MSc Thesis

Simulation model to assess the effective capacity of the wet infrastructure of a port

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TU Delft - Graduation Work
in cooperation with Systems Navigator

TU Delft

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Simulation model to assess the effective capacity of the wet infrastructure of a port

by

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Preface

This MSc Thesis presents the work performed during my graduation project as part of the Master Programme of Hydraulic Engineering from the Faculty of Civil Engineering and Geosciences of Delft University of Technology.

This final report represents the closure of a six-year phase that has led me from the freshmen courses of the bachelor degree, up to the final presentation of my MSc Thesis. The journey has been full of new challenges, opportunities and great experiences.

I would like to thank Tiedo Vellinga, Cornelis van Dorsser and Winnie Daamen, as members of the examination committee for your guidance and contributions. Your enthusiasm about the model during our meetings was greatly appreciated and helped me gain confidence in my research approach and deliverables.

Furthermore, I would like to thank everyone at Systems Navigator for making me feel at home at the office and teaching me the important skills of table football. I am also grateful to Rienk for giving me this opportunity and so much liberty in my research approach. I would also like to thank Alessandro. for helping me during my graduation and teaching me the life lesson of using queues in Simio.

I would also like to thank each of my room-mates. Hans, for introducing me to Rienk after your own internship at Systems Navigator. Gerrit, for sharing your Simio-knowledge and making all those coffees for me at the office, which was greatly appreciated. Sigurd, for listing to my frustrations and giving me valuable advice when needed. Wessel, for having every day that big smile on your face that warms the hearts of everyone in the house. Finally, Daan, for lending me your keyboard when mine died the night before handing in my green-light report. I think I speak for all of us when I say that we have a very special bond, which I cherish greatly.

Last but not least, I want to express my gratitude to my family, which has always supported me and allowed me to grasp so many opportunities that came my way during my time at Delft. Most importantly, I want to thank Guusje for always being by my side and giving me all the support I needed.

Aubin Macquart
Delft, October 2017

Summary

Port planning is a complex multidisciplinary subject. To fulfill its functions, it is essential that the different elements of a port work together. With this in mind, it is clear that the full potential of a terminal can only be reached when the wet infrastructure of a port (access channel, inner basins, turning circles) can keep up with the traffic load.

From the literature study, it has become apparent that simulation tools have become increasingly popular for assessing the capacity of ports and waterways. However, the application has often been aimed at a specific case study and the existing models are not easily reusable for new applications.

In this master thesis project, the assessment through a generic simulation tool of the effective capacity of the wet infrastructure of a port is investigated. The model will consider the processes taking place from the point a vessel arrives at the entrance of the access channel until the start of the (un)loading procedures and the departure of the port until exiting the access channel. The analysis capabilities of the model are demonstrated by studying the Port of Hazira.

Model Development

The building of the model is carried out in multiple phases. First, a verbal model is created which is then used as a basis for the model implementation. Finally, the usefulness and different functions of the model are demonstrated by studying the Port of Hazira.

Verbal Model

Before creating the model, a description must be given of the way reality is modelled within the system boundaries. This is done by defining the processes that will be included into the model, which are: arrival at the port, waiting at the anchorage, navigation through the access channel towards the port entrance, navigation through the port, berthing, (un)loading, waiting at berth, navigation towards the exit of the port and leaving the port through the access channel. The level of detail required for each process, input parameter and output is described.

The main processes relate to vessels obtaining authorisation to sail towards a destination. To receive this authorisation, the vessels have to find a moment when the correct weather conditions occur, the tidal elevation is adequate, the waterways are available and sufficient quay length is available. The authorisation is given in a dynamic way, depending on the dimensions of the vessels, waterways and quays.

The following assumptions are made: no down time of the terminal, the terminal is considered to be continuously available and ready to start (un)loading, vessel movement at the anchorage is not modelled, the speed of vessels is unaffected by the presence of other vessels and the number of tugs is considered unlimited.

Model implementation

The verbal model is implemented into Simio by creating specific processes that define the behaviour of vessels. Special building blocks are created, which can be easily reused in different case studies. The model consists of an input, run and output stage.

During the input stage, the user defines the dimensions and sailing rules of the different infrastructure elements of the port as well as the type and amount of vessels that arrive at the port.

During the run stage, the input parameters are read by Simio and vessels are generated. Based on their origin and destination, vessels can determine their route based on the shortest path available and waterways available depending on their vessel type. Once this is done, a vessel will construct a sailing plan by finding a suitable timeslot to through each section of the port. When doing so, a vessel takes into account the sailing plans of other vessels and the sailing rules that apply for each section. As a result, a vessel can construct a suitable sailing plan based on an origin and destination which can be applied to any port layout.

The output stage is used to process the output data of the model and produce the relevant KPIs.

To verify the correct implementation of the processes included in the model, the different features were tested separately and their behaviours were deemed adequate. Subsequently, the model was validated with AIS data available for the Port of Hazira. The validation showed promising results. Some differences were

found for certain terminals, which are found to be caused by the assumption that the terminals are always available to start (un)loading.

Case Study: Port of Hazira

For more information about this section, please contact Systems Navigator at info@systemsnavigator.com.

Evaluation of Simio

During this study, it has become apparent that many processes should be included in order to properly determine the capacity of port. Simulation software offers the possibility of including all these processes and observe their interactions in order to locate bottlenecks more efficiently.

Simio has proven to be able to incorporate all the required process in order to properly model the wet infrastructure of a port. However, it does not offer a user-friendly interface to handle different scenarios and facilitate the handling of both the input and output of the model. To this easier, an interface has been created with Scenario Navigator. This interface enable the storing and comparing of input parameters and results of different scenarios.

Ultimately, Simio is deemed to be an adequate tool for simulating the wet infrastructure of a port in a generic way. However, an additional interface is required to properly input different parameters and construct different scenarios.

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γ_β	Reduction factor for berm influence	–
γ_f	Reduction factor for slope roughness	–
ξ_p	Surf similarity parameter or Iribarren number for peak wave period T_p	–
a	Vertical motion due to wave response	m
B	Width of the berm	m
C_B	Block coefficient	$m^3/s/m$
C_t	Wave transmission coefficient	–
D	Draught	m
H_i	Incident wave height	m
H_s	Significant wave height	m
H_t	Transmitted wave height	m
h_T	tidal elevation above reference level, below which no entrance is allowed	m
h_{gd}	Guaranteed depth	m
H_{mo}	Significant wave height calculated from the spectrum	m
h_{net}	Remaining safety margin or net UKC	m
k	Blockage coefficient	–
q	Specific discharge	$m^3/s/m$
R_c	Crest freeboard, level of crest relative to still water level	m
s	Squat	m
v_s	Vessel speed	m/s

1 Introduction

During this MSc-thesis a simulation tool was developed to help assess the capacity of the nautical infrastructure of a port. The tool is demonstrated by using it to analyse the Port of Hazira. In this chapter, background information on port planning is given as well as a description of the Port of Hazira and the challenges it is facing. Finally, the research objectives and approach are discussed.

1.1. Background information

In the past, Systems Navigator has built many models to assess the capacity of logistical infrastructure. Depending on the project, the implementation of the correct model behaviour can be time-consuming. Recently, Systems Navigator has seen an increased interest from port authorities to invest in simulation models. In order to respond to this demand, Systems Navigator wants to develop a generic and reusable model with their available software, Simio, to assess the performance of the wet infrastructure of ports.

According to Ligteringen and Velsink (2012) a port has two primary functions, namely: a traffic function, acting as a nodal point by connecting water with various land modes, and a transport function, acting as a turntable for various cargo flows. To fulfil its functions, it is essential that the different elements of a ports work efficiently and coordinated. Therefore, it is important that the planning of a port is seen as a multidisciplinary activity combing all the different processes within a port. With this in mind, it becomes clear that the full potential of a terminal can only be reached when the wet infrastructure of a port (access channel, inner basins, turning circles) can keep up with the traffic load. Furthermore, it has been stressed in Scott et al. (2013) that climate change might increase the downtime of ports, due to the increased water level and occurrence of extreme weather conditions. These effects can cause breakwaters to become less effective against wave overtopping and wave transmission. Port planners must therefore be able to identify the vulnerability of their infrastructure, taking into account the future restrictions induced by climate change.

According to Bellsolà Olba et al. (2014), there is often a confusion between the term port capacity and terminal capacity. The capacity of a terminal is generally defined as the maximum throughput with a quay occupancy of 100%. However, this assumption could lead to congestion on the sea side of the terminal depending on the configuration of the port. Bellsolá Olba concluded that a suitable definition for port capacity would be: "the maximum amount of vessels that can be handled by a port, with its specific configuration, satisfying the maximum throughput feasible for the system". In Notteboom (2002) this is also referred to as the effective capacity of a system. Port planners should therefore be able to determine the effective capacity of their port as is gives a better view of the capacity of the total system.

Multiple hand calculation methods to assess the capacity of a quay are available. However, most of these methods assume that ships arrive directly at the port and ignore the navigation through the wet infrastructure. As a result, the effects of the external factors that reduce the availability of a port such as tidal and/or current windows, weather conditions, available tug boats, availability of the access channel, inner channels and turning circle, etc., are not taken into account. These factors can lead to ships having to wait at anchorage. During this time, other vessels arrive which will further increase the waiting times. Bellsolà Olba et al. (2015) investigated the use of simulation models to determine the capacity of ports. Over the past years, simulation models have tried to combine the different factors that influence the capacity of a harbour and have shown promising results compared to the available hand calculations.

