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Scheduling methods in liquid bulk terminals

To what extent can the implementation of scheduling methods improve the performance of liquid bulk terminals?

by

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Subject: **Scheduling methods in liquid bulk terminals**

Over the last few years liquid bulk terminals have been expanding. A higher terminal capacity has become available, thus clients have more opportunities to handle or store their liquid bulk materials. Competition between liquid bulk terminals has increased and efficient planning to offer fast, efficient and cost-effective services has become more important. Therefore, the question arises if the implementation of certain scheduling methods can improve the operation of a liquid bulk terminal to become more attractive for clients.

The aim of this assignment is to review and document current scheduling methods in liquid bulk terminals and determine the relation between certain terminal types, terminal KPIs and scheduling methods.

The research should cover the following:
- Review of the literature on liquid bulk terminal scheduling
- Categorization of liquid bulk terminals
- Analysis of scheduling methods and KPI's applied in practice
- A model to test multiple scheduling methods in liquid bulk terminals
- Critical evaluation of the performance of the model
- Conclusions on the applicability of the model and scheduling methods
- Suggestions for future research directions

This report should be arranged in such a way that all data is structurally presented in graphs, tables, and lists with belonging descriptions and explanations in text.

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

The professor,

Prof. dr. ir. G. Lodewijks

Preface

This report is the result of a graduation project at the Technical University of Delft, performed in cooperation with Royal HaskoningDHV. I would like to express my gratitude to Hugo Huges for his time and valuable advice throughout this project.

Readers who are particularly interested in the categorisation of liquid bulk terminals, key performance indicators and scheduling methods can find it in Chapter 5.

C.J.E. Dohmen
Delft, December 2016

Summary

Over the last few years liquid bulk terminals have expanded. Clients have more opportunities to handle or store their liquid bulk materials because more capacity has become available. Competition between liquid bulk terminals has increased and efficient planning to offer fast, efficient and cost-effective services has become more important. Therefore, the question arises if the implementation of certain scheduling methods can improve the operation of a liquid bulk terminal to become more attractive for clients. The purpose of this report is to investigate how certain scheduling methods can impact the performance of liquid bulk terminals.

Various types of liquid bulk terminals, key performance indicators and scheduling methods are studied from literature and in practice to construct a categorisation of liquid bulk terminals and investigate the relation between type, KPI and scheduling method. Literature promoted a categorisation based on the function of the terminal in the supply chain, but practice showed a categorisation based on ownership: independent, joint or single ownership. For each terminal category corresponding key performance indicators and scheduling objectives were found. Unfortunately, after the analysing phase no link was identified between different scheduling methods because all investigated terminals apply first come first serve. However, by administering different exceptions from this rule each category strives for different scheduling objectives. These objectives range from maximising service, minimising turnaround time to maximising profit.

Next, a model is set up to test the effect of different scheduling methods on actual terminals. First come first serve, fastest job first, largest vessel first, product priority and vessel priority are tested by adjusting the berth allocation sequence of arriving vessels. The terminal characteristics, vessel characteristics and arrival pattern are taken from a simulation based on historical data and performance is measured by average waiting time. Modelling multiple liquid bulk terminals under different scheduling methods leads to a most suitable scheduling method for each terminal.

From the five independent terminals that were tested it is concluded that no links can be identified between independent terminals and scheduling methods. The most suitable scheduling methods range from First Come First Serve, Fastest Job First, Largest Vessel First and Product Priority based on number of loading arms or berths. Some scheduling methods showed improvement of the average waiting time up to an 8% decrease. However, most scheduling methods had an insignificant impact of 1 or 2 % or even an unwanted increase in average waiting time. Thus, it is concluded that scheduling methods can effect the performance of a terminal positively, but the relation between these effects, the terminal specifications/type and arrival pattern requires more research.

Recommendations include improving the model by expanding the number of interviewed terminals, modelling terminals from all categories, varying the berth time of a vessel per berth and including effects on the availability of terminal infrastructure like internal transfers, cleaning and maintenance. But better results are expected to follow from a modified model and experiment. This experiment should evaluate the effect of all scheduling methods on terminals with variable characteristics representing all terminal types. By changing the terminal characteristics and arrival patterns the impact on more key performance indicators can be determined. To set up such an experiment an extensive analysis of common characteristics and arrival patterns per liquid bulk terminal type is required.

Samenvatting

De afgelopen jaren zijn het aantal en het formaat van vloeibare bulk terminals toegenomen. Omdat er meer capaciteit beschikbaar is gekomen hebben klanten meer mogelijkheden om hun vloeibare bulk op te slaan. Hierdoor is de concurrentie toegenomen en is er meer vraag naar een efficiente planning om kosteffectieve en snelle diensten te leveren. Dit is de aanleiding voor dit onderzoek naar het effect van planningsmethodieken op de prestatie van terminals. Het doel van dit rapport is om in kaart te brengen hoe bepaalde planningsmethodieken de prestaties van vloeibare bulk terminals beinvloeden.

In literatuur en praktijk worden verschillende soorten vloeibare bulk terminals, prestatie-indicatoren en planningsmethodieken bestudeerd om een categorisatie op te stellen en verbanden te leggen tussen terminal type, prestatie-indicator en planningsmethodiek. Literatuur promoot een categorisatie gebaseerd op functie in de leveringsketen, maar in de praktijk bleek een categorisatie gebaseerd op eigendom meer geschikt: onafhankelijk, gedeeld eigendom of enkele eigenaar. Voor elke van deze categorieen zijn er overeenkomstige prestatie-indicatoren en planningsdoelstellingen gevonden. Helaas zijn er geen verbanden met planningsmethodieken gevonden omdat alle onderzochte terminals dezelfde methodiek hanteren: first come first serve (wie het eerst komt wordt het eerste behandeld). Echter, door het toedienen van uitzonderingen op deze regel kan elke terminal zijn eigen doelstelling nastreven. Deze doelstellingen varieren van het maximaliseren van de bediening/diensten, het minimaliseren van de doorlooptijd tot het maximaliseren van de winst.

Vervolgens is een model opgezet om het effect van verschillende planningsmethodieken op werkelijke terminals te testen. First come first serve, fastest job first (snelste taak eerst), largest vessel first (grootste vaartuig eerst), product priority (prioritaire productgroepen) en vessel priority (prioritaire vaartuiggroepen) worden getest door de volgorde van aanwijzing van schepen aan de kade te wijzigen. De kenmerken van de terminal, de kenmerken van de schepen en hun aankomstpatroon worden gegenereerd door een simulatie gebaseerd op historische data. De prestatie van de terminal wordt gemeten met de gemiddelde wachttijd van alle schepen. De meest geschikte planningsmethodiek per terminal kan gevonden worden door de terminal te modelleren onder verschillende planningsmethodieken.

Aan de hand van de vijf onafhankelijke terminals die getest worden kunnen er geen links geidentificeerd worden tussen deze categorie terminals en de planningsmethodieken. De meest geschikte planningsmethodiek varieert van first come first serve, fastest job first, largest vessel first en product priority (afhankelijk van het aantal laadarmen of ligplaatsen). Somminge planningsmethodieken toonden een verbetering van 8%, maar de meeste hadden een insignificant effect van 1 of 2% of zelfs een ongewenste stijging van de gemiddelde wachttijd als resultaat. Daarom wordt er geconcludeerd dat planningsmethodieken een terminal positief kunnen beinvloeden, maar de verhouding tussen dit effect, de kenmerken/categorie van de terminal en het aankomstpatroon van de schepen vereist meer onderzoek.

Onderdeel van de aanbevelingen is onder meer verbeteren van het model door het uitbreiden van het aantal geinterviewde terminals, het modelleren van terminals uit alle categorien, de tijd aan de kade aanpassen per kade en de beschikbaarheid van infrastructuur meenemen. Maar naar verwachting worden betere resultaten behaald als het model en experiment aangepast wordt. Dit experiment zou alle planningsmethodieken mee moeten nemen en de kenmerken van de terminals flexibel moeten houden zodat alle type terminals gemodelleerd kunnen worden. Door de terminal kenmerken en het aankomstpatroon van schepen aan te passen kunnen ook de effecten op meerdere prestatie-indicatoren getest worden. Op dit experiment op te zetten is er meer onderzoek vereist naar gemeenschappelijke kenmerken per terminal categorie en aankomstpatronen.

List of abbreviations

AFRA	Average Freight Rate Assessment
ATA	Actual Time of Arrival
BAP	Berth Allocation Problem
C	Container
DB	Dry Bulk
ETA	Estimated Time of Arrival
FCFS	First Come First Serve
FJF	Fastest Job First
GSSP	Generalised Segregated Storage Problem
IASP	Integrated Allocation and Scheduling Problem
KPI	Key Performance Indicator
LB	Liquid Bulk
LNG	Liquefied Natural Gas
LPF	Liquefied Petroleum Gas
LVF	Largest Vessel First
MILP	Multi Integer Linear Problem
MNC	Multi National Company
PP	Product Priority
PSRP	Petrol Station Replenishment Problem
SSP	Segregated Storage Problem
TAP	Tank Allocation Problem
UNCTAD	United Nations Conference on Trade and Development
VOTOB	Vereniging van Nederlandse Tankopslagbedrijven
VP	Vessel Priority
VLCC	Very Large Crude Carrier

Contents

1 Introduction

Terminals are an important link in maritime transport because they can connect various modalities. 75% of the EU imports and exports depend on maritime transport (European Commission, 2015) and therefore the efficiency of the supply chain is crucial. In order to provide a competitive rate and compete globally operators must improve port efficiency, increase throughput and reduce terminal cost.

Over the last few years Royal HaskoningDHV has seen liquid bulk terminals expanding. A higher terminal capacity has become available, thus clients have more opportunities to handle or store their liquid bulk materials. Competition between liquid bulk terminals has increased and efficient planning to offer fast, adept and cost-effective services has become more important. Therefore, the question arises if the implementation of certain scheduling methods can improve the operation of a liquid bulk terminal to become more attractive for clients.

Unfortunately, at the moment there is limited information available about scheduling methods at liquid bulk terminals. Therefore, this assignment was initiated to evaluate current scheduling methods in liquid bulk terminals and investigate opportunities to improve them.

The purpose of this report is to investigate how scheduling methods can positively impact the performance of liquid bulk terminals. By increasing the performance of the terminal, its position in the market and function in the supply chain will improve. This leads to the following research question: "To what extent can the implementation of scheduling methods improve the performance of liquid bulk terminals?" In order to answer this question various types of liquid bulk terminals, key performance indicators and scheduling methods will be studied from literature and in practice. By modelling the various types of liquid bulk terminals under different scheduling methods, the most suitable scheduling method for different types of liquid bulk terminals will be discussed.

Next to the main research question, this research will also aim to answer the following questions:

- What types of liquid bulk can be identified?
- What types of liquid bulk terminals can be identified?
- Which KPIs can be defined in liquid bulk terminals?
- Which scheduling methods are currently applied in liquid bulk terminals?
- Can links be identified between terminal types, KPIs and current scheduling methods?
- Which scheduling methods can be applied in liquid bulk terminals?
- Which scheduling methods are most suitable for different types of liquid bulk terminals?
- Do suitable scheduling methods vary per liquid bulk terminal type?

Although scheduling methods can be applied in all types of terminals, the scope of this assignment is limited to applications in liquid bulk terminals. In the analysing phase other applications of scheduling methods will be studied to find appropriate methods that could be applied to liquid bulk. In the liquid bulk terminals scheduling of equipment, infrastructure, berth allocation and ship arrivals will be investigated. Based on the results of this phase a new scope is defined for the modelling phase. Based on the characteristics of liquid bulk terminal types a scope is determined that allows a clear distinction between terminal types but is simplified enough to support effective modelling results.

The structure of this research is split in two parts; the first part focuses on the evaluation and categorisation of liquid bulk terminals and current scheduling methods, and the second part describes the approach to modelling the terminals and scheduling methods. The structure of the report is set up as follows.

To investigate previous research on scheduling methods in (liquid bulk) terminals a literature review is performed on terminal scheduling methods. Chapter 2 presents the literature review on terminal scheduling problems, the integration of these problems and uncertainty in terminal scheduling. In order to understand the background to this research a background study on the liquid bulk market is performed. Chapter 3 presents the materials, general supply chain, stakeholder analysis, types of carriers, trade routes and trends of the liquid bulk market. To understand the terminal specifications a background study is performed on the functions, characteristics, equipment and types of liquid bulk terminals. In Chapter 4 the results are presented. Based on the evaluation of terminal specifications, the terminals with similar specifications will be categorised in certain types of liquid bulk terminals. For each type a set of characteristics will be determined to generalise a type of liquid bulk terminal. Section 4.4 presents examples of the terminal categories. In order to understand the driving factors for the terminal operators and possible drivers for the scheduling method, the possible key performance indicators for liquid bulk terminals are investigated. Section 5.1.1 presents these key performance indicators. Unfortunately, not much is known about scheduling methods in liquid bulk terminals. Therefore, multiple liquid bulk terminals will be visited to analyse their current scheduling practices. Scheduling methods in related industries (such as container terminals) and comparable systems will be studied from literature. Chapter 5 presents a summary of scheduling objectives from literature and the lessons learned in practice. The analysis of the categorisation of terminal types and the experiences in scheduling methods at the actual terminals will be combined. From this data conclusions will be drawn on relations between scheduling methods and terminal types or characteristics in Section 5.3.

Next, from the analysis the most suitable scheduling methods for modelling are selected. Chapter 6 presents the boundaries, assumptions, set-up, verification and validation of this model. Then, an experiment is performed where multiple scheduling strategies are tested on a certain terminal type. Chapter 7 presents the set-up and input of the experiment, but also the experimental plan, its results and the discussion of results. From the results of the experiment conclusions can be drawn if a certain scheduling method can be more beneficial than the others. Based on the analysis of current practices in liquid bulk terminals and the results from the experiment conclusions will be drawn on the most suitable scheduling method(s) in liquid bulk terminals. Chapter 8 presents these conclusions and Chapter 9 discussed recommendations for further research.

2

Literature review

Transportation planning has been widely discussed in literature, but most attention has been devoted to transportation by air or road. Unfortunately, pipeline, water and rail transport has attracted less attention. One of the reasons maritime transportation planning problems are unpopular is the less structured character of maritime transportation planning due to customisation of support systems. Also the uncertainty due to weather delays, mechanical problems or strikes resulted in low attention drawn in literature (Christiansen et al., 2007). However, in spite of these conditions research in maritime transportation has grown significantly. This chapter presents a review of literature on scheduling problems in maritime terminals. Firstly, an overview of literature on various terminal scheduling problems is presented. Next, the integration of multiple scheduling problems and the uncertainty in these scheduling methods are discussed.

2.1. Terminal scheduling problems

Terminal operations planning is a complicated task because all the operations (berth and vessel activities, ship loading or discharge, quay to storage transfer, storage, inter-modal transfer and inland distribution (Umang et al., 2011)) are highly interdependent. The entire terminal scheduling problem is usually decomposed into smaller sequential problems because it is virtually impossible to plan all operations as a single problem due to the complexity of terminal operations and the high arrival rate of vessels (Ya Xu, 2012). The ship arrival problem, the berth allocation problem, tank and pipeline allocation problem are the decomposed problems that will be presented in this section.

2.1.1. Berth allocation

The berth allocation problem consists of the assignment of vessels to a berth of a marine terminal. The berth allocation problem can have different objectives to optimise the performance, varying from maximising the service level to the carriers or minimising the terminal operator's costs.

The arrival process of ships can determine the delays in the (un-)loading process if there is limited jetty capacity available in the port. The arrival processes of vessels at liquid bulk terminals have been simulated by van Asperen et al. (van Asperen et al., 2003b) in order to find an optimum between the jetty capacity and expected delays for arriving ships. They identify three types of scenarios: stock-controlled arrivals, equidistant arrivals and uncontrolled arrivals. Simulation environments usually offer Poisson as a first-choice option for the specification of arrival processes because the assumption is made that arrival in client-oriented processes cannot be controlled. Unfortunately, the uncontrolled process has by far the worst performance in terms of waiting times (and required storage capacity). Therefore, it is important to manage the logistical process such that a beneficial arrival process can be realised (van Asperen et al., 2003b). But an optimization procedure for jetty allocation can already yield a performance improvement over a first come first serve (FCFS) allocation (van Asperen et al., 2004a). The ship arrival problem which is highly interdependent with the berth allocation, just like the availability of landside infrastructure is, will be discussed in Section 2.1.2.

The beneficial effect of the application of priority rules on the efficiency of (un-)loading was proven by van Asperen et al. (van Asperen et al., 2003a). A two-class priority scheme was used to assign ships to mooring points, which showed large benefits for the high priority ships and relatively small disadvantages for low priority ships. Sometimes priority rules set by the port owner are already applied to determine the berth allocation in addition to the FCFS rules (Pratap et al., 2015b). These priority rules can be set based on different criteria, such as business contracts, quantity of product or frequency of visit. However, a more sophisticated allocation strategy could further improve the terminal's performance.

An option for a more sophisticated choice would be a cost-based approach that includes the waiting costs of various types of ships. Also, an enumeration algorithm could be applied to select the optimal allocation scheme based on a cost function taking into account all possible schedules using a look-ahead time window (van Asperen et al., 2004b). In reality, the ATA of a ship can be known days beforehand, by a so-called pre-arrival notice, and can be used in more advanced allocation algorithms (van Asperen et al., 2004a).

The berth allocation problem has received more attention related to container terminals and dry bulk terminals. Therefore, the studies on the berth allocation problem in container and dry bulk terminals will be discussed next.

Berth allocation problem in container terminals Programming and the allocation of ships to berths can have a primary impact on the efficiency in port operations (Hansen et al., 2008). In container terminals berth allocation is one of the most important activities because it is an input to the yard space allocation and crane planning (Ya Xu, 2012).

For container terminals the Berth Allocation Problem (BAP) consists of the allocation of berths to arriving vessels and assigning a number of cranes to each vessel. The difficulty lies in the variation in ship arrival times, arriving ships of various sizes, drafts and TEUs, different lengths and dynamic draft of berths, entrance channel constraints and limited tugboats (Ilati et al., 2014).

A study by Ilati et al. (Ilati et al., 2014) on the BAP in a container terminal, aimed at minimizing the total wait time for ships, concluded that their objective function value was most affected by arrival disruptions. Port disruption management and the design of flexible and robust resource allocation plans are therefore important to investigate.

In Hansen's model of berth allocation in a container terminal, the objective is to minimise the total costs for waiting and handling as well as earliness or tardiness of completion, for all ships (Hansen et al., 2008). Which is more realistic due to the implementation of earliness premiums and lateness penalties and it does not assume that the handling costs are proportional to the handling times. Lin's objective is to minimise the total service time, that is, waiting time plus handling time (Shih-Wie Lin, 2014). Lalla-Ruiz et al. minimise the vessel turnaround times but also include time dependent limitations due to water depth and tidal constraints (Lalla-Ruiz et al., 2016).

The berth allocation problem (BAP) in container terminals can be categorised as static or dynamic, where the static BAP disregards the ship arrival time, and discrete, continuous or hybrid spaces can be used (Shih-Wie Lin, 2014). In case of container terminals the continuous berth allocation problem is much closer to the real world operation (Ching-Jung Ting, 2014). In liquid bulk terminals a continuous berth allocation is not possible due to the jetty infrastructure that is placed rigid along the quay.

Various studies have been performed on the problem of allocation arriving ships to discrete berth locations at container terminals. Burhkal et al. reviewed three of the main models (multiple integer problem, heterogeneous vehicle routing problem and generalised set-partitioning) and concluded that a generalised set-partitioning model outperforms the other models (Buhrkal et al., 2011)

Berth allocation problem in dry bulk terminals Very few studies have been carried out for berth allocation as a ship scheduling problem for bulk material handling port (Pratap et al., 2015b). The studies that could be found on the berth allocation problem in dry bulk terminals will be discussed in this section.

In a study performed by Lardinois for the EMO dry bulk terminal in Rotterdam two unloading methods, FIFO (First In First Out) and SSF (Small Ships First), were tested in the berth allocation problem. From this study it was concluded that the average ship waiting time did not differ significantly between the two berth scheduling methods. Therefore Lardinous recommended that the choice between these two methods should be based on other characteristics, e.g. economics or safety (Lardinois, 2011).

Pratap et al. (Pratap et al., 2015b) developed a decision support system for bulk material handling ports in relation to ship scheduling and discrete berth allocation in order to minimise ship waiting times and deviation of customer priority. The estimated arrival time of a ship at the anchorage was assumed to be known and uncertainty in this arrival time was not taken into account. The results showed a good utilization of the available berths and resources.

Ribeiro et al. (Ribeiro et al., 2016) include the maintenance activities, extra fees (demurrage) and awards (despatch) for port administrators in their berth allocation problem in an ore terminal. They have found optimal solutions on small instances to minimise demurrage and despatch fees.

To find the optimal scheduling for a bulk terminal Mooijman aimed to minimise the costs, but because of the complex nature of terminal cost an approximation was used (Mooijman, 2011). This approximation used four filters: minimal end time, minimal waiting time, minimal energy consumption and minimal reverses of equipment (e.g. belt conveyors or bidirectional pipelines). In this study the berth allocation, ship priority, tidal restrictions, terrain scheduling, bridge allocation and equipment scheduling are used as a basis for the terminal scheduling (Mooijman, 2011).

For some terminals the stock level depends on a continuous process of consumption and production of minerals. In these cases the basic criterion for decision making is to give priority to the vessels related to the most critical mineral stock level (Barros et al., 2011). For example, a material with stock below a certain critical level would gain high priority for unloading. The second criterion is based on the overall demurrage within a given planning horizon which is influenced by contractual costs. Barros et al. (Barros et al., 2011) studied the problem to determine the berths in such a way to minimise the total demurrage incurred given the tidal conditions and the stock level conditions in a dry bulk port with stock level demands. Even when a berth position is available, vessels may still need to wait for mooring in tidal ports (Barros et al., 2011).

2.1.2. Ship arrival

The ship arrival problem focusses on predicting the ship arrival times in order to predict the expected time at berth. Therefore it is directly linked to the berth allocation problem, which has been presented in Section 2.1.1.

Long-term contracts in the bulk oil and chemical sector include detailed price specifications but they are less rigid concerning exact delivery dates. The logistics department agrees with clients and suppliers on pick-up and delivery scheduling. On the other hand, there are also short term deals that require additional planning efforts because of traders disregard of logistical feasibility (van Asperen et al., 2004a).

Next to that, bad weather conditions and unexpected failures during the sea journey can cause positive or negative deviations from the berth allocation plan and cause additional waiting time (Ilati et al., 2014). The actual time of arrival (ATA) can differ substantially from the expected time of arrival (ETA). Figure 2.1 presents an overview of the difference between ETA and ATA for the RAJAEE Port in Iran to give an indication.

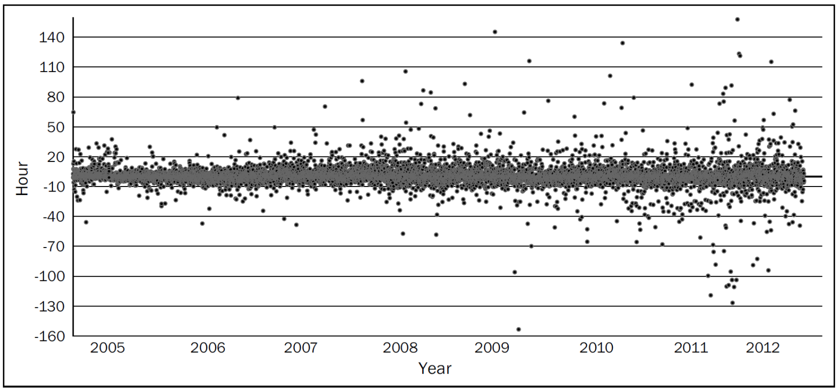

Figure 2.1: Deviation between ETA and ATA in RAJAEE Port (Ilati et al., 2014)

Once the expected time of arrival is known, the expected time of berth, expected time of completion and expected time of sailing can still vary because they depend on berth availability, operational constraints, tidal variations, vessel handling time and the priority of the vessels (Ilati et al., 2014). And the ship arrival time can also be influenced by port delays, breakdowns or bureaucratic problems (Fioroni et al., 2010).

Therefore, the arrival pattern in simulation studies are mostly based on comprehensive historical data and follow a negative exponential distribution (Ilati et al., 2014). However, unpredictable events and disruptions in the ship arrival problem and thus the berth allocation problem have become an in demand subject in studies on container terminals (Ilati et al., 2014).

2.1.3. Tank and pipeline allocation

Connected to the berth allocation and ship arrival problem, scheduling on the terminal has also been subject for research. Seaside and landside operations are interdependent, because once the ship has berthed the cargo must be unloaded/loaded and transported from/to storage. In liquid bulk terminals cargo is usually transported by pipes or hoses and stored in tanks. This section discusses the literature found on the tank allocation and pipeline allocation problems.

Stowage problem in liquid bulk shipping The literature on the maritime tank allocation problem (TAP) is scarce, but studies have already shown that models can outperform manually constructed plans (Fagerholt and Christiansen, 2000; G.A. Vouros, 1996; Pintens, 2008). Additional related problems are the segregated storage problem (SSP), the generalised segregated storage problem (GSSP) and petrol station replenishment problem (PSRP), where (different types of) products are assigned to (different types of) compartments (Hvattum et al., 2009).

Scheduling pipeline networks Optimal scheduling has also been studied in petroleum pipeline networks, from the simplest case (an unidirectional pipeline with a single origin and destination) to mesh-structured pipeline networks connecting refineries, distribution centres and customer facilities (Cafaro et al., 2012). The goal was to find the optimal transport schedule that satisfies all terminal requirements at minimum pumping, interface, idle transport capacity and inventory carrying costs (Cafaro and Cerdá, 2011). Several alternative paths may be possible to move a batch from a particular entry station to the assigned destination. Proper route scheduling is a key issue to avoid congestion and reduce pumping and interface costs for every shipment (Cafaro and Cerdá, 2012). Using a Multiple Integer Linear Problem (MILP) formulation batch sizes, product sequences, pump rates and flow directions can be determined all at once whilst product stocks at depots can be continuously controlled (Cafaro et al., 2012).

Boschetto et al. (Boschetto et al., 2011) studied a planning model to address the allocation and transportation of products among different producing/consuming areas in a complex pipeline network in order to minimise the use of the resources as tanks, pipelines and valves. Together with the scheduling method presented in Boschetto et al. (Boschetto et al., 2010) a complete operational solution for the pipeline network is created.

Scheduling methods using operations research are also investigated for refinery systems. Better analysis of the scheduling methods accommodates better use of the system's resources and control over the supply chain (Saharidis et al., 2009). The target of these scheduling models is to minimise the operating costs, maximise the profit or minimise the set-up costs for the loading and unloading (Saharidis et al., 2009; Yüzgeç et al., 2010). Results have proven that these can lead to an increased profit, provide more intelligent crude scheduling and recommend production level scheduling to benefit the operational mode of the refinery (Robertson et al., 2011).

2.2. Integration of terminal scheduling problems

As mentioned before, terminal operation planning is a complicated task and the entire terminal scheduling problem is therefore usually decomposed into smaller sequential problems. However, multiple studies have been performed on integrating different scheduling problems within the terminal because integrated planning of related port operations can significantly enhance the terminal efficiency due to their high interdependency.

The increase of containerised trade and the resulting increase in congestion and operating costs of container terminals have stimulated extensive research on integrated management of port resources. In container terminals research has been conducted on the integration of multiple decisions problems, such as an integration of berth allocation (BAP), tugboat and quay crane assignment (Ilati et al., 2014; Turkogullari et al., 2016) or the integration of scheduling on the yard such as quay cranes, yard cranes, storage space and internal trucks (Zhang et al., 2003; Assadipour et al., 2014). The solution of such approaches can be effective tools for port planners to generate an integrated resource allocation plan. Exact solution approaches to the berth allocation problem may be unable to solve the instances of realistic size optimally in reasonable time

(Ching-Jung Ting, 2014; Hansen et al., 2008). But even though obtaining optimal solutions is desirable, deriving high-quality solutions quickly can be beneficial for practical applications (Hess et al., 2008).

Between the allocation and utilization of berth and quay cranes there exists an inherent interrelationship. These valuable resources are also often the bottlenecks for serving vessel customers. Therefore the berth allocation problem is often combined with quay crane scheduling in container terminal optimization studies (Xiao-le Han, 2010).

Also in dry bulk terminals the berth allocation is linked to yard performance. Umang et al. (Umang et al., 2013) tested three formulations for a dynamic hybrid BAP in a dry bulk port terminal that enhance coordination between the berthing and yard activities.

Babu et al. (Babu et al., 2014) studied increasing efficiency by minimizing potential delays in port operation through simultaneous ship scheduling, stockyard planning and train scheduling in a dry bulk terminal. The model offers efficient and quick planning that exceeds current manual planning. However, further research on implementing multiple berths and daily capacity constraints on stacker/reclaimer machines, ship unload-er and train loader is required.

Pratap et al. (Pratap et al., 2015a) studied a model to optimise the stockyard operations and rake schedule for outbound cargo, in conjunction with the arriving vessels and the status of the stockyards at a dry bulk port. They found a large reduction or rake turnaround time as a consequence of reduction in rake waiting time and service time. However, the vessel berthing sequence was assumed predetermined and the arrival times of vessels and availability of handling equipment were assumed deterministic. Including these uncertainties would make the model closer to reality.

Tang et al. also studied the integrated storage space allocation and ship scheduling problem (IASP) in a bulk cargo terminal and their MILP solved by a Benders decomposition algorithm proved to be more efficient than standard CPLEX software solutions (Lixin Tang, 2015).

