SIMULATING THE NAUTICAL CHAIN OF OPERATION IN THE DEEP-SEA PORT

A PORT OF ROTTERDAM CASE STUDY

Thesis

to obtain the degree of master at the Delft University of Technology

by

Zhirun GAN

Transport, Infrastructure and Logistics, Civil Engineering

This thesis has been approved by

Promotor: prof. dr. ir. Lori Tavasszy

Assessment committee:

Prof. dr. ir. Lori Tavasszy,	Chair
Ir. Mark Duinkerken,	Technische Universiteit Delft
Shahrzad Nikghadam,	Technische Universiteit Delft
Raymond Seignette,	Port of Rotterdam Authority

Preface

This report concludes my graduation work at the faculty of Technology, Policy and Management at the Delft University of Technology for the master study Transport, Infrastructure & Logistics. The report embodies the research from April 2019 until the end of September 2019 at TU Delft and the Port of Rotterdam.

This thesis report represents the closure of my two-year master study career in this university, this city and this country, where is full of challenges, new experiences, confusion and gratitude. It was a great honour for me to be able to work with Port of Rotterdam Authority to conduct research on maritime operation, with special thanks to Prof. Lori Tavasszy for offering me this wonderful research opportunity.

I would like to thank my MSc Thesis committee group for all their valuable direction and feedback. Thank you Lori Tavasszy, Mark Duinkerken for all your constructive guidance and advice, which guided me towards this final report. Thank you Shahrzad Nikghadam, as daily supervisor, always kept me on the right track when the moment I am missing direction. I also want to thank Raymond Seignette for joining my thesis committee and helping me deeply understand the main contribution of my work.

Furthermore, I want to thank Yongrui Chen, my big bro, supported me with programming issues. Thank you my love Moyu Zhou, for encouraging me to keep moving forward and gave me a lot of confidence when I was stuck in the middle of the research. I would like to express my gratitude to my family and friends, who are always standing by me during the hard time of these two years.

Zhirun GAN
Delft, October 2019

SUMMARY

The Port of Rotterdam (PoR), as the largest deep-sea port in Europe, owes its leading position to its outstanding accessibility for sea-going vessels. In seaport, many activities are needed to service a ship with many actors involved, which together form the so-called nautical chain (NC). The complexity of nautical service network boosts the request from Port of Rotterdam Authority to ask for a state of the art simulation model that reflects the current practice of the NC in the PoR as close as possible, which is also one of the principal initiatives of Swarmport project. This master thesis research is conducted in order to benefit the Swarmport project.

The big picture of Swarmport is to develop an agent-based model (ABM) of the NC in the PoR. As a sub-project of Swarmport, this master thesis aims to provide a base for future advanced model – develop abstract discrete-event simulation model (DES) to mimic ship handling processes and assess port performance in terms of the queuing system inside the NC. Here we call it an abstract model, because due to the limitation of research duration and the workload for the master student, the model cannot be created to cover all the activities and actors as operating in reality. The boundary of this research is thus proposed to make the work clear and doable.

The main objective of this research project is to develop the first version of a tool to get insight into the current nautical processes of vessels in the PoR. Therefore, the main research question for this project is as follows:

"How to develop a model that can simulate nautical service in the deep-sea port in order to evaluate the performance of the NC?"

To answer this question, a literature study has done firstly to get to know what the nautical chain consists of, how it operates in the PoR, followed by a selection on KPIs of port performance. It shows turnaround time and waiting time are the two most commonly used time-related indicators to evaluate the performance of ship handling operation. The nautical service system is then analyzed in detail by using CATWOE and Black box approach. The analysis identifies the characteristics of the system from different aspects, leading to the translation from input/output to inner processes of nautical service system. The empirical data are organized and analyzed to generate more ideas on port maritime operation in real life.

After that, a conceptual model is constructed based on the information from network analysis. A typical discrete event conceptual modelling framework is selected as the guidance for modelling the simulation, which is mainly used for manufacturing and service systems. The framework leads the way to specify each elements of modelling step by step. There are in total six classes of model objects included in this simulation: vessels, pilots, tugboats, terminals, river sections and vessel generator, forming the abstract model to simulate the major activities of the NC. The conceptual model is then implemented in Anylogic software, which is one of the best simulation packages supporting multi-method simulation. Using historical data of the NC in the PoR, a simulation model is constructed that correctly simulates the chain of ship handling activities from vessel entering the port until leaving the port.

The simulation model is verified to see that the network is correctly constructed, and all the actors perform appropriately. Moreover, the model is then validated through a series of experiments. The experiments are designed to test the model under given different circumstances. The outputs show that waiting time accounts for the largest part of turnaround time, the unavailability of nautical service providers will profoundly influence the duration of vessel waiting at anchorage area before entering the port.

The simulation study has not completed yet, as we know the model boundary is limited, at the same time, many assumptions are proposed, that all make the model not so useful for port authority. This study implements the necessary logic to reproduce vessel service flow and congestion pattern, but additional logic should be implemented to obtain more realistic results. To move one step closer to develop an agent-based model, the interactions among all the actors involved in the nautical service system should be constructed. Such facilitation on information flow could probably the main direction further work will follow on the basis of this research.

Contents

LIST OF FIGURES

List of Tables

1

INTRODUCTION

This project is part of SwarmPort project which aims to improve people's understanding on the chain of nautical handling services offered at seaports to vessels. The introduction to this graduation work is given in this chapter. The background information of this project is introduced first, then what the main challenge is. Subsequently, the details of this research are discussed, including research gap, objective and several major research questions. Section 1.6 describes the process of selection on model paradigm and model tool to find the best way to work with this simulation study. The last paragraph presents the outline of this report.

1.1. CURRENT SITUATION IN THE PORT OF ROTTERDAM

Market globalization boosts the development of maritime trade. As the largest deep-sea port in Europe, Port of Rotterdam (PoR) is visited by thousands of sea-going vessels every month [4]. A series of activities are conducted to support a ship entering or leaving the port. Each activity is either handled by one actor or collaborated by several actors, which together form the so-called nautical chain (NC). The main activities in NC are positioning, piloting, mooring/un-mooring, and bunkering or fueling, while the relevant service providers are Harbour Master, pilot organization, tugboat companies, boatmen organization and terminal [1].

It has been proved that turnaround time of NC is one of the key factors to reflect the competitiveness of the port, while short turnaround time requires seamless service flow during ship visiting [5]. However, there is no central command in the PoR currently to direct the NC. Nautical service providers balance their interests with the cooperation in the NC, at the same time, they are obliged to respect company's benefit in order to survive in the market. Therefore, the Port of Rotterdam Authority has no intention to bring them under public control. Instead, what PoR wants to achieve is to organize the interaction within the actors in the NC, and perform greater contribution to the collective performance of the port.

In general, the performance of NC relies on the fluctuation of service demand, i.e. volume and size of ships, external circumstances, the capability of actors in the chain and the collaboration work among them [6]. The recent research shows that collaboration between stakeholders in port service chain is vital to maintain overall port service performance level [7]. Due to the complexity of nautical service chain and a variety of parties involved, problem emerged in one step will influence the conduction of the next step. For example, the delay on the pilotage of first vessel will lead to the queue for the second or third vessels. In another words, disturbances will propagate along the NC, resulting in the delay or congestion of the service chain, which severely deteriorates the performance of port operation processes in a global level. The collaboration works which lack efficient interaction will lead to such disturbances.

1.2. PROBLEM STATEMENT

The Port of Rotterdam is Europe's largest sea port. The port owns its leading position to its outstanding accessibility for sea-going vessels. Nowadays, the complexity of nautical network is increasing due to the larger amount of container ships and various traffic rules for different vessel classes. Port authority found that a good threshold of turnaround time of ship arrival or ship departure is one of the key factors determining the competitiveness of ports. The turnaround time of ship visiting consists of the time for traffic management, positioning, piloting, towage, anchoring and mooring/unmooring. These services are offered by different actors in NC, thus if one actor failed to well connect with another actor, the rest service operations might be disrupted.

Two major nautical service providers, represented by pilot station and tugboat station, assist vessels to traverse through river sections until successfully reach the berth during ship arriving process and vice versa. The maneuvering of ship sailing is contributed by pilots and tugboats, while ship sailing behavior has changed when they start to provide nautical service. Port authority has noted that the causes of delays in ship handling of arriving voyage usually derive from a mismatch between the arrangements among the service providers, non-availability of service resources (pilots and tugboats in our case), or last-minute changes in logistics. On the other hand, for departure situation, it happens that vessels delay because of cargo which is not yet arrived at or released from the terminal.

In the PoR, Mass-corridor is divided into many river sections with their corresponding traffic rules in terms of ship sailing behavior. Considering the large amount of seagoing vessels sail in the PoR, the impact of traffic rules for vessels' sailing behavior is hard to simply look at. Such complexity in the environment of NC requires an advanced tool to help people 'see' the nautical process in a visualized manner.

1.3. RESEARCH GAP

The scientific gap of this research is that, even though a lot of studies have done on model simulation of deep-sea port, the discrete event simulation model structured for studying port nautical operations has not been researched yet. It will be a good way to take a look at the chain of the nautical service processes, when the state of objects changes.

The practical application of this idea is the Port of Rotterdam needs a state of the art simulation model that reflects the current practice of the NC in the PoR as close as possible, so they launched a project named 'SwarmPort'. As a sub-project of SwarmPort project, this research will be initiated and developed based on the background of PoR, and the major activities in the NC will be structured based on the real case in the PoR as well, which have not been discovered before.

1.4. RESEARCH OBJECTIVE AND SCOPE

The main objective of this project is to develop a simulation model as a tool for port decision makers to examine the potential consequences resulting from disruptions or changed input. They can use simulation for comparing and analyzing the outcome of different scenarios. The idea is to firstly identify Key Performance Indicators (KPIs) which are able to reflect the effectiveness of the NC, then design a model that mimics the execution of activities in the NC. The model will be seen as the first version of an advanced tool to evaluate and improve the nautical performance of the deep-sea port. The functionality of the simulation model will be validated when collecting and analyzing the outputs based on predefined KPIs from different scenarios.

This research is based on the real operation case in the PoR, while not every detail can be reflected in the model. In order to clarify the boundary of this research, several aspects have to be considered respectively.

Vessels There are dozens of vessels types handled by Port of Rotterdam, such as cargo vessels, passenger vessels, tankers, high speed craft, tugs, pleasure craft, and so on. Due to the limitation of collected data, not all of them are researched in this study. The data collected from port authority contains seven vessel classes (1, 2, 3a, 3b, 4, 5, 6), all the vessels can be assigned in specific class. The operation of nautical chain is structured only for these seven vessel types.

Actors Many actors involved in the NC play different roles during the service. Generally, harbour master, pilot organization, tugboat organization, boatmen organization and terminal operators are parties commonly existing in the NC. In this research, only pilots and tugboats are considered as nautical service providers whose behavior poses great influence on the efficiency of NC.

Activities The researched activities contain the sequence of vessel port visiting process, starting from vessel arrives before port entry, to vessel leaving PoR. However, the quay-side terminal activities are excluded in this study.

More details about the boundary of the simulation study will be further described in Chapter 4.

1.5. RESEARCH QUESTION

According to the current problem described in section 1.2, the main research question can be defined as:

"How to develop a model that can simulate nautical service in the deep-sea port in order to evaluate the performance of the NC?"

1.***What is nautical chain and what are the Key Performance Indicators (KPIs) of ship handling services in the NC?***
A definition and explanation of nautical chain will be given first. A research on defining KPIs of ship handling activities must be done before conducting simulation model. KPIs aims for demonstrating the objectives of nautical services from port manager perspective. By determining KPIs, dependency variables and independency variables will be defined to form the structure of simulation model.

2.***How does the current NC perform in the PoR?***
A research on the NC in the PoR have to be done in order to get insight into the current

performance of the NC quantitatively and qualitatively. The research with case study methodology will be reflected throughout this project. Firstly, PoR environment will be described and NC related datasets provided by harbour master are going to be analyzed. In model building section, the behaviors of ships and service providers will be mimicked as real as possible, in line with the result of case study on PoR.

3.***How to develop the conceptual model for simulating the NC in the deep-sea port?*** A conceptual model is representation of a real system. After having done system analysis, the conceptual model can then be structured. A well-structured conceptual model is the prerequisite to build a simulation model. There are several aspects have to be clarified: model goal, model boundary and assumptions, model inputs/outputs, etc. The development of simulation model in the software should comply with the details regulated in the conceptual model. It contains several steps for model implementation. The first step is to create simulation environment elaborately, which includes the configuration of infrastructures, river path sections, etc. These are where the nautical services operate and service providers are located. Subsequently, the sailing behavior of vessels and, pilotage and tugboat assistance of pilot station and tugboat station have to be specified to shape service chain of ship handling. The final step is model testing, verification and validation.

4.***How to validate the simulation model in different circumstances, by forming different scenarios?***
Several validation methods are going to be used in this section. For example, model outcome will be collected and compared with empirical data provided by harbour master of PoR in order to prove that the model is correct and useful. The further validation is to experiment the simulation model with different scenarios. At the beginning, the experiment topic should be determined, for example, to see how the performance of nautical service system changes when the number of in-coming vessels are increasing. A group of scenarios are then designed to see which input parameter can be changed to assign the value in a threshold. The simulation outputs generated from designed scenarios will be in comparison with the data from base scenario.

5.***What are recommendations for improving the model with a higher level of intelligence?***
As a sub-project of Swarmport project, this study will hopefully lead to good direction for future research. The simulation model cannot reach to a high level of complexity immediately, so the recommendation will be given on how to extend the content of simulation study and how to embed more characteristics of current NC into the simulation model. More specifically, the ultimate goal of Swarmport is to design an agent-based simulation model to realize real-time interaction among all the actors in the NC. The suggestions will be given how these information flow or interactions can be structured in a simulation model.

1

1.6. MODEL SELECTION

It is critical to determine the most suitable model/tool for solving a real-life problem. We will proceed model selection in the following three steps.

1.6.1. SIMULATION VS ANALYTICAL MODEL

Simulation method is preferable to analytical model in our case. Simulation can model the randomness of ship handling activities in the port network, thus leave us the room that play with the combinations of input parameters that we want to explore. The outcome will be shown in a visualized manner, for example, any congestion or disruptions can be discovered on the simulation panel or in form of reporting diagram. On the other hand, analytical model such as mathematical model, is good at discovering the relationships among dependency variables and independency variables. However, many unrealistic assumptions have to be made before building a model which makes the model unreliable and less authentic. Therefore, it seems mathematical model is hard to reflect the real process of nautical service, while simulation model is a better choice.

1.6.2. DISCRETE EVENT VS SYSTEM DYNAMICS

There are many simulation paradigms that commonly used in scientific research, such as discrete event (DES), system dynamics (SD) and agent-based simulation (ABM). Here a comparison is made between DES and SD.

Definition DES models the system as a network of queues and activities, where state changes in the system occur at discrete points of time [8]. However, it is assumed that no state changes existed between two consecutive events, thus simulation time can directly jump to the occurrence time of the next events [9].

SD models a system as a series of stocks and flows, where state changes are continuous [8]. The entities in the model are continuous, such as fluid flowing through a system connected by pipes.

System orientation In DES, the behavior of entities are modelled in a linear fashion, and normally no feedback loop forms. The historical data are imported to capture the process characteristics and variances, and once entered into the model these parameters often remain fixed [10].

However, SD model covers all the aspects of process within a closed system. The feedback loop plays a significant role to reflect the changes of parameters over time in a causal-loop diagram [10].

Adaptiveness A DES model usually uses accurate data to analyze the performance of a real-world process, or generates accurate estimates on the operating characteristics of a proposed system [10]. Therefore, the evaluation of DES on a system is from statistics perspective, for example, the number of entities waiting in a queue.

SD often combines with causal-loop diagram approach, thus analyzes the problem in a qualitative manner. There is a tendency to use SD at a strategic level in order to gain insight into the interrelations between the different parts of a complex system [8].

To sum up, DES is chosen as research approach in order to monitor and analyze the critical events derived from NC processes in PoR. As a top-down modelling approach, DES is built on the structure of the overall service system in the port area, then vessels are regarded as entities moving in the corridor. Queuing of waiting vessels at the entrance of port can be directly monitored.

1.6.3. SIMULATION PACKAGE SELECTION

To choose an appropriate simulation software is a good start for forming a decent simulation model for real case. Here a group of the most popular simulation softwares are chosen and compared based on their characteristics.

Table 1.6.3: Simulation softwares comparison [11]

Simulation Packages	Orientation	Formalism	Programming	Interaction
Anylogic	Objects	DES,SD,Agent	Yes,Java	Yes,Java
Arena	FLow	Discrete	No	Yes,Excel,files
Enterprise Dynamics	Atoms	Discrete	No	Yes
ExtendSim	Flow	DES	No	Yes,many
Simio	Objects/Flow	Discrete	No	Yes,some
Plant Simulation	Objects/Flow	Discrete	Partly,script	Strong

Table 1.6.3 elucidates the features of each simulation tool from four aspects: orientation, formalism, programming and interaction.

Orientation Objected-oriented model is our aim to simulate the movement of ships who will be regarded as objects. Each object (ship) can contain data, and has specific attributes, such as length, speed. The ship moves in a chain of processes, under the control of methods in the simulation environment. In objected-oriented model, objects can interact with one another, and usually objects are divided into different classes, to form complicated interaction and communication.

While flow-based model, also called activity-based model, represents how data objected are transformed when they move through the system. A so-called data flow diagram have to be created as diagrammatic form of the model, which leads to develop the information domain and functional domain.

However, information flow will not be monitored in this research, and any information transfer activities will be set as fixed, thus object-oriented model paradigm is our first choice.

Formalism The most popular simulation formalisms are discrete event simulation, system dynamics and agent-based simulation. Based on the description from section 1.6.2, DES model formalism has powerful capability for this research, as the activities of nautical chain could be seen as a series of events. It seems all the simulation tools are capable of building DES model, however, Anylogic is the best as it is never limited by a single modelling method. Users can choose the most efficient one, or combination of these formalisms, to get the best modelling and simulation to address the problem.

Programming Programming function leaves users a room for customizing the model wherever it requires. For example, in Plant Simulation, users can design custom 'method' as control algorithm in order to simulate the movement of objects as real as possible. Even though some packages don't support custom coding, they still have a large library of pre-defined building blocks to satisfy colorful modelling requirements.

Interaction This criteria aims for testing the ability of each package to connect with out source data or files. From the table, all the chosen simulation tools can realize data sharing with other softwares. Specifically, Anylogic support users to create Anylogic database tables and export them to Excel files and vice versa. The connection with other softwares can go through standalone Java applications.

According to the brief comparison among several popular simulation tools, Anylogic shows its powerful function and applicability for this project. Moreover, Anylogic is the only hybrid/multi-paradigm simulator in the market that delivers complex modelling capabilities in an all-in-one solution [12]. Therefore, using Anylogic simulator, discrete event simulation environment will be implemented and the activities of ship handling operation will be modelled. For DES model development, Anylogic provides the Process Modelling Library, which is a primary toolkit of highly customizable objects for defining process flows and resources. Specifically, the service flow of nautical chain in PoR can be easily simulated with Anylogic animation framework for clear identification and evaluation.

1.7. RESEARCH STRUCTURE

The outline of this research is shown in Figure 1.1.

In Chapter 2, literature research on nautical chain and KPIs are given. It provides theoretical basis for simulation modelling in Chapter 4. Chapter 3 analyzes the nautical system based on the background of PoR case with different system analysis tools. Furthermore, the historical data is organized and analyzed to be prepared as the model input.

Then it is the step to start modelling in Chapter 4. It follows the framework for structuring the conceptual model first, defines the content of the model. After that, the steps that how to transfer the conceptual model to simulation model in Anylogic software are given. The final part of this chapter is model verification.

In Chapter 5, the experiments to be performed with the model are then structured in order to validate the model under different circumstances. Chapter 6 is to conclude the model outcome from all the scenarios and promote recommendations for future research based on this simulation study.

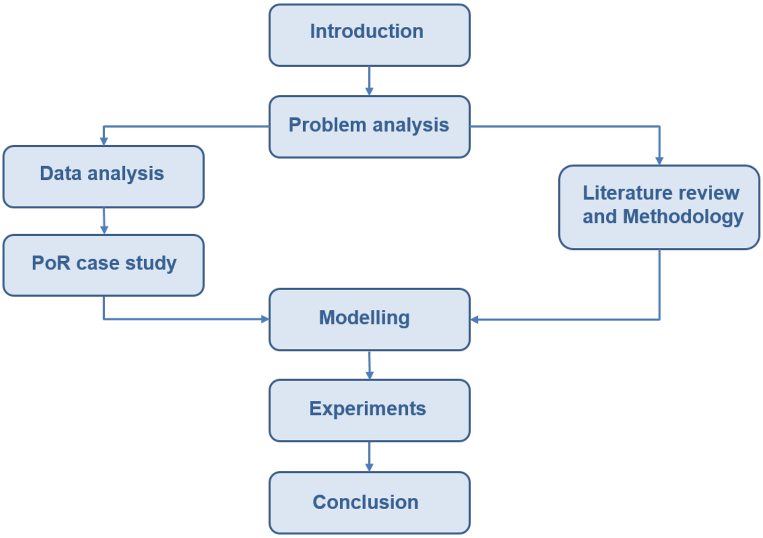

Figure 1.1: Research outline

2

LITERATURE

2.1. NAUTICAL CHAIN

To easily understand ship handling process in deep-sea port, the definition of nautical chain will be clarified. In this research, nautical chain is defined as 'all the events of the nautical service providers in the operational domain performed for a vessel during the time that vessel is sailing in the Port of Rotterdam' [1]. Furthermore, the information sharing activities in the tactical level are also included in the chain to support operational events.

The parties involved in NC are the Harbour Master, the pilot organization, the tugboat company, the boatmen organization, the terminal operator and the vessel.

Specifically, the Harbour Master is responsible for the safe and smooth traffic in the port, as a special division within the Port of Rotterdam Authority. Pilots guide the vessel from the entrance of the port to its designated berth in a safe and efficient manner. Tugboats assist a vessel with maneuvering by pushing or towing service, while the main work for boatmen organization is mooring or un-mooring the ships. As the destination of ship calling at the port, terminal performs loading and unloading activities when the vessel is berthed at the quay. In our research, vessels as the only nautical service recipient will be further categorized and analyzed in the following chapter.