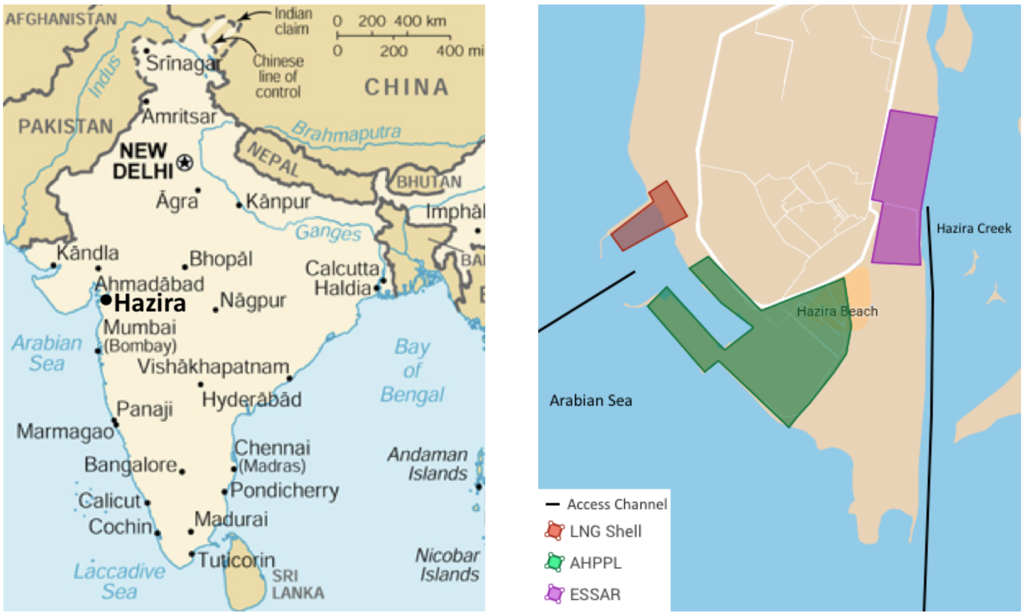
As a result, it becomes clear that port planning should be seen as an integral process, which should take into account the relevant internal and external effects. Simulation models have proven to be a useful tool in determining the effective capacity of ports. However, these models have not yet incorporated the effects that climate conditions have on the availability of the port. In this study, a generic tool is developed to assess the future performance of the wet infrastructure of a port and enabling planners to evaluate changes made to the infrastructure. The application of this tool will be demonstrated with a case study.

1.2. Case Study - The Port of Hazira

To demonstrate the usefulness of the simulation tool, a closer look at the Port of Hazira will be taken. In this section, a general description of the Port of Hazira is given as well as an overview of the challenges it faces.

1.2.1. General information

The town of Hazira is located 25 kilometers from Surat in the western part of the Gujarat region in western India, as can be seen in figure 1.1a. It is regarded as the industrial hub of India. Many companies such as Larsen & Toubro (L&T), ESSAR, Shell, Gurajarat State Petroleum Corporation, Reliance Industries, Ultra Tech Cement, Oil & Natural Gas Corporation Limited (ONGC), National Thermal Power Corporation Limited (NTPC) and Gas Authority of India Limited (GAIL) have chosen to operate from Hazira. The proximity of the Arabian Sea means big industries can transit their products across the sea easily.



(a) Map of India (b) Overview of the Port of Hazira

Figure 1.1: Map of India and Hazira

The idea behind the Port of Hazira started in 1997 when the Gujarat Maritime Board (GMB) investigated the possibilities of development of port facilities in Gujarat. In 2002, Hazira Port Private Limited (HPPL), led by The Shell Group, signed an agreement to start the construction of the LNG terminal, which started commercial operation in 2006. In agreement with the government of Gurajat, the LNG terminal had an initial capacity to handle about 2.0 Million Ton Per Annum (MTPA) and would later be expanded to a long-term throughput of 10.0 MTPA. The port development plan included the long-term port development with non-LNG cargo terminals (container and bulk terminals, and a proposed liquid terminal). In 2007, ESSAR received approval to start construction of 550 m with navigation channel and reclamation at Hazira. By 2010, the berth came into use and soon ESSAR received approval to expand by another 1100 m which is currently being constructed. In 2009, HPPL and Adani Hazira Port Pvt Ltd (AHPPL) entered an agreement for the development of 7 non-LNG berths, which came into operation in 2012. Table 1.1 gives an overview of the available berths at Hazira, while figure 1.1b shows the general layout of the port.

On the long-term AHPPL is planning to increase the number of berths to 13. The capacity of the LNG terminal was increased from 2.0 MTPA in 2006 to 7.5 MTPA in 2016, with a potential increase to 10.0 MTPA

Table 1.1: Overview of the berths available at the Port of Hazira

Company	Type of Berth	Length (m)	Capacity	Max draft (m)	Products handled
Adani	Multipurpose	860	3	14	Bulk, Steel, General Cargo
	Container	680	2	14	Container
	Liquid Bulk	500	2	14	Oil
Essar	Multipurpose	550	3	16	Iron ore, coal, limestone, finished steel products, project cargo, containers
Shell	LNG	-	1	13	LNG

in the future. The ESSAR port is currently undergoing expansion which will increase the capacity from an existing 30 Million Metric Ton Per Annum (MMTPA) to 50 MMTPA. In addition, ESSAR is planning to build a LNG terminal to import gas to keep the nearby factory running. The proposed expansion should enable the ESSAR port to import 12.5 MTPA of gas. The current and projected capacity of the different terminals at Hazira can be viewed in table 1.2.

Table 1.2: Current and planned capacity of the terminals at Hazira

Company	Capacity in 2017	Planned capactiy in 2026
Adani	31.15 MMTPA	84.10 MMTPA
Essar Bulk	30 MMTPA	50 MMTPA
Essar LNG	0 MTPA	12.5 MTPA
Shell LNG	7.5 MTPA	10 MTPA

As can be seen in figure 1.1b, both HPPL and ESSAR have dredged access channels to permit the safe entering of vessels. Both channels have been dredged to -13 CD. Their respective width of 450 m and 350 m make for a one-way access. However, the maximum allowed draft at the berths is 16 m. As a result, tidal windows are used to accommodate larger vessels. Table 1.3 shows the tidal range at the port of Hazira.

Table 1.3: Tidal range at Hazira (m)

Hazira Water levels	Astronomical Tide
Highest Astronomical Tide [HAT]	CD + 8.68 m
Mean Higher High Water [MHHW]	CD + 6.96 m
Mean Lower High Water [MLHW]	CD + 5.84 m
Mean Sea Level [MSL]	CD + 4.19 m
Mean Higher Low Water [MHLW]	CD + 2.11 m
Mean Lower Low Water [MLLW]	CD + 1.37 m
Lowest Astronomical Tide [LAT]	CD + 0.32 m

The climate at Hazira is tropical and conditions at sea can fluctuate greatly depending on the season. At Hazira, winds can become quite strong during the hot season (March-Mid June) and the SW monsoon (Mid Jun-Sept), causing large waves. According to AHPPL (2015), vessels cannot access the port when the significant waves height exceeds 1.5 m. Table 1.4 shows the historical wave data at Hazira from 1992 to 2014. These measurements reveal that the occurrence of waves above 1.5 m can be significantly higher between May and August than during the rest of the year, which limits the windows for ships to enter the port. With climate change, winds and waves are expected to become stronger which will increase the amount of time the port is unavailable.

Table 1.4: Wave height at Hazira per month for the period 1992-2014, a darker colour implies a higher occurrence (BMT Argoss)

lower	upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.5	46.8%	56.2%	47.8%	27.0%	5.5%	0.6%	0.0%	3.2%	40.5%	75.6%	63.2%	52.8%
0.5	1	41.5%	37.4%	47.1%	60.4%	51.5%	39.3%	33.6%	52.3%	44.0%	22.5%	33.2%	37.9%
1	1.5	11.1%	6.0%	4.7%	11.7%	31.9%	41.6%	49.3%	35.3%	11.3%	1.8%	3.4%	8.9%
1.5	-	0.7%	0.5%	0.3%	1.0%	11.1%	18.5%	17.1%	9.2%	4.1%	0.1%	0.2%	0.5%

1.2.2. Problem definition for Hazira

As described in section 1.2.1, the port authorities are planning a substantially increase of their throughput in the upcoming years. However, the dimensions of the access channel, tide and the weather can limit the windows available for ships to access the port. Due to the stochastic nature of these effects it is difficult for port authorities to estimate whether a port can cope with the increased traffic and which investments should be made to improve the situation in case of unacceptable ship delays.

1.3. Objectives

Considering the problem definition, several objectives have been defined for this study. Multiple research questions must be answered in order to achieve the different objectives.

1.3.1. Main objective

The main objective of this thesis is to produce a simulation tool which can assess the effective capacity of the wet infrastructure of a port in order to guide port authorities in their future investments. The usefulness of this tool should be demonstrated by means of a case study.