Robenek et al. (Robenek et al., 2014) combined the berth allocation and yard assignment problem in a single large scale optimization problem for bulk ports in order to minimise the total service time of vessels berthing at the port. Because a wide variety of equipment is used for discharging or loading operations, the cargo type on the vessel needs to be known in order to allocate a vessel to a berth (Robenek et al., 2014). The storage location and routing of materials also depend on the material type and berth location. Therefore, it makes sense to combine the berth allocation and yard management in an optimization model. Their results indicate that the algorithms successfully solve instances containing up to 40 vessels within reasonable computing time. Assumptions include that each vessel only carries a single type of cargo and the uncertainty in arrival times of the vessels and delays in handling operations are not taken into account.

Concerning liquid bulk terminals, Oliveira et al. (Oliveira et al., 2016) take into account both the scheduling of berthing and unloading activities at the terminal and the scheduling of pumping activities through the pipeline. The model is extended to consider the uncertainty in oil supply availability due to maritime conditions. In a terminal-refinery system (shown in Figure 2.2) petroleum scheduling problems include the selection of crude flows, the allocation of vessels to tanks, the allocation of tanks to crude distillation units and the calculation of crude compositions (Oliveira et al., 2016). This can be compared to a batch process scheduling problem. It is important that the vessel unloading activities are synchronised with the refinery operations and the best way to guarantee that the complete system must be optimised as a whole.

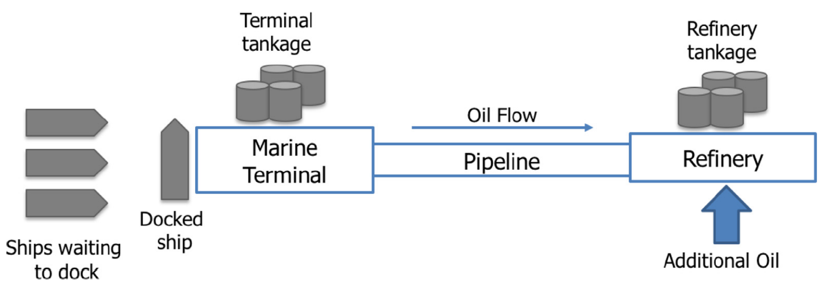

Figure 2.2: Schematic representation of the terminal-refinery system (Oliveira et al., 2016)

2.3. Uncertainty in terminal scheduling

When planning schedules are executed uncertainty is naturally inevitable and has its influence on the actual performance of the terminal operation (Xiao-le Han, 2010). The large number of complexities and uncertainties involved in bulk port operations must be considered at the planning level because they can disrupt the normal functioning of the port and require quick real-time action (Umang et al., 2011). Some of the common sources of disruption are uncertainty of information, changing ETA's of vessels, barges and trucks, change of modalities, last minute changes (cargo suppliers and traders), variety of product conditions, variety of ship's conditions, damages, weather, or reliability equipment (Umang et al., 2011). Disturbances in the work schedule at the terminal can be caused by (Mooijman, 2011):

- System errors
- Damages
- Client requests
- Company requests
- Train, truck or barge delays
- Environmental restrictions
- Unsafe situations

When container vessels are travelling to their destination port the estimated time of arrival (ETA) is updated periodically and communicated to the port. Based on this ETA and information about the cargo loading/unloading tasks from the vessel company and cargo agents the container terminal generates a predictive ship operation plan (Xiao-le Han, 2010). Because ship data is being collected dynamically planners may have to reschedule the berth plan of some vessels once new information gets in. However, frequent rescheduling of the berth plan may result in poor performance of the overall terminal efficiency (Ya Xu, 2012).

To incorporate uncertainties due to accidental events, equipment breakdown or major delay caused by weather conditions different approaches like reactive or rescheduling are necessary (Xiao-le Han, 2010). To minimise the probability of disruption in operations and enable fast recovery in real time it is also crucial to include robustness in planning operations (Umang et al., 2011). "The major objective of planning robust port operations is to minimise operational costs while maximizing system reliability" (Umang et al., 2011). In context of container terminals Gao et al. (Gao et al., 2010) studied robust planning by considering stochastic vessel arrivals. Robustness of the baseline berth plan is important for the overall performance of container terminals (Ya Xu, 2012). Using buffers in the operational plan has been widely adopted in scheduling problems to account for robustness.

In case of a terminal-refinery system, shown in Figure 2.2, Oliveira et al. (Oliveira et al., 2016) designed a framework to support decision making under supply uncertainty in order to minimise operational costs. After evaluating the proposed framework considering real-world data it is concluded that feasibility becomes the main issue in short-term planning. Therefore it is imperative that the uncertainty is represented within optimization models in order to provide a wider reach to the decision-making process in terms of foreseeing possible outcomes.

Umang et al. (Umang et al., 2016) modelled the uncertainty in the vessel arrival times by making appropriate assumptions about probability distributions of the uncertain parameters based on past data. The model modified the schedule real-time in response to new information (about disruptions). Results indicated that the algorithms can significantly reduce the total costs of the berthing schedule as compared to reassigning vessels at the port.

Uncertainties, inherent to the terminal scheduling process, present one of the major difficulties associated with operational planning activities. This often compromises the efficiency of the decision support tools that are unable to take the uncertainties into consideration. Despite the benefits, very few researchers take these uncertainties into account due to the challenging scale and the computational complexity associated with these models (Oliveira et al., 2016).

3

Liquid bulk

Port terminals that specialise in storing and handling of non-containerised bulk cargo are called bulk terminals. These terminals can be split in two categories, dry and liquid bulk. The focus of this research is liquid bulk terminals. In order to understand the setting of this research an introduction to liquid bulk is given by explaining for each type of materials, the general supply chain, the stakeholders, the different types of carriers and trade routes. Finally, the trends in the liquid bulk market will be addressed.

3.1. Materials

Liquid bulk cargoes are free-flowing liquids that are not boxed, bagged or hand stowed but poured into and sucked out of large tank spaces for transport (Maritime Industry Foundation, 2016). According to Vopak liquid bulk materials can be classified in five groups (Vopak, 2016):

- Oil products (such as crude oil, gasoline, naphtha, diesel and fuel oil)
- Chemicals (such as methanol, xylene, MEG and styrene)
- Bio-fuels and vegetable oils
- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG) (propane, butane)

'Bulk chemicals are characterised by high volumes of liquids, which are transported by pipelines, tank trucks, rail wagons and ships: the inventories are stored in tanks' (de Swaan Arons et al., 2004). Because most of the liquid bulk materials transshipped are classified as 'dangerous', special safety requirements are set up for handling, storing and transporting these materials.

The characteristics of liquid chemicals can be split up in physical properties, chemical properties, flammability, materials of construction, toxicity and cargo handling. All these characteristics have to be known if they are proposed for bulk water movement (U.S. Department of Homeland Security, U.S. Coast Guard, 2016). According to this classification chemicals are assigned to property groups (Hanninen and Rytkonen, 2006). These property groups define how a chemical will react if a spill occurs.

Another classification that can be used to identify liquid bulk types is presented by Leo (Leo, 2015):

- Chemicals
  - Organic (contain carbon, like methanol or styrene)
  - Inorganic (do not contain carbon, like phosphoric acids or sulphuric acids)
  - Fat/bio-oils (edibles, oils)
- Oil
  - Crude oil
  - Oil products (diesel, gasoline)

3.2. General supply chain

The general supply chain of liquid bulk starts at the exploration and production sites. Here the product is extracted from natural reservoirs. The products can be stored (in tanks) temporarily at the production site before it is transported to a (tank) terminal. At this point three types of materials can be considered: ready for end-user, needs processing or switch owner. The liquid bulk will be transported to the end-user, processing plant or an intermediate depot (van Duijn, 2009). From the processing plant the finished products can be transported to the end-user or to an intermediate depot if it is to switch owners. Depending on the demand in the area the product will be distributed to the hinterland or transported overseas. From an intermediate depot the new owner can collect the liquid bulk. The liquid bulk can be transported by either pipelines, inland waterway barges, sea-going vessels, trucks or trains.

The supply chain of different liquid bulk products varies due to material specific characteristics. In the following paragraphs these differences will be shortly addressed.

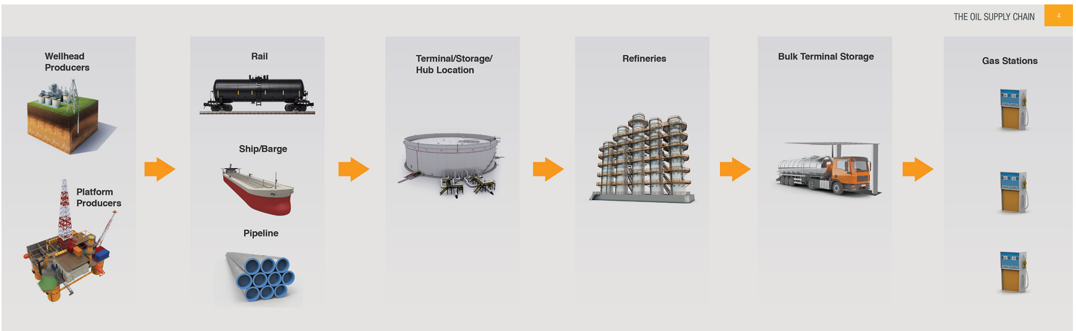

Figure 3.1: General oil supply chain (API, 2016)

Oil A general overview of the oil supply chain is given in Figure 3.1. Crude oil is transported from the well to the refinery in large batches (up to 300,000 dwt), but the oil products are transported in smaller batches (about 50,000 dwt) from the refinery to the user (Huges, 2016). Figure 3.1 shows a terminal storage at hub location, but the crude oil can also be stored at the production site or refinery or an intermediate bulk terminal awaiting transport. Typically, a refinery system receives crude oil through a pipeline network from an oil terminal that is directly served by tankers coming from overseas sources (Yüzgeç et al., 2010). It can also be transported by trucks, trains or barges.

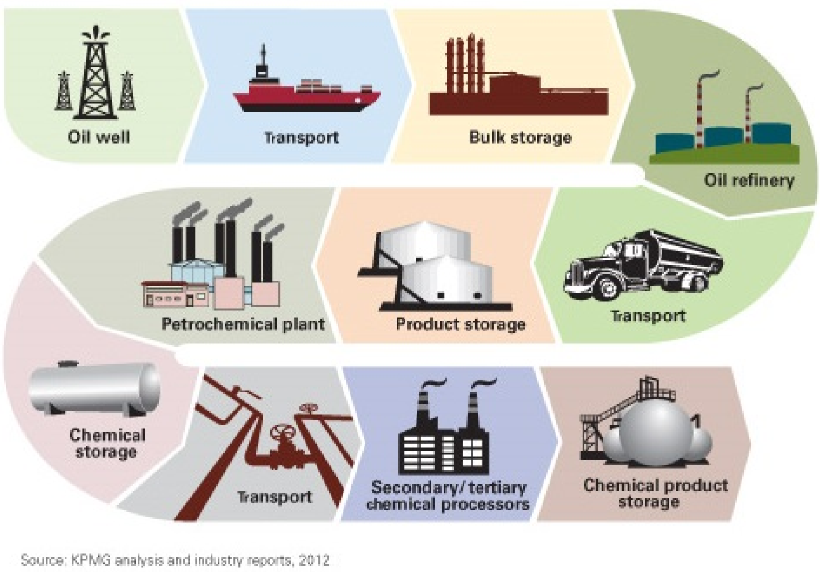

Figure 3.2: The oil and liquid chemical supply chain

Chemicals Chemical transport is characterised by very small parcels that are transported on ships with up to 60 different parcels on board. These parcels are shipped together on a larger ship because they have to travel a large distance between production plants and this is not beneficial with small carriers.

The supply chain of petrochemicals is linked to the supply of oil products. Figure 3.2 shows the oil and liquid chemical supply chain from oil well to chemical product storage. This supply chain shows the extensive number of storage and processing locations, and thus the need for storage of different grades of the product. The distance between oil well, oil refinery, petrochemical plant, secondary or tertiary chemical processors can be significant.

The operators of large chemical tankers usually operate and own large storage facilities in major export and import ports in order to provide the entire door-to-door shipment and storage (also known as "industrial shipping"). Their ships are generally employed on the intercontinental routes and run according to a fixed schedule (also called "line service"), but spot business can also be accepted if it fits in the schedule (Danish Ship Finance, 2016).

Roughly 60% of the deep-sea market for shipping bulk liquid chemicals is controlled by four large operators. In the short-sea market, with a capacity of roughly 3.5 million dwt, there are more operators, each with a small fleet of carriers (Jetlund and Karimi, 2004).

The expansion of manufacturing in South East Asia, Asia-Pacific and Middle East is located far from the major demand centres in the US, Europe, Japan, etc. Also, the expanding (oil, gas and chemical) export in the Caspian Sea, Africa, South America and Arabian Gulf are far from their customers in the East and West. Thus, the presence of large transport hubs (Houston, Singapore, Rotterdam, etc.) are crucial to the success of chemical supply chains (Li et al., 2010). An example of a supply and delivery scheme for a multi national company (MNC) in the chemical industry is given in figure 3.3.

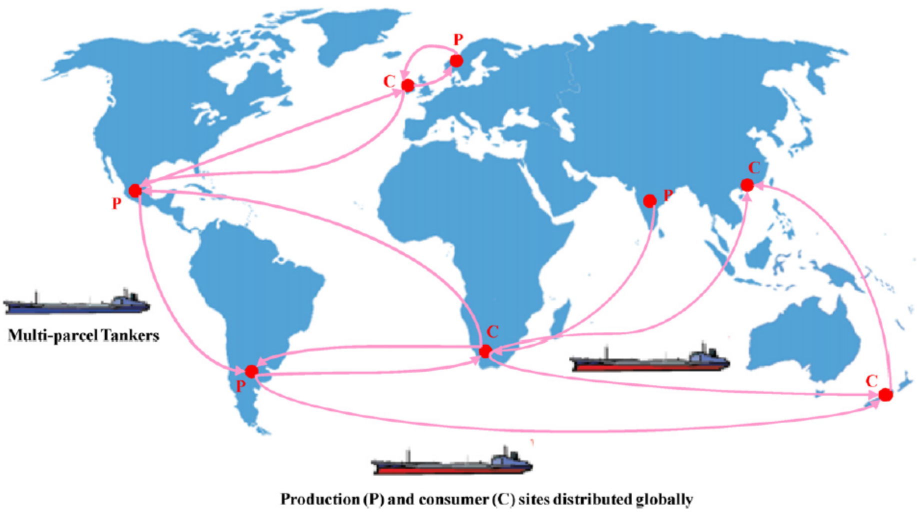

Figure 3.3: Schematic of the supply and delivery of multiple materials for a chemical MNC (Li et al., 2010)

Biofuels and vegetable oils The supply chain of biofuel starts at feedstock production, because the fundamental source of biofuel is the biomass feedstock. The harvested biomass is collected (regionally) and transported to biorefineries. At the biorefinery ethanol is produced, which is transported to blending facilities where the ethanol is mixed with gasoline. The biofuel is ready to be distributed after blending (Lim and Ouyang, 2015).

Palm oil is the most widely used vegetable oil in the world (Johnson & Johnson, 2016), because it can be used in cooking and used to make biofuel. Figure 3.4 shows the supply chain of palm oil as an example. From the plantation the biomass is transported to a mill where the palm oil is produced. In general the production of vegetable oils is achieved by using an oil mill or by chemical extraction using a solvent. Next it is transported to a refinery, with two collection ports in between to accommodate shipping in larger carriers. At the refinery/fractionation plant the oil is refined and by-products are extracted. These by-products can be used for other purposes, such as margarine production.

LNG Natural gas is produced in subsurface gas reservoirs and reached through drilling. After extraction the gas is cleaned of impurities and liquefied by cooling it to a temperature of approximately minus 160 degrees centigrade at a processing plant. The liquefied gas is one six hundredth of its original size and therefore easier to transport (South Hook, 2016). The natural gas is cooled when it is loaded onto the vessel, and LNG vessels do not have cooling capacity. This means that the tanks must be properly insulated to keep the temperature at minus 161.5 degrees Celsius for natural gas to remain liquefied during the entire transport. At the receiving terminal the LNG can be re-gasified. After regasification the gas is transported via pipelines for distribution to residential, commercial or industrial end-users (South Hook, 2016).

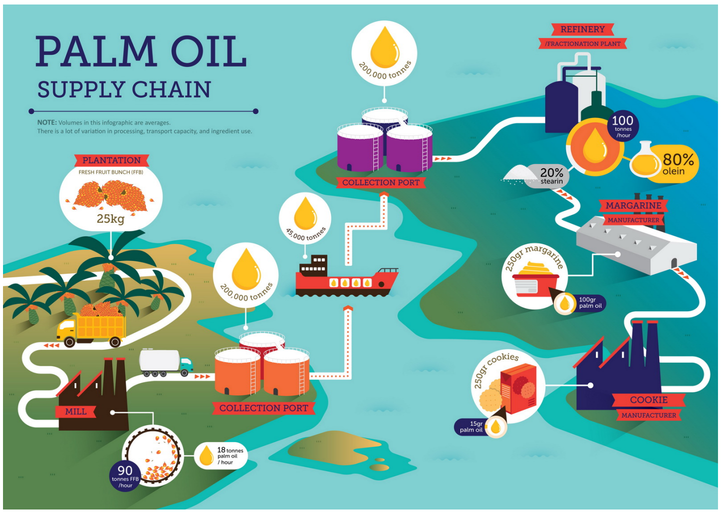

Figure 3.4: Schematic of the palm oil supply chain (Roundtable on Sustainable Palm Oil (RSPO), 2016)

LPG The LPG supply chain starts with production at oil and gas wells. Next, the unrefined oil and gas are shipped to refineries and gas processing plants. Raw natural gas is processed to remove acid gases, after which a liquid stream is extracted, this can be fractionated to produce propane and butane along with other LPG products. Alternatively, LPGs are produced as a by-product of the crude oil refining process (Jefferies LLC, 2013). From the refinery or processing plant the LPGs are transported to downstream storage terminals just like other oil products. The LPG is shipped in liquid form just like LNG, but unlike LNG it is pressurised or refrigerated in order to keep the gas in liquid form.

Table 3.1: Stakeholders and objectives (Gaur, 2005)

Stakeholder	Objective
Port authority/Operator	Maximise throughput
	Maximise net profit
	Operate at least cost
Port authority	Maximise value addition
Port authority/Government	Reach financial autonomy
	Efficient management of assets
	Minimise required capital investment
Central government/trade unions	Maximise employment level
Central government	Secure national independence as regards maritime transport
Local government	Promote regional economic development
Shipping company	Minimise vessel's time in port
Shipper	Minimise total cost of maritime transport
	Maximise quality of service to shipper
Users	Minimise port user cost
	Transparency of charges
Economist	Minimising welfare loss
Financial company of port	Maximise return on capital investment
Pressure groups	Ensure full environment protection

3.3. Stakeholders

The stakeholders involved in the liquid bulk industry are shown in Figure 3.5. Each stakeholder has its own objective that can vary from maximising quality to minimising loss or ensuring environmental protection. Table 3.1 gives an overview of the port players and their objectives presented by Gaur (Gaur, 2005).

From the liquid bulk supply chain perspective, next to the port players presented by Gaur also the liquid bulk owners, terminals, refineries and producers have to be included. The owner of the refinery or production site can also be the owner of the liquid bulk material and terminal. The objectives for the terminal can be taken from the literature review and will be discussed in detail in Section 5.1. These objectives vary between financial and operational performance. Just like the operator presented by Gaur, the refinery and producer will most likely aim to maximise net profit and throughput. The owner or trader might have the objective to maximise their profit, but will be dependent on other stakeholders to achieve this because their profit will depend on shipping performance, terminal performance and refining performance.

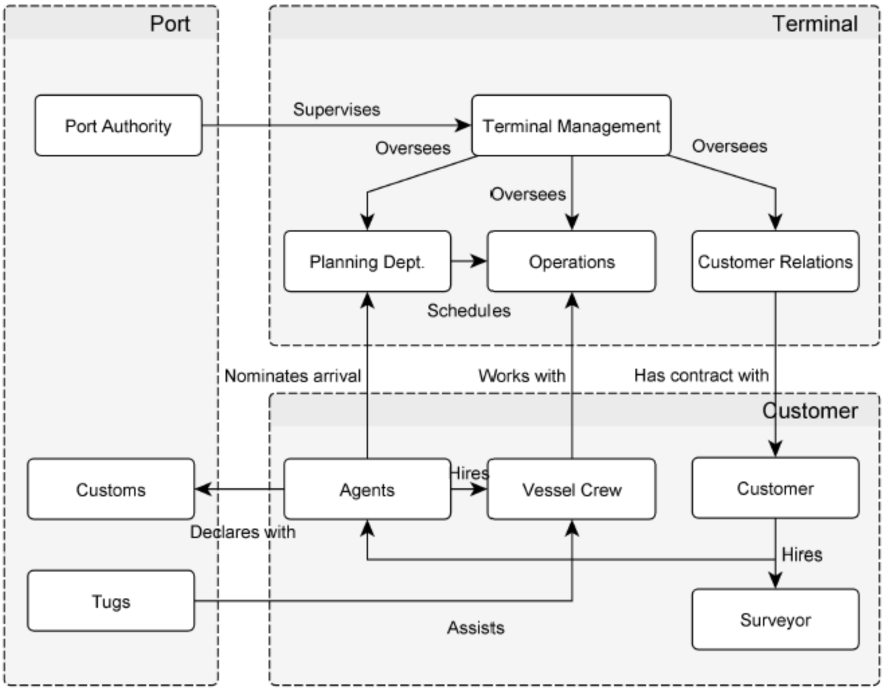

Figure 3.5: Stakeholders map of stakeholders involved in the liquid bulk scheduling process (Brouns, 2015)

3.4. Carriers

Liquid bulk materials can be transported in various types of ships. The following five types of bulk material carriers can be identified:

- Crude oil tanker
- Product tanker
- Parcel tanker
- Liquefied (natural) gas carrier
- Specialised tankers

Crude oil tankers and product tankers are both designed to transport oil. Crude oil tankers are dedicated ships that usually carry crude oil. It is possible for these tankers to carry petroleum but the costs of cleaning the tank make it uneconomical so that in practice it is rarely done. Product carriers are built to facilitate the carriage of segregated multiple products simultaneously. The difference is that product tankers are usually smaller and designed to move refined products instead of crude oil (Benjamin Atkinson, 2016). Figure 3.6 gives an overview of the crude oil and oil product tankers and their size. Due to the combustive properties and high market value of petroleum special attention is needed in the process of cargo movement (Ming and Shah, 2008).

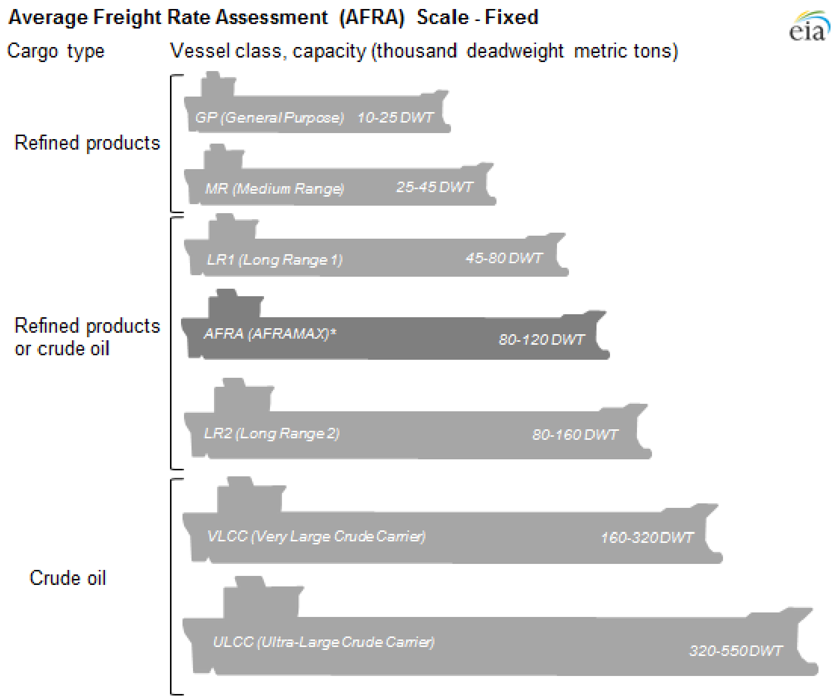

Figure 3.6: Average Freight Rate Assessment (AFRA) (U.S. Energy Information Administration, 2014)

A parcel tanker on the other hand is designed to move an assortment of liquids, typically consisting of 10 to 60 separate cargo tanks. Chemicals are usually carried in parcel sizes of 2 - 6,000 tonnes (Danish Ship Finance, 2016). Therefore is is economically beneficial to carry multiple parcels per carrier. This can be a combination of chemicals or different grades of a liquid such as petroleum. Most tanks are coated with stainless steel, but some specialised coatings (epoxy, zinc silicate or polyurethane) are used to ensure compatibility with a range of chemicals (Hanninen and Rytkonen, 2006).

Chemical carriers consist of multiple tank compartments of various sizes. For shipping companies using multi-parcel tankers it is an important planning problem to decide which tanks should be used for each load, also known as the tank allocation problem (TAP). The hazardous materials regulation constraints must be taken into account next to the standard constraints considering capacity and stability, such as: no mixing of different products or loads, a minimum volume to avoid sloshing, the total load must not exceed capacity and stability and strength requirements prohibit certain loading patters (Hvattum et al., 2009). Many chemicals are flammable, explosive or give off noxious vapours, but they can also be edible or immensely valuable and demand incredible standards of cleanliness to maintain purity (Hanninen and Rytkonen, 2006). Safety is a very important factor when handling chemicals and extensive regulations are in place to maintain safety standards.

Annually 125 million tonnes of chemicals are transported by chemical tankers. Of this volume half is transported regionally in small tankers (6000-10000 dwt) and the other half intercontinental in large tankers (25000-50000 dwt) (Jetlund and Karimi, 2004). The fleet of chemical tankers is divided in three shipping segments depending on their size (Danish Ship Finance, 2016):

- Deep sea - at least 20,000 dwt
- Intermediate - between 10,000 - 19,999 dwt
- Short sea - smaller than 10,000 dwt

Finally, a liquefied gas carrier designed to transport liquefied gases can transport LPG, LNG or chemical gases. These carriers can transport fully pressurised gas or semi-pressurised gas and can fully refrigerate their load. LNG tankers have between four and six tanks (Danish Ship Finance, 2016). The LPG gases are liquefied when cooled and/or compressed. As a result, LPG vessels can be segregated into four main categories: "ethylene" (extra refrigeration), "fully refrigerated" (refrigeration only), "semi refrigerated" (refrigeration and pressure) and "fully pressurised" (pressure only) (Danish Ship Finance, 2016). The fleet of LNG tankers is classified according to vessel size and can be split in five segments (Danish Ship Finance, 2016):

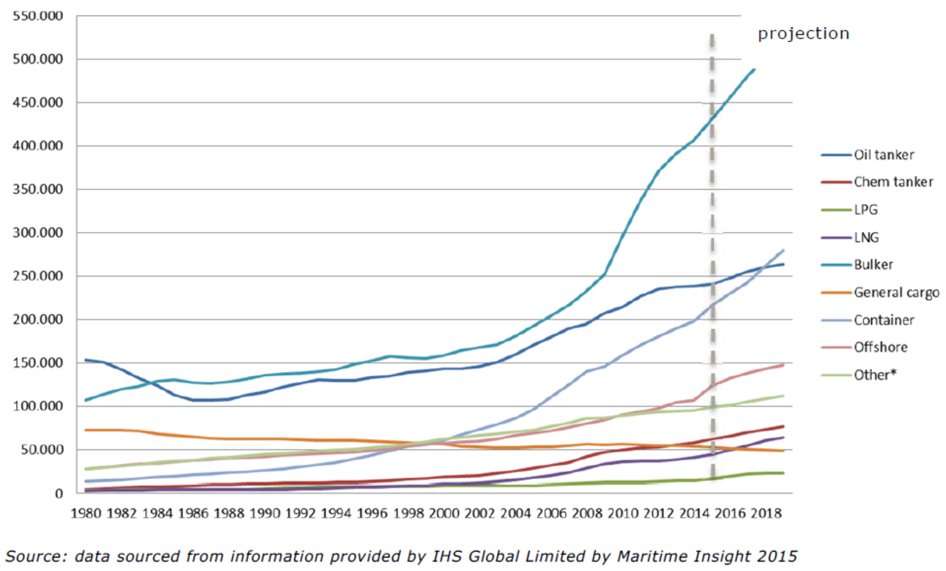

Figure 3.7: Fleet development by vessel type (in thousand GT) (European Commission, 2015)

- Very Large Natural Gas Carrier (VLNGC) - capacity of 200,000 m^3 or more
- Large Natural Gas Carrier (LNGC) - capacity between 140,000 and 199,999 m^3
- Medium Natural Gas Carrier (MNGC) - capacity between 100,000 and 140,000 m^3
- Handy Natural Gas Carrier (HNGC) - capacity between 60,000 and 99,999 m^3
- Small Natural Gas Carrier (SNGC) - capacity of less than 60,000 m^3

The fleet of LPG tankers is also classified according to vessel size and can be split in four segments (Danish Ship Finance, 2016):

- Very Large Gas Carrier (VLGC) - capacity of 60,000 m^3 or more
- Large Gas Carrier (LGC) - capacity between 40,000 and 59,999 m^3
- Medium Gas Carrier (MGC) - capacity between 20,000 and 39,999 m^3
- Small Gas Carrier (SGC) - capacity of less than 20,000 m^3

Examples of specialised tankers are wine, urea, water of shuttle tankers, where a shuttle carrier is a custom-made crude oil tanker for transport from offshore oil rigs to adjacent storage or refinery facilities (Danish Ship Finance, 2016).

As a result of the increased maritime trade in the period 1980-2014, the world fleet has increased by 44% in terms of number of ships and 185% in terms of volume (European Commission, 2015). Figure 3.7 shows the increase per vessel type and projection for the next few years. The overall growth in vessel capacity is estimated at 5% per year for the next 5 years. The difference between growth in vessel number and volume can be explained by the increase in average vessel size.