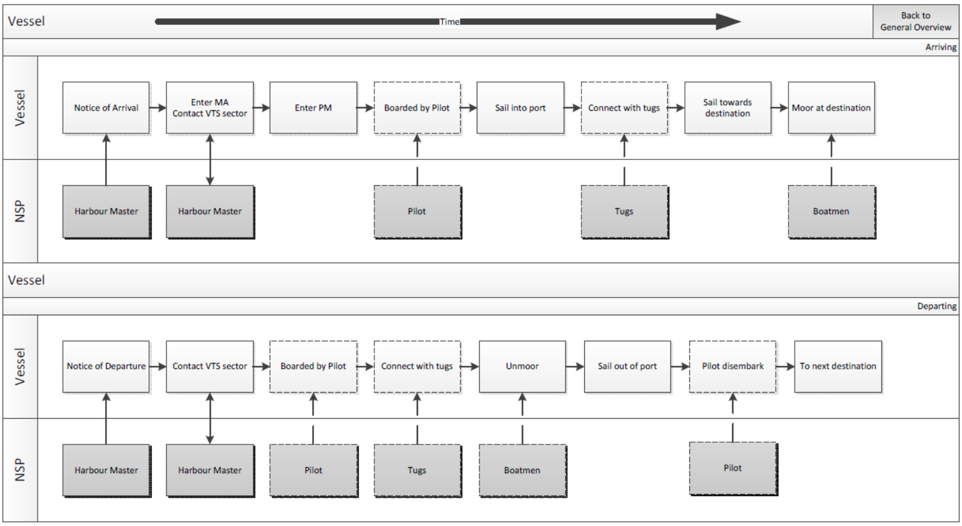

Figure 2.1: Nautical chain from vessel point of view [1]

Figure 2.1 depicts the whole process of NC from vessel point of view. The processes are connected following time line. 'NSP' at the left-side column means 'Nautical service provider', which are all actors mentioned above.

2.2. Port operations in the Port of Rotterdam

The Port of Rotterdam (PoR) is the largest deep-sea port in Europe and an international hub for global cargo flows. Due to its leading position in the North Sea, PoR has outstanding accessibility for sea-going vessels. Port operations and marine activities in the PoR extend from Maasvlakte area to Delfshaven, alongside Nieuwe Maas river corridor.

All sorts of vessels sail in and out of the port, which contains in total 29476 sea-going vessels and 107000 inland vessels in 2018. The cargo handled by PoR are categorized as dry bulk (17%), liquid bulk (45%), containers (32%) and break bulk (6%) [4]. In this research, only sea-going vessels are considered, that are classified into seven classes, according to their lengths and drafts characteristics.

Figure 2.2: Network overview

Figure 2.2 shows the overview of the PoR area, where its river corridor are divided into over 100 sections. These river sections are numbered individually, and are distinguished between sailing section (S) and maneuvering section (M). In sailing section, ships sail in a normal speed and stable status; In maneuvering section, ships are decided to choose right direction to navigate to the destined berth with the assistance of pilots and tugboats. It becomes complicated when introducing traffic rules in each section for each type of vessels. There are two kinds of traffic rules: overtaking rules and encountering rules, which have to be complied with when vessel type A and vessel type B sail in a same river section. Overtaking rules restrict which vessel class can or cannot overtake which vessel class in a section, while encountering rules limit the occurrence of two different vessel classes sail in a same section simultaneously with different directions. Such traffic rules decrease the flexibility of ship movements in the port area under the control of Harbour Master.

Red marks in Figure 2.2 are terminals located in the area of PoR. The terminals spread out in the reclaimed Maasvlakte, Europoort, Botlek and Nieuw-Mathenesse area. Specifically, each red point labels the exact position of berth in each terminal, where the destination is for every vessel arriving at the PoR. Terminals have the time windows for serving different types of sea-going vessels every day, which means ships can only be served when arriving within the appropriate time window.

According to the logged data, the two most busiest harbours are Caland and Stad, situated at section 8 and section 105, respectively. The number of vessels they handled is over 50% of total number of sea-going vessels in the PoR. Generally, port calls in Maasvlakte is much more than that in Botlek area for sea-going vessels.

2.3. KPIs FOR NAUTICAL CHAIN

KPIs reflect the goal of nautical service from port manager perspective, also align with our research objective. The selection for appropriate KPIs is critical for the feasibility and validness of created simulation model in the following research work.

NC consists of a series of activities with a group of actors involved, thus the performance of NC cannot be evaluated by individual acitivity, but be assessed as a whole in the port level. The intergovernmental organization UNCTAD (United Nations Conference on Trade and Development) developed and published a list of port performance indicator [13]. On this list, Some operational indicators such as ship arrival time, waiting time, service time, turnaround time, fraction of time berthed ships worked, reveal a common feature that they reflect time efficiency.

Many scholars have identified time-related KPIs in port operational performance. Chen-Hsiu and Kuang-Che (2004) point out the average time a ship waiting in a queue can represent the port ship handling efficiency [14]. Chung (1993) describes the importance of ship turnaround time in the port as one of the major measurements for evaluating vessel performance [15]. Ship turnaround time is defined as the time duration of ships from entering, unloading, loading till departing from a port. Nam et al. (2002) suggest the average port time, average berth time, average berth occupancy ratio, and average waiting time as primary indicators to evaluate port performance [16]. Peter and Paixao Casaca (2003) put their target at customer satisfaction, with introducing cargo dwell time at port as the performance indicator [17].

To sum it up, port performance is preferably measured by time-related indicators that represent ship handling efficiency. Here ship turnaround time and waiting time per vessel class are able to reflect the nautical performance in collective and individual manner, respectively.

Generally, ship turnaround time contains all the time a ship spent in the port area. In our research, vessel turnaround time is defined as the total time for a vessel visiting to the port, minus the duration of vessel waiting for terminal service. Ship turnaround time helps us to get insight into the collective performance of port operation on vessels [18]. However, this indicator is not easy to tell us what the underlying reason is when any problem emerged. For example, when people realized ship turnaround time is too long, it is still hard to know if the disruptions happened during ship on sailing or ship at berth.

Similarly, ship waiting time is obviously one of most important factors that judges the competitiveness of a port. Waiting in a long queue at port will reduce the attraction of port terminal to container ships, on the contrary, lower average waiting time reflects the high efficiency of nautical service and good management of ship handling services [19]. Different with ship turnaround time, waiting time is caused by queue or delay at different steps of nautical chain. An example will be when a ship nearly arrived that designated berth, it has to wait if the berth is occupied. It has to be noticed that waiting time in essence means delay time of vessels waiting for service resources, while the time ship actively waits as planned is not taken into consideration.

2.4. FISH BONE DIAGRAM

Before structuring the simulation model, different factors and variables that influence the performance of the nautical service chain have to be summarized in cause-effect diagram. Cause-effect diagram is used for examining why a certain problem happened or might happen by organizing potential causes into smaller categories, so that the relationship among contributing factors can be formed to solve the problem. Furthermore, these factors are either dependency variables or independency variables regarded as the input for simulation model.

As one type of causal diagrams, fish bone diagrams are built based on the investigation on KPIs defined from the processes of port operation, reflected in section 2.3. Three fish bone diagrams are introducing the potential factors that cause the deterioration of three KPIs, such as long waiting time, in three layers. Some branches have been discarded as the corresponding factors are out of our research scope.

2.4.1. TURNAROUND TIME

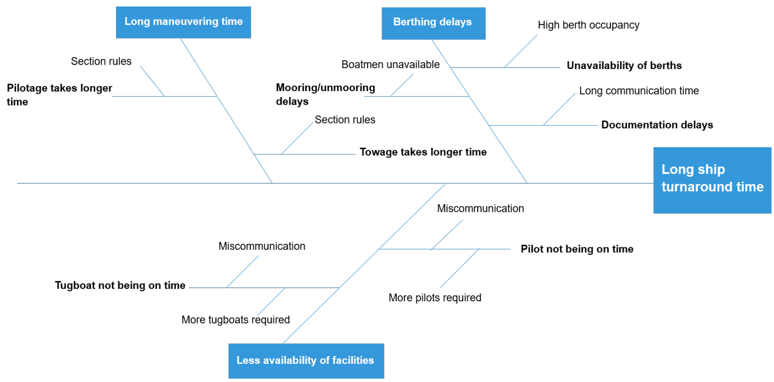

Figure 2.3: Fish bone diagram for long turnaround time

As shown in Figure 2.3, if ship turnaround time is too long, it is probably because of long maneuvering time, delays at berth and the required service facilities is lacking.

When ship sails in the port area, the pilots are responsible for guiding the vessel safely and efficiently reach the designated berth. Similarly, when ship is near the destined harbour, tugboats help to maneuver the ship towards the berth. Due to the complexity of traffic rules and vessel types combination, the maneuvering processes are not easy, and requires high quality of management.

The pilots board a vessel before it enters the port, while the tugboats connect to a vessel when the vessel sails towards the entrance of the harbour. However, it takes time for the vessel to connect with either pilots or tugboats since both physical and information activities involved. The vessel has to communicate with HM before sailing to the pilot station, and then waits for the feedback which directs the vessel to pick up the pilots. Connecting with tugboats will go through a similar process. The time spent waiting for the call of pilots and tugboats is a critical part of turnaround time.

The last influential factor will be the delay at berth. The ship has to berth at the designated harbour, but it happens when that harbour is occupied or no berth space left, the ship has to wait at the entrance of the harbour.

2.4.2. WAITING TIME

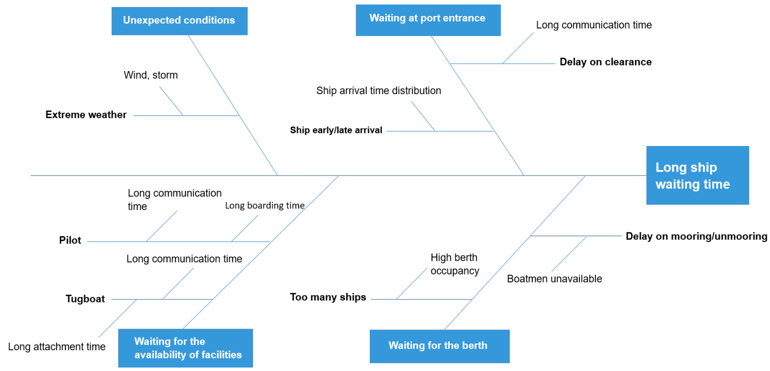

Figure 2.4: Fish bone diagram for long waiting time

Figure 2.4 depicts the potential causes of the problem if ship waiting time is too long. During the nautical chain, a ship would wait at several potential place, for instance, waiting at the entrance of the port for the available service of pilots and tugboats, or wait at terminal before leaving the port. As a time-related KPI, waiting time reflects the efficiency of ship handling activities individually, and helps to monitor the performance of nautical service chain in different stages.

The source of waiting time could be when ship arrives at the entrance of the deep-sea port. Container vessels have contacted with the port and determined the specified data of arrival. However, it happens that the ship reaches the port earlier or later, which disturbs the tactical planning of ship arrival distribution. Moreover, when vessel has finished the loading/unloading activities at terminal, it has to wait to be taken by pilots and tugs in order to successfully leave the port.

3

SYSTEM ANALYSIS

In this chapter, the nautical service system in the PoR will be described and analyzed with the assistant of several mainstream analysis methods, such as black box approach and CATWOE. After that, the datasets collected from port authority will be organized and presented as the supplement to depict the system on the current state.

3.1. SYSTEM DESCRIPTION

3

Our target system is a service chain that covers 28 terminals and 43 river sections as the environment where pilotage and mooring/unmooring services are provided by pilots and tugboats for seven types of seagoing container vessels.

3.1.1. CATWOE

To describe the system more in detail from different aspects, CATWOE method can be applied with a simple checklist to find solutions for problems.

Customer The customer element in our case represents the target of the nautical service, the users of the system. Therefore, vessel as the only service recipient, would be customer moving around in the system. The problem emerged on vessels is that the turnaround time for vessels going through the whole nautical service process is increasing and unpredictable according to the research on logged data. If any improvement on the NC process can be applied, vessels will benefit a lot from the high-efficient ship handling activities, such as eliminating delay time, reaching short turnaround time, etc.

Actor The actors refer to every participant involved in the system and who will take part of the solution. They will be pilots, tugboats and terminals whose availability would influence how long vessels have to wait for receiving the service. The implementation of changes on these actors generates direct or indirect impact on the system performance.

Transformation Transformation is the change that a system leads to, which mainly refers to the process in which input is transformed by a system into output. The transformation would involve serving the sea-going container vessels from just arriving at the port entrance to leaving the port with mission completion.

World view The world view reflects the big picture of the situation, usually used for highlighting the most critical problem and its impact. In the port service system, the world view would be increased efficiency of ship handling process, so that vessel turnaround time reduces.

Owner This element represents the ownership of the situation or the system, which in our case, refers to port authority. The port authority wants to make changes to improve the current status of the port, and has capability to decide whether a project should start or stop.

Environment The environment element may influence the organization and can limit or restrict the system. Since a group of section traffic rules existing, vessels cannot sail freely in the port river corridor. Meanwhile, the number of service unit, such as pilots and tugboats, is limited, which hampers the seamless nautical service progresses.

3.1.2. BLACK BOX APPROACH

After getting holistic understanding of the port nautical service system, black box approach are going to be used in order to translate model input/output into process model. The principle of black box approach is to determine a model of the system by applying various inputs and observing what the outputs were. The black box is composed of four basic elements, as shown in Figure 3.1.

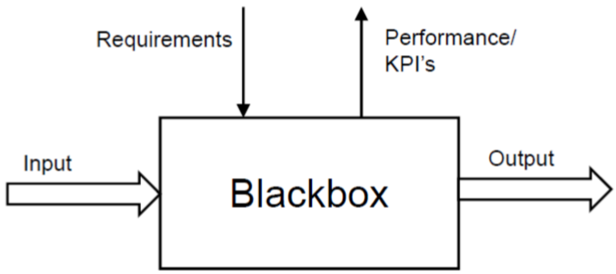

Figure 3.1: Black box approach [2]

Input The input of the system are vessel group consists of seven vessel classes, that are ready to enter the port. We have a group of data indicating vessel voyage distribution for each vessel class with each designated terminal. It will be approximately three sea-going container vessels pour into the system per hour, while most of them will sail to Stad and Caland terminal.

Output The output of the target system is the completion of nautical service for sea-going container vessels. Each vessel will successfully accomplish their logistics tasks in the PoR, and leave the port at the end of this voyage. However, what we expect is the high quality of nautical service, which will be in line with the requirements element for black box model.

Requirements Apart from inputs, a certain amount of resources is required to import into 'black box', such as pilots, tugboats and terminals. Each vessel is generated with a designated terminal, where vessel has to arrive to complete its logistics task. However, if the berths at designated terminal become unavailable, vessel is not allowed to enter the port, but wait at anchorage area instead. Similarly, the service provided by pilots and tugboats is limited, thus only the resources are available, delay will be avoided. A shortage of pilots or tugs should be considered as a temporary mismatch between "demand & supply".

3

KPIs As depicted on Chapter 2 Section 2.4, there are two KPIs: turnaround time, waiting time, used for evaluating the performance of the system. Two time-related KPIs are assessing the unavailability of resources.

3.1.3. FROM BLACK BOX TO PROCESS MODEL

The transformation process that transforming input into output is still invisible. The next stage is to disclose the process hided in the 'black box' by using flow chart.

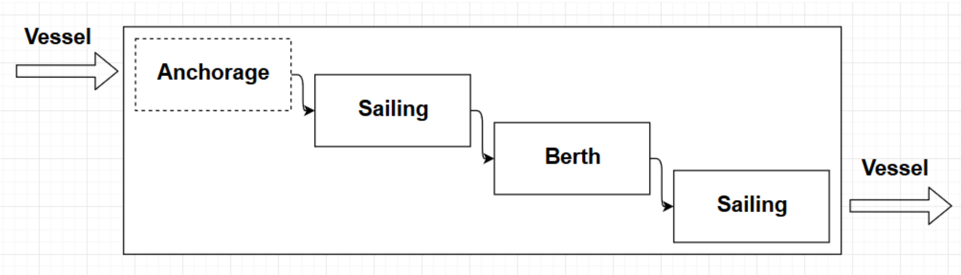

Figure 3.2: From black box to process model

As shown in Figure 3.2, there are in general four blocks to conclude the nautical process vessel going through. 'Anchorage' is not required for all the vessels, only vessels who cannot receive enough resource units will enter into this block. Two 'Sailing' sections indicates in-going sailing and out-going sailing, respectively. 'Berth' is the end of arriving voyage, at the same time, the start of departing voyage. Vessel has to stay a certain period of time at berth in terminal before leaving the port.

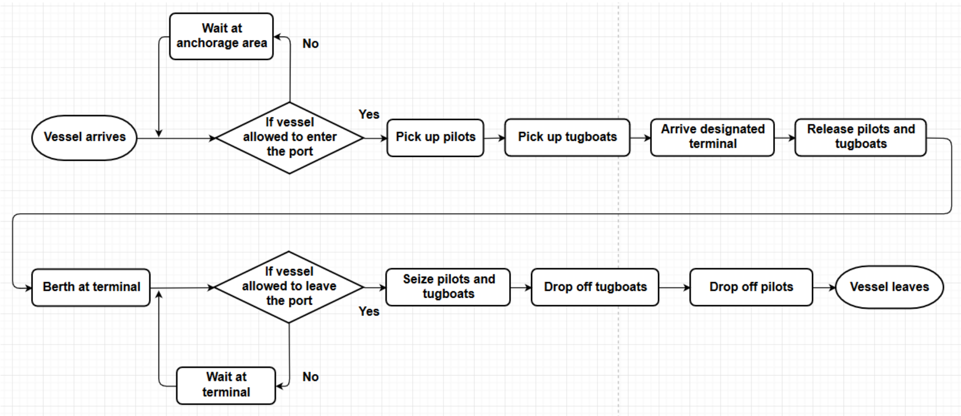

Figure 3.3: Process model

Figure 3.3 depicts the nautical service process in detail. The process starts with vessel arriving at the entrance of the port. Then the vessel will make a decision if it is allowed to sail into the port depend on the availability of three resources: pilots, tugboats and designated terminal. Once any of the three resources are not available, vessel will stay at anchorage area until it is notified to move forward. Subsequently, vessel sails to pilot station to pick up the required number of pilots, then moves to tugboat station attached with the required number of tugboats. The arrival voyage ends with vessel has been moored and fastened at berth, while the pilots and tugboats can be released and repositioned to prepare for the next tasks.

After staying for a certain period of time at terminal for loading/unloading, the departing voyage starts. The same as what happened at the start of arriving voyage, vessel has to wait at terminal until it is announced to leave the port. It is the time when pilots and tugboats are ready. On the way of sailing out of the port, when the assistance of tugboats is no longer needed, vessel releases the tugboats, similarly, releases pilots and then signalling the end of involvement for nautical service.

3.2. DATA ANALYSIS

In this section, aforementioned empirical datasets as the input are organized and analyzed in detail to prepare for model implementation in the next chapter. Note that all the datasets are shown in the appendix, derive from previous research from Alexander(2017) [1].

3.2.1. VESSELS

Vessel voyage distribution Here vessel voyages combine the information of arriving voyage and departing voyage datasets in order to form a complete vessel voyage process which starts from vessel entering the port to vessel leaving the port.

Tabel B.1 shows the frequency of seven vessel types of vessel traffic in the PoR. It seems vessel class 1 and 2 are the top two most frequent vessel types sailing in the port, while vessel 5 and 6 show up rarely.

On the other hand, Table B.2 lists the frequency of each terminal that vessels will arrive at. Stad is the busiest terminal that serves nearly half amount of total vessels, followed by Caland, where over 1/5 vessels will arrive at. Some terminals such as Indorama, EuromaxMV1 serve far more less vessels, so that less busy would be emerged normally.

In reality, vessels only sail to some specific terminals that has been contacted before. The linkage of vessel classes and vessel destinations will be considered to reach a realistic voyage distribution, This is shown in Table B.3. From regional perspective, it can be concluded that vessel class 3b, 4, 5 and 6 are only received by terminals that located at Maasvlakte area, probably due to the size of these ships.

Average voyage duration Average voyage duration is the sum of sailing time of arriving voyage and sailing time of departing voyage. As shown in Table B.4, in general, average voyage duration becomes longer with the longer sailing distance.

Table B.5 elucidates the voyage duration from vessel types respect. Due to the diversity of destinations they are going to arrive at, it doesn't show too much differences with voyage duration across all vessel classes.

Average duration before entering the port Here the information is organized to measure the time duration from operational contact until entering the port for arriving vessels, shown in Table B.6. These data will be reflected in the model that the waiting time ships stay in the anchorage area before they can proceed into the port.

Average duration before leaving the terminal The other phase is time spent from operational contact to actual time of departure for departing vessels (Table B.7). At that moment, vessels have finished the loading and unloading process, and prepare to leave the port. This is a period of time when vessels are still at berth, but should be considered as a part of departing voyage duration.

3.2.2. TERMINALS

Terminal average service time for each vessel class Terminal average service time reflects the total time of terminal activities, such as loading and unloading cargo, as well as other ancillary activities, such as bunkering, repairs, and crew change. Since the characteristics of these activities are not part of this research, here what we need to do is just uploading the terminal service time dataset to show the delay time vessels stay at berth in order to connect arriving voyage and departing voyage for each vessel entity. From Table B.8, it can be concluded that the larger the vessel type is, the longer service time the vessel has to take.

3.2.3. RIVER SECTIONS

Section separation times per vessel class Table B.9 indicates the separation times in each river section for each vessel class. This is the time gap information in minutes. However, in discrete event simulation model, time cannot be monitored continuously. It is a better way to transfer time interval into safety distance, so that each pair of vessels have to keep a safety distance in case of overtaking maneuver.

Section speed limits per vessel class Vessel sailing speeds are restricted with certain threshold in each river section. These speed limits are found in Table B.10. The speed information will be implemented in river section entity, which is able to control the object movement on it.

3.2.4. PILOTS

Number of pilots per vessel class This data will be used to determine how pilots distribute among the vessels. From Table B.11, vessel class 1, 2, 3a and 3b usually need one pilot for pilotage service, whereas sometimes no pilot required. Vessel class 4 and 5 always take one pilot on board. For class 6 vessels, two pilots are used, due to the longer duration of the voyage.

3.2.5. TUGBOATS

Number of tugboats per terminal per vessel class The number of tugboats attached for each type of vessel with each terminal is much more complicated. The data has been organized in Table B.12. Since the capacity of tugboat station is fixed, if there is no other tugboat available in time, vessel has to wait until the required number of tugs are available. With distributing the appropriate number of tugs to each terminal, the delay on vessel-tug connection process can be monitored.

3.2.6. CONCLUSION

The datasets are organized and analyzed with the aim to generate the findings on all kinds of ship handling actors.

The most frequent vessel type visiting to the PoR is vessel class 2, followed by vessel class 1 and 3a. However, vessel 3b, 4, 5 and 6 show up rarely in the PoR considering the total ship population. The most popular destination for sea-going container vessels is Stad terminal, then is Caland. The other terminals fail to attract a lot of vessels to be served. Specifically, in Stad terminal, most of visiting vessels are class 1 and class 2, whereas Caland terminal is usually visited by both vessel class 2, 3a and 3b.

It is in general larger vessel takes more time served by terminals because of the larger volumes of cargo. With respect to traffic rules of each river section, it can conclude that larger vessels are restricted by lower speed, smaller vessels can sail with a higher speed because it moves more flexible and less possibility to cause collision. Similarly, larger vessels are required larger safety gap among each other. It seems that narrow river corridor requires larger safety distances among vessels for safety issues.

Most of vessels are served by one pilot, whereas for vessel class 6, it requires two pilots due to higher technical complexity of pilotage bringing by big ship body. The requirement for the number of tugboats is increasing when the vessel becomes larger. Most of vessel class 1 can moor/unmoor without the help of tugs, on the contrary, vessel class 6 needs at least 3 or 4 tugs for berthing.

