Disruption Management in Container Terminal Operations: An MPC Approach

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Master's Thesis

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Preface

This master's thesis marks my ending of a six year period of me as a student at the University of Technology Eindhoven. After weighing the Bsc. Mechanical Engineering and the Bsc. Technology Management, I chose to pursue the Mechanical Engineering route in order to enrich my knowledge in the science of technology in general. The Bachelor Mechanical Engineering provides knowledge in many different technology fields.

After finishing my Bachelor's degree in Mechanical Engineering I considered a switch to the master track Operations Management & Logistics. However, I stayed in the department of Mechanical Engineering and joined the Systems Engineering Group. Since there is some overlap in both mater tracks, I decided to stay in the department of Mechanical Engineering. For instance, the Systems Engineering Group does research in the field of analysis, control, and optimization of machines, manufacturing systems and logistical networks.

Personally, the highlight of my master's was the internship at the University of Maryland, USA. During this 5 month trip, I conducted research at the Smith School of Business in the supply chain management field and traveled extensively throughout the USA. Not only did these experiences enrich my knowledge in this field of science, but they have contributed to my personal development and way of thinking. To have traveled abroad, alone, for this significant period of time contributed greatly to improving my language skills and my sense of independence. I not only broadened my way of thinking but my social network. From my current perspective, I would highly recommend the opportunity to participate in an internship abroad to anyone.

The research presented in this thesis is part of a large container port research project, supervised by Prof. Udding. Therefore, this thesis is the result of personal research conducted in close cooperation with Maarten Hendriks and Guido Karsemakers, who have taken part into this research project as well. They provided me with valuable discussions and different insights which greatly contributed to the quality of this research.

I would like to thank Maarten Hendriks and Guido Karsemakers for the pleasant cooperation. Furthermore, I would like to thank Erjen Lefeber for coaching and Prof. Udding for giving me the opportunity to perform this research. At last, I would like to thank Christien Vullings, who supported me throughout my entire study.

Maarten Vullings, Eindhoven, October 26, 2008

Preface

Summary

Growth

Sea transportation of container freight plays an important role in national and international trade. Overseas container transportation has grown rapidly over the last decennia, and is expected to grow even further throughout the next decennia. In order to cope with this increasing growth and survive in the competitive world of container transportation, sophisticated equipment and planning strategies must be developed concurrently to facilitate rapid container handling and cost efficient logistics processes.

Considerations

The following considerations are taken into account in this research:

- 1. System: container port where vessels run a regular service on.
- 2. Cyclic system: each week, one vessel of each shipping line calls on the port.
- 3. Expectations: each week, one vessel of each shipping line is expected to load and unload a certain container freight.
- 4. Strategic planning: cyclic, long term and based on agreements.

Disruptions

Due to (large) disruptions, it is possible that the strategic plan for the container terminal operations becomes temporarily infeasible. Potential disruptions are for instance:

- vessel arrival times,
- container freight,
- container handling equipment.

Re-planning

If the disruptions are large enough to render the strategic plan infeasible, a re-planning procedure yielding a new feasible operational plan needs to be carried out.

• Objective: prevent (further) stagnation in the container port which can result in delays, high costs and loss of goodwill.

- Goal: recover from disrupted situation as soon and as cost efficient as possible.
- Problems: complex and interdependent processes in a container port.
- Time: available decision time is short.

For an efficient recovery or re-planning method, a decision support tool for operational container terminal planning needs to be developed.

Decision support tool

In this report, a decision support tool is developed which calculates the operational planning of a container terminal over a certain planning horizon.

- DECISION SUPPORT TOOL: based on a Model Predictive Control strategy.
- OPERATIONAL PLANNING: planning is calculated over a certain planning horizon in the future, and allocates:
 - 1. vessel berth time interval,
 - 2. vessel berth position along terminal quay.
 - 3. quay cranes to vessels.
- APPROACH[†]: Based on a 3 subproblem approach [Hendriks, 2007]:
 - 1. Time Allocation Problem[‡] (TAP)
 - Main objective: calculation of berth time intervals of vessels. Minimizing:
 - * delays in departure,
 - * quay crane usage.
 - Main constraints:
 - * quay crane capacity,
 - * terminal quay berth capacity.
 - 2. Position Allocation Problem (PAP)
 - Main objective: calculation of berth positions of vessels. Minimizing:
 - * the deviation from the lowest cost berthing position.
 - Main constraint:
 - * non-overlap in berth position.
 - 3. Quay Crane Allocation Problem (QCAP)
 - Main objective: allocation of quay cranes to vessels. Minimizing:
 - $\ast\,$ quay crane usage,
 - * quay crane switches between vessels.
 - Main constraints:
 - * non-crossing of quay cranes,
 - * a restricted number of quay cranes in the terminal,
 - * a restricted number of quay cranes per vessel.

[†] The 3 subproblems are formulated as Mixed Integer Linear Programs and are executed successively.

‡ Allocation of specific terminal is not incorporated. It is assumed that a vessel does not deviate from its reference berthing terminal. *Main advantage:* each subproblem takes only one terminal at a time into account, which reduces computation time.

Performance Decision Support Tool

The decision support tool is tested in a discrete event simulation model of the container port. The following experiments have been evaluated and results are obtained:

• POSITIONING STRATEGY:

- Static positioning: lowest cost berth position determined by reference position.
- Dynamic positioning: lowest cost berth position determined online.

The dynamic positioning strategy results always in equal or lower average container transportation distance when compared to the static positioning strategy. Depending on the disruptions, the average reduction in the transportation distance can increase up to an average 8,38%.

• BALANCING TUNING PARAMETERS:

Weight factors in decision support tool can be adjusted to obtain a certain balance in between:

- quay crane usage,
- short vessel turn around times resulting in low delays in departure.

A high quay crane usage results in less and shorter delays in departure, whereas a low quay crane usage can result in more and longer delays in departure.

• STABILITY:

Due to the 3 subproblem approach and MPC strategy, measures have to taken in the decision support tool to prevent instabilities. The suggested measures provide stability even under influence of large disruptions.

• COMPUTATION TIME:

The cumulative computation time of the decision support tool is sufficiently low for real-time use of operational container terminal planning.

Summary

Samenvatting

Groei

Transport van containers speelt een belangrijke rol in de nationale en internationale handel. Het overzees transport van containers is de laatste decennia drastisch toegenomen. Naar verwachting zal deze ontwikkeling zich nog verder doorzetten in de komende decennia. Om deze groei aan te kunnen en om winstgevend te kunnen blijven in de concurrerende transport sector, zal er door ontwikkeld moet worden op het gebied van container handling en strategische en operationele planning. Dit alles moet er voor zorgen dat het logistieke process zo efficient mogelijk verloopt.

Beschouwingen

De volgende zaken worden in dit onderzoek beschouwd:

- 1. Systeem: Een container haven waarin schepen volgens een lijndienst arriveren.
- 2. Cyclisch systeem: Elke week arriveert er een schip van een bepaalde shipping line.
- 3. De verwachtingen: Elke week laadt en lost een schip van een shipping line een bepaalde container vracht.
- 4. Strategische planning: Cyclisch van aard, voor de lange termijn, en gebaseerd op contract afspraken.

Verstoringen

Doordat er (grote) operationele verstoringen plaats kunnen vinden, is het mogelijk dat het strategisch plan voor de uitvoering van de operaties in de container terminal tijdelijk niet meer voldoet. De belangrijkste verstoringen vinden plaats in:

- aankomsttijden van de schepen,
- de vracht (containers),
- de machines voor het laden, lossen en vervoeren van de containers.

Operationele planning

Als de verstoringen groot genoeg zijn is het mogelijk dat het strategisch plan tijdelijk niet meer voldoet. Dan moeten de operaties opnieuw gepland worden zodat er weer een operationeel plan ligt dat voldoet.

- Doel: het voorkomen van verdere stagnatie in de container terminal. Verdere stagnatie kan namelijk leiden tot vertragingen in vertrektijden, hogere kosten en verlies in goodwill.
- Streven: het zo snel mogelijk herstellen van de verstoorde situatie, zodat de strategisch planning weer hervat kan worden.
- Problemen: de aanwezige processen in de terminal zijn complex en afhankelijk.
- Tijd: de tijd om te reageren is kort.

Voor een efficient herstel van de operaties, moet er een decision support tool (een tool voor het nemen van beslissingen) worden ontwikkeld, die de operationele planning opnieuw berekent.

Decision support tool

Dit onderzoek richt zich op het ontwikkelen van een decision support tool voor het berekenen van een operationele planning van de container terminal.

- DECISION SUPPORT TOOL: gebaseerd op Model Predictive Control strategie.
- OPERATIONELE PLANNING: de planning wordt berekend over een bepaalde plannings-horizon in de toekomst, en legt de volgende operaties vast:
 - 1. het tijdsbestek waarin het schip geladen en gelost moet worden,
 - 2. de positie van het schip aan de kade.
 - 3. het toekennen van de aanwezige kranen op de kade aan de schepen.
- AANPAK[†]: gebaseerd op een driedelige probleem aanpak [Hendriks, 2007]:
 - 1. Time Allocation Problem[‡] (TAP)
 - Hoofddoel: Het berekenen van de tijdsintervallen van de schepen, waarin het volgende wordt geminimaliseerd:
 - * de vertragingen in vertrektijd,
 - $\ast\,$ het gebruik van kranen aan de kade.
 - Beperkingen:
 - * de totale kraan capaciteit aan de kade,
 - * een beperkte kade lengte.
 - 2. Position Allocation Problem (PAP),
 - Hoofddoel: het bepalen van de aanmeer posities van de schepen aan de kade waarbij het volgende wordt geminimaliseerd:
 - * het verschil tussen de gekozen aanmeer positie en de meest kost efficiënte aanmeer positie.
 - Beperking:
 - * schepen die tegelijkertijd in de haven liggen, mogen niet overlappen in positie.
 - 3. Quay Crane Allocation Problem (QCAP).
 - Hoofddoel: het toekennen van de kranen aan de schepen, waarbij het volgende wordt geminimaliseerd:
 - * het aantal kranen in operatie,
 - $\ast\,$ het switchen van kranen tussen de schepen.

- Beperkingen:
 - * kranen kunnen elkaar niet passeren op de kade.
 - * het aantal kranen (capaciteit) is beperkt.
 - * het aantal kranen dat tegelijkertijd een schip kan behandelen is gelimiteerd.

† Alle drie de deelproblemen worden als een optimalisatie probleem geformuleerd: Mixed Integer Linear Programs. Deze drie deelproblemen worden na elkaar uitgevoerd, waaruit de operationele planning volgt.

‡ In de TAP hoeven de schepen niet specifiek aan een terminal te worden toegekend. In het algemeen wordt aangenomen dat een schip niet van zijn referentie terminal afwijkt. *Voordeel:* Elk deelprobleem kan voor één terminal apart worden opgelost. Dit reduceert de tijd die benodigd is voor het berekenen van de operationele planning.

Performance Decision Support Tool

De decision support tool wordt getest door het te koppelen aan een simulatie model van de container haven. De volgende experimenten zijn uitgevoerd en resultaten zijn waargenomen:

- OPTIMALISERINGSSTRATEGIE:
 - *Statische positionering*: de kost efficiënte aanmeer positie is bepaald door een vaste referentie positie.
 - Dynamische positionering: de kost efficiënte aanmeer positie wordt on-line bepaald.

De dynamische positionering resulteert in dezelfde of lagere kosten. Waarbij de kosten bepaald zijn door de transport afstand van het container vervoer binnen de terminal. Afhankelijk van de grootte van verstoringen, is er een maximale reductie in transport afstand van gemiddeld 8,38% waargenomen.

• BALANS in AFSTEL PARAMETERS:

De kosten factoren in de decision support tool kunnen zo afgesteld worden dat een balans wordt gevonden in:

- kranen gebruik,
- korte process tijd (resulterend in geen/korte vertragingen).

Een hoge kraan utilisatie leidt tot minder en kortere vertragingen in de vertrektijd. Een lage kraan utilisatie kan leiden to meer en langere vertragingen in de vertrektijd.

• STABILITEIT:

Door de driedelige aanpak en de eigenschappen van MPC kan de decision support tool instabiel worden. Door extra maatregelen te nemen kan de decision support tool gestabiliseerd worden. De experimenten hebben uitgewezen dat door de genomen maatregelen de decision support tool stabiel blijft, zelfs onder invloed van grote verstoringen.

• REKEN TIJD:

De cumulatieve rekentijd van de ontwikkelde decision support tool is voldoende kort voor real-time toepassingen in operationele planning.

Samenvatting

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Chapter 1

Introduction

1.1 Container transportation through history

Sea transportation of container freight plays an important role in national and international trade. Nowadays, more than 90 percent of the international cargo is transported over sea ports [Tahar & Hussain, 2008]. The fraction of container transportation in the total world's deep sea cargo has risen to more than 60%. Today, some major freight routes are even containerized by 100% [Kim & Günther, 2007].

Therefore, it is not surprisingly that over the last 2 decades the scientific world has shown an increasing interest in the optimization of strategic and operational planning of container ports. The transportation of freight can be classified into two categories:

- transportation of huge quantities of commodities such as: grains, iron ore, crude oil, coal,
- transportation of containerized cargo.

In this report the focus lies on the transportation of containerized cargo.

Time line of container transportation

The origin of the transportation of goods in boxes goes back to 1780 or earlier. The following time line provides a quick overview in the history of transportation of containerized goods [Steenken et al., 2004], [Levinson, 2008].

- 1780s Goods in open boxes (smaller than today's standardized containers) used to transport items such as coal, by train.
- 1840 Utilization of steel and wooden boxes for transportation of goods.
- 1900s Introduction of the first closed boxes / containers for transportation of goods.
- 1950s First vessels built specifically to carry containers.
- **1955** First truly intermodal container system using the container vessel Clifford J. Rogers. During its first trip, it transported 600 containers, of considerably smaller dimensions than the standard containers used today.

- **1965** In April 1956, a refitted oil tanker from entrepreneur Malform Clean carried fifty-eight shipping containers from Newark to Houston.
- **1965** The breakthrough of the container as a main transportation device after vast investments in:
 - seaports around the world (i.e. suitable terminals and equipment for the handling of container vessels),
 - specifically designed container vessels,
 - the availability of large amounts of containers.

The introduction of containers made it possible to switch from one transportation system to another (e.g. vessels, trains and trucks), in a relatively short amount of time. Other advantages of the use of container as a transportation device were less packaging and less damaging of products.

Container standardization

During the first period of the so-called containerization, from early 1960's to begin 1970, incompatible container sizes and container corner fittings were in use. As the transportation of goods globalized due to the increasing world trade, the use of these different container types became very impractical. Therefore the properties of the containers were standardized in 1969–1970. The capacity of a container is nowadays indicated by "TEU", which stands for a "twenty-foot equivalent unit". This container capacity refers to the dimensions of a container: 20 ft (length) \times 8 ft (width). The most commonly used containers are 20 ft long (1 TEU), 40 ft long (2 TEU) and 45 feet long (2 TEU). So both the 40 and 45 ft long container are considered as 2 TEU.

Container vessels

Since the start of the containerization period, the size of the container vessels have been continuously growing. While the first container vessels were capable of carrying a very little amount of containers, vessel size has increased dramatically in recent years. Maersk Line's new flagship vessel the 'Emma Maersk', which won the title of ship of the year at the 2007 Lloyd's List awards in London, is said to be the world's largest container vessel with an operating capacity of 11,000 TEU's. The Emma Maersk is one of five such sister vessels and their actual maximum potential capacity is said to be up to 14,500 TEU's [Mangan et al., 2008].

This trend of ever building larger vessels is probably limited by the trade routes of the container vessels. "SuezMax" (14,000 TEU) for instance, indicates the largest theoretical ship capable of passing through the Suez Canal. "Malaccamax" (18,000 TEU), indicates the largest theoretical vessel capable of passing through the Straits of Malacca. Such a vessel displaces 300,000 DWT (metric tons of deadweight), is 470 meters long, 60 meters wide, has 16 meters of draft, and uses more than 100 MW (134,102 hp) for a speed of 25.5 knots. A major reconstruction of the trade routes is needed, before even larger container vessels can be used. In [Baird, 2006] more information can be found about the ongoing growth in vessel size.

Container ports

Since the beginning of the containerization, new sea ports have arisen. Analogous to the growth in size of the container vessels, the container ports itself have grown rapidly. In order to handle the large vessels with their high capacity:

- terminals expanded in length and width to enable berthing and container storage,
- major sea ports began using multiple terminals to increase capacity,
- equipment for handling containers advanced.

After new container sea ports and port operators originated, the competition increased. Especially the competition between those ports which are geographically closely situated to each other. Therefore, it became even more important to run the terminals efficiently in order to survive in the competitive world of shipping business.

Improvements of operations

Two important goals in container port planning are usually a high utilization of resources and proper management of operations. A low utilization of resources results in capital loss and high costs. On the other hand, a shortcoming in equipment results in delays and can cause customer dissatisfaction or even loss.

Due to the growth of the container sea ports, the numerous logistics operations have become more and more complex. Therefore, advanced terminal lay outs have been developed, as well as automated transportation and handling equipment, efficient IT support, improved logistics, and control software systems [Kim & Günther, 2007].

Since the start of the containerization, the scientific world has shown an increasing interest in container terminal logistics. For recent overviews of scientific literature about strategic and operational port planning, as well as properties of seaport container terminals, see [Vis & de Koster, 2003], [Steenken et al., 2004], [Kim & Günther, 2007], [Rashidi & Tsang, 2006] and [Murty et al., 2005].

1.2 Problem formulation

System description

In this report a container port is considered on which vessels run a regular service. The vessels of different shipping lines visit the different container ports according to a global sea route. Each cycle, which has usually the length of one week, one vessel of each shipping line is expected to enter the port. Hence, a container port operates according to a certain cyclic time table. This cyclic time table is the result of the agreements that are made between the terminal operator and the shipping lines about the time and dates that a vessel calls on the port. If multiple terminals are present in the port, then the vessel's berthing terminal is usually also determined in the agreement.

Terminal operator strategy

At this point, a clear distinction is made in how a container terminal is managed. Certain terminals are owned by a terminal operator which operates in service of a shipping line. Since the vessels itself are the most expensive in operation, the vessels of the shipping lines usually have priority above the terminal operations and the required resources in the terminal. From this point of view, the goal is to serve the vessel as good and quick as possible.

Other terminal operators are independent companies. Then the terminal operator and the shipping lines can have different priorities when they enter an agreement. In general, an independent terminal operator tries to reduce its costs and at the same time tries to provide a satisfactory service level to the shipping lines. Depending on the strategy, the terminal operator can satisfy the shipping lines' preferences, which implies that the date, time, and berthing terminal is determined by the preferences of the shipping line. But it is also possible that the terminal operator negotiates with the shipping line to shift the preferences in for instance the desired arrival and departure time towards a more cost efficient planning for the terminal operator. Hence, what an optimal strategic planning exactly is depends largely on the chosen strategy of the terminal operator. Throughout the report, the viewpoint of the independent terminal operator is mainly used.

Agreements and strategic planning

Once the terminal operator has finished the negotiation process with the shipping lines and the agreements have been made, it can start with the construction of a strategic cyclic planning for the long term planning of the container port. Since the agreements are usually made for a relative long period of time (often years), the strategic planning is also fixed for a relative long period of time. The strategic planning is the first key element in efficient port management and determines for each vessel its:

- berthing terminal,
- its berth position in the terminal,
- its berth time interval,
- quay cranes that process the vessel.

In general, a more sophisticated strategic planning can improve the performance of the transportation system and can result in reduced costs, less delayed departures, and a higher service level.

Operational planning

Once a strategic planning has been determined for the container port, it can be used as a reference planning for the operational planning of the container port. Under the ideal circumstances, i.e. when there are no disruptions present in the container port, the operations can be executed according to the reference planning. However, when a container port is in operation, many unpredictable events can occur which cause the operational planning to deviate from the reference planning. A vessel can arrive earlier or later than expected, the amount and type of containers that have to be loaded / unloaded can deviate, cranes can break down, etc.

By making decisions in response to these disruptions, the operational planning is continuously adapted. Making the right operational planning decisions is the second key element in efficient port management. Since the decisions about the control actions are not always straightforward, a decision support tool for operational planning could be very valuable for a terminal operator.

The decisions which are made at current time, can affect the performance of future operations as well. Therefore, the operational planning can be improved when future information is incorporated in the decision making process. This future information can for instance consist of forecasts about the expected arrival times of the vessels, forecasts about the number and types of container freights, and scheduled quay crane maintenances. These forecasts are constantly updated over time as new valuable information becomes available. As the vessels approach the port, the predictions become more accurate. Therefore, the planning has to be adapted repeatedly, such that the most recent information is always incorporated in the decision making process.

Considerations

In this report the focus lies on the operational planning of a container port. For this, a decision support tool needs to be developed. But before the contributions and outline of this report are formally stated, some relevant literature is treated.

Since a certain analogy can be drawn between the planning of a container port and the planning of other transportation systems such as railway systems, bus stations and airports, some relevant literature about disruption management of such transportation systems is considered. The techniques proposed here can be used to increase the robustness of the planning of the transportation system, as it is under the influence of disruptions. Furthermore, techniques are proposed which can be used to recover from a disrupted situation in the transportation system.

Subsequently, the techniques and approaches behind strategic container port planning are treated. There are several reasons for shortly discussing this topic here. First of all, strategic planning is a key element in container port planning, and the techniques and ideas behind strategic planning contribute therefore to a more integral understanding of efficient container port planning in general. Before any transportation system can be controlled efficiently, there needs to be a certain strategic planning for the long term planning. Furthermore, the approach that is used to calculate the strategic planning is very similar to the approach that is used in the decision support tool for the operational planning of the container port.

In the last section of Chapter 1, the specific contributions and outline of this report are formulated.

1.3 Literature

1.3.1 Disruption Management

Definition

According to [Clausen, 2007], the following definitions about disruptions are made. A disrupted situation is a state during the execution of the current operation, where the deviation from the plan is sufficiently large to render the plan infeasible, thereby necessitating re-planning. Furthermore, a disruption is an event or a series of events that renders the planning of the considered transportation system infeasible. Disruption management is the process of re-planning in case of a disruption.

Two main forms of disruption management can be distinguished:

- recovery management,
- robust planning.

While recovery management deals with re-planning, robust planning can be interpreted as proactive disruption management.

A certain analogy can be made in between disruption management of container ports and other transportation systems such as railway systems, and airports. Although these transportation systems are physically different, certain ideas and concepts used for robust planning and recovery are interchangeable.

In the airline industry there has been a long tradition of using mathematical models as the basis for planning of resources such as aircraft and crew [Ball et al., 2007]. Now, the use of mathematical models has been expanded to the field of recovery and robust planning of transportation systems. Also commercial IT-systems supplying decision support for recovery of disrupted operations has become available.

Recovery

An important problem faced in decision support for recovery management is that it must be applicable in real-time. This introduces limits on the run time of the model underlying in the decision support tool. Although it is not always possible to find the best possible solution, it is better to act based upon a sub-optimal decision than to take no action at all, or to take action without knowing the exact consequences of a decision.

In general, a recovery problem solved by a decision support tool can be handled as follows. The system is in a certain disrupted state. The objective is to get back to the normal or reference state as soon as possible, by minimizing a certain objective function which is subject to certain constraints. This concept is based on iterated re-planning, since new disruptions and information can become available over time.

Companies often have preferred recovery strategies. This however, requires knowledge of possible disturbance patterns. Very often, simulation methods are required to verify these recovery strategies. Furthermore, simulating the system can reveal knock-on effects of decisions made at current time.

Robustness

Besides recovery strategies to get back to the desired state, robust planning has gained an increased interest during the last years [Ball et al., 2007]. Robustness methods in planning can be applied in two different ways. A robust planning can make the system less vulnerable to disruptions by absorptions. This form of robustness gives the advantage that the planning does not become infeasible upon small disturbances. The other form of robustness aims on developing a planning from which it is easy to recover from in a disrupted situation [Clausen, 2007].

The sensitivity of the operational costs in response to a disruption is also crucial. If the costs for the reference planning are for instance low, but a small disruption leads to high operational costs, then the low cost reference planning can still lead to high overall operational cost (i.e. non-robust for costs). Depending on the disruptions that occur in the transportation system, it may be better to use a reference planning with slightly higher costs but which is less cost sensitive to disruptions (i.e. robust for costs).

In [Clausen, 2007] different measures for robust planning applied to the airline and railway industry can be found. In [Ball et al., 2007] robust planning techniques can be found for the airline industry. In [Hendriks et al., 2008], a method has been developed which increases the robustness of a strategic planning of a container port in response to disruptions in vessel arrival times.

1.3.2 Strategic port planning

In this subsection, the strategic container port planning is considered in detail. A strategic planning is defined here as a long term planning of the main operations in the container port. This strategic planning is party the result of the agreements that have been made between the terminal operator and the shipping line. These agreements determine the berth time intervals of the vessels and possibly the specific berthing terminal of the vessels in the strategic planning. As soon as the agreements have been made, the container terminal operator can start to construct the strategic planning for the port. The strategic planning contains information about the:

- **I** vessel's berthing terminal,
- **II** vessel's berth position in the terminal,
- III vessel's berth time intervals, i.e. its arrival and departure time,

IV allocation of the quay cranes to the vessel over the berth time interval.

Due to the continuously increasing size and complexity of container ports throughout the last couple of decades, it has become harder to construct a sophisticated strategic planning that on one hand satisfies the preferences of the shipping line and provides a satisfactory service level to the shipping lines, and on the other hand reduces the total costs for the terminal operator as much as possible.

Since fast computers are nowadays available which are capable of solving relatively large size problems, optimization techniques have become suitable for efficient container port planning. Descriptions and classifications as well as solution methods for the planning of the main logistics processes in container ports are given in [Steenken et al., 2004], [Vis & de Koster, 2003] and [Rashidi & Tsang, 2006]. In these studies, the so-called Berth Allocation Problem (BAP) is defined as one of the key issues in container port planning. A distinction is made here in between two cases of the BAP:

A the single-terminal BAP: concerned with the allocation of vessels to a single terminal,

B the multi-terminal BAP: concerned with the allocation of vessels to a cluster of terminals.

The single-terminal BAP is considered in more detailed now. After that, the multi-terminal BAP is considered.

Single-terminal BAP

Over the last 2 decades, many researches have been conducted towards the single-terminal BAP. In the single-terminal BAP two interrelated problems are solved: the allocation of each vessel to a position in the terminal and the allocation of a berth time interval to each vessel. After the single-terminal BAP has been solved the following information from the strategic planning is known:

- **I** the vessel's berthing terminal,
- **II** the vessel's berth position in the terminal,

III the vessel's berth time intervals, i.e. its arrival and departure time.

Note that in the single-terminal BAP, I does not have to be solved.

The single-terminal BAP can be represented as a two dimensional packing problem, where the vessel is represented as a small rectangle with the dimensions vessel length and berth time. These small rectangles which represent the vessels, have to be placed into a larger rectangle with dimensions terminal quay length and time. The small rectangles have to be orientated such that they never overlap each other, and never cross the boundaries of the large rectangle.

The berth time interval of a vessel depends on the amount of containers that has to be loaded and unloaded and the number of quay cranes that is allocated to the vessel during the berth time interval. In order to calculate the berth time interval in the single-terminal BAP such that the quay crane capacity is not exceeded, a continuous approximation of the quay crane allocation is usually incorporated.

In general, the objective of the single-terminal BAP is to minimize the total weighted handling time and / or to minimize the maximum number of quay cranes used over time. For more information about the single-terminal BAP and for methods to solve this problem, see for instance: [Park & Kim, 2003], [Imai et al., 2001], [Li et al., 1998], [Nishimura et al., 2001], [Hansen et al., 2008], [Kim & Moon, 2003] and [Wang & Lim, 2007].

After the single-terminal BAP is solved, the quay crane allocation, (IV of the strategic planning)

still needs to be determined. For this, the so-called Quay Crane Allocation Problem is solved. The approach which has been described here results therefore in two subproblems to obtain the strategic planning for a single-terminal container port. The Quay Crane Allocation Problem is briefly explained after the multi-terminal BAP has been treated.

Multi-terminal BAP

According to [Ottjes et al., 2006] hardly any research has been conducted towards the multiterminal BAP. However, due to the increased containerization, the container terminal operators often have to manage multiple container terminals in a sea port in order to process all the vessels. Therefore, the vessels have to be allocated to different terminals. The way in which the vessels are allocated to the terminals in the strategic planning, has consequences for the total amount of inter-terminal traffic that is required. In case a certain amount of containers coming from one vessel has to be transshipped to another vessel which is in a different terminal, then inter-terminal traffic is required, see Figure 1.1. This inter-terminal traffic is established by trucks and introduces additional costs for the container terminal operator.

In general the inter-terminal traffic needs to be minimized, because that reduces the costs



Figure 1.1: Graphical representation of a multi-terminal container port.

for the terminal operator. Furthermore, it is desirable to balance the workload over the available terminals, such that the available capacity is efficiently utilized. Due to these factors, the allocation of vessels to the terminals becomes dependent, and a multi-terminal BAP has to be considered. In [Hendriks, 2007], the multi-terminal BAP is formulated as a Mixed Integer Linear Program (MILP). In this formulation, the following information of the strategic planning is determined:

I the vessel's berthing terminal,

III the vessel's berth time intervals, i.e. its arrival and departure time.

