Reducing container barge in-port times

A Simulation Study

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TU Delft Delft University of Technology

Challenge the future

Reducing container barge in-port times

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by

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Preface

It's been a long, but rewarding, 9 months. Throughout the writing of this thesis, I've learnt a lot about barges, terminals, and shipping lines; global trade, simulation, and structuring a research project. However, my most valuable learnings have been about myself in a project management setting: I'm an optimistic planner, I like digging into numbers more than writing reports, and I enjoy discussing my findings with peers.

None of this would've been possible without the guidance of my supervisory committee. Iulia, Alexander and Bart, thanks so much for guiding me towards the result that is in front of you. Iulia, you really helped me improve my reporting, by being critical and helping me to go the extra mile to clarify my thoughts. Alexander, talks with you were always inspiring, and with hindsight I'm amazed at how you first mentioned techniques or experiments back in March, which I only started implementing in September. Bart, my apologies for frequently calling you outside office hours, whether it be for questions about the barging sector, how to structure my thinking, or what aspects were important for the model. All three of you contributed massively, for which I am grateful.

Tim and Jan, over the past few months your help has been invaluable. I really appreciate how the pair of you - and ORTEC - were so easygoing with regard to the direction of this thesis. I didn't experience any issues combining ORTEC's wishes with those of my university, for which I had been warned by many students. I also enjoyed our drinks at the ORTap, and am glad that many more of those are to come.

I'd like to express my thanks to various individuals, who were so kind to let me interview them, and call them afterwards if I had forgotten anything. In no particular order, thanks to Rene, Sander, Henk, Aranka, Maira, Frank, and Michel. If I've forgotten anyone, I'll blame that on my optimistic planning.

I'd like to thank my friends, for accepting the fact that I've become a fan of container barges, and am now quite proficient at finding ways of bringing it up in any conversation. Of course, talks with many of you also helped shape this thesis.

Finally, I'd like to thank my family, for their trust that this day would finally come, for their comments on my thesis, and for all the support throughout all these unpaid years of my life. You're the best!

Tom van Es

Summary

Global containerised cargo volumes are increasing at a high rate, requiring ports to increase their throughput. Containers are transported to the hinterland by truck, train, or barge. In the ports of Rotterdam and Antwerp, container barges have high in-port times, of which they spend a lot of time ineffectively. This affects these ports' connectivity with the hinterland.

The goal of this research, therefore, is to identify the main causes for, and most promising measures against, high barge in-port times. These causes and measures were gathered by desk research, using scientific literature, technical reports, and interviews with stakeholders. In order to asses the importance of different causes and compare different measures, a simulation model was built, based on Rotterdam. Because there are many deep-sea terminals and barges that each make their own planning, and many aspects of the in-port operations are subject to stochastics, Simio was used to make an agent-based simulation model.

Although many factors contributing to high in-port times were found in the literature, the majority of them contribute to two overarching causes: there is insufficient barge handling capacity at deep-sea terminals, and coordination problems result in inefficient utilisation of the available capacity. Therefore, many measures that are suggested in the literature aim to mitigate the negative effects of the two main causes.

The current state of the system was replicated in the model, in order to understand the response of in-port times to various system changes. Five categories of experiments were designed, and summarised in the experimental plan in Table 5.3. Experiments evaluated changes to terminals' barge handling capacity by increasing the capacity, or by changing how current capacity is distributed over time. The number of calls barges make on average was changed. Additionally, the effects of market mechanics on the in-port times of barges with different levels of willingness-to-pay were assessed, by auctioning timeslots or allowing barges to submit priority requests. Finally, increased information sharing and instantaneous reservations were implemented as an experiment. The average barge in-port time distribution for scenarios from the experimental plan are plotted in Figure 1.

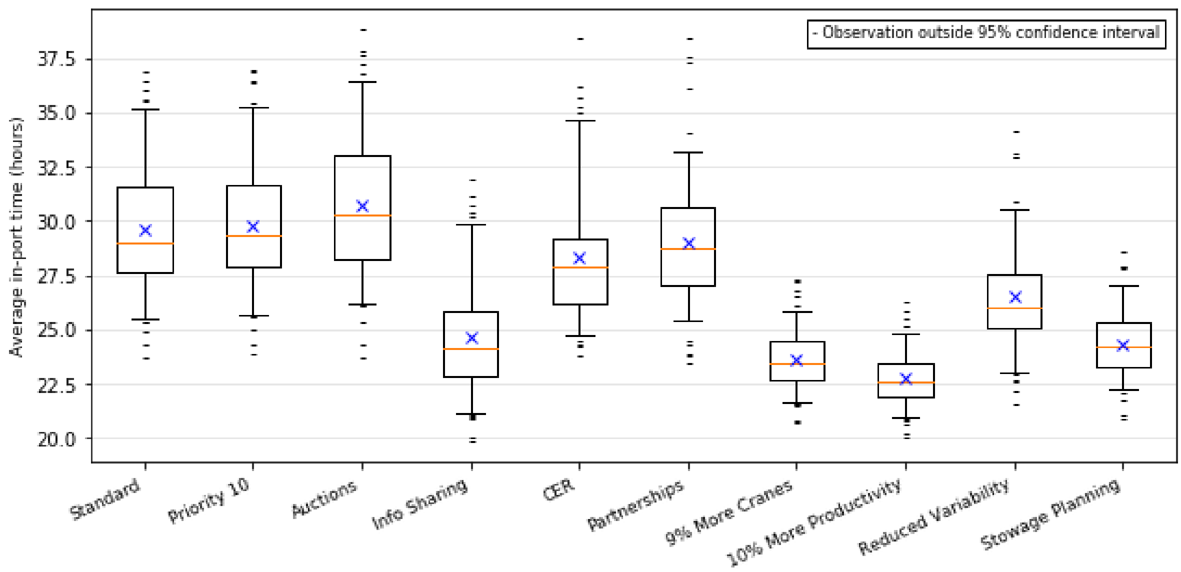

Figure 1: Average in-port times across multiple scenarios

The experiments showed that barge in-port times are very sensitive to changes in barge handling capacity: a 5% increase in capacity results in a 15% reduction of in-port times. Changes to the planning and reservation procedures yielded a 17% reduction of in-port times, by improving the rotation planning process for barges significantly. Thereby, the two overarching causes for high barge in-port times were validated by the model.

As the planning procedures and the barge handling capacity at terminals are both decided by the terminals, terminals have the ability to improve barge in-port times the most effectively. Apart from increasing capacity or changing the planning procedures, changes to the distribution of barge handling capacity can reduce in-port times at no increase in total handling capacity. As barges and deep-sea vessels compete for the same cranes and quay wall, improving the efficiency of deep-sea (un)loading will increase the available barge handling capacity, assuming total capacity is unchanged. Terminals can implement variable pricing for deep-sea vessels, to incentivise deep-sea vessels to improve their stowage planning.

Changes to barge operations only had limited effects, as denoted by the modest reduction in in-port times that is caused by partnerships or use of the Container Exchange Route. Barge operators can influence in-port times of specific barges by increasing their call sizes and reducing the number of calls.

Auctioning off all timeslots increased average in-port times by 7%. The distribution of in-port times as a function of barges' willingness-to-pay showed that the expected in-port time of a barge deviated 19.7 hours between a barge with maximum and minimum willingness-to-pay. The in-port times were found to be quite unreliable, limiting market feasibility.

Priority requests showed more promising results. When 10% of barges submit priority requests, average in-port times did not change. The in-port times of the barges that submit priority requests was reduced by 26%, while the in-port times of barges that submit normal requests increased by 3%. The in-port times of priority barges were fairly reliable. Combined with the unchanged average in-port times, this concept seems more feasible for implementation in the market.

Contents

Glossary

ABS Agent-Based Simulation.

BAP Berth Allocation Problem.

BPM Barge Performance Monitor.

BRPP Barge Rotation Planning Problem.

CER Container Exchange Route.

DES Discrete Event Simulation.

HLH Hamburg - Le Havre.

IWW Inland Waterway.

PORA Port of Rotterdam Authority.

QCAP Quay Crane Allocation Problem.

TEU Twenty-foot Equivalent Unit.

WTP Willingness to Pay.

1 Introduction: Container Barge In-port Times

The effects of global trade are ubiquitous: your iPhone was assembled in China, your sneakers were made in Vietnam, most medicine is manufactured in the USA. If you want to buy strawberries, it doesn't matter whether it's Januari or July. AliExpress ships countless items to Europe for free. All this has been made possible by low transportation prices.

Maritime transport has an important position in global trade, with a share of over 80% of global trade volume [1]. Since its invention in 1956, the standardised shipping container has been instrumental in bringing down costs of transport, and unlocking the potential for global supply chains [2]. Global containerised trade volumes grew from 45 million Twenty-foot Equivalent Unit (TEU) to 160 million TEU between 1996 and 2018 [3]. This is a growth of 255%, which translates to an average compound annual growth rate of 5.9%. In 2017, containerised trade volume increased by 6.4%, making it the fastest growing segment amongst liquid bulk, dry bulk, and general cargo.

Rotterdam is Europe's largest container port. In 2018, 8.635 million containers, or 14.5 million TEU, were transshipped in the port of Rotterdam [4]. As approximately 30% of the total throughput is transshipped onto other seaborne ships, 70% is destined to or originates from the hinterland. This can be done through truck, train or barge, and their shares are called the *modal split*. The last available data regarding the modal split of containers is from 2016, when 36% of containers to and from the hinterland was transported by barge [5]. Because transportation by barge is more sustainable than transport by truck, and to reduce congestion on roads around Rotterdam, the government is trying to instigate a modal shift, where more containers are shipped to and from the hinterland by barge and rail, as opposed to truck. Recently, however, barges have been spending a lot of time in-port, which is reducing the service level and the capacity of hinterland transport by barge.

First, section 1.1 will expand upon the issue of high barge in-port times. Then, section 1.2 will explain the goal of this research, and place this research in the context of other literature. The goal will lead to several research questions, which are presented in section 1.3. Section 1.4 will shortly expand on the scope of this research. The methods that will be used in this thesis are discussed in section 1.5. Finally, section 1.6 will combine the research goals and questions with the instruments, and visually present the approach of this research.

1.1. Problem Statement: High Barge In-port Times

In the 2017 Annual Report by the Port of Rotterdam Authority (PORA), the "congestion in and around the port of Rotterdam' was named as one of the top risks [6]. In the same year, "various inland shipping and transport organisations in the Netherlands and abroad expressed their concerns about what they see as overly long waiting times" in the Port of Rotterdam [7]. Congestion results in less efficient use of the limited infrastructure and resources. The Port of Rotterdam has developed a "Barge Performance Monitor", to clearly present a series of key performance indicators for hinterland container transport by barge [8]. In the 10 weeks prior to 27/2/2019, an average container barge sailing the Rhine spent approximately 53 hours in port. When looking at all types of container barges in April 2017, the average in-port time was approximately 36 hours [9]. Even in 2008, when in-port times were much lower, they took up a large share of barges' time. On a trip from Rotterdam to Wörth, which is about 650 kilometres, a barge would spend approximately 44% of its time in the port of Rotterdam, 43% sailing, and the remaining 13% visiting inland terminals [10]. Barge operators Contargo and BTB have been charging customers a "Barge congestion surcharge", as a result of the high barge in-port times [11]. A reduction in barge in-port times can lead to lower transportation times, and the possibility of more barge round trips, which can lead to lower transportation costs.

The PORA has formed a working group to study and alleviate the causes for high barge in-port times. Maritime congestion is detrimental to a ports' connectivity, reducing the competitiveness of the port. Congestion also increases the amount of emissions in ports [12]. Antwerp is close to Rotterdam, and can also handle large container vessels. Therefore, the PORA wants to reduce the time barges spend in the port, in order to avoid losing their place in container liner schedules to Antwerp.

Although the in-port times are already a large problem, the demand for hinterland transport by barge is expected to increase. Of all types of cargo that can be shipped to the European hinterland by IWW, containers are expected to grow the fastest [13]. Spurred by sustainability goals and congestion on road networks around the port of Rotterdam, the PORA has started adding modal split obligations to their terminal concession contracts, forcing deep-sea terminals to make use of rail and barge for hinterland transportation [14]. Therefore, the causes for the high barge in-port times must be understood, and measures to alleviate the congestion should be implemented.

1.2. Research Objective

The objective of this research is twofold. First, a better understanding of the causes for high barge in-port times will be gained. Second, several measures to reduce the barge in-port time will be evaluated. A model of the port area will be used to research the relationships between input parameters and barge in-port times, and evaluate the effects of several innovative concepts.

Some studies, notably those by Albert Douma in his PhD thesis, have recognised the problem of high barge in-port times, and researched some solutions to improve the performance of what they call the 'Barge Handling Problem' [15]. Others have looked at the opportunities for coordination [16], or new logistics concepts like the 'extended gate' concept, in order to reduce barge in-port times [17]. The existing literature points at increasing throughput numbers and insufficient terminal handling capacity as causes for high barge in-port times.

To the author's knowledge, no other scientific studies have taken such a holistic view to research the causes of high container barge in-port times. Additionally, as will be discussed in chapter 5, some experiments are based on novel pricing schemes. The novelty of this research lies there: a more complete view with regard to causes and measures, and the evaluation of innovative pricing schemes.

1.3. Research Questions

To ensure that the research goal is met, and to provide structure to the process, several research questions were drafted. A simulation model must be made. Therefore, an in-depth understanding of the operations is required. The simulation model can be used to verify causes for high barge in-port times, as suggested by the literature and industry experts. Then, several in-port time reduction measures can be tested.

These factors are combined to reach the following research question:

What causes for high barge in-port times are there, and how can the barge in-port times be reduced?

This research question can be divided in several subquestions:

SQ1: How is the market for maritime freight transportation currently structured, and how do actors operate?

SQ2: What causes high barge in-port times?

SQ3: What measures can be taken to reduce barge in-port times?

SQ4: How should the system be modelled, i) conceptually, and ii) specified in a simulation software package?

SQ5: How well do the measures reduce the in-port times?

If the subquestions are answered, an answer to the research question logically stems from these answers.

1.4. Research Scope

The focus of this research is reducing the time container barges spend in-port. While maritime congestion affects vessels that transport all kinds of cargo, the problem is more pronounced in container barges, as they have to visit many terminals per port visit. Therefore, this research focuses on container transport.
Deep-sea ships and barges visit the same terminals, and as such the operations of deep-sea ships influence the in-port time of barges. When barges are in port, they visit terminals in order to offload and load containers. Clearly, the barges and terminals are in scope. As barges also visit empty depots, they are included as well. Terminal operations consist of loading and unloading ships at the seaside, storing containers in the container yard temporarily, and facilitating container pickup and drop off by truck and train. Naturally, the operations of barge operators will be scrutinised. The way they load containers directly influences whether or not there is a clear precedence relation between the terminals in their rotations. Due to integration of inland terminals and barge operators, in the literature, the effect of inland terminals is often discussed. For instance, partnerships between inland terminals could lead to larger call sizes, or number of (off)loaded containers per terminal. However, as their effects are generally from their function as a barge operator, we will categorise these 'inland terminal effects' under barge operators.
Both import and export flows are in scope of this thesis, as both types are handled in Rotterdam concurrently. While there are differences between the two flows, such as average value of the transported goods and share of containers that is empty, most characteristics of the flows are assumed to be largely similar. Therefore, no distinction between import and export flows will be made in the remainder of this thesis, except for certain sections where this is deemed relevant.
The scope of this research is depicted in Figure 1.1.

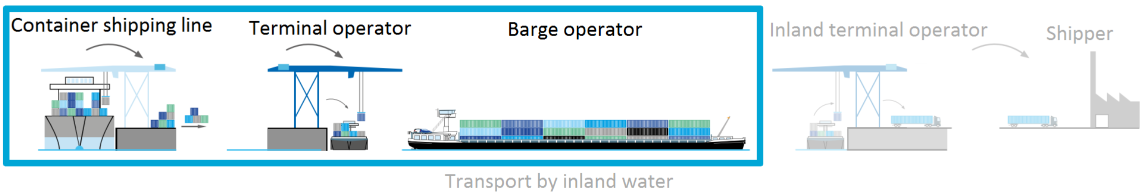

Figure 1.1: Physical freight transportation flow with scope, adapted from de Jong [9]

Because of the geographical differences between the hinterlands of ports in the Hamburg - Le Havre range, and worldwide, the modal split share for barges varies greatly [18]. In most ports, barges have a share of under 15% of hinterland transport. As a result, high barge in-port times are only an issue in Antwerp and Rotterdam. This study focuses on Rotterdam, but the author expects that most lessons are transferable to Antwerp.

1.5. Research Instruments

Different methods are suitable to help answer the research questions. Here, they will briefly be discussed. First, a good understanding of inland shipping by container barge was required. A combination of scientific literature, newspaper articles, reports, and interviews with stakeholders and experts all contribute to reaching an understanding of how the system functions, how big an impact the barge congestion has, and what the important constraints of each actor are. Subsequently, the focus shifts to causes and solutions for barge congestion. These are drawn from scientific literature, reports, and interviews.

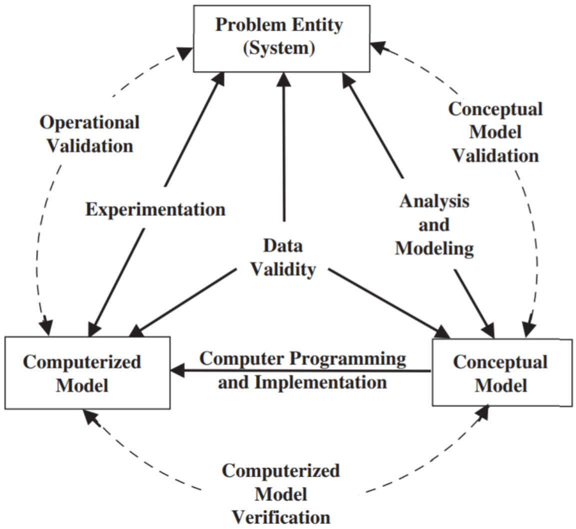

Figure 1.2: Model Development Process, from Sargent [25]

Scientific literature on the subject of container barging, terminals, and shipping is widely available, but information that is relevant to container barging in Rotterdam had to be extracted through interviews with a terminal operator [19], barge operators ([20] and [21]), the PORA [22], and sector representatives [23]. These interviews consisted of an introduction to the operations of the company that interviewee represented, followed by the interviewees' views on high barge in-port time causes and measures, and in some cases finalised with gathering of data specifically for the simulation model. In all cases, the interview was followed up by phone calls and email correspondence, in order to gather any data that may have been overlooked in previous meetings. This was compounded by sector knowledge that was gained in progress meetings with this thesis' supervisory committee.
Subquestion 4 relates to how to model the system. The high barge in-port time will be studied with a Discrete Event Simulation (DES) model. DES is used to model systems that can be described as variations of 'source-server-sink' models, such as queuing systems. In DES, the state of a system is changed at discrete points in time, rather than continuously [24]. As an example that is related to container barging, the travelling of a barge between terminals is not expressed as a continuous process, but as a process that starts at a discrete time, and ends at a discrete time. The barge's location will not be updated in the meantime. This makes DES computationally more efficient - and partly because of this, much more widespread - than the continuous simulation paradigm. DES is an excellent tool to study the effects of stochastics. Examples of stochastics for our system are:

- The number of barges that arrives in the port per day
- The number of terminals each barge has to visit
- The number of containers the barge wants to (off)load at each terminal

A more detailed description of the simulation model is found in chapter 4. The model requires will require a wide array of input parameters. These will be based on a combination of parameters from the literature, data from government organisations, interviews, and expert judgement. The model will be used to test several hypotheses with respect to the congestion causes, and evaluate the effects of measures.

1.6. Research Approach

This chapter provided an introduction to hinterland transport by inland waterways, the problem of high barge in-port times was discussed, and the structure of this research was outlined. In Figure 1.3, the research instruments, questions and goals are presented to illustrate their relation to one another. The research instruments are depicted in blue, on the left; the research questions are in white, in the middle; the intermediate goals can be found in green, on the right.

In some respects, the research structure reflects the ”Model Development Process”, as proposed by Sargent [25]. When the development process from Figure 1.2 is compared to the report structure, many similarities can be seen. Chapter 2 and the first three sections of chapter 4 focus on the ”Data Validity”, ”Analysis and Modelling”, and ”Conceptual Model Validation” steps, leading to the ”Conceptual Model”. Then, the fourth and fifth sections of chapter 4 add to ”Data Validity”, and reports on ”Computer Programming and Implementation”. This leads to the ”Computerised Model”, which is verified and validated in section 4.8. Finally, the computerised model is combined with insights from chapter 3, which leads to the Experiments and results as reported in chapter 5.

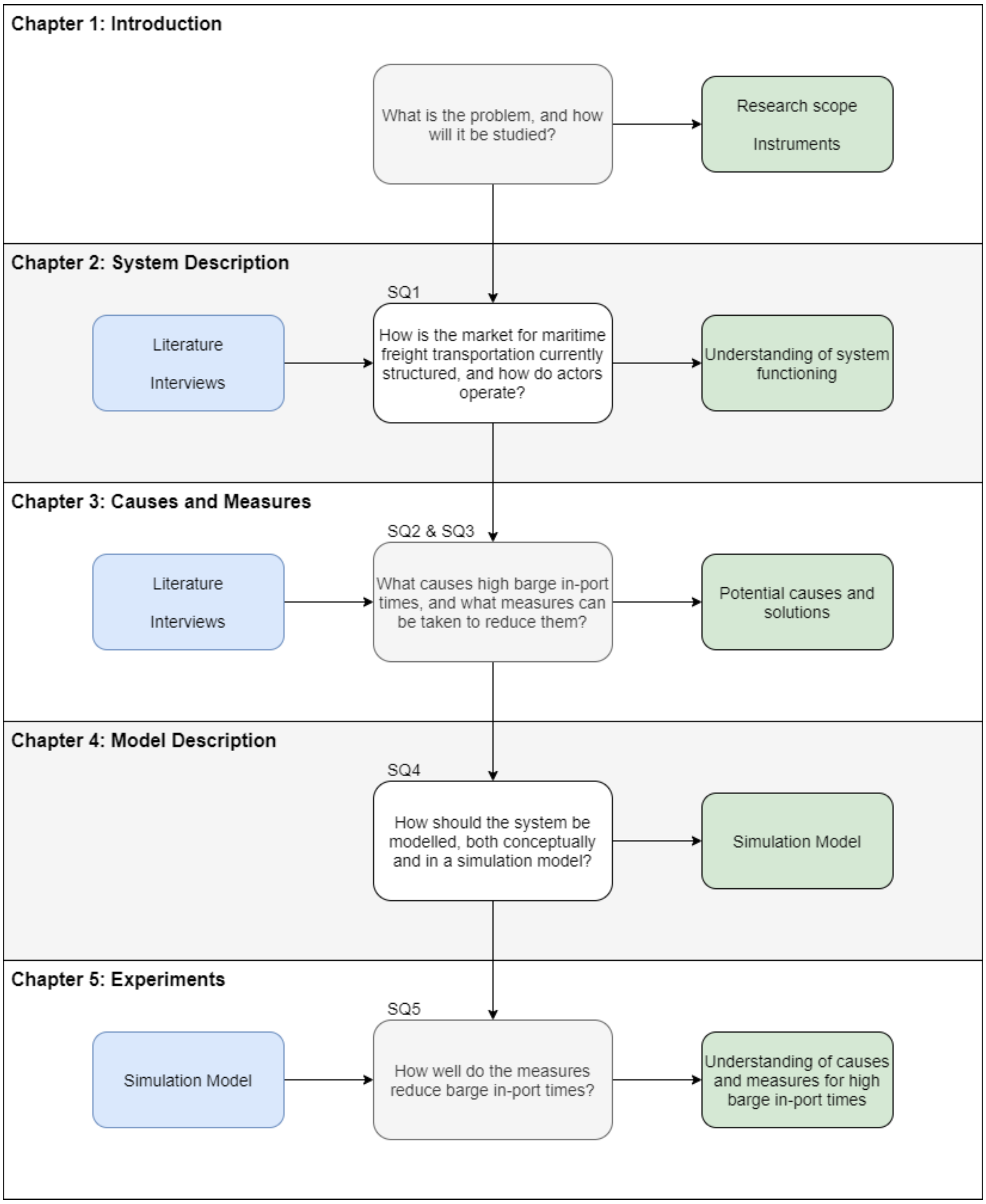

Figure 1.3: Research Structure, relating instruments (blue), subquestions (white) and intermediate goals (green)

2

System Description: Hinterland Container Transportation by Barge

This chapter aims to answer subquestion 2, and provides a starting point for answering subquestion 3. First, section 2.1 introduces the different actors in the process of hinterland shipping by container barge, along with a concise introduction to the operations along a containers journey during this process. From then on, a basic understanding of hinterland container shipping is assumed, and the three main actors will be discussed in more depth. First, hinterland container shipping by barges will be inspected in section 2.2. Second, transshipment at deep-sea terminals and empty depots is researched in section 2.3. Third, section 2.4 elaborates on deep-sea container shipping lines. All three of these sections are divided in sections on the market, resources, and operations.
The information in this chapter is based on literature, reports, and interviews. The literature and reports were used as primary sources; when information was not available using these sources, interviews were used.

2.1. Actor Analysis of Hinterland Container Transportation by Barge

This section will provide insight in the system of global container transport, of which Inland Waterway (IWW) transportation by barge is a part. It summarises the way actors operate. An understanding of how the actors operate improves understanding of the (power) relationship between these stakeholders. This section is based on the market analyses by Saeedi *et al.* [26], Notteboom and Konings [27], Notteboom and Rodrigue [28], Rodrigue *et al.* [29], and Midoro *et al.* [30].
A *carrier* performs the physical transportation of goods, whether it be by deep-sea ship, inland barge, truck or train. Examples of carriers are *shipping lines*, *barge operators* and *truck operators*. While shipments over a shorter distance are generally fulfilled by a single mode of transport, which is called unimodal transport, long distance shipping requires use of multiple modes. This is called multimodal transport, and this can be performed by different *carriers*. *Freight forwarders* arrange for end-to-end transport and the corresponding transshipment, providing *shippers* with a single point of contact. The *forwarder* contracts the *carriers* that fulfil the different parts of transportation. The aforementioned transshipment is performed by *terminal operators*.
Figure 2.2 gives an overview of the actors in the hinterland transportation system, and their contractual relations. Depending on whether or not the *shipper* makes use of a *freight forwarder*, a *shipper* has a contract with the *freight forwarder*, or with the *truck operator*, *barge operator* and *liner shipper*. Depending on whether it is an import or export flow, the container flow, as depicted by the bold line, is directed left to right or vice versa.
Through vertical integration, some of these actors are subsidiaries of the same companies [26] [30]. An example is Maersk, a company that provides long-haul shipping services with Maersk Line, short-haul shipping services with Sealand Maersk, transshipment services with APM Terminals, and freight forwarding with Damco [31]. When a shipping line arranges for the transport to and from the deep-sea

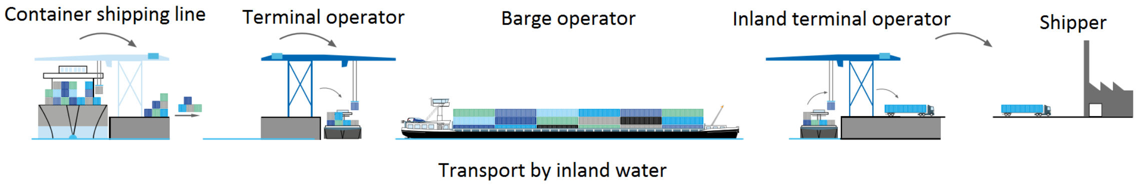

Figure 2.1: Physical freight transportation flow, from de Jong [9]

port, essentially fulfilling the task of a freight forwarder, the shipping is called *carrier haulage*. When a freight forwarder is used, it is called *merchant haulage*.
There are companies that provide complete logistics services, including services such as freight forwarding, customs clearance, tracking, and warehousing [32]. Such companies are called logistics service providers or third-party logistics companies. In the 1999 paper by Berglund *et al.* [33], such a company is defined as being responsible for 'management and execution of at least transportation and warehousing' on behalf of another party. Although these companies provide more services than freight forwarders, this distinction is not important in the remainder of this thesis, and the term freight forwarder will be used.

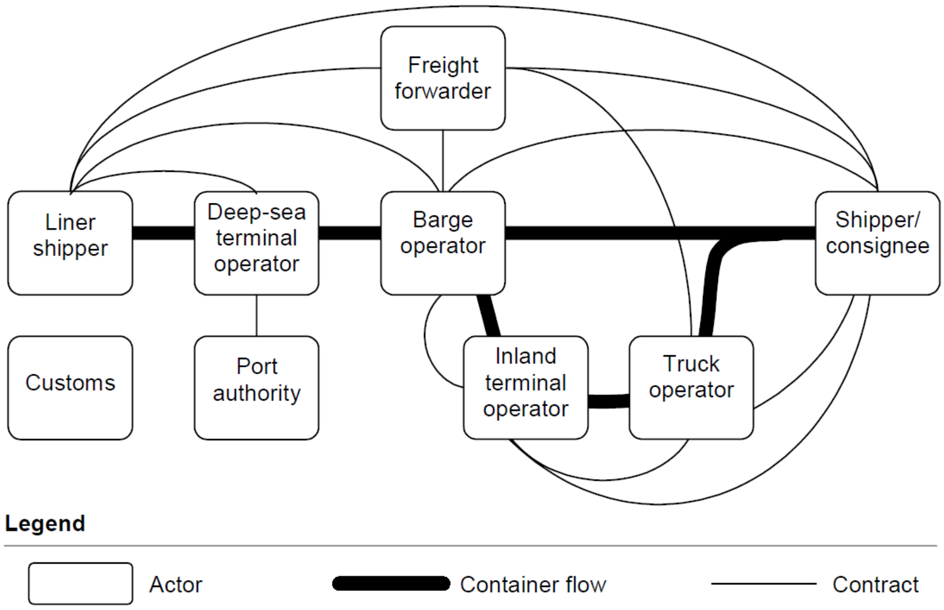

Figure 2.2: Actors in the hinterland freight transportation system by inland waterway, from Douma [15]

2.1.1. Functions in the Container Transportation System

The following paragraphs will provide a short introduction to the operations of barges, deep-sea terminals and deep-sea ships. Naturally, there are many variations in these operations, but this subsection is meant as a general introduction to the way these actors operate. These paragraphs will provide a basic understanding of how these actors *usually* operate.

Deep-sea Ships

Deep-sea ships perform long-haul transportation between deep-sea ports the world over. Shipping lines have many deep-sea ships, that they use on the routes they service. Deep-sea ships liners only visit a single terminal with each port call. They have containers for a wide variety of customers on board. Though deep-sea ships are frequently delayed, they get priority over any other ships [34].

Deep-sea Terminals
Terminals provide transshipment and storage services. They load and unload deep-sea ships, barges, trucks and in some cases trains. They temporarily store containers in the *yard*. Most terminals have dedicated cranes for handling barges and *feeder ships*. *Feeder ships*, also called short-sea ships, are between barges and deep-sea ships in size, and function as a connection in a hub-and-spoke network, to connect deep-sea hub locations to markets nearby. Terminals charge deep-sea vessels a fixed amount per moved container, or *move* in short. This price contains the handling fee related to hinterland transportation.

Barges
A container barge enters the port area loaded with export containers and empty containers. Geographically, most empty containers depots are situated further inland than the deep-sea terminals. As such, barges usually offload their empty containers first. This is also beneficial for the stability of barges. Second, they offload their filled containers at deep-sea terminals. Because they usually carry containers that will be transported to different locations by different deep-sea ships, they need to offload at different terminals. After offloading their export containers, they load import containers. Depending on where these import containers are destined, and how the containers are stacked on the barge, a certain order of visiting the terminals is required. The order in which barges visit the various terminals is called a *rotation*. In one such rotation, barges can visit up to 15 terminals [15].

Inland Terminals
Inland terminals have a similar function to deep-sea terminals, with a couple of notable differences. Inland terminals service the surrounding regional market. They are usually a lot smaller in size, compared to deep-sea terminals. Their opening hours are also more limited. Most commonly, the last or first mile is by truck. Because of the size difference between trucks on the one hand, and barge on the other hand, export goods are consolidated at these inland terminals, and import goods are unconsolidated [29]. Many companies that make use of IWWs are situated near the waterways, and many of these have their own quays. Many inland terminals are owned by barge operators, the remaining terminals are mostly owned by deep-sea terminal exploiters and dedicated inland terminal operators [27].

Shipper
The shipper's goods are transported, either between two of the shipper's locations, or to a customer, who is called a consignee. Generally, shippers decide what transportation option to choose based on transport speed, transport cost, and transport reliability [35].

2.2. Hinterland Container Shipping by Barges
This section focuses on hinterland transport by container barge. Other modalities are out of scope for this thesis. However, as container barges compete for transport orders with trains and trucks, an understanding of the differences between these modes can be helpful to understand the competitive position of barging. The reader is referred to Appendix C for more information on hinterland transport in general.

2.2.1. Market Size and Characteristics
In many countries, the share of transportation by IWW is negligible [18]. In fact, 99.8% of all European container transport by IWW, counted in ton km, is in just 4 countries: France, Belgium, Germany and the Netherlands [36]. This is largely down to the geography of these countries. The Netherlands has a dense network of waterways. The Rhine is the most important river, with the vast majority of border-crossing IWW transport making use of it [37]. Switzerland has a negligible share when it comes to ton km, because most goods are destined to Basel, which is located next to the border.
In the Netherlands, the market is fragmented, with many small operators that have just one vessel, and a small number of companies that operate multiple vessels [37]. Although the operators have come together in groups such as the "Centraal Bureau voor Rijn- en Binnenvaart" and the "Koninklijke BLN-Schuttevaer", their collective bargaining power is still fairly small, compared to deep-sea shipping lines [38]. The container barging sector "can be characterised as individualistic, where cooperation and coordination are not manifest" [16]. For instance, if a barge operator with one barge is contracted

to pick up 4 cargo's, of which one is delayed, it will have to wait for the last cargo to arrive, thereby delaying all the cargo. If a barge operator has multiple barges servicing this route, there are more options for managing the disruption.
For this research, it is important to categorise container flows into categories that capture their differences in handling in the Port of Rotterdam. The flows can therefore be segmented into four categories: transportation between Antwerp and Rotterdam, transportation between Rotterdam and the Rhine, domestic transportation, and inter-terminal transportation [23]. Due to the nature of inter-terminal transportation, information about these flows is available only at these barge operators and deep-sea terminals, as governmental organisations sort most of their data based on origin and destination. Although the author has tried, data was not clear enough to provide insight into this category. This leaves us with three distinct categories, for which data is available: domestic, Rhine, and Antwerp-Rotterdam. The paper by Konings *et al.* [10] reports volumes for 2010, but since then, volumes have grown from approximately 2.4 million TEU to over 4 million TEU. Therefore, more recent data was required.
Piecing together different data sources, the throughput figures for 2018 can be seen in Table 2.1. From left to right, data of the Centraal Bureau voor de Statistiek [39], Kuijpers [40], TU Delft, and Kennisinstituut voor Mobiliteitsbeleid [5] are given as references. The CBS data is the most recent, but is not specific for the port of Rotterdam, as it contains data on inland waterway container transport as a whole. The other 3 datasets focus on hinterland throughput volumes from Rotterdam. The TU Delft research throughput figures have been provided by LINc [23]. Combining these 4 datasets, and taking into account the total throughput increase in the port of Rotterdam, the throughput numbers for 2018 can be found in the final column. These values will be used in the remainder of this research. The yearly Rhine volumes were increased slightly when compared to the other data sources. This is to adjust for the fact that low water levels reduced Rhine throughput volumes heavily in the fall of 2018, and reach a daily throughput volume that is representative of the months where water levels allowed normal operations on the Rhine [36].

Table 2.1: Throughput per hinterland service area, in TEU per year

Area	CBS ('18)	EY-P ('16)	TUD ('15)	KIM ('16)	Thesis ('18)
Antwerp	800,000	560,000	500,000	N/A	700,000
Domestic	2,200,000	1,950,000	1,950,000	1,750,000	2,050,000
Rhine	1,250,000	1,080,000	1,080,000	1,250,000	1,400,000
Totals	4,400,000	3,980,000	3,600,000	3,000,000	4,150,000

There are differences between the long-distance trade over the Rhine, and the short-distance domestic flows. The barges sailing between Rotterdam and Antwerp have different characteristics to both those categories. Generally speaking, barges that service Antwerp are the largest, followed by Rhine vessels, who are in turn followed by domestic vessels [41]. The average number of terminals in a barge's rotation depends mostly on the hinterland area it services, the barge size, number of vessels in a barge operator's fleet [23]. Barges sailing between Antwerp and Rotterdam generally make the fewest stops, as they're frequently contracted by the large shipping lines to transfer containers from the shipping lines preferred terminal operator in one port to the preferred terminal operator in the other port. Rhine ships, especially those servicing the upper Rhine, have higher numbers of different customers, and are required to visit multiple terminals. Domestic ships, partially due to a higher share of smaller vessels, fall in the middle of these two categories.
On average, smaller barges have lower in-port times due to lower processing times at terminals and fewer terminal calls. The working principle behind the differences in vessel size seems to be the following: in principle, barge operators want to increase vessel sizes for economies of scale in operating costs. However, for the domestic market, the effects of increased in-port time and the cost reduction due to economies of scale, both caused by larger vessels, are balanced at a smaller vessel size than for Rhine vessels, as Rhine vessels sail further.

2.2.2. Resources: Barges and Waterways

The main resources in the IWW transportation system are the vessels and the infrastructure. The infrastructure consists of the waterways and locks. The Central Commission for Navigation on the

Table 2.2: Different container barge sizes in Rotterdam, provided by PoR [22]

Ship Length	Frequency (%)	Average Visits per day
<85 M	16	8
85 - 110 M	50	25
110 - 135 M	24	12
>135 M	10	5

Rhine, or CCNR, has limited the length of ”indivisible vessels” on the Rhine to 135 metres [42]. Some bridges also limit the height of vessels or their loads. While the IWW infrastructure influences the IWW vessel dimensions, the infrastructure itself is out of scope for this thesis. Container barges are constrained in their dimensions by the route they are designed to sail. Their maximum draught is determined by the water level and the river depth, their length and width are determined by what rivers they will sail and what locks they must cross, and how high they can stack is based on their stability and the bridge height on their routes.

On a yearly basis, the Port of Rotterdam is visited by 18,000 container barges [43]. The vessels used for IWW container transportation can be divided into two types: self-propelled barges and pushtows. Self-propelled vessels are far more common than pushtows, with 90% of inland container vessels in the port of Rotterdam being self-propelled [22]. The pushtows consist of up to 4 barges that are tied together, and pushed by a flat-nosed vessel called a pusher. The advantages of self-propelled barges are that they are not very expensive, quite sturdy, streamlined, and can be operated by a small crew. The main advantages of pushtows are their high transport capacity and modularity. In light of the high barge in-port times, the modularity is particularly interesting, because the barges and the pusher can be separated. This allows the pusher to be utilised while the barges are being loaded or unloaded. An example of this is found in the supply of coal and iron ore to steel factories in the German Ruhr area [44]. Six barges are tied together and pushed upstream towards the Rhine. When they arrive at the factories, they decouple the barges, couple six empty barges and immediately return downstream.

The self-propelled vessels come in different sizes, depending on the geographical restrictions of their service area, or to find a balance between economies of scale and flexibility. An overview of the distribution between the different vessel lengths can be found in Table 2.2. The vessels that have a length of over 135 meters are pushtows.

Combining the yearly throughput of 4.15M TEU with 18,000 container barge visits per year, the average container barge in Rotterdam transports 231 TEU per visit. As the TEU-factor in Rotterdam is 1.68, this translates to an average of 137 containers per visit.