4

MODELLING

The chapter describes the processes of model building, which starts with formulating a conceptual modelling framework, to define model input, output, etc. The second part is to specify the model content from describing individual object to translating their relationships. Model implementation can be done following the steps that translate the conceptual model to the simulation model. The last section of this chapter is model verification and validation to confirm the correctness of the simulation model.

4.1. CONCEPTUAL MODELLING FRAMEWORK

Conceptual model represents a system in a division of concepts that helps to simulate a subject the model presents. Usually, conceptual model is the abstraction of things in the real world.

Our work starts with structuring the framework for simulation concept modelling. Stewart Robinson [3] developed a framework based on his over twenties years experience, mainly used for developing simulation model of manufacturing and service systems. The overview of his framework shows in Figure 4.1.

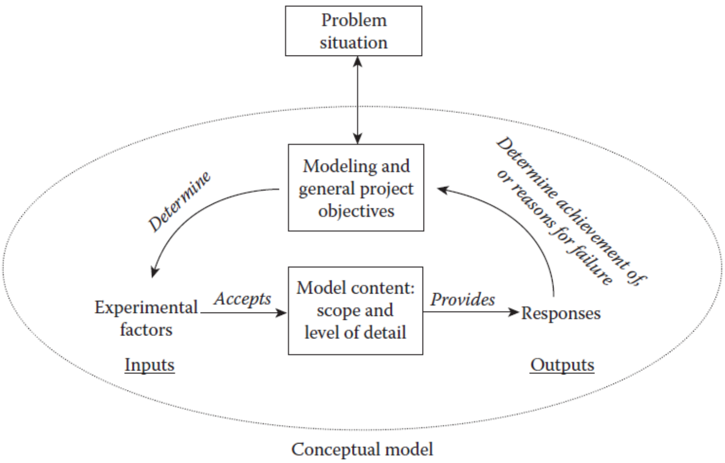

Figure 4.1: A framework for designing the conceptual model [3]

There are six key activities can be abstracted from the above figure:

- Understanding the problem situation
- Determining the modeling and general project objectives
- Defining the system boundary, assumptions and simplifications
- Identifying the model outputs
- Identifying the model inputs

- Determining the model content

Therefore, the objective of the model should be determined firstly in accordance with the objective of the overall project. Model boundary and assumptions are identified in order to ensure the feasibility of the research. Model outputs are the response coming from model content, which are used for verifying if model satisfies the general objective. Model inputs are experimental factors that people will play with in the model content. Finally, model content contains the description on model components and their relationships.

We will follow this framework to structure the conceptual model of nautical system. Considering the problem has been analyzed in Chapter 3, we will start with highlighting the model objective, then demonstrate other elements step by step in the following sections.

4.2. MODEL GOAL

The desired model in this research is able to simulate the chain of ship handling activities in the real case of PoR. Nautical service consists of a series of processes, which occur when ship is entering/leaving the port, entering/leaving the course, entering/leaving the anchorage ground, thus are regarded as discrete events. As described in Chapter 3 Figure 3.3, model should cover all the activities shown in the graph. With microscopic detail, vessel traffic behavior refers to consistent movements of vessels with different properties, such as vessel type, speed, safety gap, etc.

The model is expected to perform the following tasks:

- Monitor the ship waiting time per vessel class due to the unavailability of pilots, tugboats and designated berths at each terminal;
- Evaluate turnaround time of each vessel class;
- Calculate the optimized number of pilots and tugboats.

4.3. SYSTEM BOUNDARY AND ASSUMPTIONS

The model is able to help see and assess the efficiency of nautical service system in the PoR. Therefore, the activities from the point a ship arrives at the anchorage facility of the port until the arrival at the berth and upon departure from the berth to departure from the port are modelled.

Referring to the picture 2.2 in Chapter 2, the location of terminals are the physical boundary of the network, where are also the end of some river sections. In this case, the navigation of ships terminates in order to conduct loading/unloading activities. However, the process taking place at the terminal will not be modelled, the focus of this research is to see what happened before and after terminal service activities.

Meanwhile, during the process of vessel sailing in the port, the time spent on sailing accounts for a vital part of turnaround time, which is determined by the length of each river section and its corresponding speed limit. Any delay emerged during ship sailing can be regarded as the influence of traffic rules.

Even though in reality NC contains much higher level of complexity and more actors involved, in this research, only pilot and tugboat are taken into account as nautical service providers. The activities from other related actors like harbour master and boatmen can be researched in the future study.

Only sea-going vessels are researched in this project, including container vessels, tankers, bulk carriers, RoRo vessels, passenger vessels etc. While inland vessels and river barges are not considered in the model due to the limitation of data collection.

The central part of the simulation is the NC. The major activities have to be simulated while some details are excluded from this study. Here some assumptions will be introduced to help build the model in a generalized manner.

- Ship sailing based on nodes and arcs, arcs represent real river section, sailing time is calculated by the length of river section divided by vessel speed;
- Ship acceleration/deceleration will be neglected in the model;
- The turning movement of ships will be set as always available whenever it requires. Vessel changes direction with normal speed;
- Encountering and overtaking traffic rules are neglected;
- All the vessels waiting in queues follow FIFO (First In First Out) principle;
- No transshipment voyage taken into account;
- Only one pilot boarding station and tugboat boarding station is set;
- Vessel arrival rate is set as 3 vessels/hour;
- Port network is structured as a 'tree', no detour exists;
- The working speed of terminal on vessels is assumed to be constant;
- Pilot specialities and tugboats specialities are simplified;
- River section types: maneuvering and sailing, are not modelled.
- KPIs are defined from research perspective, as the measurement for comparison: waiting time refers to the vessel delayed due to lack of resources; turnaround time refers to the sum of time spent on each activity when ship is inside the port.

It is important to note that these assumptions and limitations may limit the usability of the model. Have known that certain constraints are not simulated, the model may produce shorter turnaround times and therefore underestimate waiting times.

4.4. MODEL INPUTS AND OUTPUTS

The model inputs are experimental factors, normally the data that can be changed in order to reach the goal of the modeling. For example, the total number of pilots and tugboats determine the capacity of nautical service, which significantly affect the delay time for sea-going vessels. These data are the inputs will be uploaded in the model, and could be modified to generate different experimentation that can aid understanding of the system or help plan for the future events. Sometimes, instead of determining a value, it is useful to identify a range over which inputs might be varied. As an example, the amount of vessels enter the port could be varied, reflecting different levels of demand of nautical service.

The model outputs are normally identified directly from the statement of model objectives. As described in Chapter 3 Section 2.4, three KPIs are the outputs and will be reported clearly as the outcome of the simulation model.

The following lists show the model inputs and outputs attached with some brief descriptions.

Model Inputs

Vessel arrival distribution
how vessel will be generated

Terminal service time distribution
how long vessel stays at berth

Resource requirements
the capacity of nautical resources and the required number of resources for each vessel

River section rules
to restrict the vessel sailing behavior, including speed limits, safety distances, etc.

Network configuration
How the network structured, the location of port infrastructure

Model Outputs

Ship waiting time at anchorage area and at terminal
ship wait because of lack of enough service resources

Turnaround time of each type of vessel
the total time that vessel takes nautical service

Sailing time of each type of vessel
equals to total turnaround time minus total waiting time

To sum up, according to the list of datasets in Chapter 3, model inputs are vessel voyage distribution, terminal service time distribution, pilots/tugs requirements distribution, river section rules. Firstly, vessels are generated at a specific arriving rate, following class and destination distribution. To determine how long a vessel stay at berth for quay-side activities, it follows service time distribution dataset. Then we will implement pilots/tugs requirements datasets to direct resource seizing and releasing activities. The fourth input is traffic rules, specifically speed limits and safety distances, to conduct a good control for vessel sailing behavior.

A set of data inputs can be used to build demand scenarios. Apart from data information, the different configurations of model environment perform different functionalities of the system, which will influence the performance of the system as well. Moreover, the model configuration can be modified with a new design of ship handling strategies. For example, if tugboat stations are set at different intersection of river network, the service time of tugboats will be changed and possibly optimized with a better configuration.

4.5. MODEL COMPONENTS

In this section, the model components of the conceptual model can be formalized by describing the characteristics of each objects individually, and then building the linkage among these objects to reflect the diverse functionalities of the complex system. Obviously, the real vessel cannot be moved on the screen of the simulation representation, thus all the objects are considered as the mental image of the familiar physical objects. The simulation context comprises a set of terminal nodes, a set of river path, as well as some areas for vessel-pilot, vessel-tugboat connections, that all will be described in the following paragraphs.

4.5.1. VESSELS

CLASS: VESSEL

Attribute:

- `vessel_class`: the type of vessel (determined by length and draught)
- `vessel_destination`: terminal
- `my_pilot`: number of pilots required
- `my_tugboat`: number of tugboats required
- `my_section`: list of river sections the vessel need to pass
- `my_speed`: vessel speed when sailing in the river

Process:

- Enter the system with defined destination;
- Routing: form the sequence of river sections to reach the destination;
- Sailing: leave one section to the next section until reaching the destination;
- Sail to anchorage area (if requires);
- Sail to pilot station to pick up pilots;
- Sail to tugboat station to attach tugboats;
- Sail to designated terminal/berth;
- Release pilots and tugboats at terminal;
- Wait at berth for pilots and tugboats;
- Sail to tugboat station to detach tugboats;
- Sail to pilot station to drop off pilots;
- Leave the system.

Vessel objects are the representation of sea-going container vessels that sail in the PoR. Here we specify vessel objects into seven classes, named 'Vessel1', 'Vessel2', 'Vessel3a', 'Vessel3b', 'Vessel4', 'Vessel5', 'Vessel6', respectively, defined by their lengths and draughts. The lengths and draughts of vessels, however, will not influence the basic nautical operation processes for ships, thus all types of vessels are treated as the same kind of entity in this research.

All the vessels have an important attribute, which is the designated berth in the terminal. Each vessel object is generated with a destination label, so that it has to move to a specific terminal rather than randomly distributes in the whole network. This property of the model is critical to show where the congestion emerged especially at those busy terminals.

As the only nautical service recipient in the model, vessel objects are the main target for simulation data collection and data analysis. As described at section 2.4, ship turnaround time and waiting time as two chosen KPIs have to be analyzed based on the outcome of the simulation model. Therefore, time-related parameters will be set for vessel objects, in order to monitor the information at different time stamp when different discrete events occur.

Figure 4.2 shows the vessel entities with its basic attributes have to be defined, and the relevant dataset will be implemented.

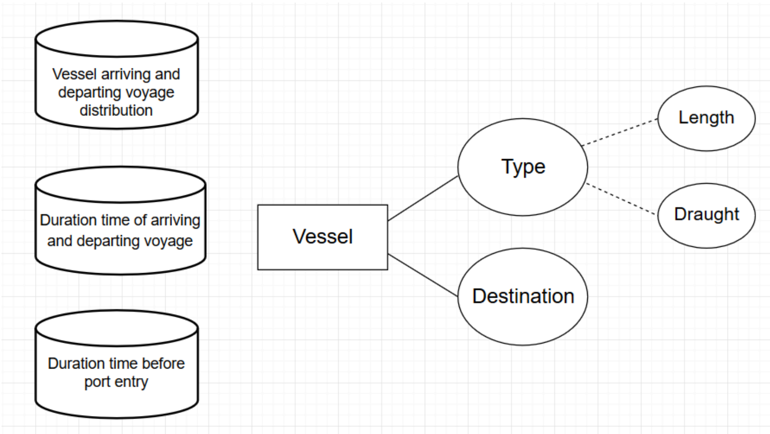

Figure 4.2: Vessel entity

Each vessel is generated with two basic attributes: 'Type' and 'Destination'. 'Type' contains seven values, while 'destination' contains 28 values, equals to the number of terminal nodes, which means all the terminals will be visited by those vessels. The value of 'type' and 'destination' parameter is assigned to each vessel randomly, so that we don't know what type the first vessel will be and which terminal it is going to visit. However, when a certain population of vessels have been generated, the number of vessels in each value of 'type' and each value of 'destination' should follow a certain frequency distribution, to make sure the simulation experiment to be in line with the real world condition.

There are three datasets collected from previous research related to vessel entities. The number of vessel arriving and departing voyages counts separately in the historical dataset, because vessel entering the port or leaving the port is always a dynamic process during any period of recording time, which makes it really hard to monitor a complete voyage for a single vessel. In the historical dataset, the number of vessel arriving voyages of each vessel class approximately equals to the number of departing voyages correspondingly. Therefore, it is valid to assume that vessels perform a complete voyage which consists of their arrival and departure voyage. The duration time of arriving voyage calculates time spent starting at port entry, and ends when the vessel is berthed, and similar calculation for departing voyage. While in the simulation model, ship sailing time will be determined by speed and length of the voyage. The voyage duration time dataset thus is going to be used to compare with the outcome of simulation experiment, and to test if the result is reliable.

4.5.2. TERMINALS

CLASS: TERMINAL

Attribute:

- `terminal_location`: geographic information
- `terminal_name`: name
- `terminal_capacity`: number of berths
- `service_time`: distribution of terminal service time per vessel class

Process:

- If vessel stays at terminal, change the vessel handling processes from arriving to departing;
- If no vessel in the terminal, do nothing.

Terminals are where port companies are located. We use a group number of berths to show the location of each terminal, as ship will eventually arrive at a berth.

For each terminal object, the information required includes the exact position on the map, the river section it connects and the number of berths available. First two characteristics are depicted in the animation map, while the number of berths can be specified based on the real world data which indicates the capacity of terminals. The loading and unloading processes when ship at berth is out of this research scope, so ship waiting time at berth is simply regarded following a certain distribution based on average terminal service times retrieved from port authority.

Figure 4.3 highlights the information required for structuring terminal entity in the model as well as the relevant dataset.

Terminal entities will be generated with three basic attributes, 'Name' used for tracking the specific entity, 'Location' marking the position of terminal on representation level, 'Number of berth' indicating the capacity of each terminal entity, in another word, the maximum number of vessels a terminal allows to berth at the same time.

The dataset of average terminal service times aims for determining the time ship waiting at berth for loading/unloading. As loading/unloading process will not be simulated in the model, the time vessel stay at berth will be considered following a time distribution retrieved from this dataset.

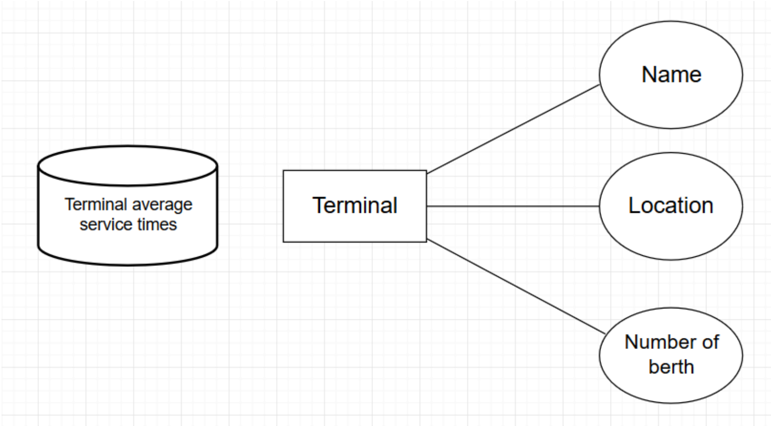

Figure 4.3: Terminal entity

4.5.3. RIVER SECTIONS

CLASS: RIVER SECTION

Attribute:

- `section_end_point`: geographic information
- `section_name`: name
- `section_length`: length
- `section_type`: type
- `target_vessel`: vessel that sails in the section
- `speed_limit`: maximum and minimum speed for vessels
- `safety_distance`: gap required for each pair of vessels

No Process

The waterway network in the PoR is complicated with many branches extending to different terminals. To simplified such complexity of the environment, the river corridor is split up some of the sections. There are in total 43 river sections discovered in this research, spreading over the port area.

River sections contains three parameters: 'name', 'type' and 'length'. The length of each river section should be in line with the length of path shown in the animation panel, which means the longer the path looks like, the longer the section truly is. 'Type' of section is classified into 'Sailing' or 'Maneuvering', which indicate two kinds of ship behavior during sailing. Compared with in 'Sailing' type section, ship sailing in 'Maneuvering' type section will take more time because ship has to swing around to have the bow facing the right way.

On the other hand, some regulations embedded in each river section restricts the ship sailing behavior in the port area. Vessel separation times is one of the regulation. For safety reason, each section has certain separation times for each vessel classes. Separation time is the amount of time that a vessel has to keep a distance with the vessels in front or behind it. The model will show this property with a length of gap between each pair of consecutive vessels. In the environment each vessel class has a certain speed threshold in each section. The speed limits will be set every time when ships enter a new river section.

Figure 4.4 specifies the basic attributes of river section entity, as well as some relevant datasets.

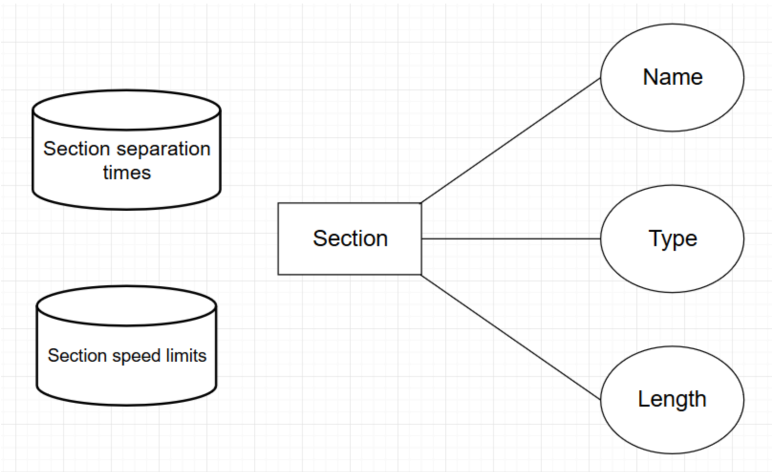

Figure 4.4: Section entity

These attributes are required when identifying the position of each vessel in the network, and applying appropriate traffic section rules for it. The length of each river section derives from the length of real river, calculating the ship sailing time during each section, with corresponding vessel speed.

The implementation of traffic rules will show the realistic vessel sailing behavior under the pilotage service. Section separation times and speed limits are the constraints between vessel and river section entity, with the same target that makes sure vessels sail safely in the port area.

4.5.4. PILOTS

CLASS: PILOT

Attribute:

- `pilot_location`: geographic location of pilot station
- `pilot_capacity`: the capacity of pilot station

Process:

- Wait at pilot station for vessel picking up;
- Sail in with vessel;
- Return to pilot station when vessel safely berthed;
- Go to vessel at terminal, serve for next voyage;
- Sail out on board of the vessel;
- Disembark the vessel.

Pilots and pilot organization play a critical role in nautical service processes for sea-going vessels. The task of pilots starts from vessels taking pilots on board in arriving voyage, to pilots disembarking in departing voyage.

To clarify the embarking/disembarking process, the positions of pilot boarding stations should be defined on the animation map. Different with passengers getting on bus, pilots embarking on vessels is a dynamic process, where ships and pilots move at the same time with the same speed. It seems more realistic to show the pilots embarking/disembarking in an area rather than at a node in the model, so that vessels coming from different directions could find their corresponding pilots in that defined rendezvous region before sailing into the port area.

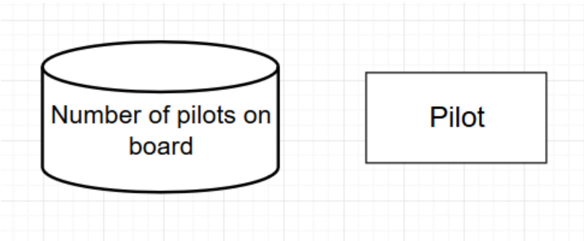

Figure 4.5: Pilot entity

Figure 4.5 shows the characteristics of pilot entity. Pilot entity in our case has no personal attribute. Dataset of this entity is the number of pilots required for each vessel class. It is a typical 'manufacturing' like process that one 'vessel' object will be assembled with a certain amount of 'pilot' objects to generate a new entity following a certain rate and time distribution. Normally, there is only one pilot was used for vessel class 1, 2, 3a, 3b, 4 and 5, and two pilots are used for vessel class 6. Pilots boarding stations are distributed at the entrance of the port in order to easily serve for vessels coming from different directions/countries, we will set a region instead of a node where the pilots taking on board process will be mimicked with more freedom.

4.5.5. TUGBOATS

CLASS: TUGBOAT

Attribute:

- `tugboat_location`: geographic location of tugboat station
- `tugboat_capacity`: the capacity of tugboat station

Process:

- Wait at tugboat station for vessel attaching;
- Sail in along the vessel;
- Return to tugboat station when vessel safely berthed;
- Go to vessel at terminal, serve for next voyage;
- Sail out along the vessel;
- Detached at tugboat station by leaving vessel.

Tugboats, as another nautical service provider, experience the similar process as pilots will do. Vessels will attach with a certain amount of tugboats in order to successfully reach the berth. The amount of tugs that were needed for each vessel class has been retrieved from the logged data.

Before conducting service for vessels, the tugboats will sail towards rendezvous location and connect with the vessel. Similarly, tug rendezvous location will be ranged in an area, since the connecting process is dynamic, where ships and tugs are in continuous movements.

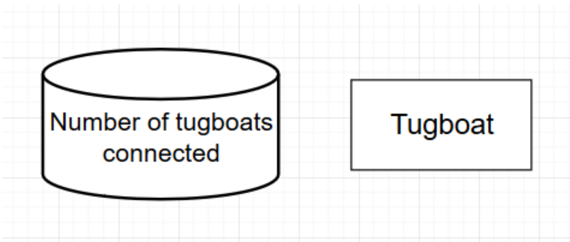

Figure 4.6: Tugboat entity

There are no attribute for tugboat entity need to be considered. The dataset we have for this entity is the number of tugs a vessel will connect. In reality, the number of tugboats required for one vessel is diverse, from one to four, while sometimes no tugs needed. Such diversity can be implemented in the model following the distribution analyzed from logged data.

4.5.6. VESSEL GENERATOR

CLASS: VESSEL GENERATOR

Attribute:

- `Arrival_rate`: how frequently vessels enter the system
- `Arrival_pattern`: the two dimensional distribution of vessel class and vessel destination

Process:

- Generate vessels and their relevant attributes.

As an attachment for vessel object, the aim of creating the vessel generator is obvious to generate vessels with their relevant attributes, as the vessel cannot be produced by itself. Two attributes are defined for vessel generator, which relate to vessel entity as well. This object can decide how many vessels will be produced per hour firstly. The more the vessels enter the port system, the more congestion or disturbance might occur. Moreover, some vessel classes have a lot more times of visiting to the PoR, at the same time, some terminals are more popular to be visited. These characteristics of arrival pattern will be produced by vessel generator as well.

4.6. MODEL IMPLEMENTATION IN ANYLOGIC

Having defined the components of the model, it is ready to implement the conceptual model in the simulation software, Anylogic. The characteristics of Anylogic is given in the first paragraph. The work of implementation follows three steps, indicating input stage, run stage and output stage, respectively.

