52	2400	1405	4132
Total	275	55	2409	2762	5501

D.2 Average number in the yard

These are the average results of daily (8AM) measurements over one month (January):

	Full dry	Reefer	Empty	IMO	Total
Import	3248	167	1175	118	4708
Export	2513	198	216	170	3097
Transshipment	1240	210	141	95	1686
Other	41	4	1294	6	1345
Total	7042	579	2825	389	10835

Other: Moves with no vessel involved, e.g., barge-truck.

D.3 Dwell times for January 2005

D.3.1 All containers

	Barge	ITT	Truck	Vessel	Total
Barge	6.9	4.5	9.0	6.3	6.5
ITT	9.3	7.9	14.4	6.9	7.1
Truck	9.9	5.7	3.8	7.0	6.9
Vessel	4.8	6.2	4.9	6.8	5.6
Total	5.4	6.1	5.0	6.8	6.1

D.3.2 Full dry

	Barge	ITT	Truck	Vessel	Total
Barge		17.1	12.4	4.9	5.0
ITT	10.0	8.2	6.3	6.6	6.6
Truck		8.7	4.7	7.4	7.4
Vessel	4.3	6.0	5.3	5.4	5.1
Total	4.3	6.0	5.3	6.1	5.5

D.3.3 Empty

	Barge	ITT	Truck	Vessel	Total
Barge	6.9	4.2	8.8	11.2	9.0
ITT	9.4	8.1	15.6	10.9	10.9
Truck	9.9	5.4	3.8	8.1	7.0
Vessel	11.1	7.4	14.0	16.0	13.2
Total	9.5	6.4	7.6	11.8	9.8

D.3.4 Reefer

	Barge	ITT	Truck	Vessel	Total
Barge				4.3	4.3
ITT		0.6		6.4	6.2
Truck		17.3	3.8	4.2	4.2
Vessel	2.0	5.5	1.7	4.6	2.8
Total	2.0	5.6	1.7	4.5	3.2

D.4 Delivery and pickup times

Figure D.1 shows the delivery patterns for the AE1 load call in January. Each colour represents a different ship of the same service and voyage in the same month.