Although the multi-terminal BAP does not allocate the exact vessel positions and the specific quay cranes in the terminal to the vessels yet, the following constraints in the multi-terminal BAP have to be taken into account:

- prevention of berthing terminal capacity exceedings,
- prevention of quay crane capacity exceedings.

If these are not guaranteed, it is possible that the berth time intervals of the vessels in the terminals are determined such that no feasible position allocation or quay crane allocation can be constructed. In order to prevent berthing terminal capacity exceedings, it is required that:

• the sum of the length of all vessels berthing at a certain terminal does not exceed the total length of that terminal at all time.

As long as the berth utilization in the terminal is not very high, this measure prevents exceedings of the terminal quay length, see [Karsemakers, 2008]. However, this restriction is only a necessary condition, (not sufficient) to prevent the exceeding of the terminal quay length at all times. An example of this is presented later on.

In order to prevent a quay crane capacity exceeding, the multi-terminal BAP roughly allocates the available quay crane capacity to the berth time intervals of each vessel:

• a continuous approximation is used for the allocation of quay cranes to the berth time intervals.

Each terminal has a limited number of quay cranes available, which all have the same average process rate. Furthermore, there is an upper bound on the number of quay cranes that can simultaneously process a vessel, which specifically depends on the vessel type that is processed. Although the allocation of continuous quay cranes prevents quay crane capacity exceedings in most cases, this is not always guaranteed. In certain cases, additional measures have to be taken such that the quay crane capacity does not become insufficient to process the vessel during the berth time interval. These additional measures are discussed later on.

The objective in the multi-terminal BAP is to minimize:

- 1. the maximum number of continuous quay cranes ever required in each terminal,
- 2. the inter-terminal traffic,
- 3. the tardiness with respect to the reference arrival and departure time of each vessel.

For more detail information regarding the multi-terminal BAP, see [Hendriks, 2007].

Approach

After the multi-terminal BAP has been executed, the following steps still need to be executed in order to obtain the strategic planning:

II the vessel's berth position in the terminal (calculated by the Position Allocation Problem),

IV the allocation of the quay cranes to the vessel (calculated by the Quay Crane Allocation Problem).

This approach, proposed in [Hendriks, 2007], results therefore in solving 3 subproblems to obtain the strategic planning for the multi-terminal container port. For convenience, an overview of the 3 subproblems is depicted in Figure 1.2. The dotted line in between sub problem 1 depicted in the upper layer, and subproblem 2 and 3 depicted in the lower layer, implies that in the upper layer a multi-terminal problem is considered, and in the lower layer the problems can be solved by considering multiple single-terminal problems independently.



Figure 1.2: Overview of the 3 subproblem approach for the calculation of a strategic planning for a multi-terminal container port.

Position Allocation Problem

In [Karsemakers, 2008], a MILP has been formulated which solves the PAP, which is the second subproblem of the approach, see Figure 1.2. Since the vessels already have been allocated to the terminals by the multi-terminal BAP, the PAP can be used to allocate the vessels to a position in the terminal, for each terminal independently.

As the input for the PAP, the berth time intervals of the vessels are used. Since these berth time intervals remain fixed in the PAP, the PAP is reduced to an independent one dimensional packing problem where only the vessels' berth positions (II) in the terminals have to be determined. Two important constraints in the PAP are:

- a vessel is not allowed to change from berth position once it starts berthing at a certain position,
- vessels which berth simultaneously along the terminal quay cannot overlap in position.

The objective in the PAP is to minimize the total weighted deviation from the lowest cost berthing position of the vessels in the terminal.

1.3. Literature

Due to the chosen cut to allocate the berthing terminal and the berth time interval of each vessel separately from its position in the terminal, see Figure 1.2, it is not always possible to construct a feasible position allocation in the PAP from the output of the multi-terminal BAP. This statement is now illustrated in Example 1.1.

Example 1.1 Feasibility problem in PAP

This is an example where the PAP becomes infeasible [Karsemakers, 2008]. The arrival and departure times of the vessels in this terminal are fixed and determined by the multi-terminal BAP. It is assumed that the arrival pattern of the vessels is cyclic over time. The objective in this example is to find any possible feasible position allocation for the vessels allocated to this terminal, given the calculated berth time intervals calculated by the multi-terminal BAP.

The given output of the multi-terminal BAP consists of the berth time intervals of the 5 vessels that are allocated to this terminal. The arrival and departure times and the lengths of these vessels are depicted in the left of Figure 1.3. Note that vessel E starts to berth at the end of the cycle, and departs at the beginning of the cycle.

It can be verified that the sum of the length of the vessels is less than or equal to 300 meters at all time. However, when a position allocation is tried to construct with this data, the conclusion can be drawn that no feasible position allocation exists for a terminal length of 300 meters. For these given berth time intervals, the terminal quay length is too small to position these vessels along the terminal quay at the given times.

Although the sum of the length of the vessels is always equal to or less than 300 meters, the terminal length has to be at least 400 meters in order to construct a feasible strategic position allocation for this data calculated by the multi-terminal BAP. A possible feasible solution of the PAP with this input data and a terminal length of 400 meters is depicted in the right of Figure 1.3.



Figure 1.3: On the left side of this figure, 5 different vessels are depicted with their lengths, arrival times and departure times. On the right side of this figure, a feasible strategic position allocation for a terminal length of 400 meters is depicted.

 \boxtimes

In case the solution to the PAP becomes infeasible, the settings in the multi-terminal BAP have to be reconsidered and a new calculation needs to be performed. Feasibility problems in the PAP such as explained in Example 1.1 are more likely to occur when the position utilization in the terminal is relatively large. However, in real life terminals the position utilization is usually not very large. Therefore, the approach can be used for most real life planning strategies without facing any problems. For more detailed information about the PAP and the mathematical formulation, see [Karsemakers, 2008].

Quay Crane Allocation Problem

Once the berth time intervals and positions of the vessels are known in the terminals, the quay cranes have to be allocated to the berthing vessels in the terminals, see Figure 1.2. In [Karsemakers, 2008], a MILP has been formulated which solves the QCAP for one terminal at a time. This formulation can therefore be used as the third subproblem in the approach depicted in Figure 1.3, but it can also be used to solve the QCAP after the single-terminal BAP has been solved. The main constraints in the QCAP are:

- a restricted number of quay cranes in the terminal,
- quay cranes can move along the quay but cannot cross each other because they are situated on the same track.

Depending on the situation that is considered, the quay cranes can have different processing capacities. The objective in the QCAP of [Karsemakers, 2008] is to allocate the available quay cranes to the vessels during their berth time interval such that the following weighted costs are minimized:

- 1. the maximum number of required quay cranes in the terminal,
- 2. the processing time of the vessels,
- 3. the number of quay crane switches in between vessels.

Feasibility problems can arise in the QCAP as a result of berth time intervals which are calculated too short in the multi-terminal BAP. The reason for this is that the berth time intervals are based on a continuous quay crane approximation, and the QCAP calculates an integer quay crane allocation. This means that the berth time interval needs to be wide enough in order to prevent a quay crane capacity exceeding in the QCAP.

This is in practice not a problem, because the berth time intervals for the strategic planning need to be determined with a sufficiently large safety margin in process time. This safety time is needed because this strategic planning is used as a reference for operational planning, where disruptions are present.

For more detailed information about the QCAP, see [Karsemakers, 2008]. After the QCAP has been successfully executed, the strategic planning $(\mathbf{I} - \mathbf{IV})$ is obtained.

Discussion

The reason for cutting the calculation of the strategic planning into 3 subproblems such as depicted in Figure 1.2, is to reduce the complexity of the models and accompanying calculation time. Idealistically, $(\mathbf{I} - \mathbf{IV})$ of the strategic planning should be calculated simultaneously in one model to prevent position infeasibilities such as described in Example 1.1 and possible infeasibilities due to insufficient quay crane capacity. However, this would result in an unacceptable and unpractical large computation time for the size of real life problems. By solving the 3 subproblems separately such as discussed above, still acceptable and practical calculation times are obtained, [Hendriks, 2007] and [Karsemakers, 2008]. So at this point, the cut into 3 subproblems seems inevitable when a multi-terminal container point is considered.

After the multi-terminal BAP, the PAP, and the QCAP have been successfully executed such that no infeasibilities have occurred, the cyclic strategic planning for the multi-terminal container port is obtained. This cyclic strategic planning can be used as a reference planning for the operational planning of the container port. The operational planning of the multi-terminal container port is the subject of the remainder of this report.

1.4 Contributions and outline

So far the container port has been examined on a strategic level. As explained, a new 3 subproblem approach has been suggested in [Hendriks, 2007] in order to obtain a strategic cyclic planning for a multi-terminal container port. Once the cyclic strategic planning is obtained, it is used as a reference planning for the operational planning of the container port. However, due to disruptions present in a container port, it is possible that the reference planning becomes infeasible for the current planning of the operations. In that case, a re-planning procedure is needed.

Contributions

For the re-planning procedure, a similar 3 subproblem approach is used as presented in Figure 1.2. If the 3 subproblem approach is fast enough, the re-planning procedure can be used as a decision support tool for real-time operational planning. The first main contribution of this report can now be formulated as follows:

1 A decision support tool for real-time operational container terminal planning is developed. This tool is based on a Model Predictive Control (MPC) strategy and consists of 3 interrelated subproblems.

Although the 3 subproblems implemented in the decision support tool have similarities with the 3 subproblems described on a strategic level, these subproblems have different formulations and should therefore not be confused with the 3 subproblems explained earlier. The three subproblems in the decision support tool are formulated as a MILP and are defined as:

- 1. the Time Allocation Problem (TAP),
- 2. the Position Allocation Problem (PAP),
- 3. the Quay Crane Allocation Problem (QCAP).

Since in reality a vessel does usually not change from its reference berthing terminal, this is also assumed here. Therefore, the first subproblem (now referred to as the TAP) does not have to allocate the vessels to a terminal anymore. This results in a large computational advantage, because each subproblem in the decision support tool can be executed independently for each terminal. A short calculation time makes the decision support tool suitable for real-time operational planning. According to the MPC strategy, the operational planning is calculated over a certain planning horizon. The length of the planning horizon in the decision support tool is in the order of days. So a short term operational planning is calculated by the decision support tool.

In order to test the performance of the decision support tool, it is connected to a simulation model which simulates the main operations in the multi-terminal container port. This leads to the second contribution of this research:

2 The performance of the decision support tool is tested in a container port simulation environment for various tool settings and strategies. The performance of the decision support tool is measured according to the following 3 performance indicators:

- A the vessels' delay in departure,
- **B** the total driving distance that the straddle carriers have to travel to transport the containers,

C the number of resources that is required on average during a shift.

The first performance indicator is a measure for the service level that is provided to the shipping line, whereas the second and third performance indicator is used to measure the operational costs for the terminal operator.

Of course an important issue is the stability of the decision support tool. Due to the chosen cut of subproblems, measures are required to prevent infeasibilities as a result of berth capacity and quay crane capacity exceedings. And due to stability issues in MPC also measures are required to prevent instabilities. The stability of the decision support tool is also tested under different circumstances.

This research is supported by the terminal operator PSH Hesse-Noord Natie, located in Antwerp, Belgium, where a multi-terminal container port is in operation.

Outline

The report is structured as follows: In Chapter 2 the Simulation Environment is treated in detail. First, the structure of the simulation environment is briefly discussed in section 2.1. Then in section 2.2. the simulation model assumptions are given. Subsequently, in section 2.3 the different disruptions/disturbances considered in the simulation model are discussed. In the last section of Chapter 2, the tactical agreements between the terminal operator and shipping lines are formulated.

In Chapter 3 the decision support tool for operational planning, referred to as the Planning Controller, is considered in detail. First, a brief introduction in Model Predictive Control (MPC) theory is given in section 3.1, which is followed by the specific application of MPC theory in the design of the Planning Controller. In section 3.2, certain definitions are made which are required for the remainder of the report. In section 3.3, the stability issues in the Planning Controller are discussed. Of particular interest are stability issues due to horizon length, berth positions and quay crane capacity. In the section 3.4, the TAP is formulated. First the system description of the TAP is given, followed by a detailed description of the objectives in the TAP. Then the mathematical formulation of the TAP is given. In section 3.5 the PAP is formulated, where first the system description is given followed by the mathematical formulation of the PAP. Chapter 3 is concluded with the QCAP in section 3.6, where the system description of the QCAP is given. In chapter 4, the simulation experiments are formulated and the results are discussed. First, an experimental set up is given in section 4.1. Subsequently, in section 4.2 two different positioning strategies are compared which influence the resulting straddle carrier driving distance that is needed to transport the containers in the terminal. In section 4.3, experiments are performed which test the different tuning parameters in the Planning Controller. These tuning parameters influence the quay crane usage, and the vessel departure times. The influence of these tuning parameters are tested in a sensitivity analysis, and are eventually compared with each other. In section 4.4 the stability of the Planning Controller is tested in an exceptional recovery case. In section 4.5 the calculation time of each sub problem is considered.

Finally a conclusion is given with recommendations for future research.

Chapter 2

Simulation environment

In this chapter the simulation environment is treated. This environment is needed to test the decision support tool. In section 2.1, an overview of the simulation environment is given. In section 2.2, the simulation model assumptions are given. The disturbances present in the simulation model are discussed in section 2.3. This chapter is concluded with section 2.4, where the agreements between the terminal operator and shipping lines are treated.

2.1 Overview

In Figure 2.1 an overview of the simulation environment, represented here at the highest abstraction level, can be found. The upper block in the figure represents the simulated reality of the container port, which is referred throughout the report to as the simulation model. The lower block in the figure represents the decision support tool, which is throughout the report referred to as the Planning Controller.



Figure 2.1: Overall structure of the simulation environment.

In the simulation model and Planning Controller, a discrete time setting is considered (time slots). In order to know how the operations for the current time slot have to be executed, a new planning needs to be calculated. This is executed by the Planning Controller. The Planning Controller is based on Model Predictive Control theory. At the beginning of each discrete time slot, the simulation model sends information about the current and forecasted state of the port and vessels to the Planning Controller. Then the Planning Controller calculates the operational plan over a certain horizon in the future. After the calculations in the Planning Controller have been successfully executed, the operational plan for the current time slot (current executions) is sent back to the simulation model.

The Planning Controller is the subject of Chapter 3. In this chapter, the simulation model of the port is treated. In the next section, the assumptions of the simulation model are discussed.

2.2 Model assumptions

The discrete event model is formulated in the language Chi. For detailed information about the programming language Chi, see [Hofkamp & Rooda, 2002] and [Vervoort & Rooda, 2004]. The main events that occur in reality in a container port are modeled at relative high abstraction level in the simulation model. Only those events which are necessary to test the Planning Controller are incorporated in the simulation model. The following events are therefore modeled in the simulation model:

- the arrival of vessels,
- the vessels berthing along the terminal quay,
- loading and unloading of the vessels by quay cranes,
- transportation of the containers in the terminal by straddle carriers.

The assumptions that are made for these events are discussed now in the order as stated above.

Arrival time assumptions

Initially, each vessel is expected to arrive according to its reference arrival time. However, as the vessel is approaching the port it becomes gradually clear what the actual arrival time is. This arrival information becomes available through forecasting. As the vessel arrives closer to the port, updated and more accurate forecasts become available. In reality, these predictions about the arrival times are obtained by communication with the vessels or shipping lines. In the simulation model, these forecasts are generated by introducing disturbances on the arrival times is and containers. How these forecasts in the model are generated by disturbing the arrival times is explained in more detail in section 2.3.

Berth assumptions

Once a vessel has arrived at the port, the vessel can start berthing. It is possible that the vessel has to wait a certain amount of time before it can actually start berthing, dependent on the decisions made by the Planning Controller. The vessel berths at a certain position in the terminal which is allocated by the Planning Controller. As soon as the vessel starts to berth at a position in the terminal, it cannot move from position anymore. It is assumed that a vessel requires time to start berthing at the terminal, and to leave the terminal. During this berthing and departure event, the vessel cannot be processed.

Vessel processing assumptions

As soon as the vessel is berthing along the terminal quay, the quay cranes can start loading and unloading the vessel. How many and which quay cranes process the vessel is determined by the Planning Controller.

The event of loading and unloading of each individual container on and off the vessel is not modeled in high detail in the simulation model. For instance, which specific container is exactly being handled at a certain point in time is not considered in the model. It is assumed that each quay crane has a certain average process rate.

Certain vessels can be loaded and unloaded more efficiently than others. Larger vessels can usually be processed more efficiently, and therefore have a higher process efficiency factor. Depending on the specific quay cranes that process a vessel, a certain amount of work is assumed to be processed each hour. After a vessel has been fully processed, it leaves the terminal. The actual departure time of such a vessel is recorded and the vessel is at that point not considered in the simulation model anymore.

Container transportation assumptions

Each vessel is expected to load and unload a certain number of containers, which is indicated by Q_v . These containers are transported by straddle carriers from their source location to their destination location. At which point in time each specific container is transported by a straddle carrier is not modeled specifically in the simulation model. It is assumed that by processing the vessel the relevant containers are eventually all transported from source to destination.

It is assumed that a sufficient number of straddle carriers is in operation, such that the quay crane rate is a valid assumption. However, if the total driving distance is large, then more straddle carriers are required to obtain a certain process speed. Therefore, the total driving distance that the straddle carriers have to travel to load and unload a vessel is measured in the simulation model.

In order to measure the straddle carrier driving distance, the source and destination of each container needs to be known. The source and destination of each container is dependent on the berth position of the vessel and the stack position of a certain container type. This implies that the container type needs to be known in order to know where the container is transported to. The different container types that are considered in this report are defined next.

Container type definitions

The containers are first divided into the following 3 main categories:

- import containers,
- export containers,
- transshipment containers.

Depending on the category, a container is transported by a straddle carrier from vessel to vessel (transshipment), from vessel to container stack (import), or from container stack to the vessel (export).

The import containers are unloaded from the vessel and are (temporarily) stored in certain stacks on the terminal from where they can continue their journey land inwards. The export containers are located in stacks on the terminal and have to be loaded onto the vessel from where they leave the port. Transshipment containers can be loaded as well as unloaded from the vessel. Each transshipment containers is first unloaded from a vessel and temporarily stored in the terminal from where it later is loaded onto a different vessel. So each transshipment containers is always handled twice by a quay crane (unloading and loading). Transshipment containers which have been brought in by other vessels and which are destined for vessel v are temporarily stored in the terminal until vessel v arrives.

The import and export containers are now further divided into the following 5 container types:

- 1. reefers (cooled goods),
- 2. imco's (hazardous goods),
- 3. regular (regular goods),
- 4. empty 1,
- 5. empty 2.

This results in combination with the transshipment containers in a total of 11 different container types.

If the positions of the container stacks in the terminal and the positions of the vessels along the terminal quay are known, then the travel distance of each container can be reconstructed in the model. For this, the model measures the travel distance for each container by using functions. For each container type, a function is available which gives the transportation distance as a function of the vessel position along the terminal quay. These functions can be obtained by taking measurements in a real life terminal for instance. In Chapter 4, a case is observed where straddle carrier travel distance functions are used, which are obtained from real life terminal measurements. Since no real life data about the container types are available, an assumption needs to be made about how the container types are distributed for each vessel. For the remainder of this report it is not necessary to formulate this procedure here. However, for a detailed description of the approach that is used to generate the container data for each vessel in the strategic planning, see Appendix A.

The reference planning contains the information about the planned arrival time of each vessel and about the planned number and type of containers that have to be handled for each vessel. Although a vessel is expected to arrive at the time as stated in the reference planning, and a vessel is expected to load and unload the container freight such as stated in the reference planning, it is possible that the actual arrival time and container freight deviates from the reference planning. These deviations are in reality forecasted for each vessel. Therefore, these forecasts are also generated in the model. How these forecasts are generated is explained in the next section, where the disturbances in the model are treated.

2.3 Disturbances

In this section, the disturbances present in the simulation model are treated. Three different disturbances are considered:

- disturbances on vessel arrival times,
- disturbances on the container freight,
- disturbances on quay cranes.

These three disturbances are now considered successively.

2.3.1 Arrival times

Initially, at the start of the simulation, each vessel in the simulation model is expected to arrive such as stated in the reference planning. As the vessels are approaching the port, the arrival times are under the influence of disturbances. In reality, the actual arrival time of a vessel is dependent on many factors, such as weather conditions and previous port visits. Usually, the management of the port receives forecasts from the vessels about their expected arrival time. These forecasted arrival times can then be used to adapt the planning if necessary.

In the model, it is assumed that the information about these disturbances in arrival times becomes available by forecasts. These forecasted arrival times can then be used in the Planning Controller to calculate the operational planning.

It is assumed in the model that disturbances in arrival times are generated at three moments in time. The information about these disturbances becomes then available, from which the new forecasted arrival time is obtained.

The first arrival disturbance / forecast is generated 3 days prior to the vessel is expected to arrive at the port, i.e. 3 days prior to its reference arrival time A_v^* . So before this first forecast is received, the vessel is expected to arrive at its reference arrival time A_v^* , such as stated in the reference planning. The first forecast is generated in the data generator as follows. A disturbance is generated by drawing a random value χ_v^1 from a normal distribution with mean A_v^* and a standard deviation σ_v^1 . Since there is an upper and lower bound on the disturbance χ_v^1 , the normal distribution is truncated. The first forecast, A_v^1 , is then obtained by: $A_v^1 = A_v^* + \chi_v^1$.

An example of how the model generates the first forecast is graphically depicted in the first time line of Figure 2.2. In this example a time slot represents 3 hours. The reference arrival time of this vessel is located at day 11 at 0:00 hours. The depicted normal distribution is in this case lower bounded by -8 time slots and upper bounded by +8 time slots (which is -1 day and +1 day). The first forecast of the expected arrival time lies in this example always within the following time interval: $A_v^* - 8 \le A_v^1 \le A_v^* + 8$. These bounds are indicated in Figure 2.2 by a grey box around A_v^* . In this example $\chi_v^1 = 6$ time slots. Hence, the vessel is expected to have a delay of 18 hours, and the first forecast arrival time becomes: $A_v^1 = \text{day 11}$ at 18:00 hours.

The second forecasted vessel arrival time, indicated by A_v^2 , is received around 2 days prior to A_v^1 . The second disturbance χ_v^2 is calculated by drawing a random value from a normal distribution with mean A_v^1 and a standard deviation σ_v^2 . Since the accuracy of the forecast in general improves as the vessel gets closer to the port, $\sigma_v^2 < \sigma_v^1$. Also the upper and lower bound on the second disturbance χ_v^2 becomes smaller.

In the second time line of the example, depicted in Figure 2.2, the normal distribution is lower bounded by -5 and upper bounded by +5. Hence, the second forecast of the actual arrival time lies in this example always in the following time interval: $A_v^1 - 5 \le A_v^2 \le A_v^1 + 5$. In this example, the vessel is expected to arrive 3 time slots later than the first forecast. The second forecast becomes then $A_v^2 = A_v^* + \chi_v^1 + \chi_v^2$, which in this case results in $A_v^2 = \text{day } 11 + 18$ hours + 9 hours = day 12 at 3:00 hours.

The third and final forecast of the arrival time of the vessel, indicated by A_v^3 , is received 1 day prior A_v^2 . The third disturbance χ_v^3 is then calculated by drawing a random value from a normal distribution with mean A_v^2 and a standard deviation σ_v^3 . Since the accuracy of the forecast in general has improved, the standard deviation of the last disturbance is the lowest: $\sigma_v^3 < \sigma_v^2 < \sigma_v^1$. In the example of Figure 2.2 the normal distribution is lower bounded by -2 and upper bounded by +2. Hence, the third forecast of the expected arrival time lies in this example in the following interval: $A_v^2 - 2 \le A_v^3 \le A_v^2 + 2$. In this example $\chi_v^3 = 1$ time slot. The third forecast becomes then $A_v^3 = \text{day } 11 + 18$ hours + 9 hours - 3 hours = day 12 at 0:00 hours. In this example, the total delay in arrival is exactly 24 hours (1 day).

After the third forecast is received from a vessel, it is assumed that the vessel arrives according to this last forecast. This implies that the third forecast is equal to the actual arrival time of the vessel: $A_v = A_v^3$. As depicted in the fourth time line of Figure 2.2 the vessel arrives exactly on day 12 at 0:00 hours, and arrives therefore 1 day later than stated in the reference planning.

This procedure is applied to each vessel as it approaches the port. Note that the 3 forecasted



Figure 2.2: Introducing disruptions in the arrival time of a vessel. At 3 moments in time, a disturbance on the arrival time is generated from which a new updated forecasted arrival time is obtained.

arrival times are actually directly obtained from the 3 disturbance moments. This however, does not mean that the predictions are exact. Only the last arrival prediction is in fact equal to the actual arrival time of the vessel. The initial reference arrival forecast, and the first and second updated arrival forecast can (and are likely to) be different from the actual arrival time. This procedure corresponds to what happens in reality where the arrival time of the vessel can be predicted more accurately as the vessel comes closer to the port.

Each vessel always provides 3 forecasts about its (expected) arrival time. Note that the disturbance at each point must always be lower bounded by -1 day and upper bounded by + 1 day. If $|\chi_v^1| > 1$

day or $|\chi_v^2| > 1$ day, then the next forecast/disturbance moment is skipped. If $|\chi_v^3| > 1$ day, then it is possible that the vessel already has arrived before the forecast has even been received. This would not make any sense. Therefore the disturbance level of the arrival time is bounded at each disturbance moment.

2.3.2 Containers

Although each week similar vessels arrive in the port which are expected to load and unload a certain container freight, it is possible that the actual container freight (in numbers and types) deviates from the reference planning. In reality, the number and type of containers that have to be loaded and unloaded depend on the number and type of orders that the shipping line has received from its customers, and depend on the events during previous port visits. Usually, the port management receives information about these container load fluctuations from the vessel or shipping line. With this information, the terminal operator can adapt the operational planning if this is necessary.

In the model, it is assumed that a disturbance on the container freight is introduced at the same 3 moments in time as when a disturbance on the arrival time is generated. From this container freight disturbance, a new container forecast is obtained, which can be used by the Planning Controller to calculate the operational planning.

Before the first container disturbance is generated, the vessel is expected to load and unload the number and type of containers such as stated in the reference planning. Then at each disturbance moment, the total number of containers, Q_v , is disturbed first, followed by a disturbance in the distribution of container types. By modeling the disturbances in this way, it is possible to run simulations where the disturbances in the total number of containers are for instance lowly variable, and the disturbances on the container types are highly variable.

The level of variance in the disturbance of the total number of containers is set by the coefficient of variation α_i , and the level of variance in the disturbance of container types is set by the coefficient of variation β_i , where $i \in \{1, 2, 3\}$ indicates the first, second and third disturbance moment respectively.

It is likely that the container forecast becomes more accurate as the vessel approaches the port. Therefore, the coefficients of variation become lower as a subsequent disturbance for the vessel is generated: $\alpha_1 \geq \alpha_2 \geq \alpha_3$, and $\beta_1 \geq \beta_2 \geq \beta_3$.

After the third and last container disturbance is generated it is assumed that the container freight of the vessel does not change anymore. Similar to the arrival forecasts, after the last container freight disturbance has been generated, the container forecast becomes exact.

For a more detailed description of the container freight disturbance procedure, see Appendix B. For the remainder of the report it is not necessary to explain this procedure in more detail now.

2.3.3 Quay cranes

In reality, a quay crane can be down due to malfunction. Furthermore, a quay crane can be kept down due to scheduled maintenances. In the model these disturbances on quay cranes can also occur. A scheduled maintenance is usually known beforehand, and can therefore be forecasted. The advantage of this is that this information can be sent to the Planning Controller ahead of time, which can react accordingly to this down time in the future. However, disturbances such as quay crane break downs cannot be forecasted because these occur suddenly.

Due to the disturbances discussed throughout this section, strict agreements need to be made about how to handle in certain situations. In the next section, the agreements which are made between the terminal operator and shipping line are discussed.

2.4 Agreements

In this section, the agreements made between the terminal operator and shipping line are given. The agreements about arrival times are treated first. Then the agreements about the berthing terminal are discussed.

Vessel arrival time agreements

The agreements which are made between the terminal operator and the shipping lines determine the reference arrival and departure times of the vessels in the strategic planning, indicated by A_v^* and D_v^* respectively. The time span between the reference arrival and departure time is defined as the maximum process time of a vessel: $P_v^{max} = D_v^* - A_v^*$.

As explained, the actual arrival time of a vessel v, indicated by A_v is dependent on many factors such as weather conditions, the number of containers that had to be handled during previous port visits, etc. In practice, it is not always possible to arrive exactly at the reference arrival time. Therefore, agreements are made between the terminal operator and the shipping line which define when a vessel is on time. A so-called arrival window is introduced which defines when the arrival time of a vessel is still considered "on time". With this arrival window, the following definition is made to indicate when a vessel is "on time", "early", or "late":

- **Early:** When a vessel v arrives / has arrived early and outside the arrival window, i.e. when: $A_v < A_v^* - |C_v|.$
- **On time:** When a vessel v arrives / has arrived within the arrival window, i.e. when: $A_v^* - |C_v| \le A_v \le A_v^* + |C_v|.$
- Late: When a vessel v arrives / has arrived late and outside the arrival window, i.e. when: $A_v > A_v^* + |C_v|.$

For the remainder of the report, this definition is used. The width of the arrival window, indicated by $2 \cdot |C_v|$, depends on the specific agreement that is made with each shipping line. Usually, shipping lines have agreements for $|C_v| = 4$ hours. However, certain shipping lines agree on a larger arrival window.