3.5. Trade routes

A trade route is defined as a logistical network identified as a series of pathways and stoppages used for the commercial transport of cargo. The trade routes of each type of liquid bulk material differs, depending on the supply and demand. This section shortly addressed the largest liquid bulk trade routes. Appendix B shows a graphical representation of the largest import and export regions per liquid bulk type.

Oil The five busiest routes for crude oil tankers measured in terms of volumes are from the Middle East to Asia, from South America to North America, from Africa to Europe, from Africa to North America and from the Middle East to Europe (Danish Ship Finance, 2016). This can be accounted to the geographical location of the oil fields. 60% of the world's known oil reserves are located in the Middle East and with 44% of the world's combined crude oil exports in 2010 this region is the largest exporter. The largest import regions are

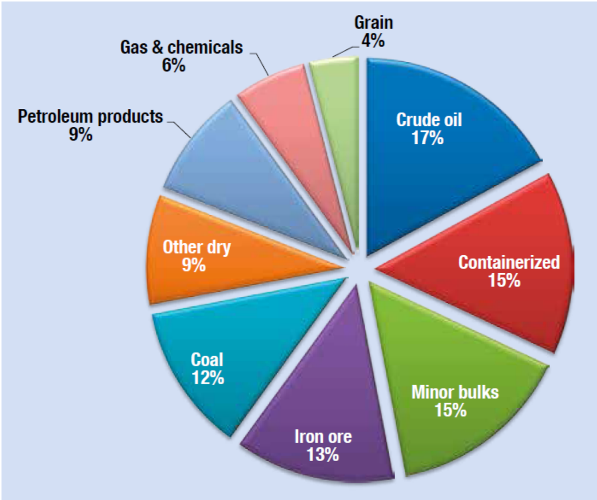

Figure 3.8: Structure of the international seaborne trade, 2014 (United Nations Conference on Trade And Development (UNCTAD), 2015)

Asia (33%), North America (26%), Europe (25%) and the Pacific region (14%) (Danish Ship Finance, 2016). The five largest product tanker routes are intra-Asia, from Europe to North America, from the Middle East to Asia, from North America to South America and from North America to Europe (Danish Ship Finance, 2016).

Figure B.1 and B.2 show the crude oil and oil product export and import in 2010 respectively. The major oil trade movements (crude and product) in 2015 are presented in Figure B.8. In this picture a large oil trade between North America and Europe can be seen. This can be accounted to the supply and demand of gasoline and diesel fuel. Both regions produce a certain amount of gasoline and diesel, because refineries cannot produce just one product and their yield is fixed, but their demand differs. Europe uses mostly diesel fuel and North America has a high demand on gasoline, therefore these oil products are transported between the regions (Huges, 2016).

Chemicals and vegetable oils In 2010, about 100 million tonnes of organic chemicals, 40 million tonnes of inorganic chemicals and 60 million tonnes of vegetable oils were transported. Figures B.3, B.4 and B.5 show the top 5 export and import regions of these chemicals respectively. Generally speaking, the largest routes are intra-Asian, from North America to South America, from the Middle East to Asia, from North America to Asia and from Asia to Europe (Danish Ship Finance, 2016).

LNG and LPG The Middle East, Asia and the Pacific region and Africa are the three principal LNG export regions and Asia, the Pacific region, Europe and North America are the largest import regions. The major LNG trade movements in 2015 are presented in Figure B.9. The LNG is transported over large distance, for example, the voyage from Qatar to the UK is about 6,000 miles and takes up to 18 days (South Hook, 2016).

The largest LPG exporters are found in the Middle East, West Africa (primarily Algeria) and the North Sea (Norway), whilst the largest importers include Northeast Asia (Japan, China and South Korea), the USA and the EU (Danish Ship Finance, 2016).

Figure B.7 and B.6 show the LPG and LNG export and import in 2010 respectively. It should be mentioned, however, that Malaysia and Australia account for the bulk of LNG exports in Asia and Pacific, whilst Japan and South Korea represent most of the LNG imports (Danish Ship Finance, 2016).

3.6. Trends

According to UNCTAD estimates the global seaborne trade has increased by 3.4% in 2014, bringing the total volume to 9.84 billion tons, and is expected to continue growing at a moderate pace (United Nations Conference on Trade And Development (UNCTAD), 2015). Of these 9.84 billions tons 17% is crude oil, 9% petroleum products and 6% gas and chemicals, as shown in Figure 3.8. The shipping tonnage for dry bulk and liquid bulk cargo has risen by 52% and 48% respectively over the last decade (Robenek et al., 2014).

The port and maritime industry has always been a highly competitive sector due to the large number of players, large volumes transported and long distance covered (due to a considerable distance between production and consumption sites) (European Commission, 2015). Due to deteriorating quality of crude oil coupled with tighter product specifications and more stringent environmental regulations, petroleum refining has become an extremely competitive business (Robertson et al., 2011). However, the nature of the competition has changed in recent years. Ports and the maritime industry compete as part of the supply chain that they belong to. This has motivated shipping companies to take over terminal operating companies and shipping agents all over the world. The terminal operating companies are the main suppliers of throughput services and agents coordinate all transactions in a port. When shipping companies integrate with them the quality and services can be better controlled. This is part of the trend of shipping companies that try to gain more control over large international logistics chains. In the tanker market this is different, because mostly production and handling are already in the same hands due to the nature of operations involved and need for transfer superstructure other than pipeline connections with refineries for example (European Commission, 2015). "The driving forces of integration include: increasing control over costs, pricing, entry and exit behaviour, access to technology and knowledge, reduced uncertainties, supply assurance and reduced complexities" (European Commission, 2015). De Swaan Arons et al. (de Swaan Arons et al., 2004) studied the coordination in a supply chain for bulk chemicals and found the beneficial influence of improved coordination on the logistics of a supply chain through simulation. Integrating different levels within a supply chain can improve profitability (Robertson et al., 2011). Therefore, an increasing emphasis on integrating maritime transportation into the supply chain is expected (Christiansen et al., 2013). This will motivate more research on routing and scheduling, such as inventory routing, collaboration, and cost/profit sharing along the supply chain. The research focus on oil refinery operations has already paid attention to optimization of the whole supply chain, including manufacturing and distribution operations (Cafaro and Cerdá, 2012).

Oil The global oil industry is increasingly dynamic and competitive due to sudden fluctuations in oil and product prices, new limits for exploration and exploitation of oil reserves, the new global awareness regarding environmental conservation and partnerships between major players in the market (Oliveira et al., 2016).

In the oil market specifically, a change in movements has occured. Certain oil wells have become depleted, so crude oil must come from larger distances. Also multiple crude oil supplies must be mixed to accommodate the specific requirements of the refinery that has been designed for the oil characteristics from the previously depleted wells. Refineries receive shipments of crude oil from a variety of sources with a different quality and composition. Blending these various crude oils can improve the economics of the refinery (Robertson et al., 2011). However, this creates a dynamic schedule of incoming crude oil. Thus more crude oil is transported over large distances because it is more expensive to relocate the refinery. However, this also influences the storage capacity. Due to the larger distance (and longer transport times) the uncertainty in arrival time has increased and requires refineries to build up a larger buffer. The tremendous increase in number of new entrants and continuous expansion in storage capacity globally pushes the petroleum terminals to be ready for stiff competition (Ming and Shah, 2008). Next to that, a change in large consumers has occurred, for example India is using more oil. Therefore, an overall increase in liquid bulk storage capacity can be seen (Huges, 2016).

Chemicals There is severe price competition in the chemical industry because many chemical products have commodity characteristics. The prices are however not always listed and the number of suppliers and users is limited, thus from a strategic perspective it is wise to use multiple suppliers. Unfortunately, this negatively impacts the logistical process (de Swaan Arons et al., 2004). A tank farm can provide a buffer for any uncertainty in the supply coming from sea transport. Over the last few years, the processing capacity of chemical industry has increased in regional markets. This increase in output has increased regional trade and resulted in a less varied and more specific deep-sea trade. Regional tanker fleets have increased and at tank terminals the chemicals are transshipped to larger deep-sea carriers (Jetlund and Karimi, 2004).

Biofuels and vegetable oils Biodiesel use in the EU has grown 34% since 2010. Rapeseed oil, the mainstay of biodiesel has remained stable, soybean oil has declined, sunflower oil is niche but the increase in palm oil use accounts for almost the complete growth (Transport and Environment, 2016).

LNG Natural gas (methane) is the third major energy source transported by sea, after oil and coal. The transportation of LNG is one of the most rapidly growing shipping activities. Over the past decade, the natural gas industry has experienced an increase in demand and a resulting rise in trading activity. This development has also been driven by rising oil prices and new technology, which has improved transport efficiency (Danish Ship Finance, 2016).

LPG Traditionally, the demand for LPG tankers was driven by demand in developing countries for LPG. LPG (propane, ethane and butane) was used for heating in rural areas. But higher oil prices have pushed up LPG prices and alternative heating methods have become available, resulting in weaker demand from the developing countries. On the other hand, the higher oil prices have fuelled demand for LPG in the petrochemicals industry as LPG can be used an alternative raw material in this sector (Danish Ship Finance, 2016). Unfortunately, the massive inflow of new vessels (the LPG fleet expanded by 17% in 2015) has created a drop in freight rates. Although the demand is expected to be relatively strong it will be probably be insufficient to absorb the new LPG tankers (Danish Ship Finance, 2016).

4

Liquid bulk terminals

After presenting the types of liquid bulk materials, supply chain, stakeholders, carriers, trade routes and trends, a closer look is taken at the terminals that handle these materials. Because liquid bulk handling differs from container handling or dry bulk handling, liquid bulk terminals are separately classified in ports. To define the scope of this research assignment a short introduction to liquid bulk terminals is given. This section presents the functions, characteristics, equipment, and a categorisation of types of liquid bulk terminals.

4.1. Functions

A terminal is an organisation offering a total package of activities and services to handle, store and control cargo to and from transportation modes with a balance in handling and services against minimised costs (van Duijn, 2009). The functions of a terminal can be split in three categories (Verheul, 2010):

- Storage
- Transport, transshipment and transfer (to facilitate storage)
- Value added logistics, such as blending, tank to tank transfers or adding additives.

Each terminal can vary in their storage and transport capacity or equipment. Value added logistics are optional for each terminal and can differ from elaborate services to terminals that only offer storage, transport and transshipment. Storage and transport are primary functions of a terminal, but performing value added logistics are secondary. Next to the primary and secondary function, a terminal must perform supporting activities to ensure safety, such as (van Duijn, 2009):

- Sampling and testing of products
- Fire prevention, odour removal, vapour treatment
- Heating, cooling, pressurising or other product specific activities
- Maintenance, inspection and cleaning of installations

When the scope is extended beyond the isolated terminal and the functions are analysed from a supply chain perspective, the liquid bulk terminal has several functions it must fulfil (van Duijn, 2009):

- Connecting different modalities in order to maintain product flow
- Temporarily storing products to provide a buffer between different modalities, for strategic reasons or compensate for scheduling differences in supply and demand.
- Changing product flow size (combining or distributing)
- Performing value added logistics (e.g. blending)

Next to this distinction between terminal functions, the operations can also be split in three functional systems (Ching-Jung Ting, 2014): seaside operations, yard operations and land-side operations. Each functional system has its own characteristics and operations, some may however overlap. Bulk terminal managers are faced with the challenge to both maximise efficiency along the quay side and on the yard (Robenek et al., 2014). This may require integrated scheduling methods.

4.2. Characteristics

Characteristics of a liquid bulk terminal can vary. Based on these characteristics a categorization will be made to identify different types of terminals. The factors that are expected to influence the categorization are:

- Products
- Services
- Capacity
- Equipment
- Layout
- Connection with hinterland
- Location
- Ownership
- Function in supply chain
- Clients
- Ship arrival rate
- Types of ships arriving

Besides the differences between various types of liquid bulk terminals a clear distinction between liquid bulk, dry bulk and container terminals can be made. From the literature review it has become clear that extensive research is available on scheduling methods in container terminals and some on dry bulk, but liquid bulk is certainly under-represented. By determining the analogies and differences between these terminals, an assessment can be made to what measure the approaches and results of these performed studies are applicable to liquid bulk terminals.

Container versus liquid bulk handling The major difference between container terminals and bulk ports is the need to account for the cargo type on the vessel (Robenek et al., 2014). For discharging and loading operations in bulk ports specialised equipment like conveyors and pipelines are necessary. This equipment not only depends on the type of material but also the type of vessel (Umang et al., 2011). Therefore, liquid bulk berths have a non-flexible capacity (with pipes and hoses) unlike container terminals with flexible berthing opportunities due to moving quay cranes. Also the loading stations (train or truck) on the terminal require specific infrastructure to handle liquid bulk, where straddlecarriers or automated guided vehicles (AGVs) can be used to transport containers on either land- or quayside. Contrary to container terminals the (un)loading of cargo is a continuous process for liquid bulk. Due to the need for dedicated equipment, like pipelines, some equipment might need to be available in multifold (varying in specifications). In case equipment is used for multiple products the scheduling department also needs to take into account cleaning activities.

Next to that, additional restrictions on the storage of specific cargo types are in place to prevent mixing or as safety measures because multiple products can be stored on the same terminal. Storage is also restricted to tanks unlike containers that can be placed on the yard flexibly. In container terminals multiple loads from different vessels can be stored in the same area, but liquid bulk must not be mixed and stored in separate tanks to maintain product integrity and quality. Due to the hazardous material regulation liquid bulk handling requires extensive safety and spill prevention measures. These measures can influence procedures in the terminal and require preparation.

Contrary to container vessels, liquid bulk carriers can transport multiple cargo types at once. Multiple cargo types on the same vessel requires a more detailed definition of the internal structure of each vessel and is usually not considered in any studies related to berth allocation problem (Robenek et al., 2014).

Other specific considerations for liquid bulk terminals include unpredictable vessel arrival rates due to oil trading and the link between production scheduling of (chemical) processes in supply and demand. In comparison with containers, oil products are exchangeable.

Dry bulk versus liquid bulk handling Dry bulk material handling is more similar to liquid bulk material handling, with characteristics like inflexible equipment, the storage of multiple products on the terminal and contamination prevention. However, the equipment does vary and storage is a bit more flexible in dry bulk terminals with larger stockyards. Research on scheduling methods in dry bulk terminals also focus on stockyard scheduling because multiple products can be placed on the same stockyard.

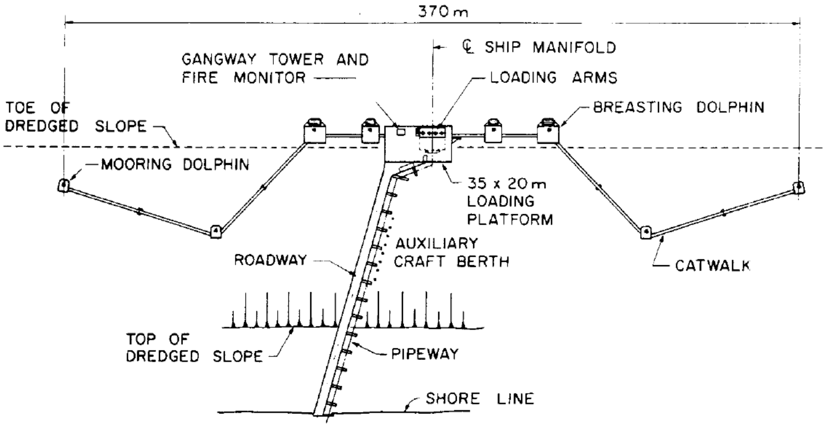

Figure 4.1: A typical oil-tanker berth layout (Ghoos et al., 2004)

From this general comparison it can be concluded that the specific characteristics of liquid bulk require a more detailed case study, including product characteristics, vessel characteristics, berth layout, terminal layout and pipeline network to schedule terminal operations. However, the scheduling objectives in both terminals can also be applied to liquid bulk terminal in order to investigate similar benefits.

4.3. Equipment

The equipment available at terminals is dependent on the types of materials the terminal handles. A liquid bulk terminal consists of the following construction elements (Leo, 2015):

- Tank farm
- Berthing structure
- Access channel
- Maritime conditions
- Hinterland access

How these elements are constructed and in which capacity can vary per terminal or terminal type. In this section all construction and handling elements and equipment will be shortly addressed.

Storage tanks Liquid bulk materials are usually stored in tanks. Tanks can be rented for one product during a certain time or co-mingled storage can be set up if multiple customers want to store similar products. Some tanks can be used for multiple materials (if properly cleaned) providing the terminal with some flexibility. Oil products are mostly stored in large-sized tanks and chemicals in smaller tanks. For chemicals it is important that certain conditions are met to ensure safe storage, such as controlled temperatures or atmospheres. The same holds for bio-ethanol, but bio-diesel and vegetable oils can be stored in similar sized tanks under less restricted conditions. Finally, LNG has to be stored in dedicated full containment large tanks that allow atmospheric pressure cooling to minus 160°C (Vopak, 2016).

Jetty A conventional jetty (also known as berth) consists of a central loading platform with a number of berthing and mooring dolphins (Ghoos et al., 2004), as shown in Figure 4.1. The liquid bulk is transferred through flexible devices to accommodate for the motion of the carrier relative to the loading platform.

The difference in the jetty between oil and chemical handling is the pipeway. For oil handling a limited number of large pipelines are used for loading and unloading, but chemical products require dedicated pipelines and thus the pipeway consists of multiple smaller pipelines.

A utilization rate of the jetty of 61% is considered busy but not overloaded according to industry norms (van Asperen et al., 2004a).

Buoys Because the liquid materials are transported in pipelines special offshore facilities have been developed, such as conventional buoy moorings and single-point moorings. There are three different types of single-point moorings: catenary anchor leg mooring (CALM), single-anchor leg mooring (SALM) and tower moorings. These off-shore installations can lessen the risk of catastrophes in the port by servicing large tankers outside the confines of the port (Ghoos et al., 2004).

However, buoys are only used when the depth at the quay is insufficient and a jetty is too expense to build because there are additional risks involved in using a buoy.

Pipeline system In order to transfer chemicals dedicated pipelines are necessary. Different oil products can use the same pipelines. In order to switch between different products however, cleaning of the pipelines is necessary. Because an oil terminal is designed with a limited number of pipelines cleaning is an important factor in scheduling. Chemicals, on the other hand, usually cannot share pipelines and use dedicated pipelines and tanks in order to prevent dangerous chemical reactions. Biofuels and vegetable oils must also be handled with care in order to prevent contamination. Because LPG and LNG must remain on a certain pressure or temperature, these products require a dedicated (insulated) pipeline system.

Hoses/loading arms Loading arms and hoses can be used to load or unload liquid bulk. The number of loading arms or hose towers at the jetty is an important factor when planning loading or unloading operations. Where loading arms are static and cannot cross each-other and hoses are more flexible, also the ships layout is a factor to be taken into account. Oil tankers usually carry only one or a small number of products, chemical parcel tankers can carry up to 60 parcels and the right material for unloading must be in reach of the loading arm or hose tower.

Pumps Liquid bulk cargoes are usually discharged from the vessel using the vessel's pumps and loaded using the terminal's pumps. In case of a large distance between the terminal and the jetty booster pumps can be used for both discharging and loading operations (Ming and Shah, 2008).

Loading stations In order to connect the terminal to the hinterland (other than by water) loading stations for trains and trucks can be present. These loading stations consist of dedicated equipment for loading or unloading a truck or train.

Other facilities In order to meet material specific demands some terminals might have additional facilities, such as (van Duijn, 2009):

- Cooling or heating systems, boil-off systems, hot-flare system s or vapour recovery systems
- Pigging stations for emptying pipelines
- Nitrogen stations for inerting empty space above a liquid in storage
- Slops buffer and waste water treatment
- Fire fighting facilities

4.4. Categorisation

Terminals can be classified based on multiple characteristics. In this section categorisations based on function in the supply chain and ownership will be discussed. But other classifications can be established to identify types of terminals. For example, terminals can be designed for special commodities (handling specific products) or designed for specific modes of transportation (van Duijn, 2009).

4.4.1. Function in supply chain

Verheul has classified terminals by their position in the supply chain (Verheul, 2010): strategic terminals, industrial terminals, import or export terminals, and hub terminals. In addition to the four terminals types presented by Verheul, make or break bulk terminals that are used for logistical benefits can be identified (Huges, 2016). Terminals that make or break bulk can be necessary if the production or end-user site is only accessible by smaller ships.

Strategic terminal The strategic terminals identified by Verheul are storage sites that are created by governments in accordance with legislation.

An example of a strategic terminal is Vopak Terminal Eemshaven. This terminal has only one berth, but 11 tanks with a total capacity of 660,000 cubic meters available for crude oil and petroleum products storage

(Koninklijke Vopak NV, 2016c). Due to the strategic nature of the terminal one berth is enough to exchange the stored oil with a new bath every once in a while.

Industrial terminal The function of an industrial terminal is the storage of raw materials and finalised goods at production sites, such as refineries. The terminals belonging to a refinery have a specific set of requirements set by de refinery's production rate. The annual throughput and product diversity demand a certain capacity of storage, carriers and berths.

An example of an industrial terminal is Gunvor Petroleum Rotterdam (GPR). The refinery and distribution center of GPR have direct access to the open sea and the European hinterland. The refinery produces LPG, gasoline, diesel and bunker fuel from the crude oil that is received in cargos up to VLCC standard. Next to a crude oil processing refinery and petrol plant, GPR also has supporting service plants and a large storage area. The crude oil and oil products are stored on their own tank farm with a capacity of 1.7 million cubic meters. The terminal has 2 berths at ocean jetty and 4 at barge jetty to accommodate for the large crude carriers coming in and the smaller barges with finished products going out (Gunvor Petroleum Rotterdam, 2016).

Import terminal Import terminals are focused on collecting large quantities of liquid bulk. For import or export terminals it is important that there is a balance between product arrivals and ship arrivals, otherwise the storage space might not be sufficient (Fioroni et al., 2010).

An example of an import terminal is the Maasvlakte Olie Terminal (MOT) that receives large amounts of crude oil for Dutch refineries. Due to the favourable maritime infrastructure it is possible to receive crude oil tankers up to 400,000 DWT with a depth of 22 meters. MOT offers a large tank farm (39 tanks of 114,000 cubic meters, total capacity of 4,5 million cubic meters) to store crude oil and is connected to the hinterland with an underground pipeline network. Yearly, about 240 tankers transport 35-40 million tonnes of crude oil to MOT (which is a third of all crude oil in the Port of Rotterdam). At the 2 berths 4 loading arms are available to unload the very large carriers in 24-48 hours (Maasvlakte Olie Terminal, 2013).

Export terminal Export terminals, opposed to import terminals, are focused on distributing large quantities of liquid bulk. At an export terminal small batches of a product are gathered to be transported together in a large batch.

An example of an export terminal is Vopak E.O.S. - Tallinn where the fuel oil from Russia is gathered for transport by large carriers. The terminal is accessible by barge, rail, truck and vessel and has 7 berths for vessels available. On the tank farm (with a total capacity of 1,0 million cubic meters) are 78 tanks available varying in size from 1,500 to 100,000 cubic meters. Additional services offered are blending, heating, lab on site, railtank car and truck (un)loading, bunkering services and additives (Koninklijke Vopak NV, 2016b).

Make bulk terminal A make bulk terminal is defined as a terminal that collects shipments from a lot of smaller ships and sends them of on one larger shipment. The collection of smaller shipments can be for logistical benefit (accessibility limitations at extraction/production site) or financial benefit.

An example of a make bulk terminal is Vopak Terminal Amsterdam Westpoort. At this terminals clean petroleum products are gathered for transport to North America. The terminal is accessible by barge and vessel and offers additivation, blending, butanising and filtration services. The 41 tanks, varying in size from 10,000 to 50,000 cubic meters, provide a total storage capacity of 1,2 million cubic meters. The clean petroleum products arrive by barge (at 1 of the 8 available berths) and leave by sea-going vessels (at 1 of the 3 available berths) (Koninklijke Vopak NV, 2016d).

Break bulk terminal Break bulk terminals operate in the opposite direction of make bulk terminal, one large shipment is split in multiple smaller shipments. This can also be for logistical or financial benefit.

An example of a break bulk terminal is Vopak Terminal Europoort where diesel arrives from North America in large carriers and are transported to the hinterland by barge and pipeline. With 99 tanks varying in size between 2,000 and 100,000 cubic meters the terminal has a storage capacity of 3,9 million cubic meters. 15 barge berths and 7 vessel berths are available to (un)load the barges and vessels. Additional services such as blending, heating, dedicated systems and additives are available (Koninklijke Vopak NV, 2016a).

Hub terminal Hub terminals are defined as high volume market places with many logistics services.

An example of a hub terminal is Vopak Terminal Europoort. As discussed previously, Vopak Terminal Europoort is a also categorised as a break bulk terminal. It is not uncommon that a terminal is part of multiple supply chains, therefore it can fulfil different roles simultaneously and be affiliated with multiple categories.

Vopak Terminal Europoort is an large scale independent terminal that handles crude oil and the full spectrum of petroleum products. It is known as a market place and trading hub with intra and inter terminal trading possibilities. The hub terminal has a strategic location and also pipeline connections to 10 refineries and connections to the main product pipelines (including pipeline connection to key airports in North West Europe) (Koninklijke Vopak NV, 2016a).

4.4.2. Ownership

According to Dekker and van Duijn, bulk terminal types can also be classified by ownership, which influences the ship arrival process at the terminal (Dekker, 2013; van Duijn, 2009). Next to ownership classification, Dekker also uses the type of product (crude oil, chemical or LNG) to identify the type of terminal.

Single (oil) company ownership One company owns and operates a terminal on its own behalf and services their own manufacturing plant or refinery. The product process drives ship arrivals or departures and therefore the ship arrival process can be predicted. Examples of terminals with single ownership are the Shell Europoort Terminal and BP Raffinaderij Rotterdam (Port of Rotterdam, 2016).

Joint/consortium ownership Two or more companies own a terminal together and share its operating costs. An example of a terminal with joint ownership is TEAM Terminal Rotterdam with ESSO, BP, and Aramco as shareholders (TEAM Terminal BV, 2008).

Independent ownership An independent trader owns and operates a terminal. Ship arrivals can be much more random at an independently owned terminal because they are possibly driven by trading opportunities. An example of an independent third party terminal operator is Odfjell Terminals Rotterdam (Odfjell, 2015).

5

Terminal performance and scheduling methods

The aim of this chapter is to answer the following research (sub-)questions; *Which KPIs can be defined in liquid bulk terminals?*, *Which scheduling methods are currently applied in liquid bulk terminals?* and, *Can links be identified between terminal types, KPIs and current scheduling methods?*. Therefore this chapter presents a link between an evaluation of literature and practice.

Section 5.1 presents the evaluation of key performance indicators in literature and a summary of scheduling objectives presented in the literature review in Chapter 2. In Section 5.2 a comparison will be made with an evaluation of scheduling methods currently applied in liquid bulk terminals. Finally, Section 5.3 will link the key performance indicators and scheduling objectives to liquid bulk terminal types.

5.1. Evaluation of literature

Bulk terminal operations planning on the tactical level can be based on "rules of thumb" or operations research (Robenek et al., 2014). Unfortunately, operations research problems have received almost no attention thus far in the context of bulk port terminals (Robenek et al., 2014). Even though operations research methods and techniques have proven to enhance port operations and terminal efficiency (Umang et al., 2011). In the field of container terminal management significant contributions have been made, but little attention has been paid to bulk port operations and it is only recently gaining attention (Pratap et al., 2015a). Therefore the literature review includes research on container terminals and dry bulk terminals. However, because the mode of operation of a liquid bulk terminal is different from a container terminal there is a need for a separate approach and practices may differ. This section presents an evaluation of literature, consisting of a summary of key performance indicators and scheduling objectives applied to marine terminals.

5.1.1. Key performance indicators

Control of a process or an operation is only possible if there is some form of feedback on the performance or results. This feedback must involve the measuring of the actual output and comparing it with the desired output to determine the performance. The data collected from calculating key performance indicators can be used to improve port operations and provide a basis for planning future port development (United Nations, 1976). Key performance indicators (KPIs) can be used to measure performance of terminals and maintain consistent quality of work, but KPIs and the way they are measured vary from terminal to terminal (Rademacher, 2011).

The United Nations Conference on Trade and Development (UNCTAD) has identified financial and operational indicators. The port performance indicators presented by UNCTAD in 1976 are still in use globally (Ming and Shah, 2008). Figure 5.1 and 5.2 present a summary of the performance indicators from UNCTAD. The financial performance indicators are proposed to answer the following questions:

- What revenue is produced from a service?
- What is the cost of the service?

However the operational performance indicators are more important for port management initially to select for medium-term planning and control. The performance indicators that are important in the terminal depend on the port authorities' particular requirements and may vary. Some of the key performance indicators that have been identified by Verheul and Umang are (Verheul, 2010; Umang et al., 2011):

- Berth occupancy
- Tank occupancy
- Turnover factor
- Throughput per berth/quay - *The throughput cargo depends on many factors including designed pump capacity, pressure drop as a result of distance of the terminal away from the jetty front and the pipe's diameter size (Ming and Shah, 2008).*
- Number of vessels
- Average waiting time - *In short-sea operation port delays are significant as carriers can spend about 40% of their time in ports, including time spend servicing cargo's and waiting for anchorage (Jetlund and Karimi, 2004).*
- Vessel turnaround time
- Revenue per vessel
- Revenue per m^3 tank volume
- Realised loading capacity
- Berth efficiency

Indicators	*Units*
Tonnage worked	Tons
Berth occupancy revenue per ton of cargo	Monetary units/ton
Cargo-handling revenue per ton of cargo	Monetary units/ton
Labour expenditure per ton of cargo	Monetary units/ton
Capital equipment expenditure per ton of cargo	Monetary units/ton
Contribution per ton of cargo	Monetary units/ton
Total contribution	Monetary units

* Calculated monthly for each berth group servicing a cargo class.