1.3.2. Secondary objectives

To build the simulation tool, a list of secondary objectives has been set up. On one hand the relevant stages for the model building have to be carried out, while on the other hand the Port of Hazira will be used to demonstrate the use of the model and how it can be used to help port planners. The secondary objectives are as follows:

- Identify the factors that determine the capacity of a port from a marine perspective.
- Identify all the relevant processes between the arrival and departure of a vessel at a port and implement these into a simulation model.
- Develop a tool which can incorporate different port layouts.
- Evaluate the current and future performance of the Port of Hazira.
- Identify bottlenecks in the nautical infrastructure of the Port of Hazira.
- Demonstrate the effects of changes made to the infrastructure of the Port of Hazira.
- Evaluate the use of Simio as a simulation tool to determine the effective capacity of the wet infrastructure of a port.

1.3.3. Research questions

To achieve the main and secondary objectives, several research questions will have to be answered. The main question is as follows: how should a simulation model be set-up in order to easily guide port planners in evaluating the capacity of the wet infrastructure of their port? Several other research questions will have to be answered in order to complete the objectives:

1. What is the definition of the capacity of a port?
2. Which aspects of the wet infrastructure are of interest in order to respond to the demands of port planners?
3. Which processes are necessary to implement into a simulation model in order to correctly asses the effective capacity of the wet infrastructure of a port?
4. What is the performance of the Port of Hazira for the current and projected throughput and what are the bottlenecks?
5. What are the effects of changes made to the wet infrastructure of the Port of Hazira?
6. How adequate is Simio for the assessment of the wet infrastructure of a port?

1.3.4. Scope

By completing these objectives and answering the research questions a generic simulation model for a port wet infrastructure will be created. To make the model reusable, it is important to create an algorithm that allows the implementation of different port layouts. The model should therefore be able to autonomously generate the route logic for vessels and incorporate the given traffic restrictions. Not only the nautical functions have to be implemented into the model, but also the physical characteristics playing a role for the sea-defences of the port.

1.4. Research approach

The following research approach has been adopted during the course of this thesis:

- **Literature Study**

An extensive literature study summarising the key components of port planning and performance indicators that determine the capacity of a port is performed. This should enable the answering of the first and second research question, as well as determining the Furthermore, an overview is given of past models and their functionalities. From this a list can be made of the processes that have to be taken into account can be made. This answers the third research question.

- **Verbal model**

The verbal model is used to define the model. Based on the findings of the literature study, an explanation is given of how all the different processes interact with each other and which logical steps will have to be followed by the simulation model. A clear description of the required input parameters and boundary conditions is given. The verbal model will be supported by flow charts. Whenever more information is required concerning the requirements of the model, additional literature study is done.

- **The simulation model**

Based on the verbal model, algorithms are created in Simio that incorporates all the relevant processes. During the building of the model, changes can be made to the verbal model when a specific process is found to be inadequately described. Different model features are verified and calibrated separately by running scenarios which will trigger the specific feature. Once all the features have been verified, the model is validated with AIS data from the Port of Hazira. If there is no explanation can be found for differences between the AIS data and model data, additional literature study should be done and the verbal model has to be changed accordingly.

- **Case study - Port of Hazira**

A case study is conducted to demonstrate the usefulness of the model. In this case, the Port of Hazira will studied. First of all, a scenario for the current situation is run, which serves as a reference scenario in terms of waiting times. Once this step is completed, future scenarios are run and compared with the current situation. Scenarios will be formed based on the expected throughput and expansion plans. Finally, some examples of infrastructure changes are run. The aim is to establish whether the current and future capacity is sufficient in order to handle the expected throughput and the effectiveness of different measures.

- **Evaluation of the use of Simio**

The adequateness of Simio is evaluated. The evaluation will primarily check the ability of the software to include all the relevant processes. Simio should allow the algorithm to be built in a generic way, avoiding any hard coding. Furthermore, the software has to be flexible and allow for different input values in order to easily implement multiple scenarios. Finally, the runtime should be kept at an adequate level and the KPIs should be easily derived from the model.

1.5. Report structure

- Chapter 1 - Introduction: introduces the problem definition, objectives and research questions. In addition, a description of the Port of Hazira is given.
- Chapter 2 - Literature Study: the literature reviewed for this study is described. It is divided into two phases: port planning and simulation models.
- Chapter 3 - Verbal model: based on the findings of the literature study, all the relevant processes included in the model, as well as the underlying assumptions, requirements and limitations are described.
- Chapter 4 - Model implementation: the implementation of the verbal model into the Simio environment is discussed.
- Chapter 5 - Model verification: the different features introduced in chapter 4 are verified and the model is validated with AIS data available for the Port of Hazira.
- Chapter 6 - Case study: Port of Hazira: the model is demonstrated by studying the Port of Hazira. Scenarios are run with the current and projected throughput. Changes to the infrastructure are also investigated.
- Chapter 7 - Evaluation of Simio: the adequateness of Simio for this type of application is discussed.
- Chapter 8 - Conclusions and recommendations: the conclusion drawn from this study are presented as well as recommendations for future research.
- Chapter 9 - References

2
Literature Study

The literature study is one of the preliminary steps of the MSc-thesis. The aim is to gain insight into the domain of interest and give an overview of the studies that have been carried out in the past. Their findings, recommendations and limitations will be discussed in this chapter.

In section 2.1, the different aspects of port planning and how capacity can be determined will be discussed in order to answer the first and second research question. Section 2.2 will focus on the different types of simulation models currently available. This should provide the necessary knowledge to answer the third research question. Recently, Bellsolá Olba has been conducting research concerning risk assessment of ports concerning future capacity. During his research, special attention was paid to the wet-infrastructure of ports. As a result, papers published by Bellsolá Olba form the basis of this literature study.

The literature study enables us to determine which processes have to be implemented into a simulation model in order to correctly asses the effective capacity of the wet infrastructure of a port.

2.1. Port planning

Port planning is a complex multidisciplinary subject. Section 2.1.1 focusses on the different aspects that have to be taken into account by port planners. These aspects should be incorporated into the simulation model. Section 2.1.2 introduces the different definitions of the term capacity for ports and indicators that help to determine it.

2.1.1. Master Planning

According to Taneja et al. (2009) ports have "evolved from being cargo loading/unloading locations to being crucial hubs in value- driven logistic-chain systems" (p. 1). As a result, ports should be able to cope with the demands of the volatile world market. When developing a Master Plan, port authorities try to incorporate future changes in their activities. However, these plans are made with assumptions which come with some level of uncertainty.

In Taneja et al. (2012), the flexibility of a port's infrastructure is described as a key aspect in the long-term feasibility of a port. Although the physical-infrastructure is static, an effort should be made to enable the port to handle the ever-changing demand. Although this MSc-thesis will not focus on creating a sustainable Master Plan, the developed simulation tool can serve to test the port's capacity by performing a sensitivity analysis. Multiple scenarios can be tested concerning the planned throughput of the port which can reveal potential bottlenecks. Potential changes to the physical-infrastructure of a port can be tested and evaluated to see which changes should be made to keep the same service level (e.g.: deepening or widening an access channel or building additional quay length). Therefore, it is important that the developed tool allows the user to easily make changes to the layout of a port.

In recent years, port authorities have started to include climate change in their risks assessments. According to Scott et al. (2013), climate change may cause a higher occurrence of extreme weather conditions. Wind speeds and wave height may become higher, which in turn can increase the down time of ports. Furthermore, the higher sea level renders breakwaters less effective against wave overtopping and transmission.

Given that the extent of the effects of climate change is not yet known, it is important to incorporate multiple scenarios into the planning process. In Scott et al. (2013), it is stressed that climate adaptation can be partly done through technological, engineering, planning and design changes. Port authorities should therefore be able to evaluate the vulnerability of their system while taking into account more extreme weather conditions and higher sea levels. A simulation model can be used to run different climate scenarios. By implementing the necessary calculations, the downtime due to more extreme weather conditions and a higher water level can be better quantified. The simulation model proposed in this study should therefore incorporate the dimensions of the breakwaters in order to compute the effects of waves on the downtime of the port. This may lead planners to decide to improve the effectiveness of a breakwater or compensate the additional downtime by increasing the capacity of a port in order to handle more ships outside of the port shut down period.

As a result, the tool developed in this study should help planners to assess their assumptions and uncertainties. The model should be built in such a way that allows planners to test multiple configurations of their port and incorporate climate change factors.

2.1.2. Capacity of a port

The aim of this study is to develop a tool which can determine whether the nautical capacity of a port is sufficient to cope with the planned throughput of the terminals. Before being able to answer this question, one should take a closer look at how the capacity of a port is defined and how it can be assessed.

Definition

In Bellsolà Olba et al. (2014), capacity is seen as "a relevant indicator that helps to identify the main constraints of any network and allows the evaluation of the performance of a system (port) in economical or safety terms". However, the current port capacity definition often refers to the capacity of the terminals but does not consider the transport system. Bellsolá Olba defines two types of capacities: link capacity, used to define the capacity of an isolated stretch, and network capacity, defined for the whole combination of links or nodes and their interactions.