This definition is used to determines whether the terminal operator must guarantee a certain departure time or not. The terminal operator guarantees an upper bound on the departure time whenever a vessel arrives early or on time. This upper bound is indicated by the maximum departure time D_v^{max} . If a vessel arrives within the arrival window, the terminal operator guarantees the shipping line that the vessel is processed within a time span of P_v^{max} , which is exactly the original time span between A_v^* and D_v^* . So, the maximum departure time of a vessel which arrives somewhere within the arrival window is defined as: $D_v^{max} = A_v + P_v^{max}$. In this case, D_v^{max} lies always within a so-called departure window which can be defined as: $D_v^* - |C_v| \leq D_v^{max} \leq D_v^* + |C_v|$. In Figure 2.2 a graphical representation can be found of the maximum departure times that are guaranteed by the terminal operator for different arrival scenario's. The time is stated on the horizontal axis, and the vertical axis has no dimension. Scenario's A through E represent vessels which arrive on time (the actual arrival time lies within the arrival window). As can be seen, the maximum process time is always equal to P_v^{max} and the maximum departure time lies always within the departure window.

When a vessel arrives early, i.e. earlier than the arrival window, the terminal operator guarantees a maximum departure time of $D_v^{max} = D_v^* - |C_v|$. In this case, the maximum departure time is always at the minimum of the departure window. This implies that a larger maximum process is allowed than P_v^{max} . This is an advantage for the terminal operator, because the flexibility in time increases. The vessel can start berthing earlier if this is desirable. Scenario F in Figure 2.2 indicates the location of the maximum departure time for a vessel which has arrived early.


Figure 2.3: Arrival and departure agreements.

The delivered service level is dependent on the departure time of a vessel. In general, the earlier the vessel can depart, the higher the delivered service level. If a vessel has arrived on time or early and it departs later than the maximum departure time D_v^{max} , then the goodwill of the terminal operator decreases. Therefore, a violation of these agreements should always tried to be avoided. If a vessel has arrived late, then there exists no maximum departure time. In that case, the container terminal operator does not have to guarantee any maximum departure time. Scenario G in Figure 2.2 indicates that no maximum departure time is guaranteed if a vessel has arrived late. Of course a realistic and acceptable departure time must tried to be obtained for these vessels in order to increase the goodwill of the terminal operator.

Berthing terminal agreements

In case of a multi-terminal container port, the agreement between the terminal operator and shipping line does also determine in which terminal the vessel berths. Therefore, the berth terminal is not freely chosen on an operational level. This however, is not a major limitation. In the reference planning the vessels have been allocated to the terminals such that the costs for interterminal traffic are minimized. Furthermore, a large amount of the containers that are destined for a certain vessel are already stacked in the reference terminal. If a vessel is suddenly allocated to a different terminal than stated in the reference planning, then these containers all have to be transported from the reference terminal to the different terminal. This would introduce large transportation costs and would be very time consuming. Therefore, it is reasonable not to change from the reference terminal. In general, there are no agreements about the specific berth position in the terminal. Therefore, the berth position in the terminal can be freely determined by the terminal operator.

Now the simulation model has been discussed, and the agreements between the terminal operator and shipping line are known, the Planning Controller is investigated. The Planning Controller is the subject of Chapter 3.

Chapter 3

Planning controller

In this chapter, the Planning Controller is explained in detail. The Planning Controller is based on a Model Predictive Control strategy. In the first section of this chapter the general principle of MPC is given, followed by the overall implementation of MPC in the Planning Controller. In section 3.2, certain definitions required for the remainder of this chapter are given. In section 3.3, the stability of the Planning Controller is discussed. The first subproblem of the Planning Controller, called the Time Allocation Problem, is treated in section 3.4. In section 3.5, the second subproblem of the Planning Controller is given, which is called the Position Allocation Problem. Finally, in section 3.6, the last subproblem of the Planning Controller is discussed, which is called the Quay Crane Allocation Problem.

3.1 Model Predictive Control

3.1.1 General Principle

The Model Predictive Control (MPC) theory originated in the late 1970s, when various articles appeared showing an incipient interest in MPC in the industry. Since then, MPC became increasingly popular in the industry as well as in the scientific world. At first, MPC appeared to be a very useful control technique for linear and rather slow systems. Therefore MPC was often encountered in the process industry. However, more recent scientific results show impressive results for the implementation of MPC in fast processes, as well as in non-linear or hybrid systems. In this report only a general overview of MPC is given. For details and various formulations of MPC, see [Camacho & Bordons, 2004] and [Rossiter, 2003].

MPC does not designate a specific control strategy, but represents a wide range of control techniques which make specific use of a model of the system to predict future system behavior, and where an objective function is used to obtain the future control inputs of the system. In general, the following ideas specifically characterize the MPC strategy:

- The control law depends on predicted behavior of the system over a certain time horizon.
- The output predictions are computed using a model of the system.
- The future control sequence is calculated by minimizing an objective function.
- A receding horizon is used which means that at each time instant the horizon is displaced towards the future, where the future control sequence is updated and where only the current control action is actually used as the input of the system.

The main advantage of using predictions of the system's behavior, is that the current control action is not only based on the current state of the system, but also explicitly on the future predicted state of the system. In this way the current control action can be determined such that this control action will not lead to poor system performance in the future. In fact, the current input can already react on predicted system behavior in the future. In traditional PID controllers for instance, the control actions are based on the past and current state of the system. The future implications of the current control actions are not taken explicitly into account.

MPC has a strong resemblance with the way in which human beings perform control tasks in daily life. Consider for instance the human activity in driving a car on the road. The driver has a certain reference trajectory in mind, that is the driver knows the desired path on the road for a certain horizon length. The driver has a certain mental model of the car in his mind, which depends on the car characteristics. Depending on this mental model of the car and the information the driver receives from seeing the road ahead, the driver determines the control actions (throttle, brakes, steering) in order to follow the desired trajectory. How far the driver is able to see the road ahead is limited by a certain horizon length. The control actions are determined for the length of this horizon, where predictions about disturbances can be included, such as bumps in the road, the wind force, etc. However, after the control inputs are determined, only the current control action is actually executed, since this procedure is constantly repeated by the driver as the car moves forward. In this way the driver can constantly determine the best current control input with the most accurate information available, which leads to a satisfactory performance now and in the future.

An example of the MPC strategy is depicted in Figure 3.1. In general, MPC is characterized by the following sequence:



Figure 3.1: MPC strategy

1. The future outputs of a system during a prediction horizon H, are determined at each time instant t using a model of the system. The predicted outputs of the system, y(t + k|t), for $k = \{0, \ldots, H\}$ depend on the past inputs and outputs (or the current state of the system), and on the future control inputs u(t + k|t), $k = \{0, \ldots, H - 1\}$.

- 2. The set of future control inputs is calculated by minimizing an objective function, where the predicted outputs are kept as close as possible to the reference trajectory. Depending on the system, the control effort is included in the objective function.
- 3. The control input u(t|t) is sent to the system whilst the next control inputs are discarded. At the next time instant, y(t+1) is exactly known and new information has become available. According to the receding horizon concept, step 1 is repeated with all the updated information. Note that therefore u(t+1|t+1) can be different from u(t+1|t), because updated information is used for the calculation of u(t+1|t+1).

Performance

The performance of a system controlled by an MPC strategy depends mainly on:

- the accuracy of the model of the system,
- the accuracy of disturbance predictions,
- the optimization with cost function and possible constraints to determine the inputs,
- the length of the horizon.

The system model is not limited to linear models such as transfer functions or state space models, but can have many implementations. Furthermore, the model does not always have to be a very precise model of the reality. Even a simple model can lead to very accurate control. Since the control decisions are constantly being updated, the control strategy can deal with some model uncertainty as well as disturbances. In general, if a simple model gives the desired accuracy, then it can be used for the considered control problem.

The optimization is used to determine the optimal control trajectory over the considered horizon. The cost function which is minimized, determines which predicted input trajectory results in the lowest costs. The choice of the cost function depends on the problems considered, and can have various forms. Often a linear or quadratic cost function is used where the difference between the future output and the reference output is minimized over the considered horizon length. Furthermore depending on the control problem, it is possible to take the control effort u or Δu into account in the cost function. Also constraints can be incorporated in the optimization problem. Also here, a simple cost function be chosen if this leads to the desired performance.

An import question in MPC strategy is: how long should the horizon be? A longer horizon could lead to a more accurate control sequence, but this is not guaranteed. However, a longer horizon does lead to a higher computational effort which can become critical in fast systems. Consider for instance the MPC strategy in driving the car on a road again. How long the horizon should be mainly depends on the speed of the car. Imagine if the car drives 120 km/h and the horizon length, which is the distance that the driver can observe, is limited to 15 meter. This horizon length is far under the braking distance, and can lead therefore to severe problems. Therefore, the selected horizon length should include the important dynamics of the system [Camacho & Bordons, 2004]. A last remark is that an appropriate horizon length also depends on the accuracy of the model. It makes no sense to compute the control inputs over a very large horizon length if the model is very poor. On the other hand, if a very accurate model is used and a very short horizon, then this does can also lead to poor performance.

3.1.2 Implementation Planning Controller

In section 2.1. the highest abstraction level of the simulation environment has been treated briefly. As explained, at the beginning of each time slot the simulation model provides the necessary information to the Planning Controller to calculate the operational planning, see Figure 2.1. The principles of the Model Predictive Control theory are applied in the Planning Controller. Then the interaction between simulation model and Planning Controller can be described by the control loop indicated in Figure 3.2.



Figure 3.2: Overview of the MPC control loop with the Planning Controller and the simulation model.

At the current time slot $t = k_c$, the Planning Controller determines the operational planning according to the following information:

- 1. actual and predicted vessel arrival times and containers (state feed-back from simulation model),
- 2. the reference planning,
- 3. the previously calculated operational planning at $t = k_c 1$ (feed-back from planning controller).

Based on this information, the operational planning is determined over a certain planning horizon into the future, see Figure 3.2. Then only the current time slot from the operational planning is sent to the simulation model and is executed.

As explained in Chapter 2, disturbances in vessel arrival times, containers, and quay cranes can occur in the simulated reality. This actual and forecasted information is provided to the Planning Controller. The previously calculated operational planning at $t = k_c - 1$ is used for stability measures and is explained later on.

Internal structure Planning Controller

Now the interaction of the Planning Controller with the simulation model has been defined, the internal structure of the Planning Controller can be considered in more detail. Similar to the 3 subproblem approach discussed in the introduction to calculate a cyclic strategic planning, 3

optimization models are used inside the Planning Controller to calculate the operational planning. The following 3 subproblems, formulated as MILP's, are implemented in the Planning Controller:

- 1. the Time Allocation Problem (TAP),
- 2. the Position Allocation Problem (PAP),
- 3. the Quay Crane Allocation Problem (QCAP).

Although these 3 subproblems have similarities with the 3 subproblems discussed in Chapter 1, these are different formulations and should not be confused with the 3 subproblems explained in Chapter 1.

Besides these 3 optimization problems, a transshipment verification procedure is required. An overview of this transshipment verification procedure with the 3 subproblems connected together to form the Planning Controller, is depicted in Figure 3.3.

The 3 subproblems of the Planning Controller are briefly discussed now. After this, the transshipment verification procedure is explained. Later on in this chapter, the 3 subproblems are formulated in detail where also the mathematical formulations are given.

Time Allocation Problem

The TAP calculates the berth time intervals (arrival and departure times) of the vessels on the planning horizon. Unlike the Multi-terminal BAP used on a strategic level, the TAP does not have to allocate a vessel to a terminal. This is because a vessel does not change from its reference berthing terminal. For the calculation of the berth time intervals of the vessels on the planning horizon, the TAP uses the following input parameters which are available at $t = k_c$:

- actual / forecasted arrival time (from simulation model),
- actual / forecasted contain freight (from simulation model),
- the desired arrival and departure times (from reference planning),
- currently available quay cranes in the terminal (from simulation model),
- the previous berth allocation calculated at $t = k_c 1$ (from Planning Controller).

This is also depicted in Figure 3.3. How this information is exactly used is explained in section 3.4, where the TAP is formulated in detail.

The main objective is to calculate the berth time intervals of the vessels such that the workload is balanced over the planning horizon and/or such that the turn around times of the vessels (and delays in departure) are minimized.

In order to make sure that the calculated berth time intervals in the TAP do not lead to infeasibilities in the PAP or QCAP, the following constraints in the TAP have to be taken into account:

- prevention of berthing terminal capacity exceedings,
- prevention of quay crane capacity exceedings.



Figure 3.3: Internal structure of the Planning Controller with the transshipment verification procedure, the 3 subproblems, and the inputs and outputs.

These constraints are also necessary in the Multi-terminal BAP, as briefly discussed in Chapter 1. As explained, the multi-terminal BAP formulation cannot always prevent infeasibilities in the PAP and QCAP. The strategic planning only needs to be calculated once in a very large time period (in the order of months or years). An infeasibility does in that case not lead to urgent problems. The settings in the Multi-terminal BAP can be slightly changed and a new calculation

can be performed. However, the TAP is used in the Planning Controller which is used as a decision support tool for operational planning. In that case, infeasibilities could lead to urgent problems, because the run time of the Planning Controller is limited.

The measures that are taken to prevent infeasibilities are explained in section 3.3, where the stability issues regarding berthing terminal capacity exceedings and quay crane capacity exceedings are discussed. The detailed description and the mathematical formulation of the TAP are given in section 3.4.

The output of the TAP is a time allocation which contains the allocated berth time intervals for all vessels currently on the planning horizon.

Position Allocation Problem

The time allocation from the TAP is used as the input of the PAP. Therefore, the PAP uses the same planning horizon length as used in the TAP. The PAP calculates the berth positions of the vessels defined on the planning horizon. The objective in the PAP is to allocate the positions of the vessels on the planning horizon, such that the deviation from the lowest cost berthing position is minimized.

Two different implementations of the PAP are considered throughout this research:

- a static positioning strategy,
- a dynamic positioning strategy.

The static version uses fixed reference positions, determined from the reference planning, as the lowest cost berthing position of a vessel. The dynamic version on the other hand, determines the lowest cost berthing position online, depending on the number and type of containers that have to be loaded on and unloaded from the vessel.

For the position allocation calculated at time $t = k_c$, the PAP uses the following input parameters:

- the berth time intervals (from TAP),
- the previous berth allocation calculated at $t = k_c 1$ (from Planning Controller),
- in case of static positioning: reference positions (from reference planning),
- in case of dynamic positioning: functions for straddle carrier travel distance.

The two most important constraints in the PAP are:

- a vessel is not allowed to change from berth position once it starts berthing at a certain position,
- vessels which berth simultaneously along the terminal quay cannot overlap in position.

Both the static and dynamic positioning strategy of the PAP are explained in more detail in section 3.5. The output of the PAP is an operational berth allocation which contains the time interval and position in the terminal of each vessel on the planning horizon, see Figure 3.3.

Quay Crane Allocation Problem

The berth allocation which contains the berth time intervals and positions of the vessels, is used as the input of the QCAP. The QCAP allocates the available quay cranes to the vessels over a certain planning horizon. This planning horizon can have the same length as used in the TAP and PAP, but it is also possible to choose a shorter planning horizon. The QCAP can be rather computational expensive when a large planning horizon is used. Since a very detailed quay crane allocation far into the future is not always necessary, it is possible to use a shorter planning horizon.

The main objective in the QCAP is to allocate the available quay cranes to the vessels during their berth time interval such that the following weighted costs are minimized:

- 1. the maximum number of required quay cranes in the terminal,
- 2. the processing time of the vessels,
- 3. the number of quay crane switches in between vessels.

For the quay crane allocation calculated at time $t = k_c$, the QCAP uses the following input parameters:

- the berth allocation (berth time intervals and position (from TAP and PAP),
- the previous quay crane allocation calculated at $t = k_c 1$ (from Planning Controller).

The main constraints in the QCAP are:

- a restricted number of quay cranes in the terminal,
- quay cranes can move along the quay but cannot cross each other because they are situated on the same track.

A more detailed description of the QCAP can be found in section 3.6. After the QCAP has been executed successfully, the operational planning calculated at the current time slot k_c , is obtained.

Transshipment verification

According to the reference planning, each vessel loads and unloads a certain container freight. The specific container types have been defined in section 2.2. The planning controller needs information about the exact container freight (numbers and types), in order to determine the length of the berth time interval in the TAP, and to position the vessels in the PAP. However, a problem arises with the transshipment containers, because the amount of transshipment for each vessel is dependent on how the vessels are arranged in time.

Due to disturbances in arrival times, it is possible that a vessel berths earlier or later than was planned in the reference planning. Depending on how the TAP in the Planning Controller determines the berth time intervals of the vessels, certain containers can be transshipped in between two vessels or not. Whether containers between certain vessels on the planning horizon can be transshipped, is estimated by a transshipment verification procedure, which is executed before the TAP, see Figure 3.3. This procedure uses the following information at $t = k_c$:

1. the number of transshipment containers for each vessel,

2. the previous berth allocation calculated at $t = k_c - 1$ (from Planning Controller).

The transshipment containers from the source vessel are unloaded. Then based on the information of (1) and (2), the verification procedure determines which transshipment containers can make it to the destination vessels and which cannot. The verification procedure is implemented such that if the arrival time of the source vessel is lower than the arrival time of the destination vessel, it is assumed that the transshipment containers can be transshipped from the source vessel to the destination vessel.

If the arrival time of the source vessel is later than the arrival time of the destination vessel, then the containers are not transshipped from the source vessel to the destination vessel. In that case, the verification procedure checks whether the containers can be transshipped to the vessel of the same shipping line in the subsequent cycle.

Note that this verification procedure is only needed for transshipment containers in between two vessels. The export containers can always be loaded onto the vessel because these are waiting in the stack on the terminal, and import containers can always be unloaded from the vessel because these are located on the vessels. Of course it is possible that a truck with an export container has arrived late and therefore cannot make it to the vessel. In reality, if it is known that a certain container is delayed by a truck, then this container is simply not included in the container load data for the specific vessel that is sent to the Planning Controller. In that case, the container is also forwarded to the next similar vessel in the subsequent cycle. In the model however, these events are assumed to be included in the disturbances of import and export containers of the individual vessels. This is explained in the next section.

How the verification procedure is exactly modeled can be found in Appendix C. This section is concluded with a graphical example of the transshipment verification procedure in Example 3.1.

Example 3.1 Transshipment verification

Figure 3.4 shows a graphical example of the transshipment verification procedure. As can be seen in the reference berth allocation, 3 different vessels are planned in each cycle of this terminal, which are named vessel 1, 2, and 3. In this example, the current time is at the beginning of cycle 7, and the time horizon includes cycle 7, 8, and a part of cycle 9. According to the reference berth allocation, vessel 1 is expected to berth first, followed by vessel 2, and then vessel 3.

Vessel 1 has a certain amount of transshipment containers which are destined for vessel 2 and 3 in cycle 7, and vessel 3 has transshipment containers destined for vessel 1 in cycle 8. The flow of transshipment containers from the source vessel to the destination vessel is indicated with a black arrow in between the vessels.

As depicted in the operational berth allocation in Figure 3.4, vessel 1 in cycle 7 berths later than stated in the reference. The arrival time of vessel 1 is later than the arrival time of vessel 2 of cycle 7. This means that the transshipment containers from vessel 1 destined for vessel 2 of cycle 7 are now forwarded to vessel 2 in cycle 8. Vessel 2 in cycle 8 is able to load these containers, since vessel 2 of cycle 8 berths later than vessel 1 of cycle 7.

Although there is some overlap in time in between vessel 1 and 2 in cycle 7, it cannot be guaranteed that the transshipment containers can all be transshipped from vessel 1 to vessel 2 of cycle 7. Note that in the example, vessel 2 in cycle 8 receives now transshipment containers from both vessel 1 in cycle 7 and vessel 1 in cycle 8. \boxtimes

The internal structure and overall functioning of the Planning Controller has been discussed now. In the next section certain berth definitions are made and sets have to be defined. These definitions are required in the subsequent sections of this chapter.



Figure 3.4: Graphical representation of the transshipment verification procedure.

3.2 Definitions

In this section, the necessary definitions required for the discussion of the subproblems in the Planning Controller are given. In the first part, the berth definitions of a vessel (in time and position) are given. In the second part, certain vessel sets are defined.

Berth definition

The following definitions are used for a vessel that is allocated in time and position on the planning horizon. The allocated berth time interval is defined as $[a_v, d_v]$, where a_v is the start of berth time of vessel v and d_v the departure time of vessel v. A vessel's start of processing is indicated by p_v^s and its end of processing time is indicated by p_v^e . So the processing interval is defined as $[p_v^s, p_v^e]$ A logical and natural property of each vessel is that $A_v \leq a_v < p_v^s < p_v^e < d_v$. An overview of these events can be found in Figure 3.5, where the berth properties of a single vessel are graphically depicted. The vessel is represented as a rectangle, where the total length of this rectangle represents the berth time interval, and the height of the rectangle represents the vessel length. The position of the vessel in the terminal, p_v , is indicated by the center of the vessel.

If $A_v = k$, then the vessel arrives during time slot k which is during time interval $[k, k + 1\rangle$. If $a_v = k$ the vessel starts berthing during time slot k, which is in time interval $[k, k + 1\rangle$. An important remark is that the actual start of berthing, a_v , does not necessarily occur immediately at the arrival time, A_v . It is possible that a vessel must wait a certain number of time slots, before it can start berthing at the terminal, depending on the decisions made in the Planning Controller. Furthermore, it is assumed that the start of berthing consumes one time slot. This is depicted in Figure 3.5 by the shaded part at the begin of the berth time interval. During this first time slot of the berth time interval, the vessel cannot be processed. If $p_v^s = k$, processing vessel v is started in time slot k which is in time interval $[k, k + 1\rangle$. Given this, the following relationship is always

3.2. Definitions



Figure 3.5: Definition of a vessel represented as a rectangle with its properties depicted over position and time.

valid: $p_v^s = a_v + 1$. If $p_v^e = k$, then processing vessel v is finished somewhere during time slot k - 1, which is during time interval $\langle k - 1, k \rangle$. Finally, if $d_v = k$, the vessel departs somewhere during time slot k - 1 which is during time interval $\langle k - 1, k \rangle$. It is assumed that the departure of a vessel also consumes one time slot. Hence, $p_v^e = d_v - 1$. This is depicted in Figure 3.5 by the shaded part at the end of the berth time interval. During this last time slot of the berth time interval, the vessel cannot be processed.

In the example of Figure 3.5 the allocated berth time interval has a duration of 7-3=4 [time slots], and the duration of the process interval is equal to 6-4=2 [time slots]. During the process interval, a certain amount of work Q_v has to be processed.

For the remainder of this report, the vessel's process interval, $[p_v^s, p_v^e]$, is not explicitly indicated anymore, because it can always be derived from the vessel's berth time interval $[a_v, d_v]$. From now on, only the vessel's berth time interval is indicated. A last remark is that the reference berth time interval, explained in section 2.4, also reserves one time slot for berthing and one time slot for departing.

Vessel sets definition

The Planning Controller is executed repeatedly and uses a discrete time setting. Therefore, all sets which are defined here hold for the current time slot. Therefore, the sets are a function of k_c . However, this is explicitly indicated. The sets defined here hold for the remainder of the report. The set of discrete time slots is defined as: $k \in \{k_c, \ldots, k_c + H\}$, where k_c is the current time slot and H is the planning horizon length in number of discrete time slots.

- The vessels which arrive within the so-called arrival horizon, $a_v \leq k_c + H_a$ where $H_a \leq H$, are currently considered on the planning horizon, $[k_c, k_c + H]$, of the Planning Controller. These vessels are in the set: \mathcal{V}_h .
- All the vessels that are currently not considered on the planning horizon are in the set \mathcal{V}_{nh} . This set includes vessels which have departed, and vessels for which is valid $a_v > k_c + H_a$.
- All vessels considered in a simulation run are in the set \mathcal{V}_s .

From these definitions it follows that: $\mathcal{V}_s = {\mathcal{V}_h, \mathcal{V}_{nh}}.$

If a vessel v has been fully processed and it has left the terminal, then the vessel is not considered in the model anymore and is therefore not considered on the planning horizon anymore. In that case $v \in \mathcal{V}_{nh}$.

Unless stated differently, vessel $\{v, i, j\} \in \mathcal{V}_h$.

The definition of a vessel arriving on time, early or late has been given in section 2.4. According to this definition, each vessel is classified to one and only one of the following two categories:

"+" Vessel v has arrived or is expected to arrive "on time" or "early".

"-" Vessel v has arrived or is expected to arrive "late".

Based on whether the vessel is already berthing or not, each vessel is also classified to one and only one of the following two categories:

- "berthing" Vessel v is currently berthing. This implies that the vessel has started to berth earlier (before k_c).
- "non-berthing" Vessel v is expected to start berthing somewhere in between the beginning of current time slot and the arrival horizon, $k_c \leq a_v \leq (k_c + H_a)$. This means that the vessel on the planning horizon is not berthing yet or it is going to start berthing at the beginning of the current time slot.

So each vessel is classified to category "+" or "-", and to category "berthing" or "non berthing". Given these 2 pairs of categories, there are 4 combinations possible. With these 4 combinations, 4 vessel sets are defined as:

- $v \in \mathcal{V}_{\mathcal{B}}^+$ if vessel v is in category "+" and "berthing".
- $v \in \mathcal{V}_{\mathcal{B}}^{-}$ if vessel v is in category "-" and "berthing".
- $v \in \mathcal{V}^+$ if vessel v is in category "+" and "non-berthing".
- $v \in \mathcal{V}^-$ if vessel v is in category "-" and "non-berthing".

So each vessel belongs to one and only one of these 4 sets, where:

 $\begin{array}{l} \mathcal{V}_{\mathcal{B}}^{+} \subseteq \mathcal{V}_{h}, \\ \mathcal{V}_{\mathcal{B}}^{-} \subseteq \mathcal{V}_{h}, \\ \mathcal{V}^{+} \subseteq \mathcal{V}_{h}, \end{array}$

$$\mathcal{V}^{-} \subseteq \mathcal{V}_h,$$

and

 $\mathcal{V}_h = \{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-, \mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\}.$

The vessel sets defined in this section are conveniently arranged in Table 3.1. A complete overview of all sets and parameters used throughout this report can be found in Appendix D.

Set	Definition
\mathcal{V}_s	The set of vessels that are considered throughout the entire simulation run.
\mathcal{V}_h	The set of vessels that are currently considered on the planning horizon, and for
	which is valid that: $k_c \leq A_v \leq (k_c + H_a)$.
\mathcal{V}_{nh}	The set of vessels that are currently not on the planning horizon.
\mathcal{V}^{-}	All vessels on the horizon which are not currently berthing yet, and are expected
	to arrive late.
$\mathcal{V}_{\mathcal{B}}^{-}$	All vessels on the horizon which are currently berthing, and have arrived late.
$\mathcal{V}^{\widetilde{+}}$	All vessels on the horizon which are not currently berthing yet, and are expected
	to arrive on time or early.
$\mathcal{V}_{\mathcal{B}}^+$	All vessels on the horizon which are currently berthing, and have arrived on time.

Table 3.1: General definitions of vessel sets

3.3 Stability

In this section the stability issues in the Planning Controller are discussed. Three main causes of instabilities/infeasibilities are discussed here:

- 1. horizon length,
- 2. berth capacity,
- 3. quay crane capacity.

Each stability issue is first discussed, and then measures are presented to solve these instabilities/infeasibilities. Most of the measures are implemented in the TAP, since this is the first subproblem which can prevent instabilities in later subproblems (PAP and QCAP).

3.3.1 Horizon length

Cause of infeasibility

An important issue in MPC control is the stability of the method. Therefore, infeasibilities have to be avoided. An important question which comes into play, is what to do with vessels that arrive close to the end of the horizon. If a vessel arrives close to the end of the horizon, it is possible that the berth time interval becomes too small to process all the necessary amount of work Q_v of the vessel.

A different stability issue arises when suddenly a large number of vessels is considered on the planning horizon. Such a situation can occur when many vessels have been delayed for a relative long time, and which then arrive around the same time. Another situation wherein a large number of vessels is considered on the horizon, is for instance when a different terminal in the port is closed for a certain period of time, because of an accident for instance or due to other safety reasons. In such a situation it is possible that these vessels must berth at the terminal under consideration. Then the available capacity in the considered terminal could become temporarily insufficient, and the planning horizon could be too short to process these vessels on the horizon.

Measures to prevent infeasibility

To prevent instabilities/infeasibilities in the TAP due to a limited horizon length, an appropriate solution is needed to solve this problem. The following three measures are implemented in the TAP:

- 1. the creation of a safety margin on the planning horizon,
- 2. temporary reduction of Q_v of vessels located at the end of the planning horizon,
- 3. limitation of the number of vessels considered on planning horizon, by a maximum process capacity.