Figure 5.1: Summary of UNCTAD financial indicators (United Nations, 1976)

Indicator	*Units*
Arrival late	Ships/day
Waiting time	Hours/ship
Service time	Hours/ship
Turn-round time	Hours/ship
Tonnage per ship	Tons/ship
Fraction of time berthed ships worked	–
Number of gangs employed per ship per shift	Gangs
Tons per ship-hour in port	Tons/hour
Tons per ship hour at berth	Tons/hour
Tons per gang-hour	Tons/gang-hour
Fraction of time gangs idle	–

* Calculated monthly for each berth group servicing a cargo class.

Figure 5.2: Summary of UNCTAD operational indicators (United Nations, 1976)

5.1.2. Scheduling methods

According to literature, first come first served is one of the most frequently used scheduling rules (Strandenes, 2004). Unfortunately, the application of a first come first serve policy causes delays in loading and unloading because the resources are not used optimally (Pratap et al., 2015a). However, the tradition of "first come first served" irrespective of the different vessels' contribution to port revenue in the berth allocation are still in practice (Ming and Shah, 2008). Due to the disadvantages of applying the first come first served policy, research has focused on optimising terminal performance by applying scheduling methods as discussed in Chapter 2.

Considering scheduling objectives to optimise terminal operations, usually minimising the service time or turnaround time of vessels is used, which includes the vessel waiting time and vessel handling time at the berth (Umang et al., 2011). However, the objective can differ from minimising the service times of vessels, minimising the port stay time, or minimising the deviation between actual and planned berthing schedules (Robenek et al., 2014). But even more objectives can be identified in literature on terminal scheduling. Table 5.1 presents an overview of these scheduling objectives found in literature, including an indication if the paper studies a dry bulk (DB), container (C) or liquid bulk (LB) terminal.

Table 5.1: Scheduling objectives in literature

	Minimising deviation of customer priority	Minimising earliness/tardiness of completion	Minimising total wait time	Minimising total delays	Minimising total/operational costs	Minimising total demurrage	Minimising total service time	Minimising turnaround time
(Babu et al., 2014)				DB				
(Barros et al., 2011)					DB			
(Buhrkal et al., 2011)			C				C	
(Cafaro and Cerdá, 2011)					LB			
(Chiara Briano, 2005)						C		
(Ching-Jung Ting, 2014)							C	
(Hansen et al., 2008)					C			
(Ilati et al., 2014)			C					
(Lalla-Ruiz et al., 2016)								C
(Li et al., 2010)					LB			
(Lixin Tang, 2015)					DB			
(Menezes et al., 2016)					DB	DB		
(Oliveira et al., 2016)					LB	LB		
(Pratap et al., 2015a)							DB	
(Pratap et al., 2015b)	DB		DB					
(Ribeiro et al., 2016)						DB		
(Robenek et al., 2014)							DB	
(Robertson et al., 2011)					LB			
(Sayareh and Ahouei, 2013)				DB				
(Shih-Wie Lin, 2014)							C	
(Turkogullari et al., 2016)					C			
(Umang et al., 2011)							DB	
(Umang et al., 2013)							DB	
(Umang et al., 2016)					DB			
(Xiao-le Han, 2010)		C					C	
(Ya Xu, 2012)	C			C				
(Yüzgeç et al., 2010)					LB			
(Zhen, 2015)						C		

5.2. Evaluation of current methods

Because not everything can be found in literature or online, multiple visits to liquid bulk terminals were scheduled to interview actual planners. This section includes the results from six interviews with liquid bulk terminals in the Netherlands about the scheduling methods applied in practice. The goal of the interviews was to find out which scheduling methods are in use, but also to find out other details that can influence the scheduling such as guidelines, the planning horizon and scheduling tools in use. Based on the information provided by the terminals conclusions can be drawn on the categorisation of terminals (presented in Section 5.3. Next to that, the interviews also form the baseline for setting up the model presented in Chapter 6.

5.2.1. Guidelines

VOTOB conditions are applied in almost all Dutch liquid bulk terminals (Terminal C, 2016). These conditions regulate the arrival and handling sequence of vessels and vehicles, but also define the consequences of delay (Vereniging van Nederlandse tankopslagbedrijven, 2014). According to the VOTOB general conditions a vessel must be nominated at least two working days in advance. This nomination must include the estimated time of arrival (ETA), the type and volume of the goods to be (un-)loaded, and other necessary information or instructions. However, as will be discussed later on, the clients do not always honour the two working day period between nomination and arrival. Regarding scheduling method, the VOTOB states that: "In principle, vessels and vehicles are handled in the sequence of their arrival at or alongside the premises. The storage company shall have the right - but not the obligation - to give priority to sea-going vessels over inland waterway vessels" (Vereniging van Nederlandse tankopslagbedrijven, 2014). In practice this rule is almost always applied, exceptions will be discussed in Section 5.2.3. However, VOTOB also states that the storage company reserves the right to deviate from the first come, first serve sequence if it deems so necessary. It can be necessary in order to comply with government regulations, if it enables smooth operation at the terminal or if there are other valid grounds based on objective criteria (Vereniging van Nederlandse tankopslagbedrijven, 2014). Thus other scheduling methods than FCFS may be applied by liquid bulk terminals under VOTOB conditions, as long as they are based on objective criteria.

VOTOB conditions also define the consequences of delay. VOTOB states that the client will be liable for the costs of delay, if the goods are not delivered within the timespan defined in the contract between client en terminal. But also when they are on time, the client will have to pay the demurrage regardless of the grounds (Vereniging van Nederlandse tankopslagbedrijven, 2014).

The Tank-barge terms and conditions of transport guide the agreement between client and contractor (vessel owner) and determine the demurrage conditions (Centraal Bureau voor de Rijn- & Binnenvaart, 2010). According to the tons of cargo, the type of tanker (single-hulled or double-hulled) and the pump capacity the free loading and discharging time is determined. If this free loading and discharging time is exceeded, the client must pay the agreed demurrage to the contractor. From the literature review it has already become clear that minimising demurrage is an important objective for terminals. If they have to pay these costs or if their clients are responsible, it is a charge that is preferably avoided.

5.2.2. Key performance indicators

Previously, the key performance indicators that were found in literature have been presented. By visiting multiple terminals and performing interviews with the planning department, customer services, operations and sales department the performance measures used in practice were investigated. The key performance indicators used in practice are:

- Turnaround time (Terminal A, 2016; Terminal F, 2016; Terminal E, 2016; Terminal D, 2016; Terminal G, 2016)
- Idle time (at berth) (Terminal F, 2016; Terminal D, 2016)
  - Administrative time (Terminal F, 2016)
  - Pre- and post-processing time (Terminal F, 2016)
- Pump time (Terminal D, 2016)
- Average (un-)loading speed per product (Terminal G, 2016)
- Average product flow per berth (Terminal F, 2016)
- Berth occupancy (Terminal C, 2016; Terminal E, 2016)
- Terminal occupancy (Terminal G, 2016)
- Throughput (Terminal C, 2016)
- Average waiting time (Terminal D, 2016; Terminal G, 2016)
- Costs of delay (demurrage) (Terminal B, 2016)

The categorisation of key performance indicators per terminal type will be discussed in Section 5.3. These kpi's are measured to determine the performance of the terminal and look for points of improvement. However at most terminals some points of improvement are already known. These bottlenecks not only influence/limit the performance, but also have to be taken into account when scheduling operations.

One of these bottlenecks can be the storage if the terminal has a high occupancy rate of the storage tanks (Terminal E, 2016; Terminal A, 2016). In order to cope with this bottleneck sometimes other vessels are given priority over a ship waiting for their designated tank to be available. Another possible bottleneck is the pump rate of the jetty-lines (Terminal A, 2016). Especially for larger vessels the loading or discharging time can be significantly increased if the capacity of the jetty-lines is lower than the pump capacity of the vessel. The operational crew can be a bottleneck if pre- and post-processing cannot be performed optimally (Terminal F, 2016). Due to a shortage of manpower during peak hours this pre- and post-processing times can increase and delay the operation. However this is usually not taken into account during planning and most terminals work with a standard minimum occupancy of work crew. This can cause unexpected extra delays at already busy hours. Maintenance can also be a bottleneck for the terminal operation (Terminal G, 2016). Therefore maintenance activities must be taken into account in operational planning. For another terminal where the berth is not a bottleneck, the performance is not ideal because of limited pump and pipeline availability (Terminal C, 2016). At operational level these limitations have to be taken into account, but they are not considered during scheduling. Finally, bottlenecks can influence the terminal to make deviations from their usual scheduling method. The exceptions that were encountered during the interviews will be discussed in the next section.

5.2.3. Scheduling methods

During the analysis of scheduling methods used in practice the supposition was confirmed that most terminals use a first come, first serve scheduling approach. However, also some different scheduling methods came to light that can be applied but are under-represented. This section presents the application of first come, first serve and the alternative scheduling methods that will be investigated.

First come, first serve All terminals that were consulted for this research study use first come, fist serve (FCFS) to assign incoming vessels to their jetties. From these interviews it became clear that FCFS is used by almost everyone and in all types of terminals. However, in certain situations these terminals deviate from this FCFS rule. Exceptions from FCFS can be made in agreement with the partners (Terminal A, 2016) or clients (Terminal D, 2016). Examples of exceptions that are made in practice are:

- priority for vessels carrying urgent feedstock (Terminal F, 2016,?)
- priority for vessels loading from storage tanks about to overflow (Terminal B, 2016; Terminal F, 2016)
- priority for vessels arriving within the timespan documented in the contract (Terminal B, 2016)
- priority for large carriers over barges (Terminal D, 2016)
- priority for vessels carrying cargo that have hinterland connections waiting (trucks or trains) (Terminal C, 2016)
- priority for vessels with larger costs of delay (demurrage) (Terminal B, 2016)
- one shareholder/client is not allowed to occupy all berths, therefore another shareholder/client has priority (Terminal E, 2016; Terminal D, 2016)
- priority for vessels with available infrastructure (storage, pipelines) and products over vessels waiting on infrastructure (Terminal G, 2016; Terminal F, 2016)
- priority for vessels given by owner (only priority over vessels from same owner) (Terminal A, 2016)

Although the scheduling method is similar for all types of terminals, the scheduling objectives, exceptions from FCFS and key performance indicators are different. Section 5.3 presents theses objectives, exceptions and KPI's per terminal type.

Largest vessel first It goes without saying that the scheduling method largest vessel first (LVF) gives priority to vessels based on their size. In practice sea-going vessels already have priority over barges, as defined in the VOTOB conditions in Section 5.2.1. But also between sea-going vessels or barges with different sizes priority rules can be applied.

Fastest job first It also goes without saying that the scheduling method fastest job first (FJF) gives priority to vessels based on the time needed at the berth. This time at berth can be defined by the loading or discharging time. But also idle times or administration times can be included.

Product priority Not only based on the vessel size or berth time, but also based on the product priority can be given to certain vessels. The scheduling method product priority (PP) can be useful when a certain product can only be loaded/discharged at one specific berth. By giving this product priority the terminal can ensure that a vessel containing this product is always assigned to that specific berth as soon as it becomes available.

Preferred berthing The previously presented scheduling method PP is an example of a sort of preferred berthing method. Based on product, vessel type or client a preferred berth can be assigned to a certain category of vessels. Vessels in this category will be assigned to their preferred berth with priority if it is available, whereas vessels not in this category will have to wait on these category vessels. For example a terminal can operate with 6 berths and 6 clients, each client has their preferred berth. If a client has two vessels arriving one of them can be assigned to a non-preferred berth of another client, but only if that client has no vessels waiting.

Dedicated berthing One step further than preferred berthing is dedicated berthing. Instead of the flexibility of averting to another berth if the preferred berth is taken, when dedicated berthing is in use the client/product-category/vessel-type can only be assigned to one (or more) dedicated berth(s). This has a high impact on the flexibility of the terminal. Because the use of dedicated berthing and most cases of preferred berthing are very specific for a terminal, its infrastructure and client database, these scheduling methods will not be considered in the modelling phase of this study.

Slot booking According to literature, in the liquid chemical industry the planning horizon is typically less than 4 weeks. There is a contrast between contract cargoes that are planned weeks in advance and spot cargoes that can be requested at any time and can be planned only a few days in advance (Jetlund and Karimi, 2004). But not only the amount of spot cargoes, also the unpredictability of barges and delays due to unforeseen circumstances make slot booking systems very inefficient. The actual time of arrival and time needed to (un-)load can only be known for certain once the vessel has arrived at the terminal.

7 out of 7 terminals interviewed do not use slot booking because of this uncertainty. The schedule is usually only made 1/2 to 1 day in advance (Terminal D, 2016). For seagoing vessels the planning is made 24 hours in advance, but for barges there is no advance planning because their arrival is very unpredictable (Terminal F, 2016). Seagoing vessels have an advantage that they can be tracked by AIS data, but the influence of the port administration and pilot can shift the ATA last minute (Terminal A, 2016). Therefore, sometimes even seagoing vessels will only be scheduled 8 hours in advance (Terminal E, 2016). Most terminals make a schedule per day, this schedule includes a list of vessels arriving that day. The detailed schedule will be determined by the operational crew once the vessel has arrived (Terminal C, 2016). Due to this uncertainty extensive research will be necessary to determine the applicability and optimality of slot booking in liquid bulk terminals. Therefore, slot booking will not be considered in the modelling phase of this study.

5.2.4. Scheduling tools

For some terminals the infrastructure is also scheduled in advance together with the berth allocation (Terminal D, 2016). Other terminals make an operational schedule on ship arrival (Terminal C, 2016). When creating a schedule for the terminal the following factors are taken into account to make sure the schedule is viable:

- Unavailability due to maintenance
- Berth specifications
- Pipeline availability
- Loading arm availability
- Storage tank availability
- Pump availability
- Flow meter availability

Therefore it is important to use scheduling tools to keep an overview of the terminals availability and operation. Multiple departments are involved in making the terminal schedule: customer services organise the orders, the planners organise the scheduling system, the control room supervises the operation. From the control room there is feedback to the customer services and planners in order to provide everyone with an up to date overview and keep an eye on the key performance indicators (Terminal D, 2016). Most terminals use an Enterprise Resource Planning (ERP) system or excel to make the schedule. These tools help to keep an overview of the current operation at the terminal and allocate the ships that are scheduled to arrive.

None of these tools however act as a decision support tool when allocating vessels to berths or time slots. Most planners make decisions based on experience that is (lightly) supported by data (Terminal F, 2016). Systems Navigator has proven that the use of data can improve terminal scheduling. With their scheduling software (Dropboard) different scenarios can be simulated in order to aid the planner in making these decisions. Also, historical data is used to predict berth times for returning vessels. Using this data can improve the terminal's expectations and thus its operation by enhancing the berth efficiency and lowering the turnaround times.

5.3. Categorisation

This section will present the conclusions drawn from the interviews on terminal types, key performance indicators and scheduling methods (and objectives). These conclusions will answer the research (sub-)question on identifiable links between terminal types, KPIs and current scheduling objectives. Table 5.3 summarises the results from the investigation of KPI's and scheduling objectives applied in practice.

5.3.1. Function in supply chain

Terminals that operate under joint ownership or independent ownership are only custodians of the liquid bulk on their terminal. Opposed to terminals with single company ownership they can be a part of multiple supply chains for each shareholder or client. Thus they can (and usually do) fulfil multiple functions as part of these supply chains. As shown in Table 5.2, the functions an independent terminal performs can even change over time. For example, when a new contract is arranged with a client to deliver or receive new products. Because of this flexibility and custodianship, the categorisation according to function in the supply chain is not suitable in practice.

Due to difference in ownership/custodianship of products on the terminal and their flexibility, the key performance indicators and scheduling objectives do vary per terminal type according to ownership. Section 5.3.2 presents these characteristics per type and concludes the analysing phase.

Table 5.2: Terminal ownership versus function in supply chain

Terminal ownership	Flexibility	Function in supply chain
Single company ownership	1 function	Strategic or industrial
Joint ownership	multiple functions	Definite functions determined by shareholders
Independent ownership	multiple functions	Flexible functions determined by clients

5.3.2. Ownership

This section presents the categorisation according to ownership of the terminal. As mentioned in the previous section, this categorisation was found most applicable in actual liquid bulk terminals. The procedures, key performance indicators and scheduling objectives per type are presented in this section. Finally, the results will be summarised in two tables to conclude the analysing phase.

Single company ownership Single company ownership can have functions such as a strategic or industrial terminal. As mentioned in Section 4.4 strategic terminals will not be considered, therefore an interview was conducted with an industrial terminal under single company ownership. An industrial terminal is categorised by the refinery it serves. From an interview with an industrial terminal in the Rotterdam area it becomes clear that the refinery operation steers the complete schedule (Terminal B, 2016). The main focus of the refinery operation is to maximise profit, therefore economical models determine the operation at the refinery and terminal. These models determine which products will be produced and which raw materials are required. The terminal has to store and blend the incoming raw materials (crude oil) and store the products. The capacity of an industrial terminal is designed in order to facilitate the refinery's requirements. The purchase of crude oil and the sale of products is organised by traders in service of the refinery. Because these traders aim to buy crude oil at the lowest price and sell products at the highest price, the schedule of arriving ships at the terminal is very unpredictable. Large crude tankers can be acquired last minute or storage tanks of oil products must be emptied with short notice to make sure the refinery can keep producing 24/7.

The industrial terminal operates with the first come first serve scheduling method. However, because the continuous operation of the refinery has priority some exceptions from FCFS will be made if the refinery operation demands it. Crude oil tankers may have to give way to a tanker arriving later if it is carrying a specific grade of crude oil that is needed in the blend to feed the refinery. Product tankers arriving to empty a specific storage tank that is about to overrun will receive precedence over other product tankers.

Contracts between the terminal and the client define a timespan in which the vessel must arrive for (un-)loading. But 1 or 2 days in advance the vessel must nominate itself for arrival. The arriving ships will be placed in a queue according to FCFS. If a vessel arrives outside the timespan recorded in the contract it will be placed at the end of the queue. The vessels arriving on time will be served first in order to minimise demurrage costs. If the terminal cannot serve the vessel within the documented timespan in the contract, the terminal has to pay the costs of delay (also known as demurrage). Known causes of demurrage costs for the terminal are:

- Contracts; clients determine the day of arrival and nominations can arrive only 1 day in advance even if the terminal knowns it has already met its capacity.
- Breakdowns; if a pump or loading arm breaks down the terminal operation at the jetty can come to a standstill and delay the vessels in the queue.
- Refinery operation; vessels can arrive if the product is not ready yet and will have to wait on the refining process.

The demurrage depend on the size of the vessel and are determined in costs per hour. If a large queue has developed the terminal will make exceptions from the FCFS rule in order to minimise demurrage. The strategic terminal is not driven to minimise the waiting time of vessels, unless demurrage must be paid (Terminal B, 2016).

Joint ownership In two interviews with terminals with multiple shareholders it becomes clear that for a terminal with multiple owners the main task is to meet demands from all parties (Terminal A, 2016; Terminal E, 2016). For example, at Terminal A Company 1 and Company 2 store and blend crude oil for their refineries in the port, and Company 3 stores crude oil that is sold to companies in the Rotterdam area, Antwerp area or Germany. Therefore Terminal A performs an industrial and import function. Crude oil is imported by seagoing vessels and transported by pipelines to the next location. All three owners provide the terminal with a schedule about a month in advance. Conflicting demands can be spotted and in consultation with both owners the schedule can be adjusted. Conflicts due to vessel delays are solved by applying FCFS or other sequences can be negotiated with the owners. These delays are estimated based on the vessel AIS data that gives the exact location of the vessel at all times. Through the website www.marinetraffic.com the planner is always up to date on the ship's location.

The planner receives a schedule for the vessels (including product characteristics) and storage locations. Because each owner has his own dedicated storage tanks and pipelines, there are no conflicts in scheduling the storage location or pipeline network. The objective of the scheduling method is to use its infrastructure efficiently. The terminal aims to minimise the turnaround time in order to facilitate the demand of its owners. If the berth time of the vessel is minimised the jetty capacity can be used by more vessels (Terminal E, 2016).

Independent ownership Independent terminals rent storage capacity to their clients and do not own the products on the terminal. Therefore the terminal can perform various functions in multiple supply chains. The demand for storage on the terminal is thus very unpredictable and the terminal must be flexible. Flexibility means the jetties must have capacity for multiple product groups and extensive connections on the terminal must be available. This flexibility offers generous options to the client for berthing and storage, but also increases the complexity of scheduling at the terminal. Due to free market processes the demand for storage and (un-)loading at the terminal is not constant but can be very irregular. Price shifts can yield peak hours at the terminal when multiple clients want to store or sell large amounts of the same product or result in low occupancy for certain product groups (Terminal C, 2016). Work shift at minimum capacity cannot facilitate the work at peak hours, but peak hours cannot be predicted by the terminal (Terminal C, 2016; Terminal F, 2016).

The characteristics of a sea vessel are usually known in advance. For barges these characteristics can remain unclear until the barge arrives at the terminal. Without the knowledge of the ship's size and pump capacity it is impossible to make a detailed (un-)loading plan. This lack of information causes delays because the (un-)loading plan must still be determined after arrival. If this information is known beforehand the plan can be ready to take in action at the moment of arrival (Terminal C, 2016). Next to that, large amounts of barges cause long waiting queues because their arrival time can be unknown in advance. Some estimated times of arrival can only be known 1 hour in advance. Also, the barges can visit multiple terminals in the port without indicating the sequence of these visits. This adds to the uncertainty in their arrival time (Terminal C, 2016). This discrepancy between initial communicated arrival time and actual arrival time can be as large as one to two days (Terminal D, 2016).

The aim of an independent terminal is to maximise service to their clients (Terminal D, 2016; Terminal F, 2016). Among others this can be achieved by minimising time spent on non value adding activities (like administration) or the total turnaround time (Terminal F, 2016). This includes trying to minimise the waiting time (Terminal G, 2016). However, next to the service to their clients it is also important to maximise their throughput in order to make the terminal profitable.

Conclusions With the results presented in this chapter the analysis phase can be concluded and the following question can be answered; *Can links be identified between terminal types, KPIs and current scheduling methods?* Table 5.3 summarises the terminal types and their key performance indicators and scheduling objectives. Unfortunately, no distinction was found between the scheduling methods but the scheduling objectives do drive the exceptions from the FCFS rule, as shown in Table 5.4.

Table 5.3: Scheduling objectives and key performance indicators in practice

Terminal type	**Key performance indicator**	**Scheduling objective**
Single company ownership	Costs (demurrage)	Minimise demurrage, Maximise profit
Joint ownership	Turnaround time	Minimise turnaround time
Independent ownership	Turnaround time and throughput	Maximise service

Table 5.4: Exceptions from FCFS scheduling method in practice

Terminal type	**Exceptions from FCFS**
Single company ownership	priority for vessels carrying urgent feedstock
	priority for vessels loading from storage tanks about to overflow
	priority for vessels arriving within the timespan documented in the contract
	priority for vessels with larger costs of delay (demurrage)
Joint ownership	one shareholder is not allowed to occupy all berths, therefore another shareholder has priority
	priority for vessels given by owner (only priority over vessels from same owner)
	always in agreement with all shareholders involved
Independent ownership	one client is not allowed to occupy all berths, therefore another client has priority
	priority for large carriers over barges
	priority for vessels carrying cargo that have hinterland connections waiting (trucks or trains)
	priority for vessels with available infrastructure (storage, pipelines) and products over vessels waiting on infrastructure
	priority for vessels loading from storage tanks about to overflow
	priority for vessels carrying urgent feedstock for distillation at terminal
	always in agreement with all clients involved

6
Model

Based on the literature study and evaluation of scheduling methods used in practice, a model is developed that will provide an answer to the research question: *To what extent can the implementation of scheduling methods improve the performance of liquid bulk terminals?*. This section presents the model objective, the boundaries, the assumptions used to simplify the model, the set-up and verification and validation of the model. In Chapter 7 experiments will be performed to test the various scheduling methods.

6.1. Objective

The objective of the model is to test if a scheduling method including priority settings can improve the performance of a liquid bulk terminal through varying the berth allocation sequence. The performance of test case terminals with predefined ship arrival patterns will be measured using different scheduling methods: First Come First Serve and priority scheduling. The priorities that will be tested are: Largest Vessel First (LFV), Fastest Job First (FJF), Product Priority (PP) and Vessel Priority (VP). The performance will be measured by the average waiting time. At least one of the test case terminals represents an oil and one represents a chemical terminal. The characteristics are based on actual terminals of which the ship arrival patterns and designs are available. By comparing the performance of the oil and chemical terminal using FCFS, LFV, VP, FJF and PP, conclusions can be drawn if the implementation of priority scheduling can improve the efficiency of liquid bulk terminals.

6.2. Boundaries

Boundaries have to be set in order to define the limitations of the model. Not the complete terminal including its hinterland connections is modelled to test the influence of the scheduling methods. The scheduling methods have the most impact on the sequence of ships at berth. Therefore the focus is on the berth allocation problem including ship arrivals, berth and infrastructure characteristics. The scheduling and details of the pipeline network and storage tanks are simplified in order not to complicate the model.

There is a lot of uncertainty in the arrival time of ships, which is a subject of research on its own (as shown in Section 2.1.2). Therefore, at the seaside boundary the arrival of ships is simplified and represented by a long queue of ships with predetermined arrival times. The boundaries at land side are represented by available storage tanks, pipelines and berths. The specific infrastructure of the terminals will be discussed in Section 7.1. An overview of the model boundaries is given in Figure 6.1. The boundaries applied to the model also imply the application of certain assumptions. The assumptions made are presented and justified in the next section.

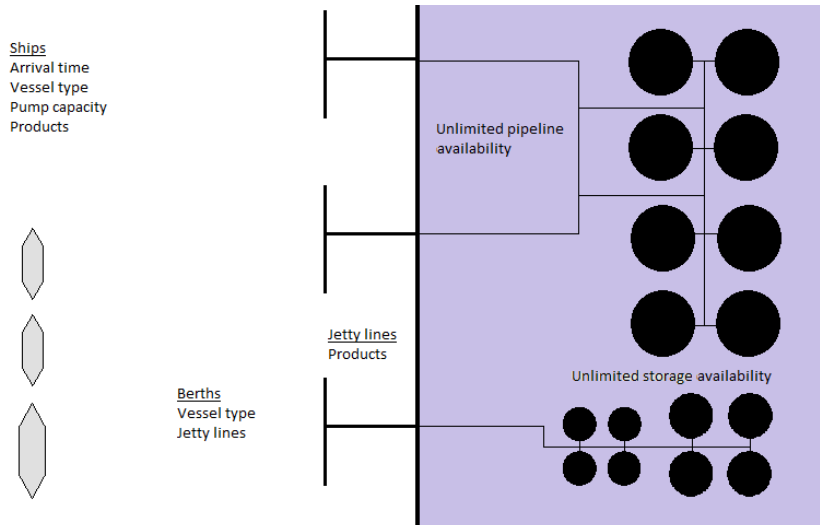

Figure 6.1: Model boundaries

6.3. Assumptions

Certain assumptions are used to simplify the model. Simplification is necessary due to limited availability of data and to keep the complexity and computing time reasonable.

- Unlimited storage and pipeline capability. Thus the infrastructure behind the berth is always available at the time of arrival at berth.
- The effect of value adding services, such as blending, on the availability of infrastructure is ignored.
- The effect of maintenance or breakdown on the availability of infrastructure is not taken into account.
- Cleaning of pipelines is not taken into account on the availability of jetty lines.
- There are no tide restrictions on VLCCs.
- Weather effects are not taken into account.
- The work crew is not a limiting factor on the availability or efficiency. Maximum operation at the terminal is assumed.
- ETA/ATA is fixed. The arrival time is set, but vessels are only added to the queue at arrival therefore no previous knowledge of vessel arrival time would have been necessary.
- There is no distinction between loading or unloading.
- Idle times are taken from a simulation validated with historical data. Idle times include pre-processing and post-processing. There is no unforeseen delay.
- Time to move from waiting area to berth is not taken into account.
- Pumping time is taken from a simulation validated with historical data. Assuming all product loading arms have the same capacity per product and per berth. Thus the pumping time is exactly the same at all berths that can facilitate (un-)loading of all products on the vessel. Not taking into account to possibility of simultaneous (un-)loading of multiple products per berth.
- Arrival time and end time are rounded down and up respectively.

The influences of these assumptions on the model and the results will be discussed in Section 6.5.2 and Section 7.4.

6.4. Set-up

The model set-up includes the configuration and algorithm of the models. First, the scheduling methods that will be modelled are presented. Next, the algorithm that is used will be explained. This set-up is used to perform the experiment presented in Chapter 7.

6.4.1. Scheduling methods

The scheduling methods that will be tested are first come first serve (FCFS) and priority scheduling. Priority scheduling is translated to three variables that give a vessel priority: (un-)loading time, vessel size and product type. Therefore the scheduling methods are called Fastest Job First (shortest (un-)loading time), Largest

Vessel First (largest vessel size) and Product Priority (one or more selected products are prioritised). This section explains all scheduling algorithms.

First Come First Serve In case of FCFS the berth allocation depends on the ship arrival time, ship characteristics and berth characteristics. If a ship arrives and a berth is available and capable of receiving the ship, the ship will be assigned to this berth. If there is no berth available the ship will be placed in a queue. From this queue the ship is placed at a suitable berth as soon as it becomes available. If another ship arrives it will be placed at the back of the queue. However, if this ship can be (un-)loaded at an available berth (at which the other ships in the queue cannot (un-)load) it will be removed from the queue and placed at this berth.

Fastest Job First In case of FJF the berth allocation depends on the ship arrival time, ship characteristics, berth characteristics and (un-)loading time. The fastest job first algorithm works similarly to the first come first serve algorithm, the only exception is the order of ships in the queue. The ships in the queue will be ranked according to their (un-)loading time. The vessel with the shortest (un-)loading time will be placed first in the queue. From this queue the ship is placed at a suitable berth as soon as it becomes available. If another ship arrives the queue will be sorted again to place the new ship in the correct place in the queue. However, another vessel than the first can be (un-)loaded at an available berth (at which the ships before it in the queue cannot (un-)load) it will be removed from the queue and placed at this berth.