4.6.1. INTRODUCTION TO ANYLOGIC

An advanced simulation software, Anylogic, are chosen to be used to create a simulation model translated from the conceptual model. Anylogic allows users to build simulation model in multimethod modeling environment. The combination of discrete-event, agent-based, system-dynamics helps to create a model with any complexity. Moreover, Anylogic provides a unique suite of industry-specific tools in one package, including process modeling library, material handling library, pedestrian library, and so on.

Specifically, process modeling library contains the functionality that models a detailed-level operation in wide range of processes and services of a dynamic nature. The library facilitates workflow simulation and allows users to understand process dynamics and inter-dependencies between process components. By using process modeling library, we can model the system composed of a set of processes, entities go through the process flow, and resources that entities use to perform an action and influence the process.

Process modeling library in Anylogic is a toolkit which contains many blocks with different functionality. It would be nice that some simple models could be created by simply dragging and dropping these blocks, however, if more sophisticated functionality required, users can also design the corresponding algorithms with an object-oriented language – Java, to make the model better reflect the real world.

Here some library blocks and model elements are introduced in the following list, to improve the understanding of the concepts and the package itself.

- **Agent** : Agent is main building block of Anylogic model. An agent can be designed with identifying its attributes, behavior, and interface with the external world. Vessel objects will be set as a population of agents in our study.

- **Resource pool** : This block defines a set of resource units that can be seized and released by agents. In this study, we will set two or three resource pools to group different service providers for vessels.

- **Source** : A source is used to generate agents of a specific type and arrival pattern, usually a starting point of a process model.

- **Sink** : A sink is used to dispose agents, which is usually an end point of a process model. Vessel entities will be removed from sink block once it has completed its tasks at the port, and finished the visiting voyage.

- **Seize** : In this block, vessels seize a given number of resource units from a given resource pool. With different 'Seize' blocks, the agent is able to seize any number of different resources, representing receiving different services.

- **Release** : This block is used together with 'Seize', has the functionality that releases a given number of resource units previously seized by 'Seize' block. Moving resources can return to home location, or stay where they are after being released.

- **MoveTo** : Vessels can move to a new location through 'MoveTo' block. If any resources are attached to the agent, they will move with it. By default, the time spent by the agent in this block equals the length of the shortest route from the current location to the destination divided by the agent speed. The speed can be modified with defining the value of parameter.

- **Delay** : Agents stay in this block for a given amount of time. Agents that either wait at anchorage area or wait at terminal can be put in 'Delay' block to calculate the waiting time for the next task.

- **Queue** : 'Queue' block is a buffer where agents are waiting to be accepted by the next object in the process flow. The queuing discipline will be FIFO as described in the assumption.
- **Node** : Node defines a place where agents can reside.
- **Path** : Path graphically defines a movement path for agents. Nodes can be connected with paths, to compose a network. When agent moves inside a network, it always takes a shortest route.

4

The chain of above blocks represents the process of nautical service in a generic manner. To specifically solve the problem in the case of Port of Rotterdam, a number of parameters will be created in each block and model object. More details about model formation are shown in the following sections.

4.6.2. INPUT STAGE

The first stage of model implementation is to set up required input parameters which are used to determine the behavior of the model throughout a simulation run and can be modified in different scenarios.

PORT LAYOUT

The model has been structured on the background picture of Port of Rotterdam with a revised scale in accordance with the actual distance from one point to another. Nodes spread out in the figure to pinpoint the position of each terminal and berth, as well as the position of pilot station and tugboat station. Port waterway network consists of a set of paths, while each path indicates a river section with its specific traffic rules.

Different space makeup elements can be dragged and dropped to the graphical editor in order to be assigned at the correct location. Moreover, process modeling library blocks enable users to easily simulate the desired behavior of those space makeup elements. Inside the building blocks, it is allowed to specify parameters which are able to determine the properties of agents and the time information of the certain process. Different block has its specialized functionality for a specific problem, thus choosing the most suitable block is critical to improve the model building efficiency.

Table 4.1 shows us the list of objects for constructing the port layout.

Table 4.1: Port layout

Physical object	Presentation	Library block	Parameter
Berth	Rectangular node	Delay	Capacity, Service time
Waterway	Path	MoveTo	Length, Speed limits
Pilot station	Node	Resource pool	Capacity
Tugboat station	Node	Resource pool	Capacity

VESSEL

The vessels pour into the system are all sea-going container vessels, which have been categorized into seven classes. Table 4.2 represents the input information that determines the details of vessel generation mode. Note that vessel arrival pattern is determined by class-destination frequency distribution, while the arrival rate is average 3 vessels per hour.

Table 4.2: Input of vessel entity

Vessel characteristics	**Description**
Class	Vessel class 1, 2, 3a, 3b, 4, 5, 6
Destination	The location of terminal they will arrive at
Arrival rate	Number of arrivals per hour
Arrival pattern	Vessel Class-Destination frequency distribution
Service requirements	Number of pilots, tugboats required to receive nautical service

RIVER SECTION

In reality, ship sailings are under control of traffic rules regulated by port authority for safety issues. Some parameters are set to build the linkage between vessel and section, in order to constrain free vessel flow, to make it more realistic. However, the model structure would not see a big change with the implementation of river section characteristics. The nautical process remains unchanged, only vessel sailing time in the river will be longer when taking traffic rules into account.

Table 4.3: Input of river section

Section characteristics	**Description**
Length	The physical length of each river section
Direction	Movement on path in both directions
Speed limits	Threshold vessel speed for sailing (m/s)
Safety distances	Minimum space between two ships

4.6.3. RUN STAGE

With the completion of input stage, the second stage will start with the initialization of the simulation model.

INITIALIZATION

At the stage of model initialization, the initial values of model parameters are established before simulation can begin. In our study, model time unit is set as hours, to maintain the effectiveness of model experiment and data collection.

Vessel agents are generated by a 'Source' block following the distribution of the amount and type of arrivals specified in the input stage. 'Source' block determines the arrival rate of vessel generation, which can be also translated into an exponentially distributed inter-arrival time. Resource agents, such as pilots and tugboats, are initialized from 'Resource pool' block. There is current no difference among all the pilots or tugboats, that means all the resource agents can serve for any type of vessels. Furthermore, 'Resource pool' defines the maximum number of resource units as capacity of this block, the number of busy resource agents and idle agents can always be monitored during model run.

Upon initialization, the model conducts some control algorithms to determine the process of checking the position of vessel sailing and assigns the corresponding value of sailing speed and safety distance to the vessel agent. The traffic rules information on river network are imported in the input stage.

VESSEL ARRIVAL

Once a vessel has been generated and ready to sail towards the port, it must firstly determine which terminal it will arrive at. This is done by checking if the terminal name equals to the string value of vessel's 'Destination' parameter. After that, according to the geographical position of target terminal, vessel will find the shortest route moving through one path to another to reach the destination. The shortest route selection is done by the embedded algorithm inside Anylogic. Vessel can dynamically choose the best route, as a result, even if any changes apply to the layout of the port, the routing logic would never change.

DELAY FROM RESOURCE UNAVAILABILITY

Before proceeding towards the port, a vessel has to check the availability of all the resource units it requires. Similarly, vessel needs adequate number of resource units to leave the port.

Figure 4.7 shows the decision making process if delay would emerge before vessel entering the port. Three condition must be satisfied simultaneously to permit a vessel to enter the port: idle berth at designated terminal; pilots available; tugboats available. The vessel can only be announced to sail into the port when there is at least one vacant berth at the destined terminal at that moment. After that, vessel has to check if the nautical service resources are ready. We have assumed that vessel would never stop during the way of sailing to the destination, in another word, only if the required number of resources become available, the vessel can be allowed to start port sailing. Vessel will sail into anchorage area when any of required resources are lacking, and stay inside until all the resources become available. The total time vessel waiting for the service will be collected, which is able to find out the source of delay in the further experimentation stage.

Figure 4.8 shows the decision making process if delay would emerge when vessel just finished the terminal service activities and is ready to leave the port. Likewise, vessel has to check if there are enough number of pilots and tugboats can come to serve for it. Vessel will continuously occupy the berth until it can be announced to leave the port (all the resources are ready). It seems that the delay of the first vessel will propagate to the next one, especially when berth are fully occupied, one stays longer at berth means longer delay time for the next ship wait outside the port. This phenomenon is in line

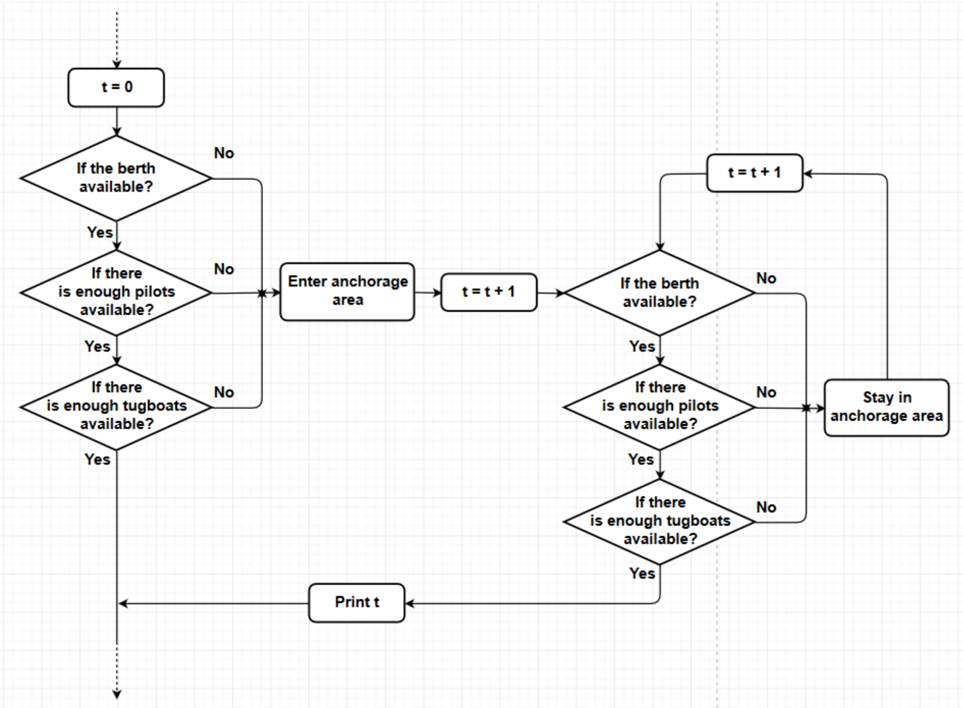

Figure 4.7: Delay before port entry

with what is experienced in reality, which has been explained in Chapter 1. The extra waiting time of vessel staying at berth will also be collected as the output of the model.

DELAY ON SAILING

'Delay on sailing' does not mean ship stops in half way alongside the port river corridor. It means the extra time vessel spent on sailing because of the regulation of traffic rules which force vessel sailing with a lower speed, compared with the free flow speed.

In our research, vessel speed is restricted by section speed limits, moreover, the safety distance between each pair of two consecutive vessels. Speed limits rules ask vessel to sail with a normal speed at trunk line, while slow down at branch river lines. In the model, vessel speed controlling is placed outside the vessel handling process, but with setting up a 'speed control center'. The algorithm of speed control is shown in the following Figure 4.9. For all the vessel agents in the system, the algorithm will run every 10 minutes to check their (x,y) coordinates, find out which river section they are currently situated, and then assign the appropriate speed for agents based on the vessel type. The algorithm can be set to run faster, if more accurate speed control requires.

Safety distance rules can be implemented directly on 'Vessel' agent. A distance block is set in the front of ship body, means that a 'prohibited' area where other vessels can-

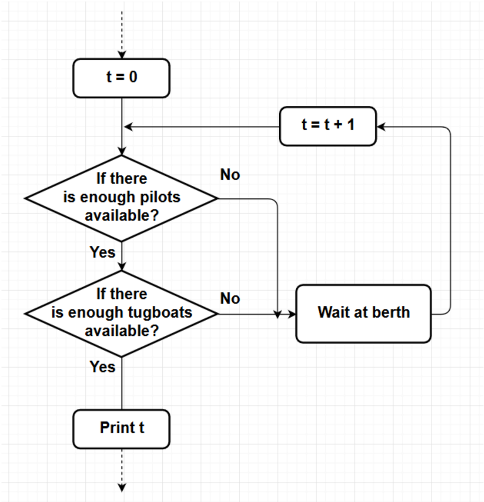

Figure 4.8: Delay before leaving the terminal

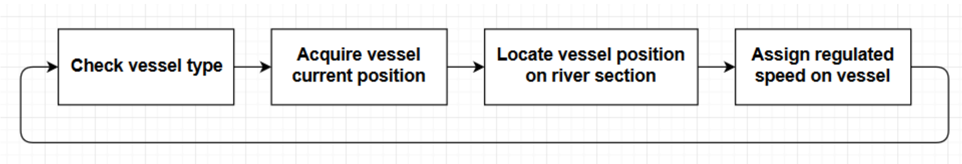

Figure 4.9: Speed control algorithm

not sail into. We use algorithm to trace the nearest vessel of ego vessel, to see if it is in the distance block. The idea is if the nearest vessel is not in that block, means it keeps enough gap with ego vessel, the speed of ego vessel remains; if not, the ego vessel has to slow down until maintain a certain value of distance with others. The control algorithm is displayed in Figure 4.10.

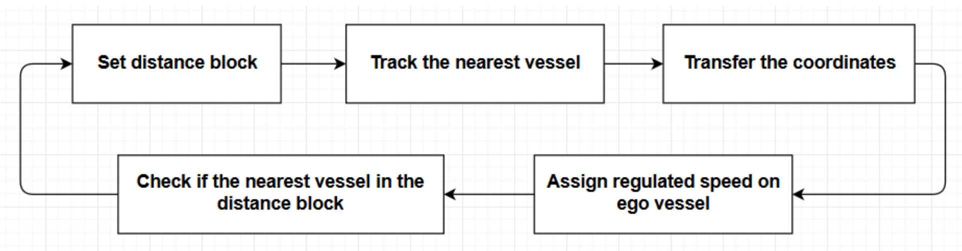

Figure 4.10: Safety gap control algorithm

4.6.4. Output stage

In this stage, the outcome of model runs will be exported into a file, and represented graphically in form of histograms and cumulative probability distribution functions. Anylogic provides a so-called 'Analysis' palette that supports a variety of methods to collect and analyze the model output.

With implementing statistical analysis blocks, we can gather the output data with more information attached, such as max/min value, mean, deviation, variance and confidence interval. In addition, it has figure blocks that transfer data items into histogram or any type of the chart. Specifically, probability distribution function or cumulative distribution function will be created to show the probability of occurrence of different possible outcomes in an experiment. The outputs are continuously logged with keeping track of the running time of the experiment.

According to the defined KPIs in Section 2.3, the following data are going to be collected:

- **Average turnaround time of a visit**
- **Average turnaround time of arriving voyage**
- **Average turnaround time of departing voyage**
- **Average waiting time due to berth unavailability**
- **Average waiting time due to pilots unavailability**
- **Average waiting time due to tugboats unavailability**
- **Average sailing time of arriving voyage**
- **Average sailing time of departing voyage**

Based on the definition of turnaround time in this study, turnaround time of a visit will equal to the sum of turnaround time of arriving voyage and turnaround time of departing voyage, thus terminal service time will be excluded. Considering the data collection on waiting time, several aspects may cause delay of a vessel voyage simultaneously. The model is able to collect the total waiting time due to the unavailability of berth, pilots or tugboats, however, it is hard to log the waiting time caused by different reasons separately. For example, if a vessel waits at anchorage area for 3 hours, maybe 2 hours for the berth and 1 hour for tugboats, however, there will be only 3 hours logged in the exported file. The exact reason of this delay may identify at the stage of experimentation, when modifying the total number of pilots and tugboats, to see how waiting time is going to change.

To have a good overview of the model outputs, the waiting time and turnaround time will be classified under two categories: vessel class and vessel destination. It help us to get to know what the differentiation of waiting time among different vessel types or different terminals as voyage destination will be.

4.7. VERIFICATION

Model verification is the process that confirming model has been correctly implemented with respect to the conceptual model. To verify the model, it takes several steps to trigger some specific behaviors of the model in order to check the correct implementation of the features.

First of all, the river network in port area is checked. It is important to make sure that all the sections are well-connected, otherwise the vessel will lose the track of route, and move freely on the map. Secondly, the sailing behavior of vessels is tested. Vessels can sail to their corresponding terminals through port layout with shortest route. Thirdly, the movement of pilots and tugboats follows the correct service process in reality. Last but not least, the traffic rules implemented on vessel sailing behavior are checked.

RIVER NETWORK

The completeness of port river network has been done at the initialization of the model. Each pair of consecutive section is connected with a node, in this way, the length of each river section is determined by the distance between two vertex. The vessel agents with path-guided type of navigation conduct their movement along paths and nodes connected to create a network. In order to simulate the smoothness movement of vessels entering into the berth, a so-called 'free space navigation' has been transferred. In free space mode, vessel agents detect their surroundings and avoid the obstacles using the most efficient route to reach the destination point.

The actual length of rivers and actual size of entities are adjusted with 'Scale' element. The scale in the model is set as a ratio of pixels of the animation to the physical units of length. Apart from defining animation scale for the length of river, different agents have different scales according to their real size.

Figure 4.11 shows the part of network configuration in Anylogic.

VESSEL BEHAVIOR

As the only customer in such service system, vessel agents go through a chain of complicated decision making processes to sail to the assigned destination. It will check if the routing of vessels is correct as well as the order of nautical service processes is appropriate during model verification stage.

The model has been designed that vessels can find their routes through a port based on an origin and destination pair. The routing of vessels works well thanks to a good implementation of river network. For example, when vessel sails to the end of section 4, it will select the right path to go to the region where its berth locates at. A conditional algorithm is structured to make sure vessel always chooses correct path to sail to the terminal that corresponds to the value of 'Destination' parameter a vessel embedded.

When routing of vessel has been fixed, it is the time to handle the details of vessel taking nautical service processes. In order to reveal a good animation of the nautical

Figure 4.11: River network in Anylogic

service process, several aspects have to be highlighted. Vessel who is authorized to enter the port will sail to meet with pilots/tugboats somewhere nearby pilot/tugboat station. It has proved that during the sailing of vessel-pilot and vessel-tugboat connection, vessel and pilots/tugboats will move simultaneously with the same speed. Here we replace the point of meeting with an area, in order that vessel moves freely in the area with picking up pilots/tugboats before leaving that area. There are a certain number of berths has been set for each terminal. These values are open to any change for model users.

RESOURCE BEHAVIOR

Two groups of resource entities: pilots and tugboats, are generated from areas named 'Pilot station' and 'Tugboat station', respectively. These are where resource pools are situated.

In the real case of nautical operation in the PoR, resource behaves differently between vessel arriving voyage and departing voyage. When ship is entering the port, it will sail to pick up pilots and seize tugboats actively, while release resource units when it has been berthed. On the contrary, during departing voyage, vessel will wait for service providers passively, while release them when it arrives at tugboat station and pilot station subsequently. Such difference depicts the service behavior of resource. In order to reflect this trait of resource behavior in the animation, the parameter of 'Seize' block has been configured properly with either sending the resource units to a specific location, or attaching to the resource units when ship moves to the right place.

In addition, all the resource units are set as moving entities, therefore, it has its own speed to move around in the port river corridor. It has considered the waiting time of vessels contains the time that resource entity moving from their station to the spot of served vessels. The number of attached pilots or tugboats for each vessel is determined by historical data, such pattern can be checked in model animation as well.

Figure 4.12 is a thumbnail that when model animation runs. Note that black particles are pilots and yellow particles are tugs, who are waiting at separate locations, for taking by vessels. Vessel sails alongside the route we have structured by paths and nodes.

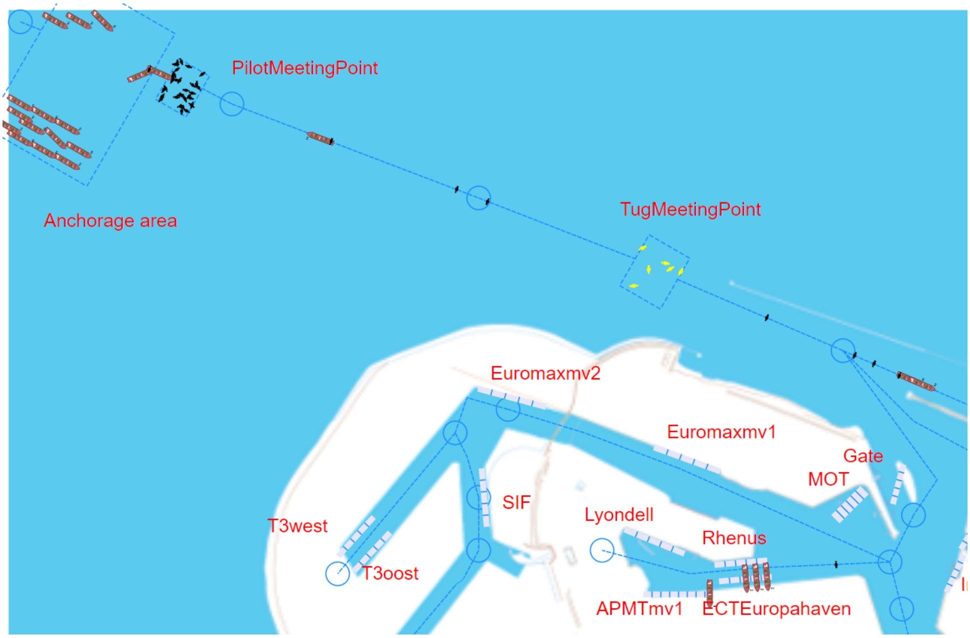

Figure 4.12: Model animation

TRAFFIC RULES

Traffic rules are implemented in the model by means of setting up two control units. Each of these control units will run in a closed-loop, to monitor and modify the speed and gap of vessels every short period of time. Figure 4.13 shows how speed control works in the simulation. Here a state chart is created in order to execute control algorithm with a specified time interval.

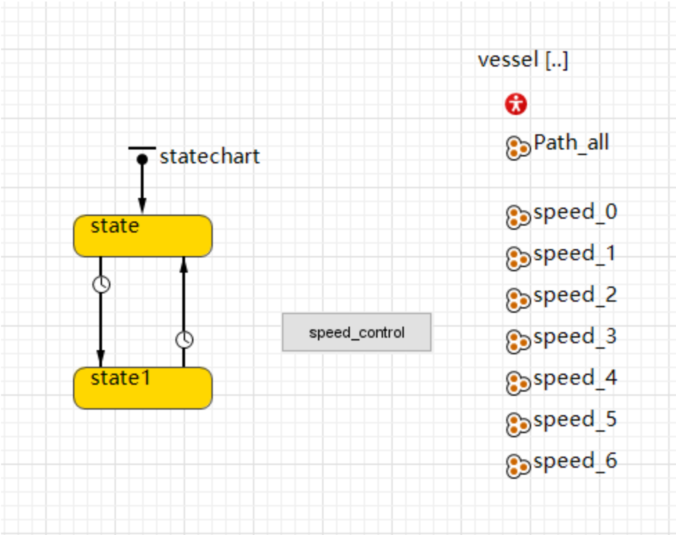

Figure 4.13: Speed control units

4.8. CONNECTION WITH PREVIOUS WORK

A research on identifying the relationships of nautical chain actors for PoR case have been done by Alexander (2017) [1]. In order to make sure that this simulation is in line with the information collected from previous research, and provides a good start at model formation stage, the details of this simulation model will be checked referring to the points mentioned from Alexander's report [1].