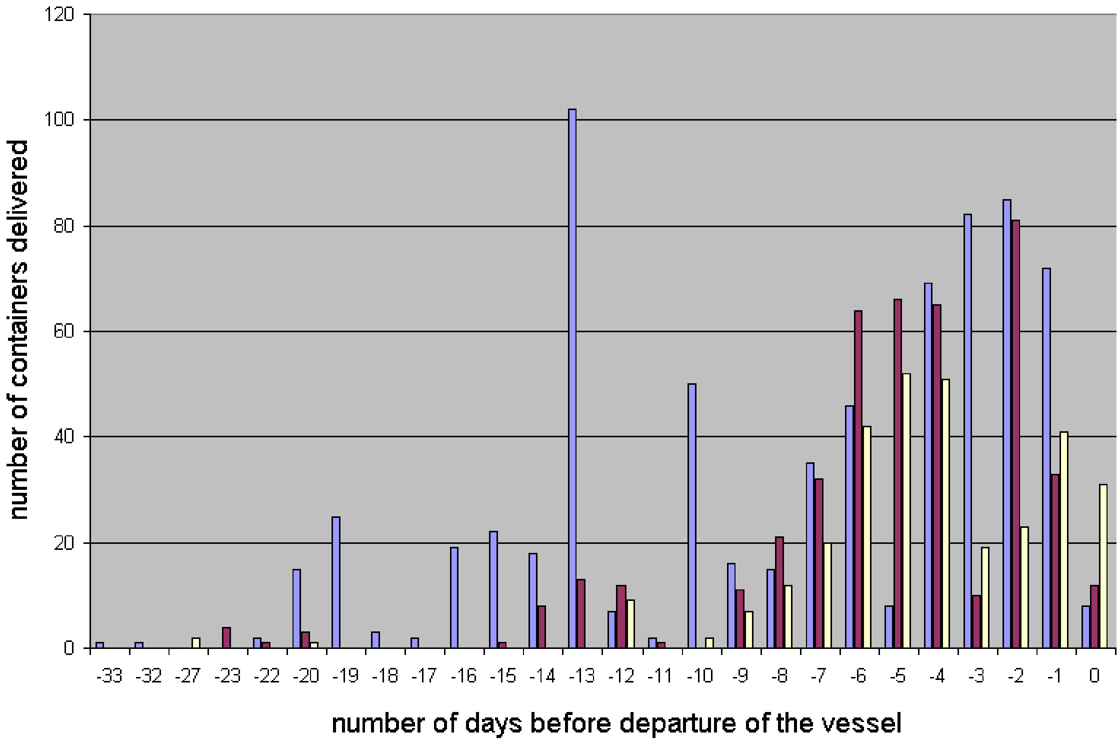

Figure D.1: Delivery pattern comparison AE1

D.5 Stacking height

No data available yet.

D.6 Data quality

No data available yet.

D.6.1 Empty containers with unknown outgoing modality

In Section 5.3 we stated that most of the import containers with unknown outgoing modality which turn into transshipment are empty. Here we provide a motivation.

Unfortunately, we do not have information on the number of containers with unknown outgoing modality on arrival, but we do have information on the number of containers in the yard with unknown outgoing modality. We use the latter data as a substitute for the former.

The number of full containers *in the yard* which has entered by vessel and will leave by vessel is 20% of the total number of containers in the yard. When we look at the number of moves instead of at the number of containers in the yard, we observe that eventually the total number of full containers which have entered by vessel and have left by vessel is 20% of all containers which visit the yard.

For empty containers, these values are different: When looking at the yard overview, the number of empties which is know to be leaving by vessel is 4% of all containers in the yard. However, when we consider the number of moves, we observe that eventually 15% of all containers are empty and enter and leave by vessel. This implies that many empty containers which have entered by vessel and have an unknown outgoing modality will leave by vessel, otherwise the 4% cannot increase to 15%

D.7 Yard usage

No data available yet

D.8 Move distances

No data available yet.

D.9 Yard moves

No data available yet.

D.10 Total handling time

No data available yet.

Appendix E

Mathematical model formulation

This appendix follows the same structure as Chapter 7 and should be not be read independently.

E.1 Lay-out model

E.1.1 Input parameters

K: set of stacking areas

k: stacking area, $k \in 1, ..., |K|$

g_k: number of ground-slots in area k, $g_k \in \mathbb{N}$

T: set of all different containergroups you want to distinguish

t: one containergroup, $t \in 1, ..., |T|$

c: cycle length (in days), $c \in \mathbb{N}$

h^t: (optimal) stacking height of containergroup t, $h^T \in \mathbb{R}$

s^t: (average) dwell time of containergroup t, $s^t \in \mathbb{N}$

n^t: number of containers of containergroup t which enters the terminal in one cycle, $n^t \in \mathbb{N}$

w: day of the cycle, $w \in \{1, ..., c\}$

a^t: day in the cycle on which containergroup t arrives

m_w^{max}: maximum housekeep capacity (number of moves which can be carried out) for day w (night between day w and day $w + 1$)

din_k^t: distance a container of containergroup t has to cover from its incoming modality to area k

$dout_k^t$: distance a container of containergroup t has to cover from area k to its outgoing modality

i: index for counting the number of days a containergroup is stacked in its first position, $i \in \{1, ...s^t\}$

In this model, the stacking position right after entering the terminal might differ from the one right before leaving the terminal. Therefore we cannot just add the total distance a container has to cover to/from a certain stacking position, but to consider if a certain position is the first or the last stacking position. In the former case we have to consider the distance from the incoming modality to the stacking position and in the latter case the distance form the stacking position to the outgoing modality. For example, the incoming distance of an import container to area A is quite small, but the outgoing distance (from A to a truck interchange zone) is quite large.

E.1.2 Decision variables

$x_k^{t,i}$: number of ground-slots in area k reserved at day $a^t, a^t + 1, ..., a^t + i - 1$ for containers of containergroup t which stay in their first position for i days, $1 \leq i \leq s^t$, $x_k^{t,i} \in \mathbb{R}$

$y_k^{t,i}$: number of ground-slots in area k reserved at day $a^t + i, a^t + i + 1, ..., a^t + s^t - 1$ for containers of containergroup t containers which stay in their first position for i days, $1 \leq i \leq s^t - 1$, $y_k^{t,i} \in \mathbb{R}$

One might want to have integer-valued decision variables, because containers cannot be split. However, as in reality the number of containers is variable instead of deterministic, as we assume in this model, the time spent on searching for a integer-valued solution is not worth it. Also, the number of containers is that large, that the effect of putting one single container in a different position than planned can be neglected. This implies that a solution which places a container partially in one position and partially in another, can be applied by stacking the container in one of those positions. For example, if the results state that 100.4 containers should be put in one area and 60.6 in another, it does not matter much if one area hosts 101 containers and the other 60 or one 100 and the other 61.