Largest Vessel First In case of LVF the berth allocation depends on the ship arrival time, ship characteristics, berth characteristics and vessel size. The largest vessel first algorithm works similarly to the first come first serve algorithm, the only exception is the order of ships in the queue. The ships in the queue will be ranked according to their size. The vessel with the largest size will be placed first in the queue. Again, from this queue the ship is placed at a suitable berth as soon as it becomes available. If another ship arrives the queue will be sorted again to place the new ship in the correct place in the queue. However, another vessel than the first can be (un-)loaded at an available berth (at which the ships before it in the queue cannot (un-)load) it will be removed from the queue and placed at this berth.

Product Priority In case of PP the berth allocation depends on the ship arrival time, ship characteristics, berth characteristics and product on the vessel. The product priority algorithm also works similarly to the first come first serve algorithm, the only exception is the order of ships in the queue. The ships in the queue will be ranked according to the priorities of the products on board. The vessel carrying the products of highest priority will be placed first in the queue. Again, from this queue the ship is placed at a suitable berth as soon as it becomes available. If another ship arrives the queue will be sorted again to place the new ship in the correct place in the queue. However, another vessel than the first can be (un-)loaded at an available berth (at which the ships before it in the queue cannot (un-)load) it will be removed from the queue and placed at this berth.

Vessel Priority A Vessel Priority (VP) scheduling method is added to determine the priority scheme of vessels based on other characteristics than the vessel size. Some vessel types can have similar sizes, but differences in pump rates or berths capable of receiving them. The scheduling method works similar to the others, such that the queue is ordered according to the vessel's priorities.

6.4.2. Algorithm

The final model, that is generated in Matlab, is presented in Appendix C. The model is split in multiple blocks, as shown in Figure 6.2. The input, output and datasets with terminal characteristics are indicated by A, B and 1 to 4 respectively. The test terminals, the ship arrival pattern and performance indicators will be discussed in Section 7.1.

The model is initiated by creating a queue for the arriving vessels. If the arrival time of the vessel is equal to the time in the simulation the vessel is added to the queue. The effect of the scheduling method that is used is applied to this queue. According to the vessels loading time, vessel size or products the queue is sorted in the correct order according to the priority scheme (FJF, LVF, PP or VP).

Next, the algorithm to find a matching berth is started. At each time instance the complete queue is run through this section, starting with the first in the queue and moving to the end. For each vessel in this queue the vessel characteristics are compared to the terminal characteristics to find which berth location is suitable. First the vessel type is checked (1), next the loading arms are checked (2 and 3) and finally the tank pits are checked (4). If a list of suitable berths is found the availability of these berths must be checked to make sure a vessel is not assigned to an already occupied berth. If one of these berths is available the vessel will be assigned, if not the vessel remains in the queue.

Once a vessel is assigned to a berth it will be removed from the queue, the berth availability will be updated and the time and berth will be logged in a vessel log. The model will go back to the queue and repeat the process for the next vessel in the queue. If there is no next vessel in the queue the model will go to the next time step. This procedure will be repeated for 9000 hours (a little over a year) with time steps of 1 hour.

Input (A) The input dataset contains all of the vessel characteristics and defines the arrival pattern for the terminal in one year. Per vessel the following characteristics are included:

- Arrival time
- Number of parcels
- Product parcel 1-10
- Size parcel 1-10
- Tankpit parcel 1-10
- Vessel type
- Pumping time
- Idle time
- Vessel priority
- Product priority

Output (B) The output datasets shows the assignment of vessels to berths including their waiting time. A vessel log is created to show per vessel the time of arrival, time at berth and finish time. From this table the average waiting time can be determined. Next to the vessel log, also the availability matrix that is used to check availability is printed. In this matrix with the berths in the first row and a column per hour, the time the berth is occupied is indicated with ones. From this matrix the berth occupancy can be determined. Because the availability matrix is based on the arrival time and end time, which have been rounded off in the model, the total berth occupancy in the availability matrix must be corrected. This correction factor is determined by dividing the total berth time by the total occupancy in the availability matrix. The final corrected berth occupancy is calculated by multiplying the initial availability occupancy with the correction factor.

Datasets Datasets 1 to 4 dictate the terminal characteristics per terminal. Dataset 1 includes a matrix with the berths on one axis and the vessel types on the other. If a vessel type can be served at the berth the matrix has a value 1. Dataset 3 and 4 have a similar set-up, but they link the loading arms to the berths and tank pits to the berths. Dataset 2 is an overview of all the loading arms with the products they can carry. These datasets represent the complete infrastructure of the terminal.

6.5. Verification & validation

To make sure the model performs as it should the model is verified and validated. Verification checks if the model is built right and is presented in Section 6.5.1. The validation, presented in Section 6.5.2, checks if the right model was built.

6.5.1. Verification

As discussed in the previous section the model can be split in multiple blocks. Each block of the model will be verified to make sure the model is working correctly. Firstly, the queue and influence of the scheduling methods on the queue will be verified. Next, the assignment of vessels to berths is checked to see if there is a match in vessel type, product type, loading arm, tank pit and berth. Finally, the availability of the berths is checked to make sure a vessel cannot be assigned to an occupied berth.

Queue and scheduling methods The first block of the model creates a queue of the arriving vessels. By applying different scheduling methods the order of the queue is altered. Table 6.1 shows the queues at time steps 179, 180 and 319 for the FCFS scheduling method for Terminal 1. Tables 6.2, 6.3 and 6.4 present three

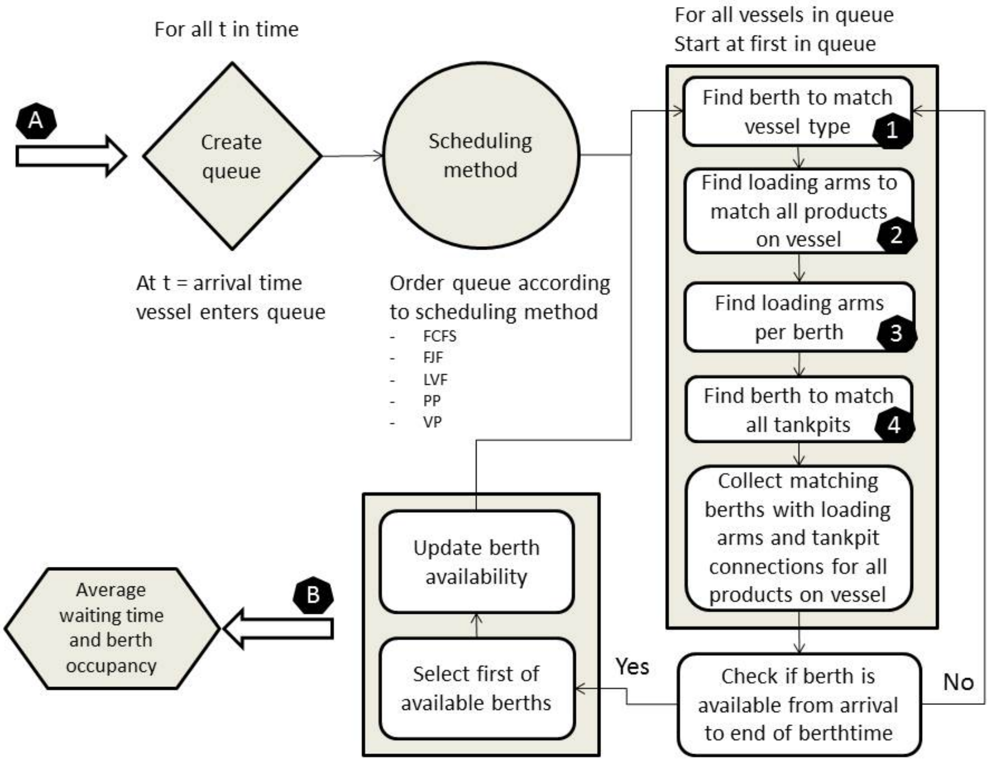

Figure 6.2: Model overview

queues at three or four time steps per scheduling method (FJF, LVF and PP) for Terminal 1. Between these queues there is a clear difference in the order of the vessels in the queue. Each scheduling method dictates the order based on the loading time, vessel priority or product priority. These values are shown in the queue and from the results it can be concluded that the scheduling methods are applied correctly.

Table 6.1 shows clearly that for the First Come, First Serve (FCFS) application in Terminal 1 the decision was made to incorporate the vessels before barges rule. This rule is also applied in practice and therefore included in the verification and validation of the model. For the other scheduling methods in Terminal 1 this rule is also taken into account, and is given priority over the priority rules of the specific scheduling method.

Table 6.1: Queue of FCFS model at time step 179, 180 and 319

Vessel ID	Vessel type	Arrival time	Loading time	Vessel priority
113	Vesselclass1	179	31.2565	1
105	Barge	169	11.4487	2
108	Barge	172	10.4057	2
109	Barge	172	10.9391	2
115	Vesselclass1	180	19.5733	1
105	Barge	169	11.4487	2
108	Barge	172	10.4057	2
109	Barge	172	10.9391	2
114	Barge FO	180	7.9496	2
207	Coaster	319	23.4996	1
192	Barge	301	16.6615	2
205	Barge	317	17.1861	2
206	Barge	319	10.5162	2

Table 6.2: Queue of FJF model at time step 179, 180 and 319

Vessel ID	Vessel type	Arrival time	Loading time	Vessel priority
113	Vesselclass1	179	31.2565	1
109	Barge	172	10.9391	2
105	Barge	169	11.4487	2
103	Barge	167	11.6200	2
115	Vesselclass1	180	19.5733	1
114	Barge FO	180	7.9496	2
109	Barge	172	10.9391	2
105	Barge	169	11.4487	2
103	Barge	167	11.6200	2
207	Coaster	319	23.4996	1
206	Barge	319	10.5162	2
192	Barge	301	16.6615	2
205	Barge	317	17.1861	2

Table 6.3: Queue of LVF model at time step 113, 179, 180 and 319

Vessel ID	Vessel type	Arrival time	Loading time	Vessel priority
71	Vesselclass4	112	193.6255	1
67	Vesselclass1	108	26.1056	2
69	Vesselclass2	108	54.4205	2
72	Barge FO	113	15.5682	4
113	Vesselclass1	179	31.2565	2
105	Barge	169	11.4487	4
108	Barge	172	10.4057	4
109	Barge	172	10.9391	4
115	Vesselclass1	180	19.5733	2
105	Barge	169	11.4487	4
108	Barge	172	10.4057	4
109	Barge	172	10.9391	4
114	Barge FO	180	7.9496	4
207	Coaster	319	23.4996	2
192	Barge	301	16.6615	4
205	Barge	317	17.1861	4
206	Barge	319	10.5162	4

Table 6.4: Queue of PP model at time step 113, 179, 180 and 319

Vessel ID	Vessel type	Arrival time	Loading time	Vessel priority	Product priority
67	Vesselclass1	108	26.1056	1	1
69	Vesselclass2	108	54.4205	1	1
71	Vesselclass4	112	193.6255	1	2
72	Barge FO	113	15.5682	2	2
113	Vesselclass1	179	31.2565	1	2
105	Barge	169	11.4487	2	2
108	Barge	172	10.4057	2	2
109	Barge	172	10.9391	2	2
115	Vesselclass1	180	19.5733	1	2
105	Barge	169	11.4487	2	2
108	Barge	172	10.4057	2	2
109	Barge	172	10.9391	2	2
114	Barge FO	180	7.9496	2	2
207	Coaster	319	23.4996	1	2
192	Barge	301	16.6615	2	2
205	Barge	317	17.1861	2	2
206	Barge	319	10.5162	2	2

Vessel - berth assignment The next block in the algorithm is responsible for assigning vessels to berths. In order to make sure a vessel is assigned to a berth that can facilitate (un-)loading of all products on the vessel the vessel characteristics must be compared to the terminal infrastructure. As discussed in Section 6.4 multiple datasets are analysed to find the following matches:

- Vessel type - berth
- Loading arms - berth, with a previous step finding loading arms - products
- Tank pits - berth

To verify the algorithm is working correctly 6 vessels and their assigned berth are analysed step by step. Table 6.5 shows the vessel characteristics that make up the input data to the model. Table 6.6 shows the results in the vessel log of the same example vessels. For each of these vessels the link between vessel type - berth, loading arms - products, loading arms - berth and tank pits - berth is looked up manually. The vessel type - berth possibilities are as follows:

- Vessel 1, 3 and 70 type Barge can be facilitated at berths: CS, NH1, NH2, NH3, NH4, NH5, T1, T2, T3, TRONOX1, TRONOX2, VP30, VP3W, VP4OB, VP4WB.
- Vessel 2 type Barge FO can be facilitated at berths: CS, NH1, NH2, NH3, NH4, NH5, T1, T2, T3, TRONOX1, TRONOX2, VP30, VP3W, VP4OB, VP4WB.
- Vessel 69 type Vesselclass2 can be facilitated at berths: VP10, VP1W, VP20, VP2W, VP40V, VP4WV.
- Vessel 71 type Vesselclass4 can be facilitated at berths: VP10, VP1W, VP2W.

These vessel type - berth combinations are taken from input dataset 1 as explained in Section 6.4.2. Figure 6.3 shows how these combinations are determined. Similarly, the other datasets include matrices that define loading arm - berth connections and tank pit - berth connections. Per loading arm the types of products that can be transported are listed in dataset 2. The examples include the products ULSD, Fuel oil and Condensate. These products can be transported by the following loading arms:

- Product ULSD can be transported by loading arms: Steiger2, Steiger4, Steiger7, M1, VP4-7, VP4-8, VP4-10, V2, V6, N20, N22, N24, Tiof8, Tiof9, JL-VPL17.
- Product Fuel oil can be transported by loading arms: Stook3, Steiger3, JL-L16, Stook1, Stook2, JL-Stook4, Stook5, Stook6, Stook7, Stook8, Fuel2, Fuel3, VP4-1, VP4-2, VP4-3, VP4-4, VP4-5, VP4-6.
- Product Condensate can be transported by loading arms: Steiger5, V5.

These loading arms are connected to the following berths:

- Loading arm Fuel2 is connected to berth: T2.

- Loading arm Fuel3 is connected to berths: VP10, VP1W.
- Loading arm JL-L16 is connected to berth: CS.
- Loading arm JL-Stook4 is connected to berths: T1, T2, VP30, VP3W.
- Loading arm JL-VPL17 is connected to berths: NH1, NH2, NH3.
- Loading arm M1 is connected to berths: VP1W, VP30, VP3W.
- Loading arm N20 is connected to berths: NH1, NH2, NH3.
- Loading arm N22 is connected to berths: NH1, NH2, NH3.
- Loading arm N24 is connected to berths: NH1, NH2, NH3.
- Loading arm Steiger2 is connected to berths: VP10, VP1W.
- Loading arm Steiger3 is connected to berth: VP10.
- Loading arm Steiger4 is connected to berths: VP10, VP1W.
- Loading arm Steiger5 is connected to berth: VP10
- Loading arm Steiger7 is connected to berths: VP30, VP3W.
- Loading arm Stook1 is connected to berths: T1, T2, T3, VP10, VP1W.
- Loading arm Stook2 is connected to berths: T1, T2, T3.
- Loading arm Stook3 is connected to berths: T1, T2, T3.
- Loading arm Stook5 is connected to berths: T1, VP10 VP1W.
- Loading arm Stook6 is connected to berth: T1.
- Loading arm Stook7 is connected to berths: T2, T3, VP20, VP2W.
- Loading arm Stook8 is connected to berths: T3, VP20, VP2W.
- Loading arm Tiof8 is connected to berths: TRONOX1, TRONOX2.
- Loading arm Tiof9 is connected to berths: TRONOX1, TRONOX2.
- Loading arm V2 is connected to berths: VP20, VP2W.
- Loading arm V5 is connected to berths: VP20, VP2W.
- Loading arm V6 is connected to berths: VP20, VP2W.
- Loading arm VP4-1 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-2 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-3 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-4 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-5 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-6 is connected to berths: VP40B, VP40V, VP4WB, VP4WV.
- Loading arm VP4-7 is connected to berths: VP40B, VP40V, VP4WV.
- Loading arm VP4-8 is connected to berth: VP40B.
- Loading arm VP4-10 is connected to berths: VP40V, VP4WB, VP4WV.

Finally, the connections between the tank pits and berths for the examples are:

- Tank pit T0902 is connected to berths: VP1O, VP2O, VP2W.
- Tank pit T1011 is connected to berths: T1, T2, T3, VP1O, VP1W, VP2O, VP2W, VP3O, VP3W.
- Tank pit T1018 is connected to berths: T1, T2, T3, VP1O, VP1W, VP3O, VP3W.
- Tank pit T1030 is connected to berths: T1, T2, T3, VP1O, VP1W, VP2O, VP2W, VP3O, VP3W, VP4OB, VP4OV, VP4WB, VP4WV.
- Tank pit T1032 is connected to berths: T1, T2, T3, VP1O, VP1W, VP2O, VP2W, VP3O, VP3W, VP4OB, VP4OV, VP4WB, VP4WV.
- Tank pit T1035 is connected to berths: T1, T2, T3, VP1O, VP1W, VP2O, VP2W, VP3O, VP3W, VP4OB, VP4OV, VP4WB, VP4WV.
- Tank pit T1401 is connected to berths: NH1, NH2, NH3, VP40B, VP40V, VP4WV.
- Tank pit T2001 is connected to berths: NH1, NH2, NH3, TRONOX1, TRONOX2, VP10, VP1W.

This concludes that the vessels can be accommodated at the following berths:

- Vessel 1: NH1, NH2, NH3, TRONOX1, TRONOX2.
- Vessel 2: T1, T2, T3, VP30, VP3W, VP4OB, VP4WB.
- Vessel 3: NH1, NH2, NH3, VP4OB, VP4WB.
- Vessel 69: VP10, VP20, VP2W.
- Vessel 70: NH1, NH2, NH3, TRONOX1, TRONOX2.
- Vessel 71: VP10, VP1W.

	CS	NH1	NH2	NH3	NH4	NH5	T1	T2	T3	TRONOX1	TRONOX2	VP1O	VP1W	VP2O	VP2W	VP3O	VP3W	VP4OB	VP4OV	VP4WB	VP4WV
Barge	1	1	1	1	1	1	1	1	1	1	1					1	1	1		1	
Barge FO	1	1	1	1	1	1	1	1	1	1	1					1	1	1		1	
Coaster												1	1	1	1	1			1		1
Vesselclass1												1	1	1	1	1			1		1
Vesselclass2												1	1	1	1				1		1
Vesselclass3												1	1		1				1		1
Vesselclass4												1	1		1						
External transfer																					
Barge K1 preload		1	1	1	1	1												1		1	

Figure 6.3: Dataset 1 with vessel type - berth combinations, highlighting combinations for Vesselclass4

Comparing these results to the vessel log in Table 6.6, it can be seen that the assigned berths are chosen correctly from the possible matches. The last check that remains is the availability of the berth, this will be discussed in the next section.

Table 6.5: Input vessel data, examples for verification

	Example 1	Example 2	Example 3	Example 4	Example 5	Example 6
Vessel ID	1	2	3	69	70	71
Vessel type	Barge	Barge FO	Barge	Vesselclass2	Barge	Vesselclass4
Arrival time	1.893	4.445	5.669	108.377	111.461	112.580
Berth time	9.444	5.750	6.027	54.420	5.352	193.625
Number of parcels	1	1	1	2	1	5
Parcel 1	ULSD	Fuel oil	ULSD	Condensate	ULSD	Fuel oil
Parcel 2				Condensate		Fuel oil
Parcel 3						Fuel oil
Parcel 4						Fuel oil
Parcel 5						Fuel oil
Tankpit 1	T2001	T1030	T1401	T0902	T2001	T1018
Tankpit 2				T0902		T1011
Tankpit 3						T1035
Tankpit 4						T1032
Tankpit 5						T1032
Vessel priority	2	2	2	1	2	1

Table 6.6: Output vessel log, examples for verification

Vessel ID	Arrival time	Time of assignment	Berth time	Time finished	Berth
1	1	1	9.444	11	NH1
2	4	4	5.750	10	T1
3	5	5	6.027	12	NH2
69	108	127	54.420	182	VP2W
70	111	111	5.352	117	NH3
71	112	129	193.625	323	VP1W

Berth availability In the previous examples used to verify the berth allocation it can be seen that not all vessels can be assigned at their arrival time. Sometimes the matched berths are all occupied and the vessel has to wait. In order to verify the occupancy of the berths this section will show the availability matrix created in the last block of the model. This availability matrix contains ones if the berth is occupied and zeros if it is available. After each vessel assigned the matrix is updated. Table D.1 in Appendix D shows the availability matrix at the time of arrival of Vessel 69 (example 4) to verify all possible berths are occupied. Next, Table D.2 in Appendix D shows the availability matrix at the end of the run (t = 9000 hours) to show that the new vessels have been added to the matrix.

6.5.2. Validation

Validation of the model has to show the right model was built. Table 6.7 and 6.8 present the average waiting time and berth occupancy of Terminal 1 and 2 respectively. They are compared to the average waiting time and berth occupancy generated by a simulation performed by the company supervisor at Royal HaskoningDHV (RHDHV). The simulation programme of Royal HaskoningDHV has been validated with historical data for all terminals used in the experiment. The comparison of results between the FCFS model and RHDHV model yields a small difference between the models for Terminal 1, but larger deviations for the other terminals, as can be seen in Table 6.9. Because of the exploratory and broad objective of this study the differences are deemed acceptable.

These differences can be explained by the application of the simplifying assumptions. For instance, assuming the pumping time is constant over all berths has affected the average waiting time, especially for the chemical terminals 2. In the simulation performed by RHDHV for each vessel the shortest turnaround time is calculated based on all infrastructure capabilities. Therefore a vessel can choose to wait if another berth would ensure a lower end time (thus shorter turnaround time). This capability is not included in the FCFS model and can increase or decrease the waiting time.

The difference in berth occupancy can be accounted to the rounding down of arrival times and rounding up of end times. This results in a longer berth time per vessel and a higher berth occupancy rate as outcome. The higher berth occupancy can in turn also influence the average waiting time of the vessels, because the availability of berths is lower.

Influences on the readiness of infrastructure are also taken into account in the RHDHV model and not in the FCFS model. The assumption of available infrastructure lowers the average waiting time in comparison to the RHDHV model. As can be seen in Table 6.9 the validated model takes into account a waiting time for infrastructure, storage space (tank) and planning. Al these factors impact the availability and thus the time of service for a vessel. This can also alter the order of vessels allocated to a berth, which in turn influences the average waiting time of all vessels.

Overall, the influences of these assumptions are deemed acceptable and proposals for efforts to improve the model will be presented in Section 9.

Table 6.7: Validation data Terminal 1

	Average waiting time (hours)	Berth occupancy (%)
Model FCFS	2.17	45.20
Model RHDHV	2.44	44.67

Table 6.8: Validation data Terminal 2

	Average waiting time (hours)	Berth occupancy (%)
Model FCFS	9.82	60.32
Model RHDHV	20.84	59.73

Table 6.9: Comparison of average waiting time per terminal between FCFS model and RHDHV model

	Original dataset	**All datasets**	**RHDHV**				
Terminal	Wait	Wait	Total wait	Wait for berth	Wait for infra	Wait for tank	Wait for planning
1	2.17	2.1	2.45	1.47	0.89	0	0.4
2	9.82	9.01	20.84	15.7	7.88	0	2.08
3	3.6	3.74	6.94	5.69	3.47	2.89	1.91
4	1.94	2.01	5.82	2.88	0.82	0	2.32
5	5.06	5.05	7.54	7.24	2.24	0	0

7

Experiment

By using the model presented in Chapter 6 an experiment can be performed to answer the research question. This chapter includes the set-up of the experiment, including the experimental plan, and the results. Finally, the results of the experiment will be discussed to check which conclusions can be drawn.

7.1. Set-up

This section includes the details of the terminals that are modelled and their ship arrival pattern, the scheduling methods and performance measures.

7.1.1. Terminals

The model includes oil terminal and chemical terminal configurations. This separation is made due to the distinctive differences between oil handling and chemical handling. Chemical tankers usually carry multiple products and require dedicated infrastructure. Therefore the capabilities of the berths can limit the available berths for a ship. It is possible that a certain ship can only (un)load its products at one berth. This will most likely influence the performance of the terminal and its berth allocation scheduling methods.

Because the model is set-up based on simulation results from a Royal HaskoningDHV simulation, only terminals can be tested that have been simulated by Royal HaskoningDHV. A graphical representation of Terminal 1 and 2 are shown in Figures 7.1 and 7.2. Therefore the amount and types of terminals are limited. Unfortunately, the available terminals for this experiment are all independent terminals. This means the effects between different terminal types/categories cannot be tested in this experiment. However, the similarities between different independent terminals can be tested.

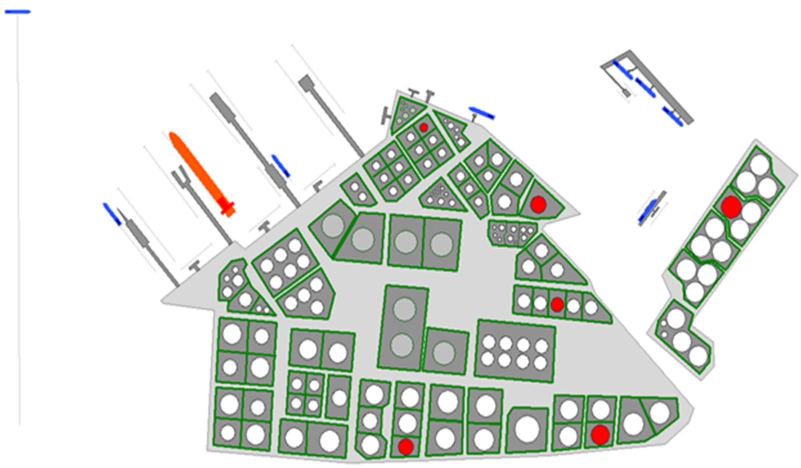

Figure 7.1: Screen-shot of Terminal 1 in simulation (Huges, 2016).

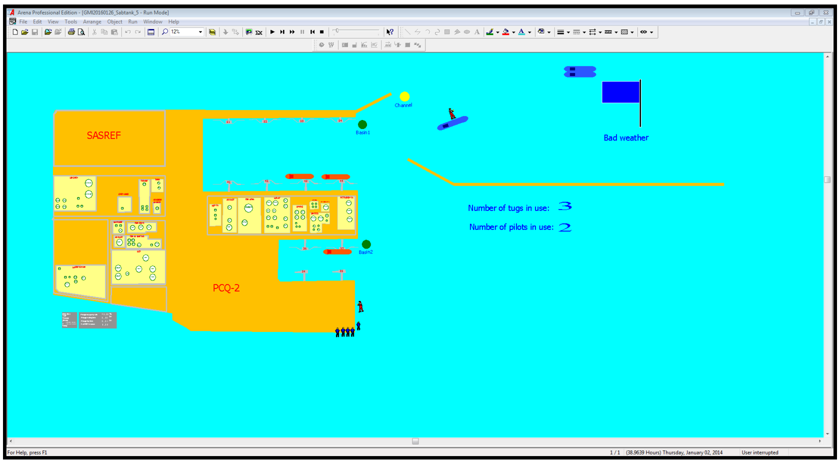

Figure 7.2: Screen-shot of Terminal 2 in simulation (Huges, 2016).

Multiple terminals will be tested by running the model on different datasets from actual terminals. The terminals that are modelled are summarized in Table 7.1, and can be categorised as follows.

- Terminal 1 is modelled after an oil terminal. The terminal consists of 21 berths and can be categorised as an independent terminal. The annual throughput is 50.7 million m^3 and 5893 vessels (un-)load at this terminal per year.
- Terminal 2 is modelled after a chemical terminal. The terminal consists of 8 berths and can be categorised as an independent terminal. The annual throughput is 16.7 million m^3 and 876 vessels (un-)load at this terminal per year.
- Terminal 3 is modelled after an oil terminal. The terminal consists of 6 berths and can be categorised as an independent terminal. The annual throughput is 5.43 million m^3 and 1030 vessels (un-)load at this terminal per year.
- Terminal 4 is modelled after an oil terminal. The terminal consists of 10 berths and can be categorised as an independent terminal. The annual throughput is 23.1 million m^3 and 1674 vessels (un-)load at this terminal per year including internal transfers.
- Terminal 5 is modelled after a chemical terminal. The terminal consists of 21 berths and can be categorised as an independent terminal. The annual throughput is 12.6 million m^3 and 4631 vessels (un-)load at this terminal per year.

Table 7.1: Terminal specifications

Terminal	**Product**	**Category**	**Number of berths**	**Number of vessels/year**	**Throughput [m^3]**
1	Oil	Independent	21	5893	50.7 million
2	Chemical	Independent	8	876	16.7 million
3	Oil	Independent	6	1030	5.43 million
4	Oil	Independent	10	1674	23.1 million
5	Chemical	Independent	21	4631	12.6 million

7.1.2. Ship arrival patterns

The ship arrival patterns for the oil and chemical terminals are derived from a dataset of actual arrival times. The data provided includes the actual arrival time and the ship characteristics (product, size, owner) of the terminal for 1 year. These exact arrival times and characteristics will be used as input data for the model.

To take into account the uncertainty in arrival times in practice the arrival data will be altered within a 12-hour time window and the experiment will be repeated. For each terminal multiple datasets, with varying arrival times, will be tested to see if the trends still hold under an uncertain arrival pattern.