The first measure has already been defined implicitly in section 3.2 and works as follows. The vessels for which is valid that $A_v < k_c + H_a$ where $H_a \leq H$, are considered on the planning horizon. These vessels have to be allocated on a sufficiently large planning horizon defined as $[k_c, k_c + H]$, In this way, a safety margin in time is created with length $H - H_a$.

The second measure works as follows. The amount of work Q_v for a vessel is temporarily reduced if the berth time interval of the vessel lies close to the end of the arrival horizon $k_c + H_a$. An example of this measure is given in Example 3.2.

Example 3.2 Reduction of work for vessel on horizon

Consider the graphical example in Figure 3.6, where 9 different arrival scenario's are depicted of a vessel v which arrives just before $k_c + H_a$. Time is stated on the horizon axis, and the vertical axis does not have a dimension. In scenario A through C, the vessel arrives on time, whereas in scenario D, the vessel arrives early. The grey rectangles indicate the maximum berth time interval agreement in each case. These berth agreements reach beyond the arrival horizon $k_c + H_a$. As long as $D_v^{max} > H_a$, then the amount of work is temporarily reduced to:

$$Q_v^h = \frac{k_c + H_a - A_v}{D_v^{max} - A_v}.$$
(3.1)

The berth time interval calculated by the TAP, $[a_v, d_v]$, must always lie in the interval $[A_v, k_c + H]$. For these scenarios, Q_v^h number of containers must be processed during the berth time interval $[a_v, d_v]$.

In scenario E through I, the vessel arrives late, just before the end of the arrival horizon $k_c + H_a$. Since there is no strict maximum departure time agreement when a vessel arrives late, the grey rectangles which indicated the maximum berth time interval agreement, are not indicated anymore. The temporarily reduced amount of work that needs to processed is now determined by:

$$Q_v^h = \frac{k_c + H_a - A_v}{D_v^* - A_v}.$$
(3.2)

Hence, Q_v^h containers have to be processed during the calculated berth time interval, $[a_v, d_v]$, which must lie in the interval defined by $[A_v, k_c + H]$.

In scenario H and I, the vessel is not considered on the horizon yet, since $A_v \ge k_c + H_a$.



Figure 3.6: Temporary reduction of the container amount Q_v to Q_v^h , for different scenarios of a vessel arriving at the end of the arrival horizon.

The third measure works as follows. The number of vessels that is simultaneously considered on the planning horizon is limited. If all the considered vessels consume more capacity then there is available in between k_c and $k_c + H_a$, then only a part of these vessels are actually considered on the planning horizon. The vessels are sorted on arrival time in ascending order. Then the maximum number of vessels, which do not lead to insufficient capacity, is picked successively from this sorted list. So only the vessel which are picked from this list are in the set \mathcal{V}_h . As soon as there is sufficient capacity available again to process the next vessel in the list, then the next vessel in the list is added to the set \mathcal{V}_h . Under normal operations, even under the influence of relative large disturbances, this measure is not needed.

Summarized, by temporarily reducing the amount of work Q_v to Q_v^h for vessels which lie on the arrival horizon $k_c + H_a$, and by creating a safety margin in time on the planning horizon $H - H_a$, and to restrict the number of vessels in the set \mathcal{V}_h , infeasibilities due to a limited planning horizon can be avoided.

In the next section, infeasibilities due to berth capacity exceedings are discussed. The measures to prevent these infeasibilities are also treated.

3.3.2 Berth Positions

Due to the decision to cut the Berth Allocation Problem into a separate Time Allocation Problem and a Position Allocation Problem, solutions from the TAP might not yield feasible solutions for the position allocation. As explained in section 3.1.2, constraints have to be added in the formulation of the TAP in order to prevent berthing terminal capacity exceedings in the PAP. The basic measure that is taken to prevent berthing terminal capacity exceedings, is to require in the TAP that:

• the sum of the length of the vessels has to be less than or equal to the terminal quay length.

Although this single measure provides satisfactory behavior for the multi-terminal BAP discussed on a strategic level (in Chapter 1), it results in very unstable behavior when used as a single measure in the TAP. This is because the problem formulations are different, and the TAP implemented in the Planning Controller is calculated repeatedly (at each time slot).

In order to prevent infeasibilities in the PAP due to berth capacity exceedings, additional measures have to be taken in the TAP. The measures proposed here are all based on knowledge obtained from the previously calculated berth allocation defined over $[k_c - 1, k_c - 1 + H]$, and calculated at $t = k_c - 1$, see Figure 3.3.

In this subsection different scenario's are discussed which show how in the PAP an infeasibility can arise from a certain time allocation that is calculated by the TAP based on the single measure as discussed above. Then it is explained how these infeasibilities can be prevented when the information from the previous berth allocation is incorporated in the TAP.

Infeasibility: Scenario 1

Once a vessel actually starts berthing in the terminal and a position in the terminal has been determined by the PAP, then its position remains fixed until the vessel has been fully processed. This means that once a vessel actually starts berthing at position P_v in the terminal, its position remains fixed to P_v for each future time iteration that the Planning Controller is called upon, until the vessel has been fully processed and it leaves the terminal. This restriction comes from reality, since it is unpractical to relocate the vessel along the quay after it has been positioned. As long as the vessel is not actually berthing in the terminal yet, i.e. when the vessel is allocated in future

time on the planning horizon, then the vessel's position in the terminal can be freely determined. As a result of the fixed positions of actual berthing vessels, the remaining empty quay is divided into parts. These empty parts of quay can arise in between two vessels which have a fixed position along the quay, or in between a vessel with a fixed position and the end of the quay. If the part of empty quay is too small for a vessel to berth at, then this part of the quay becomes useless until one of the vessels leave the terminal again. In that case, it is not sufficient anymore to require in the TAP that the sum of the vessel lengths have to be smaller than or equal to the quay length. This scenario can be explained in more detail with Example 3.3.

Example 3.3 Position infeasibility

Consider the berth allocations in Figure 3.7, where the time [time slots] is stated on the horizontal axis, and the vessel's position [m] is stated on the vertical axis. The upper two berth allocations show the reference and solution of the previous berth allocation defined over the time interval $[k_c - 1, k_c - 1 + H]$, which has been determined at the beginning of the previous current time slot $k_c - 1$. The lower two berth allocations show the reference and solution of the allocation defined over the interval [$k_c, k_c + H$], determined at the beginning of the current time slot k_c . For convenience, a certain part of the history is also depicted in each berth allocation.

In each operational berth allocation, the past is indicated by everything what is left from the dotted line. This shows what has already been executed at that particular time. What is allocated during the first time slot at the right of the dotted line, shows what needs to be executed during the current time slot (at $t = k_c$). Each time slot right from the current time slot shows the planned berth allocation into the future.

The previous berth allocation provides the following information. Vessel 1 has been fully processed already in the past, and is not considered in the model anymore. However, the vessel is depicted here, because during earlier berth allocation calculations it has caused vessel 2 to deviate from its reference position. Vessel 1 berthed at its reference position but arrived one time slot late, started to berth one time slot late, and departed one time slot late than stated in the reference. Therefore vessel 2 had to move from its reference position. Now vessel 2 cannot move from position anymore, because it is actually berthing in the terminal at the position determined in the past. Vessel 3, which is not currently berthing yet, is expected to arrive two time slots later than expected, and is allocated to its reference position. Vessel 4 is currently berthing, and is also allocated to its reference position.

The current berth allocation provides the following information. Apparently, the forecasted arrival time of vessel 3 has been updated. In the new arrival forecast, vessel 3 is expected to arrive two time slots earlier than the previous arrival forecast. The vessel is expected to arrive exactly according to the reference arrival time again. The available empty quay parts are indicated by the red arrows. As indicated, the sum of the length of these three empty quay parts is larger than the length of vessel 3. However, there is not one single part of empty quay which is sufficiently large for vessel 3 to berth at. When the TAP sets the start of berthing time of vessel 3 equal to its arrival time, an infeasibility in the PAP is obtained. This is indicated by vessel 3 which is highlighted in red.

The three empty quay parts indicated by the red arrows, become temporarily useless areas of empty quay (at least for vessel 3). Hence, the condition that the sum of the vessel lengths must be less than or equal to the quay length is a necessary condition, but not sufficient. \square

Solution approach 1

In order to prevent position infeasibilities similar to the one discussed in scenario 1, certain berth time intervals of vessels have to be constrained in time. Which berth time intervals of the vessels need to be constraint in time by the TAP, can be determined by observing the previously calculated berth allocation, defined over $[k_c - 1, k_c - 1 + H]$. The following concept can prevent infeasibilities similar to the one encountered in scenario 1:



Figure 3.7: Scenario 1: infeasibility as a result of a non-berthing vessel which is planned to start berthing simultaneously with already berthing vessels. The berthing vessels have a fixed berth position in the terminal.

The set W_j contains all berthing vessels *i* for which is valid that during the previously calculated berth allocation defined over $[k_c - 1, k_c - 1 + H]$:

- 1. the non-berthing vessel j starts to berth in time after the berthing vessel i has departed,
- 2. the non-berthing vessel j overlaps in position with the berthing vessel i.

This set \mathcal{W}_j is determined before the actual optimization in the TAP is executed. Then the entire berth time interval $[a_j, d_j]$ calculated on the current planning horizon in the TAP, must stay in time behind departure time d_i where $i \in \mathcal{W}_j$. This implies that a vessel j cannot overtake vessel $i \in \mathcal{W}_j$ in time. Therefore, each vessel $i \in \mathcal{W}_j$ is called a relevant predecessor of vessel j.

Evaluation solution approach 1

When solution approach 1 is applied to scenario 1, the following behavior is obtained. In the previous berth allocation in Figure 3.7, the berth time interval of vessel 3 is located in time behind vessel 2. Furthermore, vessel 3 has overlap in position with vessel 2. Hence, $2 \in W_3$. Therefore, if the time allocation is now calculated at current time k_c , the earliest start of berthing time of vessel 3 is set equal to the departure time of vessel 2.

This concept does not result in additional complexity of the model. The TAP can use the predicted future berth information calculated one time slot earlier, for the current berth time interval calculations. Although there is a cut in between allocation of time and position, the berth information from the previously calculated berth allocation can be effectively incorporated in the TAP.

In theory, solution approach 1 does not necessarily lead to an improved or optimal solution. Consider for instance a graphical example of two consecutive operational berth allocations in Figure 3.8. In the previous operational berth allocation, calculated at the previous current time slot



Figure 3.8: Consequences of the measure to prevent position infeasibilities.

 $k_c - 1$, vessel 2 overlaps in position with vessel 1. Vessel 2 is expected to start berthing three time slots after vessel 1 has departed. However, when the current operational berth allocation is calculated at the beginning of the current time slot k_c , a new forecast has been received which indicates that vessel 2 arrives 7 time slots earlier than the previous arrival forecast. In this case, the non-berthing vessel 2 stays in time behind the berthing vessel 1, whereas there is still plenty of quay available to berth at, which is indicated by the dotted vessel in Figure 3.8.

However, a situation as depicted in Figure 3.8 is unlikely to arise in realistic operational planning. In the first berth allocation of Figure 3.8, vessel 2 is expected to arrive in 10 time slots from current time (where a time slot is equal to one hour). Then 1 hour later, there is suddenly a forecast which indicates that the vessel arrives in 2 hours. This is very unrealistic, because if the vessel suddenly arrives within 2 hours, then this information should have been available much earlier. If such a dramatic change in arrival forecast had been available earlier, then vessel 1 was not berthing yet, and vessel 2 could have been positioned next to vessel 1. What this scenario implies is that the

communication between the terminal operator and the vessel has been very poor.

In general it is assumed that the berth information of vessels early on the planning horizon is quite reliable. In that case, the information obtained from the previous berth allocation can be incorporated in the TAP without resulting in poor performance.

Moreover, note in Figure 3.8 that in order for vessel 2 to depart earlier (what is in general beneficial), it has to move from its reference position. Although in terms of time a better allocation is obtained, the question still remains if this berth allocation is optimal in terms of position. This factor is discussed when the system description of the TAP is treated in section 3.5.1

Infeasibility: Scenario 2

Consider the situation depicted in Figure 3.9. During the previously calculated berth allocation,



Figure 3.9: Position infeasibility as a result of a non-berthing vessel which is planned to berth simultaneously with one berthing vessels and other non-berthing vessels.

only vessel 1 is currently berthing and has a fixed position in the terminal. The other five vessels on the planning horizon are non-berthing and therefore do not have a fixed position yet. In scenario A of the current berth allocation, a position infeasibility occurs due to vessel 6, which is suddenly expected to arrive earlier. The sum of the lengths of vessel 1, 4, 5 and 6 is less than the terminal quay length. However, non of the non-berthing vessels can berth at the left side of vessel 1, and the part of empty quay at the right side of vessel 1 is not large enough for vessel 4, 5, and 6 to berth at simultaneously. Therefore, an infeasibility in the PAP arises.

In scenario B, vessel 5 arrives earlier. The sum of the lengths of vessel 1, 2, 3 and 5 is equal to the terminal quay length. Vessel 1 has a fixed position, and the free quay space at the left of the vessel cannot be used since this is too small. Hence, an infeasibility arises because vessel 2, 3, and 5 cannot berth simultaneously at the right side of vessel 1.

As explained by scenario A and B in Figure 3.9, the process of vessels overtaking in time must be prevented in more cases.

Solution approach 2

The solution to prevent position infeasibilities such as explained in scenario 1 and 2, is to extend the concept of a relevant predecessor defined in solution approach 1. These relevant predecessors are determined by performing an algorithm prior to the actual optimization in the TAP, which searches the relevant predecessors in the previously calculated berth allocation.

Let d^{max} be defined as follows:

$$d^{max} = \max\{d_m\} \quad m \in \{\mathcal{V}_h^-, \mathcal{V}_h^+\},$$
(3.3)

where $m \in \{\mathcal{V}_b^-, \mathcal{V}_b^+\}$ is determined from the previous berth allocation. So d^{max} is the latest departure time of a currently berthing vessel on the previous berth allocation. Furthermore for now, let vessel:

- *i* be a berthing or non-berthing vessel on the previous berth allocation for which is valid that $A_i < d^{max}$,
- j be a non-berthing vessel which can arrive and start berthing anywhere on the previous berth allocation.

Then the following algorithm is executed for each vessel j, prior to the optimization in the TAP. Vessel i is considered a relevant predecessor of vessel j, i.e. $i \in W_j$, if and only if (3.4), (3.5), (3.6) hold:

$$d_i \le a_j, \tag{3.4}$$

and

$$p_i + 0.5 \cdot L_i > p_j - 0.5 \cdot L_j, \tag{3.5}$$

and

$$p_i - 0.5 \cdot L_i < p_j + 0.5 \cdot L_j, \tag{3.6}$$

where a_j , d_i , p_i and p_j are solved and known variables from the previously calculated berth allocation. Then the entire berth time interval $[a_j, d_j]$ calculated in the TAP must stay in time behind the departure time d_i $i \in \mathcal{W}_j$. Note that this new definition also includes the earlier definition of relevant predecessors made in solution approach 1.

Evaluation solution approach 2

When solution approach 2 is applied to the example explained in Figure 3.9, then the sets W_1 , W_2 and W_3 are empty since they do not have any relevant predecessors, and $2 \in W_4$, $\{2,3\} \in W_5$, $\{3,5\} \in W_6$. Since both vessel 3 and 5 are in the set W_6 and vessel 5 has the highest departure time, vessel 6 has to stay in time behind vessel 5.

Note that if there is no currently berthing vessel on the planning horizon, non of the vessels have relevant predecessors. In that case, any vessel on the planning horizon can be freely positioned. This gives exactly the desired behavior, since the restriction that the sum of the vessels needs to be less than or equal to the terminal quay length is in that case a sufficient condition.

The possible position infeasibilities discussed here are the consequence of the cut in between berth time interval and position allocation, in combination with the fact that berthing vessels cannot be moved from position anymore. As explained in the previous examples, the fixation of one currently berthing vessel in position can have knock-on effects for many other non-berthing vessels in future time on the planning horizon, especially when the berth utilization is high and when many vessels are planned to berth simultaneously in the terminal. By preventing the event of vessels overtaking in time by certain non-berthing vessels as described above, position infeasibilities in the PAP are prevented. Solution approach 2 is therefore implemented as an algorithm before actual optimization in the TAP, which determines the sets W_i .

In the next section, infeasibilities in the QCAP due to quay crane capacity exceedings are discussed. Also solutions are suggested to prevent these infeasibilities.

3.3.3 Process capacity

Cause of infeasibility

The start time and departure time of the berth time interval is determined in the TAP. The basic measure that is taken in the TAP to prevent quay crane capacity exceedings in the QCAP, is the use of:

• a continuous quay crane allocation in the TAP.

It is possible that the calculated berth time interval of a vessel based on the continuous quay crane allocation in the TAP is too short in time, in order to obtain a feasible quay crane allocation in the QCAP. The reason for this is that the berth time interval is based on a continuous quay crane approximation, and the QCAP is based on an integer quay crane allocation, which allocates each specific quay crane to a vessel. The following example explains this feasibility problem.

Assume for instance that there are only 7 quay cranes available in a terminal, and that vessel A needs to be processed for 1 time slot and it needs 3.2 quay cranes during this time slot. Vessel B berths simultaneously with vessel A and also needs to be processed for only 1 time slot and needs 3.1 quay cranes during this time slot. The two vessels need in total only 6.3 quay cranes during that time slot, which is less than 7. However when an integer quay crane allocation is executed in the QCAP, the two vessels in total need 8 quay cranes during this time slot. This would lead to an infeasibility in the QCAP.

Two different measures are suggested here to overcome this problem. Measure 1 can be applied in the QCAP, whereas measure 2 can be applied in the TAP.

Measure 1

A logical solution to prevent infeasibilities due to quay crane capacity, is to share a quay crane by different vessels during a time slot. In the QCAP however, a quay crane can only be allocated to one vessel during the duration of one time slot. A possibility to deal with this problem is to divide each original time slot in the QCAP into 2 or multiple sub-slots, such that a quay crane can switch more frequently in between vessels.

For instance during the first sub-slot there are 4 quay cranes which process vessel A and 3 quay cranes which process vessel B, and in the second sub-slot there are 3 quay cranes that process vessel A and 4 quay cranes that process vessel B. In this way, the two vessels both have an average of 3.5 quay cranes available during the length of the original time slot, which is now sufficient to process both vessels within the allocated berth time interval.

However, since hourly time slots are used and quay crane switches are time consuming (due to set-up time), it is not very practical to switch between vessels on an even shorter time basis (for instance every half an hour or 15 minutes). Moreover, increasing the number of time slots just to solve infeasibilities does not seem to be a very considerate solution, since this causes the computation time in the Planning Controller to increase significantly. Although this measure is mathematically correct, experiments have indicated that this measure is not very practical. Therefore measure 1 is avoided.

Measure 2

A strategy that can be used, is to minimize the maximum number of quay cranes in the TAP to obtain a balanced workload. In that case, the calculated berth time intervals become naturally wider. Then it is not likely that an infeasibility arises in the QCAP, because in most cases the quay cranes are not fully utilized.

However, it is possible that full quay crane capacity is required even when the workload is balanced, especially during busy hours in the terminal. Other occasions where full quay crane capacity is needed is when the turn around times of the vessels are minimized instead of the quay crane usage in order to obtain a balanced workload. In that case, the combination of berth time intervals based on a continuous quay crane allocation and a high quay crane utilization, can cause infeasibilities in the QCAP. Therefore, at least another measure is required to prevent infeasibilities or delays in the QCAP.

A measure that can be used is to use a lower average quay crane process rate in the TAP than the process rates used in the QCAP. If the difference between these process rates are tuned, then this ensures that the obtained berth time intervals in the TAP are sufficiently large to prevent quay crane capacity problems in the QCAP.

Experiments have indicated that measure 2 provides satisfactory performance when the process rate in the QCAP is set to 85% of the maximum process rate and a process rate of 70% of the maximum process rate in the TAP. However, experiments indicate that when the workload is balanced the difference in between the two process rates can become smaller. Measure 2 is implemented in the TAP.

3.4 Time Allocation Problem

This section is structured as follows: First the system description of the TAP is given, where all the properties and characteristics of the TAP are discussed. Subsequently, the objectives of the TAP are discussed in detail. Finally, the mathematical model of the TAP is formulated as a MILP.

3.4.1 System description

In this subsection the system description of the TAP is treated. All the parameters of the TAP are conveniently arranged in Table 3.2. All sets and parameters can also be found in Appendix D.

Parameter	Definition
k_c	Current time slot.
H	Planning horizon length [time slots].
H_a	Arrival horizon length [time slots].
A_v	Actual/forecasted arrival time of vessel v .
A_v^*	Reference arrival time of vessel v .
D_v^*	Reference departure time of vessel v .
D_v^{max}	Maximum departure time of vessel v .
P_v^{min}	Length of the minimum berth time interval for processing vessel v [time slots].
P_v^{max}	Length of the maximum berth time interval agreement of vessel v [time slots].
Q_v	Actual / expected $\#$ of containers which have to be processed on vessel v
L_v	Required quay length $[m]$ for vessel v to berth at the terminal.
S_v	Maximum # of quay cranes, which can simultaneously process vessel v .
L	Total quay length [m].
N	# of free quay cranes in the terminal.
N_{max}	Maximum $\#$ of quay cranes available in the terminal.
$ \bar{\lambda} $	Mean processing rate of the quay cranes in the terminal [containers/time slot]
η_v	Vessel efficiency with respect to quay crane rate [-]
C_n	Cost factor for an additional quay crane in operation above $N\left[\frac{\text{euro}}{\text{quay crane}}\right]$.
C_v	Cost factor (reward or penalty) for the deviation in departure from
	$\max\{D_v^{max}, (A_v + P_v^{min} + 1) \ [\frac{euro}{timeslot}].$
C_v^-	Cost factor (penalty) for vessel $v \in \{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-\}$ for departing later than
	$\max\{D_v^{max}, (A_v + P_v^{min} + 1) \ [\frac{\text{euro}}{\text{time slot}}].$
C_v^+	Cost factor (penalty) for vessel $v \in \{\mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\}$ for departing later than
	$D_v^{max} \left[\frac{\text{euro}}{\text{time slot}} \right].$
C_a	Cost factor (penalty) for vessel v berthing earlier than the highest departure
	time of its relevant predecessors $\left[\frac{euro}{timeslot}\right]$.

Table 3.2: Definition of parameters used in the TAP.

Problem

The main problem that needs to be solved in the TAP of the Planning Controller, is the allocation of a berth time interval for each vessel v on the planning horizon. This berth interval is defined by the berth start time a_v and the departure time d_v of a vessel v. Unlike the first subproblem considered on a strategic level, the berthing terminal does not have to be determined in the TAP. It is assumed that each vessel berths at its reference terminal, as explained earlier.

Constraints

Each berth time interval $[a_v, d_v]$ must lie somewhere in between the current time slot k_c and the end of the planning horizon k_c+H . A vessel can never start berthing before it has actually arrived, and a vessel can never depart before it has started to berth. During the berth time interval, a certain number of containers has to be handled: Q_v .

The calculation of the berth time interval is restricted to certain bounds which depend on the actual or forecasted situation of the vessel. Although A_v is referred to as the actual arrival time of a vessel, it is possible that the arrival time is a prediction, as explained earlier. The same is valid for Q_v .

A berth time interval can never be interrupted. This implies also, that if a vessel was berthing during the previous current time slot $k_c - 1$, and it has not been fully processed yet, it must continue berthing at the current time slot k_c . Vessels which are expected to arrive near the end

of the arrival horizon, only have to be processed partly. The amount of work Q_v is temporarily reduced to Q_v^h until there is enough time to fully process the vessel on the planning horizon. This has been explained in section 3.3.1.

The quay cranes in the terminal have an average processing rate, $\bar{\lambda} \in \mathbb{N}$. Each vessel has an upper bound on the number of quay cranes $S_v \in \mathbb{N}$ that can work simultaneously on a vessel. The quay cranes have a certain process efficiency $\eta_v \in [0, 1]$. Both S_v and η_v depend on the vessel type which is being processed.

The length of the berth time interval of a vessel depends on:

- 1. the number of continuous quay cranes allocated to the vessel during its berth time interval,
- 2. the average process rate of the cranes in the terminal $\bar{\lambda}$,
- 3. the type of vessel which is processed, with its process efficiency factor $\eta_v \in [0, 1]$.

The processing time of the vessel (berth time) is inversely proportional to these three factors. The number of quay cranes that is allocated to the berth time interval of vessel v, can vary per time slot.

The considered terminal has a restricted quay length $L \in \mathbb{R}^+$, with a maximum number of available quay cranes, $N_{max} \in \mathbb{N}$. Each vessel that berths in the terminal occupies a certain part of the quay, which depends on its vessel length L_v . In each time slot, the sum of the vessel lengths has to be smaller than or equal to the terminal quay length.

Due to the chosen cut, additional constraints are required to avoid position infeasibilities in the PAP. Each vessel $i \in W_j$ is a relevant predecessor of vessel j. The definition of a relevant predecessor has been given in section 3.3.2. The berth time interval of each vessel j must stay in time behind the highest departure time of its relevant predecessors $i \in W_j$.

Objective

The objective in the TAP is to minimize the total weighted costs over the current planning horizon. There are five conflicting objectives for which the total weighted costs must be minimized. The objective is to minimize:

- 1. the total weighted deviation in departure of all vessels,
- 2. the total weighted delay in departure of the vessels which are in the set $\{\mathcal{V}^+, \mathcal{V}^+_{\mathcal{B}}\}$,
- 3. the total weighted delay in departure of the vessel which are in the set $\{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-\}$,
- 4. the total weighted costs for each vessel j which starts to berth earlier than the largest departure time of its desirable predecessors $i \in \mathbb{Z}_j$,
- 5. the maximum number of additional quay cranes in operation above N, ever required on the planning horizon.

For these objectives, the following accompanying cost factors are used:

- 1. A constant cost factor C_v is assigned to each time slot that a vessel departs too early or for each time slot that a vessel departs too late.
- 2. A constant cost factor C_v^+ is assigned to each time slot that a vessel $v \in \{\mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\}$ departs too late.
- 3. A constant cost factor C_v^- is assigned to each time slot that a vessel $v \in \{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-\}$ departs too late.

- 4. A constant cost factor C_v^a is assigned to each time slot that vessel j starts to berth earlier than the latest departure time of its *desirable* predecessors $i \in \mathbb{Z}_j$.
- 5. A constant cost factor, C_n , is assigned to the maximum number of additional quay cranes above N, that is ever required on the planning horizon.

The first objective is mainly introduced to assure that a vessel does not berth any longer than necessary. If a vessel departs early, negative costs are assigned (a reward). If a vessel departs too late, positive costs (a penalty) are assigned.

The second objective is used to independently penalize delays in departure of vessels which have arrived on time or early.

The third objective is used to independently penalize delays in departure of vessels which have arrived late. Objective 1 through 3 are outlined in more detail in the first part of the next section. The fourth objective is used to obtain a certain berth sequence. This objective is explained in the second part of the subsequent section.

Finally, the fifth objective is used to penalize additional quay cranes above a certain basic quay crane usage. Quay cranes are expensive in operation. Moreover, an expensive crew is needed to operate each quay crane, and straddle carriers are required to serve the quay cranes. Therefore, above a certain basic quay crane usage N, additional quay cranes in operation are penalized.

3.4.2 Outline objectives

In this subsection, the objectives 1 through 4 of the TAP are explained in more detail. In the first part, the costs for delay are treated. In the second part, the costs for a vessel overtaking its desirable predecessor in time is outlined in more detail.

Costs for delay in departure

As explained in section 2.4, agreements are made about the departure time of a vessel. If a vessel arrives on time (within the arrival window) or early, then a certain maximum departure time D_v^{max} must be achieved, or otherwise the agreement is violated. Such a violation is undesirable since this harms the goodwill of the terminal operator. Therefore, delays must be penalized in the model.

Consider now Figure 3.10 where 6 different arrival scenario's A through F, of a vessel are depicted. The horizontal axis indicates the planning horizon where k_c is the current time slot and $k_c + H$ the last time slot of the planning horizon. The vertical dimension has no meaning here because only time is considered here. At the top of the figure, the reference berth time interval of the vessel is indicated. In each of the scenario's the vessel is non-berthing, which implies that the vessel has not actually arrived yet in the port, since $A_v > k_c$. The arrival and departure window are indicated by the grey window around A_v^* and D_v^* respectively, with width $2 \cdot |C_v|$. In this example $|C_v| = 2$ time slots. Furthermore, the grey rectangles in scenario A through D indicate the maximum berth time interval agreement.

In scenario A through C, the vessel arrives on time. If a vessel arrives "on time", i.e. within the arrival interval, then the maximum departure time becomes: $D_v^{max} := A_v + P_v^{max}$. This implies that the length of the maximum berth time interval without violating the agreement is equal to P_v^{max} , as stated in the reference planning. If the vessel departs at D_v^{max} , there are no costs introduced. This area is indicated by the green arrow. For each time slot that the vessel departs even before its maximum departure time, $d_v < D_v^{max}$, a low reward (negative costs) is obtained. If the vessel departs later than D_v^{max} , high costs are introduced. A high constant cost factor is assigned to each time slot that the departure time lies beyond D_v^{max} . This area is indicated by the red arrow.