When studying link capacity definitions, Bellsolá Olba found the capacity is defined by looking at the maximum traffic or throughput during a certain time period through a specific cross section. For the infrastructure of ports, the flow of vessels can be measured through a specific channel. However, the capacity can be limited by other factors such as availability of berths, crossings and turning basin. Bellsolá Olba defined the link capacity of a port as: "the maximum flow to be handled by a given cross section or location satisfying the requirements on navigation and safety level". This definition expresses the maximum link capacity as a relationship between the layout, fleet composition, safety level, traffic rules and demand.

Since a port is compromised of different links interacting with each other, network capacity is an important factor in port planning and management. Bellsolá Olba stated that there is often a confusion with the term port capacity and terminal capacity. The capacity of a terminal is defined as the maximum throughput with a quay occupancy of 100%. However, this assumption could lead to great congestion on the sea side of the terminal. When considering the capacity of the port, it is important to realise that travel delays increases with increasing flow because of congestion. Bellsolá Olba concluded that a suitable definition for port network capacity would be: "the maximum amount of vessels that can be handled by a port, with its specific configuration, satisfying the throughput feasible for the system".

In Notteboom (2002) three different types of capacities are distinguished for ports: physical capacity, effective capacity and economic capacity. Physical capacity is defined as "the maximum capacity at which the system can be used on a permanent basis, without any external restrictions". The effective capacity is described as "the greatest possible capacity at which the structure can operate, taking into account the external circumstances in which the physical capacity is utilised". Lastly, the economic capacity is "that part of effective capacity which is used with the greatest possible economic and commercial yield" (p.41).

The definition for network capacity proposed by Bellsolá Olba best fits the definition of the effective capacity as described by Notteboom. As this study aims to link the capacity of a port to the external factors effecting it, this study will focus on determining the effective capacity of a port. The physical capacity is considered to be of limited interest as it does not take into account enough factors, while the economic capacity is considered to be outside the scope of this study. This study will therefore refer to capacity as the network capacity defined by Bellsolá Olba.

After having investigated the theoretical scope of the capacity of a port network, Bellsolá Olba looked to several calculation methods. Queueing theory has often been used to estimate waiting times of ships and quay occupancy rates and relate this to the capacity of a port. However, many simplifications have to be made concerning facilities and complex variables. Simulation models offer the possibility to include these aspects and compute more realistic waiting times and give a better idea of the total capacity of the system.

Simulations model have already been used in the past to evaluate port capacities. An overview of these models will be given in section 2.2.

Performance indicators

As stated above, this study will focus on the development of a simulation model that has to assess the effective capacity of a port. With this in mind, it is important to define a set of indicators which will be used to evaluate the capacity and compare different scenarios with each other.

In UNCTAD (2002) a list of indicators has been set-up to quantify the efficiency of a port:

- Quay occupancy rate for each homogeneous group of berths.
- Average time spent by ship at berth loading/discharging.
- Ratio between the processing time and the total turnaround time of vessels.
- Average waiting time of a ship.

Although a high occupancy rate (> 70 %) is a potential sign of congestion and a low utilisation (< 50 %) a sign of underutilisation, Ligteringen and Velsink (2012) pointed out that occupancies of 35 % are not uncommon due to the conditions imposed by shipping lines with respect to minimum waiting times.

Furthermore, UNCTAD (2002) specifies different performance indicators concerning the amount and type of cargo handled by a quay such as the average throughput per day or the time spent by cargo in port storage. However, these figures require detailed data from the terminal, which is not necessarily available.

As a result, the simulation model will mainly focus on the producing the following performance indicators: occupancy rates, waiting times and processing times. To compare different berths and cargo types, the ratio between the processing time and total turnaround time will be calculated.

2.2. Simulation models

As stated before, simulation models allow to incorporate multiple processes that may influence the capacities of ports and give better results than the available hand calculations. This section elaborates on the different aspects related to using a simulation model. Section 2.2.1, introduces discrete event simulation, which is implemented by Simio. Section 2.2.2 gives an overview of the capabilities and limitations of simulation models that have been developed in recent years to assess the infrastructure of a port. Lastly, two existing models will be analysed and compared.

2.2.1. Discrete event simulation

The simulation model that will be built during this research will be made in the discrete event simulation software Simio. Discrete event simulation implies that the modelled system is seen as a discrete sequence of events over time. Whenever an event is set to occur, it triggers a change in the state of the systems and can proceed to the next event to be triggered.

With continuous simulation, the model and state variables are continuously updated. This method produces a higher level of accuracy. However, all the processes have to be updated which requires a lot of computational power. Due to the large amount of processes that can be required in order to correctly model a certain system, continuous simulation results in rather long run times. In turn, this causes models to be less attractive for extensive use. Ultimately, the choice between discrete event and continuous simulation is a trade off between accuracy and run time.

Given the amount of processes that have to be included to correctly simulate a port, discrete-event simulation offers the possibility to limit the run time of the model while including all the relevant processes.

2.2.2. Current simulation models

In the past years, simulation models have been made in order to simulate the wet infrastructure of a port or waterway. Bellsolà Olba et al. (2015) identified the main navigational processes and operations related to the port wet infrastructure and assess the current port simulation models.

Bellsolá Olba divided his assessment into two parts: the representation of the wet infrastructure and the modelling of the navigational characteristics. Ideally all port infrastructure parts should be included in a model, which are: 1) wet infrastructure, 2) anchoring, 3) berthing and 4) terminal(s) operations, 5) pilot/tug assistance and 6) traffic rules. Moreover, the main elements that affect navigation depending on each type of vessel are: 1) vessel arrival process, 2) fleet considered, 3) influence of infrastructure design or vessel encounter on navigation, 4) path choice possibility, 5) speed variation, 6) external effects and 7) risk assessment.

Model	Vessel arrival process	Fleet generation	Influence on vessel navigation	Path choice	Sailing speed choice	External conditions	Risk assessment	Goal
Harboursim (Groenveld, 1983)	N	✔	✘	✘	~	V S W T	✘	Port planning and expansion.
(Park and Noh, 1987)	N	✘	✘	✘	✘	✘	✘	Port planning,expansion and economic analysis.
(Hassan, 1993)	H	✔	✘	✘	✘	T	✔	Port planning, expansion and economic analysis.
(Thiers and Gerrit, 1998)	P	✔	~	✘	✔	T	✔	Port planning and expansion.
(Demirci, 2003)	N	✔	✘	✘	✘	✘	✘	Investment planning.
(Yeo et al., 2007)	P	✘	✘	✘	✘	✘	✘	Evaluate port traffic congestion.
(Almaz and Altiok, 2012)	H	✔	✘	~	✘	T	✘	Delaware River simulation (waterway)
(Piccoli, 2014)	E	✔	✘	✘	✘	T	✘	New port simulation assessment
(Hasegawa et al., 2001)	H	✔	✔	✔	✔	✘	✔	Vessel traffic in a bay
(Goerlandt and Kujala, 2011)	P	✔	✘	~	✘	✘	✔	Assess risk in vessel navigation
(Huang et al., 2013)	H	✔	~	~	✘	✘	✔	Waterway network simulation
(Rayo, 2013)	N	✔	✘	✘	~	V W T C	✘	Approach channel assessment

Abbreviations: Vessel arrival process: N = Negative exponential distribution, P = Poisson distribution, E = Erlang-1 distribution, H = Historical data.
External conditions: V = Visibility, S = Storm, W = Wind, T = Tidal conditions, C = Current.

Table 2.1: Overview of the capabilities of developed simulation models (Bellsolà Olba et al. (2015))

Table 2.1 gives an overview of the main capabilities of the models Bellsolá Olba studied. It was found that most models do not consider all the parts of the infrastructure layout. Especially anchoring operations have not been extensively implemented. Berthing can be modelled in two ways: independent of terminal operations or as a joint operation, neglecting the modelling of the manoeuvring. Most models consider the operations of tug boats, proving its importance. However, most models consider an unlimited amount of tugs available which can lead to a rather high vessel traffic. Furthermore, models mostly simulate a simplified amount of traffic rules. When considering the navigational behaviour, Bellsolá Olba observed that fleet generation plays is a very relevant for port traffic modelling and the diversity of vessels is essential in making the model realistic. Preferably some influences on vessel navigation should be included in order to assess the effect of different port layouts. Currently, simulation models have not yet implemented free path choice and only some models have variables speeds. Finally, external conditions have only seen limited implementation. Although the effects of tidal windows have been assessed by multiple models, detailed external conditions (e.g.: wind, wave, current) have not been extensively implemented.

From his research, Bellsolá Olba produced an overview of the main input parameters that should be included when setting up a model. An overview of the main aspects that have to be taken into account can be found in table 2.2. It is important to note that Bellsolá Olba was only interested in the correct modelling of the complete wet infrastructure irrelevant of the aim of the study for which it is intended. This study aims to develop a generic model and should therefore incorporate as much of these aspects as possible provided their relevance for the main objective. However, some of these aspects are extremely case specific such as the behaviour of tugs and the behaviour of vessel at anchorage. Furthermore, the behaviour of these aspects are depended on the planning made port authorities. The implementation of these aspects therefore seem inadequate for a generic model.

From table 2.2, one can note that Bellsolá Olba has not considered the implementation of the physical infrastructure, such as breakwaters. As previously stated, the model developed in this study has to be able to assess the effects of waves and sea level rise. The correct implementation of the physical infrastructure is therefore also important.