Figure 7.3 and Table 7.2 present the distribution of arrival times for all datasets in Terminal 1. Clearly, the effect of adjusting arrival time on the distribution can be seen. In general the average time between

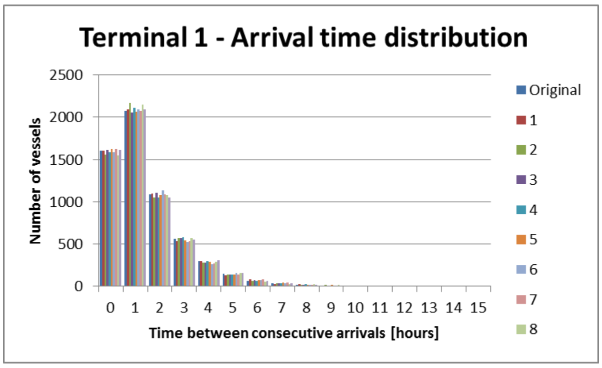

Figure 7.3: Arrival time distribution of vessels arriving at Terminal 1

consecutive arrivals is equal (1.48), but there are small deviations. The number of vessels arriving at the same time (time between consecutive arrivals is 0) varies more significantly per dataset. This is expected to influence the size of the queue and the number of vessels waiting. Therefore the average waiting time per dataset will presumably differ per dataset. Section 7.3 will thus also discuss the average waiting time over all datasets and the confidence interval of these results.

Table 7.2: Time between consecutive vessel arrivals per dataset

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	1600	1603	1558	1610	1587	1624	1588	1622	1544	1611
1	2073	2095	2164	2054	2112	2068	2088	2076	2146	2094
2	1086	1093	1048	1102	1052	1075	1130	1085	1076	1045
3	558	528	570	574	577	546	526	532	568	548
4	297	294	276	276	293	291	261	273	289	306
5	148	127	142	136	133	142	159	142	153	158
6	67	79	64	75	67	70	70	84	49	66
7	34	28	33	34	34	39	37	47	28	37
8	14	25	17	13	24	20	17	16	22	12
9	7	8	11	6	9	11	7	9	11	7
10 - 15	8	12	9	12	4	6	9	6	6	8
Average	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.49	1.48	1.48

7.1.3. Scheduling methods

The scheduling methods applied vary per terminal because they are dependent on the vessel type variety and product assortment. Per terminal the scheduling methods concerning largest vessel first and product priority are presented. Table 7.3 summarizes all scheduling methods per terminal.

Terminal 1 For Terminal 1 product priority and vessel priority scheduling methods are designed. Largest vessel first is not included, because the first come, first serve already includes a vessels before barges scheme. Therefore, the distinction between vessel priority is partly determined by size, but not solely. Terminal 1 includes the following preferred berthing scheduling methods:

- Product Priority - The 2 products (out of 8) with the smallest amount of jettylines are given high priority. The other vessels do not get priority.
- Vessel Priority 1 - Vessels are assigned to 4 priority groups according to the number of berths available per vessel type.
- Vessel Priority 2 - Vessels are assigned to 4 priority groups according to the number of berths available per vessel type, but an extra distinction is made between two types of barges.
- Vessel Priority 3 - Vessel priority is determined by the number of berths that are capable of receiving the vessel type.

Terminal 2 All vessels visiting Terminal 2 have the same size and characteristics, therefore Terminal 2 includes the following preferred berthing scheduling methods:

- Product Priority 1 - Priority based on the number of jettylines capable of carrying the product.
- Product Priority 2 - Priority based on the number of jettylines. If only one jettyline is available for a specific product group, vessels carrying this product group get high priority and vessels without do not get priority.
- Product Priority 3 - For product groups with only one capable jettyline the priority is based on the number of capable berths. Product groups with multiple jettylines get no priority.
- Product Priority 4 - Priority based on the number of capable berths per product group.

For all product priority scheduling methods the priority of the vessel is equal to highest priority of the products on the vessel.

Terminal 3 Terminal 3 includes the following preferred berthing scheduling methods:

- Largest Vessel First 1 - Priority based on the vessel-barge rule: high priority for vessels, low priority for barges and no priority for internal transfers.
- Largest Vessel First 2 - Similar set up as LVF1 except an extra distinction is made between vessels and coasters. Coasters get priority over barges and internal transfers, but not over vessels.
- Vessel Priority 1 - Similar to LVF2 with the addition of an extra priority distinction between barges with different pumping rates. Barges with higher pumping rates get priority over slower barges.
- Vessel Priority 2 - Priority based on the number of capable berths per vessel type. Except for internal transfers, they are given no priority.
- Product Priority 1 - Priority based on the number of capable loading arms per product group.
- Product Priority 2 - Priority based on the number of capable berths per product group.

Terminal 4 Terminal 4 includes the following preferred berthing scheduling methods:

- Largest Vessel First - Priority based on the vessel-barge rule: high priority for vessels, low priority for coasters.
- Vessel Priority 1 - Priority based on the average pump rate. A higher pump rate results in a higher priority.
- Vessel Priority 2 - Priority based on the number of capable berths per vessel type.
- Product Priority - Priority based on the number of capable berths per product group.

Terminal 5 Terminal 5 includes the following preferred berthing scheduling methods:

- Largest Vessel First - Priority based on the vessel-barge rule: high priority for vessels, low priority for barges.
- Vessel Priority 1 - Priority based on the average pump rate. A higher pump rate results in a higher priority.
- Vessel Priority 2 - Priority based on the number of capable berths per vessel type.
- Product Priority 1 - Priority based on the number of capable loading arms per product group.
- Product Priority 2 - Priority based on the number of capable berths per product group.

Table 7.3: Overview of scheduling methods per terminal

Terminal	**1**	**2**	**3**	**4**	**5**
First Come First Serve (FCFS)	FCFS	FCFS	FCFS	FCFS	FCFS
Fastest Job First (FJF)	FJF	FJF	FJF	FJF	FJF
Product Priority (PP)					
- based on # jetty-lines	PP	PP1, PP2	PP1		PP1
- based on # berths		PP4	PP2	PP	PP2
- based on a combination		PP3			
Largest Vessel First (LVF)					
- vessels/barges			LVF1	LVF	LVF
- multiple vessel types			LVF2		
Vessel Priority (VP)					
- based on pump rate			VP1	VP1	VP1
- based on # berths	VP1, VP2, VP3		VP2	VP2	VP2

7.1.4. Performance

The performance of the terminal is measured by the average waiting time of the arriving ships. Another important key performance indicator, the turnaround time (TAT), can also be measured but considering a given berth time the TAT is directly linked to the waiting time and therefore the focus lies on the waiting time.

Because the vessel data is a snapshot of an actual terminal, some key performance indicators that have been presented in Section 5.1.1 will remain the same. For example, the number of ships and throughput will not differ for the experiment. Also the idle time at berth and loading efficiency will not be considered for this experiment, because these factors are assumed not to influence the different scheduling methods.

7.2. Experimental plan

The experimental plan consists of multiple set-ups per terminal and scheduling method. For each terminal the arrival time of the vessels are altered to test the difference between scheduling methods under different circumstances. Next to that, for terminal 1 and 2 the experiment is extended to test the influence of the loading time and number of vessels per year. Tables 7.4, 7.5, 7.6, 7.7, 7.8 give an overview of the different cases and under which conditions the terminals will be simulated. The results of these simulations are shown in the next section.

Table 7.4: Experimental plan Terminal 1

	FCFS	**FJF**	**PP**	**VP1**	**VP2**	**VP3**
Original	0	0	0	0	0	0
Adjusted arrival time (between -6, +6 hours)	1-9	1-9	1-9	1-9	1-9	1-9
Loading time * 0.5	a	a	a	a	a	a
Loading time * 0.75	b	b	b	b	b	b
Loading time * 1.25	c	c	c	c	c	c
Loading time * 1.5	d	d	d	d	d	d
-10% vessels	k	k	k	k	k	k
-20% vessels	l	l	l	l	l	l
-30% vessels	m	m	m	m	m	m

Table 7.5: Experimental plan Terminal 2

	FCFS	FJF	PP1	PP2	PP3	PP4
Original	0	0	0	0	0	0
Adjusted arrival time (between -6, +6 hours)	1-9	1-9	1-9	1-9	1-9	1-9
Loading time * 0.5	a	a	a	a	a	a
Loading time * 0.75	b	b	b	b	b	b
Loading time * 1.25	c	c	c	c	c	c
Loading time * 1.5	d	d	d	d	d	d
-10% vessels	k	k	k	k	k	k
-20% vessels	l	l	l	l	l	l
-30% vessels	m	m	m	m	m	m

Table 7.6: Experimental plan Terminal 3

	FCFS	FJF	PP1	PP2	LVF1	LVF2	VP1	VP2
Original	0	0	0	0	0	0	0	0
Adjusted arrival time (between -6, +6 hours)	1-9	1-9	1-9	1-9	1-9	1-9	1-9	1-9

Table 7.7: Experimental plan Terminal 4

	FCFS	FJF	PP	LVF	VP1	VP2
Original	0	0	0	0	0	0
Adjusted arrival time (between -6, +6 hours)	1-9	1-9	1-9	1-9	1-9	1-9

Table 7.8: Experimental plan Terminal 5

	FCFS	FJF	PP1	PP2	LVF	VP1	VP2
Original	0	0	0	0	0	0	0
Adjusted arrival time (between -6, +6 hours)	1-9	1-9	1-9	1-9	1-9	1-9	1-9

7.3. Results

The results of the experiment are presented in Tables 7.9 to 7.13 and Figures 7.4 to 7.8 in this section. Next to the results in this section, Appendices E to I present extensive results that will also be discussed in Section 7.4.

Appendix E contains Tables E.1 to E.10 presenting the average waiting time per dataset for each terminal. Firstly, Table E.1 presents the average waiting time of all vessels under multiple scheduling methods per dataset. To clearly see the differences in average waiting time between all new scheduling methods and first come, first serve Table E.2 presents these differences in percentages. A lower average waiting time means a negative percentage and is coloured green. This is repeated for Terminals 2 to 5 in Tables E.3 to E.10.

Appendix F contains tables presenting the average waiting time per priority group per scheduling method. The scheduling methods that show improvement on FCFS have been selected to investigate further. Therefore Appendix F contains tables for FJF in Terminal 1, PP4 in Terminal 2, PP1 in Terminal 3 and LVF1 in Terminal 4.

Next, Appendix G contains the graphical representation of the number of vessels waiting and the maximum waiting time for Terminal 1 and 2 under FCFS and FJF. These results show the effect of making a large vessel with a long berth time wait while faster vessels are served with priority.

Finally, Appendix H presents the results from the experiment varying loading time in Tables H.1 to H.6. These tables not only present the average waiting time and the change in percentages, but also the average berth occupancy per scheduling method. This set-up is repeated for the results from the experiment varying the number of vessel in Tables I.1 to I.6 in Appendix I.

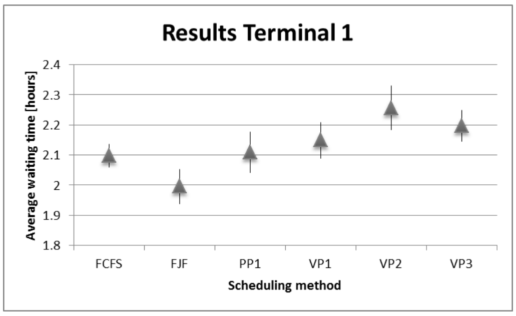

Figure 7.4: Results Terminal 1 under 95% confidence interval

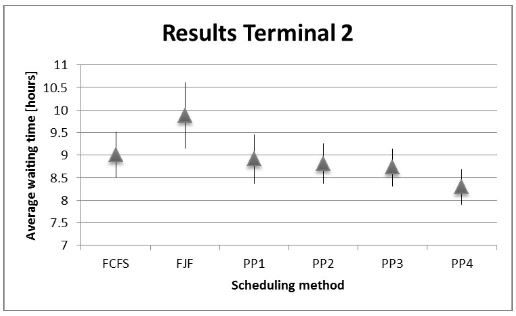

Figure 7.5: Results Terminal 2 under 95% confidence interval

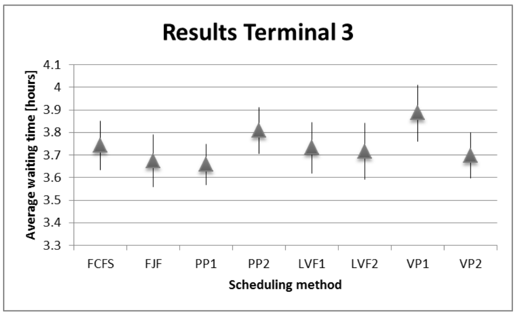

Figure 7.6: Results Terminal 3 under 95% confidence interval

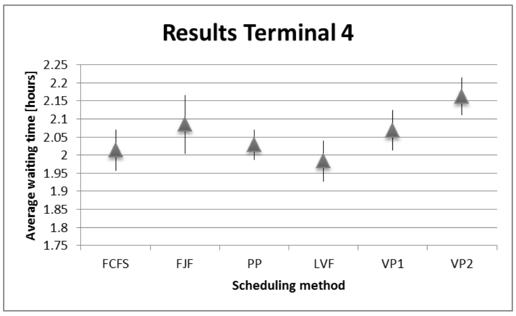

Figure 7.7: Results Terminal 4 under 95% confidence interval

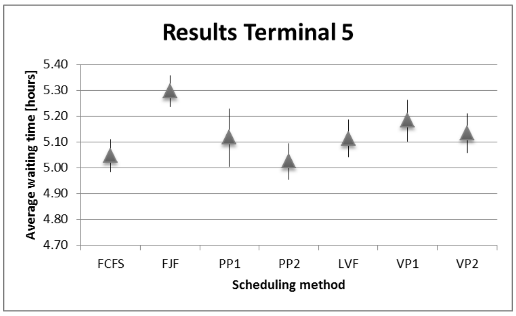

Figure 7.8: Results Terminal 5 under 95% confidence interval

Table 7.9: Results Terminal 1 with 95% confidence interval in percentages compared to FCFS

	Lower bound	Upper bound	Average
FJF	-7%	-2%	-5%
PP1	-2%	3%	1%
VP1	-1%	6%	3%
VP2	4%	11%	8%
VP3	7%	13%	10%

Table 7.10: Results Terminal 2 with 95% confidence interval in percentages compared to FCFS

	Lower bound	Upper bound	Average
FJF	1%	20%	10%
PP1	-7%	5%	-1%
PP2	-7%	4%	-2%
PP3	-8%	2%	-3%
PP4	-13%	-2%	-8%

Table 7.11: Results Terminal 3 with 95% confidence interval in percentages compared to FCFS

	Lower bound	Upper bound	Average
FJF	-4%	1%	-2%
PP1	-3%	-1%	-2%
PP2	1%	3%	2%
LVF1	-1%	0%	0%
LVF2	-2%	0%	-1%
VP1	2%	6%	4%
VP2	-3%	0%	-1%

Table 7.12: Results Terminal 4 with 95% confidence interval in percentages compared to FCFS

	Lower bound	Upper bound	Average
FJF	0%	7%	4%
PP1	-2%	3%	1%
LVF1	-3%	0%	-1%
LVF2	1%	5%	3%
LVF3	6%	9%	7%

Table 7.13: Results Terminal 5 with 95% confidence interval in percentages compared to FCFS

	Lower bound	Upper bound	Average
FJF	4%	6%	5%
PP1	0%	3%	1%
PP2	-2%	1%	0%
LVF	1%	2%	1%
VP1	2%	3%	3%
VP2	1%	2%	2%

7.4. Discussion

The discussion of the model and its results is split in multiple paragraphs. Each paragraph discusses a section of results to find the impact and confidence of the results. Also the comparison of oil versus chemical terminals is discussed. Next, the applicability of these results considering the simplifications that were made in Section 6.3 is discussed. Finally, the set-up of the model is analysed to find out to what extent they can answer the research question.

Average waiting time, including 95% confidence interval Based on results in Table 7.9 it can be concluded that the Fastest Job First scheduling method can slightly improve the average waiting time at Terminal 1. The other scheduling methods however do not seem to have a positive effect on the performance most of the time, or never. It must be noted though that not in all cases the FJF scheduling method improves performance. Table E.2 shows that for dataset 1 FJF increases the average waiting time by 1% for example. This can be caused by the difference in arrival sequence of the vessels due to the adjustment of arrival times. Because the vessel arrival times are adjusted randomly the initial distribution of vessel arrivals based on historical data is no longer uphold. Dataset 1 can for example have more vessels arriving at the same time, more vessels carrying the same product or more vessels with the same characteristics closer together. It appears the model is sensitive to these changes in arrival pattern. Therefore before a new scheduling method is implemented the arrival pattern must be studied in detail and the extend of deviation from this pattern must be tested also. However, the 95% confidence interval shows the estimated range of values which is likely to include the unknown population parameter, if the study would be extended. For the FJF in Terminal 1 this range varies from -7% to -2%, thus this scheduling method is expected to have a positive effect in most cases.

For each terminal the most suitable scheduling method differs. From results presented in Tables 7.9 to 7.13 the following scheduling methods could improve performance at the terminals:

- Terminal 1 - Fastest Job First
- Terminal 2 - Product Priority 4 (based on number of berths)
- Terminal 3 - Product Priority 1 (based on number of loading arms)
- Terminal 4 - Largest Vessel First
- Terminal 5 - First Come First Serve

Because all terminals are categorised as independent terminals, unfortunately this means that the most suitable scheduling method is not similar for all terminals in this category. Also between the three oil terminals and two chemical terminals no similar results can be witnessed.

Average waiting time per priority group and maximum waiting time Table F.1 shows the average waiting time per priority category under FCFS and FJF for Terminal 1. As previously mentioned, this scheduling method improves the overall average waiting time at Terminal 1. However, Table F.1 shows that applying the Fastest Job First scheduling method does increase the waiting time for vessels with a longer loading time. Next to that, Table G.1 shows that the maximum waiting time and the number of vessels waiting more than 24 hours increases.

Table F.6 shows that for Terminal 2 the Fastest Job First scheduling method decreases the average waiting time in all categories, even the vessels with the lowest priority. Probably because the effect of the increase in maximum waiting time (on average 194%) is too big to overcome. Figures G.3 and G.4 clearly shows the contribution of the vessels with waiting times over 40 hours on the cumulative percentage. A large share of the vessels has to wait more than 40 hours, and this number increases for the Fastest Job First scheduling method.

For scheduling methods VP and PP in Terminal 1, Tables F.2 to F.5 show the impact on the waiting time per category for each scheduling method. Table F.7 shows that implementing product priority scheduling method 4 in Terminal 2 increases the performance of product groups 1 to 4 and the average waiting time overall. However for the scheduling methods applied in Terminal 1 this is not the case. Tables F.2 to F.5 show that in some cases the vessels in priority group 1 benefit from the scheduling method, but the vessels in lower priority groups have to pay. If the overall impact is positive the terminal will have to decide if this shift in waiting time is worth the overall improvement and if they can get their clients to agree. Convincing a client to wait longer in order to improve the terminals performance will be a very hard task, and might prove to be impossible.

Next, PP1 for Terminal 3 and LVF for Terminal 4 are analysed per priority group in Tables F.8 and F.9, because these scheduling methods improve average waiting time for these terminals. But also these tables show that the vessels with low priority will have to compromise in their average waiting time. If this difference is acceptable will determine the effectiveness of the scheduling method for this terminal.

Varying berth time Next to the results from the experiment based on varying the arrival pattern, also the loading time was adjusted for Terminal 1 and 2. Table H.1, H.4, H.2 and H.5 show the average waiting time and difference in percentage per scheduling method for Terminal 1 and 2 under different loading time options. Results show that by decreasing the loading time the average waiting time is also decreased. This seems logical because a lower loading time results in a shorter berth time and thus the berth because available sooner. This is confirmed by the average berth occupancy rates shown in Table H.3 and H.6. Tables H.3 and H.6 also confirm that the berth occupancy remains constant over all scheduling methods until the point where the queue becomes so large that not all vessels can be assigned within the 1 year span. At dataset d, with 1.5 times the loading time, the berth occupancy is dissimilar due to the number of vessels that remain unassigned at the end of the test period.

Next to that, the results show an inconsistent gain for the scheduling methods that improve average waiting time once the loading time and berth occupancy are increased. More research will have to be performed to test how variable berth times affect the average waiting time.

Varying number of vessels Finally, three datasets were tested with an adjusted number of vessels for Terminal 1 and 2. Tables I.5 and I.6 show that the berth occupancy changes almost precisely similar to the change in number of vessels. This slight divergence can be attributed to the type of vessels that have been removed.

If this 10% of vessels has a lower average berth time that the remaining vessels in the dataset, the new berth occupancy will remain a bit higher than the 10% decrease. And a similar effect in the other direction can cause a lower berth occupancy, as shown in dataset m for Terminal 1.

Tables I.1, I.3, I.2 and I.4 show the average waiting time and difference in percentage per scheduling method for Terminal 1 and 2 with adjusted number of vessels. The decline in number of vessels also shows a decline in the improvement of the scheduling methods. Suggesting that at peak hours or busy terminals applying a different scheduling method can be more beneficial.

Oil terminals versus chemical terminals As mentioned previously, between the three oil terminals and two chemical terminals no similar results can be witnessed. However, both chemical terminals show a higher average waiting time. This can be explained by the higher berth time the vessels require to load or unload, as shown in Figures 7.9 and 7.10 for Terminal 1 and 2. Table 7.14 shows that not only the higher average berth time influences the difference in average waiting time, also the number of berths and number of vessels can influence this high waiting time. But comparing Terminal 2 to Terminal 3, and Terminal 5 to Terminal 1 (in Table 7.1) it becomes clear that it is not only the number of berths and vessels that influence this waiting time.

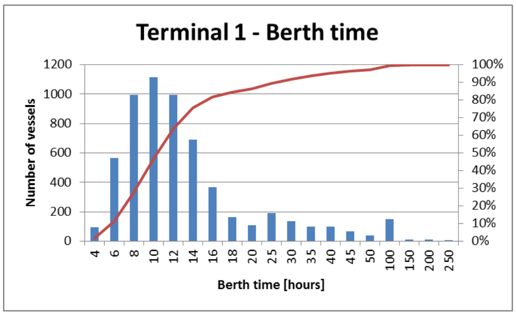

Figure 7.9: Berth time of vessels arriving at Terminal 1

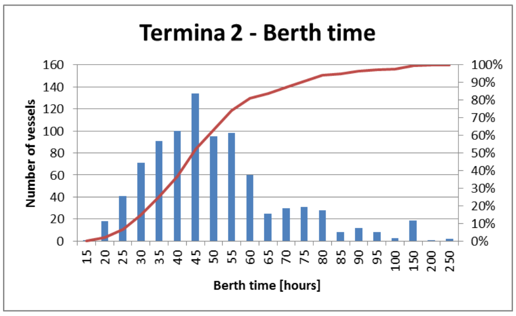

Figure 7.10: Berth time of vessels arriving at Terminal 2

Table 7.14: Minimum, maximum and average berth time for terminals 1 and 2 in hours

	Terminal 1	Terminal 2	Terminal 3	Terminal 4	Terminal 5
Min	2.78	12.46	4.06	4.86	7.60
Max	240.27	234.17	88.97	120.29	114.36
Average	14.11	48.26	14.72	18.08	17.96

Applicability Finally, the applicability of these results can be discussed. Due to the simplifications applied to the model assumptions were made that can impact the results of the experiment.

Firstly, the assumption that unlimited storage and pipeline capability are available influences the performance of the terminal. Section 6.5.2 has already shown that a waiting time for infrastructure is common. By ignoring this effect the average waiting time turns out lower. But since this effect influences all scheduling methods, it should not affect the decision for most suitable scheduling method per terminal. Similarly, the effect of value adding services, the effect of maintenance or breakdown, tide restrictions, weather effects, work crew efficiency, port sailing time and pipe cleaning times influence all scheduling methods and do not affect one more than the other. Also the effect of rounding down the arrival time and rounding up the end time has a similar impact on all scheduling methods.

The differentiation of loading or unloading should not influence the average waiting time at all because the berth time is fixed. As well as having an ETA/ATA fixed. The arrival time is set, but because the vessels are only added to the queue at arrival no previous knowledge of vessel arrival time is necessary. The pattern at which the vessels arrive does however seem to influence the most favourable scheduling method and the average waiting time. If this pattern is flexible in reality the sensitivity of the scheduling methods to this pattern must be evaluated extensively.

Finally, idle times and pumping times are taken from a simulation validated with historical data. Assuming no delays and all product loading arms having the same capacity per product and per berth simplifies the model. Creating a scenario where the berth time is exactly the same at all berths that can facilitate (un-)loading of all products on the vessel. This however does not always occur in reality. At some berths a vessel could (un-)load their product faster than others, and could even decide to wait to be served on this berth. This effect could influence the performance of each scheduling method differently, because it could motivate clients to switch positions in the waiting queue.

Next to that, also the feasibility of knowing the berth time of a vessel beforehand can be questioned. As mentioned in Section 2 there are a lot of unforeseen delays that can influence a vessel's time at berth. Especially for the Fastest Job First scheduling method, it is important to investigate the possibilities of predicting berth time and their accurateness.

Overall, due to the simplifications made an estimation of the most suitable scheduling method can be made for each terminal. But some effects should be studied to check how they affect the performance of the terminal. However, because only 5 case studies could be performed the study should first be extended to check the relation between terminal characteristics, the scheduling methods and its performance. The next section elaborates on this issue.

Research question To conclude, the big picture is analysed to consider if this experiment can answer the research question: *To what extent can the implementation of scheduling methods improve the performance of liquid bulk terminals?*

In Section 5.3 a categorisation of liquid bulk terminals was made. However not all terminal categories could be modelled. Therefore, the impact of scheduling methods could not be tested on all types of liquid bulk terminals and conclusions cannot be drawn on links between scheduling methods and terminal types. To evaluate the effect on the performance of all types of liquid bulk terminals the study should be extended to more terminals. If model terminals were generated with varying characteristics, such as arrival pattern, berths, throughput, loading arms, tank pits or more, the influence of these characteristics on the performance under different scheduling methods could also be tested. For each category a model terminal could test the differences or similarities of the effect of the scheduling methods. Section 9 will elaborate on the recommendations for further research.

Because the terminal specifications and arrival pattern are taken from a simulation and remain constant, performance is only measured by average waiting time. Other performance measures such as throughput, berth occupancy and turnaround time remain constant and therefore the effect on these KPI's cannot be measured. If the study was extended other KPI's could be included to measure the impact on performance in more detail.

Finally, the implementation of only a few new scheduling methods were included in this research. But preferred berthing, dedicated berthing and slot booking could also possibly have a positive impact on the performance of terminals. Therefore to answer the research question completely more terminals, performance measures and scheduling methods should be tested. This research serves as a preliminary study and in Section 9 recommendations will be made on how to proceed.

8 Conclusions

The purpose of this research was to investigate how scheduling methods can impact the performance of liquid bulk terminals. Multiple scheduling methods were tested on five independent terminals and for each terminal the most suitable scheduling method was found. These scheduling methods range from First Come First Serve, Fastest Job First, Largest Vessel First and Product Priority based on number of loading arms or berths. Unfortunately, no links were identified between independent terminals and scheduling methods. Some scheduling methods showed improvement of the average waiting time up to an 8% decrease. However, most scheduling methods had an insignificant impact of 1 or 2 % and other showed an increase in average waiting time.

Next to the benefits of a decreased average waiting it was found that vessels with a lower priority will have to wait longer and the maximum wait time can increase significantly. These considerations have to be taken into account when a decision is made to switch to a alternate scheduling method in practice.

Varying the number of vessels in the experiment showed that a decline of vessels also decreased the improvement of performance. Suggesting that at busier terminals or peak hours switching in scheduling method can have a larger impact.

Overall it was found that scheduling methods can effect the performance of a terminal positively, but the relation between these effects, the terminal specifications/type and arrival pattern requires more research. In the next section this proposal will be discussed together with recommendations for further research.

Next to the main research question also some sub-questions were formed at the beginning of this research considering liquid bulk types, liquid bulk terminal types, KPIs, scheduling methods and links between these characteristics. Shortly the answers to these research sub-questions (as stated in Section 1) will be presented.

Firstly, from the liquid bulk materials, general supply chain, stakeholders, carriers, trade routes and trends presented in Section 3 the following types of liquid bulk were identified:

- Oil products (such as crude oil, gasoline, naphtha, diesel and fuel oil)
- Chemicals (such as methanol, xylene, MEG and styrene)
- Bio-fuels and vegetable oils
- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG) (propane, butane)

Considering terminal characteristics that were studied later, the decision was made to focus on oil and chemical liquid bulk terminals for the model and experiment.

Secondly, multiple categorisations of liquid bulk terminals were studied. Based on literature a categorisation was established on the function in the supply chain. However, during interviews with liquid bulk terminals it became apparent that this categorisation was not applicable in practice. In practice the distinction between types of terminals was made based on ownership. The following terminal types were identified:

- Single (oil) company ownership
- Joint/consortium ownership
- Independent ownership

Next, terminal key performance indicators (KPIs) were studied both in literature and in practice. The KPIs that are most common include turnaround/idle/pumping time, average (un-)loading speed per product, average product flow per berth, berth/terminal occupancy, throughput, average waiting time and costs of delay (demurrage).

Currently, the scheduling method that is applied in liquid bulk terminals is first come, first serve. However, from this scheduling method various exceptions are made in practice. These exceptions are made based on the following priority rules:

- priority for vessels carrying urgent feedstock
- priority for vessels loading from storage tanks about to overflow
- priority for vessels arriving within the timespan documented in the contract
- priority for large carriers over barges
- priority for vessels carrying cargo that have hinterland connections waiting (trucks or trains)
- priority for vessels with larger costs of delay (demurrage)
- one shareholder/client is not allowed to occupy all berths, therefore another shareholder/client has priority
- priority for vessels with available infrastructure (storage, pipelines) and products over vessels waiting on infrastructure
- priority for vessels given by owner (only priority over vessels from same owner)

Even though most terminals apply a similar scheduling method, the terminals do aspire different scheduling objectives. These objectives can be pursued by applying one/some of the above exceptions from the FCFS rule and are subject of and incentive for most research studies. From literature the following scheduling objectives were found:

- Minimising deviation of customer priority
- Minimising earliness/tardiness of completion
- Minimising total wait time
- Minimising total delays
- Minimising total/operational costs
- Minimising total demurrage
- Minimising total service time
- Minimising turnaround time

Due to the similarity between scheduling methods applied in all types of liquid bulk terminals, unfortunately no links were identified between terminal types, KPIs and scheduling methods. However the exceptions made from the scheduling method were adapted to the terminal scheduling objectives, KPIs and terminal types. Table 5.4 presents the link between terminal types and exceptions from the FCFS rule. Table 5.3 present the links between terminal types, KPIs and scheduling objectives.