E.1.3 Constraints

This capacity constraint states that the total number of ground-slots in one area at one day reserved for all containergroups cannot exceed the total number of available ground-slots of this area:

$$\sum_{w' \equiv w \ mod \ c} \Big(\sum_{(t,i):a^t \leq w' \leq a^t+i-1} x_k^{t,i} + \sum_{(t,i):a^t+i \leq w' \leq a^t+s^t-1} y_k^{t,i} \Big) \quad \leq \quad g_k, \ \forall_{k,w} \tag{E.1}$$

The number of stacking positions reserved for one containergroup on one day should at least equal the number of stacking positions needed by this containergroup on this day. Also, the total number of containers of one containergroup stacked in their second position should equal the total number of containers of this containergroup earlier stacked in the first of the two positions (flow conservation).

$$\sum_k \sum_i h^t x_k^{t,i} = n^t, \qquad \forall_t \tag{E.2}$$

$$\sum_k x_k^{t,i} = \sum_k y_k^{t,i}, \qquad \forall_t, \forall_{i=1,\ldots,s^t-1} \tag{E.3}$$

The total number of housekeeping moves in night $w, w+1$ may not exceed the maximum number of housekeeping moves for this night:

$$\sum_k \sum_{(t,i):a^t+i-1 \equiv w \ mod \ c} h^t y_k^{t,i} \leq m_w^{max}, \qquad \forall_w \tag{E.4}$$

Additionally, because we cannot put a negative number of containers in an area, the values of all variables have to be greater than or equal to zero:

$$x_k^{t,i} \geq 0, \qquad \forall_{k,t,i} \tag{E.5}$$

$$y_k^{t,i} \geq 0, \qquad \forall_{k,t,i} \tag{E.6}$$

E.1.4 Objective

Minimise

$$\sum_{t,k} h^t \Big((din_k^t + dout_k^t) x_k^{t,s^t} + \sum_{i=1}^{s^t-1} (din_k^t x_k^{t,i} + dout_k^t y_k^{t,i}) \Big) \tag{E.7}$$

Theoretically y can also become larger than 0 when a container physically is not moved. To make sure that a $y_k^{t,i} > 0$ really reflects a move, we add an epsilon punishment for each $y_k^{t,i} > 0$. The objective then becomes:

Minimise

$$\sum_{t,k} h^t \Big((din_k^t + dout_k^t) x_k^{t,s^t} + \sum_{i=1}^{s^t-1} (din_k^t x_k^{t,i} + dout_k^t y_k^{t,i}) \Big) + \epsilon \sum_{k,t,i} y_k^{t,i} \tag{E.8}$$

E.1.5 Additional features

Say $r_k^{t,w}$ (so called *occupation*) is the number of containers of containergroup t on weekday w in area k. It is calculated from the decision variables in the following way:

$$r_k^{t,w} = h^t \sum_{w' \equiv w \ mod \ c} \Big(\sum_{(t,i):a^t \leq w' \leq a^t+i-1} x_k^{t,i} + \sum_{(t,i):a^t+i \leq w' \leq a^t+s^t-1} y_k^{t,i} \Big) \tag{E.9}$$

Say q_k is the *throughput* of area k, i.e. the number of container visits to this area in one week.

$$q_k = \sum_t \sum_i x_k^{t,i} + y_k^{t,i} \tag{E.10}$$

Long standings are only known to be long standings when the "short standings" of the same containergroup have left the terminal. This implies that until the departure of the short standings, both groups have to be treated as one group. This can be incorporated in the model in the following way.