From the list of models considered by Bellsolá Olba, two models were found to have some similarities with the model that is being developed in this study. The first model, developed by (Rayo, 2013), aimed to produce a generic and reusable model. Given that this study aims to produce a generic model, the modelling

Table 2.2: Overview of the different aspects of a simulation model

Input	Description
Anchorage	Anchorage should not be considered a simple queue line.
Tugs/pilots	Simulating tugs is necessary. Tugs and pilots should not be assumed to be infinite.
Vessel arrival	New port can best be described newline with negative exponential distribution. Historical data should be used if available.
Fleet generation	Different types of ships should be generated with specific dimensions and navigational characteristics. Ideally, variable ship speeds should be implemented.
External conditions	Tidal windows have proven to have a great effect on the capacity of ports. Other external conditions should only be included correlation can be found with vessel behaviour or port operations.

approach used by Rayo will analysed. More recently, (Piccoli, 2014) produced a model in FlexSim for a specific case study. FlexSim proposes the same type of modelling environment found in Simio and will therefore be analysed.

- **Rayo, 2013**

Recently, Rayo (2013) developed a simulation model for the assessment of approach channels using Matlab. An aim of this simulation model was to evaluate the difference between a one and two-way channel. Literature dictates the dimensions of such channels but does indicate any threshold value for the amount of ships a certain layout can handle. Rayo identified that the following processes of a ship were of interest:

- Arrival at port
- Wait at anchorage
- Navigation toward the berth
- Berthing
- (Un)loading
- Wait at berth
- Navigation towards open sea
- Leave port

For his model, Rayo considered the outer edge of the access channel and the turning circle, fixed to the inner edge of the access channel, as the physical boundaries. Some basic interactions between ships such as overtaking, encountering and minimum distance between ships are also taken into account. Rayo included the effects of tug boats in the travel time from the turning circle to the berth. However, the model assumes an unlimited amount of tugs available. The time spent at a berth was based on typical service rates found in literature.

The model was built in such a way that the traffic rules are determined dynamically, depending on the dimensions of the vessels and dimensions of the waterway. The traffic rules are therefore not hard coded and therefore become more flexible. Although Rayo only applied this method to the access channel, his approach can be extended to all waterways of the port. However, by only considering the access channel, Rayo only had to deal with one waterway. If the model is to be extended to multiple waterways, an algorithm has to be created for vessels to check the navigation conditions in all the waterways it will utilise before sailing.

Rayo validated his model in two stages. Firstly, different features of the approach channel where evaluated separately, such as sailing distances between vessels and overtaking in two-way channels. By testing every feature separately, it is easier to locate mistakes and solve them. The time step was chosen by looking at deviation of sailing times through the access channel with the theoretical sailing times. The second stage consisted of validating the entire model. As no information from a real port was available, Rayo compared his results with the results of queueing theory. To do this, a simplified port was made and results showed a high correlation. An attempt to validate the model with results of existing models proved more difficult. Rayo estimated that this was due to the difference in level of detail of other models and recommends trying to validate future models with real data instead.

In conclusion, Rayo created a generic model by implementing dynamic traffic rules which could be determined by the model in accordance with the dimensions of the waterway. This method can be reused in this study and further developed to include all sections (outer and inner basins) instead of being limited to the access channel. Furthermore, validation can take place by building a limited model which can be checked with the theory of queueing theory. Real data may also be used if available.

- **Piccoli, 2014**

Recently, Piccoli (2014) developed a discrete event simulation model in FlexSim. In her case study, the Port of Jebel Dhanna was considered. This port planned to double he throughput and an assessment had to be carried out to determine whether congestion of the access channel would become a limiting factor. One of the main objectives of her model would be to output waiting times, while specifying their origins. Piccoli identified the same processes as Rayo.

Piccoli's model simulates all the operation between the arrival and departure of vessels, including the approach channels and anchorages. Interestingly multiples routes are available depending on the type and dimensions of the vessels. The following assumptions were made: unlimited tugs, pilots, and places at the anchorages; no acceleration and deceleration rates; and same spacing (in minutes) between all vessels in the one-way sections (irrespective of the vessels size or type of cargo). To properly evaluate the performance of the studied port, Piccoli decided to focus on de following KPI's: waiting time divided by the turnaround time, waiting time divided by service time and berth occupancy. The sources of delays were identified as: tidal window, berth availability and channel availability due to traffic regulations. In her model Piccoli decided to ignore the effect of weather conditions for the availability of the port.

Unfortunately, Piccoli developed her model for a specific case, the Port of Jebel Dhanna. As a result, the model does not allow for changes to be made to the layout of the port. This means that it is inadequate for a generic use.

Piccoli validated her model by comparing turnaround times from AIS data with model results. However, some of the AIS data seemed inconsistent with the expected behaviour of vessel. Without further knowledge, no explanation could be found for these inconsistencies and the model behaviour could not be adapted. As a result, the model showed some differences with the actual data. Although validating the model with AIS data seems to be the ultimate validation, the real time operations may divert from planned operations and cannot necessarily be implemented into a simulation model. It is therefore important to treat AIS with caution.

In conclusion, Piccoli has created a case specific model, which is not suited for the objectives of this study. However, Piccoli has set-up a certain amount of output parameters which determine the performance of a port and can be implemented into the new model. Piccoli showed that validation of the model with AIS data may be a complicated task due to inconsistencies in data. One can therefore not expect a perfect validation of the model with AIS, but only an indication of the expected results.

- **Conclusion**

Piccoli and Rayo used very different approaches for their models. While Piccoli created a model to asses a specific port, Rayo created a general tool to asses a part of a port, namely the approach channel. The first leads to a higher level of detail, while the second creates a more general and reusable approach. Rayo and Piccoli identified the same processes that must be included in order to correctly model the wet infrastructure of a port. These will therefore also form the basis for the new model. Piccoli also focussed on the required output parameters of her model. These will be reused in the new model.

Given that this study aims to create a generic model, the modelling used by Rayo will be adopted and applied to the entire wet infrastructure. An algorithm will have to be built to link different sections of a port with each other.

Rayo validated his model with queueing theory but recommended using AIS data, which was done by Piccoli. Given the inconsistencies that can be found in AIS data, it is proposed to start validation of the new model with queueing theory and proceed to validating the model with AIS data if the data available allows for it.

2.3. Conclusion

In this chapter, the ambiguity of the term port capacity has been brought to light. This study will focus on evaluating the effective capacity of the wet infrastructure of a port, defined as "the maximum amount of vessels that can be handled by a port, with its specific configuration, satisfying the throughput feasible for the system" (Bellsolà Olba et al. (2014)).

Based on previous models, the following processes will be included: arrival at port, waiting at anchorage, navigation toward the berth, berthing, (un)loading, waiting at berth, navigation towards open sea and leaving the port. The following KPI's are of interest in order to assess the capacity of the port: waiting time divided by the turnaround time, waiting time divided by service time, berth occupancy.

Before building the model, a verbal model will be set-up to bring to light all the process that will be taken into account and their limitations.

3
Verbal Model

Before building the algorithm of the simulation model a verbal model has been set-up. The verbal model describes with words the simulation model. In other words, a description is given of how the real system will be translated into a simulation model. Section 3.2 defines the considered system and boundaries, while section 3.3 explains the assumptions made in the model. In section 3.4 the relevant processes and their interactions are addressed. Each of these processes are then further explained in the following sections.

3.1. Model requirement

The model serves as a generic tool to investigate the effective capacity of a port. In order to do so the model must perform the follow tasks:

- Evaluate the ability to handle a certain traffic load.
- Locate bottlenecks in the infrastructure of a port.
- Evaluate the downtime of a port due to weather conditions.

3.2. System boundaries

The simulation model enables the user to make an assessment of the wet infrastructure of a port. To do so, 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.

In this model, the quay acts as a physical boundary, the navigation of ships temporarily stops in order to allow for (un)loading procedures. The processes taking place at the terminal will not be extensively modelled. While the activities at the berths are not of interest for this study, they have to be realistically included in the model as they determine the occupancy of a berth and availability to other ships. As a result, it directly affects the waiting times of ships, hence requires a proper implementation. Historical data can be used to estimate the time a vessel spent at the berth.

It is important to note that this historical data should only take into account the time a vessel has spend (un)loading and not the total time spend at the quay. After (un)loading, the vessel can be forced to spend more time at the quay if the sailing conditions are not appropriate. However, this extra time has to be determined by the model and not by the processing time of a vessel.

3.3. Assumptions and limitations

Given that this model should be of generic use, a certain amount of processes are left out as they are very case-depended and cannot be generalised. Therefore, the following assumptions are made:

- The model will not take into account downtime of the terminals due to maintenance or unforeseen incidents.
- While the number of berths is limited, the terminal is considered to be continuously available and ready to start (un)loading.
- The vessel movements at the anchorage will not be modelled. It will be assumed that enough space is available for the waiting ships to manoeuvre properly.

- When two-way traffic is simulated and encountering or overtaking occurs, the speeds of vessels will be considered as constant and unaffected by the presence of other vessels.
- The amount of available tug boats is considered to be unlimited and the behaviour of tugs will not be modelled. Whenever a vessel requires the assistance of a tug boats, the maximum speed of that vessel will equal that of a tug boat.

It is important to realise that these limitations and assumptions can limit the usability of the model. Given that certain constraints placed of vessels are not simulated, the model may produce shorter turnaround times and therefore underestimate waiting times. As a result, the capacity of a port can be overestimated.