4.8.1. ENVIRONMENT

The environment is where the nautical service operation takes place. The configuration of actors and processes in the simulation is structured under the map of the Port of Rotterdam. First of all, Alexander [1] made a figure of showing the overview of port network in Chapter 11.1, all the network elements in the simulation are dragged and dropped in accordance with this figure, for example, the way of connecting river sections. Nautical service infrastructures, for example, pilot station and tugboat station are set based on the configuration map shown in the appendix C.1 and D.1 of his report. The location of anchorage area is set roughly near the entrance of the port. Due to some missing data for terminals and river sections, there are in total 28 terminals and 43 river sections are taken into account in the simulation.

In terms of the characteristics of river sections, the length of each river section are determined by the length of each path with implementing an appropriate scale, while sections for either sailing or maneuvering are not distinguished in the model, even if it will produce some impacts on the sailing time of vessels. Based on our assumption, vessel overtaking and encountering maneuver will not be considered in this study, while other traffic rules such as speed limits and safety distances have been implemented in the simulation according to the datasets from the appendix A.4 and A.5 of Alexander's report.

4.8.2. ACTORS

Vessel entities in the model are defined basically with the parameter of class and destination. As mentioned in Chapter 11.1 of Alexander's report [1], vessel classes are grouped based on their different lengths and draughts. We classified the vessels into seven classes in simplified manner, without defining ship length and draught characteristics. The vessel voyage distribution is imported, consisting of class distribution and destination distribution in the model. The original datasets are shown in the appendix A.7.

Pilots and tugs comply with the defined assignment distributions for serving for different type of vessels. The assignment distributions are concluded from Table 12.1 in Chapter 12, and Appendix D of his report, respectively. Similarly, terminals provide quayside service in a certain period of time for different vessel classes complying with terminal service time distribution shown in Appendix F.1.

4.8.3. PROCESSES

The processes of the nautical chain as well as the sub-processes of each actor are all structured according to the description in Chapter 12 in Alexander's thesis. However, the functionalities of information transformation during the processes are not modelled due to the limitation of discrete-event simulation paradigm.

4.8.4. CONCLUSION

Table 4.4 concludes the model details described from environment, actors and processes three aspects, with some brief remarks. The aim is to provide a good overview of the research content attached with previous work for Swarmport project.

Table 4.4: Conclusion of model details

Network	
Source/Sink	Done, the same node
Location of terminals	Done
Connection of river sections	Done
Location of pilot/tugboat station	Done, but only consider one place
Location of anchorage area	Done, but assumed to be on sailing channel
River section	
Length	Done
Type	Not done, should implement swing-table
Separation time rules	Done, use distance gap
Speed limit rules	Done, use average speed
Overtaking/Encountering rules	Not done
Vessel	
Class	Done, but not define length and draught
Vessel arriving/departing voyage distribution	Done
Vessel shifting voyage distribution	Not done
Pilot	
Pilot assignment distribution	Done, only for arriving/departing voyage
Tugboat	
Tugboat assignment distribution	Done, only for arriving/departing voyage
Terminal	
Terminal service time distribution	Done

5

EXPERIMENTAL DESIGN

This chapter starts with setting up the simulation model experiment, determining the details and procedure of the subsequent experimentation. The calibration on configuration of pilots and tugboats are conducted before validating the model. The simulation are going to be validated with three steps: data validation, to collect the model output in comparison with empirical data; structure validation, to make sure the port nautical network is structured referring to the reality; performance validation, to verify the value of KPIs from model outputs is in accordance with the value of indicators collected from real case in the PoR. The final part of this chapter is experimenting the model under different circumstances by designing different scenarios.

5.1. SIMULATION MODEL EXPERIMENT SET-UP

The simulation model was implemented in Anylogic 8.4.0 Personal Learning Edition in order to assess the performance of the nautical operations of the Port of Rotterdam in the current situation. The model can be experimented in virtual time mode, which means run the animation as fast as possible. It takes around 3 to 5 minutes to run an experiment in Anylogic with normal computer.

Every scenario will run for one month (720 hours) for obtaining monthly based statistics. However, at the start of the simulation, port is empty, therefore fails to represent the reality in the certain period of time. A warm-up period is required to get into conditions that are typical of normal running conditions in the system. The warm-up period is set until the system reaches statistical stability. By running the model and observing the time, it approximately takes 100 hours that the probability distribution of turnaround time and waiting time becomes stable, therefore the warm-up period should be at least 100 hours. In this research, we choose 120 hours as the warm-up time for the model experimentation. All the statistics are derived from vessels that enter the port after 120 hours.

To maintain the randomness of the experiments, we set up random number generator as 'generating random seed', which means each model run is unique and irreproducible. Therefore, the final results have to be based on the output of multiple runs, to calculate the average value. For example, in our case, vessel turnaround time indicates the performance of port nautical operation. The following function [20] can be used to determine the number of simulation runs that should be carried out to ensure that the average value of vessel turnaround time within the desired confidence interval.

$$n = (\sigma * Z_{\alpha/2})^2 / d^2 \tag{5.1}$$

Where:

- n is the number of runs
- $Z_{\alpha/2}$ is the two-tailed normal statistic for a level of confidence $1 - \alpha$
- σ is the standard deviation
- d is the accuracy we defined

For the average value of ship turnaround time, we can get that 6 runs required to be carried out for a 95% confidence level and accuracy equals to 5 hours. The simulation outcome will be validated based on the output of these 6 runs.

5.2. CALIBRATION

This section calibrates the model with data from harbour master of PoR, towards scenarios of different configuration of pilots and tugboats, to analyze how well the model could reproduce the reality.

The duration of vessel waiting time is under the integrated effect of the availability of berths, pilots and tugboats. The number of berths in each terminal is set based on the observation on digital map of PoR [21]. Therefore, the capacity of pilots and tugboats should be tested to determine the best group for validating the historical data of vessel waiting time. Many manual experiment runs has been conducted before listing a group of scenarios with different maximum number of pilots and maximum number of tugboats. Since any delay emerged due to lack of pilots or tugboats will propagate to the following waiting vessels, which would probably lead to a huge amount of delay time in total, we set scenarios with tiny changes on the value of resource capacity.

Scenarios	**1**	**2**	**3**	**4**	**5**	**6**
Pilot capacity	14	14	15	15	16	16
Tugboat capacity	4	6	4	6	4	6

Table 5.1: Scenarios for validating waiting time

Table 5.2 concludes the waiting time at anchorage and at terminal per vessel visit from historical datasets. Above six scenarios will run and collect waiting time statistics to see which combination of pilot capacity and tugboat capacity will be the best to meet the real situation.

Table 5.2: Waiting time from historical data

	Anchorage		Terminal	
Vessel class	Average duration (hrs)	Sigma	Average duration (hrs)	Sigma
1	6:54	7:50	3:32	2:30
2	6:24	7:52	2:37	1:22
3a	6:38	8:27	2:14	0:53
3b	9:53	7:59	2:55	2:11
4	8:26	8:19	2:45	1:45
5	6:58	6:24	2:40	0:28
6	14:40	6:45	3:01	0:29

WAITING TIME AT ANCHORAGE

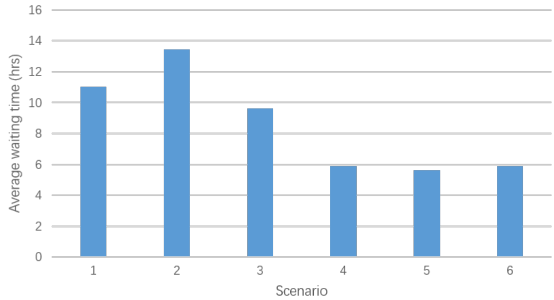

Figure 5.1: The comparison of average waiting time at anchorage among scenario1 to 6

The results are presented in Figure C.1, C.2 and C.3, showing average waiting time at anchorage area from the pair of scenarios with same pilot capacity. Figure 5.1 concludes the results into one histogram, presenting the average waiting duration at anchorage for all the vessel classes. It is obviously that more pilots are assigned in the system, less vessel waiting time will emerge before port entry. However, it seems the number of tugboats serving in the system doesn't influence the average waiting time significantly. The explanation based on empirical data is that tugboats are seldom used by smaller vessels, while larger vessels which always require tugs have far more less frequency in the model. Therefore, while above certain limit, investing on many numbers of tugboats do not have substantial impact on turnaround time and waiting time of vessels. Unfortunately, it has been proved that contradicts what happened in reality as the shortage of tugboats is still one of the main causes of delay. It could consider due to the inaccuracy of historical data of tugboats assignment distribution.

WAITING TIME AT TERMINAL

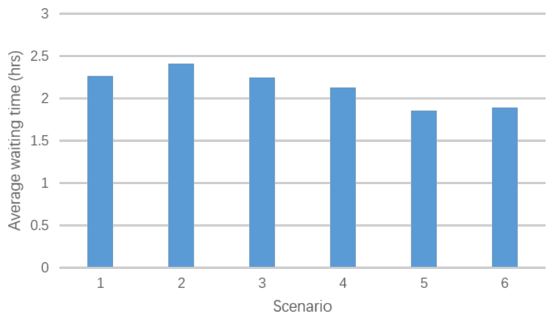

Figure 5.2: The comparison of average waiting time at terminal among scenario1 to 6

Similarly, the statistics of average vessel waiting time at terminal in different scenarios are compared in Figure 5.2. As concluded in the last section, less waiting times are monitored when more pilots are assigned to provide nautical service, which can be clearly seen from Figure C.5 to Figure C.6. However, there are no significant changes on average waiting time when more or less tugboats are assigned in the system.

It is important to notice that model outputs of vessel class 3b, 4, 5 and 6 are not accurate. According to the vessel class distribution dataset B.1, vessel type 3b, 4, 5 and 6 account for less percentage than the rest of vessel types, thus a limited number of samples can be collected to obtain the significant results.

5.2.1. CHOOSE BASE SCENARIO

Base scenario will be selected from above six tested scenarios according to their model outputs. As tugboat capacity doesn't produce huge impact on vessel average waiting time, here the outputs of scenarios 2, 4 and 6 are chosen to compare with observed waiting time abstracted from historical datasets.

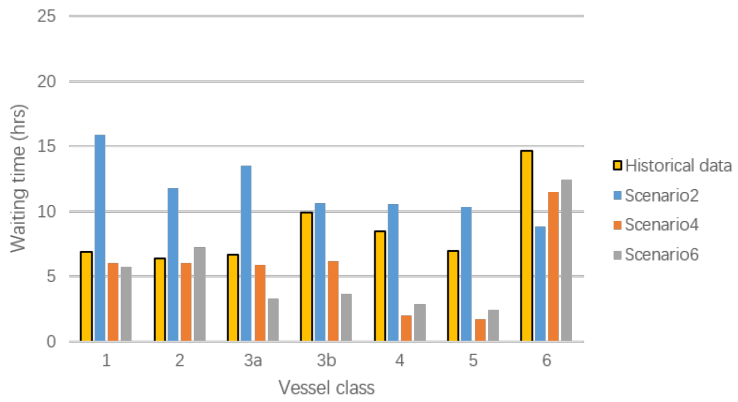

Figure 5.3: The comparison of waiting time at anchorage among historical data and scenarios

Figure 5.3 and Figure 5.4 represent the comparison of waiting time before port entry and waiting time before leaving the port, respectively. Considering the statistics of anchorage waiting time, each scenario perform in a different level. Scenario 4 generates the best waiting time output to match the time distribution from historical data. On the other hand, terminal waiting time distribute slightly different in different scenarios. It is hard to decide which scenario is the best to meet the real situation from Figure 5.4. In general, we choose scenario 4 as base scenario, so that the pilot station capacity is set as 15, while the tugboat station capacity is set as 6.

A set of parameters of base scenario is shown in Table 5.3. These parameters are going to be experimented in order to carry out performance validation in Section 5.5.

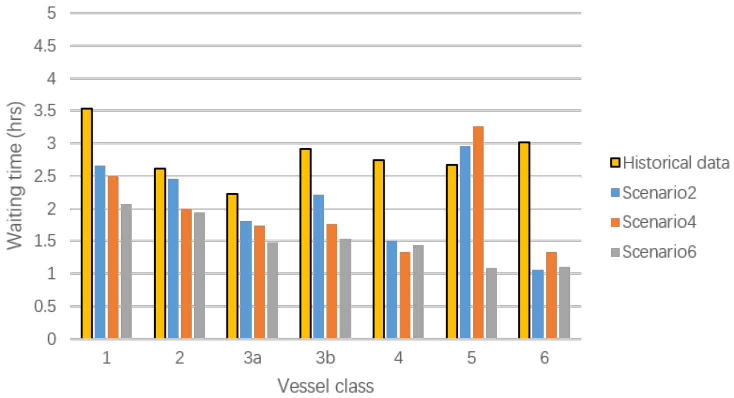

Figure 5.4: The comparison of waiting time at terminal among historical data and scenarios

Parameter	Value
Arrival rate	3 vessels/hour
Pilot capacity	15
Tugboat capacity	6
Vessel class	(see vessel class distribution)
Vessel destination	(see vessel destination distribution)
Number of pilots attached	(see pilot assignment distribution)
Number of tugboats attached	(see tugboat assignment distribution)
Stay time for terminal service	(see terminal service time distribution)
Speed limits	(see speed limits distribution)
Safety distance	(see safety distance distribution)

Table 5.3: Experimental Parameters of base scenario

5.3. DATA VALIDATION

From paragraph 3.2, we have obtained the historical data of vessel sailing time from PoR. The model of base senario will be tested to show the model outcome is in accordance with reality.

Sailing time is basically determined by the length of river section and vessel speed in corresponding section. In our model, sailing time will be influenced by speed control and safety distance control simultaneously, whereas the availability of nautical service providers will not intervene the time spent on sailing. Here the ship sailing time statistics is collected based on the output of multiple simulation runs in accordance with the theory explained in Section 5.1. Table 5.4 and Table 5.5 are sailing time data from reality and simulation, respectively.

Table 5.4: Sailing time from historical data

Vessel class	Average duration (hrs)	Threshold [Min,Max]	Sigma
1	5:21	[1:35 , 9:07]	3:46
2	4:01	[2:02 , 6:00]	1:59
3a	3:08	[1:30 , 4:46]	1:38
3b	4:08	[1:30 , 6:46]	2:38
4	3:59	[1:37 , 6:21]	2:22
5	4:14	[3:11 , 5:17]	1:03
6	4:40	[3:37 , 5:43]	1:03

Table 5.5: Sailing time from experiment

Vessel class	Average duration (hrs)	Threshold [Min,Max]	Sigma
1	3:12	[0:46 , 5:26]	1:21
2	3:04	[0:48 , 6:25]	1:42
3a	2:05	[0:45 , 6:25]	1:21
3b	2:17	[0:54 , 5:33]	1:15
4	2:36	[0:48 , 4:48]	1:24
5	3:07	[3:13 , 3:29]	0:12
6	3:10	[1:04 , 1:22]	0:14

It gives more intuitive comparison on vessel average sailing time between historical data and model output from Figure 5.5. The results show that vessels experience shorter sailing in the simulation for all the vessel classes. There are two reasons possibly to explain this finding. First, as we have assumed overtaking and encountering traffic rules are excluded in this research, the interaction among vessels are partially modelled. However, in reality, complicated vessel traffic situations may ask vessel slow down or stop on the half way in case of collision, especially going through narrow river corridors. Moreover, vessel sails in the real port environment with huge level of complexity, many factors will result in a longer sailing time, such as weather, tide, wind, and countless unexpected events. Since these unknown factors have not been modelled yet, it is accepted that ship sails faster in the simulation than in reality.

'Sigma' indicates standard deviation of collected data, that is used to quantify the amount of variation or dispersion of a set of data values. Lower sigma from simulation experiment means less variation in the model compared to the real situation due to the less complexity of the model itself.

In order to better compare the sailing time between model and reality, we set a factor to revise the model outputs of vessel sailing time. This factor is used to exaggerate the average sailing time of simulation model to supplement the missing modelling of complicated traffic constraints on ship sailing. A sensitivity analysis has been carried out in

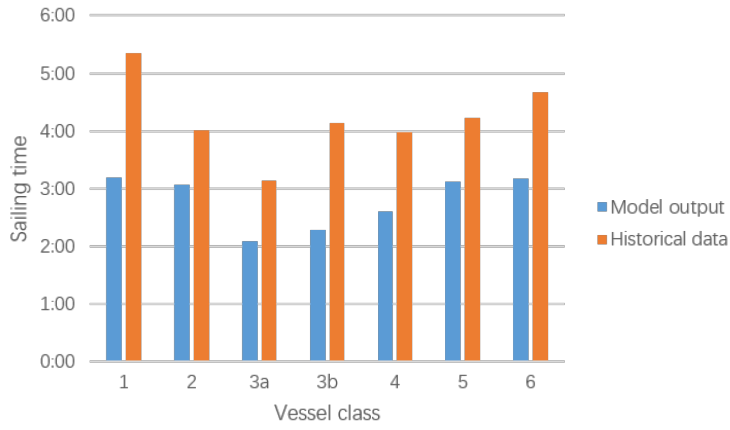

Figure 5.5: Comparison of vessel sailing time between historical data and model output

Table 5.6 to determine the value of this factor when the differences between model and real case as less as possible. The best option is when the factor equals to 1.6, the statistics differences of sailing time will be around 27%. Figure 5.6 compares the sailing time statistics one more time after the model outputs are calibrated by this factor. It can be monitored that the model outputs of sailing time highly match the data in the real case, thus we trust sailing time can validate the usefulness of the model.

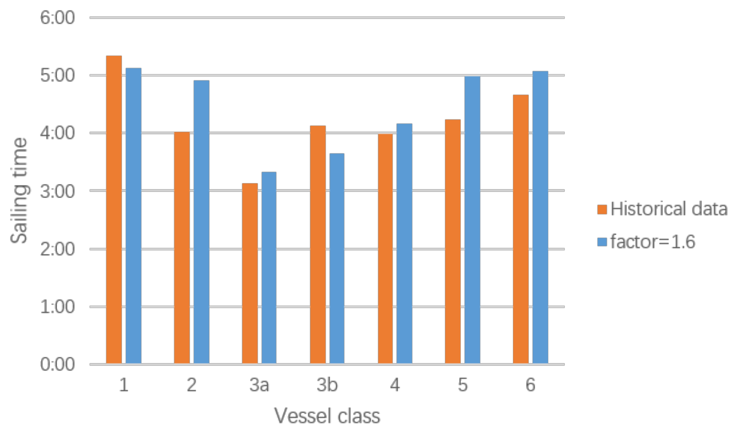

Figure 5.6: Comparison of vessel sailing time between historical data and model output after adding a factor

Table 5.6: Sensitivity analysis on factor

Value of factor	Statistics differences on sailing time between model and reality
1.4	77.7%
1.5	28.5%
1.6	27%
1.7	65.3%

5.4. STRUCTURE VALIDATION

The validation on model structure is targeted at port nautical network. The configuration of nautical infrastructure, such as geographical position of berths, is determined based on map 2.2. Moreover, how river network connects should comply with the map as well. More information which are not shown in the map, are collected from internal or external sources, for example, PoR website, report from consultancy company.

An interview has been conducted with port professionals from the PoR. The model behavior, animation was checked, and the value of this simulation study was confirmed. Even if the model may not be fully instrumented, there are still various performance measures are extracted from the model for validation purposes. The model outputs were checked as well, it allows to use factor to revise the model outputs only if giving an appropriate explanation on it.

5.5. PERFORMANCE VALIDATION

Performance validation can be used to verify that the system runs correctly and consistently throughout the range of parameters from model operation perspective. The parameters of base scenario will be designed and tested in this section. If the model outputs coincide with the operational analysis based on the operational laws, it may be taken as evidence that the model behaves correctly. Here we conduct an experiment on base scenarios, following the procedure of Section 5.2.

Two KPIs are selected, as mentioned in Chapter 2, turnaround time and waiting time. The model outputs statistics of two KPIs will be collected and compared with empirical data, then check their differences, as shown in Table 5.7.

Table 5.7: Performance validation

KPIs	Model outputs (hrs)	Historical data (hrs)	Differences
Total turnaround time	12.06	13.21	-9.5%
Waiting time at anchorage	5.89	6.53	-10.8%
Waiting time at terminal	2.12	2.69	-26.9%

It represents shorter turnaround time and waiting time vessels are experiencing in the model than in reality. The 'Differences' column is calculated by '(the value of model outputs - the value of historical data) / the value of model outputs', to display the degree of decreasing value of KPIs. It can be seen that the values of differences are around 20%, while the larger value of differences for waiting time at terminal is because the movement pilots and tugs are not explicitly modelled. Therefore, the KPIs of simulation model prove to closely reflect the reality.

5.6. SENSITIVITY ANALYSIS

Sensitivity analysis involves a series of methods to quantify how the uncertainty in the output of the model is related to the uncertainty in its inputs [22]. In our study, three experiments are designed and conducted to test the model functionalities with setting up multiple scenarios. The base scenario will be served as a reference to compare the results of different scenarios. The outcome of each experiment will be checked by operational analysis and expert intuition, so as to enhance the fidelity of the simulation model.

5.6.1. DIFFERENT CONFIGURATIONS OF PILOTS AND TUGBOATS

As a queuing system, it is valuable to figure out the minimum number of resources to serve for the entire system without causing extra delay on customer. Therefore, the first experiment is set to test different configurations of pilots and tugs to decide what the optimized capacity of pilots and tugboats is without compromising vessel waiting time. The idea is the system could use pilots and tugs as much as possible to make sure vessels no longer wait at anywhere. Several scenarios are designed to see how vessel average waiting time changes with assigning different number of pilots and tugs in the nautical system.

Having found in Section 5.3, the total number of tugboats in the system poses tiny influence on the turnaround time and waiting time of sea-going vessels in the port nautical system. To simplified the research, we set tugboat capacity in all the test scenarios are the same, equals to the value in base scenario.

As shown in Table 5.8, the maximum number of served pilots is increasing from base scenario to scenario 7, 8, 9 and 10. The model outputs generated by these scenarios will be compared in form of histogram.