Consider two groups of (import) containers t_1 and t_2 with different numbers of containers n^{t_1} and n^{t_2} and equal stacking height $h^{t^1} = h^{t^2}$. Without loss of generality, assume that $s^{t_1} < s^{t_2}$. Add the following constraint to the model:

$$\frac{r_k^{t_1,w}}{n^{t_1}} = \frac{r_k^{t_2,w}}{n^{t_2}}, \qquad \forall_{k,t}, \forall_{w \equiv w' \ mod \ c, \ a^{t_1} \leq w' < a^{t_1} + s^{t_1}} \tag{E.11}$$

E.2 Stacking height model

With the assumptions presented in Section 7.2.3, we can develop the following analytical model.

E.2.1 Input parameters

p: Probability of an information change

E.2.2 Decision variables

h: Stacking height

E.2.3 Output variables

$M(h)$: Total number of shifters for a pile with stacking height h.

$N(h)$: Expected number of shifters per container for stacking height h.

E.2.4 Calculation

In the assumptions we stated that we can handle piles of containers independently and that all piles have equal height. This implies that the expected number of shifters per container calculated for one pile equals the over all expected number of shifters per containers.

The expected number of shifters in a pile equals the total number of shifters in a pile divided by the number of containers in this pile:

$$N(h) = \frac{M(h)}{h} \tag{E.12}$$

The following reasoning leads us to the expected number of shifters in a pile. If one container in a pile gets a rolling, all containers on top of the one, plus the rolled container itself need to be removed. This means that the number of containers in one pile to be removed is determined by the lowest container in the pile which is rolled. It does not matter if the ones on top of it are rolled as well. This means that the probability p_i that exactly the top i containers have to be removed is the probability that the i^{th} container from the top of the pile has to be removed multiplied by the probability that the $h-i$ containers underneath it do not have to be removed:

$$p_i = p(1-p)^{h-i} \tag{E.13}$$

The probability of removing the j^{th} container from the top is equal to the sum over all i of the probabilities of moving exactly the first i containers from the top, with i larger than or equal to j. i and j can never be equal to h, because neither the lowest container nor the ones on top have to be moved when the lowest container is rolled.

$$\sum_{i=j}^{h-1} p_i = \sum_{i=j}^{h-1} p(1-p)^{h-i}$$

Summing this value over all containers in the pile gives the probability of having to move one container in the pile:

$$M(h) = \sum_{j=1}^{h-1}\sum_{i=j}^{h-1} p_i = \sum_{j=1}^{h-1}\sum_{i=j}^{h-1} p(1-p)^{h-i}$$

Dividing this by the number of containers in the pile gives the expected number of shifters per container:

$$N(h) = \frac{1}{h}\sum_{j=1}^{h-1}\sum_{i=j}^{h-1} p(1-p)^{h-i} = \frac{p}{h}\sum_{j=1}^{h-1}\sum_{i=1}^{j}(1-p)^{i} = \frac{p}{h}\sum_{j=1}^{h-1}\frac{1-(1-p)^j}{p} = \frac{1}{h}\sum_{j=1}^{h-1} 1-(1-p)^j$$

E.2.5 Simulation model

In this section we give a rough description of a simulation model which could be built.

The arrival and departure patterns are input to the model. Say both import arrival time and export departure time are deterministic and the dwell times are stochastic (Poisson). For transshipment both arrival and departure times are deterministic, so also the dwell time is.

The simulation model should keep track of the configuration of the stack. The stack configuration can be changed by an arrival, a departure, or an information change for one of the containers in the stack. APM Terminals has rules which state where to put an arriving container and in what order containers depart. This means that as soon as an arrival or departure is generated, the resulting stack configuration change can be derived by applying those rules.

Say the info changes follow a Poisson process and they affect a random container in the stack. As soon as a (simulated) info change occurs, the resulting number of shifters and the new stack configuration can be determined. The container groups with incomplete information (e.g., an import container which leaves by truck, but no-one knows when) should be treated separately.

Appendix F

Input scenarios

In this appendix we present the input values for some of the test cases, not for all of them, because this would give too many pages with numbers. The omitted input values can be requested via m.p.v.putten@tue.nl.