2.2.3. Operations: a barge in Rotterdam

A container barge enters the port area loaded with export goods and empty containers. Geographically, most empty containers depots are situated further inland than the deep-sea terminals at the Maasvlakte. As such, barges usually offload their empty containers first. This is also beneficial for the stability of barges. The berthing of a barge takes approximately 5 minutes. Second, they offload their filled containers at deep-sea terminals. Because they usually carry containers that will be transported to different locations by different deep-sea ships, they need to offload at different terminals. After offloading their export containers, they load import containers. Sometimes, the offloading and loading at one terminal can be combined in one visit. Depending on where these import containers are destined, and how the containers are stacked on the barge, a certain order of visiting the terminals is required. The order in which barges visit the various terminals is called a *rotation*. In one such rotation, barges that service the Rhine visit an average of about 7 terminals [8].

Based on opening times of hinterland container terminals and empty depots in the port of Rotterdam, it may be expected that there are certain peak hours at the deep-sea terminals on the Maasvlakte [40]. However, the handling times of barges at deep-sea terminals on the Maasvlakte do not follow such a pattern. Figure 2.3 shows the theoretical and actual start of barge handling times.

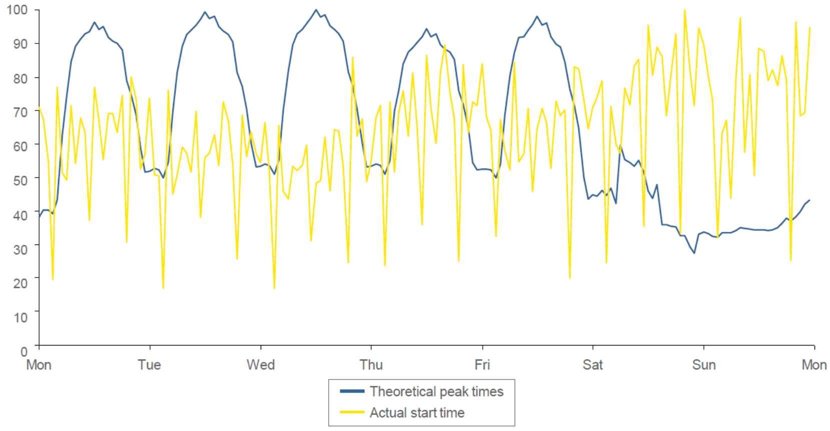

Figure 2.3: Theoretical and actual start times of barge handling at deep-sea terminals, indexed

Rotation Planning

The planning of such a rotation is based on the planning system that the terminals impose upon the barges, by unilaterally scheduling barges. It works as follows:

1. The barge determines the possible order(s) in which it should visit terminals, based on its loading plan
2. Possible rotations are created and compared, resulting in a preferred rotation
3. The barge requests the preferred slots at the terminals in its preferred rotation. Each terminal has a cut-off time, which functions as a deadline for the slot request
4. The barge receives its allocated slots from the terminals, after a delay in which the terminals make their berth schedule
5. If this is acceptable, perform rotation, otherwise, reschedule (part of) rotation.

An example of such a rotation planning process can be seen in Figure 2.4. The figure illustrates the issues that can arise when an appointment with one of the earlier terminals in a rotation does not get approved. In the figure, a barge that has to visit terminals A, B and C - in that order - plans its rotation. The ideal timeslot at B is available, but because the timeslot at A is not, the whole planning has to be changed. The second best slot at A is available, but the adapted best slots at B and C are not.

One of the side effects of the rotation planning issues is the snowball effect one infeasible rotation has on other terminals and barges: the no-shows caused by infeasible rotations can lead to under-utilisation of cranes, which is detrimental to all container barges. As can be seen, even with instant replies from terminals, planning a rotation is a time-consuming task.

However, the replies from terminals are not instant. One of the major issues in the rotation planning process arises because of the delay between requesting a time slot and hearing whether the request has been accepted. The PORA has provided an electronic system for sharing information and requesting slots, called Portbase [45], providing an improvement since the time where this was all done by fax and phone [46]. Unfortunately, the slots are still unilaterally planned by the terminals. At APM Terminals on the Maasvlakte II, a barge has to request a handling slot at 9:30 AM on the day before the requested timeslot. The response of the terminal will be at 15:00 at the latest [47]. Table 2.3 shows the cutoff times for APM terminals. If the appointed time is not suitable, officially, the barge operator will have to wait until the following day to request a new timeslot. In reality, barge operators will call the terminals and try to arrange a new timeslot. Nevertheless, replanning a rotation is a time-consuming process. As such, barge operators apply slack to their planning to reduce the number of times they must replan, and to allow the barges to supress the effects of short disruptions. This hinders their ability to come close to an optimal planning. The issue of delays in the communication with barges, and the effects of unilateral planning by the terminals can be seen in Figure 2.5. This figure expands upon Figure 2.4, by adding the temporal aspects of requesting timeslots at terminals with different cutoff times. The large time difference between the requested handling time and the cutoff time makes the barge planning process less flexible.

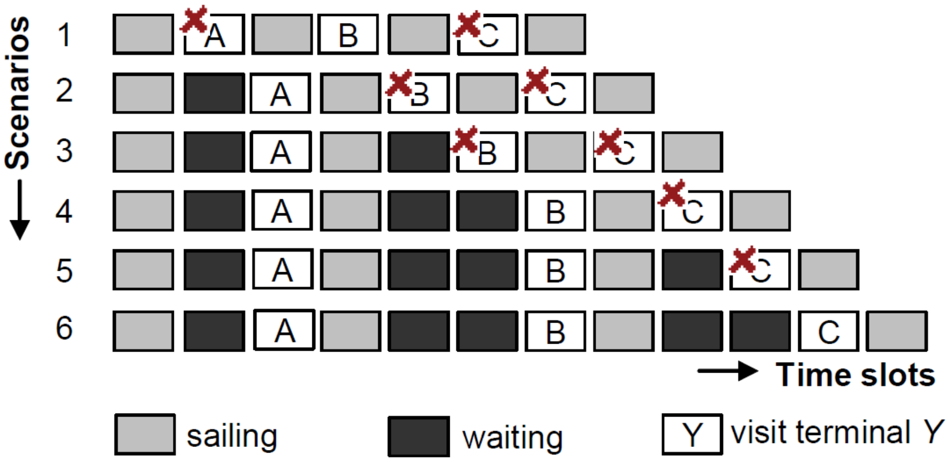

Figure 2.4: Rotation planning example, adapted from Douma [15]

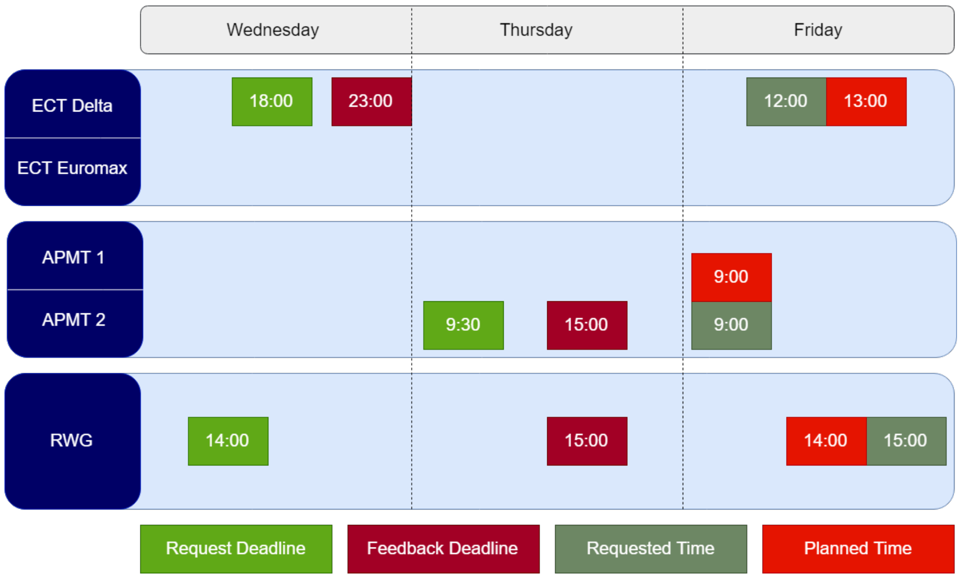

Figure 2.5: Rotation planning feedback delays, adapted from Kuijpers [40]

Naturally, there are deviations from the norm here as well. For instance, large barge operators can request timeslots for each of their barges, and then allocate the slots to the different barges they plan, providing larger operators some flexibility.

Barge Loading

When a terminal is busy, terminals do not pick containers off of barges to access the required containers, before placing the other containers back on the barge. These box movements, called shifters, would take up too much crane time, as two extra crane moves are required to offload a tower of boxes. Therefore, the way in which a barge is loaded impacts the order in which a barge has to visit terminals. While barge operators have some flexibility in their loading patterns, the stability of the barge is impacted by how it is loaded. This imposes constraints on how barges can be loaded.
As can be seen in Figure 2.6, there are two main options with regard to how to load barges: in layers, or in towers. Layers provide excellent stability, but no flexibility in terminal precedence for rotation planning. Towers, on the other hand, are much less stable, but provide higher flexibility.
The effects of barge loading plans have not been quantified in the literature. However, larger container vessels have more options to keep the containers untangled, because they have more rows and bays in which to store the containers. Anecdotally, one barge operator with large barges, that operates with mostly large call sizes, said that he could load his barge in a way to be flexible with unloading in

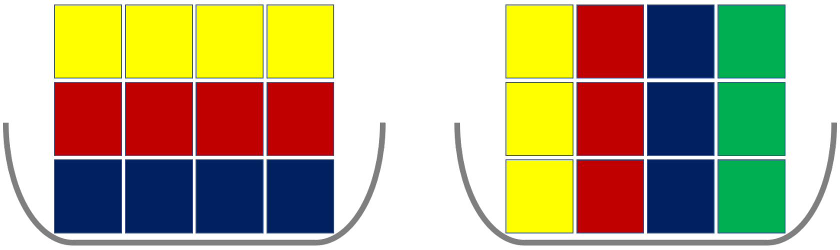

Figure 2.6: Barge loading options, with containers of the same colour destined for the same terminal. Loaded in layers on the left, and in towers on the right

Rotterdam [21].

Barge In-port Times

Due to the high variability in the system, regarding barge types, weekly container throughputs, deep-sea visits, and many more, the barge in-port times vary heavily from week to week. There are two groups that monitor the in-port times: LINc [48] and the PORA [8]. Here, the different pieces of information are discussed.
The Port Stay Index by LINc shows the average in-port time per move. As can be seen in Figure 2.7, the in-port time varied greatly in 2018. The lowest weekly value in 2018 was 9:06 minutes per move, the highest value was 25:50 per move. The average time per move was 13:59 minutes. Using the TEU-factor of 1.68 and the average number of TEU per barge visit, the average in-port time ranged from 20 to 58 hours in 2018, with an average of 31.4 hours. The TEU-factor will be explained in section 2.3. For 2019, the Port Stay Index ranges between 7:35 and 16:44 minutes per move, with an average of approximately 12 minutes, which would lead to an average in-port time of 27 hours.
The difference between 2019 and 2018 can be explained by the higher barge in-port times in the last 3 months of 2018. These were caused by low water levels, as this required more barges to visit the port to reach similar throughput levels. When the last three months of 2018 are not taken into account, the average in-port time in 2018 would also be close to 27 hours.

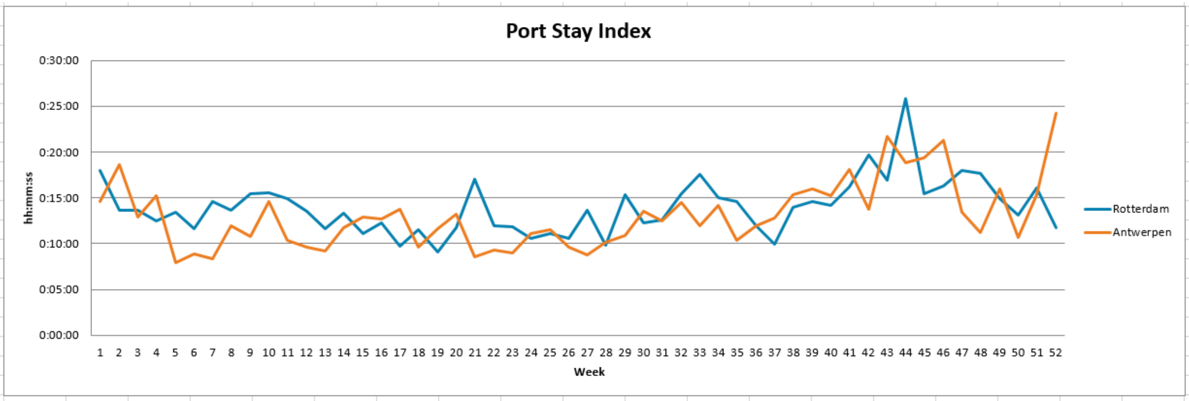

Figure 2.7: Port Stay Index for 2018 [48]

The Barge Performance Monitor presents a series of key indicators for container barges that service "various destinations in Germany and Switzerland". In this report, this is analogous to the Rhine service area. It presents these indicators for the last 10 weeks. In the first quarter of 2019, the average in-port time was approximately 53 hours. In the 10 weeks up to October 15th, 2019, the average in-port time was approximately 41 hours. One of the distinguishing features of the Barge Performance Monitor is that the in-port time is segmented in waiting, sailing and processing time. The 41 hours in port consist of an average of 9 hours of sailing, 12 hours of waiting, and 20 hours of handling at a terminal.
While the variability in in-port times is high, the average in-port time is between 25-30 hours in the majority of the weeks. The average in-port sailing time for Rhine vessels is 9 hours, their processing time is 20 hours.

2.3. Container Terminals and Empty Depots

2.3.1. Market Size and Characteristics

Over 99% of all containers that are transshipped to or from deep-sea vessels in the Netherlands are transshipped in the port of Rotterdam [39]. In 2018, the Port of Rotterdam handled 14.5 million TEU [4], or 8.6 million containers. The TEU-factor in Rotterdam is therefore 1.68. In other words, 68% of containers in Rotterdam is a 40-foot container. Due to the increasing deep-sea vessel size, and the accompanying move to a more pronounced hub-and-spoke system, the share of sea to sea transshipment through Rotterdam has increased. In 2017, 4.9 million TEU was transshipped from a seagoing to a seagoing vessel [6]. The most recent modal split data from the Port of Rotterdam, from 2016, suggests that 36% of hinterland transport of containers is done by barge [49]. The sea-to-sea containers are not taken into account in the modal split percentages in practice, which means 36% of containers that go to or come from the hinterland were transported by barge. While the total flow of containers is increasing, the modal split goal of 45% also requires an increased share of IWW hinterland transport. The PORA set this goal to reduce road congestion around Rotterdam, and improve the carbon footprint [4].

The container transshipment in the port of Rotterdam is focused around the Maasvlakte area. Here, five deep-sea terminals have a handling capacity that exceeds the total transshipment volumes of the port of Rotterdam. These five terminals are the APM terminals 1 and 2, Rotterdam World Gateway, ECT Euromax and ECT Delta. Rotterdam has approximately 118 container cranes, where Antwerp has 75. When the overall port throughput per crane is calculated, the average crane in Rotterdam only moves 83% of the average crane in Antwerp. More information on the handling capacities of terminals in Rotterdam can be found in Appendix E.

Additionally, the port of Rotterdam has 22 empty container depots. These depots are used to drop and store import containers that have been emptied. They are used to link companies that use containers for imports with companies that use containers for exports. Most empty depots provide extra services such as cleaning, repair, modification and inspection of containers. Empty depots are mostly situated in the Eemhaven and Waalhaven, further inland than the Maasvlakte, but Kramer group runs an empty depot on the Maasvlakte that is open 24/7.

As was explained shortly in section 2.1, a worldwide trend of vertical integration of terminals and container lines can be seen. Of the five main deep-sea terminals on the Maasvlakte, three - the two APM terminals and RWG - are (partially) owned by shipping lines. The other two terminals are owned by ECT, a subsidiary of Hutchison Ports, a global terminal operator. ECT has ties with COSCO shipping line, as COSCO has a 35% stake in the ECT Euromax terminal [50]. The connection with the shipping lines is detrimental to the bargaining power of barge operators.

2.3.2. Resources: Quay Wall, Cranes & Operators

A container terminal consists of a storage area, called the yard, and areas where containers can be picked up or dropped off by different modalities. Transportation between these areas in the terminals is called intra-terminal transportation. Due to the high labour price in the Netherlands, the terminals at the Maasvlakte are highly automated. Intra-terminal transportation is performed by automated guided vehicles. As this research focuses on the interaction between deep-sea terminals and inland barges, the yard and intra-terminal transportation are out of the scope of this research. The two main resources at deep-sea terminals, with regard to handling inland barges, are quay cranes and quay wall. Inland barges can be handled by the same cranes that handle deep-sea ships. However, all the deep-sea terminals have dedicated barge cranes, as they are less expensive, both in purchase and per move. The use of barge cranes generally requires intra-terminal transportation, to move the container from the deep-sea stack to the barge stack or vice versa. Due to the size of the largest cranes, it is slower to handle a barge with a deep-sea crane than with a dedicated barge crane, as the deep-sea cranes lift the the containers higher, and it is harder for the operator to latch on to the containers because of the extra height [19].

In this thesis, a lift refers to one movement from or to a ship by a crane. In theory, deep-sea cranes can perform up to 50 lifts per hour. In practice, however, most deep-sea cranes perform 20-30 lifts per hour, due to issues in supply of containers from the stack and poor stowage planning by vessels [51], [52]. Barge cranes are technologically less advanced and quite a lot smaller. Barge cranes can perform about 25 lifts per hour, but most experts in the field recognise that a maximum of 20 lifts

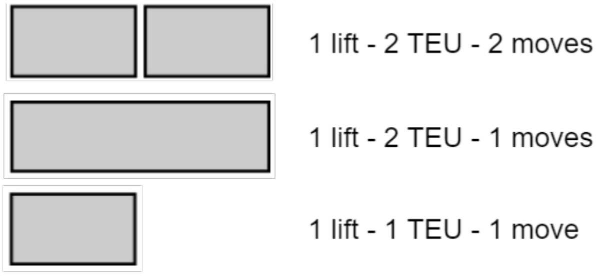

Figure 2.8: Three examples depict the relationship between lift, TEU and move for barge cranes

per hour is more realistic [19]. There are, however, examples of much worse performance. In one instance, of which the stowage plan and AIS data has been seen by this author, a call size of 102 lifts took 8,5 hours, which is a performance of only 12 lifts per hour [21]. Recently, new technology has enabled cranes to increase their productivity by moving multiple containers each move. These improved spreaders - the part of the crane that grabs and holds the container while moving it - are called twin or tandem spreaders. A twin spreader can pick up two 20-foot containers simultaneously, while a tandem spreader can pick up two 40-foot containers or four 20-foot containers simultaneously [53]. Combining the information on spreaders, the TEU-factor in Rotterdam, and our definition of a crane lift, a crane's capacity can be expressed in TEU. A lift generally moves 2 TEU, as 68% of containers in the port of Rotterdam are 40′ containers, although it can also be 1, 3 or 4 TEU, depending on the spreader that is used. Tandem-spreaders are not used to handle barges in Rotterdam, so a lift to or from a barge can only be 1 or 2 TEU [21]. The relation between a lift, a move and a TEU is clarified in Figure 2.8.

Because there is generally a waiting line of barges, the assumption can be made that barge cranes will (almost) always be operated when they are manned. When the manned deep-sea cranes are idle, they can also be utilised to handle barges. Therefore, deviations in demand from deep-sea ships lead to deviations in supply of barge handling capacity. These deviations in available barge handling capacity are one of the causes of high barge in-port times. As the demand for barge handling capacity at deep-sea terminals is also irregular, it is hard to match this supply and demand. A study that was initiated by the PORA found that as much as 55% of all barge container moves are performed by deep-sea cranes. This calculation assumed that all dedicated barge cranes were available 24 hours a day, for 360 days a year, performing 20 moves per hour, for 90% of the time [40]. Simple calculations by this author do not replicate these findings, and show that barge handling capacity is 4.06 million TEU. However, these calculations are based on less data - calculations can be found in Appendix E. However, it must be noted that terminal operators prefer to first use deep-sea cranes, before using barge cranes, as this reduces horizontal transportation demands [19]. Therefore, such calculations based on the number of barge cranes may not lead to representative findings, and the share of barges handled by deep-sea cranes may be over 55%.

The market for terminal handling capacity in Rotterdam is quite uncommon, as the amount of cranes is high, but the supply is low. Because Maasvlakte II was finished, a lot of land came available, and terminals entered into long-term leases with the PORA. The cranes have been installed, and have plenty of capacity. This overcapacity leads to heavy competition between the terminals, which compete on price. Because their margins have reduced, they focus on cutting costs. As they cannot cut down on capital expenditure costs, they cut on personnel costs, scheduling fewer crane operators than they have cranes. This reduces their effective supply. As such, based on the number of cranes, the market has large overcapacity, but effectively, there is much less supply.

2.3.3. Operations

As has been discussed, each deep-sea terminal's main focus is (un)loading a deep-sea ship quickly, so the ship can continue to its next destination. Barges are planned around the deep-sea handling. Terminals allocate ships to its berths, and then assign quay cranes to the ships. These planning problems are called the Berth Allocation Problem (BAP) and the Quay Crane Allocation Problem (QCAP). In these problems, the terminal's resources are allocated to vessels. After the cutoff period, as depicted for APM terminals in Table 2.3, the terminal planner starts planning barges around the deep-sea vessels. After the planning has been made, it is shared with the barges.

There are several exceptions from the norm as described above. These are discussed in the remainder of this section.

Barge Handling

In an attempt to help provide a more reliable service, terminals offer 'fixed windows' to barges that visit at fixed times each week, with a minimum call size that differs per terminal. This means that barges (or barge operators) have a reservation at a certain time, each week. Approximately 35% of the moves are by fixed windows barges [19]. Due to the high call size of fixed windows, the percentage of reservations that is a fixed window is much lower, between 5% and 10%. Of the non fixed-window reservations, terminals have started to notice an increase in the number of no-shows. In 2019, about 9% of reservations were cancelled under 24 hours before the reserved timeslot. Because the reservations are cancelled on short notice, terminals can struggle to schedule other barges.
As discussed in subsection 2.2.3, barges have until a cutoff time to request timeslots at a terminal. The cutoff times for APM terminals can be seen in Table 2.3. For ECT and RWG, in order to request timeslots on the same day as at APM, the cutoff times are 15.5 and 19.5 hours earlier than that of APM. When the cutoff time is reached, terminals will plan the barge requests in their berth schedule, which already contains deep-sea ships and fixed window barges. The goal for terminal planners is to reach high crane utilisation. They aim to do this by planning as many ships as possible. To decrease the likelihood of disruptions, the planners incorporate some slack to their plannings, and prioritise certain types of barges, as these are assumed to be less likely to no-show. For instance, ECT prioritises barge operators in the following categories [54]:

- good score on KPI's such as few no-shows; high visit frequency
- specific barge sails to Germany or Antwerp
- contracted to certain shipping lines whose contracts stipulate so
- sail for ECT's own hinterland network, European Gateway Services

The barges that sail to Germany and Antwerp are prioritised for two reasons: first, they generally have larger call sizes, and second, they have more reliable arrival times in the port. Because of how far in advance the cutoff time is, domestic barges that make frequent, short round trips will generally visit the port once more in this time, which makes their operations less predictable.

Table 2.3: Cutoff times for timeslot registrations at APM terminals

Registration before		**For a call between**				
Monday	09:30	Tuesday	00:01	-	Tuesday	24:00
Tuesday	09:30	Wednesday	00:01	-	Wednesday	24:00
Wednesday	09:30	Thursday	00:01	-	Thursday	24:00
Thursday	09:30	Friday	00:01	-	Friday	24:00
Friday	09:30	Saturday	00:01	-	Monday	24:00

Larger call sizes allow for higher crane productivity, but at the cost of lower flexibility. While terminal operators say to prefer larger call sizes, research has shown that smaller call sizes generally have lower waiting times, as they can more easily be planned [40]. Nonetheless, terminals have introduced minimum call sizes, in a bid to improve their crane productivity [19]. Different sources point to very different call size distributions. This can be seen in Table 2.4. According to a source at a deep-sea terminal, approximately 75% of barge calls have a call size of more than 50 moves [19]. According to two other sources, information by Nextlogic [43] and the study by Kuijpers [40], this number is much lower, and the majority of call sizes is under 50 moves.
Finally, one interesting dataset was shared by a large deep-sea terminal operator [19]: the number of barge moves per hour, for a period of 2 months in the middle of 2019. The dataset containing barge moves per hour is confidential.

Deep-Sea & Feeder Handling

Deep-sea and feeder ships are prioritised over barges, as they generate revenue for terminal operators. Due to economies of scale, the size of deep-sea container vessels has been increasing steadily.

Table 2.4: Barge call size data

Call Size (moves)	0-25	26-50	51-100	101-200	>200
DS Terminal ('18)	5%	17%	26%	27%	25%
EY-Parthenon ('17)	56%	25%	14%	combined 5%	
Nextlogic ('16)	35%	34%	23%	7%	1%

These larger ships have three important consequences for deep-sea terminals: the call sizes increase, more feeders visit the terminals, and the new vessels are wider, deeper and longer, imposing longer movement distances for the quay cranes. The increase in call size is at a smaller rate than the overall ship size growth [55]. The larger ships in the hub and spoke network require more feeder ships, which further increases the demand for quay wall. In 2018, feeder volumes grew by 9% in the port of Rotterdam.
Because shipping lines want to benefit from their economies of scale, without imposing longer handling times at the various ports along their routes, they demand higher handling rates from the deep-sea terminals. To accommodate the higher handling speeds and larger ship dimensions, terminals have had to invest in new cranes.

2.4. Deep-sea Shipping Lines

2.4.1. Market Size and Characteristics

Deep-sea shipping lines transport containers all across the globe. In 2018, global container trade volumes reached 148 million TEU [3]. Forecasted annual growth rates for containerised trade are in the range of 4.2% to 6.4% [3]. The most important routes are the route between Asia and Europe and the transpacific route between Asia and North America, that together constitute over a third of global trade volumes. Shipping lines most frequently visit Rotterdam as their port of choice in the Hamburg - Le Havre (HLH) range. They are the largest container port in North-West Europe, with a market share of 31%. There is a subtle difference between the ports of Rotterdam and Antwerp, Rotterdam's biggest competitor in the HLH range. The port of Rotterdam has historically focused more on trade from Asia; Antwerp has focused more on the Americas and Africa [56].

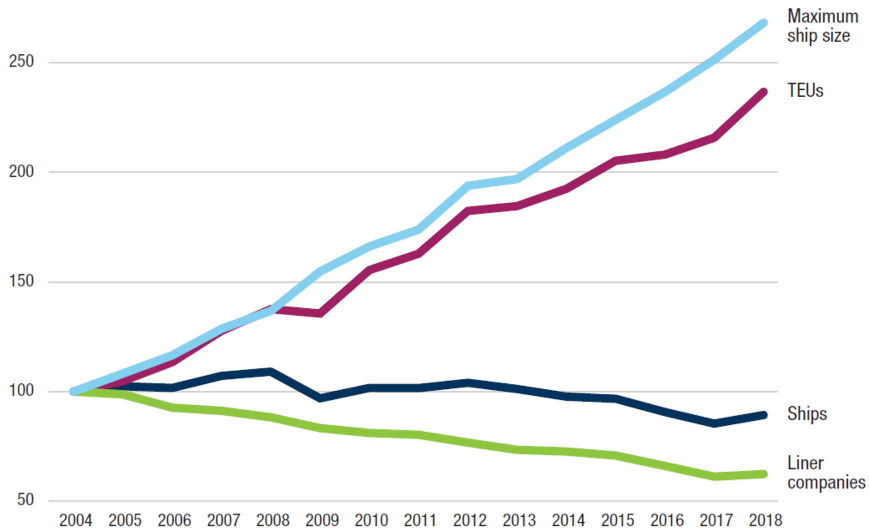

Figure 2.9: Trends in liner shipping (2004 = 100), from Asariotis *et al.* [3]

Container ship sizes have been growing since the invention of the container, as shipping lines are looking for economies of scale [57]. Due to the fierce competition between shipping lines, shippers have come to expect weekly departures. Lately, the search for economies of scale, compounded with the lead time on new ships, the financial crisis, and the high departure frequency, has resulted in overcapacity in the container shipping market. Because of this overcapacity, freight rates have gone down. Paired with the large ship sizes, shipping lines struggled to fill their ships, which meant they weren't reaching the economies of scale they had expected. In an attempt to increase utilisation rates of their ships, container lines have started working together in alliances [58]. This has lead to three large alliances that now represent over 80% of trade volumes: 2M, Ocean Alliance and THE Alliance. Apart from joining forces in alliances, the industry has also consolidated, with the larger parties buying up smaller ones. An overview of the increasing ship size, available transport capacity, number of ships, and number of shipping lines can be found in Figure 2.9.

2.4.2. Resources: Ships

As mentioned before, deep-sea vessels have been growing steadily, as shipping lines search for economies of scale. In 1970, the largest containership could fit 2,300 TEU, which grew to 8.170 TEU in 1997, and 15,550 TEU in 2006. In Febuary 2019, the largest ship was the OOCL Hong Kong, with a capacity of 21,413 TEU [3]. The OOCL Hong Kong can fit 23 containers in its width, 50 containers in its length, and about 19 layers on top of eachother. During the writing of this thesis, the OOCL Hong Kong was surpassed by the MSC Gülsün, with a capacity of 23,756 TEU.
These economies of scale can be found in the shipbuilding costs, the crew costs and the fuel costs. An example of these economies of scale for fuel costs can be found in Figure 2.10.

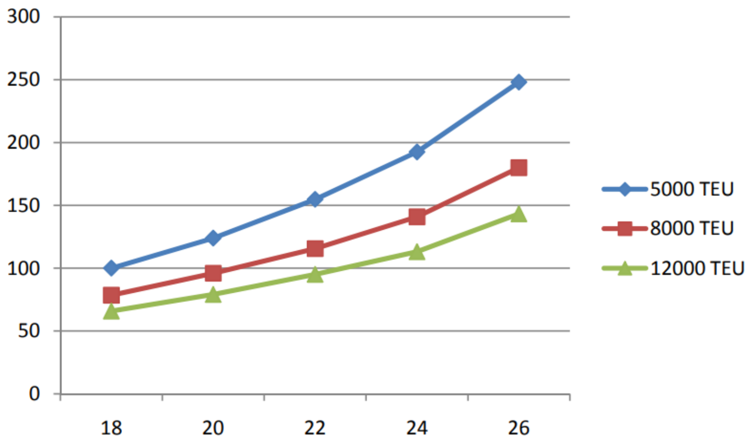

Figure 2.10: Indexed fuel cost per container per nautical mile, for different speeds in knots, from Fransoo and Lee [59]

2.4.3. Operations

Shipping lines decide what routes they want to sail, and how frequently, this is called *network design*. Because of the increasing vessel size, shipping lines have moved more towards a hub and spoke system rather than a point to point network, mainly because investments in ports require certain level of throughput to be economically viable, but also to reduce the amount of stops per round trip [60]. This means that deep-sea container vessels prefer not to visit both Rotterdam and Antwerp, but offload all their containers at one or the other, and use smaller feeder ships to redistribute from there. Deep-sea container vessels are frequently delayed by factors such as port congestion, inefficient terminal operations, and extreme weather conditions. In 2015, 27% of deep-sea container vessels arrived more than 2 hours after their scheduled arrival time [61].
A measure the shipping lines have taken to reduce overcapacity is so-called *slow steaming* [57]. When the same amount of ships of the same size all sail slower, they take longer to complete a route, and can transport fewer containers per year. Additionally, as can be seen in Figure 2.10, this has positive effects on their fuel expenses, and as a function thereof, their emissions. However, the lead time for customer shipments does increase.
Shipping containers are usually the property of the shipping lines, and as they have a limited amount of containers, they try to incentivise shippers to return them quickly. Therefore, shipping lines charge demurrage and detention fees when containers are stored in terminals for too long, either because they not picked up on time, or they were not returned to the terminal on time. After a certain free

time period, these charges are approximately €75 per 40 foot container per day [40].
Shipping lines negotiate contracts with deep-sea terminals on their routes, leaving them little flexibility to visit other terminals in the same port. In these contracts, shipping lines agree to pay for the following three services: i) the transfer of containers from or to the deep-sea ships ii) the storage in the terminal's container yard iii) the transfer of containers from or to the hinterland modality [16] [40]. This is regardless of whether the goods are sent through merchant or carrier haulage.
Perhaps the most important operational planning problems that shipping lines face is how to stow the ships. With multiple carriers stowing containers on very large deep-sea ships, with containers that can be destined for upward of 10 stops on the route, stowage planning is a complex endeavour. There are various factors that can negatively influence terminal operations, and therefore prolong a deep-sea vessel's turnaround time: imbalances in required moves per crane along the length of the vessel; containers that are stacked below other containers; layers where containers are offloaded to a much larger depth than from other bays; a high share of moves from the far side of the vessel.

2.5. Chapter Summary

This chapter provided an overview of the market dynamics, resources, and operations of container barges, container terminals, and deep-sea container shipping. Here, the most important findings with respect to high barge in-port times will be shared.
Hinterland container barging from the port of Rotterdam can be segmented into roughly three hinterland areas: domestic transport, Rhine transport, and transport to and from Antwerp. In order of descending yearly throughput volumes, the domestic market is roughly 50%, the Rhine is approximately 35%, and Antwerp is about 15%. Each of these service areas has characteristics that influence their in-port operations. On average, container barges offload and load a combined 231 TEU in Rotterdam, which takes 26.4 hours. A barge's operations in Rotterdam are characterised by their lack of control over the operations: barges request handling timeslots at the terminals, and terminals schedule the barges. The rotation planning process is time-consuming and inefficient.
Five large deep-sea container terminals on the Maasvlakte are responsible for the handling of a large majority of deep-sea ships. Here, handling capacity is in high demand by deep-sea ships, feeder vessels, and container barges. The deep-sea terminals are owned by three terminal operators, each of which has strong ties with one of the three major shipping alliances. The fact that deep-sea shipping lines pay for the handling of barges, and that there is no contractual relationship between barges and deep-sea terminals, results in an imbalance of power. Deep-sea terminals have deep-sea cranes and barge cranes, both of which perform about 20 lifts per hour when handling barges. Many barges are handled by deep-sea cranes, as this requires fewer horizontal movement in container yards, and allows crane operators to operate one crane per shift. Fierce competition between the terminals leads them to schedule fewer crane operators than they have cranes. When a terminal makes a berth planning, barges are scheduled after deep-sea and feeder vessels. Terminals aim to optimise their crane utilisation, while not impacting deep-sea vessel handling.
Deep-sea container ships have grown very quickly over the last 15 years. However, the available capacity outgrew the demand, forcing deep-sea lines to cooperate in alliances in order to utilise their new, large ships. These larger ships have led to more of a hub-and-spoke system, which requires more sea-to-sea transshipment at terminals. Additionally, the alliance ships generally have poorer stowage planning, making decoupling of containers at terminals more difficult.

3

Literature Review: Causes and Measures for High Barge In-port Times

The last chapter provided a description of container barging, with information on market structure, resources, and operations, of the different actors. This chapter builds on that information, by using the increased system understanding to list reasons for high barge in-port times, and measures to reduce them.
This chapter will review scientific literature related to high barge in-port times. Some of the keywords that were used are *operations research*, *container terminal*, *barge handling*, *hinterland transportation*. The relevant literature was mostly published in journals such as *Transportation Research E*, *Transportation Research B*, *Maritime Policy and Management*, *Maritime Economics and Logistics*, *Journal of Transport Geography*, *Flexible Services and Manufacturing Journal*, and the *European Journal of Operational Research*.
Scientific literature on container barging is not exhaustive, presumably because container barging is not widespread globally, as explained in the previous chapter. Therefore, information was also gathered by interviewing different stakeholders. Finally, technical reports from the port authority and dutch (semi-)governmental institutions was used.
The chapter is structured as follows: the first half uses literature, interviews and reports to explain why container barge in-port times are high, the second half provides measures to reduce the in-port time. Both these sections follow the structure that was used in the previous chapter, moving from container barges to terminal operations to deep-sea shipping lines. Further structure is added by summarising each of these six sections with a figure. Finally, Figure 3.8 will summarise the chapter by combining these six figures into an overview of causes and measures.

3.1. Causes for High Container Barge In-port Time

This section will discuss the root causes of the high barge sojourn times, as proposed in the literature, several reports, and interviews.

3.1.1. Causes related to Container Barges

There are three causes for high barge in-port times that are related to container barges. First, we evaluate the barge itself. The average container barge has grown larger, and this causes longer rotations. Additionally, berthing times can be significant when barges pick up small call sizes. Second, container barges apply tactical behaviour to their rotation planning, which can have a negative effect on barge in-port times. Third, the fragmented market affects barge in-port times.

Container Barges

There is evidence that the larger barges that have to call at multiple terminals in the port are one of the causes for complex barge operations, which leads to high barge in-port times [62]. Some smaller barges that call at a small number of terminals, and can transport approximately 50 TEU, have proved to provide a reliable transport service, with lower in-port times. There is, however, a balance between the value of economies of scale and the value of low in-port times. For longer round trips, small boats are much more uncommon, as the in-port times are a much smaller share of the total round trip time. Deep-sea terminals have repeatedly pointed at small call sizes as one of the reasons that barge handling performance is quite low. This is because the berthing of a barge costs approximately 5 minutes, in which time the quay crane is not moving containers.

Tactical Behaviour in Planning

Barge operators are accustomed to the long waiting times, and have learned to game the system in several ways. First, they have learned to apply slack to their own plannings, much like terminal operators do to their planning. This slack aims to reduce the effect of small delays by allowing the barge to continue on its scheduled rotation without missing timeslots. Second, they have started requesting timeslots strategically, in order to get their desired timeslots. For instance, in times of high demand, vessels that arrive in the port on Tuesday will request timeslots on Monday, and hope that all terminals are overbooked, thereby securing a slot on Tuesday. Much like the slack terminals use, this is currently beneficial to barges that do so, but can make finding a good planning for all actors more difficult. If one of the terminals from our example was not overbooked, and allots a timeslot to that barge on Monday, this might not only prevent another barge from filling this slot, but also 'wastes' handling time at a terminal. This is an example of how a form of cooperation can be beneficial for the system as a whole.

Fragmented Market

This lack of cooperation has another effect: many ships visit multiple terminals with low call sizes, reducing the terminal's crane productivity and requiring more complex planning from the barge's perspective. A second effect is that barge operators with larger fleets have more flexibility in mitigating the effects of delays at one of the deep-sea terminals [21]. When one of their ships is scheduled to pick up containers at a terminal, but the allocated timeslot is over 12 hours after their second latest timeslot, large barge operators will arrange for another barge in their fleet to take over their timeslot, thereby allowing the initial barge to leave the port far quicker. Smaller barge operators lack this flexibility; their barges will more frequently spend time waiting for a timeslot that requires them to wait for long periods of time.
The causes related to container barges have been summarised in Figure 3.1.

Barges (CB1)

- Higher capacity leads to longer rotation, which increases in-port time
- For small call sizes, berthing time is significant

Planning (CB2)

- Gaming the system can lead to unwanted timeslots
- Applying slack prevents optimal rotation planning

Fragmented market prevents cooperation (CB3)

- Lower call sizes
- Long waits for cargo

Figure 3.1: Container barge causes for high barge in-port times

3.1.2. Causes related to Deep-sea Terminals

A dive into literature shows that deep-sea terminals have profound effects on barge in-port times. The effects are categorised in one of three categories: insufficient barge handling capacity; lack of contractual relation with barges; inefficient planning system. These are discussed hereafter.