Scenarios	**Base**	**7**	**8**	**9**	**10**
Pilot capacity	15	17	18	19	20
Tugboat capacity	6	6	6	6	6

Table 5.8: Scenarios for testing configurations of resource

Based on model outcome shown in Figure 5.7, the average waiting time of vessels at anchorage area is decreasing drastically for all the vessel types with more pilots arranged in the nautical chain, in particular from scenario 7 to 8 and 9. Specifically, the output statistics from scenario 9 and 10 indicate vessels will only wait for around one

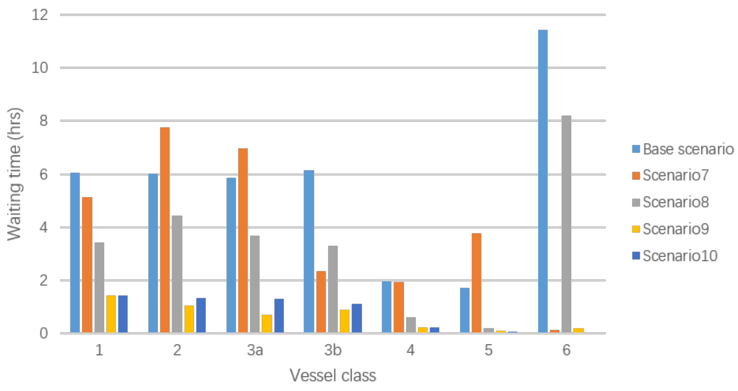

Figure 5.7: The change of waiting time at anchorage when pilot capacity increasing

hour before entering the port, which is a huge improvement compared with average 6 hours waiting time in base scenario and scenario 7.

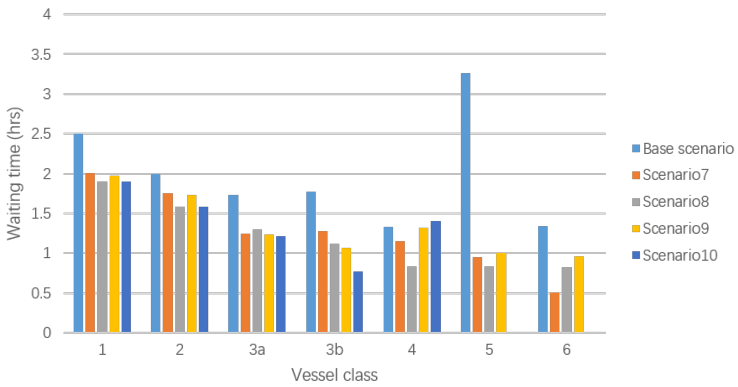

Figure 5.8: The change of waiting time at terminal when pilot capacity increasing

Figure 5.8 depicts the result of experiments from another way around. There are no significant differences on model outputs from five scenarios. Whereas it is still clear to see a decline on waiting time at terminal for all types of vessels from assigning less pilots to more pilots.

To sum up, the main finding from this experiment is vessel will wait for a shorter period of time when more and more pilots are assigned to serve for vessels. When deeply taking a look at the trend how waiting time goes by, scenario 9 and 10 provide roughly the same results, with much lower level of waiting time than scenario 7 and 8. Therefore, it can be generated that when 19 pilots are arranged in the model, it will reach the critical situation that all the vessels will be served with a dedicated manner. More pilots in the system will result in redundancy of service resource. The results will support the sensitivity analysis of the model.

5.6.2. FLUCTUATION OF TERMINAL SERVICE TIME

The second experiment is designed to see how terminal service time influences the nautical service processes. It is assumed that the efficiency of harbour quay-side activities such as cargo loading/unloading is improved with 10% or deteriorated with 10%, leading to scenario 12 and 11, respectively. The outputs of two scenarios will be generated and compared with statistics of base scenario.

Scenarios	Base	11	12
Stay time for terminal service	normal	10% more	10% less

Table 5.9: Scenarios for testing terminal service time

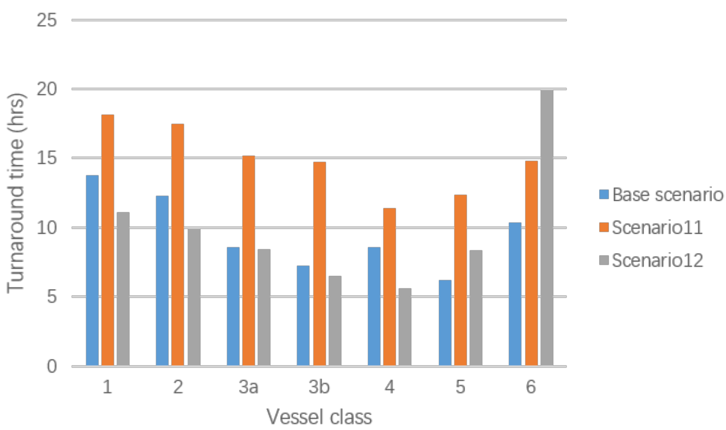

Figure 5.9: The comparison of turnaround time among base scenario, scenario 11 and 12

In general, turnaround time and anchorage waiting time experience the similar changes within three scenarios. It can be noticed that turnaround time and anchorage waiting time saw a significant increase with 10% more terminal service time implemented. When vessels stay at berth longer, the occupancy rate of berths will increase, thus more and more vessels have to wait outside the port entrance to wait for the vacancy of berths. Results show that vessel class 1, 2, 3a and 3b wait shorter in scenario 12, however, it doesn't show a big decrease with 10% less terminal service time. This phenomenon indicates the port has good management on the configuration of berths, thus the waiting time of vessels saw a sight drop even if berths are less occupied.

Results show that average waiting time of vessels at terminal is less dependent to terminal service time from Figure 5.11. Usually, when vessels are ready with loading/unloading,

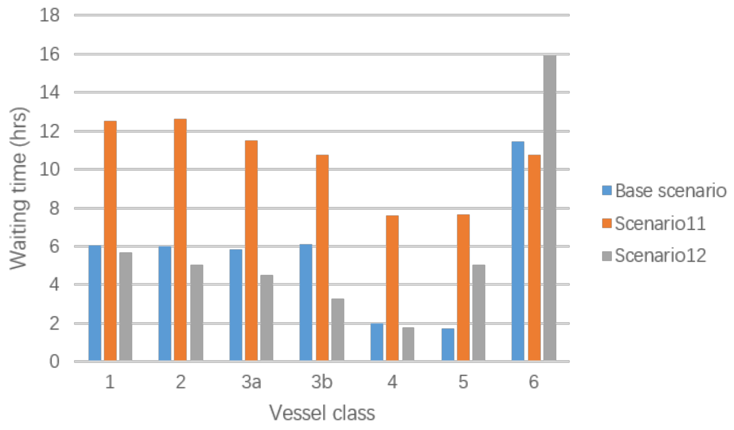

Figure 5.10: The comparison of anchorage waiting time among base scenario, scenario 11 and 12

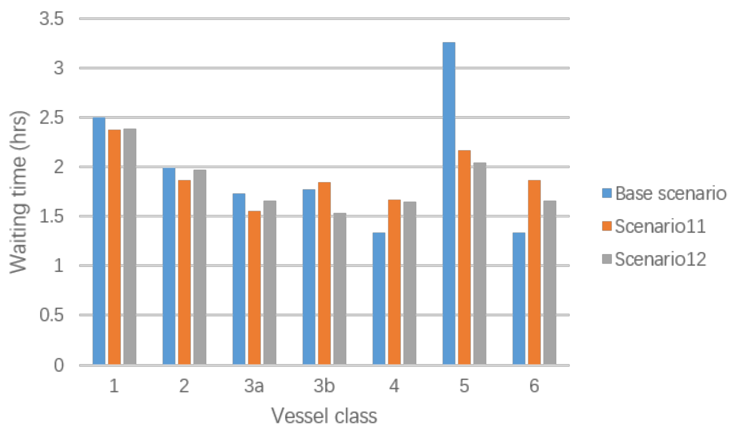

Figure 5.11: The comparison of terminal waiting time among base scenario, scenario 11 and 12

the terminal operator prefer the vessel to leave the berth and make space for another vessel. If delay occurs, it is usually due to waiting for cargo or a malfunction of the vessel himself.

The experiment on fluctuation of terminal service time brings us a better insight into how terminal activities affect the operation of nautical service system. The duration of vessels served by terminal firstly changes the occupancy rate of berths/terminals, resulting in the fluctuation on the number of berths available for vessels. Subsequently, less available berths will lead to more waiting vessels and longer waiting time, as well as longer turnaround time in total.

5.6.3. INCREASING DEMAND

Based on data analysis on collected datasets, we set 3 vessels per hour as normal vessel arrival rate in base scenario. The third experiment is structured to see how system performs when more nautical service demand emerged, in other words, more vessels are going to enter the PoR. Table 5.10 lists three tested scenarios 13, 14 and 15, with the increasing values of vessel arrival rate.

Scenarios	Base	13	14	15
Arrival rate	3	3.2	3.4	3.6

Table 5.10: Scenarios for testing demand

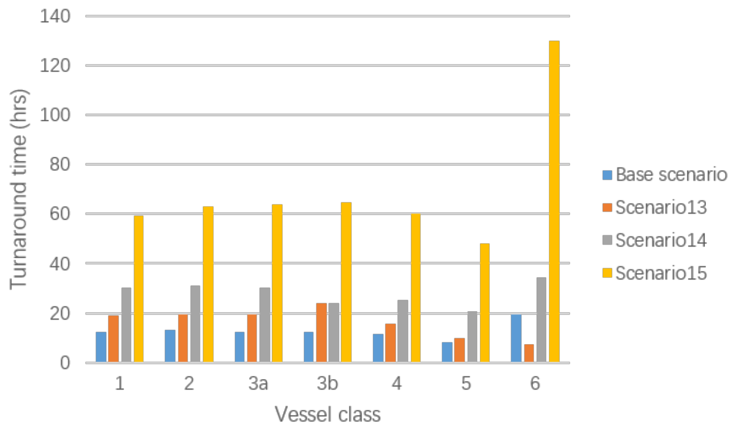

Figure 5.12: The comparison of turnaround time when demand increases

The same as the finding in the second experiment, vessel turnaround time and waiting time at anchorage go through similar changes from base scenario to scenario 13, 14 and 15. Anchorage waiting time increases moderately at the beginning, while with the growing of nautical service demand, both turnaround time and anchorage waiting time see an exponential growth. Due to the characteristics of queuing system itself, any delay on the first vessel will propagate to the following vessels in the queue. The pilots and tugboats are scarce service resources for the increasing amount of vessels. At the same time, berths as static service resources cannot satisfy the demand as well. Therefore, vessels are forced to wait longer than usual.

In Figure 5.14, a slight rise on ship waiting time at terminal are monitored with the growing of demand. More waiting time at terminal indicates all the pilots and tugs are not able to serve for the increasing number of vessels simultaneously. There are no clear trend of changes on vessel sailing time from Figure 5.15. It is because ship sailing be-

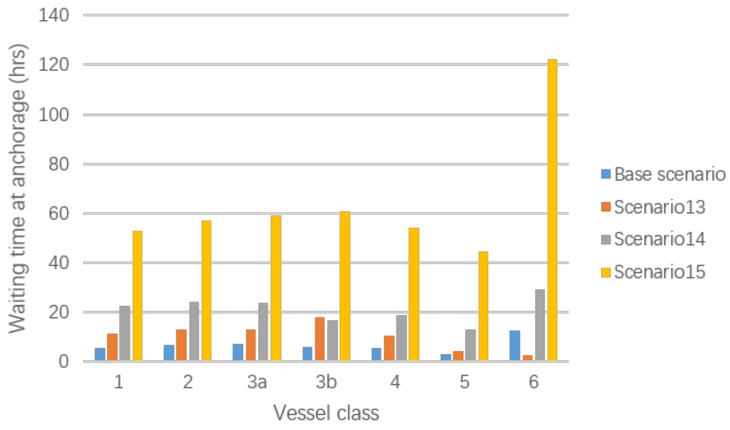

Figure 5.13: The comparison of waiting time at anchorage when demand increases

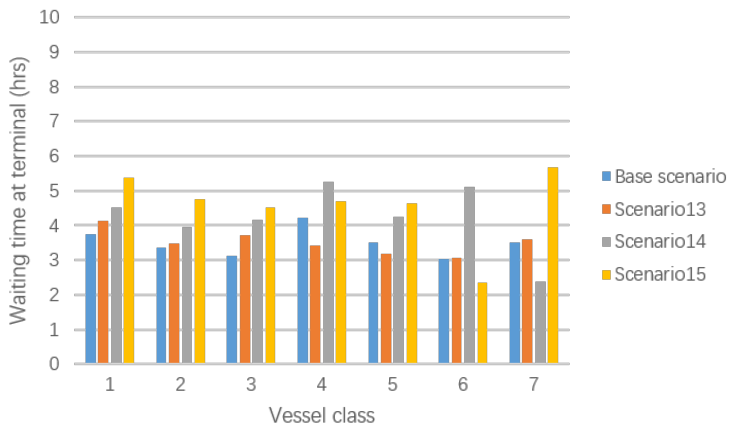

Figure 5.14: The comparison of waiting time at terminal when demand increases

havior is less modelled in the current simulation, still a lot of control rules required to be implemented in the model in the future research.

In our research, turnaround time is calculated by the sum of waiting time and sailing time. Comparing Figure 5.12 and Figure 5.13, it can be concluded that the significant increase on ship turnaround time mainly comes from the growth of waiting time at anchorage area. Therefore, if port authority wants to improve the performance of nautical chain in the port, it is recommended to better manage the orchestration of vessels waiting at the entrance of the port.

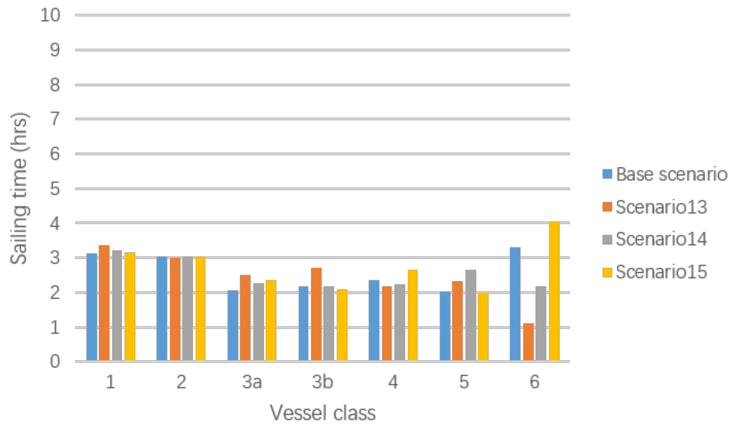

Figure 5.15: The comparison of sailing time when demand increases

5

RECOVERY FROM INCREASING DEMAND

There is a large amount of delay emerged with the increased number of vessels. Then to explore how to recover the nautical service system to normal condition, an experiment is designed to assign more pilots to cope with the growing demand. After have done a lot of trials and tests on the simulation model, the statistics of optimized pilot capacity are collected to create line chart as shown in Figure 5.16.

Scenarios	**Base**	**13**	**14**	**15**
Arrival rate	3	3.2	3.4	3.6
Optimized pilot capacity	15	18	20	22

Table 5.11: The pilot capacity required for recovering the normal condition

There are approximately two more pilots required to serve for the extra 1 vessel per 5 hours on average in order to eliminate long queue at the port entrance. However, it is definitely not a linear correlation between vessel arrival rate and optimized pilot capacity, since the waiting time in the queue are determined by multiple factors, including berth occupancy rate, pilots/tugs assignment distribution, and so on.

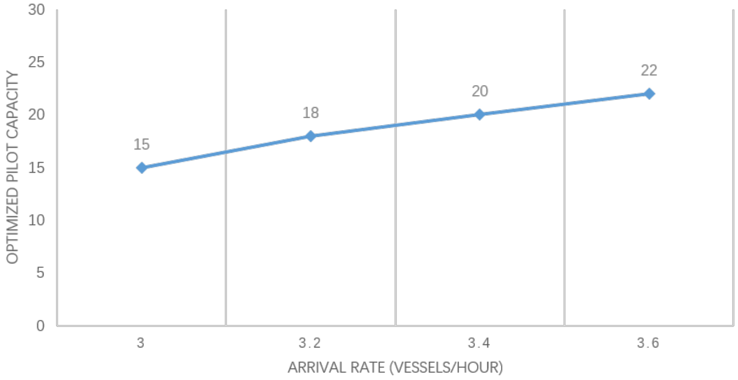

Figure 5.16: The relationship between vessel arrival rate and optimized pilot capacity

6

Conclusions and Recommendations

In this chapter, Section 6.1 discusses the main research question, following with the answers to the sub-questions. In Section 6.2, the merits and drawbacks of the developed simulation model are discussed. The recommendations for future research are made from two aspects: scientific and practical, in Section 6.3.

6.1. Conclusions

Five research sub-questions were identified as fundamental for correctly achieving the main objective of this graduation work. In this section, an answer to the main question is derived by first answering the sub-questions. The conclusions are subsequently generated from the answers to these questions.

1.***What is nautical chain and what are the Key Performance Indicators (KPIs) of ship handling services in the NC?***
A research on the basic information of nautical chain in the deep-sea port is conducted from literature and documents from port authority. The activities and actors involved in the nautical service system are identified.

In Chapter 2, some time-related KPIs are identified as essential for assessing the marine operations performance in the deep-sea port. Vessel turnaround time and average waiting time are two main KPIs, which were collected and analyzed during model experimentation stage. Beforehand, fish bone diagrams are used to determine either dependency variables and independency variables which are probably introduced in the simulation model.

The definition of ship waiting time in our study is the delay time vessel stays at anchorage area or terminal due to the lack of nautical service providers. The total turnaround time, on the other hand, is defined as the sum of waiting time and sailing time when ship sails in the port area, whereas the duration of terminal service activities is excluded.

According to the model outcome analysis in Chapter 5, it has proved that the total turnaround time of vessels in the NC is mainly contributed by the waiting time at port entrance. Furthermore, the vessel turnaround time, the waiting time due to the unavailability of service resources, are presented to assist the interpretation of differences between scenarios.

2.***How does the current NC perform in the PoR?***
By implementing CATWOE and Black-Box approach, the marine operations of nautical system are described and analyzed. Having defined various aspects of the system from the outside, the internal processes of the system are generated with flow chart. The following processes have been deemed necessary in order to correctly reflect the primary processes of ships in the nautical chain of the Port of Rotterdam: arrival at the port, waiting at the anchorage, navigation to the terminal, berthing, navigation towards to the port exit, and finally leaving the port. Apart from the main processes vessels go through, the service activities of two major nautical service providers: pilots and tugboats, are analyzed in detail to form a big picture of the holistic system.

The analysis on empirical data from port authority are organized as well to depict the system quantitatively. For example, it can be seen that vessel type 1 and 2 are the most popular visiting vessels, while Stad and Caland are the most popular visited terminals in the PoR. It brings us more straightforward insight into how the nautical system looks like with those datasets.

3.***How to develop the conceptual model for simulating the NC in the deep-sea port?***
In Chapter 4, a conceptual modelling framework is introduced to be able to develop the conceptual model in a structured manner. The model objectives, assumptions as well as inputs and outputs are specified step by step. Subsequently, the actors involved in the model are translated with their attributes and related processes.

The primary actors are, firstly the vessels as the only nautical service recipient in our study, then pilots and tugboats as service providers. They are all moving entities who have capability to move in the system if requires. Other actors, such as terminals and river sections, are static entities who are located at different spots of the port, indicating the place where nautical services perform. Moreover, some auxiliary actors perform different functionalities, for example, 'Vessel generator' is used to generate vessel entities with given amount and rate, 'Routing' is designed to cover the list of sections to direct ship sailing.

4.***How to validate the simulation model in different circumstances, by forming different scenarios?***
The model validation has been conducted in Chapter 5 with three steps: data validation, structure validation and performance validation. We assessed nautical system performs under different circumstances by designing a group of scenarios.

The sensitivity analysis study composed of three experiments on the evaluation of system performance are proposed: configuration of pilots and tugs in the normal situation; extending or shortening the terminal service time on all the terminals in the port; increasing the number of arriving vessels to see how system copes with the increasing service demand. The first experiment is to test the port performance under different configuration of nautical service resources, thus the circumstances of the system doesn't change. In the second experiment, we assume that the efficiency of quay-side terminal activities are fluctuated, while the arrival rate of vessels has increased in the third experiment, resulting in higher density of vessels in the port. KPIs, turnaround time and waiting time are collected and compared to measure the performance of each scenario.

5.***What are recommendations for improving the model with a higher level of intelligence?***
The model components have been checked and compared with previous research in Section 4.8 Chapter 4. To ensure that the created model can be utilized in the future research with implementing higher level of intelligence, the recommendations for the initiatives to start new research will be given in Section 6.3 of this chapter.

Therefore, the main research question **"How to develop a model that can simulate nautical service in the deep-sea port in order to evaluate the performance of the NC?"** can be answered with the answers to the five subquestions. To sum up, the model is structured beginning with identifying KPIs and system analysis, then conducting modelling based on a chosen framework, building scenarios to test the model with various values of input parameters, finally proposing recommendations for the further improvements.

6.2. Discussions

The outcome of this research is an abstract simulation model, regarding as the first phase of simulation in Swarmport project. The model structures the nautical service system in the deep-sea port as a queuing system, with implementing the characteristics of major actors in the nautical chain. When running the simulation, the time vessel spent on each activity can be tracked and monitored. The model brings a tool to conduct sensitivity analysis on model input parameters to see how vessel turnaround time and waiting time change with disruptions or changed input. It helps to gain insight into the impact of new decision making or new situation on ship handling operation when comparing the model outputs from different scenarios.

However, simulation is an approximate imitation of the real system, so it fails to reflect the system in real case precisely. The limitation of the developed model in our research can be discussed from many aspects. First, the model marks the position of each terminal with a group of berths. While in reality, some terminals on the map indicates an area, where probably contains many terminals inside. This inaccuracy of port infrastructure will hinder people's trust on the model outputs. Second, to simplify the procedure of nautical service in the model, we only set up one pilot station and one tugboat station in the port area. However, in the real case, there are multiple pilot and tugboat stations distributing in the network, reflecting a more flexible repositioning of nautical resources. Third, the model monitors how long ship waits at anchorage at port entrance because of lacking of available service resources. It fails to reflect the real case because many times vessel waits for economic benefits, but it is something much more complicated for the simulation model to take into consideration.

6.3. Recommendations

To sum up, an abstract simulation model has been developed which is used to mimic the nautical service processes in the PoR. Although the conclusion is drawn to illustrate the way how the model is initiated, built and tested, there are far more details and aspects needed to be done to form a useful tool for the Port of Rotterdam Authority.

The results generated from experimentation of the simulation model could only be seen as a general and basic understanding on nautical service system in deep-sea port. It contains great potential to explore more findings especially after implementing real-time interaction among actors in agent-based model.

6.3.1. CASE STUDY CONTINUATION

As discussed when initiating modelling, a bundle of assumptions have been specified to make the simulation doable, whereas reduce the usefulness of the model in reality. It is therefore valuable to put more effort on extending the model with implementing nautical chain in more detail.

First of all, more characteristics of vessel agent should be specified in the model, for instance, length, draught, the number of cargo. These parameters provide potential to explore new research topics, like how nautical service are influence by the depth of river, or cargo logistics activities at quay-side of terminal. However, this requires huge workload to collect relevant empirical data. Secondly, more actors in the nautical service chain could be simulated, specifically harbour master and boatmen organization. Adding two types of entities will profoundly increase the complexity of the nautical service system in this study, more importantly, the relations interwined among all the involved actors. Thirdly, more explicit river traffic rules, such as overtaking and encountering rules, would lead to more accurate control of vessel sailing behavior. Fourthly, if cargo handling activities are modelled at each terminal, it would bring greatest contribution to the average waiting time due to berth unavailability.