First Come First Serve was found to be the scheduling method mostly applied, but other scheduling methods do exist and can be applied. The alternative scheduling methods that were found include: largest vessel first, fastest job first, product priority, vessel priority, preferred berthing, dedicated berthing and slot booking. From this list the first four methods were tested by simulating oil and chemical terminals. From the results of the experiment presented in Section 7 it can be concluded that the scheduling methods that are most suitable vary per terminal. Within the independent terminal category the scheduling method that is most suitable thus varies. Therefore, the most suitable scheduling methods for different types of liquid bulk terminals remain flexible and have to be determined for each terminal specifically. However, the differences between joint ownership and single ownership terminals could not be tested due to the limited amount of terminal data available. Further research will have to be performed in order to test the influences on and differences between these categories. Chapter 9 elaborates on the set-up of the research to be performed.

9 Recommendations

This section includes recommendations for further research based on this research and the interviews performed with multiple terminals. Because the impact of scheduling methods was not tested on all terminal types first improvements on the current model will be proposed. Next, a proposal is made to rearrange the model and experiment set-up to include more scheduling methods, key performance indicators and terminal types.

- Firstly, only 7 terminals were interviewed. Widening the information intake might bring different aspects to light and could influence the conclusions of the categorisation. It is recommended to visit more terminals to confirm if this categorisation is correct.
- Next, the terminals that were tested in the experiment all belonged to the same category; independent. Terminals from other categories should be simulated and tested to find the effect of the scheduling methods on single company or joint ownership terminals. Also conclusions could then be drawn on the correlation between all terminal types and their most suitable scheduling method.
- Currently, this model is based on a simulation that is validated with historical data. From this simulation the berth time for each vessel is determined. In practice predicting the berth time will be more difficult and needs more research. If a method is found to correctly estimate the berth time, it should be tested to see if it is feasible in practice to predict correctly.
- The scheduling method Fastest Job First could be expanded to determine berth time per berth instead of assuming a constant turnaround time. The berth allocation would become more intricate, but decisions might be made to wait a little longer to minimize the turnaround time. If turnaround time is the most important KPI including specific service time per berth could improve the performance even more.
- Include the effect of internal transfers (due to value adding services), maintenance or breakdown, and cleaning of pipelines, on the availability of infrastructure. Dismiss the assumptions that storage tanks and pipelines are always available. Validating the average waiting time showed that all terminals have a ’wait on infra’ factor that should be included in future research.
- Next to adjustments to the current model to investigate influences on the test terminals, best would be to redesign the experiment to include all liquid bulk terminal types, more key performance measures and scheduling methods.
  - Instead of using actual terminal characteristics the option should be taken to make the terminal characteristics variable. Changing number of berths, loading arms, tank pits and their capability in the experiment can test the influence of these characteristics on the performance (under different scheduling methods). For each terminal type a representation of a general terminal in that category can be designed. In order to make this general design multiple liquid bulk terminals should be investigated to find common denominators.

  - Next to changing the terminal configuration also the arrival pattern should be adjusted. Similarly, for each terminal type a representation of a general arrival pattern can be designed after extensive research. This arrival pattern should also be adjusted in the experiment to test the sensitivity of the terminal's performance to this pattern. Adding the option to change the number and types of vessels arriving will create more possibilities to measure the performance.
  - Therefore, the key performance indicators that can be used to measure the performance can be extended. Important KPI's that should be included are berth occupancy, turnaround time, throughput and demurrage. Especially demurrage is a KPI that needs more research to determine correctly but could impact the advantage of certain scheduling methods significantly. Berth occupancy and throughput will change according to the vessel arrival pattern and depend on the availability of the terminal. Turnaround time can be influenced by incorporating variable idle times, internal transfers, maintenance and breakdown.
  - Finally, the scheduling methods that will be tested can be extended to include preferred berthing, dedicated berthing and slot booking. The impact of preferred and dedicated berthing will depend on the terminal's characteristics and vessel arrival pattern. Varying the number of berths, products or clients can show in which situations one of these scheduling methods could be beneficial. Slot booking will need a thorough understanding of the arrival pattern of all vessels and the uncertainty that is involved.

During the interviews with liquid bulk terminals in the Port of Rotterdam more issues related to terminal scheduling came to light. The following subjects were discussed and are proposed to study in more detail.

- In a port barges can be scheduled to visit multiple terminals in a day without a predetermined order. This causes uncertainty in arrival time for each terminal that will be visited and therefore the barge might have a longer total waiting time. Turnaround time of these barges in the port can be minimized by coordinating multiple terminal visits based on availability. It is recommended to share information to manage expectations of both terminals and barge operator (Terminal C, 2016). Further research should be performed on the turnaround times in ports and the implementation of information sharing.

- Currently the exchange of large vessels takes up a lot of administrative time because a lot of service parties are involved; the port, pilotage, towing-services. There can be a large delay between the time the vessel is ready to depart and the actual departure time. If all parties work together and share information on their availability, the time between departure of the first vessel and arrival of the second vessel could be minimized. This could improve the berthing occupancy of the terminals (Terminal E, 2016).

- From interviews it also became clear that work crew scheduling is a problem (Terminal F, 2016; Terminal C, 2016). Because the terminal has to deal with peak hours on short notice the usual work crew is not always capable of servicing all vessels. If infrastructure is available the work crew becomes the limiting factor and this is undesirable. Further research should be conducted on the pattern of work pressure and scheduling work crews accordingly.

A

Research Paper

Scheduling methods in liquid bulk terminals

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December 2, 2016

Abstract

Over the last few years liquid bulk terminals have expanded and competition has increased. Therefore, the purpose of this study is to investigate how certain scheduling methods can improve the performance of liquid bulk terminals. A categorisation of liquid bulk terminals is defined based on ownership. For each terminal category corresponding key performance indicators and scheduling objectives were found. After modelling five independent terminals it is concluded that there is no relation between this category and scheduling methods, because the most suitable scheduling method varied for each terminal. Scheduling methods can effect the performance of a terminal positively, but the relation between these effects, the terminal specifications/type and arrival pattern requires more research.

I. Introduction

Due to an increase in the number and size of liquid bulk terminals a higher terminal capacity has become available. Clients have more opportunities to handle or store their liquid bulk materials and thus competition between liquid bulk terminals has increased. Efficient planning to offer fast, efficient and cost-effective services has become more important. Therefore, the question arises if the implementation of alternative scheduling methods can improve the operation of a liquid bulk terminal.

Previous studies indicate that first come first served is one of the most frequently used scheduling rules [1], which has been confirmed. Unfortunately, the application of first come first serve policy causes delays in loading and unloading because the resources are not used optimally [2]. However, the tradition of "first come first served" irrespective of the different vessels' contribution to port revenue in the berth allocation are still in practice [3].

Efforts to introduce alternative scheduling methods to liquid bulk terminals are scarce. Recent studies have included the optimization of terminal-refinery systems [4] or scheduling support based on multi-agent systems [5]. But a generally accepted categorisation of liquid bulk terminals and overview of scheduling methods is non-existent. The purpose of this study is to fill this gap and to investigate how these scheduling methods can positively impact the performance of liquid bulk terminals.

II. Methods

The study is split in two parts; the first part focuses on the evaluation and categorisation of liquid bulk terminals and current scheduling methods, and the second part describes the approach to modelling the terminals and scheduling methods.

i. Analysing phase

A background study on the liquid bulk market, terminal functions, characteristics, equipment and types of liquid bulk terminals led to a categorisation based on function in the supply chain. However, after performing multiple interviews with actual terminals this categorisation was adjusted. Independent, joint or single ownership was a more fitting categorisation in practice. For each of these liquid bulk terminal types corresponding key performance indicators and scheduling objectives were found, presented in Table 1. The scheduling methods applied in all terminals were unfortunately similar: first come first serve. However, to reach their objective each type of terminal employs different exceptions from the first come first serve rule. Exceptions found in single company ownership terminals include:

- priority for vessels carrying urgent feedstock
- priority for vessels loading from storage tanks about to overflow
- priority for vessels arriving within the timespan documented in the contract
- priority for vessels with larger costs of delay (demurrage)

Exceptions in joint ownership terminals are:

- one shareholder is not allowed to occupy all berths, therefore another shareholder has priority
- priority for vessels given by owner (only priority over vessels from same owner)
- always in agreement with all shareholders involved

Exceptions found in independent ownership terminals are:

- one client is not allowed to occupy all berths, therefore another client has priority
- priority for large carriers over barges
- priority for vessels carrying cargo that have hinterland connections waiting (trucks or trains)
- priority for vessels with available infrastructure (storage, pipelines) and products over vessels waiting on infrastructure
- priority for vessels loading from storage tanks about to overflow
- priority for vessels carrying urgent feedstock for distillation at terminal
- always in agreement with all clients involved

ii. Modelling phase

The objective of the model is to test if a scheduling method including priority settings can improve the performance of a liquid bulk terminal through varying the berth allocation sequence.

Not the complete terminal including its hinterland connections is modelled to test the influence of the scheduling methods. The scheduling methods have the most impact on the sequence of ships at berth. Therefore the focus lies on the berth allocation problem including ship arrivals, berth and infrastructure characteristics.

Certain assumptions are used to simplify the model. These assumptions include:

- Unlimited storage and pipeline capability.
- The effect of value adding services, such as blending, on the availability of infrastructure is ignored.
- The effect of maintenance or breakdown on the availability of infrastructure is not taken into account.
- Cleaning of pipelines is not taken into account on the availability of jetty lines.
- There are no tide restrictions on VLCCs.
- Weather effects are not taken into account.
- The work crew is not a limiting factor on the availability or efficiency.
- ETA/ATA is fixed.
- There is no distinction between loading or unloading.
- Idle times are taken from a simulation validated with historical data.
- Time to move from waiting area to berth is not taken into account.
- Pumping time is taken from a simulation validated with historical data. Assuming all product loading arms have the same capacity per product and per berth. Not taking into account to possibility of simultaneous (un-)loading of multiple products per berth.

The model is initiated by creating a queue for the arriving vessels. If the arrival time of the vessel is equal to the time in the simulation the vessel is added to the queue. The effect of the scheduling method will reshuffle the

Table 1: *Scheduling objectives and key performance indicators in practice*

Terminal type	Key performance indicator	Scheduling objective
Single company ownership	Costs (demurrage)	Minimise demurrage, Maximise profit
Joint ownership	Turnaround time	Minimise turnaround time
Independent ownership	Turnaround time and throughput	Maximise service

order of the queue. Next, the algorithm to find a matching berth is started. At each time instance the complete queue is run through this section, starting with the first in the queue and moving to the end. For each vessel in this queue the vessel characteristics are compared to the terminal characteristics to find which berth location is suitable. First the vessel type is checked, next the loading arms are checked and finally the tank pits are checked. If a list of suitable berths is found the availability of these berths must be checked to make sure a vessel is not assigned to an already occupied berth. If one of these berths is available the vessel will be assigned, if not the vessel remains in the queue. Once a vessel is assigned to a berth it will be removed from the queue, the berth availability will be updated and the time and berth will be logged in a vessel log. The model will go back to the queue and repeat the process for the next vessel in the queue. If there is no next vessel in the queue the model will go to the next time step. This procedure will be repeated for 9000 hours (a little over a year) with time steps of 1 hour.

The input dataset contains all of the vessel characteristics and defines the arrival pattern for the terminal in one year. The output datasets shows the assignment of vessels to berths including their waiting time. Next to the vessel log, also the availability matrix that is used to check availability is printed. From this matrix the berth occupancy can be determined.

With this model an experiment is performed where multiple scheduling strategies are tested on five independent oil (1, 3 and 4) and chemical (2 and 5) terminals. Because the model is set-up based on simulation results from a Royal HaskoningDHV simulation, only terminals can be tested that have been simulated by Royal HaskoningDHV. Therefore the amount and types of terminals are limited. These terminals have varying amounts of berths, vessels per year and throughput. The ship arrival patterns for the oil and chemical terminals are derived from a dataset of actual arrival times. The data provided includes the actual arrival time and the ship characteristics (product, size, owner) of the terminal for 1 year. To take into account the uncertainty in arrival times in practice the arrival data will be altered within a 12-hour time window and the experiment will be repeated nine times. The average waiting time and 95% confidence interval over all these results are plotted to find the most suitable scheduling method. The scheduling methods that are tested are: First Come First Serve (FCFS), Fastest Job First (FJF), Product Priority (PP) based on the number of jetty-lines, berths or a combination thereof, Largest Vessel First (LVF) and Vessel Priority (VP) based on the pump rate of number of berths per vessel type. Performance is measured in the average waiting time of all vessels.

III. Results

Results from the experiment are shown in Tables 2 to 6. These tables show the differences in percentages between the alternative scheduling methods and first come first serve. Also in the tables the 95% confidence interval of these differences is included.

IV. Discussion

The discussion of these results starts with the analysis of the average waiting time. Next, considering the simplifications that were made the applicability of these results is discussed.

Table 2: *Results Terminal 1 compared to FCFS*

	Lower bound	Upper bound	Mean
FJF	-7%	-2%	-5%
PP1	-2%	3%	1%
VP1	-1%	6%	3%
VP2	4%	11%	8%
VP3	7%	13%	10%

Table 3: *Results Terminal 2 compared to FCFS*

	Lower bound	Upper bound	Mean
FJF	1%	20%	10%
PP1	-7%	5%	-1%
PP2	-7%	4%	-2%
PP3	-8%	2%	-3%
PP4	-13%	-2%	-8%

Table 4: *Results Terminal 3 compared to FCFS*

	Lower bound	Upper bound	Mean
FJF	-4%	1%	-2%
PP1	-3%	-1%	-2%
PP2	1%	3%	2%
LVF1	-1%	0%	0%
LVF2	-2%	0%	-1%
VP1	2%	6%	4%
VP2	-3%	0%	-1%

Table 5: *Results Terminal 4 compared to FCFS*

	Lower bound	Upper bound	Mean
FJF	0%	7%	4%
PP1	-2%	3%	1%
LVF1	-3%	0%	-1%
LVF2	1%	5%	3%
LVF3	6%	9%	7%

Table 6: *Results Terminal 5 compared to FCFS*

	Lower bound	Upper bound	Mean
FJF	4%	6%	5%
PP1	0%	3%	1%
PP2	-2%	1%	0%
LVF	1%	2%	1%
VP1	2%	3%	3%
VP2	1%	2%	2%

i. Performance

For each terminal the most suitable scheduling method based on performance differs. From results presented in Tables 2 to 6 the following scheduling methods could improve performance at the terminals:

- Terminal 1 - Fastest Job First
- Terminal 2 - Product Priority 4 (based on number of berths)
- Terminal 3 - Product Priority 1 (based on number of loading arms)
- Terminal 4 - Largest Vessel First
- Terminal 5 - First Come First Serve

Because all terminals are categorised as independent terminals, unfortunately this means that the most suitable scheduling method is not similar for all terminals in this category. Also between the three oil terminals and two chemical terminals no similar results can be witnessed.

However, for some of these scheduling methods results showed that the overall average waiting time decreased but vessels with low priority had to wait longer. Therefore in practice, these low priority vessels will have to compromise by waiting longer. If this difference is acceptable will determine the effectiveness of the scheduling method for the terminal.

Next to that, a decline in number of vessels also showed a decline in the improvement of the scheduling methods. Suggesting that at peak hours or busy terminals applying a different scheduling method can be more beneficial.

ii. Applicability

The applicability of these results can be discussed because due to the simplifications applied to the model assumptions were made that can impact the results of the experiment.

Firstly, the assumption that unlimited storage and pipeline capability are available influences the performance of the terminal should be adjusted. Waiting on infrastructure is common in liquid bulk terminals and by ignoring this effect the average waiting time turns out lower. However, since this effect influences all scheduling methods, it should not affect the decision for most suitable scheduling method per terminal. Similarly, the effect of value adding services, the effect of maintenance or breakdown, tide restrictions, weather effects, work crew efficiency, port sailing time and pipe cleaning times influence all scheduling methods and do not affect one more than the other.

The arrival pattern at which the vessels arrive seems to influence the most favourable scheduling method and the average waiting time. If this pattern is flexible in reality the sensitivity of the scheduling methods to this pattern must be evaluated.

Finally, idle times and pumping times are taken from a simulation validated with historical data. Assuming no delays and all product loading arms having the same capacity per product and per berth simplifies the model. Creating a scenario where the berth time is exactly the same at all berths that can facilitate (un-)loading of all products on the vessel. This however does not always occur in reality. At some berths a vessel could (un-)load their product faster than others, and could even decide to wait to be served on this berth. This effect could influence the performance of each scheduling method differently, because it could motivate clients to switch positions in the waiting queue. Also the feasibility of knowing the berth time of a vessel beforehand can be questioned. The literature review revealed there are a lot of unforeseen delays that can influence a vessel's time at berth.

Overall, due to the simplifications made an estimation of the most suitable scheduling method can be made for each terminal. But some effects should be studied to check how they affect the performance of the terminal in practice.

iii. Totality

A categorisation of liquid bulk terminals was made based on ownership, but not all terminal categories could be modelled. Therefore, the impact of scheduling methods could not be tested on all types of liquid bulk terminals and conclusions cannot be drawn on links between scheduling methods and terminal types. To evaluate the effect on the performance of all types of liquid bulk terminals the study should be extended to more terminals. If model terminals were generated with varying characteristics, such as arrival pattern, berths, throughput, loading arms, tank pits or more, the influence of these characteristics on the performance under different scheduling methods could also be tested. For each category a model terminal could test the differences or similarities of the effect of the scheduling methods.

Because the terminal specifications and arrival pattern are taken from a simulation and remain constant, performance is only measured by average waiting time. Other performance measures such as throughput, berth occupancy and turnaround time remain constant and therefore the effect on these KPI's cannot be measured. If the study was extended other KPI's could be included to measure the impact on performance in more detail.

Finally, the implementation of only a few new scheduling methods were included in this research. But preferred berthing, dedicated berthing and slot booking could also possibly have a positive impact on the performance of terminals. Therefore to answer the research question completely more terminals, performance measures and scheduling methods should be tested. This research serves as a preliminary study and recommendations are made on how to proceed.

V. Conclusions

Multiple scheduling methods were tested on five independent terminals and for each terminal the most suitable scheduling method was found. These scheduling methods range from First Come First Serve, Fastest Job First, Largest Vessel First and Product Priority based on number of loading arms or berths. Unfortunately, no links were identified between independent terminals and scheduling methods. Some scheduling methods showed improvement of the average waiting time up to an 8%

decrease. However, most scheduling methods had an insignificant impact of 1 or 2 % and other showed an increase in average waiting time.

Next to the benefits of a decreased average waiting it was found that vessels with a lower priority will have to wait longer and the maximum wait time can increase significantly. These considerations have to be taken into account when a decision is made to switch to a alternate scheduling method in practice.

Varying the number of vessels in the experiment showed that a decline of vessels also decreased the improvement of performance. Suggesting that at busier terminals or peak hours switching in scheduling method can have a larger impact.

Overall it was found that scheduling methods can effect the performance of a terminal positively, but the relation between these effects, the terminal specifications/type and arrival pattern requires more research.

VI. Recommendations

Recommendations include improving the model by expanding the number of interviewed terminals, modelling terminals from all categories, varying the berth time of a vessel per berth and including effects on the availability of terminal infrastructure like internal transfers, cleaning and maintenance. But better results are expected to follow from a modified model and experiment. This experiment should evaluate the effect of all scheduling methods on terminals with variable characteristics representing all terminal types. By changing the terminal characteristics and arrival patterns the impact on more key performance indicators can be determined. To set up such an experiment an extensive analysis of common characteristics and arrival patterns per liquid bulk terminal type is required.

References

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B

Trade routes

This appendix contains the graphical representations of the liquid bulk trade routes.

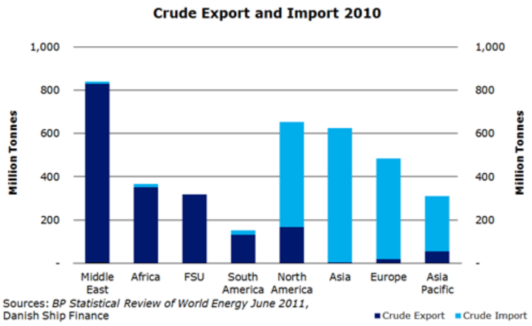

Figure B.1: Crude oil export and import in 2010 (Danish Ship Finance, 2016)

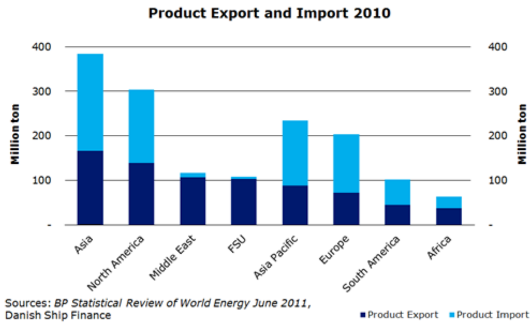

Figure B.2: Oil product export and import in 2010 (Danish Ship Finance, 2016)

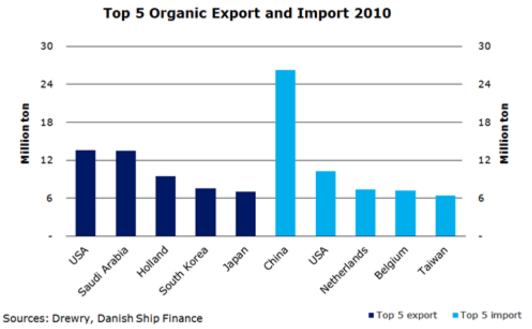

Figure B.3: Top 5 organic export and import 2010 (Danish Ship Finance, 2016)

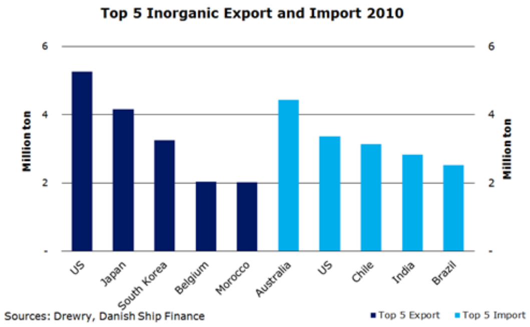

Figure B.4: Top 5 inorganic export and import 2010 (Danish Ship Finance, 2016)

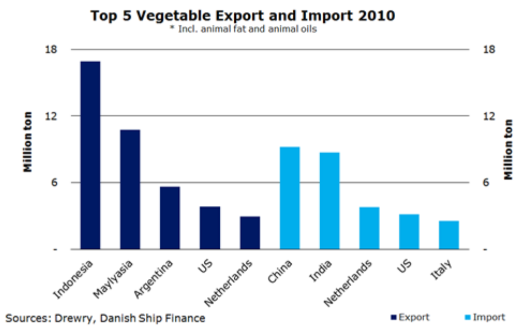

Figure B.5: Top 5 vegetable oil export and import 2010 (Danish Ship Finance, 2016)

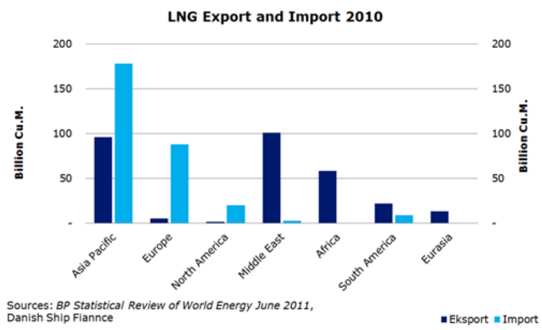

Figure B.6: LNG export and import in 2010 (Danish Ship Finance, 2016)

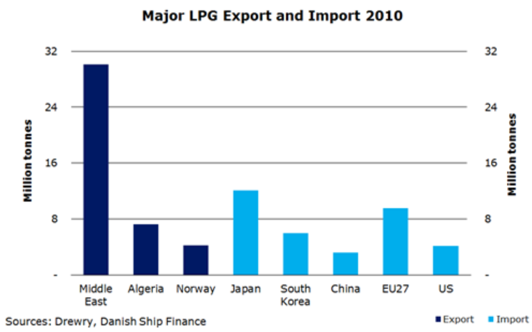

Figure B.7: LPG export and import in 2010 (Danish Ship Finance, 2016)

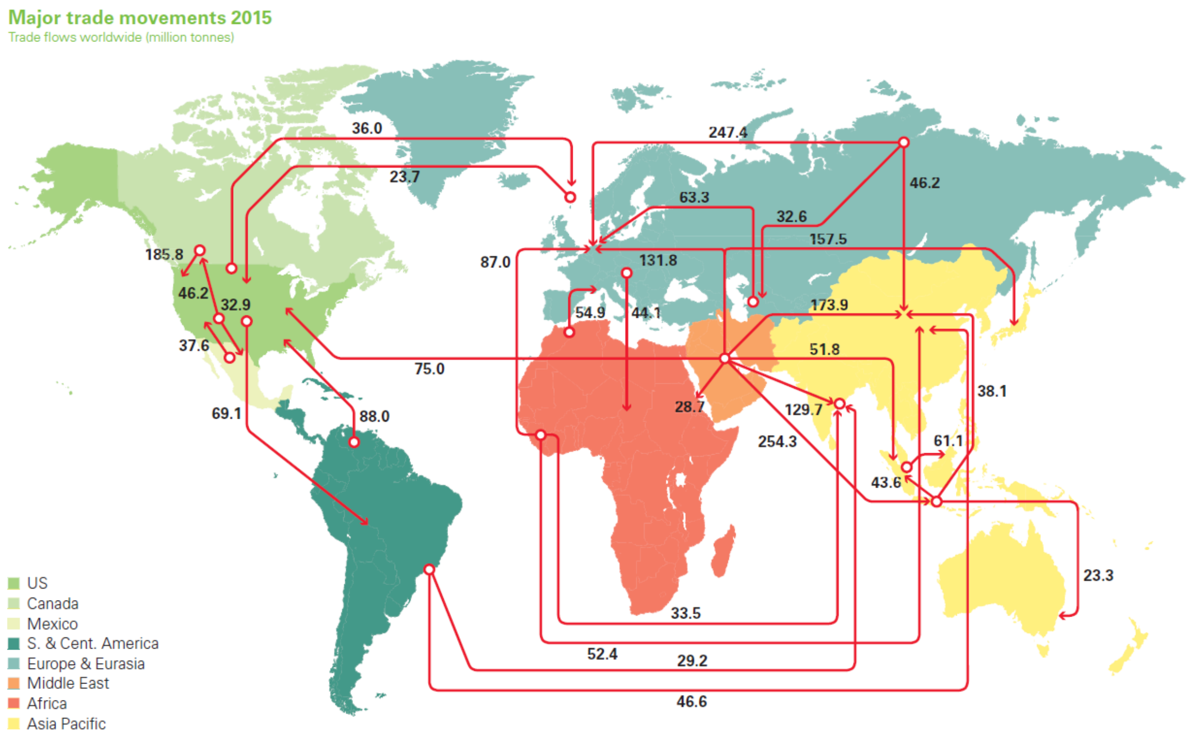

Figure B.8: Major oil trade movements 2015 (BP, 2016)

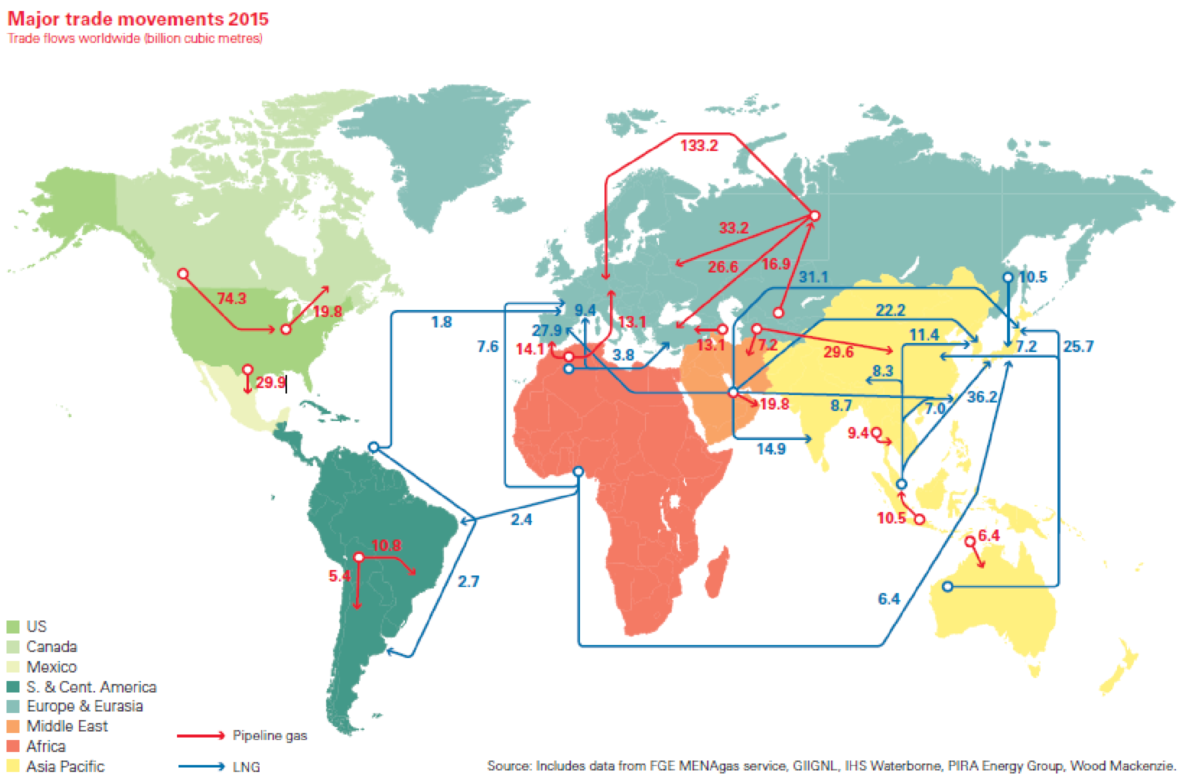

Figure B.9: Major LNG trade movements 2015 (BP, 2016)