Insufficient Barge Handling Capacity

According to queuing theory, the average system time in any queuing system depends on the arrival rate, and the handling rate. This is known as Little's law. Terminals perform the handling, and as such, can improve their handling rate. As was mentioned in section 2.3, various facts point towards insufficient handling capacity at deep-sea terminals. The fact that 55% of barge moves is done by deep-sea cranes points to a lack of dedicated barge handling capacity. Furthermore, as the average barge only has to load and offload a total of 231 TEU per port visit, which translates to about 137 moves, and the Barge Performance Monitor shows that the average barge spends about 20 hours at terminals during their rotation, this leads to the low number of 6.9 moves per hour [8]. As noted before, Rhine vessels are generally larger than average, but even when we assume that Rhine vessels are twice as big as an average barge, this leads to a crane productivity of 13.7 moves per hour, which is still far lower than the 20 lifts per hour that is generally assumed as a feasible crane productivity. As mentioned before, there is also a lack of skilled crane operators at the deep-sea terminals. The terminals concede that they cannot match the demand at certain moments, such as the big push of containers before Chinese new year, the understaffed summer months due to operator holidays, and the period when shops stock up before Christmas [19].
Barge operators state that the handling capacity at many terminals in Rotterdam is not sufficient, and say that Rotterdam is lagging behind Antwerp when it comes to technological improvements [21]. In Antwerp, the use of tandem spreaders that move up to 4 TEU per move is more common, reducing the handling times of container barges as well as their waiting times. Even if these technological improvements are only installed for deep-sea cranes, the reduced turnaround time of deep-sea vessels will increase the available barge handling capacity.

Inefficient Planning

The process barges go through in the port is quite complex. They visit multiple empty depots and terminals, in which some vessels have limited flexibility due to their loading plans. Because the terminals are competitors, they are wary of sharing information ([15], [46], [63]). This lack of information sharing between terminals and barges results in difficulties planning barge rotations. One of the main issues is that barges request timeslots at the different terminals before receiving feedback. A rejected timeslot at one terminal can lead to replanning of all or some of the requested timeslots, as illustrated in Figure 2.4. The delay in hearing whether a timeslot is allocated further complicates the rotation planning. Currently, even though timeslots are requested by barges, the planning is made by terminals unilaterally. Barges have no way of signifying whether or not a certain timeslot is important to them, or whether a delay of 3 hours from their requested time does not matter for the rest of their rotation. As this information is not available to terminals, the terminals may plan barges in ways that increase the average in-port time, where this could easily be reduced.
Because small disruptions frequently lead to small delays, terminals apply slack to their planning, as this improves their crane utilisation as opposed to a system where they reschedule each barge that is delayed slightly. While this is beneficial for both parties' own planning in current conditions, this reduces their potential efficiency in a centralised planning, or system with fewer disruptions.

Lack of Contractual Relation

The 2019 paper by van der Horst *et al.* [16] provides an institutional analysis of why there is a lack of coordination between parties in the port. According to this author, their most important conclusion is that "the present division of property and decision rights in container barging in seaports is a damaging condition for future improvement". In other words, barge operators don't have a contractual relationship with deep-sea terminals. In fact, container barges do not pay terminals for the handling. This can clearly be seen in Figure 2.2.
Because there is no contractual relationship, the barge operators have no bargaining power. There are no penalties for terminals when they do not handle barges at their communicated time. Other studies, such as that by Fransoo and Lee [59], pose similar reasons.
The causes related to deep-sea terminals have been summarised in Figure 3.2.

3.1.3. Other causes

This subsection will discuss several other causes for high barge in-port times, that cannot be categorised under terminal or barge. The three causes are: the increasing deep-sea vessel size; reduced free days before demurrage and detention fees; schedule unreliability of deep-sea vessels.

Handling speed insufficient (T1)

- Too few cranes, operators and quays
- Room for technological improvements

Planning (T2)

- Final planning is made by terminal without regard for barge rotation; barge cannot signify importance of timeslot
- Delayed response to barges

No contractual relation with barge (T3)

- No penalty if they don't keep appointment
- No payment by barge makes them a low priority for terminals

Figure 3.2: Deep-sea terminal causes for high barge in-port times

Deep-sea Vessel Size

As a result of the increasing vessel size, with the newest deep-sea ships capable of transporting 23,756 TEU, container terminals experience peak operational loads that negatively impact operations [64] [65]. As a direct consequence of the increased vessel size and the required turnaround time, deep-sea terminals have to assign more cranes to deep-sea ships for longer. The productivity of the cranes goes down because of the proximity of the other cranes [57]. This leads to fewer handling hours available for barges.

Another negative effect, caused by the size of the deep-sea vessels, is the increase in feeder volumes. Because of the consolidation of deep-sea shipping lines in shipping alliances, Rotterdam has become increasingly important as a hub for feeder vessels. Transshipment volumes to and from feeder ships have increased strongly, with an increase of 21,3% in TEU in 2017 alone [6]. These feeder vessels are taking up more quayside hours, that were previously reserved for barges.

Finally, there is one more negative effect, that is indirectly caused by the size of deep-sea vessels. In order to reach higher utilisation rates, the shipping lines have joined forces in alliances, to consolidate their orders on shared vessels. This adds operational complexity, with more different final destinations and container owners per deep-sea vessel. When all the containers are loaded at one port of call, stowage planning can mitigate most of the negative effects. However, it has become more commonplace for these vessels to 'fill up' in multiple Asian ports, thereby hampering the opportunities of stowage planning. While the shipping lines reap the benefits, terminals have to 'untangle' these containers [3]. Haralambides quotes a terminal operator: "we can do 150 moves per hour for a major independent carrier, but only 100 for an alliance ship". More information on stowage planning can be found in the following paragraphs.

Demurrage and Detention Fees

Maersk and Hapag-Lloyd have decreased the number of free days before demurrage and detention charges are incurred. This has reduced the number of days that barges can schedule to visit a terminal without incurring a cost penalty. In turn, this also reduces barge call sizes, as there is less time to consolidate containers [40]. As barges deliver containers before, and pick up containers after the corresponding deep-sea ships arrive, their peak demand is focused around the arrivals of deep-sea ships.

Deep-sea Vessel Schedule Unreliability

Another factor is the schedule unreliability of deep-sea ships. When a container barge comes to pick up a deep-sea ship's import containers, and the barge is already in the port to offload export containers, it has to wait for the deep-sea ship to be handled. Furthermore, the delays can lead to smaller gaps between the arrival of consecutive deep-sea ships, which increases the peak demands even further [34]. Planning-wise, the unreliability brings up problems from a terminals perspective, as small delays lead to small barge handling windows, which are often not, or partially, used, as terminals don't want to risk delaying deep-sea ships further, due to their power position [21].

The causes related to other factors have been summarised in Figure 3.3.

Deep-sea Vessel Size (O1)

- Crane productivity drop
- Alliances lead to bad stowage plan
- Hub and spoke network leads to higher feeder volumes

Short free days before Demurrage & Detention (O2)

- Barge handling demand in peaks to avoid penalties
- Less time for consolidation of hinterland volumes

Schedule Unreliability of Deep-sea Ships (O3)

- Deep-sea vessels visits are closer together
- More unused quay hours for terminals

Figure 3.3: Other causes for high barge in-port times

3.2. Container Barge In-port Time Reduction Measures

As most measures relate to solving one of the causes, the structure in this section will be similar to that of the causes for high barge in-port times.

3.2.1. Measures related to Container Barges

The measures in this chapter are all linked to the causes related to container barges, as given in subsection 3.1.1. First, we evaluate novel barge designs, and their effect on in-port times. Second, potential improvements with regard to rotation planning are discussed. Finally, partnerships between barge operators are examined.

Barge Designs

This section will explain three measures related to container barges. First, the effect of reducing the berthing time will be discussed. Second, the increased use of pushbarges, and the effect that can have on barge in-port times, is examined.
As the berthing of a barge takes approximately 5 minutes, gains can be made by reducing the berthing time. Mooring systems based on vacuum pads can moor a ship in under 30 seconds [66]. These gains are relatively small when call sizes are large, but for a call size of under 10 moves, the berthing time makes up at least 14% of the handling time. Approached differently, as the average barge visits 7 terminals, the total in-port time can be reduced by 35 minutes, which is just over 1% of the average in-port time of 53 hours.
As mentioned in section 2.2, 90% of container barges are self-propelled vessels. The other 10% are pushbarges, that have potential advantages over self-propelled vessels. Their modularity can allow for innovative logistics concepts, because barges are interchangeable and the pushers can continue working, thereby mitigating some of the downsides of high in-port times. An example of this is found in the supply of coal and iron ore to steel factories in the German Ruhr area, as explained in section 2.2. Although this does require a larger number of barges, and a pusher at both the origin and destination to move the barges away from the quay once they have been (un)loaded, this does allow for around the clock transportation. Because container barges generally have to move between more terminals, a likewise system would also require a fleet of pushers in the port of Rotterdam, to move barges around the port and berth or unberth the barges. Additionally, each terminal would require a dedicated barge waiting area.
Unfortunately, the implementation of such concepts is unlikely, because of difficulties determining how the costs of such a system should be distributed, and reluctance of competitors to work together. The concept might be feasible on routes with high frequencies and volumes per barge operator, such as between Antwerp and Rotterdam. However, as these barges are generally prioritised in a terminal's berth planning process, these barges are more likely to accept the status quo.

Barge Rotation Planning

In the final paragraphs of this chapter, two changes to the operations of barges are examined. First, the Barge Rotation Planning Problem (BRPP) is considered. Then, an increase in call size through

partnerships between barge operators and inland terminals is discussed.
The Barge Rotation Planning Problem deals with planning a barge rotation through a port area, given the list of call sizes per terminal and the precedence relation between these calls. It aims to minimise a barge's in-port time. As explained in subsection 3.2.2, the capability to plan a good rotation depends heavily on the information that is available to a barge.
The first paper on a BRPP is that by Schut *et al.* [46]. It uses a decentralised planning system, called APPROACH, where barges and terminals provide the information on their loading plan and call sizes, or the quay wall availability. Each day, APPROACH would plan the operations of barges and terminals. The barge operator still holds autonomy to choose from a series of suggested rotations, where the terminal operator can still accept or decline terminal visits. The main contribution is that the initial rotation plans from barges match the capacity that terminals provide, to improve the initial rotation plans. There are no simulation results, but the conceptual idea lead to further research by Douma *et al.*, which was completed in 2009. Again, a decentralised system is proposed. In their model, barges enter the port and plan their rotation instantly. The terminals instantly reserve timeslots for these barges. This is different to reality, where terminals wait until a cutoff time before planning. The main contribution of this paper is that different levels of information sharing by terminals are evaluated. The sharing of maximum waiting times for any arrival time led to good results, especially when some slack was applied. This enabled barges to plan good rotations. The slack is required to leave some flexibility for the terminals, because they plan barges without knowing all requests for the following day. The results of using waiting times are promising for three reasons: real-time barge reservations make the BRPP easier and more robust; because of the slack terminals apply, they keep some flexibility to schedule requests later in time; they showed a reduction of the average in-port time of 20 hours, although the authors state that their experimental setup is not a very good representation of the port of Rotterdam, and they "aim to apply the model to realistic data based on the port of Rotterdam."
Following the 2009 paper, Douma *et al.* expanded the waiting time profiles that were shared in the earlier paper, to incorporate uncertainties in the handling time as well. These new profiles are called service time profiles. Such profiles would be shared with barges when they start planning their rotation. In order for the terminals to still be able to prioritise deep-sea ship handling without breaking appointments with barges, timely ETA announcements from deep-sea ships to the terminals are required.
Through simulation, Douma *et al.* compared the performance of service-time profiles with a centralised optimisation by testing on a carefully crafted data set of the port of Rotterdam in 2006 and 2007. The centralised planning cut average in-port times by about 1 day per rotation, and sharing service-time profiles only performed marginally worse than the centralised planning. This shows that decentralised approaches, where actors are "autonomous and share only limited information", could greatly reduce planning inefficiencies.

Partnerships

Another way to reduce barge in-port times is by reducing the number of calls a barge has to perform. Several barge operators and inland terminals have formed partnerships, in order to bundle containers and increase call sizes at deep-sea terminals. Such initiatives are in place on the "West-Brabant Corridor" and the "Duisburg Corridor" [4]. Call sizes have doubled to quadrupled thanks to these initiatives. For instance, 2 barges can both visit 4 terminals and drop off 50 containers at each terminal. If they cooperate, both barges only visit 2 terminals for a call size of 100 each.
Due to the early succes, the PORA has since facilitated container bundling initiatives from Amsterdam and Alblasserdam. While these bundling initiatives all bundle containers at inland terminals, the Rotterdam Container Terminal on the Maasvlakte also offers unloading of small call sizes, bundling containers before loading them on inter-terminal transportation for the last mile to the deep-sea terminals [68]. This new function of the RCT has been called the "Barge Service Center". This allows for an easier form of bundling, as inland terminals do not have to consolidate further inland. The "Barge Service Center" will be connected to Container Exchange Route, an in-port time reduction measure that will be explained in subsection 3.2.2.
The measures related to container barges have been summarised in Figure 3.4.

3.2.2. Measures related to Deep-sea Terminals

Deep-sea terminals have several interesting options to reduce barge in-port times: where will barges be handled, and how quickly; improved berth planning; various pricing changes. The first option focuses

Barges (CB1)

- Reduction in berthing time
- Effect of modular pushbarges
- Autonomous barges

Planning (CB2)

- Barge Rotation Planning Problem for improved planning

Partnerships (CB3)

- Reduce number of calls
- Increase call sizes

Figure 3.4: Barge measures to alleviate high barge in-port times

on barge handling, by adding more capacity at current terminals or changing the in-port logistics by adding inter-terminal transport or a barge transferium. The second option looks at planning, both as a planning problem from a terminal perspective, and what the effect of information sharing is for barge rotation planning. Finally, pricing can be used in several ways, as a means for barges to improve their planning, or as a way to increase crane productivity.

Changes to Barge Handling

The measures can be categorised as either those that aim to improve handling capacity at current terminals, or adding resources to change the barge handling process, such as building a new transferium, or dedicated barge terminal, or facilitating easier container transfer between terminals.

Handling capacity can be improved by building more quay wall and cranes, by scheduling more crane operators, or by improving crane productivity by upgrading the crane spreaders. While changing the crane spreaders from normal spreaders to tandem spreaders doubles crane productivity, the effect on vessel turnaround time depends on many more factors. Naturally, increased handling capacity will reduce the handling time of each individual vessel, which also enables terminals to handle more vessels per day. When comparing the handling speeds in Antwerp and Rotterdam, Rotterdam is falling behind, according to an interview with a barge operator [21]. This notion is backed up by the basic analysis based on total cranes and total port throughput of Antwerp and Rotterdam. It found that on average, cranes in Antwerp move 20% more TEU per year.

The remaining two measures, a barge transferium and the CER, both aim at reducing the number of terminals a barge must visit, either by consolidating these containers at a dedicated barge terminal or by exchanging containers between the deep-sea terminals directly. The potential for a barge transferium has been researched by Konings *et al.* [10], and was the subject in the thesis by de Jong [9]. Because it is unclear what the operating costs per handled container would be at such a transferium, the research by Konings *et al.* focused on finding the cost savings by using economies of scale to sail from the Maasvlakte to the transferium, thereby resulting in a maximum allowable handling cost. The research did not take into account the time savings that this novel concept would bring to barges by cutting out long rotations around the Maasvlakte, or the added value of the more reliable service offering. These values should be added to the allowable handling cost. The research found allowable transferium handling costs in the range of €19 to €54. While a transferium is beneficial for barge in-port times, there are concerns about the feasibility of a transferium. The investment and operational costs would have to be shared by the barge operators, terminal operators, shipping lines and the port authority, but the division of costs seems too big a hurdle to overcome.

The PORA is currently working on the Container Exchange Route (CER), where inter-terminal transport between the Maasvlakte container terminals and empty depots will be facilitated on a dedicated road, in order to reduce terminal calls [6]. It will be used to bundle containers for both rail and barge connections to the hinterland. In full operation, the CER is expected to handle a yearly volume of 1 million containers. The CER will mostly be used to exchange containers that would otherwise form small call sizes, in an attempt to minimise those. The CER is expected to start operating halfway during 2020.

Improved Planning

In this section, the following measures will be discussed. First, allocating ships to berthing spots and assigning cranes to ships are specific types of resource allocation problems, aimed at making terminal operations more efficient through improved planning. These problems are called the Berth Allocation Problem (BAP) and the Quay Crane Allocation Problem (QCAP). Second, this problem will be approached from the perspective of a barge, that has to visit multiple terminals, called the Barge Rotation Planning Problem (BRPP). Increased levels of information sharing from terminals to barges result in improved rotation plans. In an extension of the BRPP and BAP, the effects of centralised planning of barge rotations and berth schedules have been researched.

The BAP and the QCAP deal with planning where vessels will berth, and how many cranes are used to load and unload a vessel. As the number of assigned cranes determines the handling duration, these two problems are generally solved in tandem [69]. The two reviews on these problems by Bierwirth and Meisel in 2010 and 2015 show the wide variety of characteristics these planning problems address. In the 5 years between those reviews, 120 publications on BAPs and QCAPs came out. The literature on BAPs predominantly takes a terminal perspective, and disregards the effects on barge rotations. However, with the aim of reducing barge in-port time, there are two interesting variations: the tactical BAP and the multi-terminal BAP.

Because most vessels sail to cyclical schedules, papers such as those by Lee and Jin [71] and Giallombardo *et al.* [72] aim to align the schedules of barges, feeders, and deep-sea ships, so that berths are available upon arrival, and container transfers are possible. These can be categorised as *tactical* BAP, as they try to align the schedules. Research by Lee and Jin found that spreading the arrival times of feeders, barges, and deep-sea ships leads to lower waiting times and higher terminal productivity [71]. However, one of the main complications of container barging in the port of Rotterdam arises due to the many different terminals that all make their own planning. The papers on tactical BAPs do not address this issue. One paper that has partially tackled this is the paper by Hendriks *et al.* [73]. While their paper approached the problem from the perspective of one terminal operator with multiple terminals, it could also be applied to a port area with several competing terminal operators. A centralised planning could improve the performance for all parties, by cutting out inefficiencies by combining the information from all parties. For instance, terminals will no longer both allocate the same timeslot to a barge, and barges on the end of their rotation will get priority over barges that just started their rotation.

In the paper by Douma *et al.* [67], such a centralised planning is compared with the status quo, through a simulation model. The results show a large improvement, reducing average barge in-port times by as much as 24 hours. Li *et al.* [74] used a two-step planning approach, where barge rotations are planned in the first step, before they are combined to mitigate issues that would arise due to lack of coordination. This two-step approach is used as a method to still give the barges autonomy, while also using some of the upsides of coordination. The two-phase planning resulted in an average in-port time reduction of 12%.

While it has often been stated (e.g. [67], [46], [16]) that the market players would not give up autonomy over their operations, such an initiative has taken root in Rotterdam. Nextlogic is an initiative by barge operators, supported by the PORA, that will provide centralised planning, based on 11 KPI's that have been agreed upon by deep-sea terminals, empty depots and barge operators. These KPI's aim to provide good crane utilisation for the terminals, and lower in-port times for the barge operators. Nextlogic has compared initial results of this centralised planning with a benchmark dataset from October 2017, and found improvements both in average in-port time and the in-port times of the 10% longest rotations. Nextlogic planned to go live in November 2019, but has postponed this to the first half of 2020 [43].

While the BAP plans from the terminal's perspective, the Barge Rotation Planning Problem views the planning from a barge's perspective. Berth Allocation Problems deal with assigning berths and cranes to incoming vessels. The BRPP plans a visiting sequence, called a rotation, between the various terminals in a port [67]. More information on the BRPP can be found in subsection 3.2.1, but we will discuss the effect that terminal information sharing has here.

Higher levels of information sharing from terminals to barges, specifically information on their available capacity, can improve rotation planning by barges. The PORA facilitates this information sharing by providing platforms for their users, such as Pronto or Portmaster [45]. The research by Douma *et al.* showed that information sharing from terminals greatly reduced the in-port time. When terminals shared the expected waiting times for any requestable timeslot, barges could improve their rotation planning. This implicitly requires real-time reservations, as the waiting times would be updated after each reservation. Later research incorporated the variable service time, as this is based on the amount of cranes that can handle the barge. This further improved the barge in-port time [62].

Pricing

Finally, four novel concepts, that are based on pricing changes, are proposed. These four methods are: i) auctioning all available barge slots ii) adding priority requests iii) pricing barge slots to spread out requests iv) variable deep-sea pricing to improve deep-sea handling. First, following the rationale that unilateral planning by terminals can be improved by giving barges a means to express the importance of receiving a certain timeslot, which is not currently available to them, it is interesting to see the effects of auctioning all timeslots on barge in-port times. Second, following that same rationale, the effects of allowing barges to file a priority request should be evaluated. To this author's knowledge, no research has studied either of these pricing mechanisms in any aspect of a container terminal.

The third pricing method focuses on spreading barge handling demand by using a revenue management approach. Pricing can be used as a mechanism to influence port calls by inland barges. This way, the arrival times of ships can be adjusted, increasing terminal utilisation, and reducing congestion and barge in-port times. According to van Riessen *et al.* [75], revenue management or pricing can be used in conjunction with operations management to create planning flexibility. Timeslots that are in high demand will be more expensive, while off-peak timeslots will be cheap. In a 2011 study, Chen *et al.* [76] use a two step approach to reduce truck congestion at a container terminal. First, they determine the system optimum arrival time distribution through a nonlinear programming optimisation model. Then, the normal demand for a set of timeslots is compared to the system optimum demand, which then functions as input into a pricing model. This research could be applied to container barge handling.

The final pricing method aims at improving stowage planning of deep-sea ships. As explained in subsection 3.2.3, improved stowage planning can increase terminal productivity. Recently, it has been posited in the market and the literature that terminals should move away from a flat rate to more variable rates, in order to provide shipping lines with incentives to improve their stowage planning [55], [57].

The measures related to deep-sea terminals have been summarised in Figure 3.5.

Changes to barge handling (T1)

- Increase barge handling capacity
- Increase call size with barge transferium or Container Exchange Route

Planning (T2)

- Berth Allocation Problem & Quay Crane Allocation Problem
- More information sharing with barges to improve their planning process
- Centralised Planning by Nextlogic

Pricing (T3)

- Auctioning all barge slots
- Priority requests to improve rotation planning
- Pricing barge slots to spread peaks
- Pricing deep-sea to reduce deep-sea handling times

Figure 3.5: Deep-sea terminal measures to alleviate high barge in-port times

3.2.3. Other Measures

The measures hereafter are not related to barge operators or deep-sea terminals. This subsection starts discussing the effects of using smaller deep-sea vessels. Then, the potential of network and schedule design is examined, as it can improve the schedule reliability of deep-sea ships. Increasing free days before demurrage and detention fees are incurred also aims to spread out operational peak loads, and is explained next. Finally, good stowage planning will be proposed as a way to mitigate the operational complexity deep-sea vessels impose upon terminals.

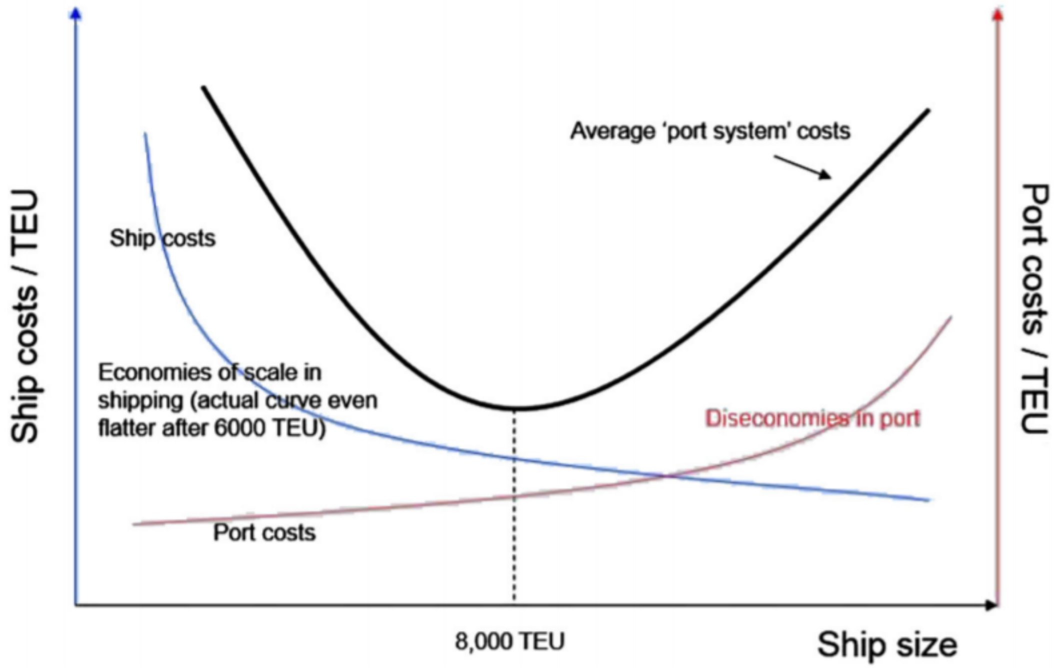

Figure 3.6: Illustration of the global optimum of shipping and terminal handling costs, from Haralambides [57]

Deep-sea Vessel Size

The three negative effects of large deep-sea vessels are the crane productivity drop, the increased operational complexity, and the increase in feeder ships. The first two effects directly reduce the terminal productivity, the last effect increases demand for quayside handling.
From the perspective of shipping lines, larger ships result in lower costs, and are therefore more attractive. From the perspective of terminals, however, from a certain threshold, larger ships result in steadily increasing costs per handled container. When combining these two unit costs, a global optimum can be found at much smaller ship sizes than currently in use, around 8.000 TEU, as seen in Figure 3.6 [57]. Under the assumption that the higher unit costs are the result of less efficient operations, it can be concluded that the large deep-sea vessels negatively impact barge operations. A move to smaller deep-sea ships will also reduce the need for such a hub-and-spoke system, and open up possibilities to directly service these feeder ports, thereby freeing up more quayside handling capacity for barges in Rotterdam.

Network and Schedule Design

Network and schedule design of the deep-sea liner routes have important implications along the supply chain. Shipping lines could opt for schedules that aren't as tight, by adding buffer days into the schedules. This would improve the schedule reliability of deep-sea ships.

Increased Free Days Before Demurrage and Detention Fees

As shippers will always try to minimize their demurrage and detention fees, having short free windows for demurrage and detention result in operational peaks. Research found that the reduced free days, combined with large deep-sea vessels has already lead to situations where penalty fees were inevitable [40]. Some terminals did not perform sufficient barge moves within the free demurrage window, thereby making it impossible for all the containers to be picked up on time.

Stowage Planning

One of the operational issues that deep-sea vessels can improve on is their stowage planning. While the poor stowage planning is partially a result of the increased vessel size and the ship-sharing by alliances, there are still operational gains to be made. Poor stowage planning greatly reduces crane productivity, which directly increases the vessel turnaround time. This leads to delays, causing schedule unreliability. In fact, variability in a vessels handling time is found to be the most important factor in

vessel delays [77]. As noted by Haralambides, ”this could offer carriers faster turnaround times [..], and ports better berth utilization; a truly win-win situation”. An example of a recent study into stowage planning is the study by Delgado *et al.*, in which 92% of the real-world instances could be solved to optimality within one second.
The measures related to other actors have been summarised in Figure 3.7.

Deep-sea Vessel Size (O1)

- Change deep-sea vessel size to approximately 8.000 TEU

Demurrage & Detention (O2)

- Increase free days

Schedule Unreliability (O3)

- Reduce unreliability through improved schedule design
- Align feeder schedules with deep-sea schedules

Stowage Planning (O4)

- Reduce turnaround time

Figure 3.7: Other measures to alleviate high barge in-port times

	Causes	Measures
Container Barges	**Barges (CB1)** • Higher capacity leads to longer rotation, which increases in-port time • For small call sizes, berthing time is significant **Planning (CB2)** • Gaming the system can lead to unwanted timeslots • Applying slack prevents optimal rotation planning **Fragmented market prevents cooperation (CB3)** • Lower call sizes • Long waits for cargo	**Barges (CB1)** • Reduction in berthing time • Effect of modular pushbarges **Planning (CB2)** • Barge Rotation Planning Problem for improved planning **Partnerships (CB3)** • Reduce number of calls • Increase call sizes
Deep-sea Terminals	**Handling speed insufficient (T1)** • Too few cranes, operators and quays • Room for technological improvements **Planning (T2)** • Final planning is made by terminal without regard for barge rotation; barge cannot signify importance of timeslot • Delayed response to barges **No contractual relation with barge (T3)** • No penalty if they don't keep appointment • No payment by barge makes them a low priority for terminals	**Changes to barge handling (T1)** • Increase barge handling capacity • Increase call size with barge transferium or Container Exchange Route **Planning (T2)** • Berth Allocation Problem & Quay Crane Allocation Problem • More information sharing with barges to improve their planning process • Centralised Planning by Nextlogic **Pricing (T3)** • Auctioning all barge slots • Priority requests to improve rotation planning • Pricing barge slots to spread peaks • Pricing deep-sea to reduce deep-sea handling times
Other actors	**Deep-sea Vessel Size (O1)** • Crane productivity drop • Alliances lead to bad stowage plan • Hub and spoke network leads to higher feeder volumes **Short free days before Demurrage & Detention (O2)** • Barge handling demand in peaks to avoid penalties • Less time for consolidation of hinterland volumes **Schedule Unreliability of Deep-sea Ships (O3)** • Deep-sea vessels visits are closer together • More unused quay hours for terminals	**Deep-sea Vessel Size (O1)** • Change deep-sea vessel size to approximately 8.000 TEU **Demurrage & Detention (O2)** • Increase free days **Schedule Unreliability (O3)** • Reduce unreliability through improved schedule design • Align feeder schedules with deep-sea schedules **Stowage Planning (O4)** • Reduce turnaround time

Figure 3.8: Overview of high barge in-port time causes & measures. Causes and measures are grouped by the actor that is responsible for the cause or measure.

4

Simulation Model to Study Barge In-port Times

Following the research approach that was laid out in Figure 1.3, so far, an understanding of the system functioning was gained in chapter 2. It was followed by studying high barge in-port time causes and alleviation measures, in chapter 3. This thesis aims to validate these causes and measures by using a simulation model. This chapter aims to answer subquestion 4: *How should the system be modelled, both conceptually and in a simulation model?*

This chapter is split in two main parts: the conceptual model and the simulation model. First, the conceptual model to study barge in-port times is explained. This starts with a short introduction to conceptual modelling, which is then applied to container barge in-port operations, leading to a scope and detail that is presented in section 4.1. Consecutively, the conceptual model and computerised model are discussed in more detail. Both of these parts are structured similarly, starting with input parameters, continuing with the main model, and ending with model output. Each of the sections on the conceptual model will explain how the conceptual model is built. In the simulation model description, the conceptual model will be 'computerised' or 'translated' to computer code. The sections on the simulation model will discuss how the data was manipulated to fit the conceptual model, elaborate on how the required functionality from the conceptual model was implemented in software, and report values for, and reasoning behind, simulation-related parameters such as number of replications.

However, before the conceptual model is discussed, recall that the simulation model will be a Discrete Event Simulation (DES).

4.1. Conceptual Model: Scope and Level of Detail

Following the formal definition by Robinson [79], a conceptual model is "a non-software specific description of the computer simulation model [..], describing the objectives, inputs, outputs, content, assumptions and simplifications of the model." The inputs, content, and outputs will be discussed in the following three sections, respectively. Assumptions and simulations will be discussed in the report sections that elaborate on the model elements where the assumptions and simplifications were made. This section will present two major simplifications with regard to scope and detail, that should be discussed up front, as they are instrumental to how the rest of the conceptual model is defined.

A conceptual model will always be an abstraction of the real-world system. Nevertheless, the model should be detailed enough to be a valid representation of the real-world system. According to Robinson [79], the scope and detail of the model are a function of the modelling objectives, as they lead to input variables and output indicators whose relations are to be studied. Simultaneously, as stated by Law [24], "the level of model detail should be consistent with the type of data available". To summarise, a balance must be struck between simplicity and completeness, keeping in mind what relations should be studied and what data is available. When applied to barge in-port times, this leads to two main simplifications that are incorporated in the conceptual model: the fact that deep-sea ships and containers are not modelled explicitly. They will be discussed in the next paragraphs.

Unfortunately, data on the deep-sea vessels' planned and actual arrival times, handling times, and what terminals they visit, is not available. Therefore, modelling them explicitly will likely be detrimental to model validity; they will not be modelled. As a result of their absence from the conceptual model, the effects of changes to deep-sea handling can not be studied directly. The absence of deep-sea ships from a model to study barge in-port times in Rotterdam is not unprecedented: the earlier work by Douma *et al.* [67] omitted deep-sea ships from their model. The effect that deep-sea vessels have on the terminals' handling capacity is incorporated in the model by using the barge moves dataset as mentioned in subsection 2.3.3. The effects of other changes to deep-sea handling can be evaluated by 'translating' these changes to their effects on barge and terminal properties that are modelled explicitly. The incorporation of deep-sea vessels into deep-sea terminal crane availability is discussed in section 4.2 and section 4.6. The changes to deep-sea handling, and how they are evaluated with this model, are discussed in section 5.3.

Containers are not modelled explicitly either, as entities that flow through the model. This would require data on their last acceptable drop-off or pickup time, which is unavailable. In the conceptual model, barges have call sizes at the various terminals that dictate their operations, rather than a list of entities that they have to pick up. Because containers are not modelled, there is no distinction between moves of 1 or of 2 TEU. As a simplification, each move is assumed to move 2 TEU. As the TEU-factor is 1.68, 68% of containers are 40-foot containers, making all these moves 2 TEU. The other 32% are 20-foot containers, and are simplified to always be moved in pairs.

The conceptual model is presented in Figure 4.1. In the figure, a distinction between input parameters, model functionality, and output indicators is seen. These will be discussed in the following sections.

4.2. Conceptual Model: Input Parameters that Influence Barge In-Port Times

The goal of this research is to understand and reduce high barge in-port times. Potential causes for these high in-port times were provided in the literature review in section 3.1. In order to test the influence of these factors, these causes should be validated by the model. As can be seen in Figure 4.2, decisions by Barge Operators, Deep-sea Terminals, and Deep-sea Shipping Lines influence important barge and terminal properties. This section is split in two parts: first, barge properties and influences on these properties are explained; second, we do the same for terminal properties.

4.2.1. Barge Properties

Both subsection 2.2.3 and subsection 3.1.1 discussed properties that determine barge in-port operations. The properties that will be used to model barge operations are:

- the number of calls a barge has to make in port
- what terminals these calls are at, and in what order
- the call sizes of each of these calls
- the slack a barge uses while planning

The effect of loading plans, which store what containers are on board a vessel, and in what order they must be offloaded or loaded, are simplified to be incorporated in the sequence that a barge visits terminals in. Similarly, the absence of explicit containers from the conceptual model means it is not possible to model their closing times at the various container terminals. The effect of these is also simplified to be included in a barge's sequence. These four properties can be influenced by different actors.

A barge operator can instigate partnerships, or bundling initiatives, which can lead to higher call sizes, and fewer calls. A barge operator's fleet size can influence both the call sizes and number of calls, because a large fleet, and the resulting larger total transport volumes allow for bundling. The rotations a barge follows are more flexible, when part of a larger fleet: a second barge can pick up containers that would require a lengthy delay for the first barge, enabling the first barge to leave the port and avoid the waiting times. Of course, the barge type is decided in combination with the fleet size, when a certain transport volume is assumed. Here, smaller barges require fewer calls. Finally, planning rules determine what slack barges use when planning a rotation, and how barges act upon receiving infeasible rotations.

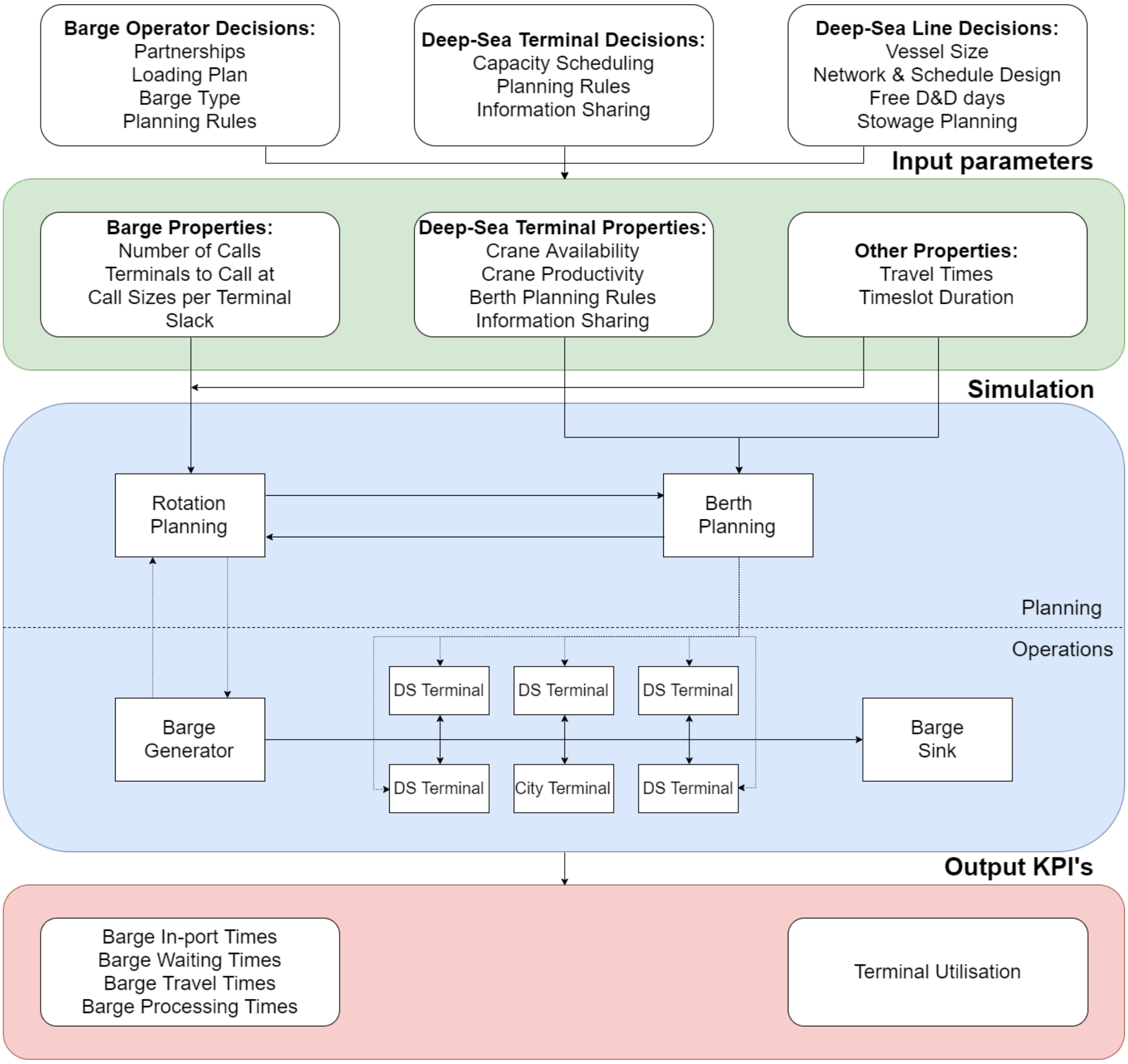

Figure 4.1: Conceptual model

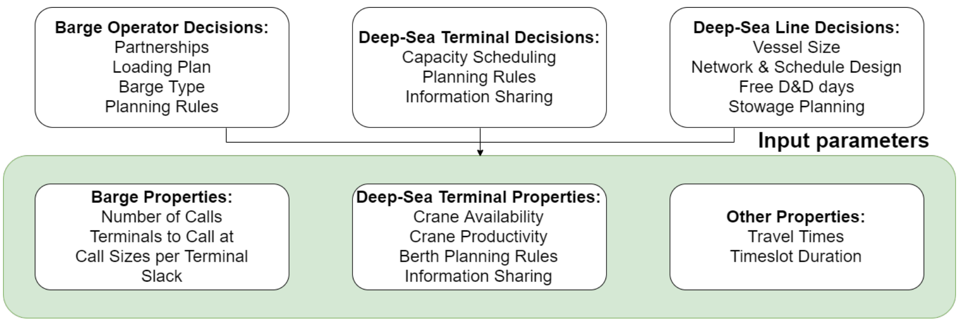

Figure 4.2: Conceptual model: input parameters, and decisions influencing these parameters for the three main actors

Terminals can also influence barge planning, by deciding how much information to share with the barges. More information sharing could benefit both parties, as it aims to reduce the prevalence of infeasible rotations that negatively impact terminal utilisation.