Therefore, the user of the model should check whether the considered terminals are not too often unavailable and whether the number of tugs used during the simulation resembles the number of tugs available. If this is not the case, a correction factor can be determined based one the difference between the simulation results and historical data. The user can decide to apply this factor to the simulation results and compensate for the effects of the assumptions made in the model.

3.4. Processes

Based on the findings of the literature study, the following processes are modelled:

- Arrival at the port
- Wait at the anchorage
- Navigate through the access channel towards the port entrance
- Navigate through the port
- Berthing
- (Un)loading
- Wait at berth
- Navigate towards the exit of the port
- Leave the port through the access channel

A flowchart showing the interaction between these processes is shown in figure 3.1. Vessel are generated based on the input data and log the relevant data in order to produce the desired KPIs once they have left the port.

3.5. Input parameters

To properly model a port, a certain amount of input data must be defined beforehand. These parameters influence the behaviour of vessels and allow to determine whether authorisation can be granted to vessels to sail towards the port. The following parameters have to be specified by the user:

- Weather conditions: preferably historical data of offshore wave heights and wind conditions;
- Tidal variations: the effects of the tide will be modelled using tidal constituents;
- Water depth: depth limitations of the different sections a vessel can access;
- Speed limitations: when applicable speed limitations in the approach channel and different parts of the harbour;
- Operational hours: opening hours of the port and operational windows of the terminals;
- Quays: available quay length and amount of berths;
- Breakwater: dimensions of the breakwater;
- Arrivals: amount and type of arrivals per company and possible berths.

The amount of arrivals are specified per year. This means that any seasonality in the arrival pattern cannot be taken into account.

3.5.1. Tidal variations

To model the effects of the tide, the model makes use of tidal constituents. By using these components, the tidal elevation can be computed using the following formula:

$$\eta(t) = a_0 + \sum_{n=1}^{N} a_n cos(\omega_n t - \alpha_n) \tag{3.1}$$

Where:

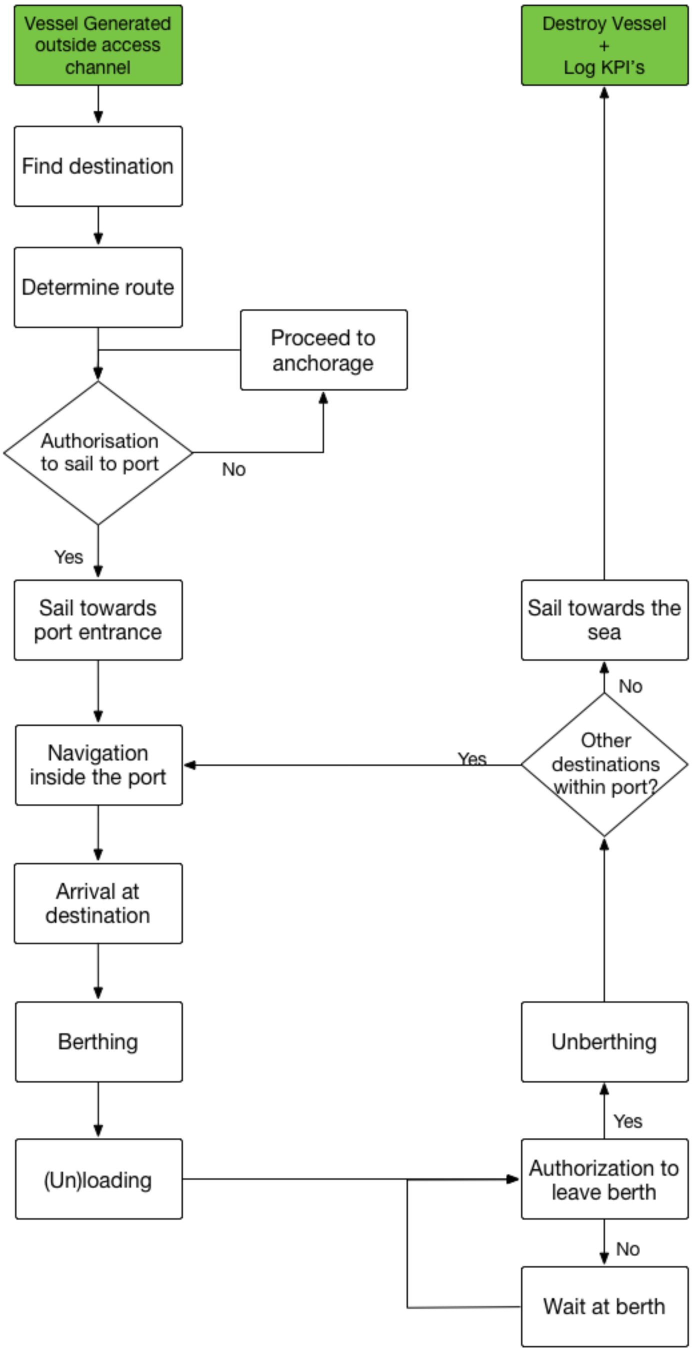


Figure 3.1: Overview of the main processes of the model

$\eta(t)$: tidal level with reference to chart datum (m)
a_0: mean level (m)
a_n: amplitude of component number n (m)
ω_n: angular velocity of component number n (1/hr)
α_n: phase angle [-] of component number n (-)
t: time (hr)
N: number of harmonic components

3.5.2. Breakwater

Depending on the weather conditions, a port can halt activities or even shut down completely and force ships to temporarily leave the quay. Different types of weather thresholds can be distinguished. Certain thresholds can be directly linked to the current weather conditions, such as the threshold wind speed. However other thresholds, such as the wave height within the harbour or the amount of overtopping, are more complex to determine.

Both wave transmission into the harbour and the amount of overtopping are dependent on the dimensions of the breakwater and the combination of wave height and water level. The required calculations are explained in A.3. To perform these calculations, the following parameters of the breakwater must be specified:

- Height of the crest;
- Width of the crest;
- Slope of the breakwater on the sea-side;
- Type of material used for the revetment.

It is important to note that these calculations do not take into account diffraction at the entrance of a port. Furthermore, the effects of short waves entering through the entrance of the port is not taken into account when determining the downtime of the port.

3.6. Vessel generation

In general, the arrival process of the ships is stochastic. Ideally, the arrival pattern of vessels should be determined by fitting a distribution function to historic data. In case insufficient data is available to produce a correct distribution, standard distribution functions will be used based on the type of arrival. When the arrival times between ships are completely random the negative exponential distribution (N.E.D.) is often used, while the vessels with a regular arrival pattern follow an Erlang-K distribution.

Based on historic data or traffic forecasts, a list of vessels per company can be generated. Each company can then pick randomly vessels from this list according to the assigned inter arrival times. Each generated ships receives the following parameters:

- Type of cargo handled;
- Company name;
- Dimensions: length (LOA), width, draught and deadweight;
- Thresholds: wave height and wind speed;
- Priority number.

Once a vessel has been generated it can search for a possible destination.

3.7. Finding the destination and route

Once a ship has been generated it will start searching for a possible destination. In order for a destination to become eligible for a vessel, it must be able to handle both the vessel type and associated company.

Once a list of potential quays has been established, a vessel has to check whether there are other vessels at the anchorage which are waiting for the same destination to become available. If this is the case, the vessel will proceed to the anchorage, where it will wait for the other vessels to have left the anchorage. Whenever the anchorage does not contain any relevant vessels, the vessel can proceed to checking whether the quay has enough space available to receive it.

According to Ligteringen and Velsink (2012), the required quay length in order to determine whether a berth is capable of receiving a ship should be calculated by evaluating equation 3.2.

$$L_q = \begin{cases} L_s + 2 * 15 & \text{for } n = 1 \\ 1.1 * \sum\limits_{i=1}^{n} (\bar{L}_{i,s} + 15) + 15 & \text{for } n > 1 \end{cases} \tag{3.2}$$

with:

L_q: required quay length (m)
L_s: length of the ship (m)
n: number of ships using the quay (-)

When multiple quays are available, a vessel will select the one where it will utilise the most space in order to leave the other quay available for larger vessels. In the case where no adequate quay is found, the vessel will wait at the anchorage until a quay is released.

Once a suitable destination has been found, the vessel will determine the route to follow based on the shortest route possible. Once the route has been determined, authorisation to sail towards the port can be requested.

3.8. Authorisation to sail to the port

Before a ship can proceed towards the port, the following checks must be carried out:

- Status of the port
- Sailing conditions
- Infrastructure availability

3.8.1. Status of the port

A vessel can only access the port if it is operational. There can be multiple reasons why a port is not operational:

- Working hours/days: certain ports may not be open 24 hours a day or in the weekends.
- Weather conditions: weather conditions (wave height and wind speed) might lead to dangerous working conditions which can result in a halt in operations in the port or closure of the port.
- Time of day: some access channels may only be navigated under daylight conditions.

As described in section 3.5.2, port operation may cease under a certain combination of water level and wave height. Depending on the situation, the model should evaluate the extent of the consequences of the weather conditions for the activities within the port. The limiting wave heights within a port are shown in table 3.1, while the limiting wave overtopping can be found in table 3.2.