In scenario D, the vessel arrives "early". The maximum departure time is set equal to the minimum



Figure 3.10: Different scenario's for delay costs of a non-berthing vessel on the planning horizon.

of the departure window: $D_v^{max} := D_v^* - |C_v|$. In this case, the maximum length of the berth time interval without violating the agreement, becomes larger than P_v^{max} . Again, if the vessel departs at D_v^{max} , no costs are introduced (indicated by the green arrow). If the vessel departs even before its maximum departure time, i.e. when $d_v < D_v^{max}$, then a low reward (negative costs) is assigned to each time slot that the vessel departs earlier than D_v^{max} . For each time slot that the vessel departs earlier than D_v^{max} . For each time slot that the vessel departs beyond D_v^{max} , high costs are introduced, indicated by the red arrow.

If a vessel arrives "late", the maximum departure time is set equal to the maximum of the departure window: $D_v^{max} := D_v^* + |C_v|$, see scenario E and F in Figure 3.10. However a vessel can never be processed faster than $A_v + P_v^{min}$. And in order to prevent infeasibilities in the QCAP due to a too short berth time interval, an extra time slot is added to this minimum berth time interval. Then the delay of a late vessel is measured with respect to the violation of max $\{D_v^{max}, (A_v + P_v^{min} + 1)\}$.



Figure 3.11: Different scenario's for the costs for a delay in departure of a berthing vessel on the planning horizon.

If the vessel departs at $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$, then no costs are introduced. If $d_v < \max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$, then low negative costs are introduced (reward) for each time slot the vessel departs earlier. For each time slot that the vessel departs beyond $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$, medium costs are introduced. This area is indicated by the orange arrows. In this case, a medium constant cost factor is used for a delay in departure, since there is no strict violation of a departure agreement as is the case when an early or timely vessel is delayed in its departure. However, by assigning medium costs to each time slot that a late arrived vessel departs late, an acceptable berth time interval length can be obtained.

3.4. Time Allocation Problem

In Figure 3.11 the 5 arrival scenario's A through E are repeated for the case of a berthing vessel. All the time slots earlier than time slot k_c are history. The historic part of the maximum berth time interval is indicated in dark grey, whereas the light grey part shows the remaining part of the maximum berth time interval. The vertical axis has no dimension, since only time is considered here.

Depending on the arrival scenario, a certain amount of work has been processed already in the past. The amount of processed work depends on the total time that the vessel has been berthing already, and how many cranes have been processing the vessel during this time period. Depending on how much work has been processed, a certain part of Q_v still needs to be processed.

The remaining berth time interval $[a_v, d_v]$ is determined exactly the same way as explained for the non-berthing vessel. The only difference is that start of berth time must be equal to k_c , since the berth time interval cannot be interrupted. If the berth time interval lies within the green arrows low negative costs can be achieved. If the berth time interval lies within the orange part, medium costs are introduced, and if the berth time interval lies within the red area, high costs are introduced.

Costs for overtaking desirable predecessors: static positioning

The berth time intervals calculated in the TAP, influence the quality of the obtained positions in the PAP. This is because the obtained position is dependent on time. Therefore, the berth time intervals of the vessels need to be determined such that low cost berth positions of the vessels are obtained in the PAP.

The concept that is used to obtain low cost berth positions, is to determine desirable predecessors of certain vessels (not to be confused with relevant predecessors to prevent infeasibilities). However, the approach that is used to search and define the desirable predecessors has similarities with the approach discussed earlier for the relevant predecessors. The set Z_j contains all desirable predecessors of vessel j. This information is obtained from the:

- reference berth allocation, in case of a static positioning strategy,
- previously calculated berth allocation, in case of a dynamic positioning strategy.

The algorithm which determines the sets Z_j is also executed before the actual optimization in the TAP. Depending on the positioning strategy that is used (static or dynamic), a different algorithm is used to determine the set Z_j .

In case of a static positioning strategy the following algorithm is used. For each vessel j, verify from the reference berth allocation whether:

$$D_i^* < A_j^*, \tag{3.7}$$

and

$$R_i^* + \frac{1}{2} \cdot L_i > R_j^* - \frac{1}{2} \cdot L_j, \qquad (3.8)$$

and

$$R_i^* - \frac{1}{2} \cdot L_i < R_j^* + \frac{1}{2} \cdot L_j.$$
(3.9)

If (3.7), (3.8), (3.9) hold, then $i \in \mathbb{Z}_j$. This implies that each vessel *i* is a desirable predecessor of vessel *j* if is valid that:

- the reference departure time of vessel i is less than or equal to the reference arrival time of vessel j, and
- the reference position of vessel *i* overlaps with the reference position of vessel *j*,

Then in the TAP, a constant cost factor is assigned to each time slot that vessel j starts to berth earlier than $\max\{d_i\}, i \in \mathbb{Z}_j$.

By using this concept of desirable predecessors in the TAP, it is tried to remain the same berth sequence in time as stated in the reference. The main reason for using this concept of desirable predecessors on the start of berth time of a vessel, is to obtain low cost berth positions for the vessels in the terminal.

Example 3.4 shows the application of this algorithm, and the consequences of objective 4 in the TAP for the static positioning case.

Example 3.4 Desirable predecessors: static positioning

Consider for instance the graphical example in Figure 3.12, where the berth behavior (in time and position) of vessel 5 is considered in detail. The first berth allocation shows the reference over a planning horizon. The second berth allocation shows the calculated planning over the same planning horizon without using desirable predecessors, and the third berth allocation shows the calculated planning over the same planning horizon with the concept of desirable predecessors.

In both scenario's, with and without desirable predecessors, vessel 1, 2, 3 and 4 arrive exactly



Figure 3.12: Graphical example of desirable predecessors, for a static positioning strategy.

according to the reference arrival time, whereas vessel 5 arrives five time slots earlier than stated in the reference. In case the concept of desirable predecessors is not used, vessel 5 can start to berth at its arrival time, since there is enough unoccupied quay available and there is no relevant predecessor for vessel 5 (all vessels on the planning horizon are non-berthing). However, this means that both vessel 5 and vessel 4 have to deviate from their reference berth position, see Figure 3.12. In case the concept of desirable predecessors is used, there are costs assigned to each time slot that vessel 5 starts to berth earlier than the maximum of the departure times of the vessels which are in the set \mathbb{Z}_5 . Since in this example vessel 4 is the desirable predecessor with the largest departure time, vessel 5 waits to start berthing until vessel 4 has departed. Therefore, the berth time interval of vessel 5 remains behind the berth time interval of vessel 4. Now both vessel 4 and 5 can berth at their reference position. Hence, a lower cost position allocation is obtained. In case a desirable predecessor $i \in \mathbb{Z}_j$ arrives very late, the model weighs if the berth time interval of vessel j should remain behind the departure time of vessel i. In general, the cost factors have to be chosen such that the event described here does not cause a delayed departure for vessel j, especially not when the vessel arrives early or on time.

Costs for overtaking desirable predecessors: dynamic positioning

In case of a dynamic positioning strategy, a very similar concept is used to determine the sets \mathcal{Z}_j . The following procedure is used in case of a dynamic positioning strategy and consists of two possibilities:

if:

- 1. $A_v k_c \ge 24$: the set with desirable predecessors \mathcal{Z}_j is determined the same way as in the static case,
- 2. $A_v k_c < 24$: the set \mathcal{Z}_j is determined in a different way to be explained next.

So in situation 1, $i \in \mathbb{Z}_j$ if (3.7), (3.8) and (3.9) hold. In situation 2, the following approach is used. The dynamic version of the PAP positions the vessels according to the ratio of container types that have to be loaded and unloaded. The optimal

positions of the vessel in the terminal could have changed with respect to the reference. Therefore it is possible that a certain vessel i which was a desirable predecessor for vessel j in the reference berth allocation, is no longer a desirable predecessor for vessel j anymore. This information must be incorporated in the TAP to determine the berth time intervals.

The following algorithm is used to determine Z_j when $A_v - k_c < 24$. For each vessel j, verify from the reference berth allocation and the previously calculated berth allocation whether:

$$D_i^* < A_j^*, \tag{3.10}$$

and

 $d_i < a_j, \tag{3.11}$

and

$$p_i + \frac{1}{2} \cdot L_i > p_j - \frac{1}{2} \cdot L_j,$$
 (3.12)

and

$$p_i - \frac{1}{2} \cdot L_i < p_j + \frac{1}{2} \cdot L_j, \tag{3.13}$$

where d_i , a_j , p_i and p_j are known variables obtained from the previously calculated berth allocation, and the information needed for (3.10) is directly derived from the reference berth allocation. Then $i \in \mathbb{Z}_j$ if (3.10), (3.11), (3.12) and (3.13) hold. Similar to the static case, this algorithm is executed prior to the TAP optimization in order to determine the set Z_j . Then in the objective of the TAP, a constant cost factor is assigned to each time slot that vessel j starts to berth earlier than max $\{d_i\}, i \in Z_j$.

Example 3.5 shows the application of this algorithm, and the consequences of objective 4 in the TAP for the dynamic positioning case.

Example 3.5 Desirable predecessors: dynamic positioning

Consider the situation in Figure 3.13 where 2 successively calculated berth allocations are depicted with their reference berth allocation (in time and position). In this graphical example, vessel 5 is observed in particular.

The previous berth allocation calculated at $t = k_c - 1$, provides the following information. The berth time intervals of vessel 1, 2, 3 and 4 are allocated exactly as stated in the reference, whereas vessel 5 starts to berth two time slots earlier. The position of each vessel has changed from its original reference position. Apparently, the vessels have a different ratio of container types that have to be loaded and unloaded, and therefore the vessels are allocated to a lower cost berth position by the dynamic version of the PAP. Vessel 5 is expected to arrive during time slot 24.



Figure 3.13: Graphical example of desirable predecessors, for a dynamic positioning strategy.

However, it cannot start berthing at time slot 24 yet. This is because its desirable predecessors are determined according to (1), where Z_5 is determined by (3.7), (3.8), and (3.9). According to (1), vessel 4 is a desirable predecessor of vessel 5. Therefore, the distance between the start of berth time of vessel 5 and the departure time of vessel 4 is minimized. As depicted, vessel 5 starts

to berth at the departure time of vessel 4, which implies zero costs.

Although vessel 5 has no overlap in position with vessel 4 anymore in the operational berth allocation, it is attempted to keep the same berth sequence in time as stated in the reference. The advantage of this, is that vessel 5 is still able to reach its reference position again when the position is determined in the PAP. This can be observed in Figure 3.13, where vessel 5 can still move in vertical direction.

The current berth allocation at $t = k_c$, provides the following information. Vessel 5 is now expected to arrive during time slot 23. Now the set of desirable predecessors of vessel 5, \mathcal{Z}_5 , is determined according to (2), because $A_v - k_c < 24$. As can be observed from the previous berth allocation, this means that only vessel 2 is still a desirable predecessor of vessel 5. In this example, vessel 5 starts to berth at the departure time of vessel 2, which implies zero costs again.

As explained by Example 3.5, it is attempted to keep the vessels first in the same berth sequence as in the reference planning, if possible. By attempting to keep the vessel behind its desirable predecessor according to (1), it is tried to remain freedom in vertical direction (position) in the PAP. Notice in Figure 3.13 for instance, that once vessel 5 is positioned next to vessel 4, the PAP cannot position the vessel to its reference position anymore.

At 24 hours before actual berthing, if it appears that the optimal berth position has moved from its reference, then the desirable predecessors are determined according to (2). At that point, the vessel can move forward in time until it either starts to berth at its arrival time, or it starts to berth at the departure time of its new desirable predecessor.

The weight factor for holding vessels behind desirable predecessors needs to be chosen appropriately. For instance, this strategy should in general not cause any delays in departure.

Now the system description of the TAP has been given, and the objectives have been explained, the mathematical formulation of the TAP can be given.

3.4.3 MILP

In this subsection, the TAP is formulated as a MILP.

Continuous variables

$m_v(k)$	=	Amount of quay meters consumed in the terminal by vessel v during
		time slot k, which is in between time instant $\langle k, k+1]$.
$q_v(k)$	=	Number of quay cranes processing vessel v in the terminal during
		time slot k, which is in between time instant $\langle k, k+1 \rangle$.
n	=	Number of quay cranes required in the terminal.

Integer variables

a_v	=	The time instant where vessel v starts berthing. If $a_v = k_c$, then the
		vessel is currently berthing. When $a_v = k$, the vessel berths
		during time slot k, which is in between time instant $[k, k+1)$.
-		

 d_v = The time instant where vessel v departs or has departed. When $d_v = k$, the vessel leaves in time slot k - 1, which is in between time instant $\langle k - 1, k \rangle$.

Auxiliary integer variables

- Earliest departure time of vessel v which assures a start of berthing after \hat{a}_v =the last desirable predecessor has departed.
- Δ_v^a = Absolute value of the difference between a_v and \hat{a}_v .
- Δ_v = Number of time slots vessel v departs early or late.
- $\begin{array}{c} \Delta_v^+ \\ \Delta_v^- \end{array}$ Number of time slots vessel $v \in \{\mathcal{V}_{\mathcal{B}}^+, \mathcal{V}^+\}$ departs too late. =
- Number of time slots vessel which a vessel $v \in \{\mathcal{V}_{\mathcal{B}}^{-}, \mathcal{V}^{-}\}$ departs too late. =
- Maximum number of additional quay cranes above N, ever used on Δ_n = the planning horizon .

Auxiliary binary variables

$$b_v(k) = \begin{cases} 1 & \text{if vessel } v \text{ is berthing during time slot } \langle k, k+1 \rangle \\ 0 & \text{otherwise.} \end{cases}$$

Constraints

For each vessel considered on the time horizon, a_v and d_v have to be larger than or equal to the current time slot k_c , and a_v and d_v have to be smaller than the end of the planning horizon. Furthermore a_v should always be smaller than d_v :

$$k_c \le a_v \le k_c + H \qquad \forall v, \tag{3.14}$$

and

$$k_c \le d_v \le k_c + H \qquad \forall v, \tag{3.15}$$

and

$$a_v < d_v \qquad \forall v. \tag{3.16}$$

A vessel cannot start berthing before it actually has arrived. Therefore, the following constraint must be valid for each vessel that is not actually berthing yet:

$$a_v \ge A_v \qquad \forall v \in \{\mathcal{V}^+, \mathcal{V}^-\}. \tag{3.17}$$

For all vessels which were berthing during the previous time slot $k_c - 1$, (3.18) must hold. This means that if a vessel v was berthing during the previous time slot, it must continue berthing until the vessel has been fully processed. A berth time interval cannot be interrupted:

$$a_v = k_c \quad \forall v \in \{\mathcal{V}_{\mathcal{B}}^+, \mathcal{V}_{\mathcal{B}}^-\}.$$
(3.18)

Vessel v berths between a_v and d_v respectively. Generic constraints are needed, which relate a_v and d_v to $b_v(k)$ as well as $b_v(k)$ to a_v and $b_v(k)$ to d_v :
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$$\sum_{k=k_c}^{k_c+H} b_v(k) = d_v - a_v \qquad \forall v,$$
(3.19)

and

$$(k_c + H - k + 1) \cdot b_v(k) \le k_c + H - a_v \qquad \forall v, k, \tag{3.20}$$

and

$$(k_c + k) \cdot b_v(k) \le d_v \qquad \forall v, k. \tag{3.21}$$

If vessel v is berthing during time slot k, then it consumes L_v quay meters in the terminal during time slot k:

$$m_v(k) = L_v \cdot b_v(k) \qquad \forall v, k. \tag{3.22}$$

Furthermore, the sum of the lengths of all vessels berthing at the terminal quay during time slot k should be less than or equal to the total quay length of the terminal:

$$\sum_{v \in \mathcal{V}_h} m_v(k) \le L \qquad \forall k. \tag{3.23}$$

When a vessel actually starts berthing, its position along the quay becomes fixed. In order to prevent infeasibilities on the planning horizon when the PAP is solved, certain vessels must remain in time behind their relevant predecessor such that overtaking in time is prevented. The start of berthing time of a non-berthing vessel j needs to stay in time behind the departure time of each vessel $i \in W_j$:

$$a_j \ge d_i \quad \forall i \in \mathcal{W}_j, j \in \{\mathcal{V}^+, \mathcal{V}^-\}.$$
 (3.24)

If possible, a vessel j should not berth before all its desirable predecessors $i \in \mathbb{Z}_j$ have departed. Which vessels are considered desirable predecessors depend on whether a dynamic or static PAP is solved, and has been explained in section 3.4.2. In order to do this, an auxiliary variable \hat{a}_j is introduced first, which needs to be equal to or larger than each departure time of vessel $i \in \mathbb{Z}_j$:

$$\hat{a}_j \ge d_i \qquad \forall i \in \mathcal{Z}_j, j \in \{\mathcal{V}^+, \mathcal{V}^-\}.$$
(3.25)

In order to obtain a start of berth time of non-berthing vessel j which is not larger than the highest departure of its desirable predecessors $i \in \mathbb{Z}_j$, the distance $|a_j - \hat{a}_j|$ is minimized. Since the TAP is formulated as a MILP, the absolute value needs to be eliminated. For this, an auxiliary variable Δ_i^a is introduced which is minimized in the objective:

$$\Delta_j^a \ge a_j - \hat{a}_j \qquad \forall j \in \{\mathcal{V}^+, \mathcal{V}^-\},\tag{3.26}$$

and

$$\Delta_v^j \ge \hat{a}_j - a_j \qquad \forall j \in \{\mathcal{V}^+, \mathcal{V}^-\}.$$
(3.27)

A maximum number of quay cranes S_v can be allocated to vessel v during time slot k:

$$q_v(k) \le S_v \cdot b_v(k) \qquad \forall v, k. \tag{3.28}$$

Vessel v has to be fully processed on the planning horizon. This means that the total number of quay cranes allocated to vessel v over time has to be sufficient to process the total amount of remaining / forecasted work Q_v :

$$\sum_{k=k_c}^{k_c+H} \eta_v \cdot \bar{\lambda} \cdot q_v(k) = Q_v \qquad \forall v.$$
(3.29)

The maximum number of additional quay cranes in operation above N which is ever required on the planning horizon is minimized. The first N quay cranes can be used without introducing any costs. But first, an auxiliary variable n is introduced which is a soft upper bound on the number of quay cranes used in the terminal during the planning horizon:

$$\sum_{v \in \mathcal{V}_h} q_v(k) \le n \qquad \forall k.$$
(3.30)

Then the maximum number of additional quay cranes in operation above the basic quay crane usage N, which is ever required on the time horizon is defined as: $\max\{n - N, 0\}$. An additional auxiliary variable Δ_n is required to eliminate the max function, which is then minimized in the objective function:

$$\Delta_n = n - N, \tag{3.31}$$

and

$$\Delta_n \ge 0. \tag{3.32}$$

Furthermore, the maximum number of quay cranes ever required in the terminal on the time horizon cannot be larger than the actual number of quay cranes that are available in the terminal:

$$n \le N_{max}.\tag{3.33}$$

When a vessel arrives on time or early, it should leave before or at D_v^{max} . When the vessel arrives later than D_v^{max} , the agreement is violated. The delay in departure is measured specifically for the vessels that have arrived on time or early and is defined as: $\max\{d_v - D_v^{max}, 0\}$. An additional auxiliary variable Δ_v^+ is required to eliminate the max function, which is then minimized in the objective function:

$$\Delta_v^+ \ge d_v - D_v^{max} \quad \forall v \in \{\mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\},\tag{3.34}$$

and

$$\Delta_v^+ \ge 0 \qquad \forall v \in \{\mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\}. \tag{3.35}$$

When a vessel arrives late, there is no strict agreement on the maximum departure time. However, the vessel should depart within in an acceptable time interval to obtain a good service level. The shortest process time wherein a vessel can be processed is equal to $A_v + P_v^{min}$. However, an additional time slot is required to prevent infeasibilities in the QCAP. The delay in departure is measured specifically for the vessels that have arrived late and is defined as:

$$\max\left\{ \left(d_v - \max\{D_v^{max}, A_v + P_v^{min} + 1\} \right), 0 \right\}.$$

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An additional auxiliary variable Δ_v^- is required to eliminate the outer max function (the inner max function is only dependent on parameters and does not have to be eliminated). This auxiliary variable is then minimized in the objective function:

$$\Delta_v^- \ge d_v - \max\{D_v^{max}, A_v + P_v^{min} + 1\} \quad \forall v \in \{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-\},\tag{3.36}$$

and

$$\Delta_{v}^{-} \ge 0 \qquad \forall v \in \{\mathcal{V}^{-}, \mathcal{V}_{\mathcal{B}}^{-}\}.$$

$$(3.37)$$

If a vessel departs earlier than $\max\{D_v^{max}, A_v + P_v^{min} + 1\}$, then this must be rewarded. The auxiliary variable Δ_v which is minimized in the objective function is defined as:

$$\Delta_v \ge d_v - \max\{D_v^{max}, A_v + P_v^{min} + 1\} \quad \forall v.$$
(3.38)

Notice here that actually the deviation in departure from $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$ is minimized, which implies that a reward is obtained when vessel v departs earlier than $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$, and (additional) penalty costs are introduced when vessel v departs later than $\max\{D_v^{max}, A_v + P_v^{min} + 1\}$. In the latter situation, these penalty costs are in addition to the delay costs already introduced by Δ_v^+ or Δ_v^- .

Finally, some of the continuous variables have to be lower-bounded:

$$q_v(k) \ge 0 \qquad \forall v, k. \tag{3.39}$$

Objective function

The decision variables are represented in vector $\vec{u}(k) = [a_v, d_v, q_v(k)]^T$. The objective function can be defined as:

$$\min_{\vec{u}(k_c),\dots,\vec{u}(k_c+H)} \sum_{v \in \mathcal{V}_h} C_v \Delta_v + \sum_{v \in \{\mathcal{V}_{\mathcal{B}}^+, \mathcal{V}^+\}} C_v^+ \Delta_v^+ + \sum_{v \in \{\mathcal{V}_{\mathcal{B}}^-, \mathcal{V}^-\}} (C_v^- \Delta_v^- + \sum_{v \in \mathcal{V}_h} C_a \Delta_v^a + C_n \Delta_n.$$
(3.40)

- 1. The first term assigns low linear penalty costs, C_v , to each time slot that vessel v departs later than $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$, and low linear negative costs to each vessel that departs earlier than $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$. The latter situation is therefore a reward.
- 2. The second term assigns high linear penalty costs, C_v^+ , to each time slot that a vessel, which arrives early or on time, departs later than D_v^{max} .
- 3. The third term assigns medium linear penalty costs, C_v^- , to each time slot that a vessel, which arrives late, departs later than $\max\{D_v^{max}, (A_v + P_v^{min} + 1)\}$.
- 4. The fourth term assigns linear penalty costs, C_a , to each time slot that a vessel starts to berth earlier than the highest departure time of its desirable predecessors.
- 5. The fifth and last term assigns linear penalty costs C_n to each extra crane that is used above a basic quay crane usage N.

3.5 Position Allocation Problem

In this section the PAP is treated. The system description of the PAP is given, followed by the mathematical formulation of the PAP.

3.5.1 System Description

Problem

The PAP is formulated as a one-dimensional packing problem, where the vessels given in the set \mathcal{V}_h have to be positioned along the terminal quay.

Constraints

The start of berthing times and departure times of the vessels have already been determined by the TAP and are therefore used as input parameters for the PAP.

The terminal has a restricted quay length L. The leftmost side of the terminal is indicated by 0, and the rightmost side of the terminal by L. Each vessel requires a certain amount of quay meters L_v in between its start of berthing time and departure time. The position of the vessel is represented by its center. So each vessel is at least half its vessel length removed from both end sides of the terminal, i.e. from 0 and L.

Vessels can not overlap in position with each other. Moreover, a safety gap is added to each vessel's length, such that there is always a certain open space in between the vessel ends. In order to prevent overlap in position for vessels that berth simultaneously in the terminal, binary variables are used to indicate on which side a vessel is positioned with respect to another vessel. The set \mathcal{U} contains the indices of pairs of vessels that are berthing simultaneously during at least one time interval.

Objective

The objective in the PAP is to allocate the positions of the vessels on the planning horizon, such that the total costs are minimized. Linear costs are assigned the deviation in between the allocated berth position of a vessel and its lowest cost berthing position. A cost factor C_v^p is assigned to the size of the deviation. The cost factor C_v^p is proportional to Q_v . Two different positioning strategies are investigated: a dynamic and static positioning strategy:

- In the static positioning strategy, the lowest cost berth position is assumed to be located at the reference position R_v of a vessel, such as stated in the reference berth allocation. The reference positions are determined such that the total driving distances of the straddle carriers are minimized. This implies that on an operational level the positions R_v are optimal in case the vessels arrive and depart according to the reference, and load and unload the exact number and type of containers as stated in the reference.
- In the dynamic positioning strategy the lowest cost berth position is based directly on the distance that the straddle carriers have to travel to transport the containers. For this, the type of each container and location of the container stacks in the terminal need to be known. The vessel is positioned according to the currently available information about containers and vessels arrival times. Then the straddle carrier driving distance can be minimized by allocating the vessels to a certain position along the terminal quay. The advantage of this is that optimal berth positions of the vessels on the planning horizon are calculated online, and can react on disturbances.

The prognosis is that the dynamic positioning strategy results in an equal or lower average straddle carrier driving distance when compared to a static positioning strategy. When a vessel arrives at a different time than stated in the reference, or when a different ratio of containers types need to be handled, the lowest cost berth position is not necessarily located at R_v anymore.

The static positioning strategy is rather straightforward. The dynamic positioning strategy needs to know information about the exact container types. Therefore, the dynamic positioning strategy is explained in more detail next.

Outline dynamic positioning

In the dynamic positioning strategy, the straddle carrier driving distance are used directly to determine the optimal berth allocation. For this, the straddle carrier driving distance needs to be known as a function of the berth position of the vessel. How this is incorporated is discussed next. The straddle carriers have to travel a certain distance to transport the containers from vessel to vessel, from vessel to stack, or vice versa. This distance depends on the position of the vessels along the terminal quay and the position of the relevant stacks in the terminal. As discussed in section 2.2, there are 5 types of containers that can be imported and exported, and there are transshipment containers. The following assumptions about these container types are made:

- 1. The empty 1, empty 2, reefers, and imco containers have fixed stack positions in the terminal. Import is transported to these stacks, and export is retrieved from these stacks.
- 2. Export of regular containers are stacked at a position in the terminal which depends on the type of vessel.
- 3. Import of regular containers are stacked at a constant distance from the berth position of the vessel.
- 4. Transshipment containers are stacked at a constant distance from the berth position of the source vessel (where the containers came from).

With these assumptions, the driving distance of the straddle carriers can be estimated.

For (1), the average driving distance for these four container types are estimated by 4 different functions. For each container type there exists one function which gives the estimated driving distance as a function of the berth position of the vessel. These functions can be obtained by taking measurements in the real-life terminal. Then an approximation of these driving distance functions is constructed by using piecewise linear functions.

For (2), also functions are used which estimate the driving distance as a function of the berth position of the vessel. Since the export regular containers are stacked at a specific position in the terminal dependent on the vessel, a specific function for each vessel is used. Again for each of these functions, approximations of these driving distances are constructed by using piecewise linear functions.

For (3), The driving distance for the import of regular containers is assumed to be a constant on average, since the import regular containers are always stacked at the allocated berth position of the vessel.

For (4), the driving distance for transshipment containers is assumed to be equal to the distance between the berth position of the source vessel and the berth position of the destination vessel.

The total driving distance required for a single vessel on the planning horizon is equal to sum of all containers from a certain type multiplied by the travel distance as defined by 1, 2, 3, and 4. The optimal berth position in the dynamic positioning strategy is then obtained by minimizing the total amount of straddle carrier driving distance for the vessels on the planning horizon.

3.5.2 MILP

In this section, the PAP is formulated as a MILP. All the parameters required for the PAP can be found in Table 3.3. All the parameters, vessel sets, and container definitions required for the formulation of the PAP can also be found in Appendix D. First the variables of the problem are defined. Then the constraints of the PAP are given. Finally, the objective function is given where a distinction is made in between the static positioning strategy, and the dynamic positioning strategy.

Parameter	Definition
Н	Planning horizon length [time slots].
L_v	Required quay length $[m]$ for vessel v to berth at the terminal.
L	Total quay length [m].
C_v^p	Cost factor for vessel v berthing for the deviation from the
	lowest cost berth position.
P_v	Fixed berth position of vessel v .
ξ	Sufficiently large number.
R_v^*	Reference berth position of vessel v .

Table 3.3: Definition of parameters for the PAP.

Continuous variable

 p_v : Position of the center of vessel v.