Finally, deep-sea shipping lines can indirectly influence barge properties, by changing the number of free days before demurrage and detention charges are incurred. Increasing these days can allow barge operators to wait a bit longer before picking up containers at a terminal, thereby increasing call sizes of barges.

4.2.2. Terminal Properties

A terminal's most important property with respect to barge in-port times - as with any server's property in a queuing system - is its barge handling capacity, which is a combination of the number of free cranes over time and the crane productivity. In the model, we simplify terminal operations by assuming that quay wall is available when cranes are available. Furthermore, we assume that each available crane has the same crane productivity, ignoring the difference between deep-sea cranes and barge cranes. This productivity is assumed to be deterministic. Another property is how a terminal performs its berth planning. The logic behind berth planning at deep-sea terminals depends on the terminal's preferences. The final terminal property is the level of information that the terminal provides.

As mentioned in section 2.3, terminals compete heavily, and try to keep operational costs low by keeping utilisation rates high. By scheduling more crane operators, barge handling capacity can increase, but operational costs will increase. Terminals determine the number of required cranes, deciding how many operators to schedule per shift. The crane productivity can also be increased by technological improvements.

Terminals can also greatly influence the rotation planning and berth planning processes, in two ways. Terminals have a power position when it comes to planning barges, as they unilaterally determine what timeslots to allocate to a barge. Therefore, their berth planning rules influence barge in-port times. The initial rotation plans of barges can also be improved, by increased information sharing. Both of these decisions affect planning.

Deep-sea shipping lines influence terminal properties. As was outlined in subsection 3.2.3, vessel size has negative effects on barge handling capacity, by making terminals less efficient. Additionally, the operational peaks caused by large vessels concentrate the demand for barge handling capacity. Deep-sea vessels are frequently late, and difficulties utilising the cranes when this happens negatively impacts barge handling capacity. Network and Schedule Design by deep-sea shipping lines can reduce deep-sea delays, improving barge handling capacity. Another influence is the poor stowage planning that is frequently seen on large deep-sea vessels, as explained in subsection 3.1.3. This further impacts barge handling capacity, by requiring cranes for a longer period of time to offload the deep-sea vessel.

4.3. Conceptual Model: Functionality

The conceptual model contains five deep-sea terminals and a single city terminal. An underpinning for why these six terminals are chosen is provided in subsection 4.3.2. A network of links, each with an associated travel time, connects these terminals. Each of these terminals has values for the properties that were laid out in the previous section. The conceptual model's main functionality consists of two layers: the planning layer and the operational layer. The planning layer precedes the operational layer. Barges are generated at discrete points in time. Then, they plan their rotation, based on the call sizes at each of the terminals. Once they have planned their rotation, they file requests for the planned timeslots at all required terminals. Barges have to await the terminals' berth planning. The terminals collect the timeslot requests until their respective cutoff times, before planning the requests into their schedule, based on their barge handling capacity. When they've finished planning, they let the barges know whether or not their timeslot request was accepted or not. As soon as a barge has entered the port area, it starts following its rotation. When the barge has visited all the terminals in its rotation, it leaves the port.

Figure 4.3 shows an overview of the main functionality in the model, along with relevant input parameters at steps where they are required.

4.3.1. Barge Functionality

Barge are generated at the generator, 72 hours before their arrival in Rotterdam. The barges must be generated in advance, so that they can reserve timeslots close to their in-port arrival time, as timeslots must be requested up to 58 hours in advance at RWG, as explained in section 2.3. A barge is generated with properties, as discussed in the previous section. Some of these properties - call size, number of calls, slack - influence the rotation planning, along with other parameters such as sailing times between the terminals, and what level of information the terminals share. We assume that barges

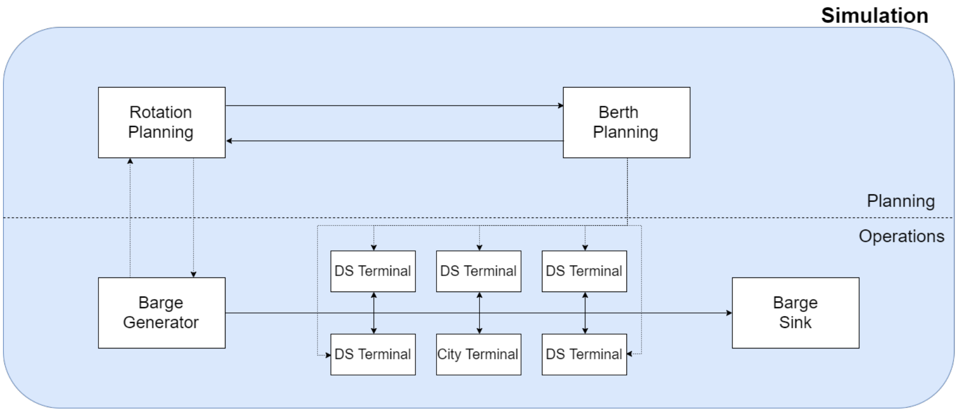

Figure 4.3: Conceptual Model: Main Functionality

have a preferential order to go through the terminals, reflecting the loading pattern, closing times for their containers, and when their import containers are ready to be picked up. As the deep-sea ships or container loading plans are not modelled, this order is based on chance.
The ideal starting timeslot at a terminal is based on the last timeslot at the previous terminal, the travel time between the terminals, and the barge's planning slack. The rotation plan leads to timeslot requests. Then, the barge waits for the different terminals to perform their berth planning. Upon arrival in the port, the barge will have received what timeslots were allocated to it by the terminals. If the responses have led to a feasible rotation, the barge visits the terminals according to its plan. If the rotation is infeasible, it follows the infeasible rotation, until it misses a reservation. When a barge reaches a terminal where it missed its reservation, the barge gets the next available timeslot for that terminal, as soon as it reaches the terminal. When all containers have been dropped off and picked up, a barge leaves the port area, and is removed from the model.
In order to ensure that the reservations are followed, the model has to check whether or not barges are allowed to go to a terminal. If barges can go directly to the next terminal in their rotation, and the terminal has available cranes, the barge will be handled. However, this may interfere with other barges' reservations, and delay the start of these other barges' handling periods. Much like in reality, a barge should not be handled without a reservation, to avoid disrupting a terminal's schedule. Therefore, while on its rotation through the port, a barge has to wait for the appropriate time before being handled at any terminal.

4.3.2. Terminal Functionality

In the conceptual model, six terminals are depicted. These six terminals consist of five deep-sea terminals and one city terminal. In Rotterdam, there are 5 deep-sea terminals and many other terminals. The other terminals have been simplified to form a single terminal in the model. The five deep-sea terminals are the main cause of delays, as they have the highest throughputs, and their handling capacity is highest in demand, as deep-sea ships frequently visit these terminals. Therefore, all five deep-sea terminals are modelled. The other terminals are a smaller source of delays, but must be modelled in some way in order to capture the travel times that result from Rotterdam's geographical structure. This was done by modelling the smaller container terminals in the city as a single city terminal. For an overview picture of Rotterdam, the reader is referred to Figure D.1 on page 106.
The terminal planning process precedes the operational activities. Only the deep-sea terminals plan their activities, the city terminal is assumed to have enough capacity to handle all visits. The five deep-sea terminals have three corresponding cutoff times, reflecting the three terminal operators in Rotterdam. Terminal 1 and 2 share a cutoff timer, terminal 3 and 4 share a cutoff timer, and terminal 5 has an individual cutoff timer. Each of these terminals has a barge handling capacity that is based on crane productivity and a number of cranes that changes over time, both of which are input properties. As explained previously, quay wall is assumed to be available when cranes are available. Combining the timeslot requests with the available capacity and a planning algorithm, the terminals plan their berth schedule. The planning algorithm is as follows: the terminals collect the list of requests, and find the request with the highest number of timeslots. If the request fits the terminal's berth planning, the

Table 4.1: Mapping of real terminals to conceptual model

Model	Terminal	Cutoff Timer
DS Terminal 1	ECT Delta	ECT
DS Terminal 2	ECT Euromax	ECT
DS Terminal 3	APM MV2	APM
DS Terminal 4	APM Rotterdam	APM
DS Terminal 5	RWG	RWG
City Terminal	Combination	N/A

request is approved. If the request does not fit the schedule, the terminal schedules the barge to visit in the first available timeslot after the requested timeslots. When the request is planned, it is removed from the list of requests, and the next request is found, based on number of requested timeslots. This is repeated until all requests have been planned.

Due to unilateral planning, barges can have infeasible rotations due to rejected timeslot requests. This means terminals will have no-shows, as barges are delayed. When a barge arrives at a terminal after having missed its timeslot, the terminal will reschedule the barge. The terminal does not want the barge to impact the entire schedule, so it finds the first available opening in its schedule, and allocates that to the barge.

One final property of the terminals is what level of information it shares. For instance, it could share the number of scheduled cranes per timeslot, or use a traffic light system, where each timeslot is green, orange, or red, based on the number of requests and the crane capacity. In the current situation, this is not done, and barges plan their rotations based on information regarding their rotation. A detailed description of changes to information sharing is presented in chapter 5.

4.3.3. Assumptions and Simplifications

The full complexity of the real life process can not be modelled. Therefore, simplifications and assumptions have been made. The assumptions have been explained in previous sections, but are summarised for clarity here. These are:

- Inter-terminal transportation by barge, called vletwerk, is neglected due to a lack of data
- All terminal operations after the quay wall are not modelled; this is assumed to be encapsuled in the handling capacity
- Deep-sea ships are assumed to have always delivered, and not be delayed. Their effect on crane availability is modelled
- Unberthing time is neglected
- There is no difference between unloading and loading operations
- Empty depots are not modelled, as they are not expected to cause (large) delays
- In the model, a move will always be 2 TEU. The TEU-factor in Rotterdam is 1.68, and most 20 foot containers are moved in pairs. Therefore this distinction will not be made in the simulation model
- No direct transshipment from deep-sea, short-sea or feeder vessels to barges
- All deep-sea terminals are modelled, but all other terminals are modelled as a single terminal. This is because congestion is mainly experienced at the deep-sea terminals. However, to incorporate sailing time in the model, the other terminals are required
- A delayed barge will get the next available timeslot at a terminal upon arrival, the free timeslots are distributed first come first serve
- There is a lack of data on barge rotations, so the rotations are drawn randomly, based on terminal throughput numbers
- The handling capacity per crane is deterministic
- No distinction is made between barge cranes and deep-sea cranes
- Fixed Windows are not planned, as there is no data available on when they are
- Terminal planning decisions have been simplified to only rank the requests on number of required timeslots

- Because terminal capacity changes hour per hour, the peaks will not be likely to be used, negatively dampening terminal utilisation
- Because terminal capacity is randomly drawn for each hour, the consecutive hours' capacities are independent of one another. In reality, these are related, and depend on events such as the arrival of a deep-sea ship

4.4. Conceptual Model: Output of Key Performance Indicators

Figure 4.4: Conceptual Model: Output KPI's

In this research, we distinguish between indicators for overall system performance, and model output per replication, that can be used to gain a more in-depth understanding. First, we will discuss the indicators for average performance; then, we define output indicators for more detailed analysis.
Other papers on high barge in-port times used a mix of average barge in-port time, average lateness and top 10% lateness [62], or average in-port time, total waiting time, and in-port time of latest vessel [74]. Lateness can only be calculated relative to an expected departure time, which was determined quite arbitrarily in the paper by Douma *et al.*: either a fixed time was used, irrespective of the barge properties, or a variable time was used, based on the number of terminals a barge had to visit. Clearly, both articles were also interested in the in-port time distribution. As both used distributed planning systems, they were interested in how equally the in-port time improvements were shared. In this research, MORE plots will be used to visualise the average in-port time distribution, as MORE plots give a good overview of the system performance and the confidence interval [80]. An example of a MORE plot can be found in Figure 4.5.
From a terminal perspective, high crane utilisation rates are preferred, as a high utilisation rate signifies cost-efficiency. These must be monitored. As the majority of terminal operations are not explicitly modelled, this is the only terminal-related KPI.
In order to gain more detailed insights, each model run should output more detailed statistics than just the average barge in-port time. We distinguish between the various activities a barge performs when in port, and do so per barge. Barge in-port activities are split in three categories: waiting times, travel times and processing times. These three should be stored separately. They serve two goals: first, they improve understanding of the reasons for high in-port times, and provide options for more insightful analysis. Second, as the Barge Performance Monitor reports the shares of these three in-port activities, they can be used to validate the model. In order to be able to more finely investigate the reasons for high barge in-port times, the three categories of activities should be stored per terminal call, to dissect

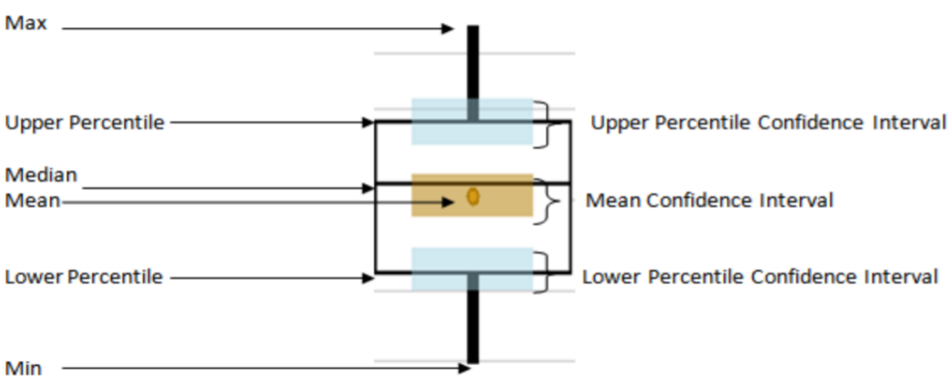

Figure 4.5: Annotated MORE plot

how the totals for these three categories are built up.

4.5. Simulation Model: Instruments

Before we specify the simulation model, the instrument in which it will be specified is presented, along with reasoning why this package was chosen.

Discrete Event Simulation (DES) is useful when stochastics are an important part of the system under study. In the case of high barge in-port times, peaks in demand, differences in barge handling capacity, and different call sizes at terminals are good examples of variability. Barges and terminals have to make several decisions. In order to replicate this, intelligence of the actors must be incorporated. The terminals should store what timeslots have already been allocated, and what requests have been received. Combining these two pieces of information, terminals must respond to these requests. On the other side, barges should be able to request slots at the terminals, based on their own planning and a certain degree of information from the terminals. However, standard DES does not allow for decision making per actor. As such, Agent-Based Simulation (ABS) should be used, to allow the terminals and barges to share information with each other, and allow them to make decisions based on that information.

Software packages aimed at agent-based modelling are generally geared towards exploring emergent properties of multi-agent systems, based on behaviour of individual agents. Examples of such systems are epidemic outbreaks, population dynamics, and stock market movements [24]. Meanwhile, DES software is focused on adding stochasticity to processes that can be modelled as queueing systems. A DES package with agent or object oriented functionality was preferred, as the barge in-port system has more characteristics of a discrete event simulation than an agent-based model. Therefore, Simio 10.174.16986 (64 bit) was chosen [81]. Simio is shorthand of **sim**ulation with **i**ntelligent **o**bjects.

When applying the object-oriented capabilities of Simio to the conceptual model, a new object class will be made for both the barges and the terminals. These object classes will have attributes, in which they store the properties and required system states for the barges and terminals to make decisions. These decisions are made in processes. This structure of object attributes and object processes will be found for the barge object in subsection 4.7.1 and subsection 4.7.2, and for the terminal object in subsection 4.7.3 and subsection 4.7.4.

4.6. Simulation Model: Data Gathering and Cleaning

4.6.1. Barge Data

As stated in section 4.2, four main properties determine a specific barge's operations in the port. These four properties are the number of terminals the barge visits, what terminals these are, the corresponding call sizes, and their slack while planning. For two data points, a data table is required, dictating the probability that a new barge becomes a certain type, signifying what area it serves. This service area will then determine the number of calls and the corresponding call sizes. Pieced together, a yearly throughput in TEU per service area results from the table. This throughput is the total of import and export containers. Table 4.2 shows the input table for the barge generator. For more information on how this data table was constructed, the reader is referred to Appendix B. The data in Table 4.2 are all subject to stochastics during model runtime. More detail on how this data table is translated to each specific barge's attributes in the simulation is provided in subsection 4.7.1.

Table 4.2: Barge Generator Dataset

Service Area	Chance (%)	Sum of Call Sizes / Visit (TEU)	Calls / Visit	Total TEU / Year
Antwerp	10	390	2	702,000
Small Domestic	16	100	3	288,000
Large Domestic	47	200	5	1,692,000
Lower & Middle Rhine	18	300	4	972,000
Upper Rhine	9	260	6	421,200

While Table 4.2 does state the average number of calls for each barge type, it is unclear at what specific terminals the barge must call. This data is only known to the barge operators. Unfortunately, as this

is sensitive information that is spread across a large group of actors, an alternative method had to be found. Therefore, the specific terminal for each call will be sampled, based on the yearly throughput of the terminals. This data will be presented in subsection 4.6.2.
The final property, a barge's planning slack, is important when planning the rotation. Unfortunately, data on what slack barges use is not available. Therefore, assumptions were made.
In the model specification, the slack is set to 1 hour. While this is not enough to absorb large delays, this value was chosen because it showed the best results in the 2011 study by Douma *et al.* [62].

4.6.2. Terminal Data

As discussed in section 4.2, three pieces of input data are required to model terminal operations: their barge handling capacity, their level of information sharing, and their berth planning rules. The last subsection explained that terminal throughput data will also be used as probabilities to determine what terminals are visited by each barge. First, the terminal throughput data is presented. Then, the barge handling capacity will be explained. Finally, information sharing and berth planning rules are discussed.
The PORA could not provide yearly throughput numbers or barge volumes for the deep-sea terminals [22]. Therefore, assumptions must be made, based on publicly available information. The total terminal area, number of quay cranes, quay wall length, and throughput information from their websites were combined. Using these throughput numbers, each terminal is given a fictive visit ratio, that is less precise than the throughput share. This leads to the and yearly throughput numbers and shares shown in Table 4.3. The construction of this table is explained in Appendix B.

Table 4.3: Aggregate Terminal Data, from Appendix B

	ECT Delta	**ECT Euro**	**APM 1**	**APM 2**	**RWG**	**City**
Visit Ratio	10	5	7	6	5	6
Percentage (%)	25.6	12.8	17.9	15.4	12.8	15.4
Barge volume (TEU) / year	1,044,923	522,462	731,446	626,954	522,462	626,954

Section 2.3 mentioned that one of the deep-sea terminals provided a dataset on their hourly barge moves for a period of two months. This dataset forms the starting point for determining the barge handling capacities for each terminal in the model. To get from the dataset to a barge handling capacity per terminal, the following procedure was used.

1. The different random distributions that are available in Simio were fitted on the provided dataset, to find what distribution fits best.
2. Each terminal in the model samples a number of moves per hour from the random distribution, for each hour, and scales this to reflect the relative terminal size.
3. This number of moves per hour is translated to a number of available cranes.
4. The barge handling capacity is the multiplication of the number of cranes and the crane productivity per terminal.

Using the Python package "Fitter", a random distribution was fitted to the barge handling capacity dataset. A lognormal distribution proved to be the best fit. The resulting number of barge moves was scaled using the capacity ratio's of the terminal in question and the terminal that provided the dataset, as seen in Table 4.3. This had to be translated to a number of cranes, to know how many barges can be handled simultaneously. This was done by dividing the amount of moves by 20, and then rounding up. To translate the number of cranes to number of lifts, each terminal has a crane productivity. This is assumed to be 20, but can be changed later, to reflect changes to their crane productivity. Finally, to go from lifts to TEU transferred, the number of lifts is multiplied by two, as discussed in section section 4.1.
In the model, terminals evaluate the requests and have a methodology to reach a berth planning. As mentioned in section 2.3, some terminals prioritise certain types of barges. One factor herein is whether or not a barge operator frequently visits a terminal, and how many no-shows they have. The link between specific barges and barge operators has not been modelled, which renders this method of prioritising barges impossible. Some terminals also prioritise barges that sail to Antwerp or Germany.

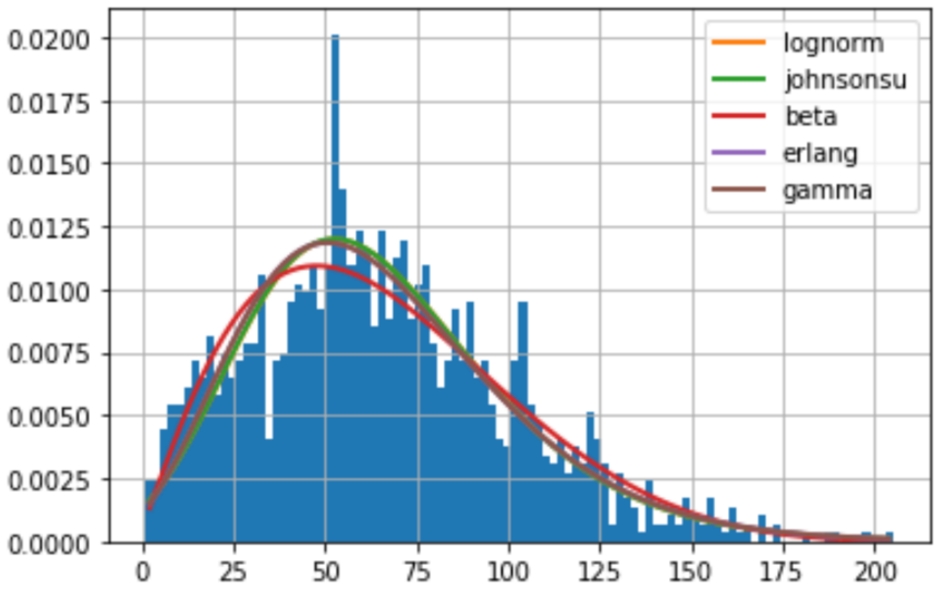

Figure 4.6: Barge moves histogram with five best fitting distributions

This could be done, as the service area of each barge is modelled. However, the planning method in the model does not take this into account. The planning rules for all terminals are as follows: from the list of requests, they find the request with the highest number of required timeslots, which they plan in the requested timeslots if they are available. If they are unavailable, the terminal schedules the barge in the first available slots *after* the requested timeslots. Then, the request is removed from the list of requests, before the terminal looks for the next largest request. With regard to information sharing, terminals currently share very limited data with barges. As such, no information sharing has been incorporated in the simulation model.

4.7. Simulation Model: Model Specification

This section will explain how the main functionality from the conceptual model is translated to the simulation model. The specification of barges and terminals in Simio is presented. Finally, some simulation parameters are discussed.

4.7.1. Barge Attributes

In order to properly model the different steps a barge takes during a rotation, and be able to model the distinctive properties of each barge, each modelled *instance* of a barge should have several attributes. These attributes can be found in Table 4.4. All vectors, except the sequence, store information per terminal. The matrices account for multiple visits per terminal, as they can store multiple data points per terminal.
Some of the attributes incorporate stochastics or represent real-world characteristics; they will be explained in the following paragraphs.

Total Calls

The total number of calls is randomly drawn, based on the average number of calls as reported in Table 4.2. The total number of calls falls between the average number of calls minus one and plus one, with all options having equal weight. For instance, if the average number of calls for a barge type is 2, then each specific barge can have 1, 2 or 3 calls. The following formula is used, in which the epsilon denotes an arbitrarily small positive quantity, to avoid rounding up to 4 calls:

$$Total\ Calls = Round\big(Random.Uniform(Average\ Calls\ -\ 1.5,\ Average\ Calls\ +\ 1.5\ -\ \epsilon)\big)$$

Table 4.4: Barge attributes, defined per instance of a barge

Attribute	Datastructure	Description
Barge Type	Scalar	Stores the barge service area
Sequence	Vector	Stores the terminal sequence
Total Calls	Scalar	Stores the total number of calls
Calls per Terminal	Vector	Stores the number of calls per terminal
Call Size	Matrix	Stores the call size per terminal call
Entry Time	Scalar	Stores the entry time in the port
Next Travel Time	Scalar	Stores the travel time to the next destination
Number of TS	Matrix	Stores the number of timeslots required per call
Requested Slot	Matrix	Stores the *first* requested timeslot per call
Allocated Slot	Matrix	Stores the *first* allocated timeslot per call
Last Timeslot	Scalar	Stores the last timeslot for planning purposes
Processing Time	Matrix	Tallies the processing time per terminal call
Waiting Time	Matrix	Tallies the waiting time per terminal call
Travel Time	Matrix	Tallies the travel time per terminal call
Visit Number	Scalar	Tallies how far on its rotation a barge is
Completed Calls	Vector	Tallies completed visits per terminal

Call Size

The call size is drawn from a random distribution for each instance of a barge, for each terminal it visits. The distribution is uniform, ranging from half the average call size to 1,5 times the average call size. The average call size is the total import and export in TEU, depending on the barge service area, divided by the number of calls. Because the call sizes are randomly drawn, the resulting total import and export volumes per barge The following formula's are used:

$$Average\ Call\ Size = \frac{Total\ transport\ volume\ per\ port\ visit\ (TEU)}{Total\ Calls}$$

$$Call\ Size = Round\big(Random.Uniform(Average\ Call\ Size * 0.5,\ Average\ Call\ Size * 1.5)\big)$$

Number of Timeslots

The number of timeslots for each call is based on the length of each timeslot, the call size, and the expected processing speed at that terminal. The following formula is used:

$$Number\ of\ TS = Ceiling\left(\frac{Call\ Size\ (TEU)\ /\ Crane\ Productivity\ (TEU\ /\ hour)}{Timeslot\ Duration\ (hours)}\right)$$

Ceiling is a mathematical function that rounds up a number. Even if a barge only requires a small part of a timeslot, it must reserve the entire timeslot.

4.7.2. Barge Processes

Barges make decisions regarding their planning. Therefore, they run processes. The processes are shortly explained hereafter, and in more detail in the following paragraphs. The order in which the processes are explained mimics the order in which a barge will perform them.

Create Sequence In this process, the barge draws the number of calls the barge will make in port, before drawing the sequence of terminals the barge must visit. It also draws call sizes for each of the terminal visits.

Rotation Planning After the sequence has been defined, the barge plans a rotation, deciding what timeslots to request at each of the terminals in its rotation.

Wait For Timeslot Once the barge is in the port, it waits until its timeslot nears, before going to a terminal.

Create Sequence

First, the barge type and service area are drawn. This dictates the number of calls, as explained in subsection 4.7.1. The sequence of each barge is generated randomly, by drawing the sequence based on a number of calls, and the probabilities for each of the terminals, as depicted in Table 4.3. If a barge has 3 calls, this results in 3 separate draws from a uniform random distribution, which then determines the next terminal in the rotation. As the sequence is based on probabilities, it would be theoretically possible that a barge sequence consists of multiple, consecutive visits at the same terminal. In reality, it is possible that a barge visits a terminal twice in a rotation, but these visits can not be consecutive, as they would be seen as a single visit. Therefore, before appending a terminal to a barge's sequence, the sequence is checked. The random number is re-drawn until the next terminal in the sequence is not equal to the previous one.
For each terminal in the sequence, a call size is drawn, as explained in subsection 4.7.1.

Barge Rotation Planning

Now that the barge has determined its sequence, the barge can plan its rotation, and request timeslots at the terminals. In the current situation, the barge does not have any information from the terminal, and will plan its rotation based on the sequence in which it must visit the terminals, the handling time at each terminal, the sailing time to the next terminal, and a certain slack period. The barge will then request these timeslots at the various terminals. The algorithm that describes how this is done can be found below. Some lines are explained beneath the algorithm, to clarify these steps.
The barge rotation planning process was programmed modularly, with one main rotation planning process calling on five separate processes to request the timeslots, and a sixth process to update some barge attributes when it plans a city terminal visit.

Algorithm 1: Barge Rotation Planning

```
   Data: Sequence, Call Sizes, Entry Time, Next Bookable slot at Terminals, Travel Times between
         terminals
   Result: Rotation Plan, Filed requests
1  while Not all terminal calls have been requested do
2  |   Determine next terminal in Sequence;
3  |   Determine Next Travel Time;
4  |   Calculate Requested Slot;
5  |   while Not as many requested slots as Number of TS do
6  |   |   File request in the terminal's Requests attribute;
7  |   |   Update the terminal's Nr of Requests attribute;
8  |   end
9  |   Update Last Timeslot;
10 |   Add barge to terminal's Request List attribute;
11 end
```

In line 4, where the timeslots are determined, the following logic is used: the first timeslot cannot be **before** any of the following: the *Next Bookable Slot* at the terminal, dictated by the terminal's cutoff time; the first bookable slot, based on the in-port *Entry Time* of the barge and the *Next Travel Time* to the terminal; the *Last Timeslot* the barge had, plus the *Next Travel Time* and planning slack. Therefore, the first timeslot is the maximum of those three variables. The total number of requested timeslots must equal the number of timeslots that were calculated for that call, as calculated in subsection 4.7.1. Line 6 requests the timeslots by inserting the barge's name in a matrix of requests, which is an attribute of the terminal. This will be explained in subsection 4.7.3.

Wait for Timeslots

As was briefly explained in the conceptual model, the barge can only be handled at a terminal when the timeslots it has been allocated are near, as it may otherwise disturb the terminal's berth schedule. Therefore, the goal of this process is to delay the barge until the allocated timeslot. The barge can be handled no earlier than the timeslot *before* the reserved timeslot has started, provided that the terminal has available cranes.

4.7.3. Terminal Attributes

Similar to the barge, the terminals must also have attributes in order to facilitate autonomous planning decisions as laid out in the conceptual model. The following table lists these attributes, and provides a short description.

Table 4.5: Terminal Attributes, defined per instance of a terminal

Attribute	**Datastructure**	**Description**
Next Bookable Slot	Scalar	Stores the next requestable timeslot
Terminal Capacity	Vector	Stores the number of cranes per hour
Crane Productivity	Scalar	Stores the crane productivity
Requests	Matrix	Stores the barge requests per timeslot
Reservations	Matrix	Stores the reservations per timeslot
Nr of Reservations	Vector	Stores the number of reservations per timeslot
Nr of Requests	Vector	Stores the number of requests per timeslot
Request List	Vector	Stores the barges that have requested timeslots
Nr of Consecutive Free Slots	Vector	Stores the available slots from each timeslot
Housekeeping Bound	Scalar	Stores the number of required TS by delayed barge

Next Bookable Slot

This attribute is used to keep track of the next bookable timeslot for any of the terminals, at any given time. For instance, if the simulation starts at 9:00 on Monday morning, the next bookable slot at ECT is at 24:00 on the night of Tuesday to Wednesday. At 18:00, which is the cutoff timer for ECT, this is incremented by 24 hours. The date and time are converted to a timeslot number, counted from the start of the simulation. Table 4.6 shows how current time, current timeslot, and next bookable slot relate for timeslots of 15 minutes.

Table 4.6: ECT Cutoff Timer: relation between time, current timeslot, and next bookable timeslot

Current Time	Mo 9:00	Mo 17:45	Mo 18:00	Tu 09:00	Tu 17:45	Tu 18:00
Current Timeslot	1	36	37	97	132	133
Next Bookable Slot	157	157	253	253	253	349

Terminal Capacity

The terminal capacity will be determined by the procedure as explained in subsection 4.6.2. At the beginning of a simulation run, it is drawn for the entire runtime, for each terminal, using the ratios from Table 4.3. The exception is the city terminal, which is assumed to have more than sufficient capacity. Therefore, the capacity at the city terminal is multiplied by 2.

Requests and Reservations

Requests and Reservations are matrices that are used to store the barge requests and allocated reservations. They have as many rows as there are timeslots in the runtime of the model. The requests matrix can store as many requests as required, and is therefore not capped in number of columns. The reservations matrix can only ever take as many reservations as there is terminal capacity. The barge requests and reservations are stored by simply adding their name to the corresponding row in the matrix.

Number of Requests and Reservations

These two attributes are used to count the received requests and allocated reservations per timeslot. They ensure that requests are not inserted over previous requests, and keep track of the number of reservations, to ensure that the number of reservations never exceeds the available terminal capacity.

Number of Consecutive Free Slots

This attribute is used to store the number of consecutive free timeslots, starting with any timeslot in the duration of the simulation. This attribute facilitates the replanning of delayed barges. For instance, if starting from timeslot 10, the terminal in question would have 8 free timeslots before there is no available capacity, a barge that requires 7 timeslots can be planned to start at timeslot 10.

Housekeeping Bound

The housekeeping bound is used to make the housekeeping process more computationally efficient. More information on how this works exactly will be provided alongside the explanation of the housekeeping process.

4.7.4. Terminal Processes

Terminals make autonomous decisions regarding their planning. To replicate this, they run processes. The processes are shortly explained hereafter, and in more detail in the following paragraphs.

Terminal Berth Planning In this process, the terminal plans barge requests in its berth planning, and communicates the allocated timeslots to barges.

Terminal Housekeeping This process is used to update the attribute ”Number of Consecutive Free Slots”.

Single Barge Planning If a delayed barge shows up at a terminal, it must reschedule this barge. This is done by this process.

Terminal Berth Planning

Terminals wait until the cutoff time is reached. Then, they go through the list of barges that have requested timeslots, and make a berth planning. The terminal planning is done with the following algorithm. After the terminal planning has been made, the terminal communicates the allocated timeslots to the barges. Because reservations make use of timeslots in their totality, whereas they may only use part of it, the use of timeslots has the side effect of implementing terminal-side slack. This slack increases for longer timeslot durations, as the average slack per reservation is a function of the timeslot duration. If we assume an equal probability of the actual handling time in a reservation's last timeslot of 3, 6, 9, 12 and 15 minutes, the average handling time is 9 minutes, and the terminal-side slack per reservation is 6 minutes. For timeslots of 30 minutes, the actual handling this leads to an average terminal-side slack of 15 minutes.

Algorithm 2: Terminal Berth Planning

```
   Data: Request List, Reservations, Nr of Reservations, Terminal Capacity
   Result: Updated Reservations
1  while Requests not all scheduled do
2      Search Request List for request with the most timeslots;
3      Check if requested timeslots are available in berth planning;
4      if Requested timeslot available then
5          Update Reservations;
6          Update Nr of Reservations;
7          Update Nr of Consecutive Free Slots;
8      else
9          Find first feasible timeslots after preferred timeslots;
10         Update Reservations;
11         Update Nr of Reservations;
12         Update Nr of Consecutive Free Slots;
13     end
14     Remove reservation from Request List
15 end
```

In line 3, the algorithm states that the berth planning is checked. For computational efficiency, the planning algorithm checks whether a request can fit in the *Reservations* matrix directly, rather than use the *Number of Consecutive Free Slots* variable. This is because updating the *Number of Consecutive Free Slots* variable, which is done in the Terminal Housekeeping process, is a time consuming process. This will be explained in the next paragraph.

Single Barge Planning

The goal of this process is for a terminal to reserve new timeslots for a delayed barge, so the rest of the berth schedule is left intact. Because of the work done in the *Terminal Housekeeping* process, this process is fairly straightforward. It finds the first timeslot, for which the *Nr of Consecutive Free Slots* attribute is sufficient, and reserves these timeslots. To do this, this process sets the *Housekeeping Bound* to the required *Number of TS* for the barge, runs the housekeeping process, and finally finds the first feasible timeslots for the barge. These timeslots are then reserved.

Terminal Housekeeping

The goal of this process is to find an available timeslot for a barge that shows up at the terminal after its allocated timeslot. The process is only called upon by the *Single Barge Planning* process. This process does so by updating the variable *Number of Consecutive Free Slots*, for timeslots in the next 48 hours, starting at the next timeslot, until it finds a suitable gap in the berth planning. For timeslots of 15 minutes each, this process updates up to 192 variables. This is done by comparing the *Terminal Capacity* with the *Number of Reservations*, and counting how many consecutive timeslots have fewer reservations than total capacity. Then, this number is stored in *Number of Consecutive Free Slots*, at the position of the current timeslot, and the process starts again for the next starting timeslot.
The algorithm runs two nested loops, one that loops through all timeslots in the coming 48 hours, and one that loops through the consecutive timeslots based on the first for-loop, resulting in a large number of calculations. In an attempt to make the process more efficient, a *Housekeeping Bound* was implemented, that prevents the while-loop from searching for more free slots than required by the barge that has called the housekeeping process. Additionally, the process stops as soon as it has found a gap in the berth planning that is suitable for the barge that called the process. These two measures, only looking for as many consecutive free timeslots as required, and then stopping the algorithm, reduce the algorithm run duration significantly.

Algorithm 3: Terminal Housekeeping

```
Data: Nr of Reservations, Terminal Capacity, Housekeeping Bound, Next Timeslot
Result: Updated Nr of Consecutive Free Slots
for Each TS from Next Timeslot to Next TimeSlot + (48 / Timeslot Length) do
    i = 0;
    while Nr of Reservations[TS + i] <= Terminal Capacity[TS + i] AND i <= Housekeeping
      Bound do
        i = i + 1;
    end
    Nr of Consecutive Free Slots = i;
    if i == Housekeeping Bound then
        break;
    end
end
```

4.7.5. General Parameters

While the majority of simulation functionality requires information on *specific* barges and terminals, there are other parameters that are of influence to the model too. These can be segmented in two groups: system-related parameters, and simulation-related parameters. The system-related parameters contain information on barges, the network, timeslots, or terminals, that hasn't been discussed in the previous sections. The simulation-related parameters determine how long the simulation runs, what should be done to get steady-state results, and how to ensure statistical significance of results.
First, system-related parameters will be presented. These are parameters that are specific for the system under study. Section 4.7.5 displays these system-related parameters. The reason that the

barge arrival frequency, berthing time, and lift to crane ratio were not discussed as barge or terminal attributes is that they apply to all terminals or barges, rather than *instances* of these agents. Some of the parameters are discussed in more detail below.

Table 4.7: System-related model parameters

Property	**Description**	**Value**
Travel Times	Travel time between terminals	6 by 6 matrix
Berthing Time	Time for a barge to berth at a terminal	5 minutes
Barge Interarrival Time	Time between barge arrivals	Exponential distribution, 50 / day
Timeslot Duration	Duration of timeslot	15 minutes
Barge Slack	Slack barges use while planning their rotation	1 hour / terminal call
Lift to Crane ratio	Parameter to convert moves to available cranes	20 lifts / crane / hour

Travel Times

As explained in subsection 4.3.2, the five deep-sea terminals are all situated at the Maasvlakte area, whereas the remaining city terminal is situated further inland. Therefore, the travel times between the Maasvlakte terminals are lower than the travel time from the Maasvlakte to the city terminal. Nevertheless, the travel time between two deep-sea terminals at the Maasvlakte is set to 1 hour. While the distance between the terminals at the Maasvlakte ranges from under a kilometre to about 12 kilometres, barges can not always sail quickly due to how busy the waterways are. For instance, barges should give way to deep-sea vessels.
The distance between the Maasvlakte area and the city terminals in the Eemhaven or Waalhaven is approximately 30 kilometres [82]. In most of the Port of Rotterdam, the maximum speed for barges is set to 13 kilometres per hour, relative to the water. Therefore, the trip takes at least 2.5 hours. In order to allow for small disruptions and the effects of tidal flows, as these can reduce the speed relative to land, the travel time has been set to be 3 hours for both ways. The travel times can be found in Table 4.8.

Table 4.8: Travel times between terminals, in minutes

From	**To**	**1**	**2**	**3**	**4**	**5**	**6**
1		0	60	60	60	60	180
2		60	0	60	60	60	180
3		60	60	0	60	60	180
4		60	60	60	0	60	180
5		60	60	60	60	0	180
6		180	180	180	180	180	0

Barge Interarrival Time

The barge arrival frequency amounts to 50 visits per day, as stated in section 2.2. No data on their arrival times is available. However, Figure 2.3 showed the starting times of barge handling at the Maasvlakte, which were spread out through the week. Therefore, we assume that barge arrival times are independent, and that they follow a Poisson distribution. The interarrival time is exponentially distributed, with mean 28.8 minutes.