In addition, more KPIs of marine operation for vessels could be identified and tested with simulation, such as berth occupancy rate, in order to evaluate the nautical service performance from various aspects. In case the model is extended, more data should be gathered to calibrate the model parameters.

6.3.2. FURTHER RESEARCH ON THE NAUTICAL CHAIN

The further step of this research is to integrate an agent-based model into a discrete-event model. Movement of entities in DES model typically requires predefined path with decision points that dictate entity movement, whereas it is still difficult to model human-like travel as it is not how free agents move and large individual differences exist in capabilities and strategies [23]. Agent-based modeling is considered a better way to simulate the real-time interaction of entities with their environment. Agent-based model is able to simulate the simultaneous operations and interactions of multiple agents in order to predict the complex phenomena, this requires us to deeply look at the information flows among all the actors and how far the simulation can reach.

The information exchange exists in the tactical planning of the nautical chain as well as the operational planning stage. The tactical planning includes the preparation of agreements and the deployment of services. In operational planning domain, when ships arrive at the entrance of the port, their activities should be already planned, for example, pilots should be assigned to the ship, tugboats should be informed about the arrival of the vessel, and each agency know when and where to meet the vessel. The terminal should acknowledge the berth will be available at the moment ship arrives.

The information transformation has been researched in Alexander's thesis [1]. When extending the port network and taking more actors into account, the information flows become diverse and complicated. The information flow among each pair of actors will be discussed in terms of the future implementation in the simulation. The discussion refers to Figure 12.1 and Figure 12.2 in Chapter 12 of Alexander's report.

Vessel and harbour master Vessel agents have frequent contact with harbour master. The information that transfers through administrative clearance and operational clearance processes before entering the port determines the queuing discipline of ship agents. In the model, each incoming vessel can be assigned with a priority value, to change the mode of queuing discipline to priority-based. The rule of setting priority, however, should be designed with coding according to the characteristics of each vessel and its task. Harbour master is responsible for monitoring the shipping traffic when vessel is on sailing for safety issues. This information flow can be designed in the simulation, with creating a dataset, which is capable of storing statistics of agents and maintaining the up-to-date data collection at each time stamp. Harbour master agent therefore can trace this dataset to analyze the position of vessel agents and their sailing condition, etc.

Harbour master and pilot Information transformation between harbour master and pilot emerge at the beginning of arriving voyage as well as departing voyage when vessel is asking for pilotage service. Harbour master will firstly check the available pilots and deploy the appropriate type of pilot to the vessel and voyage. It requires a step to verify the type of pilot and the vessel are matched. A state chart can be set up in harbour master agent to construct event-driven behavior. For example, in this case, when the desired type of pilots are available at pilot station for vessel agent, harbour master will send message to target vessel to pick up pilots.

6

Pilot and tugboat It contains two stages of information transfer between pilot and tugboat. When approaching the harbour, pilots on the vessel start to communicate with tugboats. Pilots will deploy when and where tugs needed, instruct tugs in bringing the vessel towards the berth safely. During this process, pilots play a role as coordinator, thus the condition of tugs and ego vessel can be checked by state chart as well. When pilots direct mooring/unmooring processes, pilot agent is able to receive the detail information of mooring/unmooring activities from tug agent, such as the direction, speed. The data will then be analyzed and adjusted to reflect the realistic movement of tugs.

Tugboat and boatmen The communication among tugboats and boatmen are similar to the information flow delivered from pilot to tug. As a new type of service resources, the agents of boatmen should be well specified. Since tugboats and boatmen work together on mooring/unmooring activities, a good communication should force them to perform the task simultaneously, so that no extra delay emerges. This can be done by using 'Seize' block, with defining the priority of tasks. In other words, vessel agent going through 'Seize' block will decide when to seize boatmen resources, maybe after the required number of tugboats is ready (as prior task).

Harbour master and terminal Terminal has short-term planning regulated with the assistance of harbour master. In reality, terminal is announced by harbour master that how long a vessel will come to berth. This requires a schedule to manage the ship arrival and ship departure at each terminal. In 'Schedule' element in Anylogic, users can define how value changes in time according to defined pattern. Specifically, if vessel visiting at certain terminal has clear pattern in weekly, a cyclic pattern of schedule for vessels can be constructed.

6.3.3. PRACTICALITY

The recommendations are generated from port perspective, so that the outcomes of the simulation model become as realistic as possible.

What we want to achieve in the simulation is satisfying all the demand, whereas in practice it is not feasible to reach 100% match between supply and demand in the nautical service system. The supply side of the nautical services is always under capacities because pilots and tugs cannot be available 100% of the time. There is around 70% to 80% of time they are considered to be fully operational, the rest of time might spent for boat repairs, people illness, misplanning, etc.

The model generates one ship per 20 minutes on average as assumed. However, vessel arrival and departure at deep-sea port is not scheduled, but at random. The randomness of vessel in-coming and out-going flow represents the high level of complexity of real situation, therefore requires a more clever simulation model to reflect the reality.

In addition, there is a direction for future work that brings in cost function into the model, then provides the potential to calculate the best configuration of service resource, with the objective of minimising total cost.

REFERENCES

[1] A. M. Verduijn, *Identifying the relations between and mapping the processes of the nautical service providers in the port of rotterdam,* Master thesis from TU Delft (2017).

[2] J. A. Hans P.M.Veeke and G. Lodewijks, *The Delft System Approach – Analysis and design of industrial systems* (Springer, 2008).

[3] K. K. Stewart Robinson, Roger Brooks and D.-J. van der Zee, *Conceptual Modeling for Discrete-Event Simulation* (CRC Press and TaylorFrancis Group, 2011).

[4] PoR, *Port of rotterdam,* https://www.portofrotterdam.com/en (2019).

[5] NWO, *Netherlands organization for scientific research, swarmport,* https://www.nwo.nl/en/research-and-results/research-projects/i/14/27814.html (2019).

[6] L. Tavasszy, *Self-organization among autonomous agents in nautical processes in morden seaports,* Complexity in Transport and Logistics (2016).

[7] W. K. Talley, M. Ng, and E. Marsillac, *Port service chains and port performance evaluation,* Transportation Research Part E: Logistics and Transportation Review **69**, 236 (2014).

[8] S. Brailsford and N. Hilton, *A comparison of discrete event simulation and system dynamics for modelling healthcare systems,* Operational Research Applied to Health Services (2001).

[9] DES, *Discrete event simulation,* https://en.wikipedia.org/wiki/Discrete-event_simulation (2019).

[10] A. Sweetser, *A comparison of system dynamics and discrete event simulation,* Andersen Consultng (1999).

[11] J. J.Swain, *Software survey: Simulation – back to the future,* ORMS-Today **38** (2011).

[12] Q. Hao and W. Shen, *Implementing a hybrid simulation model for a kanban-based material handling system,* Robotics and Computer Integrated Manufacturing **24**, 635 (2008).

[13] *Port performance indicators* (United Nations Conference on Trade and Development - UNCTAD, New York, 1976).

[14] Chen-Hsiu and Kuang-Che, *The optimal step toll scheme for heavily congested ports,* Journal of Marine Science and Technology **12**, 16 (2004).

[15] *Port performance indicators* (The World Bank, Transport, 1993).

[16] K.-C. Nam, K.-S. Kwak, and M.-S. Yu, *Simulation study of container terminal performance,* Journal of Waterway, Port, Coastal, and Ocean Engineering **128**, 126 (2002).

[17] P. B. Marlow and A. C. P. Casaca, *Measuring lean ports performance,* International Journal of Transport Management **1**, 189 (2003).

[18] N. Sarwar, *Time-related key performance indicators and port performance: a review of theory and practice,* Master thesis from Vestfold University College (2013).

[19] A.Shahpanah, A.Hashemi, G.Nouredin, S.M.Zahraee, and S.A.Helmi, *Reduction of ship waiting time at port container terminal through enhancement of the tug/pilot machine operation,* Jurnal Teknologi **68**, 63 (2014).

[20] R. Groenveld, *Analysis of input and output data,* (2001).

[21] H. Havenkaart, *Arcgis web application,* `https://portofrotterdam.maps.arcgis.com/apps/webappviewer/index.html?id=19a593c767cc4142a4ef07ac3fa7fbd8` (2019).

[22] J. D. Salciccioli, Y. Crutain, M. Komorowski, and D. C. Marshall, *Sensitivity analysis and model validation,* Secondary Analysis of Electronic Health Records (2016).

[23] B. Dubiel and O. Tsimhoni, *Integrating agent based modeling into a discrete event simulation,* Proceedings of the 2005 Winter Simulation Conference (2005).

Appendices

A

RESEARCH SUMMARY

B

DATA ANALYSIS

B.1. VESSEL VOYAGE DISTRIBUTION

Table B.1: Vessel class distribution

Vessel class	Percentage
1	36.64 %
2	43.08 %
3a	14.35 %
3b	2.13 %
4	3.02 %
5	0.40 %
6	0.39 %

B

Table B.2: Vessel destination distribution

Vessel destination	Percentage
HoekvanHollandStena	3.85 %
Caland	22.19 %
Tennesseehaven	0.97 %
Indorama	0.02 %
BP	1.02 %
Amazonehaven	5.06 %
Steinweg	0.44 %
ECTEuropahaven	3.47 %
APMTmv1	2.55 %
MOT	2.33 %
Euromaxmv2	0.04 %
T3west	0.26 %
SIF	0.24 %
APMTmv2	3.40 %
Werkhaven1e	0.47 %
PETcentraal	1.47 %
PETnoord	0.64 %
PETzuidoost	1.21 %
PETzuidwest	0.94 %
Botlekcentraleoost	0.02 %
BotlekcentraleWH	0.13 %
Werkhaven2e	0.96 %
BotlekcentraleTH	0.74 %
Botlekcentralewest	0.28 %
SintLaurenshaven	1.77 %
Chemiehaven	1.51 %
BotlekWest	0.47 %
Stad	43.53 %

Table B.3: Voyage distribution in total

Destination	Class 1	2	3a	3b	4	5	6
HoekvanHollandStena			26%	2%			
Caland	12%	29%	28%	41%	4%	3%	62%
Tennesseehaven	1%	1%	3%	11%	1%	3%	38%
Indorama	1%	1%					
BP	1%	1%	1%	5%			
Amazonehaven	1%	5%	6%	21%	32%	26%	
Steinweg	1%	1%	1%	1%			
ECTEuropahaven	1%	2%	12%		14%		
APMTmv1	1%	2%	5%	1%	16%	5%	
MOT	1%	4%		12%	10%	13%	
Euromaxmv2	1%						
T3west		1%	1%	4%		3%	
SIF	1%	1%					
APMTmv2	1%	3%	7%	1%	22%	47%	
Werkhaven1e	2%	2%	2%				
PETcentraal	2%	1%					
PETnoord	1%	1%					
PETzuidoost	2%	1%	1%	1%			
PETzuidwest	1%	1%					
Botlekcentraleoost	1%						
BotlekcentraleWH	1%	1%					
Werkhaven2e	1%	1%	1%				
BotlekcentraleTH	1%	1%					
Botlekcentralewest	1%	1%					
SintLaurenshaven	3%	1%	1%				
Chemiehaven	3%	1%					
BotlekWest	1%	1%	1%				
Stad	65%	43%	8%		1%		

B.2. AVERAGE VOYAGE DURATION

Table B.4: Average voyage duration with each destination

Destination	Average duration (hrs)	Threshold [Max,Min]	Sigma
HoekvanHollandStena	1:40	[1:01 , 2:19]	0:39
Caland	3:27	[1:52 , 5:02]	1:35
Tennesseehaven	3:32	[2:41 , 4:23]	0:51
Indorama	3:31	[3:31 , 3:31]	0:00
BP	2:57	[2:23 , 3:31]	0:34
Amazonehaven	2:58	[2:00 , 3:56]	0:58
Steinweg	3:57	[0:00 , 8:45]	4:48
ECTEuropahaven	2:55	[1:10 , 4:40]	1:45
APMTmv1	3:19	[0:47 , 5:51]	2:32
MOT	3:03	[0:47 , 5:19]	2:16
Euromaxmv2	2:43	[2:19 , 3:07]	0:24
T3west	4:18	[3:30 , 5:06]	0:48
SIF	8:12	[1:11 , 15:13]	7:01
APMTmv2	3:56	[2:02 , 5:50]	1:54
Werkhaven1e	4:40	[3:40 , 5:40]	1:00
PETcentraal	4:31	[3:51 , 5:11]	0:40
PETnoord	4:22	[3:09 , 5:35]	1:13
PETzuidoost	4:36	[3:25 , 5:47]	1:11
PETzuidwest	4:36	[3:52 , 5:20]	0:44
Botlekcentraleoost	4:58	[4:58 , 4:58]	0:00
BotlekcentraleWH	4:29	[3:39 , 5:19]	0:50
Werkhaven2e	5:19	[2:35 , 8:03]	2:44
BotlekcentraleTH	4:32	[3:50 , 5:14]	0:42
Botlekcentralewest	4:50	[4:03 , 5:37]	0:47
SintLaurenshaven	5:02	[3:33 , 6:31]	1:29
Chemiehaven	4:42	[3:55 , 5:29]	0:47
BotlekWest	4:58	[4:10 , 5:46]	0:48
Stad	5:15	[2:09 , 8:21]	3:06

Table B.5: Average voyage duration for each vessel class

Vessel class	Average duration (hrs)	Threshold [Max,Min]	Sigma
1	5:21	[1:35 , 9:07]	3:46
2	4:01	[2:02 , 6:00]	1:59
3a	3:08	[1:30 , 4:46]	1:38
3b	4:08	[1:30 , 6:46]	2:38
4	3:59	[1:37 , 6:21]	2:22
5	4:14	[3:11 , 5:17]	1:03
6	4:40	[3:37 , 5:43]	1:03

B.3. AVERAGE DURATION BEFORE ENTERING THE PORT

Table B.6: Average duration before entering the port with each destination

Destination	Average duration (hrs)	Threshold [Max,Min]	Sigma
HoekvanHollandStena	1:57	[1:41 , 2:13]	0:16
Caland	6:33	[0:00 , 14:35]	8:02
Tennesseehaven	12:53	[3:20 , 22:26]	9:33
Indorama	6:47	[6:47 , 6:47]	0:00
BP	15:06	[3:44 , 26:28]	11:22
Amazonehaven	7:43	[0:28 , 14:58]	7:15
Steinweg	8:44	[0:00 , 20:30]	11:46
ECTEuropahaven	8:38	[0:00 , 17:38]	9:00
APMTmv1	9:19	[0:11 , 18:27]	9:08
MOT	6:25	[0:33 , 12:17]	5:52
Euromaxmv2	4:17	[3:50 , 4:44]	0:27
T3west	7:07	[0:26 , 13:48]	6:41
SIF	3:59	[3:33 , 4:25]	0:26
APMTmv2	8:06	[0:00 , 16:28]	8:22
Werkhaven1e	5:05	[1:30 , 8:40]	3:35
PETcentraal	13:14	[2:21 , 24:07]	10:53
PETnoord	12:22	[1:32 , 23:12]	10:50
PETzuidoost	18:06	[6:45 , 5:27]	11:21
PETzuidwest	11:05	[0:52 , 21:18]	10:13
Botlekcentraleoost	3:46	[3:46 , 3:46]	0:00
BotlekcentraleWH	8:58	[0:00 , 18:31]	9:33
Werkhaven2e	8:29	[0:31 , 16:27]	7:58
BotlekcentraleTH	7:07	[0:00 , 14:43]	7:36
Botlekcentralewest	6:43	[0:26 , 13:00]	6:17
SintLaurenshaven	8:22	[0:00 , 17:48]	9:26
Chemiehaven	9:40	[0:24 , 18:56]	9:16
BotlekWest	10:51	[1:58 , 19:44]	8:53
Stad	5:30	[0:00 , 12:15]	6:45

B.4. AVERAGE DURATION BEFORE LEAVING THE TERMINAL

Table B.7: Average duration before leaving the port with each destination

Destination	Average duration (hrs)	Threshold [Max,Min]	Sigma
HoekvanHollandStena	1:36	[1:07 , 2:05]	0:29
Caland	2:22	[1:17 , 3:27]	1:05
Tennesseehaven	2:27	[2:04 , 2:50]	0:23
Indorama	1:47	[1:47 , 1:47]	0:00
BP	2:12	[1:51 , 2:33]	0:21
Amazonehaven	2:05	[1:27 , 2:43]	0:38
Steinweg	3:15	[0:00 , 7:48]	4:33
ECTEuropahaven	2:14	[0:47 , 3:41]	1:27
APMTmv1	2:23	[0:26 , 4:20]	1:57
MOT	2:11	[0:30 , 3:52]	1:41
Euromaxmv2	1:47	[1:41 , 1:53]	0:06
T3west	2:43	[3:00 , 2:43]	0:17
SIF	6:45	[0:15 , 13:15]	6:30
APMTmv2	2:34	[1:16 , 3:52]	1:18
Werkhaven1e	2:45	[2:15 , 3:15]	0:30
PETcentraal	2:47	[2:28 , 3:06]	0:19
PETnoord	2:47	[1:58 , 3:36]	0:49
PETzuidoost	2:46	[2:00 , 3:32]	0:46
PETzuidwest	2:53	[2:28 , 3:18]	0:25
Botlekcentraleoost	2:36	[2:36 , 2:36]	0:00
BotlekcentraleWH	2:50	[2:27 , 3:13]	0:23
Werkhaven2e	3:35	[1:24 , 5:46]	2:11
BotlekcentraleTH	2:43	[2:13 , 3:13]	0:30
Botlekcentralewest	3:04	[2:37 , 3:31]	0:27
SintLaurenshaven	3:03	[1:58 , 4:08]	1:05
Chemiehaven	2:49	[2:27 , 3:11]	0:22
BotlekWest	3:01	[2:35 , 3:27]	0:26
Stad	3:24	[1:09 , 5:39]	2:15

B

B.5. TERMINAL AVERAGE SERVICE TIME

Table B.8: Terminal average service times (hrs)

Destination	Class 1	2	3a	3b	4	5	6
HoekvanHollandStena	6:00	6:00	6:00	6:00	6:00	6:00	6:00
Caland	6:00	11:00	11:00	11:00	19:00	19:00	19:00
Tennesseehaven	15:31	15:31	17:49	17:49	19:42	19:42	5:38
Indorama	10:00	10:00	10:00	10:00	10:00	10:00	10:00
BP	16:00	16:00	16:00	16:00	18:00	17:00	17:00
Amazonehaven	10:00	10:00	10:00	10:00	18:00	18:00	18:00
Steinweg	6:00	11:00	11:00	11:00	11:00	11:00	11:00
ECTEuropahaven	10:00	10:00	10:00	10:00	18:00	18:00	18:00
APMTmv1	10:00	10:00	10:00	10:00	18:00	18:00	18:00
MOT	21:00	21:00	21:00	21:00	21:00	21:00	21:00
Euromaxmv2	5:15	10:20	10:20	10:20	18:30	18:30	18:30
T3west	5:15	10:20	10:20	10:20	18:30	18:30	18:30
SIF	5:15	10:20	10:20	10:20	18:30	18:30	18:30
APMTmv2	5:15	10:20	10:20	10:20	18:30	18:30	18:30
Werkhaven1e	15:00	16:40	16:40	18:20	18:20	18:20	18:20
PETcentraal	15:00	16:40	16:40	18:20	18:20	18:20	18:20
PETnoord	15:00	16:40	16:40	18:20	18:20	18:20	18:20
PETzuidoost	15:00	16:40	16:40	18:20	18:20	18:20	18:20
PETzuidwest	15:00	16:40	16:40	18:20	18:20	18:20	18:20
Botlekcentraleoost	15:00	16:40	16:40	18:20	18:20	18:20	18:20
BotlekcentraleWH	15:00	16:40	16:40	18:20	18:20	18:20	18:20
Werkhaven2e	15:00	16:40	16:40	18:20	18:20	18:20	18:20
BotlekcentraleTH	15:00	16:40	16:40	18:20	18:20	18:20	18:20
Botlekcentralewest	15:00	16:40	16:40	18:20	18:20	18:20	18:20
SintLaurenshaven	15:00	16:40	16:40	18:20	18:20	18:20	18:20
Chemiehaven	15:00	16:40	16:40	18:20	18:20	18:20	18:20
BotlekWest	15:00	16:40	16:40	18:20	18:20	18:20	18:20
Stad	7:38	12:38	12:33	12:33	20:33	20:33	20:33

B.6. RIVER SECTION SEPARATION TIMES

Table B.9: Section separation times (min)

Section	Class 1	2	3a	3b	4	5	6
1	0.1	0.1	0.1	0.1	0.1	0.1	45
2	0.1	0.1	0.1	0.1	0.1	0.1	45
3	0.1	0.1	0.1	0.1	0.1	3.7	45
4	0.1	0.1	2.8	2.8	3.5	3.7	45
5	0.1	1.7	2.8	2.8	3.5	3.7	45
6	1.1	1.8	3.5	3.5	4.6	4.9	45
7	1.1	1.9	3.5	3.5	4.6	5.4	45
8	1.2	1.9	3.5	3.5	5.1	5.4	45
10	1.2	1.9	3.5	3.5	4.6	4.9	45
11	1.3	2.1	4.1	4.1	5.1	5.4	45
17	1.3	2.3	4.1	4.1	5.1	5.4	45
18	1.3	2.3	4.1	4.1	5.1	5.4	45
19	1.3	2.3	4.1	4.1	5.1	5.4	45
22	2.4	3.8	6.2	6.2	7.6	8	45
27	1.6	2.6	4.1	4.1	5.1	5.4	45
32	1.4	2.3	3.7	3.7	5.9	6.3	45
35	1.4	2.3	4.8	4.8	5.9	6.3	45
42	1.3	2	3.5	3.5	4.3	4.5	45
45	1.6	2.6	4.8	4.8	5.9	6.3	45
46	1.4	2.3	3.7	3.7	4.6	4.9	45
49	1.6	2.6	4.8	4.8	5.9	6.3	45
50	1.6	2.6	4.8	4.8	5.9	6.3	45
55	1.6	2.6	4.1	4.1	5.9	6.3	45
59	1.6	2.6	4.1	4.1	5.9	6.3	45
60	1.6	2.6	4.8	4.8	5.9	6.3	45
70	1.5	2.5	2.5	2.5	5	6.3	45
71	1.5	2.5	2.5	2.5	5	6.3	45
78	5	7	15	20	20	6.3	45
79	5	7	15	20	20	6.3	45
80	5	7	15	20	20	6.3	45
81	5	7	15	20	20	6.3	45
82	5	7	15	20	20	6.3	45
83	5	7	15	20	20	6.3	45
84	5	7	15	20	20	6.3	45
85	5	7	15	20	20	6.3	45
86	5	7	15	20	20	6.3	45
87	5	7	15	20	20	6.3	45
88	5	7	15	20	20	6.3	45
89	5	7	15	20	20	6.3	45
90	5	7	15	20	20	6.3	45
91	1.5	2.5	2.5	2.5	5	6.3	45
92	1.5	2.5	2.5	2.5	5	6.3	45
100	1.5	2.5	2.5	2.5	5	6.3	45
104	1.5	2.5	2.5	2.5	5	6.3	45
105	1.5	2.5	2.5	2.5	5	6.3	45