F.1 Global test cases

F.1.1 Division in import/export and A/B

Containergroup	# Containers	Arrival day	Dwell time	Stacking height
Import	2	Monday	5	2
Export	5	Thursday	8	3

Distance in (meters):

	A	B
Import	1	2
Export	2	1

Distance out (meters):

	A	B
Import	2	1
Export	1	2

Area	Number of groundslots
A	3
B	3

F.1.2 Division in import/export/transshipment and A/B/C/D

Containergroup	# Containers	Arrival day	Dwell time	Stacking height
Import	4800	Monday	5	2
Export	3100	Friday	6	3
Transshipment	1800	Wednesday	5	3

Distance in (meters):

	A	B	C	D
Import	100	200	300	400
Export	400	300	200	100
Transshipment	100	200	300	400

Distance out (meters):

	A	B	C	D
Import	400	300	200	100
Export	100	200	300	400
Transshipment	100	200	300	400

Area	Number of groundslots
A	2000
B	1500
C	1000
D	1000

F.1.3 Division per modality

Containergroup	# Containers	Arrival day	Dwell time	Stacking height
Barge-Vessel	1000	Friday	5	3
Truck-Vessel	1300	Wednesday	7	3
ITT-Vessel	1000	Sunday	7	3
Vessel-Vessel	1900	Monday	5	3
Vessel-Barge	2000	Tuesday	4	2
Vessel-Truck	1900	Thursday	5	2
Vessel-ITT	900	Saturday	6	2

Area	Number of groundslots
A	2000
B	1500
C	1000
D	1000

The different importance of the distance to the landside interchange zones is incorporated in the test cases by weighing the respective distances with a suitable factor. If each distance is equally important, this factor is taken to be one for each distance. The resulting distance tables look as follows:

Distance in (meters), each distance equally important:

	A	B	C	D
Barge-Vessel	700	800	900	1000
Truck-Vessel	500	400	300	400
ITT-Vessel	1000	900	800	700
Vessel-Vessel	100	200	300	400
Vessel-Barge	100	200	300	400
Vessel-Truck	100	200	300	400
Vessel-ITT	100	200	300	400

Distance out (meters), each distance equally important:

	A	B	C	D
Barge-Vessel	100	200	300	400
Truck-Vessel	100	200	300	400
ITT-Vessel	100	200	300	400
Vessel-Vessel	100	200	300	400
Vessel-Barge	700	800	900	1000
Vessel-Truck	500	400	300	400
Vessel-ITT	1000	900	800	700

When the distance to modalities other than vessel is not taken into account at all, we multiply these distances with zero:

Distance in (meters), distances to landside interchange zones not important:

	A	B	C	D
Barge-Vessel	0	0	0	0
Truck-Vessel	0	0	0	0
ITT-Vessel	0	0	0	0
Vessel-Vessel	100	200	300	400
Vessel-Barge	100	200	300	400
Vessel-Truck	100	200	300	400
Vessel-ITT	100	200	300	400

Distance out (meters), distances to landside interchange zones not important:

	A	B	C	D
Barge-Vessel	100	200	300	400
Truck-Vessel	100	200	300	400
ITT-Vessel	100	200	300	400
Vessel-Vessel	100	200	300	400
Vessel-Barge	0	0	0	0
Vessel-Truck	0	0	0	0
Vessel-ITT	0	0	0	0

In the last case the distances to and from landside interchange zones are weighed with $\frac{1}{100}$:

Distance in (meters), distance to the quay 100 times more important than distances to other interchange zones:

	A	B	C	D
Barge-Vessel	7	8	9	10
Truck-Vessel	5	4	3	4
ITT-Vessel	10	9	8	7
Vessel-Vessel	100	200	300	400
Vessel-Barge	100	200	300	400
Vessel-Truck	100	200	300	400
Vessel-ITT	100	200	300	400

Distance in (meters), distance to the quay 100 times more important than distances to other interchange zones:

	A	B	C	D
Barge-Vessel	100	200	300	400
Truck-Vessel	100	200	300	400
ITT-Vessel	100	200	300	400
Vessel-Vessel	100	200	300	400
Vessel-Barge	7	8	9	10
Vessel-Truck	4	3	4	5
Vessel-ITT	10	9	8	7

F.2 Distance computations

Distances over the yard can computed in several ways. Therefore we describe our method here. All distances are Manhattan distances, generally measured from the middle of the area to the middle of the interchange zone or vessel (according to the pro-forma berthing). There are some exceptions. *In the last case the shortest distance to the quay is chosen. (nog niet af)* The quay length is approximately 1250 meters. The barge crane and the ITT interchange zone are both located at the west side of the yard, the barge crane at the quay and the ITT interchange zone in the back of the yard. One of the truck interchange zones (*grids*) is located in the C area east from the middle and the other in the D-area west from the middle. Whenever possible, the closest truck grid is used.