Timeslot Duration

In the simulation, timeslots are used to keep track of reservations and requests, and dictate when barges are handled. Although it is technically possible to model reservations on a real-time basis, this is more inefficient computationally, and does not reflect reality. The timeslot duration determines how fine or coarse the planning is. A longer timeslot duration leads to more reserved time that is not utilised, as timeslots can not be partially reserved. This is essentially a form of slack from the terminal side. The timeslot duration is set to 15 minutes.

4.7.6. Simulation Parameters

Finally, the simulation-related parameters will be discussed. They can be seen in Table 4.9. The goal of these parameters is to ensure the results are representative of the average behaviour of the simulation, and avoid bias due to stochastics.

Table 4.9: Simulation-related model parameters

Property	Description	Value
Warmup Period	Time before results are saved	2 Weeks
Runtime	Runtime of the model (excluding warmup)	6 Weeks
Number of Replications	Independent model runs	100 Replications

Warmup Period

Because all queues are empty at the beginning of the simulation, called a 'cold start', the results would be biased if the gathering of results starts immediately. Of the five categories of solutions to this problem, as stated by Hoad *et al.* [83], here, the warmup method was chosen. After this warmup period, the queues have reached normal levels, and the statistics are cleared. The warmup period was determined as follows: first, the in-port times of barges in a replication were plotted as a function of the barge creation time in a scatter plot. Then, linear regression models were fitted to this scatter plot. As there should be no relation between the barge creation time and the in-port time when the system is in a steady state, the time from which data was collected was changed until the R^2 - a measure that signifies the proportion of variance in a dependent variable that is caused by an independent variable - of the linear equation was under 1%. This process was repeated for 10 different replications of the simulation, as it is impossible to determine the warmup period from a single replication, because of the inherent variability between different replications Law [84]. This was reached when omitting the barges that were created in the first 3 days of the simulation. As a barge leaves the simulation about 5 days after its creation date, this means that statistics must be reset after 8 days. However, because computing power has not proven to be an issue, and the warmup time was based on a single simulation run, a safety margin was taken, and the warmup period was set to 2 weeks.

Runtime and Number of Replications

The runtime and the number of replications of the model together determine the volume of data that will be investigated. However, both have distinct effects on the output, and what analysis can be performed on it. Statistical methods to determine the mean, variance, percentiles, and other indicators of the distribution of the simulation output all assume that each observation from the model is independent [24]. When applied to our model, this means that the in-port time of consecutive barges in a single simulation run should be independent, in order to validly infer statistics such as the 95% confidence interval of barge in-port times. However, this is not true: if two barges enter the port on a day that capacity is not sufficient, the high in-port time for these two barges are related. Therefore, multiple replications of the simulation are required, as these do result in independent statistics. In order to have narrow confidence intervals for output parameters for a certain amount of computing time, the number of replications and runtime per replication must be balanced. For instance, if the runtime is set to be short, the spread of different outcomes per replication is large, which can lead to a wide confidence interval. Conversely, having a long runtime with only a handful of replications leads to a wide confidence interval, simply because there are few independent results.

Most literature states that the runtime must be large, to mitigate the effects of the transient state that the system is in until the steady state has been reached. As the warmup period ensures that the simulation results are only gathered once a steady state has been reached, this aspect of requiring a high runtime has been mitigated. However, the runtime should still be long enough to ensure that the

output indicators of each replication are representative of the system, rather than a collection of outlier data points.
In order to find suitable values for number of replications and runtime, given a certain amount of computing time, and with the objective of finding a narrow confidence interval, various setups were run, ranging from 1000 replications of 1 week each to 20 replications of 52 weeks each. For a set total runtime, the marginal effect of one extra replication versus one extra day of runtime should be balanced, with the goal of reducing the width of the confidence interval. As a result of these tests, the runtime was set to a relatively short period of 6 weeks, excluding the warmup period. Assuming an in-port time of about 48 hours - for easy calculations - and the entry delay of 72 hours, this results in statistics on all barges that are generated more than 5 days before the end of the runtime. These are generated in the first 37 days after the warmup period, resulting in approximately 1850 data points per replication. As one replication takes approximately 120 seconds, it was chosen to run 100 replications per experiment. This takes approximately 200 minutes. For the standard situation, this results in a 95% confidence interval for the average in-port time of about 2% above and 2% below the expected average in-port time, which was deemed sufficient.

4.8. Model Verification & Validation

Model verification deals with ensuring that the simulation model performs as the conceptual model dictates it should; often called "building the model right". Model validation deals with ensuring that the simulation model is suitable for studying the system, and evaluating the experiments; often referred to as "building the right model". This section is split in two subsections, one for verification and one for validation. Both sections present the methodology that will be used, before presenting the results of this methodology.
As a general comment on this section, it should be noted that it is preferable to have verification and validation performed by a different party to the party that developed the model [25]. Typically, this would be done by either the end users or an independent third party. In this research, the opinion of relevant parties was taken into account at different steps in the model development, such as the gathering of input data, but in-depth validation and verification was not done by external parties.

4.8.1. Verification of the Simulation Model

Verification of the simulation model is aimed at ensuring that the programming contains no bugs. Kleijnen names four verification techniques [85]: "general good programming practice such as modular programming, checking of intermediate simulation outputs through tracing and statistical testing per module, comparing (through statistical tests) final simulation outputs with analytical results, and animation". An alternative method is to add extra processes to the model, to evaluate if variables do not violate constraints. In this report, the main methods will be the checking intermediate simulation outputs through tracing and the use of such value checks. General programming practice was adhered to as much as possible, but should not be judged by the developer. The third option, comparing outputs with analytical results, assumes "that the analysts can indeed find a 'test case' with a known solution". Because of the planning operations in the model, normal queuing theory does not apply, and an analytical solution cannot be found.
Verification by tracing will be used to verify the barge generator and barge rotation planning process, and the physical movement of barges through the port area. The terminal berth planning will be verified by use of value checks. Total terminal throughputs will also be verified through value checks. Value checks are more suitable when we are interested in aggregate model behaviour - such as throughputs, number of infeasible berth plans, utilisation. Model traces are suitable for checking the operations of single entities - such as the barge processes or their movement through the simulation model.

Verification through Traces

Verification by traces will focus on the following areas of the simulation: generation of a barge and its attributes, and the rotation planning process. Simio allows users to write each event in the simulation to an output file, in order to troubleshoot and verify the working of the simulation model.
The intent of the simulation model's specification is for a barge to execute the following procedure: the barge is created by the generator, stores its sequence, plans its rotation, and follows the planning in the port area. A model trace of the barge generation and the "Create Sequence" process can be

found in Appendix F. It was redacted slightly, to improve readability. The trace shows that the process functions as it should. A barge of type 3 is created, which represents large barges that service the Dutch market. The total number of calls is drawn, and turns out to be five. The approximate number of total moves is 100. The call sizes should be between 50% and 150% of the average, which is 20 moves. The consecutive random draws for this specific barge are shown in Table 4.10. As can be seen from the table, after 5 terminals have been added to the barge sequence, the barge leaves the model, by going to the *sink*.

Table 4.10: Barge Generator Trace of Barge 3.46

Visit Number	Terminal	Call Size (lifts)	Allowed
1	Terminal 6	18	Yes
2	Terminal 2	22	Yes
3	Terminal 6	16	Yes
4	Terminal 6	N/A	No, consecutive visit
4	Terminal 4	21	Yes
5	Terminal 4	N/A	No, consecutive visit
5	Terminal 4	N/A	No, consecutive visit
5	Terminal 1	14	Yes
6	Sink	N/A	Yes

The rotation planning process is checked next. The rotation planning process goes through a barge's sequence, and reserves timeslots at the various terminals the barge should visit. Again, a redacted model trace can be found in Appendix F. Following the sequence as shown in Table 4.10, the rotation planning process calls on the specific terminal request processes. Some key output can be seen in Table 4.11. Recall that the timeslot duration is 15 minutes, the slack is 60 minutes, and the travel times are 60 or 180 minutes.
The rotation planning functions as it should. The first timeslot the barge can request depends on the in port arrival time. As the barge was created at the start of the model, the entry delay is 72 hours, and the travel time to get to terminal 6 is 3 hours, the timeslot that should be requested is timeslot $(72+3)*\frac{60}{15} = 300$. The other timeslots are also correct. They are based on the last requested timeslot, the planning slack, and the travel time. This was explained in the paragraph on rotation planning in subsection 4.7.2. The call sizes should affect the number of requested timeslots. Visits 1, 3 and 5 request four timeslots, or one hour, whereas visits 2 and 4 request 5 timeslots, to reflect their larger call sizes.

Table 4.11: Rotation Planning Trace of Barge 3.46

Visit Number	First Requested Slot	Last Requested Slot	Constraining Factor
1	300	303	Entry Time
2	319	323	Last Timeslot
3	339	342	Last Timeslot
4	358	362	Last Timeslot
5	370	373	Last Timeslot

Finally, the barge's movement through the port area will be verified. The specific barge that was used in the previous two traces will be followed. This will consist of the following steps: the various terminals will allocate timeslots to the barge. Then, the barge follows the rotation. Again, this trace can be found in Appendix F. Table 4.12 shows the operations through the port, demonstrating how the barge follows its rotation plan, and adheres to the reserved timeslots. It shows how only terminals 1, 2 and 4 run a planning process and communicate the allocated slots, as terminal 6 is assumed to have sufficient capacity. Because of insufficient capacity at terminal 1 at times 369-372, the barge is scheduled to start handling in timeslot 373.

Table 4.12: Operations Trace of Barge 3.46

Time (TS)	Terminal	Process	Description
38	4	Terminal4Planning	Received requested timeslot (358)
72	1	Terminal1Planning	Received delayed timeslot (373)
72	2	Terminal2Planning	Received requested timeslot (319)
288	N/A	WaitforTS	Arrived in port
300	6	N/A	Arrival at terminal 6
304	6	N/A	Leaving terminal 6, sailing to terminal 2
312	N/A	WaitforTS	Waiting for timeslot
319	2	N/A	Arrival at terminal 2
324	2	N/A	Leaving terminal 2, sailing to terminal 6
338	6	N/A	Arrival at terminal 6
341	6	N/A	Leaving terminal 6, sailing to terminal 4
349	N/A	WaitforTS	Waiting for timeslot
358	4	N/A	Arrival at terminal 4
364	4	N/A	Leaving terminal 4, sailing to terminal 1
364	N/A	WaitforTS	Waiting for timeslot
374	1	N/A	Arrival at terminal 1
378	1	N/A	Leaving terminal 1
378	N/A	N/A	Leaving port area

Verification through Value Checks

It is difficult to piece together the berth planning from the information in the simulations output trace, in order to verify whether the process functions as intended, as the model trace of the planning processes consists of large amounts of data. Therefore, at the end of the simulation time, value checks should be performed to check how well the berth planning process functions. The verification process should compare the available capacity with the number of reservations for each timeslot, for each deep-sea terminal. When the number of reservations exceeds the available capacity, the berth planning process contains bugs. The verification process confirmed that the berth planning process was implemented correctly.

In the model, the terminals a barge visits are drawn, based on terminal throughput. However, this process has been adapted, in order to prevent successive terminal calls to be at the same terminal: if a random draw would lead to two consecutive visits at one terminal, a new random draw is taken, until the next terminal is a different one. The effect this change has on terminal throughputs was evaluated, by comparing the total number of visits per terminal with the expected number of visits. The expected number of calls per terminal is compared to the simulated average number of calls per terminal, and displayed in Table 4.13. From the table, a clear pattern can be seen that the terminals with high throughput have fewer visits than expected, and the terminals with lower throughput have more visits. The result for each terminal depends on the balance between two mechanisms: first, the terminal will get fewer visits because consecutive visits are not allowed; second, when other terminals are drawn but they are annulled, the terminal gets an increased chance to be drawn. Logically, larger terminals will have more missed visits than gained visits; likewise, smaller terminals will get more new visits than missed visits. While there is a clear difference between the expected and the simulated visits, the results are fairly close to the input parameters. The simulated visits are still representative of the system, as the input dataset is based on information with limited precision.

Table 4.13: Barge visits per terminal, expected number and average from simulation

	Term. 1	Term. 2	Term. 3	Term. 4	Term. 5	Term. 6	Total
Input Dataset	2310	1155	1617	1386	1155	1386	9009
Shares	25.6%	12.8%	17.9%	15.3%	12.8%	15.3%	
Simulated	2124	1204	1614	1422	1209	1416	8989
Shares	23.6%	13.4%	18.0%	15.8%	13.4%	15.8%	
Difference	-8.1%	4.2%	-0.2%	2.6%	4.7%	2.2%	-0.2%

4.8.2. Validation of the Simulation Model

Validation refers to evaluating if the model is a good tool to study a system. Two types of validation can be distinguished, as seen in Figure 1.2: validation of the conceptual model, and validation of the simulation model. Validation of the conceptual model was done throughout chapter 4, to ensure that the model is suitable to study the in-port times of barges. This section deals with validation of the simulation model. From the validation techniques that are mentioned in Sargent [25] and Kleijnen [85], historical data validation and sensitivity analysis will be used. Historical data validation was chosen for its simplicity, and because it is expected to be valued by real-life stakeholders. A sensitivity analysis was chosen for multiple reasons: first, many of the input-output relations can be logically deduced, providing a wide array of tests for the model. Second, a sensitivity analysis provides a starting point for inducing system behaviour from the model, as it checks the effect of various input changes. Third, sensitivity analysis will expose input parameters that have a large influence on the model performance, which can then lead to extra effort in improving the values for these parameters, thereby improving the model's performance.

Historical Data Validation

The average in-port times from the model will be compared to information from the Port of Rotterdam [8] and the Port Stay Index by LINc [48]. The Barge Performance Monitor (BPM) also provides insight in how many hours are spent sailing, waiting, and processing. To conclude the historical data validation, the average utilisation rate of the deep-sea terminals will be compared to other work, and compared to average in-port times to judge how reasonable they are.

As discussed in section 2.2, the average barge in-port time in 2018 was 31.4 hours, and ranged from 20 to 58 hours throughout the year. The majority of the weeks showed an in-port time between 22 and 34 hours. In 2019, the average barge in-port time up till November is approximately 27 hours. The average barge in-port time from the model is 29.6 hours, with all 100 replications between 23.7 and 36.9 hours. The 95% confidence interval for the average barge in-port time ranges from 29.0 to 31.2 hours. The average barge in-port time from the model is 6% lower than the average over 52 weeks from 2018, but 10% higher than the average barge in-port time in 2019, up to November. It can be concluded that the model results are well within the expected values for average barge in-port times.

In order to evaluate the contribution of waiting, travel, and processing times to the in-port time, average values for these categories should be retrieved from the 100 replications, and compared to the distribution as provided by the BPM. As the BPM only presents data for ships servicing the Rhine area, the same must be done for the simulation results. The results can be found in Table 4.14. When comparing the data from the simulation to the data from the BPM, the average Rhine barge in-port time is 30.8 hours, whereas the BPM states that Rhine barges have an average in-port time of 41 hours. The processing time from the simulation is 7.1 hours, which is much lower than the 20 hours that Rhine ships spend at terminals. The travel time averages 7.2 hours in the simulation, where in reality ships spend 9 hours sailing. The waiting time, conversely, is simulated to be more than the 12 hours that the BPM shows.

The biggest discrepancy between the BPM and the simulation is the difference in processing time. This mismatch greatly contributes to the difference in total in-port time. It seems unlikely that the sum of the call sizes per visit - set to 260 or 300 TEU - is far too low, causing the low processing times. If barges spend 20 hours being processed at terminals, with a crane productivity of 20 lifts per hour, and a TEU factor of 1.68, a barge would (off)load a minimum of 672 TEU per port visit. Only the largest barges that can sail the Rhine have sufficient capacity, and would require very high load factors. This is not

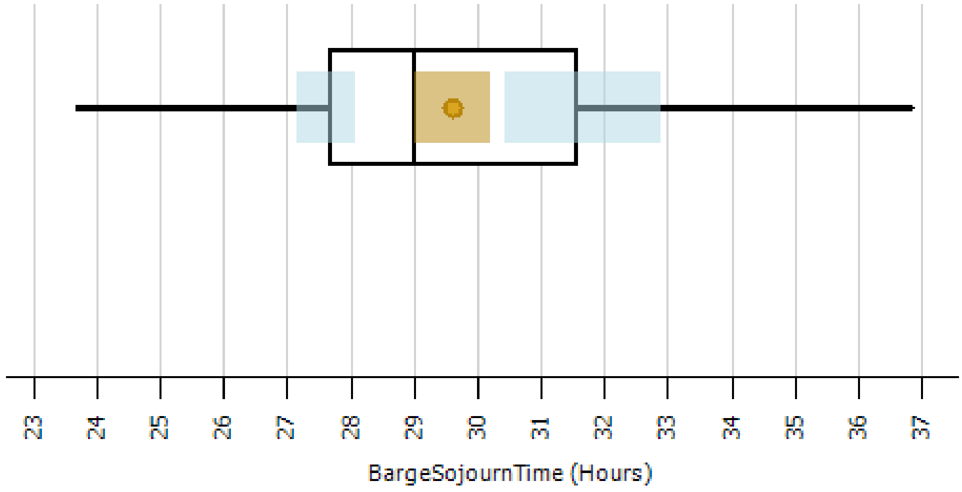

Figure 4.7: MORE plot of average in-port time

Table 4.14: In-port time of barges servicing the Rhine, per activity, in hours

	In-port time	Waiting time	Travel time	Processing time
Simulated	30.8	16.5	7.2	7.1
Standard Deviation	3.1	3.1	0.2	0.0
BPM [8]	41	12	9	20

likely. One potential reason for the difference in processing times could be that barges may sometimes wait at terminals, causing AIS data to categorise this as if barges are being handled, thereby increasing the 'processing time' in the BPM. Another reason could be that the actual crane productivity is lower than in the simulation model, leading to higher handling times for similar call sizes. Because of this result, experiments were performed with lower crane productivity. One last reason could be that the BPM is based on a group of barge operators that provides data, but that isn't representative of all Rhine barges. Changes to crane productivity are required to increase the processing time. However, this also greatly influences the waiting times, as will be shown in the sensitivity analysis. Therefore, despite the difference in processing time with the BPM, the crane productivity was set at 20 lifts per hour.

A detailed look at the standard deviation of the average time spent on in-port activities shows that the average processing times and travel times show very little variability. The waiting time changes much more, and is the main contributor to the variability in total in-port time. Because travel and processing times are not dependent on how busy the system is, this lack of variability makes sense. The runtime is sufficient for the various replications to converge to similar average processing and travel times. As waiting times are much more dependent on the system state, the variability here is as expected.

The average utilisation rate of the five deep-sea terminals is 74.8%. Here, a comparison with the work by Douma *et al.* provides an insight on how reasonable this is. Douma *et al.* did not use input data to determine the demand for barge handling capacity, but set different utilisation rates, upon which the input data was crafted to match those rates. The utilisation rates that were used were 50%, 75%, and 90%. Unfortunately, their reporting focuses on the scenarios with utilisation rates of 50% and 90%. Nonetheless, when comparing the results from the two models, it is clear that the handling capacity is more than sufficient to prevent lengthy delays when the utilisation rate is under 50%, and a utilisation rate of 90% leads to delays that are much longer than in reality. Therefore, we can conclude that the real-life utilisation rate should be between 50% and 90%. We conclude that a 74.8% utilisation rate leads to representative in-port times.

The next section will evaluate the sensitivity of simulation results with regard to various input parameters, such as the crane productivity.

Sensitivity Analysis

A sensitivity analysis is used to check how a simulation model reacts to changes in the input parameters. In effect, a sensitivity analysis is one of the first steps in understanding the mechanisms between input parameters and output data. When used for validation purposes, the input parameters that are changed should have logical effects on the output, such as a reduced in-port time when crane productivity is increased. The model should exhibit the expected behaviour. A sensitivity analysis can also be used when the quality of input data is questionable, to understand how precise input data must be, and what effects slight changes might have.

Table 4.15: Sensitivity Analysis: changes to input parameters and their results

		Lower Bound	Normal	Upper Bound	Low	High
Timeslot Duration	Input	7.5	15	30		
	Results	27.9	29.6	41.0	-6%	40%
Crane Productivity	Input	15	20	25		
	Results	170.9	29.6	18.5	479%	-38%
Move-to-Crane Ratio	Input	15	20	25		
	Results	47.6	29.6	26.2	62%	-12%
Barge Slack	Input	0	60	120		
	Results	28.0	29.6	31.4	-5%	6%
Average Number of Calls	Input	1 less	Equal	1 more		
	Results	28.3	29.6	33.9	-6%	12%
Daily Barge Visits	Input	45	50	55		
	Results	23.3	29.6	48.9	-22%	66%
Crane Productivity Stochastics	Input	10%	0%	25%		
	Results	30.0	29.6	32.7	1%	10%

In Table 4.15, the mean barge in-port time of different scenarios is shown. The model was run for both a higher and a lower value of the property, with 100 replications per scenario.

All these changes should lead to logical results; for instance, higher crane productivity should lead to lower in-port times. The expectations will be discussed here. For each property, a positive effect for an increase should lead to a negative effect for a decrease. For an increased timeslot duration, the terminals will have more hours where cranes have been reserved but aren't working, and therefore, in-port times should increase. This is caused by the increased terminal-side slack, as explained in subsection 4.7.4. Naturally, higher crane productivity should lead to lower in-port times, as both processing times and waiting times reduce. The move-to-crane ratio is slightly more complicated. It is used to translate the number of moves, which is drawn from a random distribution, to a number of cranes. The following two effects oppose each other: if the random distribution returns 15 moves, this no longer rounds up to 20 but to 25 moves. However, for higher values from the random distribution it can lead to fewer cranes, as 70 moves would lead to 4 cranes with a ratio of 20, but 3 with a ratio of 25. The first effect outweighs the second effect for the terminal handling capacity distribution, leading to a slightly higher theoretical throughput for a higher move-to-crane ratio. In these scenario's, the crane productivity is set to be equal to the move-to-crane ratio. The expected result for an increased or decreased barge planning slack is not so clear. A slack of 0 should make the barges much more susceptible to infeasible rotations, leading to higher in-port times. A higher slack makes the barges less susceptible, but whether this effect outweighs the increased slack cannot be known beforehand. The number of calls barges make was changed, in order to assess how important this data is. If a barge type initially would visit 4, 5 or 6 terminals, this was changed to 3, 4 or 5 in the lower scenario, and 5, 6 or 7 in the higher scenario. Fewer calls should lead to lower in-port times, as travel times are reduced, and fewer terminals have to be planned. Changing the demand for barge handling capacity can be done through the barge arrival frequency. It was changed to 45 or 55 barges per day. Fewer barges

should lead to lower in-port times, as demand for handling capacity decreases. Finally, the crane productivity was set to be deterministic. However, two experiments were run with different levels of variability, to assess the effects of stochastics in the crane productivity. The crane productivity was set to change either 10% or 25%, leading to crane productivity ranges of 18-22 and 15-25 lifts per hour. Increasing the variability should increase in-port times, as the effects of barges missing appointments should outweigh the effects of barges finishing appointments a bit early. This effect is expected to be non-linear, as small delays will be absorbed by the planning slack barges use.
The effects of most measures in the sensitivity analysis are in line with expectations. The MORE plots of the sensitivity analysis scenarios can be found in Figure 4.8 on page 59. The reduced crane productivity experiment was left out, as the large values made the rest of the plot much more unclear.
The only measure that had surprising effects was the changing of the barge planning slack. Reducing the planning slack leads to lower in-port times, whereas an increase leads to a higher in-port time. The mechanism here is likely to be that the chosen slack is not sufficient to adapt to any issues, but only brings the barge further from its ideal rotation. Because the slack is most effective to adapt to small disruptions in handling productivity, that do not exist in the model (as crane productivity is deterministic), the slack's negative effects are more pronounced. Another interesting result is that a timeslot duration of 15 minutes does not perform much worse than 7.5 minutes, at almost twice the computation speed. Finally, incorporating stochastics into crane productivity hardly affects barge in-port times at low levels of variability, as the margin absorbs delays without rendering the remainder of a rotation infeasible; at higher levels of variability, the effects are more profound.
The most striking finding from the sensitivity analysis is just how sensitive the system is to the barge handling capacity. Crane productivity, crane ratio, and barge frequency all disturb the balance between handling supply and demand directly. Crane productivity and the move-to-crane ratio influence the supply, where number of barges and their call sizes influence the demand. If the supply decreases by 25%, the system clogs up and a steady state is never reached, indicating that the systems handling capacity is insufficient. If the supply increases slightly, barges almost always get their requested timeslots, and their waiting time is greatly reduced. The balance between supply and demand is further explored in section 5.3.

4.8.3. Conclusion of Verification and Validation

To conclude, the model was verified by investigating the model trace and using value checks, and validated by comparing the results with historical data, and checking the input-output sensitivities in a sensitivity analysis. The verification showed that the conceptual model was implemented in Simio correctly. The results of the historical data comparison are positive, as the average barge in-port time from the model does not differ much from reality. When looking at the division of time spent on in-port activities for Rhine barges, the model showed a large difference between processing time spent at terminals in the model and according to the Barge Performance Monitor. Several explanations for this discrepancy were posited.
The sensitivity analysis shows that model behaviour is in line with expectations, as the direction and magnitude of changes to resulting barge in-port times can be logically explained as a function of changes to the input parameters. Nonetheless, because of how sensitive the results are to changes to the supply of, and demand for barge handling capacity, the quantitative results from the model should be taken with a grain of salt. It is unwise to expect that a 3 hour in-port time reduction from the model would translate to similar time savings in reality. That being said, the model can be used to understand what causes high in-port times, what input parameters mostly determine a barge's in-port time, and what effects potential measures have. Therefore, for the intents of this research, the model is valid.

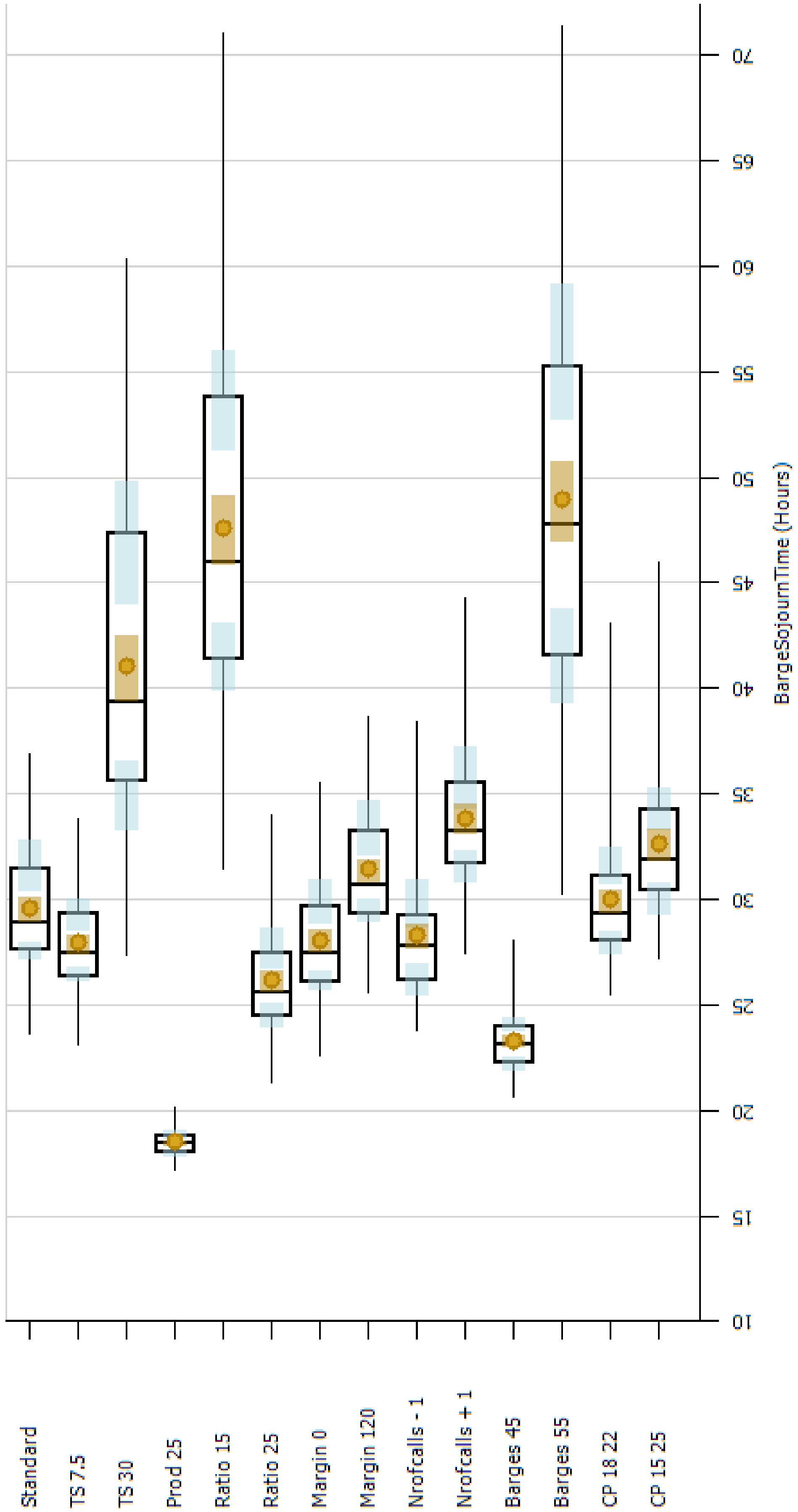

Figure 4.8: MORE plots of sensitivity analysis scenarios

5

Experimentation

So far, this report has introduced the problem of high barge in-port times in chapter 1, provided a description of in-port operations in chapter 2, reviewed causes and measures from the literature in chapter 3, and explained how the complex system should be simulated in chapter 4. Now, using the simulation model, the causes and measures can be checked.
This chapter starts with more in depth analysis on the results in the standard scenario, in section 5.1. Then, various different experiments are performed. An overview of the experiments is given in section 5.2. Section 5.3 discusses the effect of changing the model's input parameters that relate to the handling capacity at terminals, before continuing with parameters that relate to barge operations in section 5.4. The last four experiments require larger changes to the model. Section 5.5 discusses the implementation and effects of auctioning the timeslots, followed by incorporating priority requests, which is presented in section 5.6. The chapter ends with section 5.7, in which the effect of real-time information sharing by the terminal is evaluated.

5.1. Standard Scenario: In-depth Analysis

In the model validation, the in-port time from the simulation model was given. The sensitivity analysis discussed the effects of changes to input parameters, which forms a starting point for understanding the mechanisms that define a barge's in-port time. Here, the results will be analysed in more detail. Therefore, five replications will be studied, as data on these is available per barge. The 5 replications that were combined for this analysis were chosen to be a representative subset of the whole experiment. Three replications were chosen because their average was close to the average across 100 replications, with one replication close to the minimum average in-port time, and one replication close to the maximum average in-port time. The chosen replications and their average in-port times can be seen in Table 5.1.

Table 5.1: Chosen replications for in-depth analysis

Replication	4	15	16	19	20
In-port Time	28.7	33.4	29.4	31.0	24.8

First, the in-port times are segmented per hinterland service area, and presented as a distribution, providing a sense of how in-port times are distributed. Then, relations between variables such as *average call size*, *sum of call sizes*, and *number of calls*, and output indicators such as *in-port time*, *time per move*, and *waiting time* are shown. Throughout the analyses that follow, the independent variables - plotted along the x axis - that will be used in the plots will not be solely responsible for the effects on *in-port time* and a barge's *time per move*. This is due to two facts, that will be explained with two examples: first, both small domestic barges and barges servicing Antwerp can have 2 calls. However, due to the large difference in average call size, they will have very different in-port time characteristics. Second, the *average call size*, *sum of call sizes*, and *number of calls* are related. If two of the three are determined, the last one can be calculated.

From here on, several probability density plots are used to visualise the results. These are based on histograms of the underlying data, but changed to probability density plots to be easier to comprehend visually, as overlap between histograms of different colours makes it difficult to distinguish between the different histograms. The probability density plots are actually plots of the kernel density estimations that are based on the histograms. Kernel density estimations work as follows: at each data point, a standard Gaussian - or normal - density function is placed. These are then summed and normalised. Kernel density estimations require a *bandwidth* input parameter, that determines how smooth the lines will be. Here, the bandwidth is estimated by using Scott's estimator [86]. As a result of using kernel density estimation, some of the plots may show that infeasible values, such as negative time durations, are possible. The underlying histograms do not show infeasible values.
The average in-port time per barge type is shown in Table 5.2, along with the two properties that dictate their operations. Interestingly, the barges that service Antwerp have the lowest in-port time, even though they are the largest barges, and transport the highest number of containers per visit. They only visit an average of 2 terminals, resulting in large call sizes. As barges are scheduled based on their call sizes, it is not surprising that barges that service Antwerp have the lowest waiting times. The second lowest average in-port time is for small domestic barges. They transport the fewest containers. The time per move was also calculated. Here, an inverse relation can be seen between average call size and time per move: a higher sum of call sizes results in lower time spent per move.

Table 5.2: Results of standard scenario per barge type, average input variables that determine their in-port operations

Service Area	**Sum of Call Sizes (TEU)**	**Calls**	**Average In-port Time (hrs)**	**Time per Move (mins)**
Antwerp	390	2	19.9	6.2
Small Domestic	100	3	23.8	29.2
Large Domestic	200	5	33.2	20.4
Lower & Middle Rhine	300	4	27.5	11.34
Upper Rhine	260	6	35.7	17.28

The distributions of in-port times per service area are plotted in Figure 5.1. Small domestic barges have the lowest minimum in-port time, because they transport the least containers, and have relatively few calls. Conversely, barges that service the upper Rhine have the highest minimum in-port time, as they visit many terminals and transport many containers. Barges that service Antwerp have the most reliable in-port times, as they have the highest peak, and the smallest tails in the probability density plot. This is caused by their large call sizes, which means they frequently get their requested timeslots. Continuing with this logic, the second most reliable in-port time is that of ships servicing the lower & middle Rhine, as they have the second highest average call size.

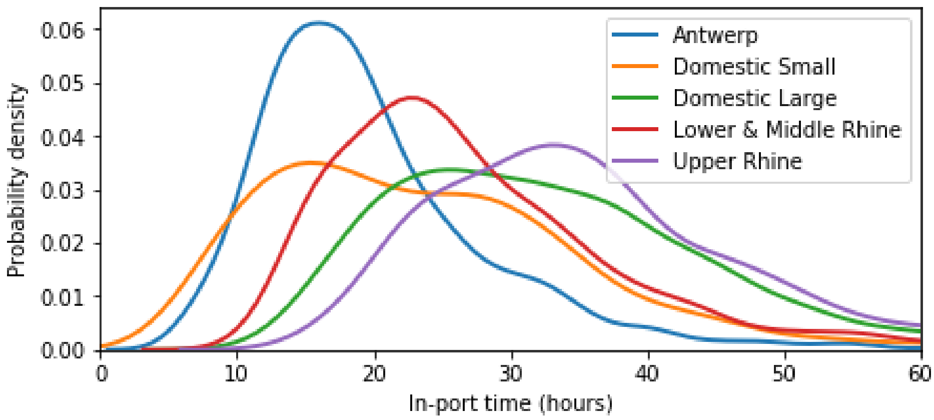

Figure 5.1: Probability density plots of the in-port times of barges that serve different hinterland areas

As Table 5.2 shows, a higher sum of call sizes leads to a lower time per move. This is plotted in Figure 5.2. This figure clearly shows that larger vessels are more efficient, as their time per move is

lower than that of smaller vessels. This efficiency also leads to higher in-port times, as more containers have to be moved.
As shown in Table 5.2, the lowest average barge in-port time was found in barges sailing back and forth to Antwerp, which pick up and drop off the most containers per port visit. The second lowest in-port times were found in small domestic barges, with the lowest summed call sizes. This suggests that the effect of the sum of call sizes on in-port time is not very important. In Figure 5.3, the relation between these two variables is shown.

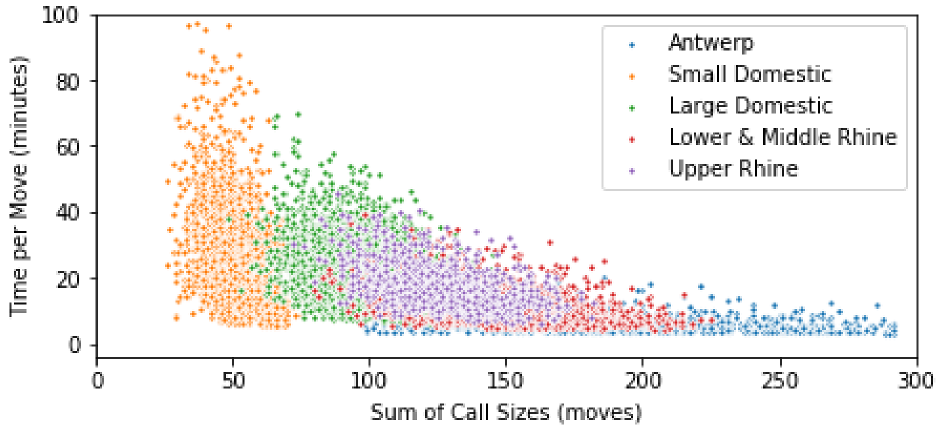

Figure 5.2: Scatter plot of the time per move versus the sum of call sizes, for barges that serve different hinterland areas

Interestingly enough, the range of in-port times seems to decrease for higher transport volumes. Two effects cause this: first, the theoretical minimum in-port time increases for higher summed call sizes; second, higher summed call sizes increase the average call size, which appears to have a positive effect on in-port times. This effect will be studied next.
As processing times increase for higher summed call sizes, and travel times do not depend on call sizes, the high transport volumes with fairly low in-port times must be caused by reduced waiting times. This hypothesis is tested next. As can be seen in Figure 5.4, high call sizes do - generally speaking - result in low waiting times. As waiting times are the foremost source of in-port time variability, this finding confirms the reasoning that was explained earlier in this section, when explaining why barges that service Antwerp have the lowest in-port time variability.
One final variable that we will inspect is the number of calls a barge makes, and its effect on in-port time. Of course, the number of calls is related to barges that service different areas, with different characteristics. Nevertheless, the density plots of in-port time distributions for barges with different numbers of calls are plotted in Figure 5.5. From the figure, with the exception of the change from 1

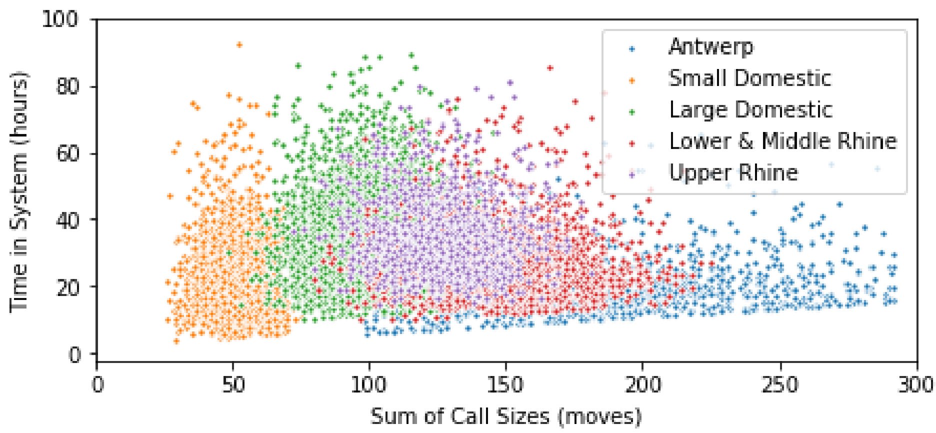

Figure 5.3: In-port time versus sum of call sizes

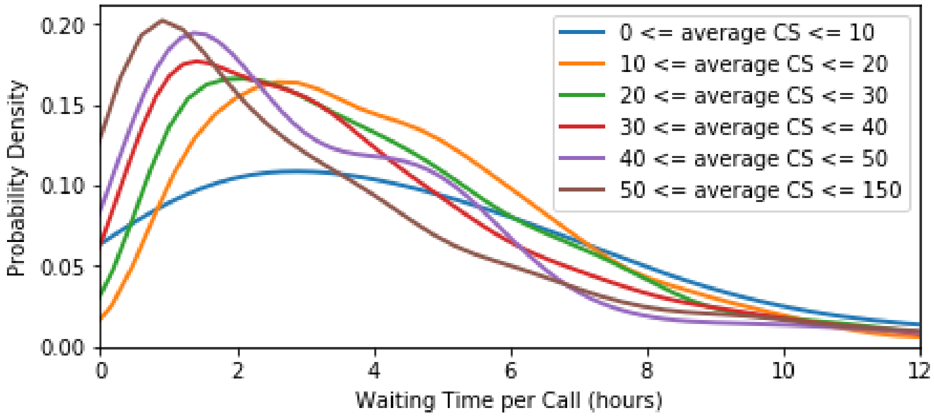

Figure 5.4: Distribution of waiting times per call, segmented on average call size

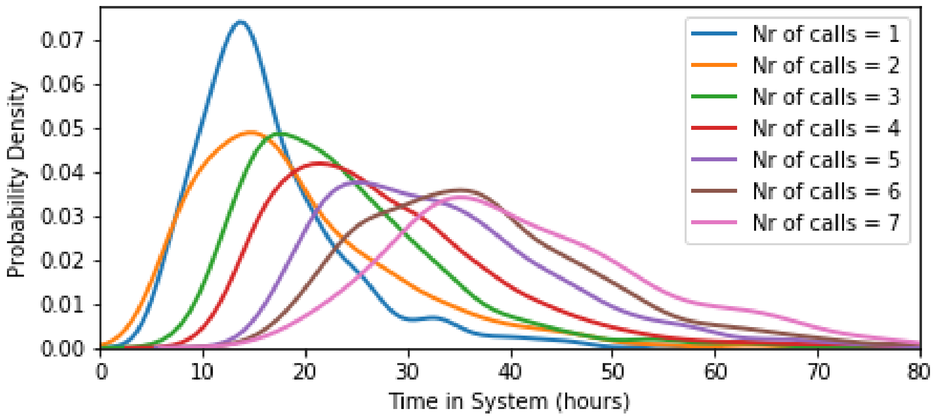

Figure 5.5: In-port time distribution for different number of calls

to 2 calls, a clear increase in minimum in-port time can be seen, with an increase in number of calls. This is because the minimum travel times increase, when number of terminal calls increase. Although it can not be distilled from the graph, the average in-port time also increases for each extra terminal call. However, here, it can not be concluded that more calls alone leads to high in-port times.
The findings from the in-depth analysis are summarised here.