Binary variable

$$s_{ij} = \begin{cases} 1 & \text{if vessel } i \text{ is positioned to the left of vessel } j, \\ 0 & \text{otherwise.} \end{cases}$$

Constraints

Each vessel has to stay entirely within the boundaries of the terminal quay length:

$$\frac{L_v}{2} \le p_v \le L - \frac{L_v}{2} \qquad \forall v. \tag{3.41}$$

Two vessels, which berth simultaneously cannot overlap in position with each other:

$$p_i - p_j \ge \frac{L_i + L_j}{2} - s_{ij} \cdot \xi \qquad \forall \{i, j\} \in \mathcal{U},$$
(3.42)

and

$$p_i - p_j \ge \frac{L_i + L_j}{2} - \left(1 - s_{ij}\right) \cdot \xi \qquad \forall \{i, j\} \in \mathcal{U}.$$

$$(3.43)$$

Vessel *i* is either allocated to the left or to the right from vessel *j*. If vessel *i* is allocated to the left from vessel *j*, i.e. $p_i - p_j < 0$, constraint (3.42) can only be fulfilled when $s_{ij} = 1$, since then the

sufficiently large number ξ is deducted. In that case, constraint (3.43) ensures that the centers of vessel *i* and *j* are at least half the vessel's lengths separated from each other. If vessel *i* is allocated to the right of vessel *j*, i.e. when $p_i - p_j > 0$, then s_{ij} is forced to 0 by constraint (3.43). In that case constraint (3.42) ensures that the centers of vessel *i* and *j* are at least half the vessel's lengths separated from each other. An appropriate choice for the sufficiently large number ξ would be the terminal length *L*.

Vessels which are currently berthing on the planning horizon (and which were berthing at $t = k_c - 1$), have to be allocated to the same position as in the previous berth allocation. Hence, the position of these vessels are fixed and already determined by:

$$p_v = P_v \qquad \forall v \in \{\mathcal{V}_{\mathcal{B}}^+, \mathcal{V}_{\mathcal{B}}^-\},\tag{3.44}$$

where P_v is the fixed berthing position of vessel v, determined from the previous berth allocation.

Objective function static case

In case when the static positioning strategy is used, the objective is to minimize the distance to each vessel's reference berth position R_v :

$$\min \sum_{v \in \mathcal{V}_h} C_v^p \cdot |p_v - R_v|.$$
(3.45)

where the reference berth position is obtained from the reference berth allocation. The size of the cost factor depends on the amount of containers that have to be handled for each vessel: $C_v^p = \frac{Q_v}{Q_{max}}$, where Q_{max} is the maximum number of containers that can be loaded and unloaded from the largest vessel in the simulation model. The more containers have to be handled for a particular vessel, the higher the cost factor C_v^p , and the more important it is to position this vessel close to R_v .

Since the problem is formulated as a linear optimization problem, the absolute value in (3.45) needs to be eliminated. For this, an auxiliary variable Δ_v^p is introduced, which transforms the objective of (3.45) into:

$$\min \sum_{v \in \mathcal{V}_h} C_v^p \cdot \Delta_v^p, \tag{3.46}$$

where

$$\Delta_v^p \ge p_v - R_v \qquad \forall v, \tag{3.47}$$

and

$$\Delta_v^p \ge R_v - p_v \qquad \forall v. \tag{3.48}$$

Objective function dynamic case

In case when the dynamic positioning strategy is used, the objective is to minimize the total driving distance of the straddle carriers over the current planning horizon. The objective function of the dynamic positioning strategy is formulated as:

$$\min \sum_{i \in \mathcal{V}_h} \left((q_v^2 + q_v^7) \cdot D_{reef}(p_v) + (q_v^3 + q_v^8) \cdot D_{imco}(p_v) + q_v^4 \cdot D_{ireg}(p_v) + q_v^9 \cdot D_{ereg}(p_v) + (q_v^5 + q_v^{10}) \cdot D_{emp1}(p_v) + (q_v^6 + q_v^{11}) \cdot D_{emp2}(p_v) \right) + \sum_{i \in \mathcal{V}_h} \sum_{j \in \mathcal{V}_h} \Omega_{ij} \cdot |p_i - p_j| + \sum_{i \in \mathcal{V}_{hh}} \sum_{j \in \mathcal{V}_h} \sum_{j \in \mathcal{V}_h} \left(\Omega_{ij} + \Omega_{ji} \right) \cdot |P_i - p_j|.$$

where $q_v^2 + q_v^7$ represent the number of reefer import and export containers, $q_v^3 + q_v^8$ the number of imco import and export containers, q_v^4 the number of regular import containers, q_v^9 the number of regular export containers, $q_v^5 + q_v^{10}$ the number of empty 1 import and export containers, $q_v^6 + q_v^{11}$ the number of empty 2 import and export containers, and Ω_{ij} the number of transshipment containers from vessel *i* to vessel *j*, respectively.

The functions $D_{reef}(p_v)$, $D_{imco}(p_v)$, $D_{ireg}(p_v)$, $D_{ereg}(p_v)$, $D_{emp1}(p_v)$, and $D_{emp2}(p_v)$ are the approximations of the straddle carrier driving distances for the transportation of reefers, imco's, import regular, export regular, empty 1, and empty 2 containers respectively, as a function of the allocated berth position p_v .

It is possible that there is transshipment from vessel i to vessel j, where both these vessels are currently on the planning horizon, i.e. $\{i, j\} \in V_h$. Furthermore, it is also possible that there is transshipment from vessel i which is currently not on the planning horizon, i.e. $i \in V_{nh}$, to vessel j which is on the planning horizon, i.e. $j \in V_h$, and vice versa. The position of the vessel which is not on the horizon P_v , is either determined by the location where the vessel has berthed in the past, or if the vessel has not berthed yet the position of the vessel is determined by the reference position.

In order to obtain a linear optimization problem, the absolute values of the objective function have to be eliminated. Hence, an auxiliary variable Δ_{ij} is introduced which transforms the objective function into:

$$\min \sum_{i \in \mathcal{V}_h} \left((q_v^2 + q_v^7) \cdot D_{reef}(p_v) + (q_v^3 + q_v^8) \cdot D_{imco}(p_v) + q_v^4 \cdot D_{ireg}(p_v) + q_v^9 \cdot D_{ereg}(p_v) + (q_v^5 + q_v^{10}) \cdot D_{emp1}(p_v) + (q_v^6 + q_v^{11}) \cdot D_{emp2}(p_v) \right) + \sum_{i \in \mathcal{V}_h} \sum_{j \in \mathcal{V}_h} \Omega_{ij} \cdot \Delta_{ij} + \sum_{i \in \mathcal{V}_{nh}} \sum_{j \in \mathcal{V}_h} \left(\Omega_{ij} + \Omega_{ji} \right) \cdot \Delta_{ij},$$

where

$$\Delta_{ij} \ge p_i - p_j \quad \forall \{i, j\} \in V_h,$$

$$\Delta_{ij} \ge p_j - p_i \quad \forall \{i, j\} \in V_h,$$

$$(3.49)$$

$$(3.50)$$

and

$$\Delta_{ij} \ge P_i - p_j \qquad \forall i \in V_{nh}, j \in V_h, \tag{3.51}$$

 $\Delta_{ij} \ge p_j - P_i \qquad \forall i \in V_{nh}, j \in V_h.$ (3.52)

3.6 Quay Crane Allocation Problem

In this section, the Quay Crane Allocation Problem (QCAP) is discussed. Only the system description is given here.

3.6.1 System Description

Problem

The problem in the QCAP is to allocate the available quay cranes to the vessel present on the planning horizon. For this, a discrete formulation is used as presented in [Karsemakers, 2008]. The advantage of the discrete formulation is that a quay crane can switch from vessel in between the discrete time slots.

Constraints

In each terminal a restricted number of quay cranes is available to process the vessels, where each quay crane has its specific process rate. In general, the quay cranes at the middle of the terminal have higher process rates, since the straddle carriers can reach the quay cranes at the middle of the quay more easily than the quay cranes at the side of the terminal. The quay cranes are able to move along the terminal and thus along the vessels. Since the quay cranes are all situated on the same track, it is not possible for the quay cranes to cross each other.

During a discrete time slot, a quay crane is either idle or it processes a certain vessel for that time slot. Because a discrete formulation is used, it is possible for a quay crane to switch from vessel in between the discrete time slots.

Each vessel has a certain number of containers Q_v that need to be handled. Furthermore, each vessel has a certain process efficiency factor η_v . Larger vessels can usually be processed more efficiently, and therefore have a higher process efficiency factor. The maximum number of quay cranes that can simultaneously process a vessel is determined by S_v .

Quay cranes can process a vessel v by obtaining a position somewhere in between $p_v - \frac{1}{2}L_v$ and $p_v + \frac{1}{2}L_v$, where p_v is the position of the middle of the vessel determined by the PAP, and L_v the vessel length. In between two neighboring quay cranes, there exists a minimal gap G.

Each vessel must have been fully processed before it can depart. The start of berthing and departure time is determined in the TAP. So the possibility of a delay in the QCAP is excluded. This implies that the berth time interval calculated in the TAP, must be sufficiently large to fully process the vessel within this berth time interval.

Objective

The objective in the QCAP is to minimize:

- 1. the maximum number of quay cranes ever required on the planning horizon,
- 2. useless quay crane processing interruptions during a berth time interval of a vessel on the planning horizon,
- 3. useless quay crane processing interruptions during a berth time interval of a vessel in between the previous hour $k_c 1$ (at the beginning of the previous planning) and the current hour k_c (at the beginning of the current planning),
- 4. the isolations of an idle quay crane in between two processing quay cranes,

5. the movements of all the quay cranes in the terminal over the planning horizon.

The first contribution in the objective is used to balance the workload over the planning horizon. The second contribution in the objective is used to process the vessel as fast as possible/desirable, and to prevent unnecessary quay crane idling when a vessel is processed.

The third contribution of the objective function is required due to the fact that the quay crane allocation is constructed at each hour. It is preferred that quay cranes that have been processing vessel v during the previous hour continue to process vessel v in the current time slot at the beginning of the current planning horizon. Otherwise, it is possible that unnecessary quay crane switches arise.

The fourth contribution in the objective is used to prevent blocking of quay cranes. Due to the non-crossing constraint of the quay cranes, it is possible that an idle quay crane is locked in between two active quay cranes. In order to use the this idle quay crane, one of the active quay cranes needs to move.

The fifth contribution in the objective is used to minimize the number of quay crane switches. The reason for this is that these switches cause set-up times, and must be prevented if this does not lead to a faster process time of a vessel.

Horizon and heuristics procedure

The length of the planning horizon H_{qc} is chosen on-line. For example, the standard length of this planning horizon can be set equal to $H_{qc} = x$. If the number of vessels considered on the horizon is less than 2, then a longer planning horizon $H_{qc} > x$ is temporarily used until 2 vessels are considered on the horizon. Furthermore, if the number of vessel on the planning horizon of length $H_{qc} = x$ is larger than y, a heuristics procedure is applied to solve the QCAP. This heuristics procedure is only required when many vessels are considered on the horizon, since the QCAP can then become computational expensive.

For more information about the heuristics procedure of the discrete QCAP, and for the mathematical formulation of the QCAP, see [Karsemakers, 2008].

In this chapter, the Planning Controller has been thoroughly discussed. The three subproblems of the Planning Controller have been defined, and the stability issues due to the chosen cut and a limited horizon length haven been discussed. Different measures have been suggested to solve these instabilities. In Chapter 2, the simulation model has been discussed. The performance of the Planning Controller can now be tested by connecting it to this simulation model. In Chapter 4, an experimental set-up is given and the results of the experiments are discussed.

Chapter 4

Simulation experiments

In this chapter, the performance of the Planning Controller is investigated. In the first section, a general experimental set up is given of the terminal under investigation. The assumptions for the experiments are given here. After the experimental set up has been treated, a further outline of the experiments in this chapter is given.

4.1 Experimental set up

This section is structured as follows. First the terminal layout of the investigated terminal is treated. Then the available strategic planning of this terminal is shortly discussed. Subsequently, it is explained how the simulation replications are performed. The section is concluded with the formulation of the performance indicators, followed by a further outline of the experiments in this chapter.

Terminal layout

One particular terminal is investigated here. For this terminal, the following real life data is available:

- Terminal length: 1125 meters.
- Number of installed quay cranes: 7.
- Container stack positions in terminal:
 - empty 1: stacked at the center of the terminal,
 - empty 2: stacked at the rightmost side of the terminal,
 - reefers: stacked at the rightmost side of the terminal,
 - imco: stacked at three positions in the terminal, where all three positions are located at the rightmost side of the terminal,
 - regular:
 - * import: stacked at the berth position of the vessel,
 - * export: stacked at a specific position in the terminal depending on the vessel,
 - transshipment: stacked at the berth position of the source vessel,



Figure 4.1: The distance that a single SC has to travel to transport a container to a certain stack in the terminal as a function of the vessel position.

where, the imco containers are located at this position due to safety regulations, and the reefer containers located at this position due to the availability of power outlets to cool the containers. The transshipment containers are explicitly not of the type reefer or imco, since in that case a transshipment container is stored in the reefer stack to cool the container or to the imco stack due to the regulations.

As explained in section 2.2, the straddle carrier (SC) driving distances are measured in the simulation model by functions. These function are also used in the dynamic PAP to minimize the total SC driving distance on the planning horizon, as explained in section 3.5.1. For this terminal, these functions are obtained from [van Overmeire, 2008].

An example of these SC driving distance function is given in Figure 4.1 a, where the representative straddle carrier driving distance for imco containers with dangerous goods are depicted as a function of the berth position of a vessel. Since the three fixed stacking positions for the containers with dangerous goods are on the right side of the terminal, the driving distance for the straddle carriers is the smallest at the right side of the terminal. The approximations of the measured driving distances by piecewise linear functions are indicated by the dashed lines in the figure.

Another example is given in Figure 4.1 b, where the representative SC driving distances for regular export containers of a certain vessel is depicted as a function of the berth position along the quay. Apparently, most regular export containers for this vessel are stacked somewhere between position 700 and 1000 m. Namely, the mean driving distance for straddle carriers is smallest for this region. The driving distance of the straddle carriers is again approximated by piecewise linear functions. For the export of regular containers, each vessel in the strategic planning has its own function for the SC driving distance.

Strategic planning

It is assumed here, that a cyclic strategic planning is available for the container port under consideration. The strategic planning is partly based on real life data and is calculated by [Hendriks, 2007] and [Karsemakers, 2008]. Also robustness for deviation in vessel arrival times is incorporated according to [Hendriks et al., 2008]. This cyclic strategic planning is used as reference planning for the Planning Controller.

The strategic planning has been calculated such that the quay crane workload is balanced over the cycle.

Simulation replications

The simulation model is designed such that the same input data, i.e. the parameters and disturbance samples, can be used repeatedly. This input data is generated before the actual simulation run and is stored in files, from where it later can be loaded into the simulation model. The advantage of using the same simulation replications to test different settings, is that the outputs of the different settings become correlated. Then the variance in the outputs of the different model settings reduces when these are compared with each other. This makes it easier to compare the different settings and strategies of the Planning Controller.

For all the experiments, hourly based time slots are used.

Performance indicators

The performance of different settings and strategies in the Planning Controller are investigated. The following performance indicators are used to test the Planning Controller:

- 1. the total weekly delay in departure [hours],
- 2. the number of quay cranes that is required during each hour or during each 8 hour shift [#],
- 3. the total weekly driving distance [km] that the straddle carriers have to travel to transport the containers,
- 4. the total average calculation time of the Planning Controller [s].

The first performance indicator is a measure for the delivered service level to the shipping line. In order to increase the goodwill of the terminal operator, delays in departure should be avoided if possible. Especially if the vessel has arrived on time or early, a violation of the berth agreement should be avoided.

Besides an adequate service level, the terminal operator tries to minimize its operational costs. An important contribution in the operational costs is determined by the number of quay cranes that is in operation. The number of quay cranes in operations is a representative measure (approximately) of the required resources in the terminal. For instance, the more quay cranes are required, the more straddle carriers and employees are needed.

A tradeoff has to be made in between early/timely departures, and sufficiently large berth time intervals which facilitate low requirements of resources.

The third performance indicator tests the quality of the positioning strategy. Depending on this strategy, this results in a certain average SC driving distance, which also affects the operational costs. The lower the average SC driving distance, the lower the operational costs.

The fourth performance indicator, the total average calculation time of the Planning Controller, determines whether the Planning Controller can be used as a decision support tool in real-time. Unlike the total calculation time required for the strategic planning, the total calculation time of the operational planning by the Planning Controller is very limited.

Outline experiments

In section 4.2, the static positioning strategy is compared to the dynamic positioning strategy. As a performance indicator, the SC driving distance is used. First the behavior of both strategies is observed. Then a statistical analysis is made where the performance of these two strategies are compared with each other under different circumstances. In the analysis it is investigated in which situations the outcome of the dynamic and static positioning strategy are significantly different from each other.

In section 4.3, a sensitivity analysis is performed which measures the influence of the different

parameter settings in the TAP on the resulting delays in departure and the quay crane usage. Also a significance test is performed to compare the outcomes of the different TAP settings.

In section 4.4, the stability and recovery performance of the Planning Controller is verified. In this section, the behavior of the Planning Controller is observed in case of an exceptional large disruption in the port.

In section 4.5, the computation times of the TAP, PAP, and QCAP are observed. Since the computation time of the QCAP is relatively time consuming, and the measured output is mainly influenced by the TAP and PAP settings, the QCAP is left out of the Planning Controller in section 4.2 and 4.3.

4.2 Static vs Dynamic positioning

In this section, the influence of the static positioning strategy is compared to the dynamic positioning strategy on the distance that the straddle carriers have to travel to transport the containers. Since the total SC driving distance is dependent on the number and type of containers that have to be handled for each vessel, the comparison is made for different levels of stochasticity. Due to the disturbances in arrival times and container types, it is likely that the reference planning does not indicate the lowest cost berthing positions anymore.

The expectation is that the dynamic positioning strategy results in less or at least equal SC driving distance when compared to the static positioning strategy. This is because the dynamic version determines the optimal berth position online dependent on the number and type of containers that have to be handled. Furthermore, it is expected that it becomes more beneficial to use a dynamic positioning strategy when the disturbances on container type fractions becomes larger. First the settings of the experiments are given. Then the performance of the two strategies are analyzed. Finally, the performance of the two strategies is compared for different levels of stochasticity.

Experiments

In Table 4.1 an overview can be found of the different stochastic container parameters in each input set. The performance of the static and dynamic positioning strategy is compared for 6 different stochastic input parameter sets. Each input set uses the same coefficient of variation α_i to disturb the total number of containers Q_v . The disturbance level on container type fractions (in

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
α_1	0.05	0.05	0.05	0.05	0.05	0.05
α_2	0.025	0.025	0.025	0.025	0.025	0.025
α_3	0.01	0.01	0.01	0.01	0.01	0.01
β_1	0.0	0.15	0.3	0.45	0.6	1.0
β_2	0.0	0.1	0.2	0.3	0.4	0.1
β_3	0.0	0.05	0.1	0.15	0.2	0.01

Table 4.1: Overview of the different stochastic parameter input sets.

the distribution of the containers) is increased by each set, starting with a coefficient of variation $\beta_i = 0$ in set 1. In set 6 for instance, the first container disturbance is likely to be very large, $(\beta_1 = 1.0)$, and during the second and third forecast only small deviations in container types are likely to occur.

Besides the disturbances in containers, disturbances on arrival times are generated. The disturbances on the arrival times are generated according to the method which has been explained in section 2.3.1., with the following standard deviations in the arrival times:

- 1. $\sigma_v^1 = 6$ time slots,
- 2. $\sigma_v^2 = 4$ time slots,
- 3. $\sigma_v^3 = 2$ time slots.

In this case, the lower and upper bound on the disturbance is in each case equal to -23 hours and +23 hours respectively, for each disturbance moment.

All simulation experiments are performed with hourly based time slots. Furthermore, the following horizon lengths are used: $H_a = 48$ and H = 68.

Analysis of performance

In this section the behavior of the positioning strategy on the resulting SC driving distance is observed over time. Let Y_{ij}^d be the total weekly SC driving distance of week *i* in replication *j* for the dynamic positioning strategy, and Y_{ij}^s the total weekly SC driving distance of week *i* in replication *j* for the static positioning strategy.

In Figure 4.2 Y_{i1}^d and Y_{i1}^s (for i = 1, 2, ..., m) are plotted over time in weeks for stochastic set 2. In this case the length of replication 1 equals m = 10 weeks. The total weekly SC driving distance in case of a static positioning strategy is indicated by the solid line, and in case of a dynamic positioning strategy indicated by the dotted line.

Of particular interest is the average difference in the resulting SC driving distance of the two different positioning strategies when the system is in steady state, which is in fact the average weekly difference in between the two lines in Figure 4.2 for many replications. For this, it needs to be known when the average weekly SC driving distance is in steady state for both positioning strategies.

When the statistical comparison is executed, the initial transient in the average weekly SC driving distance should not be included. If the initial transient is included, then the estimations of the average weekly SC driving distance, \bar{Y}_j^d and \bar{Y}_j^s , become biased estimators of the steady state average weekly SC driving distance $v_j^d = E(Y_j^d)$ and $v_j^s = E(Y_j^s)$ respectively.

In order to see the effect of the initial transient, the Welch moving averages, as defined in [Law & Kelton, 2000], of the average weekly SC driving distance for both positioning strategies have to be plotted over time. Let n be the number of replications. Then the average SC driving distance summed over n replications for week i is defined as: $\bar{Y}_i^d = \sum_{j=1}^n Y_{ij}^d$ for the dynamic case,

and $\bar{Y}_i^s = \sum_{j=1}^n Y_{ij}^s$ for the static case.

In order to smooth out the high frequency oscillations in \bar{Y}_i^d and \bar{Y}_i^s , the moving averages $\bar{Y}_i^d(w)$ and $\bar{Y}_i^s(w)$ need to be fined. In general, the moving average is defined as:

$$\bar{Y}_{i}(w) = \begin{cases} \frac{\sum\limits_{s=-w}^{s} \bar{Y}_{i+s}}{2w+1} & \text{if } i = w+1, \dots, m-w, \\ \sum\limits_{s=-(i-1)}^{v} \bar{Y}_{i+s}} & \frac{1}{2i-1} & \text{if } i = 1, \dots, w, \end{cases}$$

where w is the so-called window length. Then the moving averages, $\bar{Y}_i^d(w)$ and $\bar{Y}_i^s(w)$ (for $i = 1, 2, \ldots, m - w$) have to be plotted over time. From this, the warm-up period, or initial transient length l can be observed.

For stochastic set 2, the moving averages of the weekly SC driving distance, $\bar{Y}_i^d(2)$ and $\bar{Y}_i^s(2)$ are plotted over time in Figure 4.3, with window length w = 2, replication length m = 10, and number of replications n = 6. As can be verified, the system is almost immediately in steady state, since



Figure 4.2: Overview of the total weekly SC driving distances over replication 1 for stochastic set 2. Y_{i1}^d and Y_{i1}^s represents the total weekly SC driving distance for a dynamic and static positioning strategy respectively.



Figure 4.3: Moving averages of the average weekly SC driving distances, $\bar{Y}_i^d(w)$ and $\bar{Y}_i^s(2)$, for stochastic set 2, with w = 2, m = 10, and n = 6.



Figure 4.4: Overview of the total weekly SC driving distance over replication 1 for stochastic set 6. Y_{i1}^d and Y_{i1}^s represents the total weekly SC driving distance for a dynamic and static positioning strategy respectively.



Figure 4.5: Moving averages of the average weekly SC driving distances, $\bar{Y}_i^d(w)$ and $\bar{Y}_i^s(2)$, for stochastic set 6, with w = 2, m = 10, and n = 6.

the difference in between the two lines do not change much over time. This is not surprisingly, since at t = 0 a cycle starts immediately in the simulation model. Only during the first week, the difference in resulting SC distance in between the static and dynamic positioning strategy is on average less than in the subsequent weeks. Hence, the first week needs to be discarded, i.e. l = 1. This is because at t = 0 the arrival times and containers of the first three vessels on the planning horizon have not been disrupted yet.

In Figure 4.4 the total weekly SC driving distance for replication 1, Y_{i1}^d and Y_{i1}^s (for i = 1, 2, ..., m) are plotted over time in weeks for stochastic set 6. The Welch moving averages, $\bar{Y}_i^d(2)$ and $\bar{Y}_i^s(2)$ for stochastic set 6 are plotted over time in Figure 4.5, with also in this case a window length w = 2, replication length m = 10, and number of replications n = 6. Here it can be also concluded that the first week needs to be discarded in order to estimate the steady state mean difference in SC driving distance.

Another observation that can be made from this is that the difference in average SC driving distance in between the two positioning strategies has becomes larger compared to set 2. So the prognosis that the difference in SC driving distance becomes larger in between the two different strategies when the disturbance parameter β_i increases seems to be underwritten so far.

The Welch moving averages of both positioning strategies have been plotted over time for all 6 input sets. From this it is concluded that in all cases l = 1. Therefore, for the statistical analysis, the measurement of SC driving distance in the first week of each replication is always discarded.

Comparison of performance

Now the statistical analysis is performed. For both positioning strategies and for each input set, a total of n = 9 replications are executed, with replication length m = 10. The average weekly SC driving distance for a certain input set and a certain replication j for the dynamic positioning strategy is defined as:

$$X_{j}^{d} = \frac{\sum_{i=l+1}^{m} Y_{ij}^{d}}{m-l},$$
(4.1)

and the average weekly SC driving distance for a certain input set and a certain replication j for the static positioning strategy as:

$$X_{j}^{s} = \frac{\sum_{i=l+1}^{m} Y_{ij}^{s}}{m-l}.$$
(4.2)

Since the input data of each replication j is the same for both positioning strategies, the $X_j^{d's}$ and $X_j^{s's}$ are positively correlated and dependent. The following stochastic is then used in the comparison analysis:

$$Z_j = \frac{X_j^d - X_j^s}{X_j^s} \cdot 100.$$
(4.3)

Hence, Z_j is defined as the difference in SC driving distance in between a dynamic and static positioning strategy, indicated in percentages relative to the static positioning strategy.

Table 4.2 shows the output statistics for Z_j for each stochastic set. It includes measures of central tendency, measures of variability, and measures of shape. As can be seen, the average $\bar{Z} = \sum_{j=1}^{n} Z_j$ increases as the level of stochasticity in β_i increases. Of particular interest in this table are the standardized skewness and standardized kurtosis, which can be used to determine whether

the samples come from a normal distribution. Values outside the range of -2 to +2 indicate a significant departures from normality, which would tend to invalidate many of the statistical procedures which are usually applied to the data [StatPoint, 2005]. In this case, the statistics are within the range of -2 and 2, which implies that the statistical procedures can be applied.

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
Replications	9	9	9	9	9	9
Average (\bar{Z})	-1.27	-2.02	-3.19	-5.38	-6.45	-8.38
Standard deviation	0.19	0.14	0.70	1.05	0.23	1.07
Coeff. of variation [%]	-15.02	-6.89	-22.07	-19.53	-3.62	-12.78
Minimum	-1.59	-2.27	-3.98	-6.85	-6.75	-10.34
Maximum	-0.98	-1.83	-2.07	-3.76	-6.05	-6.79
Range	0.61	0.43	1.91	3.09	0.69	3.54
Stnd. skewness	-0.17	-0.42	0.52	0.12	1.13	-0.31
Stnd. kurtosis	-0.28	-0.07	-0.89	-0.82	-0.07	0.27

Table 4.2: Summary statistics for Z_j 's.

	Mean (\bar{Z})	Stnd. error	Lower limit	Upper limit
Set 1	-1,27	0,06	-1,42	-1,12
Set 2	-2,02	0,05	-2,12	-1,91
Set 3	-3,19	0,23	-3,74	-2,65
Set 4	-5,38	$0,\!35$	-6,18	-4,57
Set 5	-6,45	0,08	-6,63	-6,27
Set 6	-8,38	0,36	-9,20	-7,56

Table 4.3: 95% confidence intervals of the \overline{Z} 's.

95 % Confidende Intervals of Mean difference in SC driving distance



Figure 4.6: Graphical representation of the 95% confidence intervals of the \bar{Z} 's.

Table 4.3 shows 95% confidence intervals for the mean difference in SC driving distance in percentages, \overline{Z} . These confidence intervals bound the sampling error in the estimates of \overline{Z} . The confidence intervals can be used to judge how precisely the \overline{Z} have been estimated for each input set. The 95% confidence intervals for the means of the difference in SC driving distance in percentages is also depicted in Figure 4.6.

A first observation is that none of the confidence intervals contain the value 0. This implies that the difference in SC driving distance in between a dynamic and static positioning strategy is significantly different for each input set. For each set, the dynamic positioning strategy results in less SC travel distance compared to the static positioning strategy. The prognosis that the difference in SC driving distance becomes larger when the disturbances on the container types increase, is validated.

A second observation is that the CI intervals of set 4 and 6 are relatively large. In order to narrow the confidence interval for set 4 and 6, more replications should be executed.

An interesting result is that even though there is no disturbance on the container types in set 1, the dynamic positioning strategy can still reduce the SC driving distance by an average of 1,27% when compared to the static positioning strategy. This results is caused by the fact that there are also disturbances on arrival times present in the replications. When a vessel berths earlier or later than stated in the reference planning, it is possible that the vessel can obtain a different berth position in the terminal.