C

Model

```
clear all
clc

hours = 9000;      % input hours out of 9000
vessels = 4631;     % input vessels out of 4631

% read data input
[~,~,log] = xlsread('Log_MOT_Generated_Botlek_0_10_7_All_9.xlsx');
[~,~,berth] = xlsread('Berth_MOT_combinations_Botlek_0_10_72.xlsx');
[~,~,product] = xlsread('Definition_JettyLines_Botlek_0_10_7.xlsx');
[~,~,jetty] = xlsread('Connection_JettyLines_and_Berths_Botlek_0_10_7.xlsx');
[~,~,routes] = xlsread('Routes_Botlek_0_10_7.xlsx');

% create output array
vessellog_array = cell(vessels+1,1);

% create availability matrix with berths in column 1 and all zeros
% size of matrix determined by time step of 1 hour
availability = num2cell(zeros(size(berth,2)-1,hours));
B = berth(1,2:size(berth,2));
C = transpose(B);
availability(1:size(berth,2)-1,1) = C;

% create queue array
queue_array = cell(1,5);

% create time loop. At time nomination add vessel to queue
for t = 1 : hours
    if mod(t,100) == 0
        disp(t)
    end
    % for selection of vessels
    for v = 1 : vessels
        if t == floor(cell2mat(log(v+1,2)));
            % arrivaltime = nominationtime
            nominationtime = t;
            % select vessel ID
            vessel = cell2mat(log(v+1,1));
            % select vessel type
            vesseltype = log(v+1,34);
            vesselpriority = cell2mat(log(v+1,35));
            % select loading time
            loadingtime = cell2mat(log(v+1,46));
            % select idle time at berth
            idletime = (cell2mat(log(v+1,45)) + cell2mat(log(v+1,47)));
            % calculate berth time
            berthtime = (loadingtime + idletime);
            % add vessel to queue with ID nomination time, vessel type, vessel
priority and berthtime
            queue_array{size(queue_array,1)+1,1} = vessel;
            queue_array{size(queue_array,1),2} = vesseltype;
            queue_array{size(queue_array,1),3} = nominationtime;
            queue_array{size(queue_array,1),4} = berthtime;
            queue_array{size(queue_array,1),5} = vesselpriority;
        end
    end

    % for each vessel in the queue find an available berth
    i = 2;
    for loopa = 2 : size(queue_array,1)
```

```
    % create output array
    berthmatch_array = cell(1,1);
    % select vessel arrival time in hours
    arrivaltime = t;
    % calculate vessel end time in hours, round off up
    endtime =  ceil(arrivaltime + queue_array{i,4});

    % for all berths
    for j = 2 : size(berth,1)

        % if vesseltype matches name in berth matrix
        if strcmp(queue_array{i,2}, cell2mat(berth(j,1)))

            % create output array
            berth_array = cell(1,1);
            % for all berths with matched vesseltype
            for k = 2 : length(berth)
                % if matrix value is 1 (berth-vesseltype capacity)
                if str2double(cell2mat(berth(j,k))) == 1
                    % write all possible berths per vessel in matrix
                    berth_array{size(berth_array,2)+1} = berth(1,k);
                    % easy check: do ship and berths match?
                    ship = cell2mat(berth(j,1));
                end
            end

            % create output arrays
            loadingarm_array = cell(1,1);
            berthtank_array = cell(1,1);
            for h = 1 : vessels
                if ((queue_array{i,1}) == cell2mat(log(h+1,1)))
                    % for all products
                    for s = 1 : cell2mat(log(h+1,3))
                    counter = 0;
                    counter2 = 0;
                        % for all jettylines
                        for u = 2 : size(product,1)
                            % if product matches name in product matrix
                            if strcmp(cell2mat(log(h+1,(3+s))), cell2mat(product(u,↙
3)))
                            % write all possible jettyline/loadingarm per berth for↙
each vessel in matrix
                             counter = counter + 1;
                             loadingarm_array{s,counter} = product(u,2);
                            end
                        end
                        % for all tankpits
                        for f = 2 : size(routes,1)
                            % if tankpits matches name in routes matrix
                            if strcmp(cell2mat(log(h+1,(23+s))), cell2mat(routes(f,↙
1)))
                                % for all berths in matrix
                                for e = 2 : size(routes,2)
                                    % if there is a link
                                    if cell2mat(routes(f,e)) == 1
                                        % add berth to berthtank_array
                                         counter2 = counter2 + 1;
                                         berthtank_array{s,counter2} = routes(1,e);
                                    end
                                end
```

```
                    end
                end
            end
        end
    end

    % create output array
    jetty_array = cell(1,1);
    % for all possible berths for each vessel
    for w = 2 : size(berth_array,2)
        counter = 0;
        % for all berths in jetty matrix
        for y = 2 : size(jetty,2)
            % if berth matches name in jetty matrix
            if strcmp(cell2mat(berth_array{1,w}), cell2mat(jetty(1,y)))
                % for all jettylines
                for x = 2 : size(jetty,1)
                    % if matrix value is 1 (jetty-berth link)
                    if  str2double(cell2mat(jetty(x,y))) == 3
                        % write available jettylines per berth in matrix
                        counter = counter + 1;
                        jetty_array{w,counter} = jetty(x,1);
                    end
                end
            end
        end
    end

    counter = 0;
    % for all possible berths per vessel
    for n = 2 : size(jetty_array,1)
        match = true;
        for h = 1 : vessels
            if ((queue_array{i,1}) == cell2mat(log(h+1,1)))
                % for all products per vessel
                for m = 1 : cell2mat(log(h+1,3))
                    match_cycle = false;
                    % for all jettylines per berth
                    for o = 1 : size(loadingarm_array,2)
                        % for all jettylines per product
                        for p = 1 : size(jetty_array,2)
                            % if one jettyline per product m matches with a↙
jettyline per berth n
                            if strcmp(cell2mat(loadingarm_array{m,o}),↙
cell2mat(jetty_array{n,p}))
                                match_cycle = true;
                            end
                        end
                    end
                    % match is untrue if not all products can be handled at↙
the berth
                    if ~match_cycle
                        match = false;
                    end
                    match_tank = false;
                    for g = 1 : size(berthtank_array,2)
                        if strcmp(cell2mat(berthtank_array{1,g}), cell2mat↙
(berth_array{1,n}))
                            match_tank = true;
                        end
```

```
                    end
                    if ~match_tank
                        match = false;
                    end
                end

                if match
                % matrix containing all possible berths for vessel
                 counter = counter + 1;
                 berthmatch_array(counter,1) = berth_array{1,n};
                end
            end
        end
    end
end
end

% limit berth matches to available berths
availableberthmatch_array = cell(1,1);
counter2 = 0;
% for all available berths
for a = 1 : size(berthmatch_array,1)
    match = false;
    % over the complete time span
    for b = 1 : size(availability,1)
        % if the berth matches the berth in availability matrix
        if strcmp(cell2mat(berthmatch_array(a,1)), availability(b,1))
            % and the berth is available
            if cell2mat(availability(b,arrivaltime+1:endtime+1)) == 0;
                % the berth can be an available match
                 match = true;
            else match = false;
            end
        end
    end
    if match
        % collect al available matched berths
        counter2 = counter2 + 1;
        availableberthmatch_array(counter2,1) = cellstr(berthmatch_array{a,1});
    end
end

% select first available berth
berthing = availableberthmatch_array{1,1};
% if berthing is empty, leave vessel in waiting queue.
TF = isempty(berthing);
if TF == 0
    % assign vessel ID to availability matrix
    for h = 1 : size(availability,1)
        if strcmp(availability(h,1),cellstr(berthing))
            % assign vessel ID to availability matrix if berth is occupied
            for g = (arrivaltime + 1) : (endtime + 1)
                 availability{h,g} = 1;
            end
        end
    end

    ID = queue_array{i,1}+1;
    vessellog_array{ID,1} = queue_array{i,1};
    vessellog_array{ID,2} = queue_array{i,3};
```

```
        vessellog_array{ID,3} = t;
        vessellog_array{ID,4} = queue_array{i,4};
        vessellog_array{ID,5} = endtime;
        vessellog_array{ID,6} = berthing;
        vessellog_array{ID,7} = queue_array{i,5};
        vessellog_array{ID,8} = (t - queue_array{i,3});

        % remove vessel from waiting queue
        e = queue_array(1:i-1,:);
        f = queue_array(i+1:size(queue_array,1),:);
        queue_array = [e ; f];
    else
        i = i+1;
    end

    end

end

vessellog_array{1,1} = 'vessel ID';
vessellog_array{1,2} = 'nominationtime';
vessellog_array{1,3} = 'arrivaltime';
vessellog_array{1,4} = 'berthtime';
vessellog_array{1,5} = 'endtime';
vessellog_array{1,6} = 'berthing';
vessellog_array{1,7} = 'vesselpriority';
vessellog_array{1,8} = 'waitingtime';

%disp(vessellog_array)
xlswrite('ResultsFCFS_Botlek_9.xlsx', vessellog_array, 1)
xlswrite('ResultsFCFS_Botlek_9.xlsx', availability, 2, 'A2')
```

D

Berth availability matrix

This appendix contains Tables D.1 and D.2 that show the berth availability matrix at two different time steps. These tables are used to verify the berth occupancy block in the model.

Table D.1: Output availability matrix from time step 108 until 130 at t = 108

	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130
CS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
NH2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH4	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRONOX1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRONOX2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
VP1W	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
VP20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VP2W	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
VP30	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP3W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP40B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP40V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP4WB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP4WV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D.2: Output availability matrix from time step 108 until 130 at t = 9000

	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130
CS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NH1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1
NH2	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
NH3	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
NH4	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
NH5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
T1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
T2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
T3	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
TRONOX1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRONOX2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP1O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VP1W	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VP2O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VP2W	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VP3O	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1
VP3W	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
VP4OB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP4OV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP4WB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP4WV	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

E

Results: Average waiting time per dataset

Table E.1: Average waiting time at Terminal 1

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total average**
FCFS	2.17	2.12	2.08	2.09	2.08	1.96	2.17	2.07	2.14	2.11	2.10
FJF	2.04	2.13	1.90	2.01	1.86	1.88	1.97	2.06	2.01	2.10	2.00
PP1	2.24	2.12	2.12	1.92	1.97	2.00	2.24	2.15	2.19	2.13	2.11
VP1	2.09	2.27	2.22	1.97	2.08	2.07	2.12	2.20	2.28	2.19	2.15
VP2	2.21	2.39	2.37	2.05	2.14	2.18	2.26	2.32	2.42	2.23	2.26
VP3	2.22	2.20	2.27	2.08	2.07	2.14	2.20	2.23	2.34	2.22	2.20

Table E.2: Difference between average waiting time at Terminal 1 for all scheduling methods compared to FCFS

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total average**
FJF	-6%	1%	-8%	-4%	-10%	-4%	-9%	-1%	-6%	-1%	-5%
PP1	3%	0%	2%	-8%	-5%	2%	4%	4%	2%	1%	1%
VP1	-3%	7%	7%	-6%	0%	6%	-2%	6%	6%	4%	3%
VP2	2%	13%	14%	-2%	3%	12%	4%	12%	13%	5%	8%
VP3	9%	3%	20%	4%	11%	14%	11%	9%	17%	5%	10%

Table E.3: Average waiting time at Terminal 2

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total average**
FCFS	9.82	7.74	8.24	8.97	9.41	8.89	9.41	9.83	9.87	7.90	9.01
FJF	9.63	7.76	9.37	11.23	8.83	12.00	9.73	10.02	9.89	10.37	9.88
PP1	9.69	7.32	8.68	9.03	9.06	9.99	8.09	10.11	8.34	8.74	8.90
PP2	9.04	7.14	9.13	8.95	9.43	9.09	8.50	9.72	8.34	8.77	8.81
PP3	8.95	7.14	9.05	8.94	9.30	8.91	8.22	9.50	8.57	8.68	8.73
PP4	7.99	7.75	7.50	7.79	8.82	8.30	8.09	9.54	8.34	8.84	8.30

Table E.4: Difference between average waiting time at Terminal 2 for all scheduling methods compared to FCFS

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total average**
FJF	-2%	0%	14%	25%	-6%	35%	3%	2%	0%	31%	10%
PP1	-1%	-5%	5%	1%	-4%	12%	-14%	3%	-16%	11%	-1%
PP2	-8%	-8%	11%	0%	0%	2%	-10%	-1%	-15%	11%	-2%
PP3	-9%	-8%	10%	0%	-1%	0%	-13%	-3%	-13%	10%	-3%
PP4	-19%	0%	-9%	-13%	-6%	-7%	-14%	-3%	-16%	12%	-8%

Table E.5: Average waiting time at Terminal 3

	Original	1	2	3	4	5	6	7	8	9	Total average
FCFS	3.60	3.77	4.05	3.76	3.44	3.79	3.81	3.75	3.90	3.55	3.74
FJF	3.41	3.51	4.03	3.60	3.62	3.91	3.74	3.69	3.67	3.55	3.67
PP1	3.48	3.63	3.95	3.58	3.49	3.68	3.80	3.68	3.76	3.55	3.66
PP2	3.61	3.87	4.16	3.79	3.64	3.88	3.84	3.85	3.84	3.60	3.81
LVF1	3.61	3.65	4.04	3.81	3.42	3.80	3.81	3.76	3.91	3.53	3.73
LVF2	3.53	3.65	4.04	3.81	3.42	3.80	3.81	3.76	3.91	3.45	3.72
VP1	3.62	3.75	4.12	4.01	3.54	4.07	3.89	3.99	4.08	3.79	3.89
VP2	3.48	3.58	3.91	3.74	3.53	3.83	3.79	3.77	3.86	3.50	3.70

Table E.6: Difference between average waiting time at Terminal 3 for all scheduling methods compared to FCFS

	Original	1	2	3	4	5	6	7	8	9	Total average
FJF	-5%	-7%	0%	-4%	5%	3%	-2%	-2%	-6%	0%	-2%
PP1	-3%	-4%	-2%	-5%	1%	-3%	0%	-2%	-4%	0%	-2%
PP2	0%	3%	3%	1%	6%	2%	1%	3%	-2%	1%	2%
LVF1	0%	-3%	0%	1%	-1%	0%	0%	0%	0%	-1%	0%
LVF2	-2%	-3%	0%	1%	-1%	0%	0%	0%	0%	-3%	-1%
VP1	1%	-1%	2%	7%	3%	8%	2%	6%	5%	7%	4%
VP2	-3%	-5%	-3%	0%	2%	1%	-1%	0%	-1%	-1%	-1%

Table E.7: Average waiting time at Terminal 4

	Original	1	2	3	4	5	6	7	8	9	Total average
FCFS	1.94	1.97	2.00	2.12	1.89	2.18	1.93	2.03	2.08	2.00	2.01
FJF	2.05	1.93	1.98	2.06	1.99	2.38	2.19	2.16	2.01	2.11	2.08
PP	2.01	2.04	2.02	2.10	1.92	2.01	1.93	2.09	2.02	2.14	2.03
LVF	1.92	1.95	1.99	2.10	1.86	2.07	1.91	1.93	2.14	1.97	1.98
VP1	2.05	2.05	1.96	2.20	1.95	2.12	2.02	2.01	2.16	2.16	2.07
VP2	2.14	2.16	2.06	2.24	2.06	2.31	2.14	2.07	2.22	2.21	2.16

Table E.8: Difference between average waiting time at Terminal 4 for all scheduling methods compared to FCFS

	Original	1	2	3	4	5	6	7	8	9	Total average
FJF	6%	-2%	-1%	-3%	5%	9%	13%	7%	-3%	5%	4%
PP	4%	3%	1%	-1%	2%	-8%	0%	3%	-3%	7%	1%
LVF	-1%	-1%	0%	-1%	-1%	-5%	-1%	-5%	3%	-1%	-1%
VP1	6%	4%	-2%	4%	3%	-3%	5%	-1%	4%	8%	3%
VP2	11%	10%	3%	6%	9%	6%	11%	2%	6%	11%	7%

Table E.9: Average waiting time at Terminal 5

	Original	1	2	3	4	5	6	7	8	9	Total average
FCFS	5.06	5.12	4.93	5.01	5.05	5.27	5.01	4.90	5.04	5.10	5.05
FJF	5.29	5.31	5.45	5.31	5.23	5.45	5.24	5.13	5.26	5.30	5.30
PP1	5.24	5.15	5.01	4.87	5.01	5.45	5.00	5.00	5.36	5.08	5.12
PP2	5.12	5.12	5.07	4.86	4.91	5.17	5.03	4.86	5.09	5.02	5.03
LVF	5.14	5.13	5.00	4.98	5.16	5.37	5.06	5.00	5.14	5.16	5.11
VP1	5.22	5.19	5.07	5.02	5.26	5.43	5.16	5.00	5.25	5.25	5.18
VP2	5.15	5.15	5.00	5.00	5.16	5.39	5.11	4.98	5.21	5.21	5.14

Table E.10: Difference between average waiting time at Terminal 5 for all scheduling methods compared to FCFS

	Original	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total average**
FJF	4%	4%	11%	6%	4%	4%	5%	5%	4%	4%	5%
PP1	3%	1%	2%	-3%	-1%	4%	0%	2%	6%	0%	1%
PP2	1%	0%	3%	-3%	-3%	-2%	0%	-1%	1%	-2%	0%
LVF	2%	0%	1%	-1%	2%	2%	1%	2%	2%	1%	1%
VP1	3%	1%	3%	0%	4%	3%	3%	2%	4%	3%	3%
VP2	2%	1%	2%	0%	2%	2%	2%	2%	3%	2%	2%

F

Results: Average waiting time per priority group

Table F.1: Average waiting time at Terminal 1 per loading time category for the original dataset

Loading time	Number of vessel	**FCFS**	**FJF**
0 - 4	92	0.04	0.01
4 - 6	564	0.82	0.40
6 - 8	993	0.88	0.55
8 - 10	1116	1.21	0.75
10 - 12	994	1.23	0.89
12 - 14	692	1.53	1.47
14 - 16	366	1.23	2.02
16 - 18	162	3.01	3.73
18 - 20	109	3.43	4.17
20 - 22	69	10.62	5.55
22 - 24	85	8.1 8	4.99
24 - more	650	7.80	9.06
All	5892	2.17	2.04

Table F.2: Average waiting time at Terminal 1 per vessel type under VP1

Priority	**Number of vessels**	**FCFS**	**VP1**
1	87	16.60	13.26
2	716	6.35	8.00
3	135	1.29	0.72
4	4954	1.34	1.12
All	5892	2.17	2.13

Table F.3: Average waiting time at Terminal 1 per vessel type under VP2

Priority	**Number of vessels**	**FCFS**	**VP2**
1	87	16.60	13.26
2	716	6.35	7.94
3	135	1.29	0.73
4	2024	0.71	0.31
5	2929	1.77	1.92
All	5891	2.17	2.24

Table F.4: Average waiting time at Terminal 1 per vessel type under VP3

Priority	**Number of vessels**	**FCFS**	**VP3**
3	54	17.48	13.63
5	33	15.15	12.00
6	201	6.62	7.16
7	650	5.22	7.56
15	4953	1.34	1.17
All	5891	2.17	2.25

Table F.5: Average waiting time at Terminal 1 per vessel product priority

Priority	**Number of vessels**	**FCFS**	**PP**
1	83	7.87	5.34
2	5808	2.09	2.23
All	5891	2.17	2.27

Table F.6: Average waiting time at Terminal 2 per loading time category for the original dataset

Loading time	Number of vessel	**FCFS**	**FJF**
0-24	6.84	5.52	
24-28	6.94	5.61	
28-32	9.02	6.77	
32-36	16.84	13.19	
36-40	6.99	6.56	
40-44	7.38	5.95	
44-48	12.48	14.81	
48-52	4.78	6.44	
52-56	11.96	13.25	
56-60	3.61	4.26	
60-64	10.91	14.82	
64-68	9.51	9.22	
68-72	4.79	5.86	
72-76	21.61	16.72	
76-80	18.35	10.15	
80 - more	11.46	13.81	
All	9.82	9.63	

Table F.7: Average waiting time at Terminal 2 per vessel product priority under PP4

Priority	**Number of vessels**	**FCFS**	**PP4**
1	156	25.92	14.51
2	190	11.08	10.01
3	90	8.53	7.02
4	66	7.09	5.11
5	209	5.28	7.83
6	88	0.93	1.36
7	77	0.48	1.38
All	876	9.82	7.99

Table F.8: Average waiting time at Terminal 3 per vessel product priority

Priority	Number of vessels	FCFS	PP1
1	404	2.85	2.06
2	302	6.59	6.57
3	324	1.74	2.36
All	1030	3.60	3.48

Table F.9: Average waiting time at Terminal 4 per vessel type under LVF

Priority	Number of vessels	FCFS	LVF
1	511	4.99	4.83
2	1163	0.60	0.64
All	1674	1.94	1.92

G

Results: Maximum waiting time

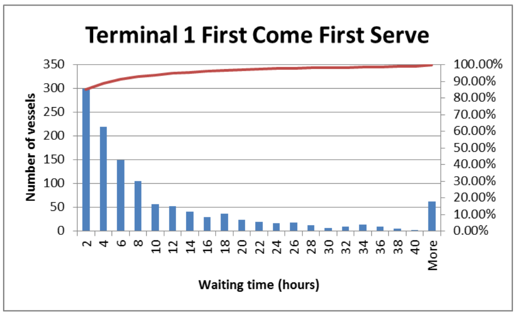

Figure G.1: Number of vessel waiting for Terminal 1 under FCFS

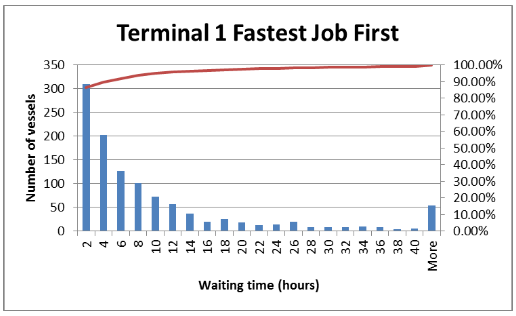

Figure G.2: Number of vessel waiting for Terminal 1 under FJF

Table G.1: Maximum waiting time for Terminal 1 under FCFS and FJF

	FCFS	FJF	Difference [%]
Original	129	322	150%
1	90	257	186%
2	121	215	78%
3	119	250	110%
4	118	229	94%
5	99	202	104%
6	142	238	68%
7	148	151	2%
8	117	198	69%
9	103	173	68%
Average	118.60	223.50	93%
lower bound	107.33	193.73	62%
upper bound	129.87	253.27	124%

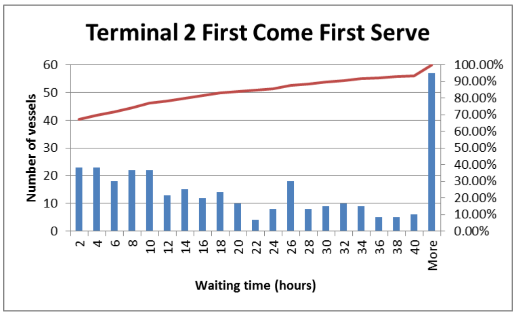

Figure G.3: Number of vessel waiting for Terminal 2 under FCFS

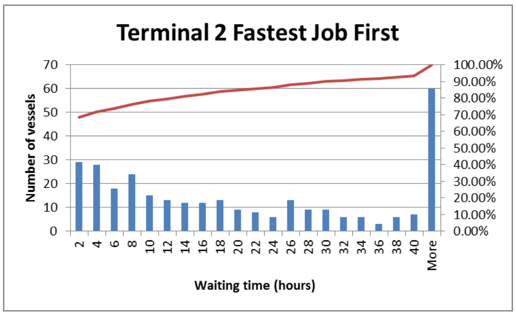

Figure G.4: Number of vessel waiting for Terminal 2 under FJF

Table G.2: Maximum waiting time for Terminal 2 under FCFS and FJF

	FCFS	FJF	Difference [%]
Original	254	416	64%
1	113	250	121%
2	198	584	195%
3	251	949	278%
4	250	376	50%
5	125	921	637%
6	146	350	140%
7	254	425	67%
8	258	483	87%
9	136	549	304%
Average	198.50	530.30	194%
lower bound	160.13	385.32	83%
upper bound	236.87	675.28	305%

H

Results: Average waiting time/Berth occupancy with varying berth time

Table H.1: Average waiting time at Terminal 1, varying loading time

	a	**b**	**O**	**c**	**d**
FCFS	0.26	0.81	2.17	4.92	12.63
FJF	0.26	0.80	2.04	4.57	11.79
PP1	0.27	0.82	2.24	5.18	12.57
VP1	0.26	0.83	2.09	5.05	12.83
VP2	0.27	0.84	2.21	6.02	42.80
VP3	0.26	0.85	2.22	5.37	13.96

Table H.2: Difference between average waiting time at Terminal 1 for all scheduling methods compared to FCFS, varying loading time

	a	**b**	**O**	**c**	**d**
FJF	0%	-1%	-6%	-7%	-7%
PP1	1%	2%	3%	5%	0%
VP1	-1%	2%	-3%	3%	2%
VP2	1%	4%	2%	23%	239%
VP3	-1%	6%	9%	17%	10%

Table H.3: Average berth occupancy at Terminal 1, varying loading time

	a	**b**	**Original**	**c**	**d**
FCFS	22.60%	33.90%	45.20%	56.50%	67.80%
FJF	22.60%	33.90%	45.20%	56.50%	66.79%
PP1	22.60%	33.90%	45.20%	56.50%	67.80%
VP1	22.60%	33.90%	45.20%	56.50%	67.80%
VP2	22.60%	33.90%	45.20%	56.50%	67.59%
VP3	22.60%	33.90%	45.20%	56.50%	67.80%

Table H.4: Average waiting time at Terminal 2, varying loading time

	a	**b**	**O**	**c**	**d**
FCFS	1.35	4.42	9.82	28.13	154.69
FJF	1.38	4.42	9.63	29.70	74.89
PP1	1.31	3.36	9.69	31.93	161.48
PP2	1.31	3.33	9.04	26.68	158.33
PP3	1.31	3.29	8.95	24.68	158.38
PP4	1.31	4.35	7.99	24.13	128.84

Table H.5: Difference between average waiting time at Terminal 2 for all scheduling methods compared to FCFS, varying loading time

	a	**b**	**O**	**c**	**d**
FJF	3%	0%	-2%	6%	-52%
PP1	-2%	-24%	-1%	14%	4%
PP2	-2%	-25%	-8%	-5%	2%
PP3	-2%	-26%	-9%	-12%	2%
PP4	-2%	-2%	-19%	-14%	-17%

Table H.6: Average berth occupancy at Terminal 2, varying loading time

	a	**b**	**Original**	**c**	**d**
FCFS	34.31%	51.46%	68.62%	75.41%	89.91%
FJF	34.31%	51.46%	68.62%	75.41%	85.28%
PP1	34.31%	51.46%	68.62%	75.41%	88.30%
PP2	34.31%	51.46%	68.62%	75.41%	89.56%
PP3	34.31%	51.46%	68.62%	75.41%	89.56%
PP4	34.31%	51.46%	68.62%	75.41%	90.49%

Results: Average waiting time/Berth occupancy with varying number of vessels

Table I.1: Average waiting time at Terminal 1, varying number of vessels

	Original	k	l	m
FCFS	2.17	1.47	0.95	0.50
FJF	2.04	1.40	0.91	0.51
PP1	2.24	1.47	0.95	0.50
VP1	2.09	1.49	1.00	0.50
VP2	2.21	1.51	1.01	0.51
VP3	2.22	1.56	1.04	0.51

Table I.2: Difference between average waiting time at Terminal 1 for all scheduling methods compared to FCFS, varying number of vessels

	Original	k	l	m
FJF	-6%	-5%	-5%	1%
PP1	3%	0%	0%	0%
VP1	-3%	2%	5%	0%
VP2	2%	3%	6%	1%
VP3	9%	12%	14%	0%

Table I.3: Average waiting time at Terminal 2, varying number of vessels

	Original	k	l	m
FCFS	9.82	8.72	5.36	4.52
FJF	9.63	9.41	5.31	4.51
PP1	9.69	8.07	5.45	4.48
PP2	9.04	8.75	5.61	4.72
PP3	8.95	8.66	5.61	4.72
PP4	7.99	8.78	5.07	4.47

Table I.4: Difference between average waiting time at Terminal 2 for all scheduling methods compared to FCFS, varying number of vessels

	Original	k	l	m
FJF	-2%	8%	-1%	0%
PP1	-1%	-7%	2%	-1%
PP2	-8%	0%	5%	4%
PP3	-9%	-1%	5%	4%
PP4	-19%	1%	-5%	-1%

Table I.5: Average berth occupancy at Terminal 1, varying number of vessels

	Original	k	l	m
Berth occupancy	45.20%	40.53%	36.15%	31.14%
Difference		-10%	-20%	-31%

Table I.6: Average berth occupancy at Terminal 2, varying number of vessels

	Original	k	l	m
Berth occupancy	68.62%	62.80%	56.60%	48.66%
Difference		-8%	-18%	-29%

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