- Barges with larger average call size have more reliable in-port times
- There is no clear relation between barge size and in-port time; larger barges do have lower times per move
- The waiting times per call increase for lower average call sizes
- All else remaining equal, reducing the number of calls a barge makes reduces its in-port time

5.2. Experimentation: an Overview

The experiments in this chapter can be divided in two groups: the first type of experiments involve parameter changes; the second type of experiments involve changes to the working principles of the system. The experiments involving parameter changes, such as changes to call sizes and terminal handling capacity will be discussed first. These parameter changes can be caused by various system changes, of which most stem from the literature review. However, as the effect of these system changes on the input parameters has not been quantified, the results will be reported based on the parameter changes. The input parameters that are changed deal with changing the demand and supply of barge handling capacity. First, section 5.3 section will discuss changes to parameters that define the terminal handling capacity. Second, the effects of changes to barge operations in port will be discussed in section 5.4.

Table 5.3: Conversion from list of measures to experimental plan

Actor	Measure	Modelled	Changed parameter	Reason
Barge Operator	Partnerships	✓	Nr. Of calls for domestic barges	
Barge Operator	Berthing time	✗		Limited effect
Barge Operator	Pushbarges	✗		Model not suitable
Deep-sea Terminal	Container Exchange Route	✓	Nr. Of calls for all barges	
Deep-sea Terminal	Increased capacity - more cranes	✓	Move-to-crane ratio	
Deep-sea Terminal	Increased capacity - productivity	✓	Crane Productivity	
Deep-sea Terminal	More constant capacity	✓	Terminal capacity distribution	
Deep-sea Terminal	Information Sharing	✓	Reservation system	
Deep-sea Terminal	Auctioning	✓	Reservation system	
Deep-sea Terminal	Priority Requests	✓	Reservation system	
Deep-sea Terminal	Nextlogic	✗		High complexity
Deep-sea Terminal	Barge Transferium	✗		Model not suitable
Deep-sea Terminal	Improved terminal planning	✗		High complexity
Deep-sea Terminal	Dynamic pricing - Barge	✗		High complexity
Deep-sea Terminal	Dynamic pricing - Deep-sea	✗		Model not suitable
Shipping Line	Reduce vessel turnaround time	✓	Terminal capacity distribution	
Shipping Line	Vessel size reduction	✗		Model not suitable
Shipping Line	Demurrage & Detention change	✗		Model not suitable
Shipping Line	Improved schedule reliability	✗		Model not suitable

The second type of experiments require more modifications to the simulation model, as they fundamentally change certain mechanisms in the system. Two experiments change the reservation system, adding priority requests to the requesting mechanism, or allocating timeslots based on auctions. These experiments are discussed in section 5.5 and section 5.6. Finally, the last experiment changes the way barges plan their rotation, as information sharing is incorporated. The results are presented in section 5.7. The reporting on experiments that require model changes is structured as follows: the concept of the experiment is discussed, followed by a short explanation of how this was implemented, before the results of the experiment are presented.

The remainder of this section will elaborate on the experimental plan for the experiments involving parameter changes. Not all measures that were presented in chapter 3 have equal potential. Additionally, not all measures can be evaluated, as the measures require changes to system parameters that have not been modelled explicitly. These are mainly measures relating to deep-sea shipping lines. Finally, some measures could not be evaluated due to time limitations, as they are complex, and can not be implemented easily. Table 5.3 shows all the measures that were shown in Figure 3.8, along with which actor the measure is linked to. Depending on whether or not the measure is evaluated, the third column states what parameter should be changed, or the fourth column states why the measure was not evaluated.

5.3. Experimentation: Handling Capacity Changes

Concept and Hypothesis

The lack of sufficient handling capacity was hypothesised to be one of the reasons for high barge in-port times. Therefore, this section reports on changes to handling capacity at container terminals. The parameter changes are caused by measures that were given in chapter 3, and the connection between these measures and changes to input parameters will be given qualitatively. Quantifying the effects of, for instance, improved stowage planning by deep-sea vessels on barge handling capacity at deep-sea terminals, is difficult, and depends on many factors. Therefore, the results are presented based on changes to input parameters, to give an indication of the effects of such measures.

Four measures from Table 5.3 aim to reduce barge in-port times by changing the barge handling capacity at the container terminals, either by increasing the total theoretical handling capacity, or changing how handling capacity is distributed over time. In the order that they were presented in Table 5.3, these measures are:

- Increasing capacity by increasing the number of cranes
- Increasing capacity by increasing crane productivity
- Keeping average barge handling capacity the same, but reducing variability
- Penalising deep-sea vessels for poor stowage planning to reduce their turnaround time, making more cranes available for barges handling

From the sensitivity analysis, we learnt how sensitive the model is to changes in the balance between handling capacity and handling demand. Therefore, it seems reasonable that a relatively small increase to the available capacity will lead to a significant reduction in in-port times. Additionally, a less variable barge handling capacity is expected to result in lower in-port times, as peaks in available cranes are not utilised completely, and a more reliable baseline of handling capacity will ease planning of barges with high call sizes.

Implementation

The barge handling capacity can be changed through both parameters that influence the supply of barge handling capacity: the move-to-crane ratio and the crane productivity. The move-to-crane ratio increases the average number of available cranes per hour, whereas the crane productivity increases the number of lifts per hour for each crane. While the move-to-crane ratio was also changed in the sensitivity analysis, the crane productivity was changed in parallel to the move-to-crane ratio, so the effects on total theoretical handling capacity were negated. Here, the crane productivity is left at 20 moves per hour when the move-to-crane ratio increases, so total theoretical handling capacity is increased.

However, when studying effects caused by the temporal distribution of barge handling capacity, the random distribution that is used to determine a terminal's number of available cranes should be changed. From our experimental plan, this is true for two measures: less variable barge handling capacity, and stowage planning to reduce deep-sea vessels' turnaround time. In the scenario with reduced variability in the terminals' handling capacity, the theoretical handling capacity is unchanged, but barges are offered a more constant supply of handling capacity. In this case, each terminal will reserve at least 1 crane for barge handling, and at most 6 cranes, rather than any number between 0 and 10. The effects of calculating the number of cranes using the two distributions was also checked for 100,000 random draws, and the difference was approximately .5%. In the scenario with improved deep-sea stowage planning, we assume that this leads to fewer hours with a capacity of under 50 lifts per hour, and an increase in hours with more than 50 lifts per hour. The mean of the 'Stowage Planning' distribution is 7.5% higher than the 'Standard' distribution, as a reduced turnaround time of deep-sea vessels should increase the number of available cranes. Calculating the average number of cranes as a function of this distribution, based on 100,000 random draws, lead to an increased terminal capacity of 6.4%. The 'Stowage Planning' scenario combines aspects of the 'Reduced Variability' scenario with increased handling capacity.

The three different random distributions have been plotted in Figure 5.6. The mean of the 'Standard' distribution and the 'Reduced Variability' distribution is almost the same, as this aims to keep total capacity the same.

Results

The effects of changes to the capacity can be seen in the MORE plots in Figure 5.7. To place the capacity increases in perspective, Table 5.4 shows how the parameter changes influence the total handling capacity, based on the random distribution that is used to determine terminal capacity in the simulation, using 100,000 random draws. It also shows the in-port time reduction that the measure results in. As terminals want high utilisation rates, the average utilisation rate of the 5 deep-sea terminals is also shown.

The results show that barge in-port time is sensitive to changes in handling capacity. Even without increasing the capacity, but by providing a more consistent barge handling capacity, barge in-port times can reduce. Increasing the handling capacity shows even better results. In fact, small increases to both the number of available cranes and the crane productivity show very positive effects on the in-port time, with slight utilisation decreases. Initially, increasing the number of cranes closely matches the effect of increasing crane productivity, as both measures increase the chance that barges are handled in their requested slots. Although the difference between the working principles of these two changes is subtle, the effect becomes clearer when the capacity increases further. Both measures increase the

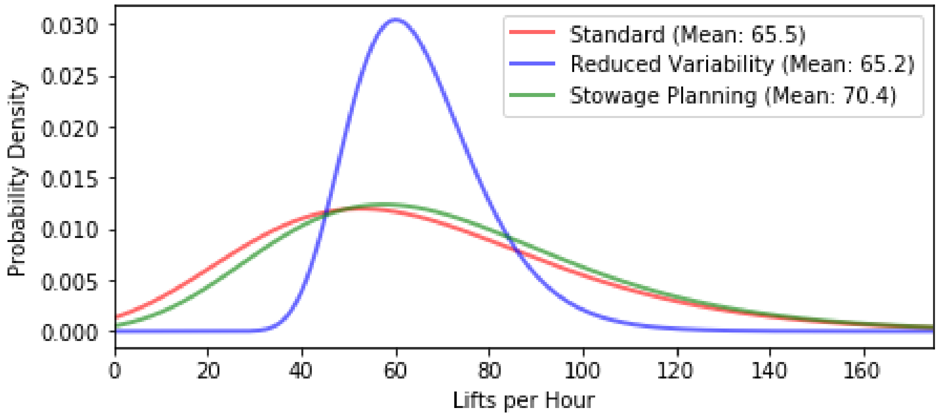

Figure 5.6: Comparison of the distributions for barge handling capacity in three scenarios

Table 5.4: Handling capacity experiments: input and results

Scenario	**Handling Capacity**	**In-port time reduction**	**Crane Utilisation**
Standard	100%	0%	75%
Move-to-crane 19	104%	12%	72%
Move-to-crane 18	109%	21%	69%
Move-to-crane 17	116%	27%	66%
Move-to-crane 16	121%	32%	63%
Move-to-crane 15	128%	35%	59%
Crane Productivity 21	105%	15%	72%
Crane Productivity 22	110%	24%	68%
Crane Productivity 23	115%	30%	65%
Crane Productivity 24	120%	36%	63%
Crane Productivity 25	125%	38%	60%
Reduced Variability	100%	11%	75%
Stowage Planning	106%	18%	71%

chance that the requested slot is available, by providing more capacity. Additionally, the increased crane productivity contributes to a lower processing time. Therefore, the increased crane productivity slightly outperforms the increased number of cranes. In the crane productivity scenarios, diminishing returns can be seen: the first 5% increase in handling capacity results in 15% in-port time reduction, a further 5% increase results in a further 9% in-port time reduction. This effect can also be seen in the move-to-crane scenarios.

While the average in-port time reduces when handling capacity increases, it is also clear that the variance in average in-port times reduces, suggesting that the in-port times become more predictable, which can allow barge operators to optimise certain aspects of their operations. For instance, if a barge operator can generally fulfil all the demand with ten barges, but keeps an eleventh barge in operation to ensure that disruptions do not cause issues for his clients, this eleventh barge could potentially be taken out of operation.

Finally, changes to the distribution of handling capacity were evaluated in the 'Reduced Variability' and 'Stowage Planning' scenarios. Both scenarios showed a reduction in barge in-port time. The reduced variability illustrates how terminals can contribute to reducing barge in-port times without increasing their available capacity. Improved stowage planning on deep-sea vessels, if the effects on berth handling capacity were assessed correctly, resulted in 6% more handling capacity, which resulted in 18% reduction of average in-port times.

Unlike the 'Reduced Variability' scenario, many of the experiments change the handling capacity without

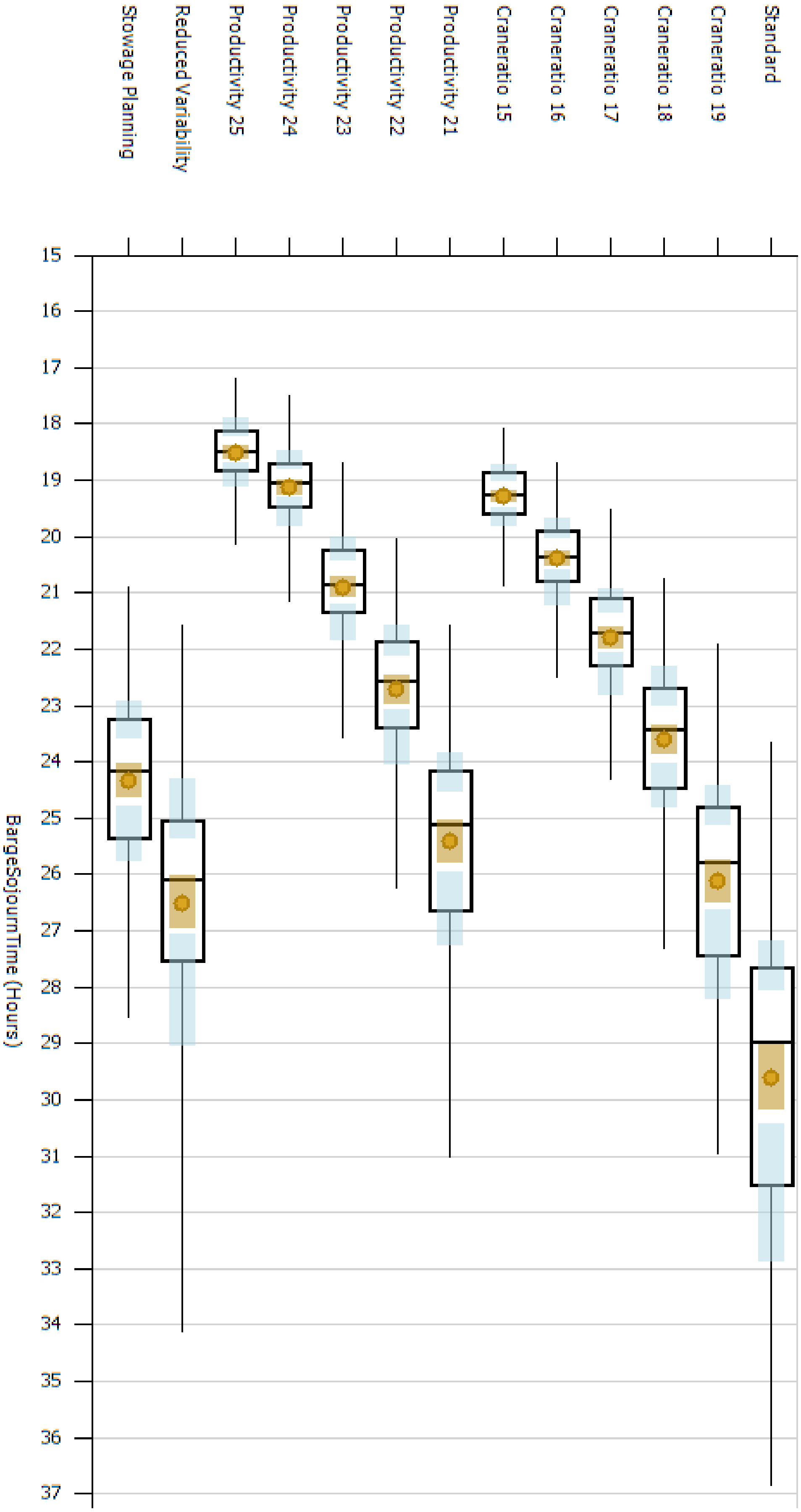

Figure 5.7: MORE Plots of Changes to Barge Handling Capacity

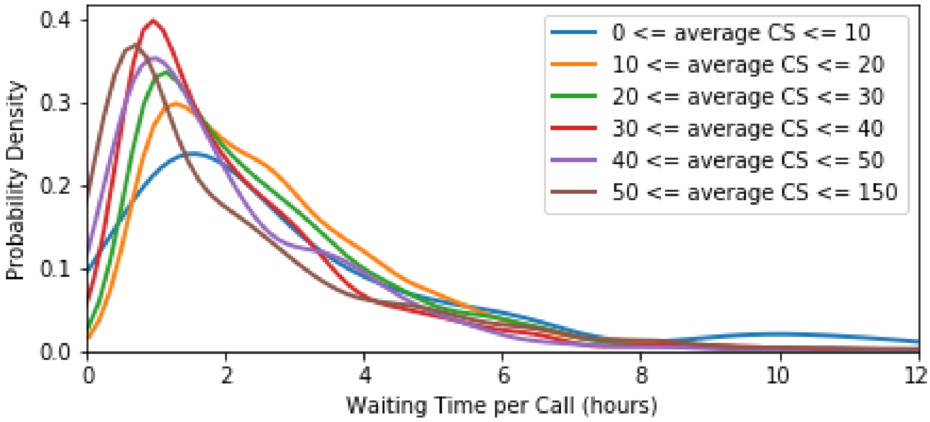

Figure 5.8: Distribution of waiting times per call, segmented on average call size, scenario with crane productivity of 22

changing the demand, thereby lowering the crane utilisation rates. This means the cost that terminals make per barge move increases.

In order to gain more detailed insights on the effects of increased handling capacity, one experiment was inspected in more detail, using 5 replications as in previous sections. The scenario with crane productivity of 22 lifts per hour was chosen, as this is a 10% increase in handling capacity, which resulted in a reduction in in-port time of 24%. As travel times remain unchanged, and processing times have reduced by 10%, the waiting times must have reduced. Therefore, the waiting times were plot, based on the call size a barge has, similar to how this was done for the standard scenario, in Figure 5.4.

As can be seen when comparing Figure 5.8 with Figure 5.4, the expected waiting times have been greatly reduced, as the probability of waiting times of under 2 hours per call have doubled, across all call sizes. This is a strong indicator that the system is much more efficient.

To conclude, our hypotheses were confirmed. Relatively small increases in handling capacity can lead to reduced barge in-port times, while utilisation is reduced slightly. The increased handling capacity reduces waiting times. The effects of a more reliable supply of handling capacity were promising, showing that a different temporal distribution reduced in-port times without reducing crane utilisation. Based on the analyses in this section, and the sensitivity analysis in the previous chapter, it is clear that an increased barge handling capacity reduces in-port times. Conversely, it can be concluded that insufficient barge handling capacity is one of the main causes for high barge in-port times.

5.4. Experimentation: Barge Operations Changes

Concept and Hypothesis

This section will evaluate changes to how barges operate in the port. As can be seen from Table 5.3, two experiments are based on measures from chapter 3: partnerships between barge operators, and the Container Exchange Route (CER). Additionally, the effects of changes to the distribution of barge sizes will be assessed.

Partnerships between inland terminal operators and barge operators have been stimulated by the PORA. The PORA has had success in partnering various domestic barge operators. Therefore, the effect of these partnerships is an increase in call size for vessels serving the domestic market. As such, domestic vessels will have the same total transport volume, but visit fewer terminals on average.

Another change to barge operations will be instigated by the use of the CER. This will increase inter-terminal transportation, thereby reducing the number of calls all barges will have to make. To place the effects of the CER in perspective, consider the following numbers. The CER is expected to facilitate one million moves per year, which is approximately 2750 per day. Not all of these transfers will facilitate barge handling, as rail consolidation will be targeted too. Conversely, the total number of barge moves per day is approximately 6600, based on the yearly throughput in TEU, the TEU-factor, and 360 days of operation per year.

Two exploratory scenarios have been performed. In these scenarios, the yearly throughput for the

domestic market remains unchanged, but all the domestic barges will be either large or small. In the scenario with solely large domestic barges, the total number of barges that visits the port is reduced, and call sizes increase. Conversely, when all domestic transport is done by small barges, the total number of barges increases heavily.
Partnerships have been fairly successful, and the expectation is that the model shows that an increased level of partnerships further reduces barge in-port times. Based on the yearly throughput numbers the CER should be able to handle, its effects are expected to be profound. The effects of the two exploratory scenarios are more difficult to predict. As the in-port time increases for larger vessels, the average in-port time will likely be reduced by using smaller vessels. The downside of using smaller vessels is the increase in total terminal-side slack that is caused by smaller calls, which could reduce terminal utilisation rates.

Implementation

In order to implement the four scenarios, just two parameters will be changed. For the CER and partnerships scenarios, the *Number of Calls* parameter is changed. This can be seen in Table 5.5. Partnerships will reduce the number of calls an average domestic barge makes by 1. The CER will also reduce the average number of calls by 1, but for each barge, as the effects are expected to be more pronounced.
For the third and fourth scenarios, the exploratory analyses that will evaluate the effects of using solely large or small domestic ships, the number of daily visits per barge type will be changed. This is done by changing the probabilities that a barge of the various types is generated, and changing the mean of the interarrival time distribution to adapt the expected number of barges that are generated per day. The results of these two changes are summarised in Table 5.6. In the table, the resulting expected number of barges per day for each barge type is depicted.

Table 5.5: Number of calls per barge type, for different scenarios

	Scenario		
Barge Type	Standard	Partnerships	CER
Antwerp	2	2	2
Small Domestic	3	2	2
Large Domestic	5	4	4
Lower & Middle Rhine	4	4	3
Upper Rhine	6	6	5

Table 5.6: Visits per day for each barge type, for different scenarios

	Scenario		
Barge Type	Standard	Large Domestic	Small Domestic
Antwerp	5	5	5
Small Domestic	8	0	55
Large Domestic	23.5	27.5	0
Lower & Middle Rhine	9	9	9
Upper Rhine	4.5	4.5	4.5
Totals	50	46	73.5

Results

The results of the changes to domestic transport can be seen in Figure 5.9. Because the experiments with only large or only small barges servicing the domestic market had zero observations of some

barge types, the results had to be plotted manually. Therefore, the figure is different to those that are output from Simio directly. Simio's MORE plots show the 95% confidence interval for the average barge in-port time, this is lacking in the plot of this experiment. The difference of the 'Partnerships' scenario with both the 'CER' and the 'Standard' scenarios is not significant. Those two scenarios do differ significantly. Although the results are not all significant, we still analyse the performance of the scenarios, as using more replications will likely show that there is a significant difference between the scenarios. Unfortunately, time limitations prevented this.
Compared to the current situation, forming partnerships and using the CER will reduce average barge in-port times. Partnerships will reduce the in-port time by 2%, and the CER wil reduce in-port times by 4% on average. The effects of both measures seem limited. Apparently, average barge in-port times are not so sensitive to the number of calls barges make. The average time savings are approximately equal to the reduced sailing and berthing time for the barge, in both scenarios. The expected time savings due to easier planning are not reflected in the model results.

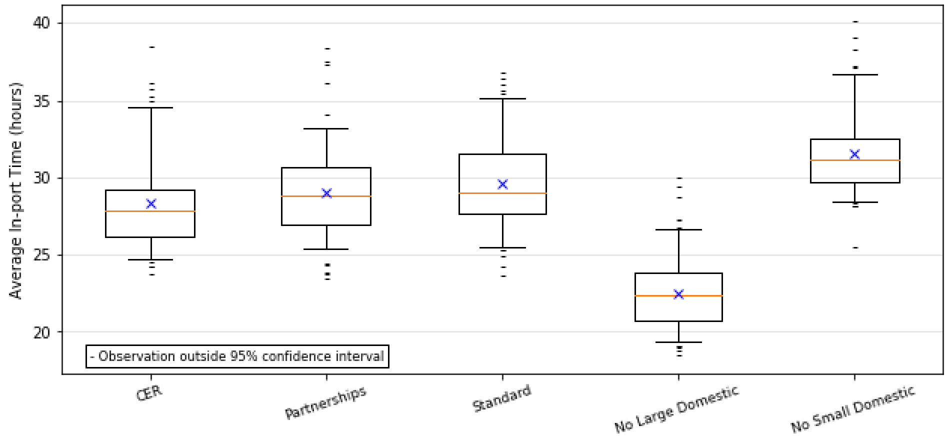

Figure 5.9: Results of Scenarios that change barges' in-port operations

The two exploratory scenarios show larger differences. The scenario without large domestic barges shows a reduction of average barge in-port time of 24%; the scenario without small domestic barges shows an increase of 6%. However, the average barge in-port time is not a suitable measure to evaluate these two scenarios: small barges spend less time in-port than large barges, and the barge type shares have been changed. Therefore, a more in-depth analysis can be found in Table 5.7. Here, the in-port times of each barge type are given, for three scenarios. Additionally, the average number of visits per barge type across the 100 replications is provided.
From Table 5.7, several interesting findings can be distilled. Without large domestic barges, all other barge types' average in-port time reduces. Conversely, using more large domestic barges increases all other barge types' average in-port times. The working mechanism here is not clear. Because of the planning algorithm that terminals use in the model - recall that larger barges are prioritised, based on the number of timeslots they require - one might suggest that fewer large barges will be prioritised over smaller barges, thereby reducing in-port times for smaller barges. However, this effects seems to only provide a limited explanation, as the average call size for large domestic barges is in fact the second-smallest, after small domestic barges. Due to stochastics, there will certainly be cases where the lack of large domestic barges does contribute to the planning of other barge types. However, the in-port time for barges sailing to Antwerp decreases too, while they are always planned first as they have the largest call sizes. The changes to in-port time are not caused by changes in utilisation rate, as they are almost exactly the same across the three scenarios, as throughput volumes remained stable. One last explanation for the system improvements as a result of many small barges visiting the port is that the increase in number of different barges results in a more even spread of barge visits, both over time and over the different terminals in the model.
Another finding is that interestingly, the total number of hours spent in port by barges decreases in the scenario that performs worst on in-port times. Calculations based on average travel times per barge type show that these differences are only partially caused by changes in barge travel times. For instance, the increased travel times cause only 20% of the increased system total barge in-port time,

when comparing the scenario without large domestic barges with the standard scenario. To optimise the time spent in-port per container move, a barge operator should increase its barge size. This relation suggests a trade-off between average barge in-port time and average in-port time per moved container, as both of these are influenced by barge size.

Table 5.7: Comparison of exploratory scenarios, averages per barge type

Scenario	**No Large Domestic**		**No Small Domestic**		**Standard**	
	Average IPT	Visits	Average IPT	Visits	Average IPT	Visits
Antwerp	18.8 hours	210	20.8 hours	209	20.4 hours	210
Small Domestic	21.5 hours	2305	0.0 hours	0	23.9 hours	339
Large Domestic	0.0 hours	0	33.6 hours	1152	33.0 hours	983
Lower & Middle Rhine	24.6 hours	381	28.2 hours	380	27.6 hours	381
Upper Rhine	33.1 hours	189	37.5 hours	188	36.7 hours	187
System total barge in-port time	69177.2 hours		60822.1 hours		62175.4 hours	
Average terminal utilisation	74.7%		74.7%		74.8 %	

5.5. Experimentation: Auctioning

Concept and Hypothesis

One of the frequently coined causes for high in-port times is that the planning that results from the autonomous decisions of the deep-sea terminals results in in-port times that are a lot longer than they would be if a centralised planning system was incorporated. Because the barges and terminals compete amongst each other, centralised planning is yet to be implemented. An alternative could be to circumvent cooperation and use market dynamics. Barges could then signify the importance of certain slots for their rotation. An interesting experiment would be to auction all slots, to allow barges to influence the terminal berth planning process. Several auctioning mechanisms could be tried, that each have different repercussions for final price. A sealed-bid second-price auction, also called a Vickrey auction, should mitigate tactical bidding, according to game theory. The downside of auctioning all slots could be that barges with a low Willingness to Pay (WTP) are duped, and potentially spend much more time in port than their competitors. As margins for barges are low, but barge handling is expensive for terminals, it might be reasonable to set boundaries within which the bids must be.

On an aggregated level, auctioning is expected to increase the average in-port time, as the changes to the berth planning algorithm will probably increase the waiting time due barges face in between terminal visits. On a more detailed level, planning slots based on auctions should lead to more skewed in-port times, as barges with a low WTP will likely spend longer in port, but barges with a high WTP will spend shorter.

Implementation

As there is no data on the distribution of barges' WTP, the WTP for all barges is drawn from a uniform random distribution, with fictive boundaries. It is assumed that barges always place bids that are in line with their WTP, and that they do not exhibit tactical behaviour. Conversely, terminals are obliged to allocate any slots to the highest bidder. The bids barges place represent a fee per timeslot, to more easily determine the highest bidder for a timeslot, as opposed to if the WTP were to represent a fee per move.

In cases that barges have overlapping requests, for instance because barge A placed the highest bid for slots 1-5 at €50,- per timeslot, and barge B placed the highest bid for timeslots 5-8 at €60,- per timeslot, the higher bidder gets prioritised. Barge C may well win timeslots 1-4 for €40,- per timeslot.

The auction for certain timeslots closes at the same time the cutoff timer dictates that those same slots can no longer be reserved. The auctioning is implemented as follows: when the auctions have closed, the terminal goes through the list of barges that have bid on slots, finds the barge with the highest bid, and allocates the slots, if this is feasible. If this is infeasible, the first timeslots after the requested ones are allocated, just as in the standard scenario.

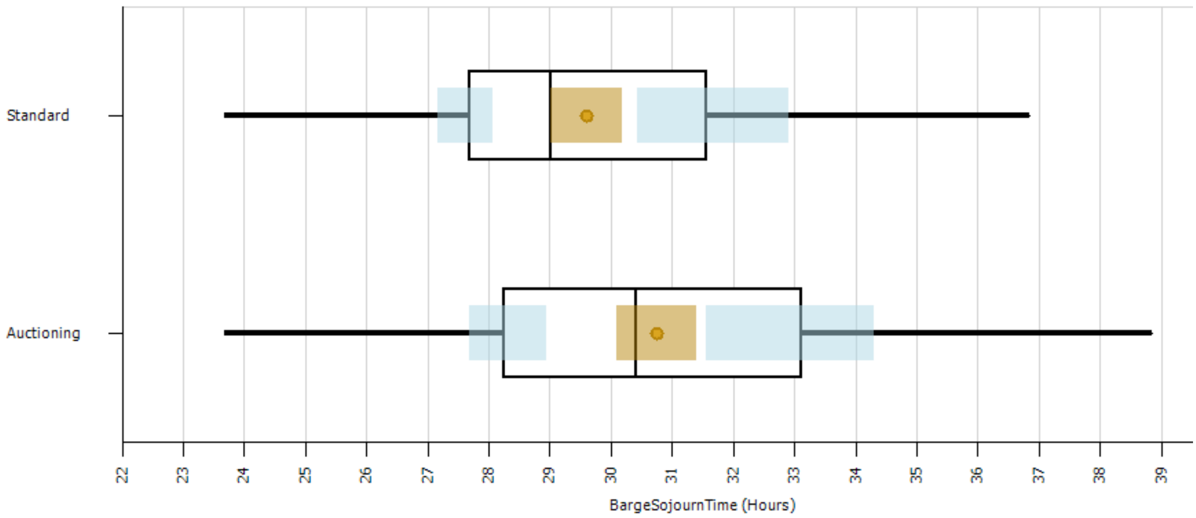

Figure 5.10: MORE plot of auctioning experiment

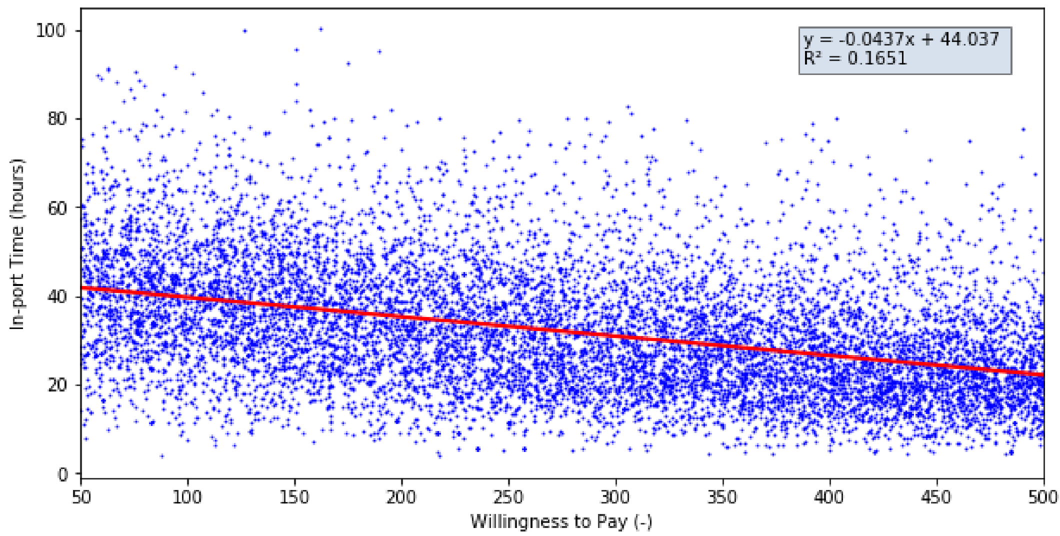

Figure 5.11: Auctioning experiment: scatter plot of in-port time versus willingness-to-pay

Results

Again, as can be seen in Figure 5.10, the results do not differ significantly after 100 replications. However, as in previous sections, we will discuss the differences regardless, as the experiments are very nearly significantly different, and increasing the number of replications would most likely have resulted in significant differences.

Implementing auctioning increases the average in-port time for barges by just over two hours, or 7%. This increase can be expected, as the initial berth planning algorithm prioritises planning large ships, which could result in higher crane utilisation rates. Upon closer inspection, however, the crane utilisation rates are almost exactly the same, with the average utilisation of the five deep-sea terminals at 74.8% for both scenarios.

In order to better understand the effects of auctioning timeslots, a number of replications was studied more closely. The same replications were studied as in previous analyses. One of the interesting relations is that between a barge's WTP and its in-port time. The scatter plot, depicting a barge's in-port time versus its WTP, can be seen in Figure 5.11.

On the scatter plot, a linear trendline was plotted. Although the R^2, a measure for the share of variance explained by the independent variable, is quite low, a clear trend can still be seen. The expected in-port time for a barge with the minimum WTP is 19.7 hours higher than that of a barge with maximum WTP.

Nevertheless, as the in-port times depends on many more factors, a low WTP doesn't neccesarily result in a large in-port time. Conversely, a high WTP does not ensure that a barge's in-port time is low.
To conclude, auctioning all timeslots does not improve the average barge in-port time. A clear relation between a barge's WTP and in-port time was found. Therefore, the auctioning scenario may score better on a different metric, that incorporates the value of a barge's goods, such as the total in-port time multiplied by a barge's WTP. The auctioning experiment here does not incorporate behaviour that would be expected in reality. For instance, barges would be likely to have a higher WTP for the last terminal on their rotation. The temporal issue of planning a rotation in advance, without knowing what timeslots a barge will be allocated, still persists.

5.6. Experimentation: Priority Requests

Concept and Hypothesis

In order to ensure that prices don't go up too much, and retain stability in the container barging market, a split could be made between two price levels: priority and standard. The priority reservations will be planned first, to increase the chance that a barge is allocated a timeslot, in order to simplify rotation planning for barges. Priority pricing would simply be an increased rate per container move, or a combination of an increased rate per container move and a minimum call size. The hypothesis is that, when only a small share of barges files priority requests, priority requests can reduce the in-port time for these barges, without impacting the other barges too much.

Implementation

The implementation of priority requests is based on the barge's WTP, as in the previous experiment. A threshold can be set to determine what share of the barges will file priority requests. If a barge passes this threshold, the barge will file priority requests at all the terminals. The terminals start planning the barges that have filed priority requests. Of the barges with priority requests, they start with barges that require many timeslots, like the planning algorithm in the current scenario. When all priority requests have been scheduled, the normal requests are scheduled.

Results

The effect of implementing priority requests on the average barge in-port time can be seen in Figure 5.12. As a form of verification, the scenario was also run with thresholds of 0, which should lead to the current scenario, as all of the barges can file priority requests. The experiment has been verified, as this scenarios does in fact show the same outcome as the standard scenario. Although the confidence intervals for the means show that there is no significant difference between the experiments, a trend can be seen that an increase of participation in priority requests leads to a higher average in-port time, which is in line with expectations. Fortunately, the average in-port times increase only slightly. The scale of the effect is smaller than the effect of auctioning, which is presumably caused by difference in berth planning algorithm. Where the auctioning algorithm determines the next barge to plan based on their WTP, the priority algorithm determines what barge to plan based on their requested number of timeslots, given they pass the threshold for priority requests. As was hypothesised in the previous section, the changes to how terminals plan could potentially reduce their crane utilisation, but this was disproven for the auctioning scenario. The same is true for priority pricing; the average terminal utilisation does not change significantly, for any of the priority thresholds that were set.
For a more in-depth understanding of the effects of priority requests on specific barges, two probability density plots were made, using the same replications as in the previous section, as this allows us to compare the systems reactions to identical input. The priority threshold that will be investigated is set at 10, meaning that 10% of barges will request priority slots. This threshold was chosen because of the expectation that this can provide a more reliable in-port time improvement for the priority barges, as opposed to setting the threshold at a higher level. At the same time, as fewer barges can request priority slots, the effects on the barges that do not file priority requests should be smaller.
The two probability densities can be found in Figure 5.13. There is a clear reduction in the in-port times for barges that use priority reservations. The average in-port time of the priority group, normal group, and all barges is summarised in Table 5.8. The scenario shows interesting results, with priority barges leaving the port in 74% of the standard scenario average time, while non-priority barges spend only an extra hour in the port, when compared to the standard scenario.