B

B

B.7. RIVER SECTION SPEED LIMITS

Table B.10: Section speed range (kn)

Section	Class 1 [Min,Max]	2	3a	3b	4	5	6
1	[0 , 15]	[0 , 15]	[0 , 15]	[0 , 15]	[0 , 15]	[0 , 15]	[0 , 10]
2	[8 , 15]	[8 , 15]	[8 , 15]	[8 , 15]	[8 , 15]	[8 , 15]	[5 , 10]
3	[8 , 15]	[8 , 15]	[6 , 12]	[5 , 12]	[5 , 12]	[5 , 12]	[5 , 8]
4	[6 , 15]	[6 , 15]	[6 , 12]	[5 , 11]	[5 , 11]	[5 , 12]	[4 , 8]
5	[6 , 12]	[6 , 12]	[6 , 12]	[5 , 11]	[5 , 11]	[5 , 12]	[4 , 8]
6	[4 , 10]	[4 , 10]	[4 , 6]	[4 , 6]	[3 , 5]	[3 , 5]	[1 , 4]
7	[0 , 10]	[0 , 10]	[0 , 6]	[0 , 6]	[0 , 5]	[0 , 5]	[0 , 4]
8	[0 , 8]	[0 , 8]	[0 , 6]	[0 , 6]	[0 , 4]	[0 , 4]	[0 , 3]
10	[4 , 8]	[4 , 8]	[4 , 6]	[4 , 6]	[3 , 5]	[3 , 5]	[1 , 4]
11	[4 , 6]	[4 , 6]	[2 , 4]	[2 , 4]	[2 , 4]	[2 , 4]	[1 , 3]
17	[4 , 6]	[3 , 5]	[2 , 4]	[2 , 4]	[2 , 4]	[2 , 4]	[1 , 3]
18	[4 , 6]	[3 , 5]	[2 , 4]	[2 , 4]	[2 , 4]	[2 , 4]	[1 , 3]
19	[4 , 6]	[3 , 5]	[2 , 4]	[2 , 4]	[2 , 4]	[2 , 4]	[1 , 3]
22	[2 , 3]	[2 , 3]	[2 , 3]	[2 , 3]	[1 , 2]	[1 , 2]	[1 , 2]
27	[2 , 4]	[2 , 4]	[4 , 4]	[4 , 4]	[2 , 4]	[2 , 4]	[1 , 2]
32	[3 , 5]	[3 , 5]	[3 , 5]	[3 , 5]	[1 , 3]	[1 , 3]	[1 , 2]
35	[3 , 5]	[3 , 5]	[3 , 3]	[3 , 3]	[1 , 3]	[1 , 3]	[1 , 2]
42	[1 , 7]	[1 , 7]	[4 , 6]	[4 , 6]	[3 , 6]	[3 , 6]	[1 , 2]
45	[4 , 4]	[4 , 4]	[4 , 4]	[4 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
46	[4 , 5]	[4 , 5]	[3 , 5]	[3 , 5]	[3 , 5]	[3 , 5]	[1 , 2]
49	[3 , 4]	[3 , 4]	[2 , 3]	[2 , 3]	[2 , 3]	[2 , 3]	[1 , 2]
50	[3 , 4]	[3 , 4]	[2 , 3]	[2 , 3]	[2 , 3]	[2 , 3]	[1 , 2]
55	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 4]	[2 , 3]	[2 , 3]	[1 , 2]
59	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 4]	[2 , 3]	[2 , 3]	[1 , 2]
60	[3 , 4]	[3 , 4]	[2 , 3]	[2 , 3]	[2 , 3]	[2 , 3]	[1 , 2]
70	[4 , 12]	[4 , 11]	[4 , 11]	[4 , 11]	[4 , 10]	[5 , 12]	[4 , 8]
71	[4 , 12]	[4 , 10]	[4 , 10]	[4 , 9]	[4 , 8]	[5 , 12]	[4 , 8]
78	[4 , 7]	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
79	[4 , 6]	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
80	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
81	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
82	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
83	[4 , 6]	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
84	[4 , 6]	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
85	[4 , 6]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
86	[4 , 6]	[3 , 4]	[3 , 4]	[3 , 4]	[3 , 3]	[3 , 3]	[1 , 2]
87	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
88	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
89	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
90	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
91	[10 , 10]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
92	[12 , 12]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
100	[4 , 4]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[3 , 3]	[1 , 2]
104	[11 , 11]	[8 , 8]	[8 , 8]	[7 , 7]	[6 , 6]	[5 , 12]	[4 , 8]
105	[6 , 6]	[4 , 4]	[4 , 4]	[4 , 4]	[3 , 3]	[3 , 3]	[1 , 2]

B.8. PILOTS

Table B.11: Number of pilots required for each vessel class (percentage)

Vessel class	No pilot	One pilot	Two pilots
1	33%	67%	
2	32%	68%	
3a	38%	62%	
3b	2%	98%	
4		100%	
5		100%	
6			100%

B.9. TUGBOATS

Table B.12: Number of tugboats required for each destination and each vessel class

Destination	Class 1	2	3a	3b	4	5	6
HoekvanHollandStena			97% 0, 3% 1	100% 0			
Caland	94% 0, 6% 1	75% 0, 8% 1, 17% 2	43% 0, 5% 1, 52% 2	6% 0, 60% 2, 34% 3	17% 0, 8% 1, 8% 2, 50% 3, 17% 4	100% 3	9% 0, 30% 2, 22% 3, 39% 4
Tennesseehaven	100% 0	100% 1	9% 0, 79% 2, 12% 4	4% 1, 74% 2, 22% 3	50% 2, 50% 4	50% 2	36% 2, 7% 3, 57% 4
Indorama	100% 0	100% 0					
BP	31% 0, 31% 1, 38% 2	56% 0, 18% 1, 26% 2	6% 0, 94% 1	9% 0, 64% 2, 27% 3			
Amazonehaven	100% 0	89% 0, 11% 1	15% 1, 85% 2	16% 2, 84% 3	15% 0, 85% 2	10% 0, 70% 2, 20% 3	
Steinweg	100% 0	50% 0, 50% 2	100% 2	100% 2			
ECTEuropahaven	100% 0	49% 0, 43% 1, 8% 2	12% 0, 59% 1, 29% 2		20% 0, 37% 1, 43% 2		
APMTmv1	100% 0	67% 0, 10% 1, 23% 2	35% 0, 16% 1, 49% 2	100% 2	12% 0, 20% 1, 68% 2	100% 0	
MOT	100% 0	90% 0, 10% 1			14% 0, 86% 1	10% 0, 80% 2, 10% 3	
Euromaxmv2	75% 0, 25% 1						
T3west		50% 1, 50% 2	10% 0, 10% 1, 70% 2, 10% 3	50% 1, 50% 2		100% 2	
SIF	50% 0, 50% 2	60% 0, 20% 2, 10% 3, 10% 4					
APMTmv2	89% 0, 11% 1	82% 0, 18% 1	34% 0, 16% 1, 50% 2	100% 2	40% 0, 44% 2, 16% 3	11% 0, 67% 2, 22% 3	
Werkhaven1e	100% 0	25% 0, 50% 1, 25% 2	20% 2, 40% 3, 40% 4				
PETcentraal	100% 0	38% 0, 22% 1, 40% 2					
PETnoord	100% 0	40% 0, 40% 1, 20% 2					
PETzuidoost	95% 0, 5% 1	68% 0, 12% 1, 20% 2	50% 2, 50% 3	100% 2			
PETzuidwest	100% 0	43% 0, 32% 1, 25% 2					
Botlekcentraleoost	100% 0						
BotlekcentraleWH	100% 0	50% 1, 50% 2					
Werkhaven2e	100% 0	38% 0, 27% 1, 35% 2					
BotlekcentraleTH	88% 0, 12% 1	25% 0, 50% 1, 25% 2					
Botlekcentralewest	100% 0	10% 0, 20% 1, 70% 2					
SintLaurenshaven	100% 0	32% 0, 7% 1, 61% 2	17% 0, 67% 2, 16% 3				
Chemiehaven	95% 0, 5% 1	33% 0, 41% 1, 26% 2					
BotlekWest	100% 0	24% 0, 6% 1, 70% 2	50% 2, 50% 3				
Stad	96% 0, 3% 1, 2% 2	74% 0, 10% 1, 16% 2	44% 0, 18% 1, 35% 2, 3% 3		100% 2		

C

MODEL VALIDATION

C.1. MODEL OUTPUTS IN SCENARIO 1

Table C.1: Waiting time outputs in scenario 1

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	10.03	11.03
2	11.98	15.08
3a	11.42	13.54
3b	11.41	12.24
4	5.94	9.33
5	10.22	8.64
6	24.85	0
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.53	2.11
2	2.24	2.2
3a	1.83	1.67
3b	0.98	0.84
4	2.03	1.42
5	1.94	0.88
6	2.56	3.54

C

C.2. MODEL OUTPUTS IN SCENARIO 2

Table C.2: Waiting time outputs in scenario 2

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	15.85	16.12
2	11.8	14.45
3a	13.52	13.37
3b	10.63	13.07
4	10.52	11.97
5	10.36	14.43
6	8.82	7.68
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.66	2.18
2	2.46	1.97
3a	1.81	1.6
3b	2.21	1.7
4	1.5	1.4
5	2.96	1.27
6	1.06	1.03

C.3. MODEL OUTPUTS IN SCENARIO 3

Table C.3: Waiting time outputs in scenario 3

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	10.09	9.7
2	10.16	9.52
3a	8.42	8.99
3b	6.26	7.07
4	3.83	4.98
5	12.54	5.11
6	10.31	9.47
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.42	1.84
2	2.29	1.78
3a	1.76	1.48
3b	2.13	1.56
4	1.95	1.6
5	2.26	0.24
6	1.53	1.95

C.4. MODEL OUTPUTS IN SCENARIO 4 (BASE SCENARIO)

Table C.4: Waiting time outputs in scenario 4 (base scenario)

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	6.04	6.16
2	6.02	6.6
3a	5.85	6.62
3b	6.13	8.05
4	1.97	9.8
5	1.72	0
6	11.45	8.09
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.5	1.78
2	1.99	1.69
3a	1.73	1.51
3b	1.77	1.78
4	1.33	1.18
5	3.26	0.12
6	1.34	0.91

C.5. MODEL OUTPUTS IN SCENARIO 5

Table C.5: Waiting time outputs in scenario 5

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	7.68	8.58
2	5.21	7.3
3a	3.31	4.94
3b	2.17	3.84
4	1	1.8
5	0.1	0
6	3.5	6.36
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.16	1.77
2	1.82	1.48
3a	1.42	1.28
3b	1.58	1.45
4	1.21	0.84
5	1	1.32
6	0.28	0.69

C.6. MODEL OUTPUTS IN SCENARIO 6

Table C.6: Waiting time outputs in scenario 6

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	5.72	6.44
2	7.21	7.84
3a	3.28	4.96
3b	3.65	4.73
4	2.85	3.1
5	2.4	3.73
6	12.4	0

Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.06	1.66
2	1.94	1.52
3a	1.48	1.22
3b	1.54	1.23
4	1.43	1.09
5	1.09	1
6	1.1	0

C.7. MODEL OUTPUTS IN SCENARIO 7

Table C.7: Waiting time outputs in scenario 7

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	5.12	6.76
2	7.75	9.36
3a	6.97	9.56
3b	2.35	3.15
4	1.92	4.05
5	3.77	5.21
6	0.12	0.07
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.01	1.49
2	1.75	1.36
3a	1.25	1.07
3b	1.28	1.17
4	1.15	1.04
5	0.95	1.35
6	0.51	0.73

C.8. MODEL OUTPUTS IN SCENARIO 8

Table C.8: Waiting time outputs in scenario 8

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	3.42	5.22
2	4.42	6.8
3a	3.68	6.26
3b	3.28	6.06
4	0.59	1.1
5	0.18	0.22
6	8.19	12.04
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	1.9	1.49
2	1.58	1.39
3a	1.3	1.03
3b	1.12	0.93
4	0.83	0.74
5	0.83	0.98
6	0.82	0.95

C.9. MODEL OUTPUTS IN SCENARIO 9

Table C.9: Waiting time outputs in scenario 9

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	1.43	2.41
2	1.04	2
3a	0.7	1.61
3b	0.88	2.02
4	0.23	0.7
5	0.09	0.02
6	0.19	0.25
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	1.97	1.5
2	1.73	1.37
3a	1.23	1
3b	1.07	0.9
4	1.32	0.91
5	1	0.88
6	0.96	0.72

C.10. MODEL OUTPUTS IN SCENARIO 10

Table C.10: Waiting time outputs in scenario 10

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	1.43	2.54
2	1.33	2.56
3a	1.29	2.59
3b	1.1	2.56
4	0.22	0.51
5	0.06	0.03
6	0	0
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	1.9	1.44
2	1.58	1.25
3a	1.21	1.02
3b	0.77	0.96
4	1.4	0.77
5	0	0
6	0	0

C.11. MODEL OUTPUTS IN SCENARIO 11

Table C.11: Waiting time outputs in scenario 11

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	12.53	12.08
2	12.6	12.4
3a	11.49	12.37
3b	10.77	11.01
4	7.6	9.36
5	7.67	7.83
6	10.75	8.35
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.37	1.83
2	1.87	1.56
3a	1.55	1.34
3b	1.84	1.45
4	1.67	1.13
5	2.17	1.45
6	1.87	0.53

Table C.12: Turnaround time outputs in scenario 11

Vessel class	Average duration (hrs)	Sigma
1	18.18	12.38
2	17.5	12.67
3a	15.19	12.77
3b	14.73	11.38
4	11.4	9.3
5	12.33	8.78
6	14.81	8.56

C

C.12. MODEL OUTPUTS IN SCENARIO 12

Table C.13: Waiting time outputs in scenario 12

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	5.7	7.7
2	5.05	7.43
3a	4.5	6.46
3b	3.28	4.76
4	1.77	3.16
5	5.02	0
6	15.96	14.37
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	2.38	1.94
2	1.97	1.8
3a	1.66	1.6
3b	1.53	1.03
4	1.65	1.82
5	2.04	0
6	1.66	0.95

Table C.14: Turnaround time outputs in scenario 12

Vessel class	Average duration (hrs)	Sigma
1	11.1	8.35
2	9.92	8.27
3a	8.4	7.16
3b	6.52	4.62
4	5.62	3.63
5	8.34	0
6	19.93	14.6

C.13. MODEL OUTPUTS IN SCENARIO 13

Table C.15: Waiting time outputs in scenario 13

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	11.5	13.04
2	12.8	13.62
3a	13.09	14.36
3b	17.82	17.79
4	10.3	13
5	4.4	4.24
6	2.69	3.68
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	4.14	3.58
2	3.49	3.21
3a	3.71	2.84
3b	3.42	2.95
4	3.17	3.12
5	3.06	3.97
6	3.59	5.08

Table C.16: Turnaround time outputs in scenario 13

Vessel class	Average duration (hrs)	Sigma
1	19	14.83
2	19.31	15
3a	19.31	15.81
3b	23.95	18.84
4	15.66	13.68
5	9.77	7.49
6	7.39	9.21

C.14. MODEL OUTPUTS IN SCENARIO 14

Table C.17: Waiting time outputs in scenario 14

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	22.64	12.88
2	24.01	15.29
3a	23.63	13.63
3b	16.53	8.74
4	18.7	14.75
5	12.9	18.11
6	29.04	4.07
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	4.51	3.59
2	3.94	3.44
3a	4.15	3.04
3b	5.26	2.93
4	4.26	3.25
5	5.11	0.44
6	2.38	3.37

Table C.18: Turnaround time outputs in scenario 14

Vessel class	Average duration (hrs)	Sigma
1	30.37	14.33
2	30.98	16.36
3a	30.04	15.15
3b	23.94	8.94
4	25.19	15.26
5	20.67	20.26
6	34.23	1.6

C.15. MODEL OUTPUTS IN SCENARIO 15

Table C.19: Waiting time outputs in scenario 15

Waiting time at anchorage		
Vessel class	Average duration (hrs)	Sigma
1	52.76	34.7
2	57.01	35.77
3a	58.91	36.06
3b	60.71	32.33
4	54.24	39.16
5	44.43	26.33
6	122.29	4.69
Waiting time at terminal		
Vessel class	Average duration (hrs)	Sigma
1	5.37	3.11
2	4.77	2.9
3a	4.53	2.5
3b	4.7	2.41
4	4.65	2.6
5	2.34	3.5
6	5.67	2.89

Table C.20: Turnaround time outputs in scenario 15

Vessel class	Average duration (hrs)	Sigma
1	59.48	34.67
2	63.21	35.59
3a	63.92	36.27
3b	64.6	32.58
4	59.97	39.03
5	47.99	28.25
6	130.11	4.18

C

C.16. SCENARIO OUTPUTS COMPARISON

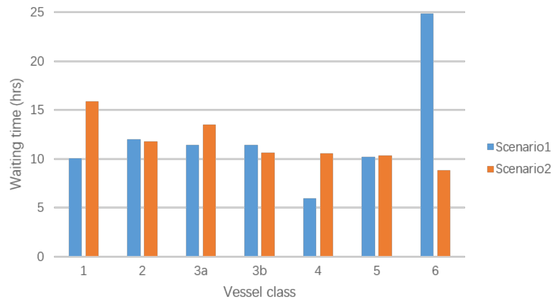

Figure C.1: Average waiting time at anchorage Scenario1 vs Scenario2

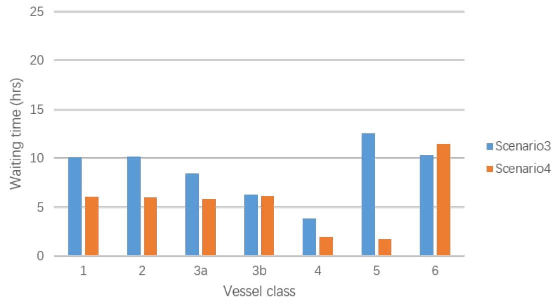

Figure C.2: Average waiting time at anchorage Scenario3 vs Scenario4

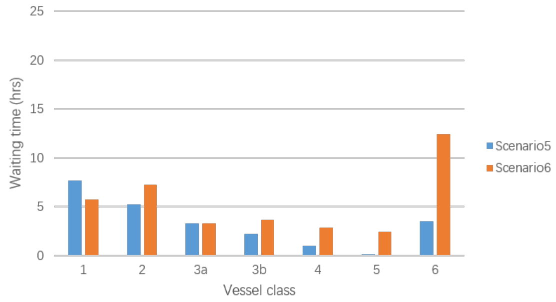

Figure C.3: Average waiting time at anchorage Scenario5 vs Scenario6

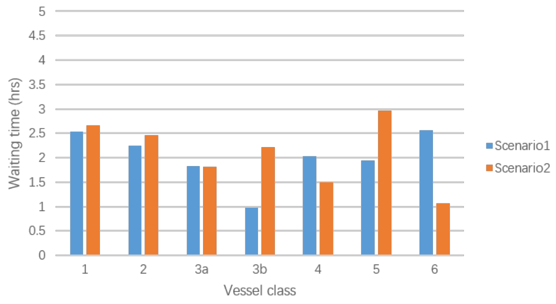

Figure C.4: Average waiting time at terminal Scenario1 vs Scenario2

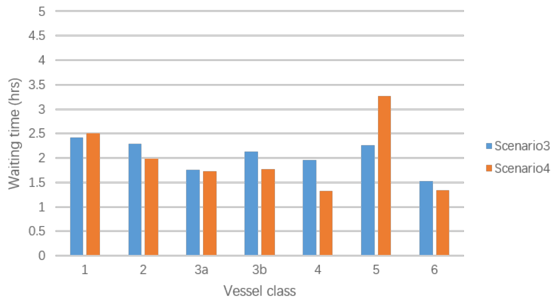

Figure C.5: Average waiting time at terminal Scenario3 vs Scenario4

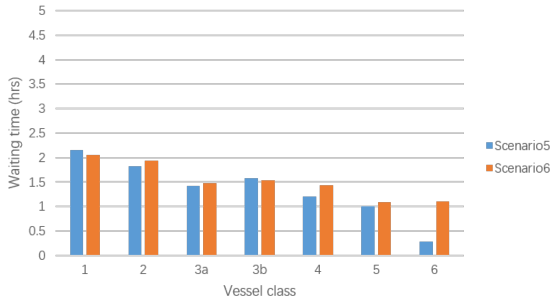

Figure C.6: Average waiting time at terminal Scenario5 vs Scenario6

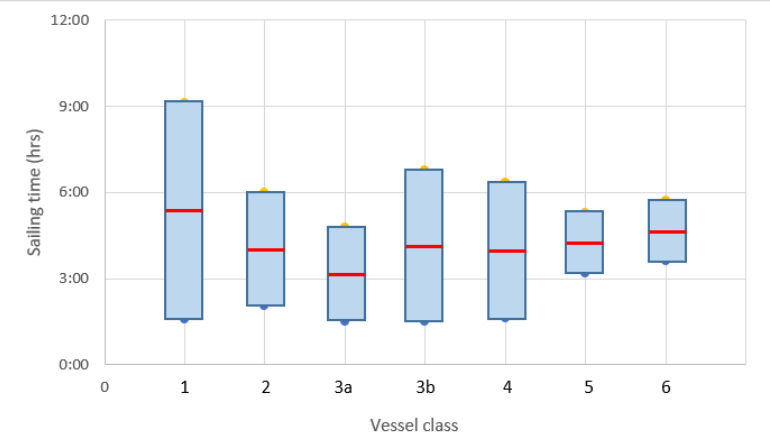

Figure C.7: Sailing time from historical data

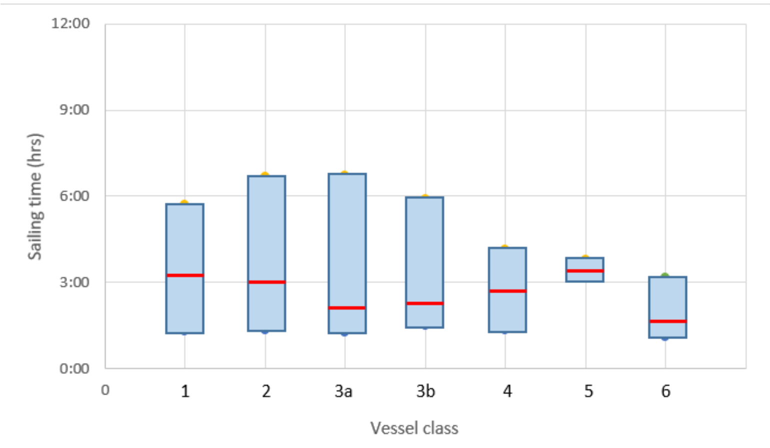

Figure C.8: Sailing time from experiment