For instance when in the reference planning two vessels berth simultaneously in time, which both have the optimal berth position at position X along the quay, then they cannot berth both at this position X. In the reference planning, the vessels berth in that case not both at their optimal berth position. Now, when these vessel can berth on an operational level subsequently in time after each other, they can both berth at the optimal berth position X. This is exactly what in the dynamic positioning strategy can occur. In the static positioning strategy the vessel berth at its reference position, although a lower cost berth position is available.

Depending on the variability in container types, the reduction in SC driving distance can increase up to an approximate 8,38% for a disturbance level as in set 6, when a dynamic positioning strategy is used instead of a static.

In the next section, the influence of the settings in the TAP are investigated on the resulting delays and quay crane usage.

4.3 Balancing between resources and delays

In the TAP the weight factors can be chosen such that a trade off is made in between the vessels' departure time and the number of resources that is required each hour. The more resources are in operation per hour or shift, the faster the vessel is processed and the earlier the vessel can depart. An earlier departure time reduces the turn around time and increases the service level towards the shipping lines. The drawback however, is that the operational costs for the terminal operator increase when additional quay cranes are used. In terms of resources, not only more quay cranes are required, but also more straddle carriers and more work forces are needed in operation in order to serve the vessel. So the required number of quay cranes in operation can be considered as a representative measure for the required resources and associated operational costs in general. First the different TAP settings are given. Then the behavior of the quay crane usage and delays of the different TAP settings are analyzed and compared. Finally, the correlation between delays and quay crane usage is discussed.

TAP settings

In this section, the settings in the TAP are given. A real life case is considered where the following coefficients of variation for container disturbances are used:

- $\alpha_1 = 0.05$,
- $\alpha_2 = 0.025,$
- $\alpha_3 = 0.01$,
- $\beta_1 = 0.3,$
- $\beta_2 = 0.2,$
- $\beta_3 = 0.1.$

The disturbances on the arrival times are generated according to the method which has been explained in section 2.3.1., with the following standard deviations in the arrival times:

- $\sigma_v^1 = 6$ time slots,
- $\sigma_v^2 = 4$ time slots,
- $\sigma_v^3 = 2$ time slots.

In this case, the lower and upper bound on the disturbance is in each case equal to -23 hours and +23 hours respectively, for each disturbance moment. Furthermore, 5 different weight factor and parameter settings in the TAP are chosen which are tested, see Table 4.4.

	C_v	C_v^+	C_v^-	C_a	C_n	N	N _{max}
Setting 1	0.001	2.0	0.15	0.01	0.00	5	7
Setting 2	0.001	2.0	0.15	0.01	0.25	5	7
Setting 3	0.001	2.0	0.15	0.01	0.50	5	7
Setting 4	0.001	3.0	0.15	0.01	1.45	5	7
(Setting 5)	0.001	1.5	0.15	0.01	10.0	5	7

Table 4.4: Overview of the different weight factor and parameter settings in the TAP.

Observation of performance

First the effect of the different TAP settings on the delays and quay crane usage are investigated for a single simulation replication over time. As an example, setting 1, 4, and 5 are considered. Setting 1 is treated first.

The quay crane usage over time in hours for model setting 1 for simulation replication 1 is depicted in Figure 4.7. As can be seen, maximum capacity N_{max} is reached frequently. This is because the cost factor for additional quay cranes is set to zero. Hence, no costs are associated with an additional quay crane in operation, and an additional quay crane is put in operation whenever this is possible.

It is assumed that a work force is hired for the duration of an eight hour shift. The required work force is then determined by dividing the hourly quay crane usage in shifts of 8 hours. Then the required number of work forces for a shift is equal to the maximum number of quay cranes used



Figure 4.7: Overview of the hourly quay crane usage for setting 1 in simulation replication 1.



Figure 4.8: Overview of the required work forces / quay cranes during each 8 hour shift, for setting 1 in simulation replication 1.

during such a shift. An example of the required number of work forces per shift for model setting 1 for a single simulation replication is depicted in Figure 4.8.



Figure 4.9: Overview of the delay in departure for each vessel in simulation replication 1 for setting 1. The red bars indicate vessel which have arrived late, whereas the black bars indicate vessels which have arrived on time / early.

Different weight factors are used for the delay of a vessel which has arrived early or one time, and for a vessel which has arrived late. As indicated in Table 4.4, the weight factor for a delay of an early or timely arrived vessel, C_v^+ , is much higher then the weight factor for the delay of a vessel which has arrived late, C_v^- . This implies that the delay of a vessel which has arrived late introduces less costs than the delay of a vessel which has arrived on time or early. C_v^+ and C_v^- are for model setting 1 more than twice as large as than C_n . This implies that in case of setting 1, a delay is never caused by saving capacity, because with these weight factor settings the maximum number of quay cranes ($N_{max} = 7$) is always allocated in order to prevent a possible delay.

However, it is still possible that a delay occurs when the capacity is temporarily insufficient to obtain timely departures. An example of the delay in departure per vessel for model setting 1 for simulation replication 1 is depicted in Figure 4.9. A zero delay implies a timely departure, a negative delay implies an early departure, and a positive delay implies a late departure. The black bars indicate an early or timely arrived vessel, whereas the red bars indicate a late arrived vessel. In this case, only late arrived vessels depart late.

Now the performance of setting 4 is observed over time for simulation replication 1. In Figure 4.10 the hourly quay crane usage over time for model setting 4 for simulation replication 1 is depicted. As can be verified, the required number of additional quay cranes over time is in case of setting 4 much less than in case of setting 1. The workload is in this case more balanced over the cycles. When setting 4 is used, one additional quay crane is used (n = 6) if the total delay of a late arrived vessel becomes 10 hours. If the total delay of a late arrived vessel becomes 20 or more, then two additional quay cranes come in operation (n = 7). Maximum resource capacity (n = 7) is allocated immediately when an early or timely arrive vessel is in danger of a delay in departure, since C_n^+ is twice as large as C_n .

The required number of work forces for each shift reduces also in case of setting 4. An overview of the required number of work forces for setting 4 for simulation replication 1 is depicted in Figure 4.11.



Figure 4.10: Overview of the hourly quay crane usage for setting 4 in simulation replication 1.



Figure 4.11: Overview of the required work forces / quay cranes during each 8 hour shift, for setting 4 in simulation replication 1.

The consequences of a more balanced workload is that the turn around time of the vessels increases. Figure 4.12 it can be seen that the overall negative delays become less negative, indicating a higher



Figure 4.12: Overview of the delay in departure for each vessel in simulation replication 1 for setting 4. The red bars indicate vessel which have arrived late, whereas the black bars indicate vessels which have arrived on time / early.

average turn around time. Furthermore, more vessels are delayed in departure, and the length of the delay can become larger. However, as can be verified early or timely arrived vessels are never delayed, which means that the berth agreement is in this case never violated.

When the same replication is repeated for the optional setting 5 where C_n is increased even more, no additional quay cranes / shifts are ever used during simulation replication 1, see Figure 4.13. In setting 5 it is possible that the berth agreement is violated, since C_v^+ is not twice as large as C_n anymore, see Table 4.4. In fact, only one additional quay crane is used when the total delay of early or timely arrived vessels is more than 7 hours, and two additional quay cranes are used when the total delay of early or timely arrived vessels is more than 14 hours. For vessels which have arrived late, the total cost of delay must add up to 67 hours in order to put one additional quay crane in operation. For 2 additional quay cranes in operation, the total delay of vessels which have arrived late must reach at least to 134 hours.

The drawback of these weight factors in setting 5, is that high turn around times and delays in departure are observed. In Figure 4.14, it can be verified that the length of the delays increase drastically in case of setting 5. The fact that none of the early or timely arrived vessels are delayed in departure, is due to the difference in weight factors C_v^+ and C_v^- . In this case, a late arrived vessel is simply delayed even more by the model, in order to let the early or timely arrived vessels depart on time.

For the further analysis, only setting 1 through 4 is considered, since the range of these weight factors seems to be reasonable for realistic use.

Analysis and comparison of performance

In this section, a sensitivity analysis and comparison is made where the influence of the relevant weight factors settings in the TAP on the obtained departure times and required quay cranes



Figure 4.13: Overview of the hourly quay crane usage for setting 5 in simulation replication 1.



Figure 4.14: Overview of the delay in departure for each vessel in simulation replication 1 for setting 5. The red bars indicate vessel which have arrived late, whereas the black bars indicate vessels which have arrived on time / early.

are investigated. The performance of the 4 remaining TAP settings (1 through 4) are tested. For the analysis of the 4 different TAP settings, n = 9 different input data replications are generated which are used as the input for all TAP settings. The main advantage of using the same input replications for each TAP setting, is that the output data of each TAP setting is positively correlated and dependent, which reduces the variance in the measured output. This makes it easier to perform the comparison.

Each replication is exactly 10 cycles/weeks long. Furthermore, hourly time slots are used. In order to test TAP setting 1 through 4, the following performance indicators are used for measurement:

- Y_{ij}^Q = the total required additional quay cranes / workforces (above N), during each 8 hours shift, per day i, in replication j.
- Y_{ij}^D = the total delay in departure during *week i*, in replication *j*, for vessels which have arrived late.

Then the average *daily* required additional quay cranes / workforces per 8 hours shift in replication j (i.e. a usage above N = 5), is defined as:

$$X_{j}^{Q} = \frac{\sum_{i=l+1}^{m} Y_{ij}^{Q}}{m-l},$$
(4.4)

where m and l are in days.

The average weekly delay in departure for vessels which have arrived late in replication j, is defined as:

$$X_{j}^{D} = \frac{\sum_{i=l+1}^{m} Y_{ij}^{D}}{m-l},$$
(4.5)

where m and l are in weeks.

Since only vessels which have arrived late are delayed by the TAP for setting 1 through 4, and not the vessels which have arrived on time or early (this has been verified for all replications for all model settings), the average weekly delay in departure is measured with respect to vessels which have arrived late. As explained in section 3.4, this delay is measured by the number of time slots that a vessel departs later than $\max\{D_n^{max}, A_v + P_n^{min} + 1\}$.

that a vessel departs later than $\max\{D_v^{max}, A_v + P_v^{min} + 1\}$. Furthermore, for both performance indicators, the first week from each replication j is discarded due to a very small initial transient. For X_j^Q this implies that l = 7 days and m = 70 days, and for X_j^D this implies that l = 1 week and m = 10 weeks. The measured data from the first week is again deleted, since during the first week of a replication the containers and arrival times of the first three vessels on the planning horizon are not disrupted.

The analysis and comparison is first based on the quay crane usage. After this, the analysis and comparison is based on the delays in departure.

Quay crane usage

First the sensitivity of the different TAP settings on the X_j^Q 's are investigated. In Table 4.5, the output statistics of the X_j^Q 's can be found for the different model settings. The average weekly required additional work forces / quay cranes per shift per day is indicated by $\bar{X}^Q = \sum_{j=1}^n X_j^Q$. Of particular interest here are the standardized skewness and standardized kurtosis, which can be used to determine whether the sample X_j^Q comes from a normal distribution. Values of these

	Repl.	Mean (\bar{X}^Q)	Std	Min	Max	Range	Stnd. skewn	Stnd. kurt.
Setting 1	9	1,95	0,14	1,69	2,18	0,49	-0,50	0,71
Setting 2	9	0,59	0,20	0,26	0,95	$0,\!69$	$0,\!13$	0,22
Setting 3	9	0,43	0,14	0,23	0,72	$0,\!49$	$0,\!68$	$0,\!34$
Setting 4	9	0,26	0,13	0,14	0,53	$0,\!39$	$1,\!59$	0,83

Table 4.5: Summary statistics of the X_j^Q 's for the different model settings.

	Mean (\bar{X}^Q)	Stnd. error	Lower limit	Upper limit
Setting 1	1,95	0,046	1,85	2,06
Setting 2	$0,\!59$	0,068	$0,\!43$	0,75
Setting 3	$0,\!43$	0,050	0,32	0,55
Setting 4	0,26	0,043	$0,\!16$	0,36

Table 4.6: 95% confidence intervals of the \bar{X}^Q 's for different model settings.

95 % CI's of the average required additional quay cranes per shift per day



Figure 4.15: 95% confidence intervals of the \bar{X}^Q 's for different model settings.

statistics outside the range of -2 to +2 indicate significant departures from normality, which would tend to invalidate many of the statistical procedures applied to the data [StatPoint, 2005]. In this case non of the statistics lie outside this range.

In Table 4.6, the approximate 95% confidence intervals of the \bar{X}^Q 's for each model setting can be found. As can be seen, the average number of additional work forces / quay cranes per shift per day decreases as the weight factor C_n increases. The approximate 95% confidence intervals of the \bar{X}^Q 's for each model setting are also graphically depicted in Figure 4.15.

As indicated in Figure 4.15, the average additional quay crane usage (above N = 5), decreases as the weight factor for quay cranes, C_n becomes higher. Whether the different output statistics, \bar{X}^Q 's, for setting 1 through 4 are significantly different from each other, is discussed next.

Although the confidence intervals give a good indication of the mean required additional work forces / quay cranes per shift per day for each model setting, these cannot directly be used to de-

	$i_2 = 2$	$i_2 = 3$	$i_2 = 4$
$i_1 = 1$	$-1,362 \pm 0.1620 *$	$-1,519 \pm 0.1420 *$	$-1,689 \pm 0.1230 *$
$i_1 = 2$		$-0,157 \pm 0.0799 *$	$-0,3269 \pm 0.1553 *$
$i_1 = 3$			$-0,1699\pm 0.1261*$

Table 4.7: Individual 98,33% confidence intervals for all pairwise comparisons of the \bar{X}^Q 's for different model settings $(\mu_{i_1} - \mu_{i_2} \text{ for } i_1 < i_2)$; * denotes a significant difference.

clare the outcome of a certain model setting significantly different from another setting. In order to verify whether there exists a significant difference in between all the \bar{X}^Q 's, the paired-t approach is used to compare the outcome of the 4 different TAP settings with each other [Law & Kelton, 2000]. Since several confidence interval statements are made simultaneously, the individual confidence intervals have to be adjusted upward so that the overall confidence level of all intervals is at the desired level $1-\alpha$. According to the Bonferroni inequality, the probability that all the k confidence intervals simultaneously container their respective true measures satisfies

$$P(\mu_s \in I_s; \ \forall s = 1, 2, \dots, k) \ge 1 - \sum_{s=1}^k \alpha_s,$$
(4.6)

whether or not the I_s are independent. In this case there are 4 different settings, and in order to make all pairwise comparisons, $4 \cdot (4-1)/2 = 6$ individual confidence intervals have to be constructed. Hence k = 6, and in order to obtain an overall confidence interval of $1 - \alpha$, each individual confidence interval must be made at the level of $1 - \alpha/[4 \cdot (4-1)/2]$. Here, α is chosen equal to 0.1, which implies that each individual confidence interval must be made at a level of 98,33%.

Table 4.7 gives the resulting 98,33% individual confidence intervals for all pairwise comparisons, $\mu_{i_1} - \mu_{i_2}$, using the paired-*t* approach, where $i_1 < i_2$ and where $\mu_{i_1} = \bar{X}^Q$ for model setting i_1 , and $\mu_{i_2} = \bar{X}^Q$ for model setting i_2 . An asterisk indicates that the confidence interval misses zero, and implies a significant difference in the average required additional work forces / quay cranes per shift per day, for the two compared model settings. As can be verified, with an approximate confidence level of 90%, the \bar{X}^Q 's for all different model settings are significantly different from each other. These results indicate that the average required additional work forces / quay cranes per shift per day indeed decrease as the weight factor C_n increases.

Delays

Now, the sensitivity of the TAP settings on the X_j^D 's is investigated for the same 9 simulation replications. In Table 4.8, the output statistics of the X_j^D 's can be found. Of particular interest here, are the standardized skewness and standardized kurtosis. Also in this case, non of the statistics lie outside the range of [-2, 2], which means that the statistical tests can applied to this data. In Table 4.9, the approximate 95% confidence intervals of the average total weekly delay in departure, i.e. the \bar{X}^D 's can be found for the different model settings. As can be seen, the average total weekly delay in departure increases as the weight factor C_n increases. The approximate 95% confidence intervals of the average total weekly delay in departure for each model setting are also graphically depicted in Figure 4.16.

The confidence intervals in Figure 4.16 suggest that the average delay in departure (for vessels which have arrived late), increases as the weight factor for quay cranes C_n . In order to verify this, a comparison test is performed for this output.

In order to determine whether the delays for the different TAP settings are significantly different for model settings 1 through 4, all pairwise comparisons are made. Again, α is set equal to 0.1, which implies that each individual confidence interval must be made at a level of 98,33% since there

	Repl.	Mean	Std	Min	Max	Range	Stnd. skewn	Stnd. kurt.
Setting 1	9	0,27	$0,\!30$	0,0	0,7	0,7	0,83	-0,87
Setting 2	9	0,48	$0,\!43$	0,0	1,0	$1,\!0$	0,092	-1,27
Setting 3	9	0,87	$0,\!51$	0,0	1,9	$1,\!9$	0,62	1,55
Setting 4	9	2,44	$1,\!29$	0,0	3,9	$3,\!9$	-0,84	-0,062

Table 4.8: Summary statistics for the X_j^D 's for different model settings.

	Mean	Stnd. error	Lower limit	Upper limit
Setting 1	0,27	0,097	0,039	$0,\!49$
Setting 2	0,48	$0,\!14$	$0,\!15$	0,81
Setting 3	0,87	$0,\!17$	$0,\!48$	1,26
Setting 4	2,44	$0,\!43$	$1,\!46$	$3,\!43$

Table 4.9: 95% confidence intervals of the \bar{X}^D 's for different model settings. (The CI's of the average weekly delay for vessels which have arrived late).

95 % Confidence Intervals of mean weekly delay for different model settings



Figure 4.16: 95% confidence intervals of the \bar{X}^D 's for different model settings. (The CI's of the average weekly delay for vessels which have arrived late).

are 6 individual confidence intervals. Table 4.7 gives the resulting 98,33% individual confidence intervals for all pairwise comparisons, $\mu_{i_1} - \mu_{i_2}$, using the paired-*t* approach, where $i_1 < i_2$ and where $\mu_{i_1} = \bar{X}^D$ for model setting i_1 , and $\mu_{i_2} = \bar{X}^D$ for model setting i_2 . An asterisk indicates that the confidence interval misses zero, and implies a significant difference in the resulting average weekly delay for the different model settings.

	$i_2 = 2$	$i_2 = 3$	$i_2 = 4$
$i_1 = 1$	$0,2111 \pm 0.2099 *$	$0,5778 \pm 0.3545*$	$2,178 \pm 1.2864*$
$i_1 = 2$		$0,3889 \pm 0.3603 *$	$1,967 \pm 1.3603 *$
$i_1 = 3$			$1,600 \pm 1.0788*$

Table 4.10: Individual 98,33% confidence intervals for all pairwise comparisons of the \bar{X}^D 's for different model settings: $(\mu_{i_1} - \mu_{i_2} \text{ for } i_1 < i_2)$; * denotes a significant difference.

As can be verified from Table 4.7, with an approximate confidence level of 90%, all pairwise comparisons in between the resulting average weekly delays for the different model settings are significantly different from each other. As the results show, the average weekly delay (for vessels which have arrived late) increases, as the parameter C_n increases.

The observations in quay crane usage and delays, suggest that there exists a correlation in between these two performance indicators. This correlation is investigated next.

Correlation delays and quay crane usage

Now the average required number of additional work forces / quay cranes per shift per day are known, and the average delay in departure per day for vessels which have arrived late are known for each model setting, the correlation between the different performance indicators can be plotted versus each other. In Figure 4.17 the correlation between the average number of daily additional work forces / shifts per shift per day and the average weekly delays in departure (for vessels which have arrived late) can be found. The solid line indicates the mean, whereas the dotted lines indicate the upper and lower 90% confidence limits.



Figure 4.17: Relationship between the average weekly delay in departure of late arrived vessels, and the average required additional quay cranes per 8 hours shift per day.

Evaluation

As the results of this section indicate, the TAP has been designed such that it becomes fairly easy to adjust the weight factors such that a desired balance in between allocation of resources and departures can be obtained. Moreover, a distinction can be made in between vessels which have arrived late, and vessels which have arrived on time or early. Delays in hours of late arrived vessels, delays in hours of early/timely arrive vessels, and additional quay cranes can be balanced relatively easy with each other in order to obtain the desired behavior.

a higher quay crane usage results in less and shorter delays in departure, whereas a low quay crane usage can result in more and longer delays in departure.

4.4 Exceptional recovery

Case description

In this section, an exceptional case is considered. In the scenario that is tested here, it is assumed that one particular terminal (called terminal B) in the port is closed for 1 week. Such a scenario can occur when terminal B is closed due to an accident in the terminal. It is assumed here, that for one week, all the vessels destined for terminal B, will berth in terminal A, which is investigated here. Furthermore, it is assumed that usually the same number type of vessels berth in terminal A and B. So twice as many vessels arrive now during week 2 in terminal A.

In this test case, all vessels arrive somewhere in the arrival window of $[A_v^* - 4, A_v^* + 4]$, which implies that the arrival time of each vessel is always considered on time. In this test case, the assumption is made that the number and type of to be handled containers are exactly as stated in the reference planning (i.e. α_i and β_i are zero). Furthermore, TAP setting 3 is used, see Table 4.4. Of particular interest now, is how many vessels are delayed by this exceptional disruption.

Observations

In Figure 4.18 and Figure 4.19, the quay crane usage over hours and shifts respectively can be found. As indicated, the resulting quay crane usage increases to almost a constant maximum capacity during the entire second week. During the other 6 weeks, the quay crane usage is nicely balanced and is in most cases equal to the basic level of 5 quay cranes in operation. Only during one shift in week 6, one additional quay crane is required for an eight hour shift.

In Figure 4.20, the delays of the vessels are depicted over time. On the horizontal axis the vessel number is depicted, and on the vertical axis the delay. Since all vessels have arrived within their arrival window (timely arrival), only black bars are observed. It can be observed that during normal operations, none of the vessels are delayed. A conclusion which can be drawn from this experiment, is that if the disruptions in the arrival times stay within the arrival window, the reference planning is robust, because no delays in departure are observed, and the quay crane usage is balanced.

During week 2, twice as many vessels berth at this terminal. Due to the exceptional disruption in week 2, many delays occur which violate the berth agreements with the shipping lines, see Figure 4.20. As indicated, twice as many vessels arrive during week 2. The total delay in departure increases now to 70 hours in total.

The conclusion that can be drawn, is that the capacity in week 2 is temporarily insufficient. Although maximum capacity is used during week 2, see Figure 4.18, still many delays in departure occur. However, as can be verified, at the start of week 3 the operations can be executed normally again. This is due to the fact that there is normally a large under utilization present in this terminal. The hourly quay crane usage indicates that during normal operation, quay cranes are often idling. This overcapacity can now efficiently be used to get back to the reference planning again.

Stability

In order to ensure stability in the Planning Controller during the second week, the safety margin in horizon is increased to $H - H_a = 78 - 48 = 30$ time slots. Another measure that is applied here to ensure stability, is to restrict the number of vessels on the planning horizon such that the quay crane capacity on the planning horizon is sufficient to process all the vessels. These measures have

4.4. Exceptional recovery



Figure 4.18: Overview of the hourly quay crane usage.



Figure 4.19: Overview of the required work forces / quay cranes during each 8 hour shift.

been explained in section 3.3. Due to these measure, the Planning Controller remains stable when the operations in the container port are severely disrupted.



Figure 4.20: Overview of the delay in departure for each vessel. The red bars indicate vessel which have arrived late (none in this case), whereas the black bars indicate that the vessels have arrived on time / early.

However, due to the high utilization on the planning horizon during week 2, the calculation time of the TAP increases drastically. This high calculation time is observed in the next section. Due to this high computation time, it is necessary to adapt the weight factors during week 2 in order to obtain a solution within an acceptable time. Therefore, for week 2 the weight factors and parameters of Table 4.11 have been used. This causes the calculation time in the TAP to decrease significantly. For the other weeks setting 3 of Table 4.4 has been used, which assures the balanced workload throughout these weeks, as discussed.

	C_v	C_v^+	C_v^-	C_a	C_n	N	N _{max}
Setting week 2	0.05	0.1	0	0	0	5	7

Table 4.11: Overview of the different weight factor and parameter settings for week 2 in the TAP.

4.5 Calculation time

One very important criterion for the Planning Controller to become a useful decision support tool for real time container port planning, is a sufficiently short calculation time of the operational planning. As explained, hourly based time slots have been used, where at the beginning of each new time slot a new operational planning is calculated based on the current information. If the Planning Controller is used in reality, then the calculation time should be sufficiently short. In this section, the calculation time of the TAP, PAP, and QCAP is discussed successively. The section is concluded with an evaluation.

TAP calculation time

All the simulations described in section 4.2 and 4.3 have been executed with the following horizon lengths: $H_a = 48$ hours and H = 68 hours. So a safety margin of 20 hours has been used. In all these simulation replications, the calculation time of the TAP stayed under 300 seconds (5 minutes) for the calculation of a time allocation, which seems a reasonable calculation time for hourly based



Figure 4.21: Overview of the TAP calculation time for a single replication.

time slots. In Figure 4.21, the TAP calculation times are depicted over time for a typical simulation run of 10 weeks, as performed often in section 4.2 and 4.3. As can be observed, the calculation time is usually far below the 5 minutes. In certain cases when the terminal utilization is high and when many vessels are present on the planning horizon, the calculation time can increase, as indicated in Figure 4.21 where the maximum calculation time for this replication equals 54,35 seconds. The average calculation time of the TAP over all replications equals 2.165 seconds.

The effect of a high calculation time in the TAP when the number of vessels present on the planning horizon is large can be observed even more closely in the case of the exceptional recovery situation described in the previous section. In Figure 4.22, the TAP calculation time of this scenario is depicted over time. As can be observed, the calculation time is very low when the vessels arrive within the arrival windows during normal operations. The operational planning is then very similar to the reference planning, which is therefore relatively easy to solve.

However, when the calculation time in week 2 is considered, a high peek in calculation time can be observed (with a maximum calculation time of 242,91 seconds). A remark has to be made that a slightly longer horizon is used, i.e. H = 78 (and $H_a = 48$) in order to increase the safety margin in time on the planning horizon. Furthermore the calculation time in Figure 4.22 is based on the adapted weight factors as indicated in Table 4.11. If the usual weight factors of setting 3 are used, as is the case in week 1 and week 3 through 7, then the calculation time becomes unacceptable large ($\gg 5$ minutes), and in certain cases a solution can hardly be find on the computer system that has been used.



Figure 4.22: Overview of the TAP calculation time for the exceptional recovery scenario.

PAP calculation time

Now the calculation time of the PAP is treated. A difference in the calculation time can be observed when the dynamic or static positioning strategy is used. In Figure 4.23 the calculation time in the PAP in case of the static positioning strategy for one replication is plotted over time. In this case, the calculation time stays always within rounded values of 0.00 and 0.03 seconds, which are common values for the calculation time of the position allocation. The average calculation time over all replications in case of the static PAP equals 0.0064 seconds.

In Figure 4.24 the calculation time in case of the dynamic positioning strategy for the same replication is plotted over time. In this case, the calculation time stays always within rounded values of 0.02 and 0.07 seconds. The average calculation time over all replications in case of the dynamic PAP equals 0.0456 seconds. Hence, a slightly larger calculation time is obtained when the dynamic PAP is used.

Large calculation times in the order of seconds have not been observed for the PAP. Independent of the positioning strategy that is used, the calculation time of the PAP is negligible on the computer system that is used.

QCAP calculation time

One replication has also been executed with the QCAP incorporated in the Planning Controller. For the length of the planning horizon H_{qc} in the QCAP, and the possibility to use a heuristics procedure, the strategy as defined in section 3.6 has been used. Usually the length of the horizon equals 16 time slots. However, the minimum number of vessels considered on the horizon has to be equal to 2. Therefore the horizon is automatically extended in case this is needed to satisfy this. The heuristics procedure is used when the considered number of vessels on the horizon of length 16 is more than 4.

According to the executed replication over 10 weeks, the average computation time to construct the quay crane allocation equals 22 seconds. However, the maximum computation time to construct


Figure 4.23: Overview of the PAP calculation time for a single replication for a static positioning strategy.



Figure 4.24: Overview of the PAP calculation time for a single replication for a dynamic positioning strategy.

the quay crane allocation equals 325 seconds. In 38 of the 1680 iterations, it has been necessary to use the heuristics procedure to solve the QCAP since the number of vessels in the considered horizon was larger than 4.

Evaluation

Summarized, the three subproblems of the Planning Controller, the TAP, PAP, and QCAP, are suitable for calculating of an operational planning in real time. Of course the length of the planning horizon needs to be taken appropriately. An increase of the number of time slots on the planning horizon increases the calculation time. This is also the case when more vessels are considered on the horizon. The experiments suggest that in case hourly based time slots are used, a 2 to 3 day horizon can easily be solved within an acceptable time.

Furthermore, it is possible to set certain weight factors to zero, in order to reduce the calculation time if this is necessary in certain situations. This is probably the most effective method when the terminal utilization becomes temporarily very large due to large disruptions. In severely disrupted situations, it is not the goal to balance the workload, but to recover from the disruption as soon as possible by allocating more resources. For instance, C_n can then be set to zero to decrease the computation time.