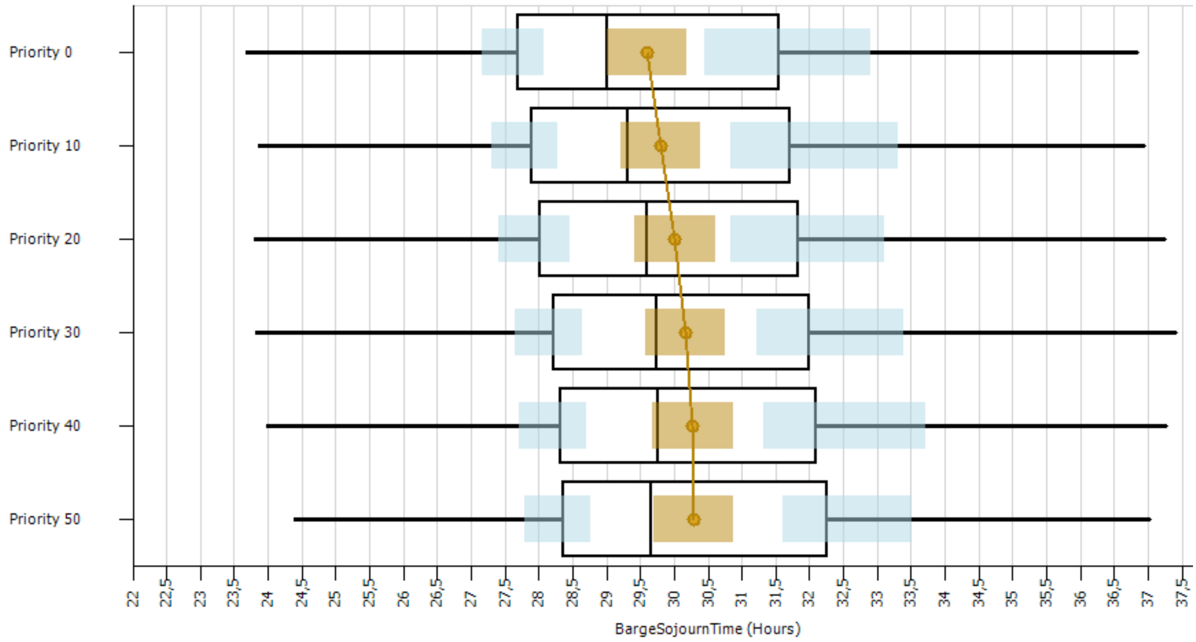

Figure 5.12: MORE plots of average barge in-port time for different levels of priority requests

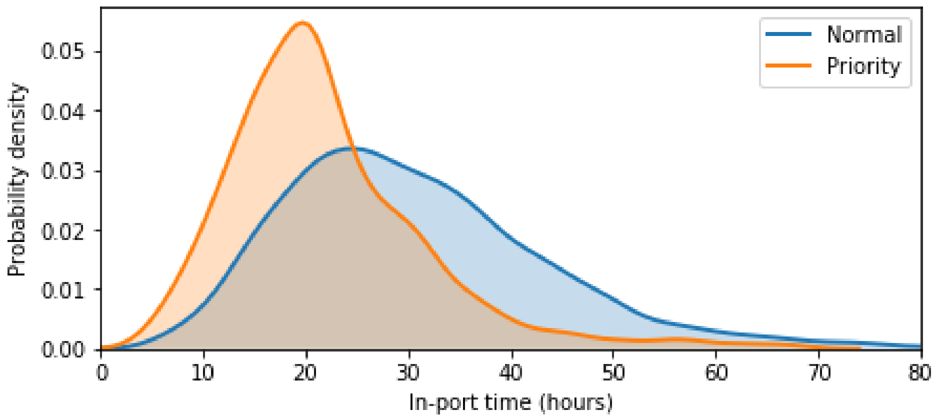

Figure 5.13: Probability density function of in-port time in priority scenario (threshold = 10), for barges filing normal and priority requests

Table 5.8: Priority requests (threshold = 10): in-port times of normal and priority barges

Group	**Average in-port time**	**Relative to Standard Scenario**
Priority	22.0	74%
Rest	30.7	103%
Total	29.7	100%

Unfortunately, priority barges are not guaranteed a short in-port time. This is caused by peaks in demand: then, a terminal plans normal barges from the previous day in the berth planning for the next day. In the version of priority requests that was implemented here, these reservations are not moved around. Additionally, terminals will sometimes have little available capacity, or even have none. Then, priority requests will still be prioritised, but those barges will still be delayed.

5.7. Experimentation: Information Sharing

Concept and Hypothesis

Currently, when barges are planning their rotation, no information is shared by terminals, while research by Douma *et al.* proved that this would improve barges' rotation planning process [62]. The version that was implemented by Douma *et al.* is fairly sophisticated: reservations are instant, but terminals keep the right to move around reservations within certain margins, thereby enabling the terminals some flexibility in planning future barge requests, while still providing the barges a latest departure time at the terminal. This helps barges plan feasible rotations. This system only improves the barge rotation planning process if terminals keep their appointments. Therefore, a contractual relation, or other organisational change is required.

As the berth planning rules will change, in comparison to the standard scenario, the in-port time distribution of the various barge types will change. In the current scenario, barges with large call sizes were planned first. This resulted in low in-port times for barges servicing Antwerp, due to their high average call size. The hypothesis is that the in-port times will be much more evenly distributed across barges servicing different hinterland areas.

Implementation

The concept could be implemented with varying levels of detail, but a simple form is evaluated here, as the model would have to be changed significantly to allow for the level of detail that was modelled in Douma *et al.* [62]. Each terminal will signify whether or not it has available capacity, and barges will only request timeslots that are available. Essentially, this changes the system to a form of first-come-first-serve with instant reservations. This will prevent infeasible rotations from occurring.

One aspect of instant reservations and information sharing that is not incorporated in the model, is that barges will not evaluate the options available to them to visit terminals in a different sequence, with the goal of minimising their in-port time. They will simply follow the same rotation as in previous experiments. To incorporate this in the simulation model, many aspects of the rotation planning process had to be changed, which was infeasible to do in the available time. Additionally, loading plans and containers were not modelled in the model explicitly. It is expected that this would further reduce in-port times, as the information sharing allows barges to compare all the possible rotations, and pick the one that best suits their needs.

Results

The MORE plot comparing the information sharing scenario with the standard scenario can be found in Figure 5.14. The information sharing reduces the average barge in-port time by 5 hours, or 17%, when compared to the standard scenario. This is in line with the hypothesis. Information sharing, in the way it was implemented here, cuts a lot of inefficiencies out of the planning process. The waiting times of barges have reduced significantly. Again, terminal utilisation rates remain unchanged. The average in-port times of the system are more reliable, as can be seen from the reduced quartile ranges in the MORE plot.

As hypothesised, the distribution of in-port times will have changed too. The distributions per hinterland service area are plotted in Figure 5.15. As expected, the in-port time distributions are much more similar to each other than in the standard scenario, in which the call sizes dictated who was prioritised in the berth planning.

To conclude, this experiment has proved that current planning procedures lead to inefficiencies, causing high barge in-port times. This was done by implementing a different planning procedure, thereby also proving the effect of changing the planning procedures.

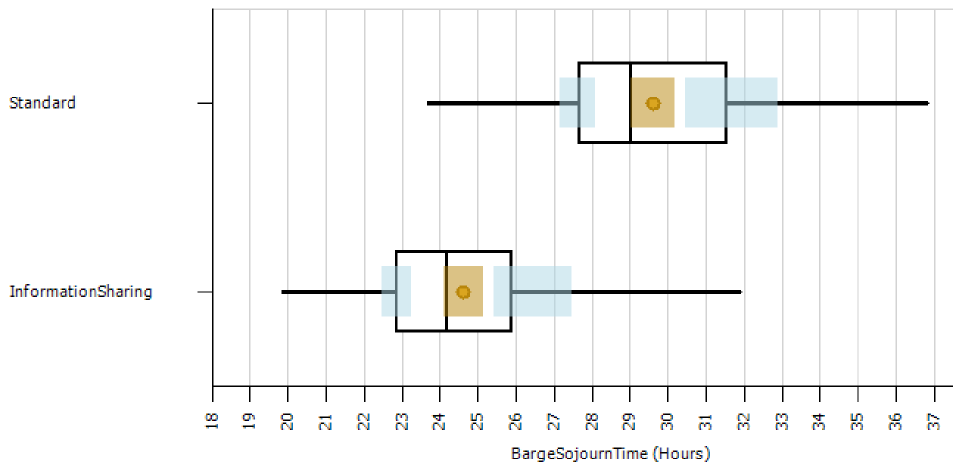

Figure 5.14: Average in-port time of the information sharing experiment compared with the current situation

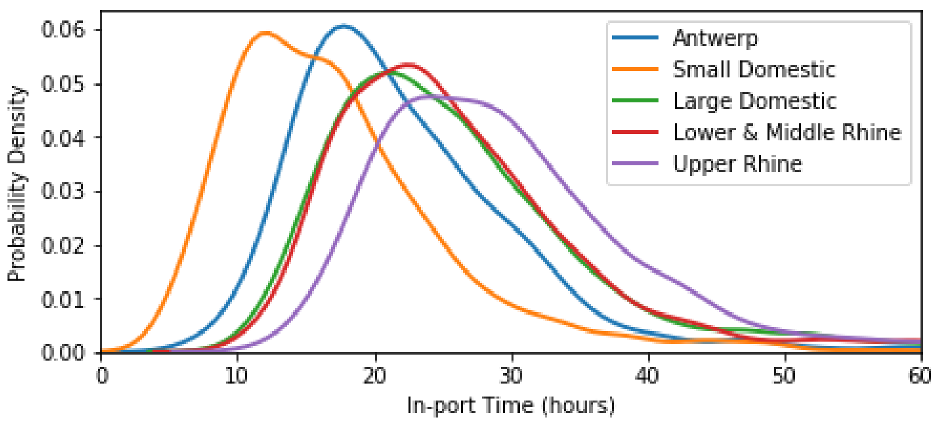

Figure 5.15: In-port time distributions for different service areas, information sharing scenario

6
Conclusions

This chapter will conclude the research by reporting the findings, assessing the limitations of this research, and indicating where this author would continue with further research. The research question of this thesis was:

What causes for high barge in-port times are there, and how can the barge in-port times be reduced?

The research question was split in several subquestions. Throughout this thesis, these subquestions have been answered. Here, the findings will be summarised, in order to answer the main research question.
A figure showing the performance of the different experiments can be found in Figure 6.1. The boxplots show the average in-port time per scenario, and how the *average* in-port time was distributed over 100 replications. It does not show how in-port times are distributed amongst the barges in each replication.

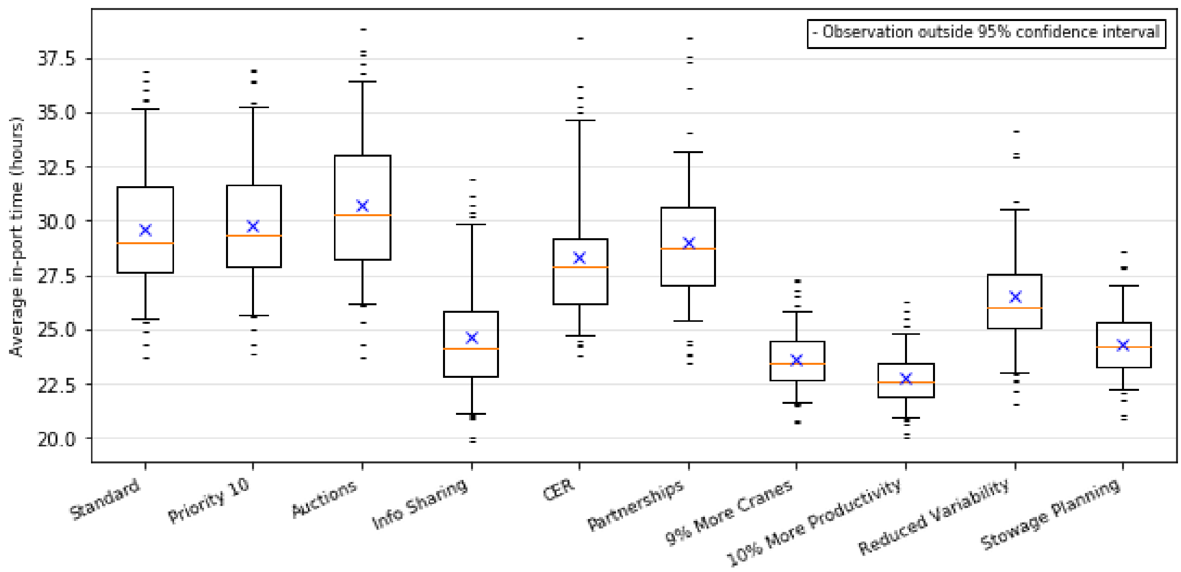

Figure 6.1: Boxplot of average in-port times from 10 scenarios

6.1. Causes for High Barge In-port Times

The causes for high barge in-port times were introduced in section 3.1, and summarised in Figure 3.8. The main causes for high barge in-port times, as validated by the model, are the i) mismatch between

demand for and supply of barge handling capacity, and ii) poor planning procedures, causing inefficiencies in rotation planning and berth planning. The effects of changes to barge handling capacity - both absolute and temporally (the reduced variability scenario) - were verified in section 4.8 and section 5.3; the effects of ineffective planning were verified by testing changes to the planning system in section 5.7. As can be seen in Figure 6.1, the scenarios that increase the handling capacity or change the planning procedures show the largest improvements in average barge in-port time. These two main causes are the result of, or compounded by, many other phenomenon, such as the size of deep-sea vessels, their schedule unreliability, and the lack of a contractual relationship between barge operators and deep-sea terminals.
From the simulation model, a more intricate understanding of high barge in-port times was gained. The results in the standard scenario were inspected, and sensitivities to input parameters were tested in the sensitivity analysis. This led to several insights with regard to the causes for high barge in-port times for specific barges:

- Higher average call sizes lead to more reliable in-port times.
- Reducing the number of calls a barge makes can reduce in-port time: expected travel and waiting time are reduced
- Waiting times per call increase as the average call size decreases
- The in-port time per move decreases as the average call size increases

6.2. Measures against High Barge In-port Times

Similar to the causes, a list of measures was introduced in section 3.2. To assess the effects of these measures, a simulation model was used. Unfortunately, not all measures could be tested in this simulation model. The measures were converted to an experimental plan, which can be found in Table 5.3.
The previous chapter discussed the experimental plan, explained how the scenarios were implemented in the simulation model, and presented the results. Here, we summarise the results of the experiments, and draw conclusions based on the results.
The pricing experiments, where timeslots were auctioned, or priority requests could be submitted, show a small increase in average barge in-port time. The effects of auctioning all timeslots were quite severe: the expected in-port time of the barges ranges from 41.9 hours for barges with the lowest WTP, to 22.2 hours for barges with the highest WTP. Because many other factors influence a barge's in-port time, a high WTP does not always guarantee a low in-port time. Likewise, a low WTP does not always result in a high in-port time. The scenario with priority requests was run for different WTP thresholds, to vary the percentage of barges that would submit priority requests. The scenario that was studied in more detail has a threshold of 10%, as this would keep the negative impact on non-priority barges low. The scenario showed that priority barges' average in-port time was 74% of the average in-port time in the priority scenario, where normal barges had an average in-port time of 103% of the average.
Following positive results by Douma *et al.*, information sharing from terminals to barges was implemented. The results of our experiment showed a 17% reduction in average barge in-port time, at no extra cost for resources. This reduction shows the inefficiencies caused by autonomous and delayed planning by terminals.
Currently, the PORA is stimulating more partnerships amongst barge operators in the Netherlands, to increase call sizes. The PORA is also building the Container Exchange Route, to facilitate inter-terminal transportation to increase call sizes. Our experiments showed that these measures have limited effects, with partnerships reducing in-port times by 2%, and the CER reducing in-port times by 4%.
Finally, as the sensitivity analysis showed how sensitive the system is to changes in barge handling capacity and demand, four experiments were designed to evaluate changes to the barge handling capacity at deep-sea terminals. Two experiments tested an increase in barge handling capacity, while following the same distribution of capacity over time as in the current state. One of these experiments increased the number of cranes, while the other experiment increased crane productivity. Both experiments were run with five levels of capacity increases. Both experiments showed diminishing returns; the in-port time reduction per percent point of increased capacity decreased, as waiting times had already been reduced. In Figure 6.1, a level of capacity increase was chosen for both experiments. Both increased capacity by approximately 10%. The experiments showed a reduction in average in-port time of 20% and 23%, respectively. Increasing crane productivity performs slightly better than

increasing the number of available cranes, as increased crane productivity results in reduced processing times. The other two experiments changed the distribution of barge handling capacity over time. One experiment, ”Reduced Variability”, kept the average number of available cranes the same as in the standard scenario, but made the capacity more constant. The other experiment simulated the effects of improved stowage planning on deep-sea ships, by assuming that this would lead to quicker turnaround times for deep-sea vessels, thereby reducing the chance that terminals have only 1 or 2 cranes available for barges. The average available capacity was increased by 6.4%. Reduced variability led to an in-port time reduction of 10%, at no extra resource cost. Stowage planning reduced in-port times by 18%.
Across all scenarios that did not change the total available barge handling capacity, the utilisation rate did not change significantly, denoting that the difference in total performed lifts between those scenarios was very small, meaning that from a terminal perspective, the different experiments would not influence yard operations and terminal throughput in a negative fashion.

6.3. Implications for the Market

The experiments in this thesis have yielded several interesting results.
Barge operators, unfortunately, have limited means to improve their barge in-port time. However, increasing call sizes, and reducing the number of calls, makes their in-port time more efficient, moving more containers per hour spent in-port. For barge operators, using larger barges results in economies of scale, both while sailing to the hinterland, and while in the port, as larger barges have reduced in-port times per move. These larger barges spend more time in port, but this seems to be a rational decision.
Deep-sea terminal operators have more opportunities to improve barge in-port times. Without incurring costs, they can reduce barge in-port times by changing their planning procedures. Information sharing helps reduce barge in-port times, as this improves the barges’ rotation planning process. Terminal operators can also reduce barge in-port times by making changes to their handling capacity. Without increasing the total available capacity, providing a more constant supply of barge cranes reduces barge in-port times. Similarly, by pricing deep-sea vessels dynamically, to incentivise them to improve their stowage planning, deep-sea vessels can reduce their turnaround times, increasing available barge handling capacity, at no extra cost to the terminal operator. Finally, terminal operators can opt to increase terminal capacity, either by adding more cranes, or by using current cranes more effectively. If a decision maker is faced with a decision between the two, improving crane productivity outperforms installing more cranes, from a barge in-port time perspective. The auctioning experiment showed interesting results, but the unreliable in-port times for barges with high bids makes such a system less attractive for barges. The priority experiment seems a lot more feasible for implementation in the market. The downside for barges that do not want to participate is limited, whereas the in-port time reduction of barges with priority reservations was sizeable. Perhaps, terminal operators could invest (part of) their profits in improved cranes, although this will deteriorate the business case for priority pricing, by reducing in-port times of all barges.
Finally, deep-sea shipping lines can improve their schedule reliability, stowage planning, and reduce their vessel size, all with the aim of increasing the available barge handling capacity at deep-sea terminals. As explained in more detail in subsection 3.2.3, stowage planning and schedule reliability go together, and provide sizeable benefits for deep-sea shipping lines as well. For interested readers, this author recommends reading two editorial articles by Haralambides, that provide interesting insights in the trends that shape maritime shipping, specifically the interaction between large deep-sea vessels and port operations.

6.4. Discussion and Recommendations

First and foremost, data gathering for this thesis was difficult. The importance of the balance between supply and demand for barge handling capacity means that data on these aspects is vital to the model outcomes. One of the main limitations of the conceptual model is the absence of deep-sea vessels. In reality, in the days before a deep-sea vessel visits a terminal, a lot of barges will drop off export containers for this deep-sea vessel. Similarly, the offloaded containers need to be transported to the hinterland, leading to a spike in barge visits once more. This relationship is absent, as deep-sea ships are not modelled. If possible, any further research should try to incorporate deep-sea vessels in their

model.
Additionally, barge operator volumes and visit frequencies are not available. Therefore, the barges cannot be linked to specific barge operators, and the effect of barge operator fleet size can not directly be tested. If possible, further research should assess the effects that large fleets have on barge operations.
The experiments could have been performed with variable crane productivity, instead of only testing the effects in the sensitivity analysis. Further research should implement this.
The berth planning algorithm that was used in the simulation model was fairly simple. It would be interesting to compare different kinds of planning algorithms, or incorporate optimisation.
Unfortunately, the results of some experiments did not differ significantly from the standard scenario. Perhaps the model could have been made more efficient computationally, which would have allowed to run more replications given the time constraints. Regardless, more replications are required to make sure all results are significant.
Due to time limitations, the model was not yet validated by market stakeholders. In January, the model and results will be presented to several barge operators.
Finally, several new ideas could be evaluated in further research: the effects of using a modular pushbarge system, and dynamic pricing for barge timeslots. Use of modular and autonomous pushbarges is being researched at Delft University of Technology. This could profoundly change container barging. Because the changes to the system would be so significant, they were not evaluated in the simulation model.
To spread demand for barge timeslots, prices for barge handling could be varied through time, in order to match demand and supply. This is similar to what the research of Chen *et al.* [76] did with trucks. Further research could show the effects of such a system. As barges would then be able to book slots directly, the in-port times would probably reduce.

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A

Scientific Paper

Slot allocation for barges at deep-sea terminals: a two-class differentiation approach

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Abstract

Service differentiation and revenue management have many applications in many sectors. Here, a two-class differentiation approach is applied to slot allocation of barges at deep-sea terminals. In the port of Rotterdam, barges have high in-port times, of which significant stretches are spent waiting. Barges may be willing to pay a premium for reduced waiting times. The effects of implementing the two-class approach in the port of Rotterdam were assessed with an agent-based simulation model. The model shows that, while the effects of choosing the priority service differ from barge to barge, the in-port times of priority barges are reduced, without increasing the average in-port time of all barges.

1 Introduction

Maritime transport has an important position in global trade, with a share of over 80% of global trade volume [Asariotis et al., 2018]. Since its invention in 1956, the standardised shipping container has been instrumental in bringing down costs of transport, and unlocking the potential for global supply chains [Notteboom and Rodrigue, 2008]. Rotterdam is Europe's largest container port. In 2018, 8.635 million containers, or 14.5 million TEU, were transshipped in the port of Rotterdam [Port of Rotterdam, 2018]. As approximately 30% of the total throughput is transshipped onto other seaborne ships, 70% is destined to or originates from the hinterland [Kennisinstituut voor Mobiliteitsbeleid, 2017]. Hinterland transport can be performed by truck, train or barge. Because transportation by barge is more sustainable than transport by truck, and to reduce congestion on roads around Rotterdam, the Dutch government is trying to instigate a modal shift, where more containers are shipped to and from the hinterland by barge and rail, as opposed to truck. Recently, however, barges have been spending a lot of time in-port, which is reducing the service level and the capacity of hinterland transport by barge. The Port of Rotterdam has developed a "Barge Performance Monitor", to clearly present a series of key performance indicators for hinterland container transport by barge [Port of Rotterdam]. In the 10 weeks prior to 27/2/2019, an average container barge sailing the Rhine spent approximately 53 hours in port. The in-port times differ greatly per barge visit, as average in-port times fluctuate from week to week, and from barge to barge [Heuvelman, 2019]. As waiting times are the main source of differences in barge in-port times, implementing two service levels could reduce in-port times for the barges that pay for premium or priority service.

This paper assesses the effects of implementing this two-class offering through an agent-based simulation model, which is applied to a case study in Rotterdam. But first, background information is provided in the remainder of this section. Then, the model is explained in section 2. The experimental setup is discussed in section 3. Finally, the results are reported in section 4, and conclusions are drawn in section 5.

1.1 Container barging in Rotterdam

Each year, 18,000 container barges visit the port of Rotterdam [van Strien, 2019]. They transfer approximately 4,150,000 TEU per year [Doornhein, 2019]. Therefore, on average, container barges offload and load a combined 231 TEU in Rotterdam [Port of Rotterdam, 2018], which takes 26.4 hours [LINc, 2019]. Barges call at multiple terminals per visit, with Rhine vessels calling at an average of 7 terminals [Port of Rotterdam]. The order in which they visit them is based on the way the barge has been loaded, the expected waiting times at the terminals, and the deadlines for dropping off or picking up certain containers. Barges can not show up at a terminal and expect to be handled; they must request timeslots to be handled at these terminals at least 15 hours, and at most 58 hours in advance. Barges plan their operations through the port area, leading to a rotation plan that contains the order in which they move through the port, and what timeslots they have requested at the different terminals. Terminals collect these requests until a certain so-called *cutoff time*, and start their berth planning process, in which they allocate quay wall and quay cranes to the barges that have requested timeslots. Quay wall and quay cranes, however, are limited resources that are in high demand. The majority of the quay wall and the cranes at deep-sea terminals are designed to handle very large deep-sea vessels. As such, barges compete for these resources with deep-sea and feeder vessels.

Several trends in deep-sea shipping have lead to reduced barge handling capacity. Deep-sea container ships have grown very quickly over the last 15 years [Asariotis et al., 2018]. However, the available capacity outgrew the demand, forcing deep-sea lines to cooperate in alliances in order to utilise their new, large ships. These larger ships have led to more of a hub-and-spoke system, which requires more sea-to-sea transshipment at terminals. Additionally, the alliance ships generally have poorer stowage planning, making decoupling of containers at terminals more difficult [Haralambides, 2017]. This leads to reduced barge handling capacity at deep-sea terminals. Deep-sea shipping lines pay for the handling of barges, leading to an imbalance of power.

Five large deep-sea container terminals on the Maasvlakte are responsible for the handling of a large majority of deep-sea ships [van der Horst et al., 2019]. At these deep-sea terminals, barges are planned in the berth schedules last, leading to large fluctuations in available barge handling capacity, as the departure or arrival of deep-sea ships free up or require many cranes at once.

A barge's operations in Rotterdam are characterised by their lack of control over the operations: barges request handling timeslots at the terminals, but terminals schedule the barges. The rotation planning process is time-consuming and inefficient.

1.2 Differentiated service offerings

Service differentiation and revenue management have many applications in many sectors [Chiang et al., 2006]. For instance, airlines and trains have different travel classes, catering to different segments of the market. In the Netherlands, goods can be shipped overnight, or same-day delivery can be booked at a premium. Tawfik and Limbourg [2018] present six characteristics that are shared by industries that apply revenue management:

- relatively fixed capacity
- demand can be segmented
- perishable inventory
- product is sold in advance
- substantially fluctuating demand
- low sales costs, high marginal capacity costs

Container terminals do not have different service offerings. However, many aspects of containerised transport are suitable for pricing concepts [Holguín-Veras and Jara-Díaz, 1998]: containerised goods can have different values, both intrinsically and from a supply chain perspective. A container filled with phones is more valuable than a container filled with footballs; a delayed container of Christmas bulbs is a small issue in August, and more problematic towards the end of December. Barge handling shows the six characteristics that are often found in revenue management industries. Therefore, the barge handling market is expected to be suitable for different service offerings at different price points.

1.3 Differentiated pricing in a maritime context

Price differentiation, whether it is for different service offerings or to influence demand for a single service, can be used to increase revenue or improve efficiency [van Riessen et al., 2015]. However, in practice, price differentiation is not applied in many aspects of container terminal operations. Several studies discuss the effects of differentiated pricing. These are discussed here.

In a 2011 study, Chen et al. [2011] use a two step approach to reduce truck congestion at a container terminal. First, they determine the system optimum arrival time distribution through a nonlinear programming optimisation model. Then, the normal demand for a set of timeslots is compared to the system optimum demand, which then functions as input into a pricing model. This research could be applied to container barge handling.

The concept of differentiated pricing of yard space is discussed in Holguín-Veras and Jara-Díaz [1998]. They also report that some shipping lines have been charging for so-called 'hot hatches', locations on deep-sea ships that are offloaded first.

Dynamic pricing of deep-sea vessels' terminal dues could lead to a win-win situation, as vessels can receive discounts for improving their stowage planning to facilitate improved terminal operations, leading to reduced turnaround times and more efficient crane operations [Glave and Saxon, 2015].

Finally, revenue management systems frequently discount spoilable goods, such as seats on a plane that is about to depart, or flowers at a market near the end of day. Akin to this form of revenue management, research by Liu and Yang [2015] and Crevier et al. [2012] has assessed the effects of maximising revenue for cargo trains in a multimodal network.

2 Methodology

A model will be used to compare the operations of barges in the current state with the operations after the two-class approach has been implemented. To this end, the current state must be replicated in the model. Therefore, an agent-based simulation model is required, as the barges and terminals in the system perform their own planning processes. The in-port times per barge are the model's output indicators that describe the effects of the two-class approach, as an increase in average barge in-port time is unwanted, and the distribution of in-port times should show a clear improvement for the priority class, when compared to the normal class.

The operations of a barge in the port area were modelled as a discrete event simulation in which multiple servers are visited. The barges are the entities that flow through the system; terminals represent the servers. Deep-sea vessels were not modelled. Their effects on barge operations were incorporated through the available barge handling capacity at the different terminals. First, the properties and processes that define the operations of barges are discussed. Then, terminal properties and processes are presented. These sections report on the current state model. Implementation of the two-class planning approach is explained in subsection 3.4.

2.1 Model formulation: barges

Several properties define the operations of a barge in Rotterdam, for the purpose of comparing in-port times:

- the number of calls a barge has to make in port
- what terminals these calls are at, and in what order
- the call sizes of each of these calls
- the slack a barge uses while planning

Using these properties, barges can plan their rotations. The following steps describe their rotation planning process:

1. Determine the next terminal in the rotation
2. Calculate the timeslots the barge should request, based on the barge's rotation plan so far, its call size, planning slack, network travel times, and the next bookable slot at the terminal
3. Repeat until whole rotation has been planned and requested

2.2 Model formulation: terminals

Terminal operations are defined by a set of properties and processes. The properties that define a terminals barge handling operations are as follows:

- The number of available cranes over time
- The crane productivity
- The cutoff time

The barge handling capacity is combined with the requests a terminal receives from the barges, and used to create a berth schedule. When their cutoff time is reached, terminals make their berth planning using the following logic:

1. Find the request that requires the most timeslots
2. If those timeslots are still available, allocate to barge, otherwise allocate the first subsequent timeslots that are available, and share the allocated timeslots with the barge
3. Repeat until all barges have been planned

An overview picture, explaining the model functionality is depicted in Figure 1.

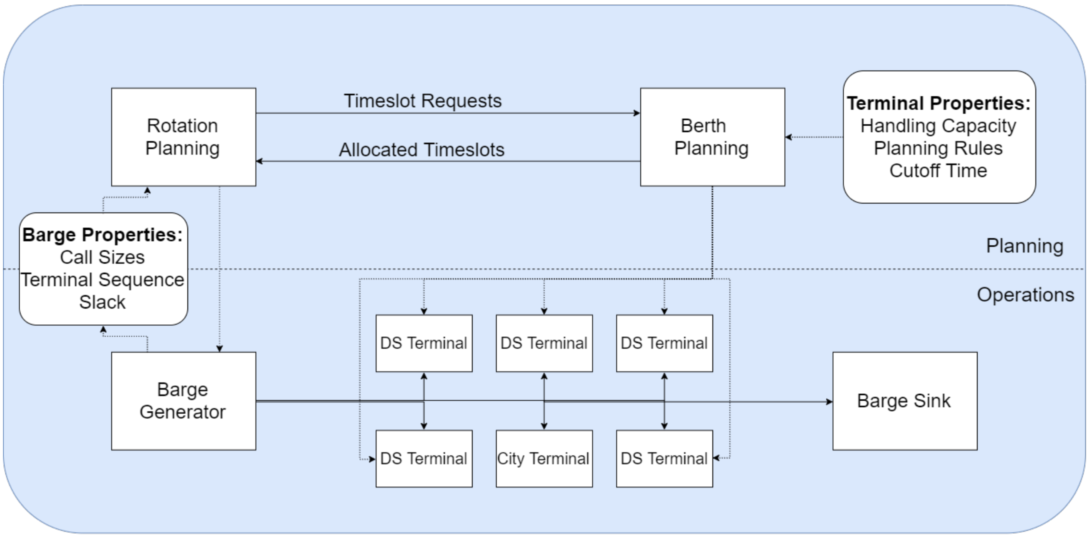

Figure 1: Model functionality: planning and operational layer

3 Experimental Setup

The first part of this section will elaborate upon the experimental settings for the current state model; the second part will explain the changes that are required to assess the effects of implementing the two-class service offering. The parameters that define the current-state simulation model are presented in three sections: first, barge-related parameters; second, terminal-related parameters; third, system- and simulation-related parameters.

3.1 Experimental settings: barges

Hinterland container barging from the port of Rotterdam can be segmented into roughly three hinterland areas: domestic transport, Rhine transport, and transport to and from Antwerp. In order of descending yearly throughput volumes, the domestic market is roughly 50%, the Rhine is approximately 35%, and Antwerp is about 15% [Centraal Bureau voor de Statistiek, 2019]. Each of these service areas has characteristics that influence their in-port operations. Therefore, this segmentation is used to determine the barge properties.

Combining the information from interviews ([van Helvoirt and Reijerse, 2019], [van Strien, 2019], [Heuvelman, 2019], [de Jong, 2019]) with a report by Bureau Voorlichting Binnenvaart [2016] and a report by Rijkswaterstaat: Dienst Verkeer en Scheepvaart [2012], Table 1 was used.

Table 1: Barge generator data

Service Area	Chance (%)	Sum of Call Sizes / Visit (TEU)	Calls / Visit	Total TEU / Year
Antwerp	10	390	2	702,000
Small Domestic	16	100	3	288,000
Large Domestic	47	200	5	1,692,000
Lower & Middle Rhine	18	300	4	972,000
Upper Rhine	9	260	6	421,200

The sum of a barge's call sizes per visit and the number of calls per visit are subject to variability. In the simulation, the number of calls is randomly drawn, with equal probabilities for $n-1$, n and $n+1$, with n set to the number of calls per visit from Table 1. The average call size for the specific barge is the sum of its call sizes, divided by the number of calls that was just drawn. The call sizes are then drawn from a discrete uniform distribution with interval $[Average\ call\ size \times 0.5, Average\ call\ size \times 1.5]$. The planning slack barges use was set to 60 minutes. The final barge property that has not been defined is its sequence; what terminals a barge visits, and in what order.

As this data is not available at the detailed level of barge types, the barge sequences were defined using the throughput of the various container terminals in the port of Rotterdam. Six terminals are modelled. These six terminals consist of five deep-sea terminals and one city terminal. The five deep-sea terminals are the main cause of delays, as they have the highest throughput, and their handling capacity is highest in demand as deep-sea ships frequently visit these terminals. The other terminals are a smaller source of delays, but must be modelled in order to capture the travel times that result from Rotterdam's geographical structure. This was done by modelling the smaller container terminals in the city as a single city terminal. The terminal throughput data that was used for this study is presented in Table 2. It is based on information on the terminals' websites, complemented by crane counts that were performed using Google [2019]. When a barge has drawn its number of calls, the rotation is drawn using the percentages that are shown in Table 2. When the same terminal is drawn in succession, the last draw is discarded, and another draw is taken, until the sequence has been completed.

Table 2: Aggregate terminal data

	ECT Delta	ECT Euro	APM 1	APM 2	RWG	City
Percentage (%)	25.6	12.8	17.9	15.4	12.8	15.4
Barge volume (TEU) / year	1,044,923	522,462	731,446	626,954	522,462	626,954

3.2 Experimental settings: terminals

The two terminal properties that must be determined are the crane productivity and the number of available cranes per hour. Barge cranes can perform about 25 lifts per hour, but most experts in the field recognise that a maximum of 20 lifts per hour is more realistic [de Jong, 2019]. Therefore, crane productivity was set to 20 lifts per hour. The terminals' barge handling capacities should reflect the variability that is caused by prioritising deep-sea vessels. Data on the hourly barge moves at one of the large deep-sea terminals incorporate these effects, rendering them suitable for use in the model. As the model requires a number of available cranes per hour, the number of moves must be translated to a number of cranes. The following steps were used to determine the number of available cranes per terminal, per hour:

1. A random distribution was fitted on the barge moves dataset, using Python package 'Fitter'
2. Each terminal draws a number of barge moves for each hour, which is scaled depending on the terminal's throughput relative to the terminal that provided the dataset

3. This number is divided by the crane productivity, and rounded up, to reach the number of cranes that are available

3.3 Experimental settings: system- and simulation-related parameters

Finally, system- and simulation-related are presented. First, some system-related parameters are presented. The timeslot duration influences computation time, and terminal utilisation. Barge berthing time reflects the fact that barges must berth before being handled. The barge interarrival time defines how quickly successive barges enter the port. Network travel times must be representative for the port of Rotterdam.

Timeslot duration was set to 15 minutes. The berthing time was set to 5 minutes. The barge interarrival time was assumed to follow an exponential distribution, with mean interarrival time of 28.8 minutes, which equals 50 barges per day. Network travel times were set to be 1 hour for all distances between deep-sea terminals; whenever the city terminal is visited, travel takes 3 hours.

Simulation-related parameters are the number of replications per experiment, the runtime per replication, and the warmup period, that is used to prevent empty queues at the beginning of model runtime to distort output data. The number of replications was set to 100. The runtime was set to 6 weeks, excluding the warmup period of 2 weeks.

3.4 Implementation of two-class service

In order to determine the effects of offering two service levels, barges must decide what service level they want. This is based on a barge's willingness-to-pay (WTP). Data on barge WTP is not available. Therefore, in order to assess the effects of the two-class system, the WTP is sampled. A threshold was used to determine what share of barges request priority service. This will be varied from 10% to 50%, in steps of 10%.

In the two-class service offering, barges that submit priority requests should be planned by terminals first. Therefore, the berth planning algorithm was changed. First, the barges that have submitted priority requests are planned, in order of declining call size. Then, the barges that have submitted normal requests are planned, again, in order of declining call sizes. If a terminal receives more requests than it can schedule on that day, the remaining barges are scheduled on the next day. These reservations are not changed to accommodate new priority requests.

4 Results

The effects of implementing the two service classes on average barge in-port times are shown in Figure 2. In the figure, the range of observations is shown, along with the first and third quartile, median, mean, and their 95% confidence intervals.

Although the results are not statistically significant for the number of replications, a trend can be seen in the average barge in-port times. As the threshold, and thus the number of barges that request priority service, increases, the average in-port time increases.

The scenario with a threshold of 10% was inspected in more detail, as low profit margins for barge operators will prevent wide adoption of priority pricing. Furthermore, having a larger share of barges requesting priority service will likely reduce the effects of the priority service, as the chance that barges get allocated their ideal timeslots reduces. From a societal perspective, this scenario has the lowest negative impact on the performance of container barging as a whole, which is favourable as this ensures the modal split is minimally affected.

A small subset of the replications was used for in-depth analysis. Five replications were chosen, of which two were outliers, and three were close to the mean. The two outliers fell outside the interquartile range, with one high average in-port time, and one low average in-port time. Using these replications, Table 3 was made.

The average in-port time of all barges remains unchanged. The average in-port time of barges with priority requests was reduced significantly, while the in-port times of the other barges increased only slightly. In order to assess the reliability of the priority service offering, the distribution of in-port times for priority barges is smoothed using kernel density estimation

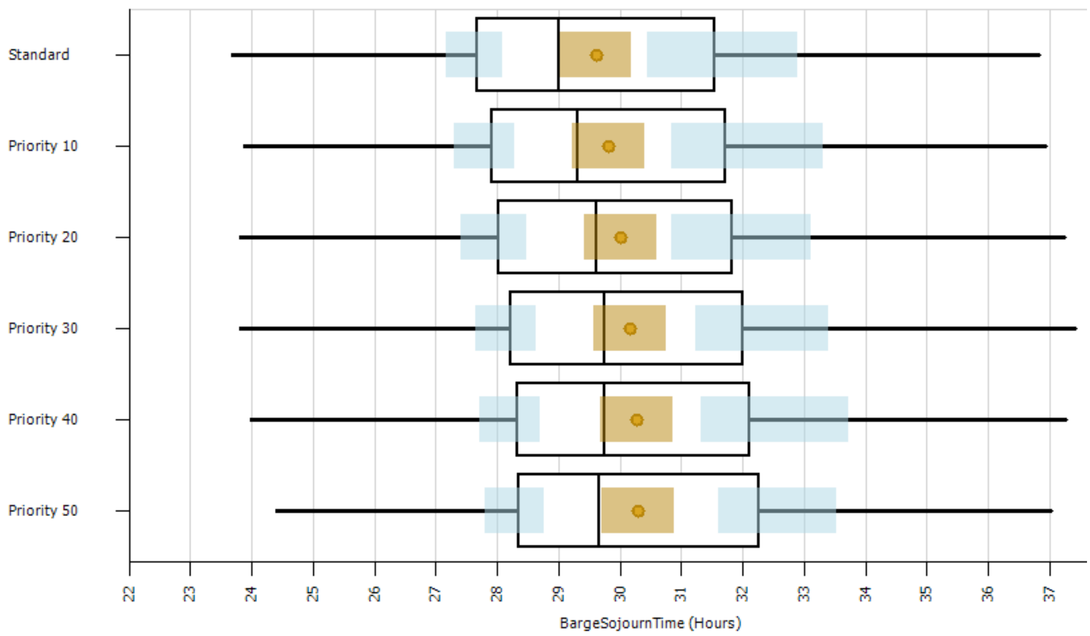

Figure 2: MORE plot of average barge in-port times across experiments

Table 3: In-port times of normal and priority barges, threshold = 10%

Group	**Average in-port time**	**Relative to Standard Scenario**
Priority	22.0	74%
Rest	30.7	103%
Total	29.7	100%

with bandwidth estimator as defined by Scott's rule [Scott, 1979]. Because of the characteristics of different hinterland service areas, and their effects on in-port times, the distribution should be plotted for specific areas. In Figure 3, the probability density plots of small barges that service the Netherlands are shown.