Table 3.1: Limiting wave height H_s (Ligteringen and Velsink (2012))

Type of vessel	**Limiting wave height H_s** (m)
General Cargo	0.8
Container, Ro/Ro ship	0.5
Dry Bulk (30,000-100,000 t); loading	1.0
Dry Bulk (30,000-100,000 t); unloading	0.9
Tankers 30,000 t	1.5
Tankers 30,000-200,000 t	1.1
Tankers > 200,000 t	1.2

Table 3.2: Limiting wave overtopping (Ligteringen and Velsink (2012))

Hazard type and reason	**Overtopping** in l/s/m
Significant damage or sinking of larger vessels	> 10
Damage to buildings, structure elements	> 1

3.8.2. Sailing conditions

A vessel requires certain sailing conditions in order to safely reach the port, such as:

- Suitable weather conditions
- Sufficient depth

Depending on the type of vessel, certain threshold weather conditions apply. This may apply for wave height, wind speed and the velocity of currents.

The required depth for ships will be computed based on the method described in appendix A.1. However, it is important to note that a ship needs enough sailing depth during the entire voyage through the channel.

The vessel will calculate its time of arrival into every section of the port and check whether the tidal elevation at that time and location is sufficient.

Currents are more difficult to model, as they are extremely site dependent and therefore difficult to predict. However, whenever a dataset is provided with expected current velocities, vessels can use it to estimate the required sailing distances between ships.

3.8.3. Availability infrastructure

Based on the origin and destination of a vessel, the availability of different infrastructure elements along the route has to be checked. Depending on the layout of the port, these elements may be of the following type:

- Approach channel(s)
- Inner channel(s)
- Turning circle(s)
- Berth(s)

Some infrastructure elements may be used simultaneously depending on the size of the vessels. When this is the case, the model should check the dimensions of the vessels it will encounter and determine whether safe travel is possible.

Depending on the input parameters of the different sections, one- or two-way traffic may be allowed. The sailing rules through these sections will be determined based on the PIANC manual, as described in appendix A.2. In case of a one-way section, ships will have to check whether other ships are currently using the section and their sailing direction. In case of a two-way access channel, a vessel will have to check whether the maximum width of the upcoming vessels allows encountering. If this is not possible the vessel will wait and re-evaluate the maximum width whenever a ship leaves the section. However, special navigational rules apply for certain ships. For instance, LNG ships are not allowed to encounter other vessels. This condition temporarily disables two-way traffic.

Certain locations, such as turning circles, can only be occupied by one ship at the time. This may cause vessels to wait before being able to proceed. Figure 3.2 shows two ships with different origins and destinations. Ships A is travelling from point 1 to point 4 (green line), while ship B wants to travel from point 5 to point 1. Both ships have to pass through the same turning circle (point 2). The first vessel has already claimed point 2 and the channels in direction of point 1 and 4. As a result, the second ships must wait for the first ship to release the turning circle before being able to proceed. However, it may already sail through point 3 as it has not yet been claimed.

To prevent deadlocks, the vessels will schedule their entire route before sailing towards the port. By taking into account the schedules of other vessels, a suitable time slot can be found for every section without having ships hinder each other.

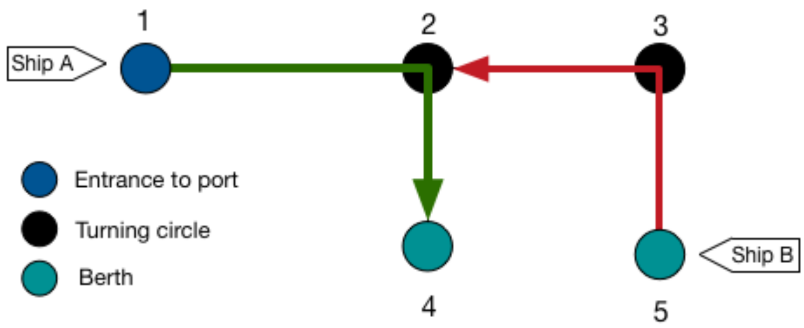


Figure 3.2: Example available infrastructure

Once all the requirements are met and a suitable time slot has been found for sailing, the vessel can start navigating towards the port. If one of the requirements is not met a ship will proceed to the anchorage location and wait for the appropriate conditions.

3.9. Anchorage

Whenever a vessel cannot proceed directly to the berth, it will proceed to the anchorage location. Here it will wait for a certain event to be triggered (e.g. a quay being released or a change in weather conditions), before requesting authorisation to access the port as described in section 3.8.3. Once all the requirements are met, the ships can proceed towards the approach channel. Furthermore, different level of priority may apply, which can change the order in which ships enter the port.

3.10. Access channel

The sailing speed in the approach channel will be considered constant up until the point of final deceleration. Ships will check before entering the access channel that sufficient distance is kept with preceding ships. The distance required for ship to slow down to the required sailing speed for sailing inside the port can be calculated with equation 3.3. The final stop stoppage length at the turning circle is estimated at $1.5 * L_s$.

$$L = (v_s - 2)\frac{3}{4}L_s \tag{3.3}$$

in which:

L: distance required for slowing down (m)
L_s: length of the ship (m)
v_s: speed of the vessel (kn)

3.11. Navigation inside the port

Once the vessel has reached the end of the access channel, it will start navigating through inner channels. Occasionally a vessel may arrive at a section where special operations may apply, such as turning circles.

In the case of a turning circle different rules apply compared to waterway sections. A turning circle can only be used by one ship at a time. An estimation of the time a vessel spends at a turning circle will be related to the deadweight of the vessel.

Once a ship has arrived at his destination, berthing procedures will take place.

3.12. Berthing

Upon arrival at the quay, the berthing procedure can commence. The berthing speed depends on the deadweight of the ship, as can be seen in figure 3.3. In the model, the berthing time will be estimated based on the deadweight of vessels. The berthing procedures will only be modelled at a high aggregate level, an estimation of the time spend berthing will be made by the user of the model. Once the berthing procedure is completed, (un)loading procedures may commence.

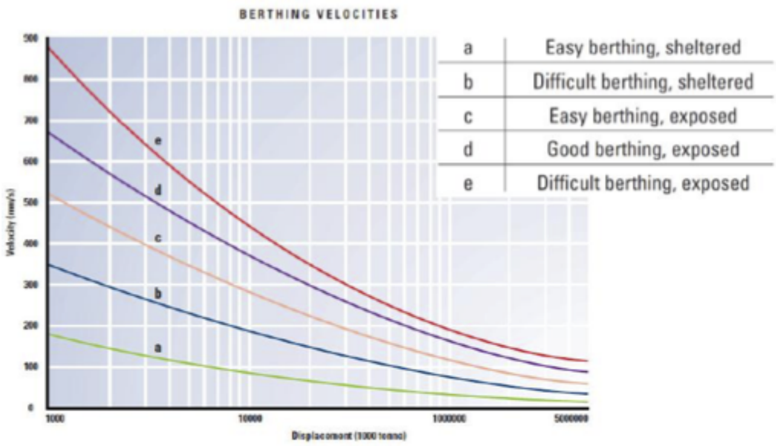


Figure 3.3: Berthing speed as a function of the displaced volume and berthing conditions (Ligteringen and Velsink (2012))

3.13. (Un)loading procedure

As stated before, the procedures at the terminal are not included in the scope of this model. However, a proper estimation has to be made of the time a vessel spends at a quay in order to properly simulate the utilisation and availability of the berths.

3.14. Authorisation to leave the berth

Once the operations at the berth have finished, a vessel will try to reach the next destination. This may either be another quay within the port or leaving the port completely.

In both cases the vessel will have to request permission to leave the berth. This permission can only be granted if all the infrastructure sections are available, as described in section 3.8.3. Depending on the situation certain steps may be skipped. For instance, a ship that leaves the port does not have to check whether sufficient quay length is available.

If the authorisation is not granted, the ship will wait at the berth until permission to leave is given. Once a vessel can leave the berth it will proceed to the next destination.

3.15. Sail towards the sea

When a vessel has finished all the operations it has to carry out within the port, it can sail toward the sea and leave the port by using the approach channel. Once the vessel has left the approach channel, it will have reached the boundary of the system and will exit the model.

3.16. Simulation Output

The model serves as a generic model to investigate the effective capacity of a port. As described by section 2.1.2 the model produces the following KPI's: occupancy rates, waiting times and processing times. In order to compare different berths and cargo types, the ratio between the processing time and total turnaround time will be calculated.

3.16.1. Occupancy rates

The occupancy rates will be calculated for each berth. This is done by taking the sum of the time all the vessels have claimed a quay, thus making it unavailable to other vessels, divided by the designed capacity of a berth times the total operational hours of the quay during the simulation run.

$$Occupancy = \frac{\sum Time\ berth\ claimed}{Capacity * Available\ Time} \tag{3.4}$$

3.16.2. Waiting times

High waiting times have been identified as one of the main indicators for congestion and an inadequate capacity. In order to identify the cause of delays and propose adequate solutions, waiting times will be subdivided into the following categories:

- Weather conditions: time spend waiting for adequate weather conditions.
- Quay availability: time spend waiting for a quay to become available.
- Tidal window: time spend waiting for the correct tide.
- Infrastructure availability: time spend waiting for the different sections of the port to become available.