Now the experiments have been evaluated, the conclusion and recommendations for future research are discussed.

Chapter 5

Conclusions and Recommendations

5.1 Conclusion

Two key elements in efficient container port planning are:

- strategic planning,
- operational planning (re-planning).

Once a strategic planning is available, it can be used as a reference planning for operational planning. Due to disruptions, it is possible that the strategic planning becomes infeasible. Then a re-planning procedure needs to be performed. In this report, the re-planning of certain operations in a container terminal has been investigated. For the-replanning procedure, a decision support tool has been developed which allocates the:

- 1. vessel berth time intervals,
- 2. vessel berth positions along terminal quay,
- 3. quay cranes to vessels.

This decision support tool, referred throughout the report to as the Planning Controller, can be a useful tool in the decision making process when re-planning of the operations in the terminal is necessary. The Planning Controller, which is based on a Model Predictive Control strategy, consists of 3 Mixed Integer Linear Programs (optimization problems) as defined in [Hendriks, 2007]:

- 1. the Time Allocation Problem (TAP),
- 2. the Position Allocation Problem (PAP),
- 3. and the Quay Crane Allocation Problem (QCAP).

These 3 subproblems are executed successively to obtain the operational planning. This cut into 3 subproblems to solve a planning is a relative new approach, and has originally been designed for the strategic planning of a multi-terminal container port [Hendriks, 2007]. However, an important assumption which can be made here is that a vessel does not change from its reference berthing terminal. Therefore the berthing terminal does not have to be re-allocated. The '3 subproblem approach' can be used for each terminal individually, which results in a computational advantage.

Results experiments

The Planning Controller has been tested in a simulation environment where party real-life data is used. The following observations have been made:

Computation time

The main advantage of the 3 subproblem approach, is that it leads to short calculation times. The observations in computation time indicate that the cumulative computation time in the Planning Controller of the TAP, PAP, and QCAP is sufficiently low in order for the Planning Controller to become useful for use as a decision support tool for real life operational container terminal planning. The computation time of the QCAP is the largest, followed by the TAP. The computation time of the PAP is negligible in the total computation time of the operational planning.

The QCAP is due to a relative large computation time in most of the experiments turned off in the Planning Controller. For the quay crane usage, the continuous approximation of the TAP is used.

Stability issues

Due to the 3 subproblem approach, measures are required to prevent infeasibilities due to:

- 1. terminal berth capacity,
- 2. quay crane capacity,
- 3. horizon length.

In order to prevent an exceeding of the terminal berth capacity in the PAP, the following measures are taken in the TAP:

- requirement that the sum of the lengths of the vessels is less than or equal to the terminal quay length,
- requirement that a vessel cannot start berthing before its relevant predecessors has departed.

In order to prevent an exceeding of the quay crane capacity in the QCAP, the following measures are taken in the TAP:

- the use of a continuous quay crane allocation,
- the use of a slightly lower process rate in the TAP than in the QCAP.

Feasibilities due to a limited horizon length are prevented by:

- 1. the creation of a safety margin on the planning horizon,
- 2. temporary reduction of work for vessels located at the end of the planning horizon,
- 3. limitation of the number of vessels which are considered on the planning horizon, by a maximum process capacity.

According to the simulation observations, the Planning Controller shows stable behavior, even in cases where the disruptions are large.

Comparison between static and dynamic positioning strategy

A statistical analysis has been performed to compare the performance of the static and dynamic positioning strategy with each other under different circumstances. For all experiments performed, the dynamic positioning strategy showed a significant reduction in the average weekly straddle carrier driving distance, when compared to the static positioning strategy.

Depending on the disturbance level, a reduction up to an approximate average of 8,38% has been observed when a dynamic positioning strategy is used instead of the static positioning strategy. Even in absence of container disruptions, a significant reduction (1.27%) in straddle carrier driving distances has been observed when there are disruptions in arrival times present.

The dynamic version determines the lowest cost berthing position online, based on the arrival times and containers of each vessel. Therefore, it can react more efficiently upon disruptions.

Balancing between delays and quay crane usage

Agreements have been made between the terminal operator and the shipping lines about when to consider a vessel on time or early, and when to consider it late. As long as the vessel arrives on time or early, the terminal operator guarantees a certain maximum departure time. A violation of this maximum departure time should be prevented, since such an event damages the goodwill of the terminal operator.

The delays and quay crane usage are determined in the TAP. The objective in the TAP is to minimize the following costs over the planning horizon:

- 1. the total number of time slots that the departure time of each vessel deviates from its maximum departure time,
- 2. the total number of time slots that late arrived vessels depart too late,
- 3. the total number of time slots that early and timely arrived vessels depart too late,
- 4. the total number of time slots that the vessels start to berth earlier than the highest departure time of their desirable predecessors, and
- 5. the number of additional quay cranes above a certain standard quay crane usage.

By choosing the weight factors for these costs, a certain desired behavior can be obtained which balances between a certain process time (which affects delays) and a quay crane usage (which affects the operational costs for the terminal operator).

Different weight factor settings in the TAP have been investigated in a statistical sensitivity and comparison analysis. As a performance indicator, the average delay in departure and the average required number of additional quay cranes are used. From these experiment observations the following main conclusion can be drawn:

• a higher quay crane usage results in less and shorter delays in departure, whereas a low quay crane usage can result in more and longer delays in departure.

The correlation between delays in departure and quay crane usage, using TAP setting 1 through 4 from Table 4.4, can be found in Figure 4.17.

5.2 Recommendations

In order to obtain a decision support tool which becomes practical for real life planning, a graphical interface needs to be designed from where the input data can be entered. The models developed here, can then be used to perform the underlying calculations. Then only the forecasted / actual arrival times and container types and numbers needs to be fed into the model, from which the model can calculate the operational planning.

Also, a graphical output is then required, which shows the operational planning. A graphical output has partly been developed, in order to analyze the behavior of the Planning Controller. It shows exactly the berth allocation over time and position, and the quay crane usage over the calculated planning horizon.

Other interesting future research is to compare the performance of the 3 subproblem approach used here for the planning of a terminal, with the conventional approach where the BAP and QCAP are solved, and with real life planning techniques that are used currently in container terminals. The performance indicators of interest are for instance: the straddle carrier driving distances, obtained delays, quay crane usage, and calculation time of the operational planning.

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Appendix A

Strategic container data generation

The container data is generated for all vessels in the cyclic strategic planning $v \in \mathcal{V}_c$. For each vessel in the strategic cyclic planning, the average amount of containers that have to handled is given by $Q_v \ v \in \mathcal{V}_c$. Given the different container types, fractions $x_v^m, m \in \{1, 2, 3, \ldots, 11\}$ can be defined for each vessel which represents the contribution of each container type in the total number of to be handled containers Q_v :

$$\begin{array}{lll} x_v^1 = \text{Transshipment} & x_v^2 = \text{Import Reefers} & x_v^7 = \text{Export Reefers} \\ x_v^3 = \text{Import Imco's} & x_v^8 = \text{Export Imco's} \\ x_v^4 = \text{Import Regular} & x_v^9 = \text{Export Regular} \\ x_v^5 = \text{Import Empty 1} & x_v^{10} = \text{Export Empty 1} \\ x_v^6 = \text{Import Empty 2} & x_v^{11} = \text{Export Empty 2} \end{array}$$

Since the sum over the 11 fractions must always be equal to one, (A.1) always has to be valid:

$$\sum_{m=1}^{11} (x_v^m \cdot Q_v) = Q_v \qquad \forall v \in \mathcal{V}_c,$$
(A.1)

where

$$0 \le x_v^m \le 1 \qquad \forall v \in \mathcal{V}_c, m. \tag{A.2}$$

Given the fractions x_v^m and the total number of to be handled containers Q_v , the total number of containers for each type, indicated by q_v^m , can be calculated by:

$$q_v^m = x_v^m \cdot Q_v \qquad \forall v \in \mathcal{V}_c, m. \tag{A.3}$$

Although Q_v is based on real life data and is obtained from the strategic planning, the 11 specific container type fractions for each individual vessel are unknown. Therefore, realistic assumptions have to be made for the container type fractions. The average container type fractions \bar{x}_v^m of the total number of to be handled containers from a certain type is known. From these average container type fractions, the individual container type fractions for each vessel in the strategic planning are randomly generated. For each vessel in the strategic planning, the total number of containers Q_v is distributed over the 11 container types according to normal distributions with the average container type fractions \bar{x}_v^m as the mean. This procedure is explained in more detail now.

Generation of container types

The number of containers for each container type have to be generated for each vessel in the strategic planning. First the 11 average container type fractions are sorted on size in descending order. For convenience, assume now that the 11 average container type fractions sorted on size in descending order are: $\{\bar{x}_1, \bar{x}_2, \bar{x}_3, \ldots, \bar{x}_{11}\}$, where \bar{x}_1 is the largest fraction and \bar{x}_{11} the smallest. Then the number of containers from each container type, denoted as $\{q_v^1, q_v^2, q_v^3, \ldots, q_v^{11}\}$, are calculated for each vessel v in the strategic planning according to the following procedure.

For each vessel $v \in \mathcal{V}_c$, do:

STEP 1:

$$\begin{split} & \mu = \bar{x}_v^1 \cdot Q_v, \\ & \sigma = c \cdot \mu, \\ & \Delta = N(\mu, \sigma^2), \\ & \text{if } \Delta \geq 0 \longrightarrow q_v^1 = \max\{\mu + \Delta, Q_v\}, \\ & \text{if } \Delta < 0 \longrightarrow q_v^1 = \max\{\mu + \Delta, 0\}. \end{split}$$

STEP 2:

$$\begin{split} \mu &= \frac{\bar{x}_v^2}{1-\bar{x}_v^1} \cdot (Q_v - q_v^1), \\ \sigma &= c \cdot \mu, \\ \Delta &= N(\mu, \sigma^2), \end{split}$$
 if $\Delta \geq 0 \longrightarrow q_v^2 = \max\{\mu + \Delta, (Q_v - q_v^1)\}, \\ \text{if } \Delta &< 0 \longrightarrow q_v^2 = \max\{\mu + \Delta, 0\}. \end{split}$

STEP 3:

$$\begin{split} \mu &= \frac{\bar{x}_v^3}{1-\bar{x}_v^1-\bar{x}_v^2} \cdot (Q_v - q_v^1 - q_v^2), \\ \sigma &= c \cdot \mu, \\ \Delta &= N(\mu, \sigma^2), \\ \text{if } \Delta &\geq 0 \rightarrow q_v^3 = \max\{\mu + \Delta, (Q_v - q_v^1 - q_v^2)\}, \\ \text{if } \Delta &< 0 \rightarrow q_v^3 = \max\{\mu + \Delta, 0\}. \\ \downarrow \\ & \cdots \\ & \ddots \end{split}$$

STEP 10:

$$\begin{split} & \mu = \frac{\bar{x}_v^{10}}{1 - \bar{x}_v^1 - \bar{x}_v^2 - \bar{x}_v^3 - \bar{x}_v^4 - \bar{x}_v^5 - \bar{x}_v^6 - \bar{x}_v^7 - \bar{x}_v^8 - \bar{x}_v^9} \cdot (Q_v - q_v^1 - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9) \cdot \sigma = c \cdot \mu, \\ & \Delta = N(\mu, \sigma^2), \\ & \text{if } \Delta \ge 0 \to q_v^{10} = \max\{\mu + \Delta, (Q_v - q_v^1 - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9)\}, \\ & \text{if } \Delta < 0 \to q_v^{10} = \max\{\mu + \Delta, 0\}. \end{split}$$

STEP 11:

$$q_v^{11} = \max\{(Q_v - q_v^1 - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9 - q_v^{10}), 0\}$$

This procedure distributes the Q_v containers of each vessel in the strategic planning over the 11 different containers types q_v^m . In order to obtain integer an number of containers for each type, q_v^m is rounded. Then:

$$\sum_{m=1}^{11} q_v^m \approx Q_v \qquad \forall v \in \mathcal{V}_c.$$
(A.4)

After this procedure has been executed for each vessel in the strategic planning, the number and type of import and export containers for each vessel in the strategic planning is known. However, the exact transshipment from vessel to vessel still needs to be determined, because only the total amount of transshipment q_v^1 is known for each vessel in the strategic planning. So the source and destination of each transshipment container needs to be determined.

Distribution of transshipment over vessels

For each vessel, transshipment can be loaded as well as unloaded. Therefore, an explicit distinction is made in transshipment containers that are loaded from the vessel and unloaded from the vessel. The number of transshipment containers for a certain vessel is defined as follows:

$$T_v = T_v^{out} + T_v^{in} = q_v^1 \approx x_v^1 \cdot Q_v \qquad \forall v \in \mathcal{V}_c, \tag{A.5}$$

where T_v^{out} denotes transshipment containers which are unloaded from vessel v, and T_v^{in} transshipment containers which are loaded onto vessel v. Since each transshipment container first needs to be unloaded from a certain vessel and then loaded onto a different vessel, the following must always hold:

$$\sum_{v \in \mathcal{V}_c} T_v^{out} = \sum_{v \in \mathcal{V}_c} T_v^{in}.$$
 (A.6)

(A.6) implies conservation of mass in a closed system. Since a transshipment container cannot disappear in this closed system with a certain number of vessels, the total number of unloaded transshipment containers must always equal the total number of loaded transshipment containers. Furthermore, the total number of transshipment containers of each vessel must be less than or equal to half the total transshipment of all the vessels combined:

$$T_v \le 0.5 \cdot \sum_{v \in \mathcal{V}_c} T_v \qquad \forall v \in \mathcal{V}_c.$$
 (A.7)

If (A.7) does not hold, then there is no solution. The only solution in such a situation would be to have transshipment containers where the source vessel is equal to the destination vessel. However, such a solution is not allowed since this is an unrealistic situation.

Stated this, a transshipment matrix for the cyclic strategic planning is sought, $\Omega_{ij}, \{i, j\} \in \mathcal{V}_c$, which denotes transshipment of containers from vessel *i* to vessel *j*. The v^{th} row in Ω contains all the transshipment containers that have to be unloaded from vessel *v*. The total outgoing transshipment is therefore defined by $\sum_{j \in V_c} \Omega_{vj} = T_v^{out}$. The v^{th} column of Ω contains all the transshipment containers that have to be loaded onto vessel *v*. The total incoming transshipment is therefore defined by $\sum_{j \in V_c} \Omega_{vj} = T_v^{out}$. The total incoming transshipment is therefore defined by $\sum_{i \in V_c} \Omega_{iv} = T_v^{in}$.

Solving the transshipment distribution matrix P

The entries in Ω_{ij} can be obtained by solving a set of equations. For this, a fraction matrix P_{ij} needs to be calculated which determines which fraction of transshipment is transported from vessel *i* to vessel *j*. The following set of equations are solved by an LP solver to obtain the fraction matrix P:

$$\sum_{j \in \mathcal{V}_c} P_{vj} \cdot T_v + \sum_{i \in \mathcal{V}_c} P_{iv} \cdot T_i = T_v \qquad \forall v \in \mathcal{V}_c,$$
(A.8)

and

$$P_{vv} = 0 \qquad \forall v \in \mathcal{V}_c, \tag{A.9}$$

and

$$0 \le P_{ij} \le 1 \qquad \forall \{i, j\} \in \mathcal{V}_c. \tag{A.10}$$

where (A.8) implies that the sum of incoming transshipment plus outgoing transshipment must equal the total transshipment for each vessel in the strategic planning, and (A.9) implies zero transshipment if the source vessel is equal to the destination vessel.

Two optional equations can be added to this set of equations. In case the assumption is made that each individual vessel has 50% outgoing transshipment, and 50% incoming transshipment, then (A.11) must hold:

$$\sum_{j \in \mathcal{V}_c} P_{vj} = 0.5 \qquad \forall v \in \mathcal{V}_c, \tag{A.11}$$

Furthermore, certain transshipment fractions can be forced to zero. If transshipment from vessel i to j must equal zero, then (A.12) can be added:

$$P_{ij} = 0. \tag{A.12}$$

Solving (A.8) through (A.10) with the optional equations (A.11) and (A.12), results in a certain transshipment fraction matrix P. Remark that the solution of P is not unique, provided that the equations of (A.12) do not fully limit the solution space.

Obtaining transshipment matrix Ω

Finally, the transshipment matrix Ω_{ij} is then obtained as follows:

$$\Omega_{ij} = P_{ij} \cdot T_i \qquad \forall \{i, j\} \in \mathcal{V}_c. \tag{A.13}$$

Remark that in principle $\Omega_{ij} \neq \Omega_{ji}$ and that from (A.12) follows that $\Omega_{ii} = 0$. After this, the number of transshipment containers and their destinations are known for each vessel in the strategic planning. Once more, this procedure is only used since there is no real life container type data of each individual vessel available. If this was the case however, then this procedure becomes redundant.

As explained earlier, the strategic planning is cyclic usually over one week. Each week the same set of vessels with a certain number of containers of each type, $\{q_v^1, q_v^2, q_v^3, \ldots, q_v^{11}\}$ are initially expected. This means that for vessel A of week 1, initially the same number and type of containers are expected to be (un)loaded as for vessel A of week 2, 3, etc. The reference planning is therefore obtained by repeating the information of one cycle as often as necessary for the duration of one simulation run.

Since transshipment can also occur in between two vessels from a different cycle, a general transshipment matrix for the simulation model is constructed. From the transshipment matrix Ω_{ij} of the cyclic strategic planning, a matrix Ω_{ij}^* , $\{i, j\} \in \mathcal{V}_s$ can be obtained which is used for the entire run of the simulation. Depending on the number of cycles that is considered during one simulation run, the matrix Ω_{ij}^* is obtained by placing the matrix Ω for each cycle in the simulation run on the diagonal:

$$\Omega^*_{ij} = \left| \begin{array}{ccccc} \Omega & 0 & \dots & 0 \\ 0 & \Omega & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \Omega \end{array} \right|.$$

Appendix A. Strategic container data generation

Appendix B

Modeling of container disturbances

The following procedure is used to introduce disturbances on the number and type of containers of a vessel. Each time when a disturbance on the containers for vessel v is generated and a container forecast is obtained, this procedure is executed:

First the current total number of to be handled containers is calculated for vessel v:

$$Q_v = \sum_{i=2}^{11} q_i + \sum_{j \in \mathcal{V}_s} \Omega_{vj}^* + \sum_{i \in \mathcal{V}_s} \Omega_{iv}^*.$$
 (B.1)

Then a disturbance is generated on the total number of containers, Q_v . This is called STEP 0: STEP 0:

$$\begin{split} \mu &= Q_v, \\ \sigma &= \alpha \cdot \mu, \\ \Delta &= N(\mu, \sigma^2), \\ Q_v &= \max\{\mu + \Delta, 0\}. \end{split}$$

Now the total number of containers has been disturbed, these total number of containers has to be redistributed over the specific container types. First, the transshipment fraction is further divided into incoming transshipment and outgoing transshipment. Then the following current 12 container type fractions for vessel v are calculated:

$$\begin{aligned} x_v^{out} &= \frac{\sum\limits_{j \in \mathcal{V}_s} \Omega_{vj}^*}{Q_v}, \\ x_v^{in} &= \frac{\sum\limits_{i \in \mathcal{V}_s} \Omega_{iv}^*}{Q_v}, \\ x_v^2 &= \frac{q_v^2}{Q_v}, \\ x_v^3 &= \frac{q_v^3}{Q_v}, \end{aligned}$$

$$\begin{split} x_v^{11} &= \frac{q_v^{11}}{Q_v}, \\ \text{where } x_v^1 &= x_v^{out} + x_v^{in}. \end{split}$$

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Incoming transshipment containers (which have to be loaded onto vessel v) are not disturbed at this point. It would not make any sense to disturb incoming transshipment containers at this point, since these transshipment containers have been brought into the terminal by other vessels in the past. This amount of transshipment has already been disturbed in the past by the vessel where these transshipment containers came from. The amount of transshipment containers that have to be loaded onto vessel v is correlated with the amount of transshipment containers that have been brought in the terminal by other vessels in the past. Disturbing these incoming transhipment containers again would break this correlation, and would cause an inconsistency with the past.

First, q_v^{in} and q_v^{out} are determined, where q_v^{in} is not disturbed:

STEP 1 A:

$$q_v^{in} = \sum_{i \in \mathcal{V}_s} \Omega_{iv}^*.$$

Since q_v^{in} remains unchanged but the total number of containers Q_v has been disturbed, the incoming transshipment fraction must be updated:

$$x_v^{in} = \frac{\sum\limits_{i \in \mathcal{V}_s} \Omega_{iv}}{Q_v}$$

STEP 1 B:

$$\begin{split} \mu &= \frac{x_v^{out}}{1-x_v^{in}} \cdot (Q_v - q_v^{in}), \\ \sigma &= \beta \cdot \mu, \\ \Delta &= N(\mu, \sigma^2), \\ \text{if } \Delta &\geq 0 \longrightarrow q_v^{out} = \max\{\mu + \Delta, (Q_v - q_v^{in})\}, \\ \text{if } \Delta &< 0 \longrightarrow q_v^{out} = \max\{\mu + \Delta, 0\}. \end{split}$$

Then the fractions $\{x_v^2, \ldots, x_v^{11}\}$ are sorted from high to low. Assume now for convenience that the fractions sorted from high to low are $\{x_v^2, \ldots, x_v^{11}\}$. Then q_v^2, \ldots, q_v^{11} are calculated according to this sequence in STEP 2 to STEP 11 respectively:

STEP 2:

$$\begin{split} \mu &= \frac{x_v^2}{1 - x_v^{in} - x_v^{out}} \cdot (Q_v - q_v^{in} - q_v^{out}), \\ \sigma &= \beta \cdot \mu, \\ \Delta &= N(\mu, \sigma^2), \end{split}$$

if $\Delta \geq 0 \longrightarrow q_v^2 = \max\{\mu + \Delta, (Q_v - q_v^{in} - q_v^{out})\}, \\ \text{if } \Delta &< 0 \longrightarrow q_v^2 = \max\{\mu + \Delta, 0\}. \end{split}$

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STEP 10:

$$\begin{split} & \mu = \frac{x_v^{10}}{1 - x_v^{in} - x_v^{out} - x_v^2 - x_v^3 - x_v^4 - x_v^5 - x_v^0 - x_v^2 - x_v^3} \cdot (Q_v - q_v^{in} - q_v^{out} - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9), \\ & \sigma = \beta \cdot \mu, \\ & \Delta = N(\mu, \sigma^2), \\ & \text{if } \Delta \ge 0 \longrightarrow q_v^{10} = \max\{\mu + \Delta, (Q_v - q_v^{in} - q_v^{out} - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9)\}, \\ & \text{if } \Delta < 0 \longrightarrow q_v^{10} = \max\{\mu + \Delta, 0\}. \end{split}$$

STEP 11:

$$q_v^{11} = \max\{(Q_v - q_v^{in} - q_v^{out} - q_v^2 - q_v^3 - q_v^4 - q_v^5 - q_v^6 - q_v^7 - q_v^8 - q_v^9 - q_v^{10}), 0\}.$$

Unlike the incoming transshipment, the outgoing transshipment has been disturbed. Therefore the transshipment matrix Ω_{vj}^* needs to be updated. The v^{th} row in Ω_{vj}^* (outgoing transshipment from vessel v) is updated as follows:

$$\Omega_{vj}^* = P_{vj}^* \cdot T_v \qquad \forall j \in V_s, \tag{B.2}$$

where

$$P_{ij}^* = \begin{vmatrix} P & 0 & \dots & 0 \\ 0 & P & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & P \end{vmatrix}.$$

After this the container disturbance procedure for vessel v is finished. The new container forecast is then obtained, i.e. $\{q_v^{in}, q_v^{out}, q_v^2, q_v^3, \ldots, q_v^{11}\}$, where q_v^{in} and q_v^{out} are derived from Ω^* . Remark that Ω^* needs to be updated with a transshipment verification procedure, which is described in Appendix C because it is no clear yet which transshipment containers can actually be transhipped. Appendix B. Modeling of container disturbances

Appendix C

Container verification procedure

The following procedure is used to determine the flow of transshipment containers between the vessels.

In general, if a vessel *i* has transshipment containers which are destined for vessel *j*, and these transshipment containers cannot be loaded onto vessel *j*, since the arrival time of vessel *i* is larger than the arrival time of vessel *j*, i.e. $A_i > A_j$, then the verification procedure checks whether $A_i \leq A_{j+V_c}$, where V_c is the total number of vessels in one cycle. If this is the case, then the transshipment containers are forwarded to vessel $j + V_c$, which is a ship from the same shipping line which arrives one week later. The matrix Ω^* is then updated as follows:

$$\Omega^*_{v,j+V_c} = \Omega^*_{v,j+V_c} + \Omega^*_{v,j}, \tag{C.1}$$

followed by

$$\Omega_{v,i}^* = 0. \tag{C.2}$$

After the procedure has been executed, the updated matrix Ω^* is sent to the TAP.

Appendix C. Container verification procedure

Appendix D

Symbol list

Parameters

Parameter	Definition
k_c	Current time slot.
H	Planning horizon length [time slots].
H_a	Arrival horizon length [time slots].
A_v	Actual/forecasted arrival time of vessel v .
A_v^*	Reference arrival time of vessel v .
D_v^*	Reference departure time of vessel v .
D_v^{max}	Maximum departure time of vessel v .
P_v^{min}	Length of the minimum berth time interval for processing vessel v [time slots].
P_v^{max}	Length of the maximum berth time interval agreement of vessel v [time slots].
Q_v	Actual / expected $\#$ of containers which have to be processed on vessel v
L_v	Required quay length $[m]$ for vessel v to berth at the terminal.
S_v	Maximum $\#$ of quay cranes, which can simultaneously process vessel v .
L	Total quay length [m].
N	# of free quay cranes in the terminal.
N_{max}	Maximum $\#$ of quay cranes available in the terminal.
$ar{\lambda}$	Mean processing rate of the quay cranes in the terminal [containers/time slot]
η_v	Vessel efficiency with respect to quay crane rate [-]
C_n	Cost factor for an additional quay crane in operation above $N \left[\frac{\text{euro}}{\text{quay crane}}\right]$.
C_v	Cost factor (reward or penalty) for the deviation in departure from
	$\max\{D_v^{max}, (A_v + P_v^{min} + 1) \ [\frac{euro}{timeslat}].$
C_v^-	Cost factor (penalty) for vessel $v \in \{\mathcal{V}^-, \mathcal{V}_{\mathcal{B}}^-\}$ for departing later than
	$\max\{D_v^{max}, (A_v + P_v^{min} + 1) \ [\frac{\text{euro}}{\text{time slot}}].$
C_v^+	Cost factor (penalty) for vessel $v \in \{\mathcal{V}^+, \mathcal{V}_{\mathcal{B}}^+\}$ for departing later than
	$D_v^{max} \left[\frac{\text{euro}}{\text{time slot}} \right].$
C_a	Cost factor (penalty) for vessel v berthing earlier than the highest departure
	time of its relevant predecessors $\left[\frac{euro}{timeslot}\right]$.
C_v^p	Cost factor for vessel v berthing for the deviation from the lowest cost berth position.
P_v	Fixed berth position of vessel v .
ξ	Sufficiently large number.
R_v^*	Reference berth position of vessel v .

Table D.1: Definition of parameters.

\mathbf{Sets}

Set	Definition
\mathcal{V}_{c}	The set of vessels that are present in the cyclic strategic planning.
\mathcal{V}_r	The set of vessels that are present in the reference planning.
\mathcal{V}_s	The set of vessels that are considered throughout the entire simulation run.
\mathcal{V}_h	The set of vessels that are currently on the planning horizon, and for
	which is valid that: $k_c \leq A_v \leq (k_c + h)$.
\mathcal{V}_{nh}	The set of vessels that are currently not on the planning horizon.
\mathcal{V}^-	All vessels on the horizon which are not currently berthing yet, and are expected
	to arrive late.
$\mathcal{V}_{\mathcal{B}}^{-}$	All vessels on the horizon which are currently berthing, and have arrived late.
$\mathcal{V}^{\widetilde{+}}$	All vessels on the horizon which are not currently berthing yet, and are expected
	to arrive on time.
$\mathcal{V}_{\mathcal{B}}^+$	All vessels on the horizon which are currently berthing, and have arrived on time.
Ũ	contains the indices of pairs of vessels that are berthing simultaneously during
	at least one time interval.
\mathcal{W}_{j}	contains the relevant predecessors of vessel j .
\mathcal{Z}_j	contains all desirable predecessors of vessel j .

Table D.2: Definition of sets.

Container types

Type	Definition
Ω_{ij}	Matrix: contains transshipment from vessel i to j
q_v^1	Total transshipment of vessel v
q_v^2	Import Reefers of vessel v
q_v^3	Import Imco's of vessel v
q_v^4	Import Regular of vessel v
q_{v}^{5}	Import Empty 1 of vessel v
q_v^{6}	Import Empty 2 of vessel v
q_v^7	Export Reefers of vessel v
q_v^8	Export Imco's of vessel v
q_{v}^{9}	Export Regular of vessel v
q_v^{10}	Export Empty 1 of vessel v
q_v^{11}	Export Empty 2 of vessel v

Table D.3: Definition of container types $[\# \mbox{ of containers}]$