The driving distances for each group are based on the number of containers in this group which leaves by a certain modality. Import containers, for example, all enter over the quay, so the distance they have to cover when they enter the terminal is at least 100 meters to the A area, 200 to B, 300 to C, and 400 to D. 40% of the import containers leaves by barge, 20% by ITT and 40% by truck. Therefore the average distance covered by one container leaving the terminal is given by 0.4 times the distance to the barge crane plus 0.2 times the distance to the ITT interchange zone plus 0.4 times the distance to the truck grid.

F.3 Number of ground slots

The real number of dry vans which left the terminal in January was 39580. This is 9895 per week. However, by only considering the ten largest vessels, we consider only 8633 of those containers. WE should lower the number of available ground slots accordingly. The real number of available TEU ground slots is 7824. The TEU factor is 1.63, so this gives 7824/1.63=4800 container ground slots. The number we should use is $\frac{8633}{9895} \times 4800 = 4185$. We "kill" 4.4 of those slots, because they are occupied by long standings (longer than two weeks). This results in a total of 4000 ground slots. This number is divided proportionally over the areas.

Appendix G

Model output

D01, d02, etc. in Figure G.1 represent the days of the week, d01 being Monday.

		Occupation										
		Barge-Vesse	Truck-Vesse	ITT-Vessel	essel-Vess	Import1	Import2	Import3	Import4	Import5	Import6	Import7
A	d01	1000	1300	600	1900	400			288		113	
	d02	1000	1300	600	1900		688				113	
	d03		1187	600	1900		288	700			113	
	d04		1187	600	1900			588	688			
	d05	1000	1187	600	1900			588	288			
	d06	1000	1187	1000				588	288		700	
	d07	1000	1300	600				588	288		413	700
B	d01					300			12	700	87	
	d02					300	12			700	87	
	d03		113			300	12				87	
	d04		113			300	12		12			
	d05		113			300	12		12	700		
	d06		113				12		12	700		
	d07								12	700		
C	d01								400		500	700
	d02					400					500	700
	d03					400	400				500	700
	d04					400	688	112				700
	d05					400	688	112	400			
	d06						688	112	400			
	d07							112	400		287	
D	d01			400								
	d02			400								
	d03			400								
	d04			400								
	d05			400								
	d06											
	d07			400								

Figure G.1: Results of distinguished modalities and unknown import

In Table G.1, under "3" the throughput is presented for three-high stacking, under "2" two-high stacking. "2s" gives the throughput measured in ground slots occupied and "2c" the throughput measured in containers. Note that the relative throughput is not necessarily equal to the relative number of slots to reserve for a certain containergroup.

		Occupation							
		Barge-Vessel	Truck-Vessel	ITT-Vessel	Vessel-Vessel	Vessel-Barge	Vessel-Truck	Vessel-ITT	/essel-Truck lon
A	d01	900	1000	460	1900				
	d02	1000	1300	460	1900	893			
	d03			460	1900	493			
	d04			600	1900	233	1600		300
	d05	900		600	1900	233	1500		
	d06	900		1000			1500	900	
	d07	900	400	460			1500	900	
B	d01	100							
	d02					1107			
	d03					1507			
	d04					1767			
	d05	100				1767			
	d06	100							
	d07	100							
C	d01		300						300
	d02								300
	d03		1300						300
	d04		1300						300
	d05		1300				100		600
	d06		1300				100		600
	d07		900				100		300
D	d01			540				900	
	d02			540				900	
	d03			540				900	
	d04			400				900	
	d05			400					
	d06								
	d07			540					

Figure G.2: Results with a separate group of long standings

	A			B			C			D		
Containergroup	3	2s	2c	3	2s	2c	3	2s	2c	3	2s	2c
Im	45%	50%	40%	77%	88%	83%	0%	94%	92%	20%	31%	23%
Ex	42%	73%	45%	21%	12%	17%	0%	1%	1%	80%	69%	77%
TS	13%	13%	15%	02%	0%	0%	0%	5%	7%	0%	0%	0%

Table G.1: Throughput per area split in percentage of import, export, and transshipment