Here, it can clearly be seen that barges that request priority service have lower in-port times. This is also quite reliable. In the replications that were studied in detail, 11% of priority barges servicing the Dutch hinterland had a higher in-port time than the average normal barge. However, small barges that service the domestic market are planned quite late in the terminal planning process, due to their small call sizes. Therefore, their expected in-port time is filled with waiting time, which can be mitigated by priority bookings. Conversely, barges that service Antwerp have much larger call sizes. Their expected in-port time is much more efficient; they spend less time waiting. The probability density plots of the two classes of barges servicing Antwerp are shown in Figure 4.

When comparing the two figures, the difference between the in-port time distribution for the two classes in Figure 4 is much smaller. However, for both barge types, the in-port times of priority barges was more reliable than that of normal barges, as signified by the higher peaks and slimmer tails in the probability density plots.

5 Conclusions

This paper posited implementing a two-class service offering in the slot allocation of container barges at deep-sea terminals. Theory underpinning why slot allocation is suitable for service differentiation was provided. A simulation model was presented, to assess the effects of a two-class reservation system. The experimental setup was chosen to replicate the port of Rotterdam.

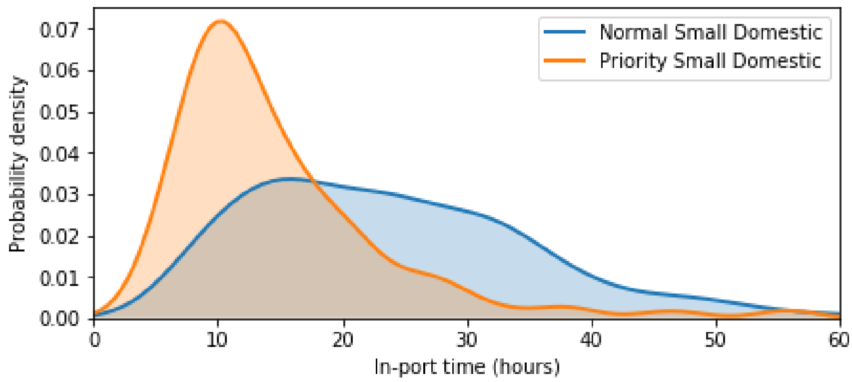

Figure 3: Probability density plot of in-port time of small barges servicing the Netherlands

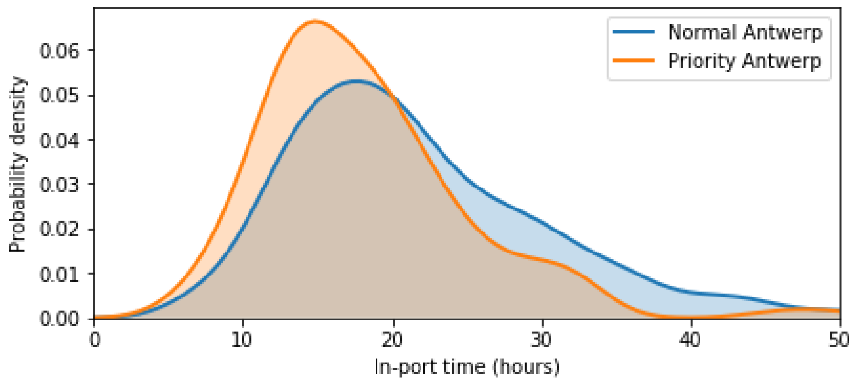

Figure 4: Probability density plot of in-port time of barges servicing Antwerp

This leads to the following conclusions.

The slot allocation process is suitable for service differentiation. The downside for barges that do not want to pay a premium is limited, whereas the in-port time reduction of barges with priority reservations was sizeable. The effects of opting for priority service depend on the barge type. For all barge types, both the average in-port time and the reliability of the in-port time were improved. However, as a rule, barges with higher waiting times whilst in the port benefit more from opting for priority reservations.

The results are based on 10% of barges opting for the priority service. As data on barges' willingness-to-pay is not available, the costs should be varied such that approximately 10% of barges are interested.

Further research should assess a more complex willingness-to-pay estimation, as the priority barges were modelled to have a 10% share across all hinterland areas. This paper shows that, if barge operators are rational, the number of priority barges depends heavily on hinterland service area.

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B

Data table construction

In chapter 2, various tables with data were provided. Two of these tables, on throughput and call sizes, can be seen in Figure B.1. A third table, Table B.1 on barge length and their visit frequency, was expanded to include vessel size, which is based on information by Bureau Voorlichting Binnenvaart [88], and combined import and export figures based on a loadfactor of 60%, which is based on Rijkswaterstaat: Dienst Verkeer en Scheepvaart [41].
A fourth table, Table B.2, contains information on how many terminals are visited, and combined import and export volumes per visit, based on what hinterland area the barge serves. This data is based on interviews [23], [21], [20], and information from the CBRB [37].

Table B.1: Barge size: frequency, capacity, and combined import and export per port visit [22], [88], [41]

Ship Length	Chance (%)	Visits / Day	Average Size (TEU)	I + E (TEU)
<85	16	8	80	96
85-110	50	25	160	192
110-135	24	12	280	336
>135	10	5	350	420

Table B.2: Barge in-port operational characteristics per service area [23], [21], [20], [37]

Service Area	# Calls	I + E (TEU)
Antwerp-Rotterdam	2	390
Small Domestic	4	100
Large Domestic	7	200
Lower & Middle Rhine	6	300
Upper Rhine	8	260

Now, four tables have been formed: a table on throughput, a table on barge length and entailing characteristics, a table on in-port operations based on barge service area, and a table on call size distribution at terminals. Together, they are used to form the dataset that functions as input for the simulation. Figure B.1 shows how these tables are used to reach the final dataset.
The following approach was taken:

1. The data on barge characteristics per service area were plugged into the final dataset. The number of calls was adapted, in order to reflect that not all terminals are modelled.

2. The probabilities for each service area were determined. The resulting throughput figures should be similar to those in Table 2.1. The probabilities should also reflect the data on ship length.

Length	Frequency (%)	Size (TEU)	I + E (TEU)
<85 M	16	80	96
85 - 110 M	50	160	192
110 - 135 M	24	280	336
>135 M	10	350	420

Service Area	TEU / Year
Antwerp-Rotterdam	700.000
Domestic	2.050.000
Lower & Middle Rhine	1.000.000
Upper Rhine	400.000

Service Area	Chance (%)	I + E (TEU)	# Calls	Avg CS (TEU)	TEU / Year
Antwerp-Rotterdam	10 %	390	2	195	702,000
Small Domestic	16 %	100	3	33.3	288,000
Large Domestic	47 %	200	5	40	1,692,000
Lower & Middle Rhine	18 %	300	4	87.5	972,000
Upper Rhine	9 %	260	6	43.3	421,200

Service Area	# Calls	I + E (TEU)
Antwerp-Rotterdam	2	390
Small Domestic	4	100
Large Domestic	7	200
Lower & Middle Rhine	6	300
Upper Rhine	8	260

Call Size (TEU)	DS Terminal	Nextlogic	EY-P
1 - 25	5%	35%	56%
26 - 50	17%	34%	25%
51 - 100	26%	23%	14%
101 - 200	27%	7%	4%
> 200	25%	8%	1 %

Figure B.1: Input data construction

3. Finally, the resulting call size distribution was compared to the call size distributions in Table 2.4. This will be elaborated on in section 4.8.

C

Comparison of hinterland transport by barge and other modes of transport

Hinterland transportation can be fulfilled by trucks, trains and barges. These modes are competing in the same market for hinterland transportation. As such, it is valuable to understand the differences between the modes, and know the main advantages and disadvantages of each of the modes. The information hereafter is based largely on the book chapter by Wiegmans and Konings [89]. An overview of the performance of the three main modes of transportation, scored on a variety of criteria, can be found in Table C.1. The masters thesis by Wanders [90] used a multinomial logit model to determine the most important transport attributes for Dutch shippers' mode choice in the hinterland transportation of perishable and non-perishable goods. For both types of goods, transport time, transport cost, and transport reliability were found to be the most important characteristics. Research by Danielis *et al.* [35] confirmed the importance of these attributes for Italian shippers, but also found that transport safety was important. In line with the importance of reliability, lost or damaged goods can disrupt supply chains.

As can be seen in Table C.1, transport by IWW scores well on costs, predictability and safety. Transport by road outperforms IWW on speed. Its convenience and flexibility also contribute to its reliability. If the gap in transport speed between hinterland transportation by road and IWW can be closed *reliably*, research suggests that use of IWW will increase. The improved total transportation time could stem from more frequent barge services, but this should not have a large negative impact on the load factor of barges, as this will negatively affect transport costs. Barges have high fixed costs, which means they must have a high load factor in order to be able to provide low transport costs. Increasing its utilisation rate is very important. In order to improve the utilisation rate, the roundtrip time should be reduced, resulting in an increase of the share of effective time. Clearly, it can be seen that reducing barge in-port times is an effective way of improving the service offering of hinterland transport by barge.

Naturally, governments can influence the competitiveness of each mode through their policies regarding infrastructure and taxation. As the Netherlands is a major gateway to the North-West of Europe, hinterland transport is an important economic sector. In 2018, the port of Rotterdam contributed €45.6 billion to the Dutch economy [4]. Due to government investments, the infrastructure in the Netherlands is strongly developed, with the world bank ranking it fourth in the world [92]. Although IWW transport outperforms rail and road on energy use, noise and emissions, it is unlikely that the Dutch government will implement policies that reduce the competitiveness of road transport, because of the importance to the Dutch economy [89].

Table C.1: Comparison of different transport modes, from Platz [91]

Feature	**Road**	**Rail**	**Inland Waterway**
Transport costs per unit	-	+	+
Ability to achieve the transport of large volumes	-	+	+
Transport speed	+	0	-
Network connectivity	+	0	-
Predictability of transport processes	0	0	+
Transport frequency	0	0	0
Transport safety	-	+	+
Transport security	-	0	+
Convenience and flexibility	+	-	-
Resistance to extreme weather conditions	-	0	-
Limitation of infrastructure capacity, congestion	-	0	+
Energy use per ton-km	-	0	+
Emission of harmful substances	-	+	0
Emission of greenhouse gas	-	+	+
Noise, negative effects on ground and water	-	-	+

D

Map of Rotterdam's container terminals

See next page.

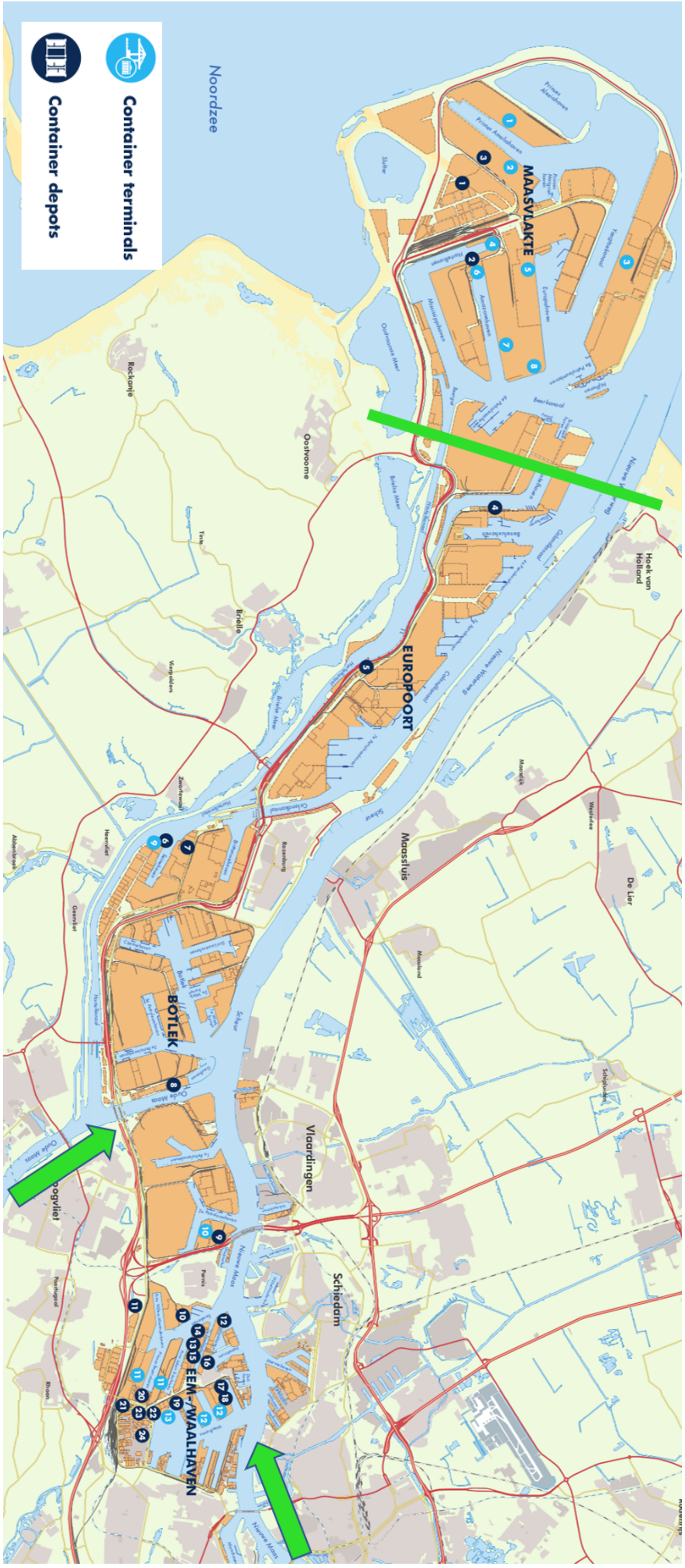

Figure D.1: Overview map Port of Rotterdam, adapted from Port of Rotterdam [93]. The area to the left of the green line is the Maasvlakte area.

E

Terminal capacity in the port of Rotterdam

Terminal	DS Quay	Barge Quay	DS Cranes	Barge Cranes	TEU yearly capacity
APM MV2	1000	500	8	3	2.700.000
APM Rotterdam	1600 combined		13	1	3.250.000
RWG	1150	550	11	3 (with feeder)	2.350.000
ECT Euromax	1500 combined		12	4	2.300.000
ECT Delta	4000 combined		38	5	5.000.000
Rotterdam short-sea	1800 combined		14 combined		800.000
Uniport	2400 combined		9 combined		1.200.000

The main text refers to calculations on throughput capacity of dedicated barge cranes at deep-sea terminals. The calculations, as performed by the author, are explained here. When all dedicated barge cranes, including 1 for RWG, are assumed to operate 24 hours a day, 360 days a year, with a productivity of 20 moves per hour, this leads to a yearly throughput of 2.42 million moves. With a TEU factor of 1.68 [4], this leads to 4.06 million TEU.
The information in the table is gathered from multiple sources, such as the Port of Rotterdam Authority website, the respective terminals' websites, and Google Maps.
https://dailyliftingmvii.com/wp-content/uploads/Folder_APMT_juli1.pdf
https://dailyliftingmvii.com/en/facts-figures/
https://www.apmterminals.com/en/rotterdam/about/our-terminal
https://apmtrupdate.com/wp-content/uploads/2014/08/5ENGDETAILEDMAPSECURITY.pdf
"Rotterdam World Gateway: Bezoekersinformatie"
https://www.rwg.nl/nl/de-terminal/feiten
Google [82]
https://www.ect.nl/en/terminals/hutchison-ports-ect-euromax
https://www.ect.nl/en/terminals/hutchison-ports-ect-delta

F

Verification: Model traces

Step	Description
[Begin]	Process 'Source1.OnEntityArrival' execution started.
[SetRow] BeforeCreatingEntities	Table reference for token 'Token.0' set to row index '3' in table 'Generator'.
[Create] Entities	Creating '1' object(s) of entity type 'Barge3' using creation method 'NewObject'.
–	Object 'Barge3.46' created.
[Assign] Import + Export Volume	Assigning state variable 'Barge3.46.Moves' the value '100'. Previous value was '0'.
[Decide] Check Service Area	Token sent to 'True' exit.
[Assign] Draw NrOfCalls	Assigning state variable 'Barge3.46.TotalCalls' the value '5'. Previous value was '0'.
[Begin]	Process 'CreateSequence' execution started.
[Assign] VisitNumber + 1	Assigning state variable 'Barge.VisitNumber' the value '1'. Previous value was '0'.
[Assign] Random Number	Assigning state variable 'Model.rand' the value '0,868765875464305'. Previous value was '0'.
[Decide] Terminal = 6	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'True' exit.
[Assign] Add to Sequence	Assigning state variable 'Barge3.46.TerminalOrder[1]' the value 'Input@Terminal6'. Previous value was 'Nothing'.
[Assign] Draw Call Size	Assigning state variable 'Barge3.46.CS6[1]' the value '18'. Previous value was '0'.
[Assign] Update CallsPerTerminal	Assigning state variable 'Barge3.46.CallsPerTerminal[6]' the value '1'. Previous value was '0'.
[Decide] Sequence finished?	Token sent to 'False' exit.
[Assign] VisitNumber + 1	Assigning state variable 'Barge.VisitNumber' the value '2'. Previous value was '1'.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,33509440952912'. Previous value was '0,868765875464305'.
[Decide] Terminal = 2	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'True' exit.
[Assign] Add to Sequence	Assigning state variable 'Barge3.46.TerminalOrder[2]' the value 'Input@Terminal2'. Previous value was 'Nothing'.
[Assign] Draw Call Size	Assigning state variable 'Barge3.46.CS2[1]' the value '22'. Previous value was '0'.
[Assign] Update CallsPerTerminal	Assigning state variable 'Barge3.46.CallsPerTerminal[2]' the value '1'. Previous value was '0'.
[Decide] Sequence finished?	Token sent to 'False' exit.
[Assign] VisitNumber + 1	Assigning state variable 'Barge.VisitNumber' the value '3'. Previous value was '2'.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,886108105769381'. Previous value was '0,33509440952912'.
[Decide] Terminal = 6	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'True' exit.
[Assign] Add to Sequence	Assigning state variable 'Barge3.46.TerminalOrder[3]' the value 'Input@Terminal6'. Previous value was 'Nothing'.
[Assign] Draw Call Size	Assigning state variable 'Barge3.46.CS6[2]' the value '16'. Previous value was '0'.
[Assign] Update CallsPerTerminal	Assigning state variable 'Barge3.46.CallsPerTerminal[6]' the value '2'. Previous value was '1'.
[Decide] Sequence finished?	Token sent to 'False' exit.
[Assign] VisitNumber + 1	Assigning state variable 'Barge.VisitNumber' the value '4'. Previous value was '3'.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,89214153890498'. Previous value was '0,886108105769381'.
[Decide] Terminal = 6	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'False' exit.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,657385660102591'. Previous value was '0,89214153890498'.
[Decide] Terminal = 4	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'True' exit.

[Assign] Add to Sequence	Assigning state variable 'Barge3.46.TerminalOrder[4]' the value 'Input@Terminal4'. Previous value was 'Nothing'.
[Assign] Draw Call Size	Assigning state variable 'Barge3.46.CS4[1]' the value '21'. Previous value was '0'.
[Assign] Update CallsPerTerminal	Assigning state variable 'Barge3.46.CallsPerTerminal[4]' the value '1'. Previous value was '0'.
[Decide] Sequence finished?	Token sent to 'False' exit.
[Assign] VisitNumber + 1	Assigning state variable 'Barge.VisitNumber' the value '5'. Previous value was '4'.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,604266199748963'. Previous value was '0,657385660102591'.
[Decide] Terminal = 4	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'False' exit.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,642095010494813'. Previous value was '0,604266199748963'.
[Decide] Terminal = 4	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'False' exit.
[Assign] Random	Assigning state variable 'Model.rand' the value '0,0495998689439148'. Previous value was '0,642095010494813'.
[Decide] Terminal = 1	Token sent to 'True' exit.
[Decide] No back to back visit?	Token sent to 'True' exit.
[Assign] Add to Sequence	Assigning state variable 'Barge3.46.TerminalOrder[5]' the value 'Input@Terminal1'. Previous value was 'Nothing'.
[Assign] Draw Call Size	Assigning state variable 'Barge3.46.CS1[1]' the value '14'. Previous value was '0'.
[Assign] Update CallsPerTerminal	Assigning state variable 'Barge3.46.CallsPerTerminal[1]' the value '1'. Previous value was '0'.
[Decide] Sequence finished?	Token sent to 'True' exit.
[Assign] Sink routing	Assigning state variable 'Barge3.46.TerminalOrder[6]' the value 'Input@Sink1'. Previous value was 'Nothing'.
[Assign] VisitNumber = 0	Assigning state variable 'Barge.VisitNumber' the value '0'. Previous value was '5'.
[End]	Process 'CreateSequenceMain' execution ended.

Table F.1: Model Trace of Generation of Barge3.46, redacted

Process	Step	Description
5.RotationPlanning	[Begin]	Process 'RotationPlanning' execution started.
5.RotationPlanning	[Assign] j = 0	Assigning state variable 'Model.j' the value '0'. Previous value was '0'.
5.RotationPlanning	[Assign] j + 1	Assigning state variable 'Model.j' the value '1'. Previous value was '0'.
5.RotationPlanning	[Decide] NextTerminal = 6	Token sent to 'True' exit.
5.RotationPlanning	[Execute] ReserveT6	Executing process 'ReservingT6'.
6.RequestT6	[Begin]	Process 'ReservingT6' execution started.
6.RequestT6	[Decide] j > 1, not first terminal	Token sent to 'False' exit.
6.RequestT6	[Assign] TravelTime	Assigning state variable 'Barge3.46.NextTravelTime' the value '180' Minutes. Previous value was '15' Minutes.
6.RequestT6	[Assign] TravelTime	Assigning state variable 'Barge3.46.TotalTravelTime' the value '3'. Previous value was '0'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.RS6[1]' the value '300'. Previous value was '0'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.NumberOfTS[6,1]' the value '4'. Previous value was '0'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Model.i' the value '0'. Previous value was '1669'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[300,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '300'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[300]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '1'. Previous value was '0'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '301'. Previous value was '300'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[301,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[301]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '2'. Previous value was '1'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '302'. Previous value was '301'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[302,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[302]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '3'. Previous value was '2'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '303'. Previous value was '302'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[303,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[303]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '4'. Previous value was '3'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'True' exit.
6.RequestT6	[Assign] ComplPerTerm + 1	Assigning state variable 'Barge3.46.CompletedPerTerminal[6]' the value '1'. Previous value was '0'.
6.RequestT6	[End]	Process 'ReservingT6' execution ended.
5.RotationPlanning	[Decide] LastTerminal?	Token sent to 'False' exit.
5.RotationPlanning	[Assign] j + 1	Assigning state variable 'Model.j' the value '2'. Previous value was '1'.
5.RotationPlanning	[Decide] NextTerminal = 2	Token sent to 'True' exit.
5.RotationPlanning	[Execute] ReserveT2	Executing process 'ReservingT2'.
6.RequestT2	[Begin]	Process 'ReservingT2' execution started.
6.RequestT2	[Decide] j > 1, not first terminal	Token sent to 'True' exit.
6.RequestT2	[Assign] TravelTime	Assigning state variable 'Barge3.46.NextTravelTime' the value '180' Minutes. Previous value was '180' Minutes.
6.RequestT2	[Assign] TravelTime	Assigning state variable 'Barge3.46.TotalTravelTime' the value '6'. Previous value was '3'.
6.RequestT2	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.RS2[1]' the value '319'. Previous value was '0'.
6.RequestT2	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.NumberOfTS[2,1]' the value '5'. Previous value was '0'.
6.RequestT2	[Assign] Decide Requested Slot	Assigning state variable 'Model.i' the value '0'. Previous value was '4'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.Requests[319,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '319'. Previous value was '303'.

6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.NrOfRequests[319]' the value '1'. Previous value was '0'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Model.i' the value '1'. Previous value was '0'.
6.RequestT2	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '320'. Previous value was '319'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.Requests[320,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.NrOfRequests[320]' the value '1'. Previous value was '0'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Model.i' the value '2'. Previous value was '1'.
6.RequestT2	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '321'. Previous value was '320'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.Requests[321,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.NrOfRequests[321]' the value '1'. Previous value was '0'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Model.i' the value '3'. Previous value was '2'.
6.RequestT2	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '322'. Previous value was '321'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.Requests[322,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.NrOfRequests[322]' the value '1'. Previous value was '0'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Model.i' the value '4'. Previous value was '3'.
6.RequestT2	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '323'. Previous value was '322'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.Requests[323,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Terminal2.NrOfRequests[323]' the value '1'. Previous value was '0'.
6.RequestT2	[Assign] Reserve	Assigning state variable 'Model.i' the value '5'. Previous value was '4'.
6.RequestT2	[Decide] Enough TS requested?	Token sent to 'True' exit.
6.RequestT2	[Assign] ComplPerTerm + 1	Assigning state variable 'Barge3.46.CompletedPerTerminal[2]' the value '1'. Previous value was '0'.
6.RequestT2	[End]	Process 'ReservingT2' execution ended.
5.RotationPlanning	[Decide] LastTerminal?	Token sent to 'False' exit.
5.RotationPlanning	[Assign] j + 1	Assigning state variable 'Model.j' the value '3'. Previous value was '2'.
5.RotationPlanning	[Decide] NextTerminal = 6	Token sent to 'True' exit.
5.RotationPlanning	[Execute] ReserveT6	Executing process 'ReservingT6'.
6.RequestT6	[Begin]	Process 'ReservingT6' execution started.
6.RequestT6	[Decide] j > 1, not first terminal	Token sent to 'True' exit.
6.RequestT6	[Assign] TravelTime *	Assigning state variable 'Barge3.46.NextTravelTime' the value '180' Minutes. Previous value was '180' Minutes.
6.RequestT6	[Assign] TravelTime *	Assigning state variable 'Barge3.46.TotalTravelTime' the value '9'. Previous value was '6'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.RS6[2]' the value '339'. Previous value was '0'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.NumberOfTS[6,2]' the value '4'. Previous value was '0'.
6.RequestT6	[Assign] Decide Requested Slot	Assigning state variable 'Model.i' the value '0'. Previous value was '5'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[339,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '339'. Previous value was '323'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[339]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '1'. Previous value was '0'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '340'. Previous value was '339'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[340,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[340]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '2'. Previous value was '1'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.

6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '341'. Previous value was '340'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[341,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[341]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '3'. Previous value was '2'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '342'. Previous value was '341'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.Requests[342,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Terminal6.NrOfRequests[342]' the value '1'. Previous value was '0'.
6.RequestT6	[Assign] Reserve	Assigning state variable 'Model.i' the value '4'. Previous value was '3'.
6.RequestT6	[Decide] Enough TS requested?	Token sent to 'True' exit.
6.RequestT6	[Assign] ComplPerTerm + 1	Assigning state variable 'Barge3.46.CompletedPerTerminal[6]' the value '2'. Previous value was '1'.
6.RequestT6	[End]	Process 'ReservingT6' execution ended.
5.RotationPlanning	[Decide] LastTerminal?	Token sent to 'False' exit.
5.RotationPlanning	[Assign] j + 1	Assigning state variable 'Model.j' the value '4'. Previous value was '3'.
5.RotationPlanning	[Decide] NextTerminal = 4	Token sent to 'True' exit.
5.RotationPlanning	[Execute] ReserveT4	Executing process 'ReservingT4'.
6.RequestT4	[Begin]	Process 'ReservingT4' execution started.
6.RequestT4	[Decide] j > 1, not first terminal	Token sent to 'True' exit.
6.RequestT4	[Assign] TravelTime	Assigning state variable 'Barge3.46.NextTravelTime' the value '180' Minutes. Previous value was '180' Minutes.
6.RequestT4	[Assign] TravelTime	Assigning state variable 'Barge3.46.TotalTravelTime' the value '12'. Previous value was '9'.
6.RequestT4	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.RS4[1]' the value '358'. Previous value was '0'.
6.RequestT4	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.NumberOfTS[4,1]' the value '5'. Previous value was '0'.
6.RequestT4	[Assign] Decide Requested Slot	Assigning state variable 'Model.i' the value '0'. Previous value was '4'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.Requests[358,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '358'. Previous value was '342'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.NrOfRequests[358]' the value '1'. Previous value was '0'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Model.i' the value '1'. Previous value was '0'.
6.RequestT4	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '359'. Previous value was '358'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.Requests[359,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.NrOfRequests[359]' the value '1'. Previous value was '0'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Model.i' the value '2'. Previous value was '1'.
6.RequestT4	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '360'. Previous value was '359'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.Requests[360,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.NrOfRequests[360]' the value '1'. Previous value was '0'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Model.i' the value '3'. Previous value was '2'.
6.RequestT4	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '361'. Previous value was '360'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.Requests[361,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.NrOfRequests[361]' the value '1'. Previous value was '0'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Model.i' the value '4'. Previous value was '3'.
6.RequestT4	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '362'. Previous value was '361'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.Requests[362,1]' the value 'Barge3.46'. Previous value was 'Nothing'.

6.RequestT4	[Assign] Reserve	Assigning state variable 'Terminal4.NrOfRequests[362]' the value '1'. Previous value was '0'.
6.RequestT4	[Assign] Reserve	Assigning state variable 'Model.i' the value '5'. Previous value was '4'.
6.RequestT4	[Decide] Enough TS requested?	Token sent to 'True' exit.
6.RequestT4	[Assign] ComplPerTerm + 1	Assigning state variable 'Barge3.46.CompletedPerTerminal[4]' the value '1'. Previous value was '0'.
6.RequestT4	[End]	Process 'ReservingT4' execution ended.
5.RotationPlanning	[Decide] LastTerminal?	Token sent to 'False' exit.
5.RotationPlanning	[Assign] j + 1	Assigning state variable 'Model.j' the value '5'. Previous value was '4'.
5.RotationPlanning	[Decide] NextTerminal = 1	Token sent to 'True' exit.
5.RotationPlanning	[Execute] ReserveT1	Executing process 'ReservingT1'.
6.RequestT1	[Begin]	Process 'ReservingT1' execution started.
6.RequestT1	[Decide] j > 1, not first terminal	Token sent to 'True' exit.
6.RequestT1	[Assign] TravelTime	Assigning state variable 'Barge3.46.NextTravelTime' the value '60' Minutes. Previous value was '180' Minutes.
6.RequestT1	[Assign] TravelTime	Assigning state variable 'Barge3.46.TotalTravelTime' the value '13'. Previous value was '12'.
6.RequestT1	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.RS1[1]' the value '370'. Previous value was '0'.
6.RequestT1	[Assign] Decide Requested Slot	Assigning state variable 'Barge3.46.NumberOfTS[1,1]' the value '4'. Previous value was '0'.
6.RequestT1	[Assign] Decide Requested Slot	Assigning state variable 'Model.i' the value '0'. Previous value was '5'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.Requests[370,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '370'. Previous value was '362'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.NrOfRequests[370]' the value '1'. Previous value was '0'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Model.i' the value '1'. Previous value was '0'.
6.RequestT1	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '371'. Previous value was '370'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.Requests[371,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.NrOfRequests[371]' the value '1'. Previous value was '0'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Model.i' the value '2'. Previous value was '1'.
6.RequestT1	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '372'. Previous value was '371'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.Requests[372,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.NrOfRequests[372]' the value '1'. Previous value was '0'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Model.i' the value '3'. Previous value was '2'.
6.RequestT1	[Decide] Enough TS requested?	Token sent to 'False' exit.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Barge3.46.LastTimeSlot' the value '373'. Previous value was '372'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.Requests[373,1]' the value 'Barge3.46'. Previous value was 'Nothing'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Terminal1.NrOfRequests[373]' the value '1'. Previous value was '0'.
6.RequestT1	[Assign] Reserve	Assigning state variable 'Model.i' the value '4'. Previous value was '3'.
6.RequestT1	[Decide] Enough TS requested?	Token sent to 'True' exit.
6.RequestT1	[Assign] ComplPerTerm + 1	Assigning state variable 'Barge3.46.CompletedPerTerminal[1]' the value '1'. Previous value was '0'.
6.RequestT1	[End]	Process 'ReservingT1' execution ended.
5.RotationPlanning	[Decide] LastTerminal?	Token sent to 'True' exit.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Model.j' the value '0'. Previous value was '5'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[1]' the value '0'. Previous value was '1'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[2]' the value '0'. Previous value was '1'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[3]' the value '0'. Previous value was '0'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[4]' the value '0'. Previous value was '1'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[5]' the value '0'. Previous value was '0'.
5.RotationPlanning	[Assign] i = 0, ComplPerTerm	Assigning state variable 'Barge3.46.CompletedPerTerminal[6]' the value '0'. Previous value was '2'.

5.RotationPlanning	[End]	Process 'RotationPlanning' execution ended.

Table F.2: Model Trace of Rotation Planning of Barge3.46, redacted

Time	Entity	Process	Step	Description
0	Model	4.TransferNode1Entered	[Scan] Wait for physical entry time	Evaluating scan condition 'TimeNow >= (Barge.TimeCreated + EntryDelay)'.
0	Model	4.TransferNode1Entered	[Scan] Wait for physical entry time	Token waiting at Scan step for scan condition to become true.
570	Model	43.Terminal4Planning	[Assign] i = 0 / Save TS	Assigning state variable 'Barge3.46.TS4[1]' the value '358'. Previous value was '0'.
1080	Model	89.Terminal1Planning	[Decide] Free capacity?	Token sent to 'False' exit.
1080	Model	89.Terminal1Planning	[Assign] i = 0 / Save TS	Assigning state variable 'Barge3.46.TS1[1]' the value '373'. Previous value was '0'.
1080	Model	76.Terminal2Planning	[Assign] i = 0 / Save TS	Assigning state variable 'Barge3.46.TS2[1]' the value '319'. Previous value was '0'.
4320	Model	4.TransferNode1Entered	[Scan] Wait for physical entry time	Scan condition is true. Releasing token from Scan step.
4500	Model	276.InputTerminal6Entered	[Begin]	Process 'InputTerminal6Entered' execution started.
4500	Terminal6	276.OnEnteredInputBuffer	[Delay] TransferInTime	Delaying token for '5' Minutes until time '4505' Minutes.
4505	Terminal6	280.OnEnteredProcessing	[Delay] ProcessingTime	Delaying token for '54' Minutes until time '4559' Minutes.
4559	Output@Terminal6	281.OnEnteredFromAssociatedObject	[Assign] OnEnteringAssignments	Assigning state variable 'Barge3.46.VisitNumber' the value '2'. Previous value was '1'.
4559	Model	16.OutputTerminal6Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.PT6[1]' the value '0,900000000000006'. Previous value was '75,0833333333333'.
4559	Model	16.OutputTerminal6Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.CompletedPerTerminal[6]' the value '1'. Previous value was '0'.
4679	Model	18.WaitForTS	[Begin]	Process 'WaitForTS' execution started.
4740	Model	18.WaitForTS	[Scan] Wait for TS	Scan condition is true. Releasing token from Scan step.
4800	Terminal2	24.OnEnteredInputBuffer	[Delay] TransferInTime	Delaying token for '5' Minutes until time '4805' Minutes.
4805	Terminal2	26.OnEnteredProcessing	[Delay] ProcessingTime	Delaying token for '66' Minutes until time '4871' Minutes.
4871	Output@Terminal2	36.OnEnteredFromAssociatedObject	[Assign] OnEnteringAssignments	Assigning state variable 'Barge3.46.VisitNumber' the value '3'. Previous value was '2'.
4871	Model	35.OutputTerminal2Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.PT2[1]' the value '1,09999999999999'. Previous value was '80,0833333333333'.
4871	Model	35.OutputTerminal2Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.CompletedPerTerminal[2]' the value '1'. Previous value was '0'.
4871	Model	26.WaitForTS	[Begin]	Process 'WaitForTS' execution started.
4871	Model	26.WaitForTS	[Scan] Wait for TS	Scan condition is true. Releasing token from Scan step.
5051	Terminal6	294.OnEnteredInputBuffer	[Delay] TransferInTime	Delaying token for '5' Minutes until time '5056' Minutes.
5056	Terminal6	20.OnEnteredProcessing	[Delay] ProcessingTime	Delaying token for '48' Minutes until time '5104' Minutes.
5104	Output@Terminal6	51.OnEnteredFromAssociatedObject	[Assign] OnEnteringAssignments	Assigning state variable 'Barge3.46.VisitNumber' the value '4'. Previous value was '3'.
5104	Model	52.OutputTerminal6Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.PT6[2]' the value '0,799999999999997'. Previous value was '84,2666666666667'.
5104	Model	52.OutputTerminal6Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.CompletedPerTerminal[6]' the value '2'. Previous value was '1'.
5224	Model	62.WaitForTS	[Begin]	Process 'WaitForTS' execution started.
5325	Model	62.WaitForTS	[Scan] Wait for TS	Scan condition is true. Releasing token from Scan step.
5385	Terminal4	50.OnEnteredInputBuffer	[Delay] TransferInTime	Delaying token for '5' Minutes until time '5390' Minutes.
5390	Terminal4	56.OnEnteredProcessing	[Delay] ProcessingTime	Delaying token for '63' Minutes until time '5453' Minutes.
5453	Output@Terminal4	67.OnEnteredFromAssociatedObject	[Assign] OnEnteringAssignments	Assigning state variable 'Barge3.46.VisitNumber' the value '5'. Previous value was '4'.
5453	Model	46.OutputTerminal4Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.PT4[1]' the value '1,05'. Previous value was '89,8333333333333'.

5453	Model	46.OutputTerminal4Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.CompletedPerTerminal[4]' the value '1'. Previous value was '0'.
5453	Model	56.WaitForTS	[Begin]	Process 'WaitForTS' execution started.
5550	Model	56.WaitForTS	[Scan] Wait for TS	Scan condition is true. Releasing token from Scan step.
5610	Terminal1	71.OnEnteredInputBuffer	[Delay] TransferInTime	Delaying token for '5' Minutes until time '5615' Minutes.
5615	Terminal1	40.OnEnteredProcessing	[Delay] ProcessingTime	Delaying token for '42' Minutes until time '5657' Minutes.
5657	Output@Terminal1	310.OnEnteredFromAssociatedObject	[Assign] OnEnteringAssign-ments	Assigning state variable 'Barge3.46.VisitNumber' the value '6'. Previous value was '5'.
5657	Model	24.OutputTerminal1Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.PT1[1]' the value '0,700000000000003'. Previous value was '93,5833333333333'.
5657	Model	24.OutputTerminal1Entered	[Assign] Assign1	Assigning state variable 'Barge3.46.CompletedPerTerminal[1]' the value '1'. Previous value was '0'.
5657	Sink1	40.OnEnteredInputBuffer	[Destroy] Entity	Destroying object 'Barge3.46'.

Table F.3: Model Trace of in-port operations of Barge3.46, redacted