3.16.3. Normalised waiting times

To compare different types of berths, the normalised waiting times will be logged per homogeneous type of berth. This KPI will be calculate in the following manner:

$$Normalised\ waiting\ time = \frac{\sum Total\ waiting\ time}{\sum Processing\ time} \tag{3.5}$$

3.17. Conclusion

In conclusion, the relevant processes identified during the literature study have been translated into a verbal model that acts as the basis for the implementation into the simulation model. It is important to realise the effects of the assumptions and limitations of the model, which can overestimate the capacity of a port. Differences can be expected when a port is often unavailable for (un)loading or has a limited amount of tugs.

Now that all the relevant processes have been explained as well as their interactions, the building of the simulation model can commence. It is important to note that vessels can find their own route through the port and decide when they can proceed toward their selected berth. A vessel has to check the status of the port, the sailing conditions and the availability of the infrastructure. A vessel must check multiple external factors, such as the weather and tide, before being able to sail to their destination.

The implementation of the verbal model into a simulation model is discussed in the next chapter.

4

Model implementation

In this chapter, the verbal model described in chapter 3 is implemented into a simulation model. Section 4.1 introduces Simio, the simulation environment chosen for this study. The input stage will be explained in section 4.3, while the main processes carried out during the running of the model will be explained in section 4.4. Finally, the different output data of the model will be explained in section 4.5.

4.1. Introduction to Simio

In this study, the simulation software Simio, developed by Simio LLC, will be used to create a simulation tool from the verbal model. Simio contains several basic objects that form the basis of most models. A user can create his own object library and customise the behaviour of objects. In this section, the main objects utilised in Simio will be explained in order to improve the understanding of the reader of the concepts developed in the next paragraphs.

4.1.1. Objects

Simio comes with a certain number of basic objects which are used to build a model. Depending on required functionality a different object is used. In this study, the following objects have been used:

- **Entity**: an entity typically represents a specific object that is dynamically created by the model and moves through the system until it is destroyed. In this case vessels will be modelled as entities.
- **Resource**: a generic object that can be seized and released by other objects.
- **Source**: a source is used to generate entities of a specific type and arrival pattern. Here, multiple sources will be used depending to generate ships on their type and destination at the outer edge of the approach channel
- **Sink**: a sink is used to destroy entities which have finished their processes. In this model, a sink will be used to remove ship from the model once it has completed their tasks at the port and left the access channel.
- **Server**: a server represents an object where an entity can perform certain tasks. These tasks are modelled as a certain time an entity has to stay in the server before the task is completed. Servers will be used to simulate the quays and the time a vessel spends at the quay.
- **BasicNode**: a BasicNode is used to connect two paths together. In certain situations, a BasicNode can be used to model a turning circle. In this case, a vessel will spend a certain amount of time at the node before proceeding towards the next path.
- **Path**: a path is a link over which entities can move at their own speed in order to go from one node to another. A path can be given a capacity and direction. Waterways through which vessel navigate are simulated as paths.

4.1.2. Elements

Besides objects, Simio also utilises the concept of elements. Elements can be used to track changes in a model and used as a reference for processes within the model. In this study, the following type of elements have been widely used:

- **Storage**: defines a queue for temporarily storing one or more entities in a specified order.
- **Network**: defines a network of links along which entities may travel

During the implementation of the simulation model, reusable building blocks have been created based on these objects and elements. In section 4.3 the required input parameters are explained to correctly use the building blocks.

4.2. Model structure

The model consists of three stages:

- Input stage
- Run stage
- Output stage

Each stage is described in the next sections. Figure 4.1 shows a general overview of the structure of the model and the main components of each stage.

The input stage requires the user to justify the necessary boundary conditions for the model to operate as explained in the verbal model. These corresponds to the input parameters described in section 4.3.

During the model run, the simulation is initiated. Upon initialisation, processes are triggered that implements the correct weather conditions and arrival of vessels based on the data provided in the input stage. The behaviour of the model is described in section 4.4.

The last stage consists of processing the model results and produce the correct KPIs.

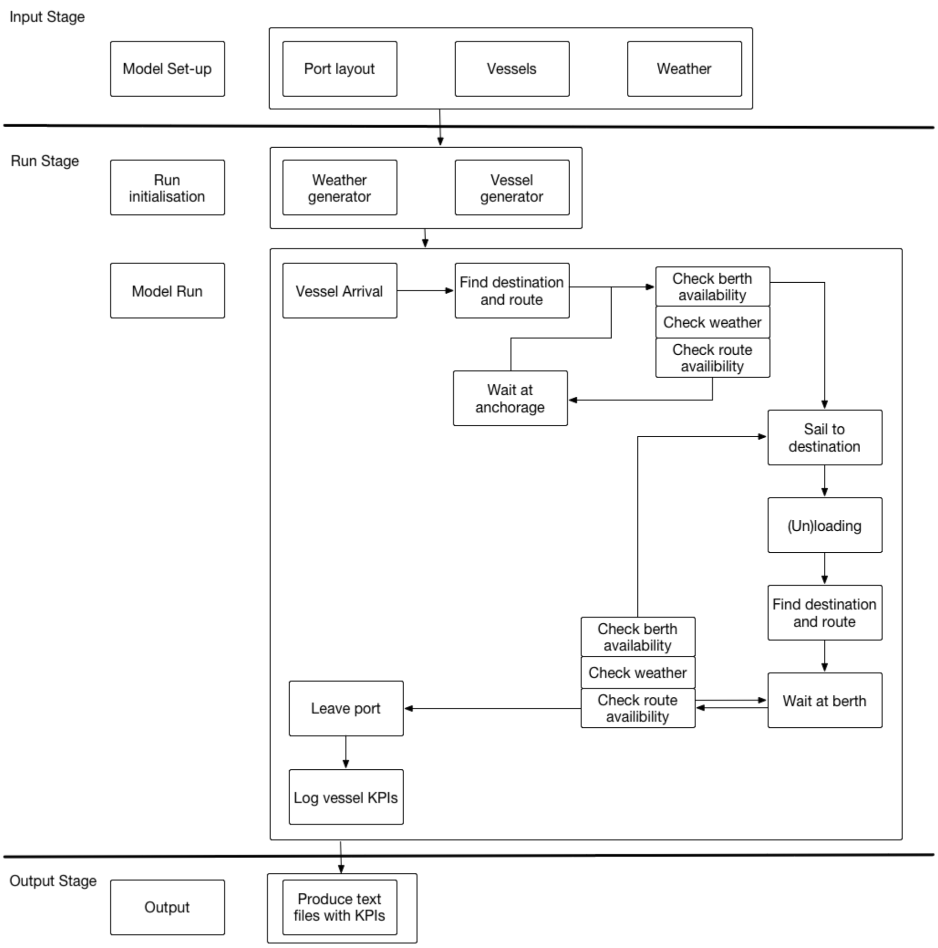


Figure 4.1: Model structure

4.3. Input stage

Before being able to run the model, a certain amount of input parameters have to be specified by the user in order to correctly simulate the performance of a port. These parameters determine the behaviour of the model throughout a simulation run and can be changed depending on the scenario. This section will discuss the input parameters that determine the layout of the port, amount and type of vessels and the weather conditions that will be used during the model run.

4.3.1. Port layout

In order to facilitate the correct implementation of the layout of a port and make the model re-usable, generic building blocks have been created for quays, waterways and turning circles. The generic building blocks enable the user of the model to easily simulate the correct behaviour of the port's elements. Whenever a building block is used, a certain amount of parameters have to be specified. These parameters have been summarised in table 4.1. Most of these parameters determine the physical properties and the time a vessel will be required to stay at a certain location.

In case of a waterway a set of traffic rules have to be included which determine the behaviour of vessels (e.g.: one- or two-way traffic and passing restrictions). Given that certain ports may require very specific traffic rules, the algorithm has been developed in such a way that additional constrains can be added relatively easily.

A turning circle is modelled as a node where vessels have to stay for a predefined time. Only one ship can occupy a turning circle at any one time.

The different elements that form the layout of the port must be dragged and dropped into the facility window of Simio in order to be assigned the correct location. As a result, the user of the model can construct the port step by step and check the correct implementation of the layout. Figure 4.2 shows an example of a port layout that has been implemented into the facility window. It is important to note that only one-directional paths may be used. As a result, two separate paths have to be used in order to simulate a multi-directional waterway.

Table 4.1: Characteristics of the building blocks for the infrastructure

Type	Object	Input
Quay	Server	- Quay length (m) - Depth alongside (m) - Capacity (-)
Waterway	Path	- Length (m) - Width (m) - Depth (m) - Maximum sailing speed (m/s) - Traffic Rules
Turning Circle	BasicNode	- Processing times (min)

4.3.2. Vessels

During the input stage, the user must enter a list of companies that use the port. Table 4.2 shows the input table that is used to determine the amount of vessels that has to be generated. In accordance with section 3.6, the type of arrival pattern determines the distribution that will used to calculate the inter-arrival times between vessels. A company can be used multiple times whenever it has different types of vessels arriving at the port. Likewise, a vessel type can be used for multiple companies. Table 4.3 shows the characteristics that must be specified by the user for each vessel type.

Table 4.2: Company Characteristics

Characteristic	Description
Company	Name of the company
Type of vessel	Vessel type
Arrivals	Number of arrivals per year
Arrival Pattern	Regular or random

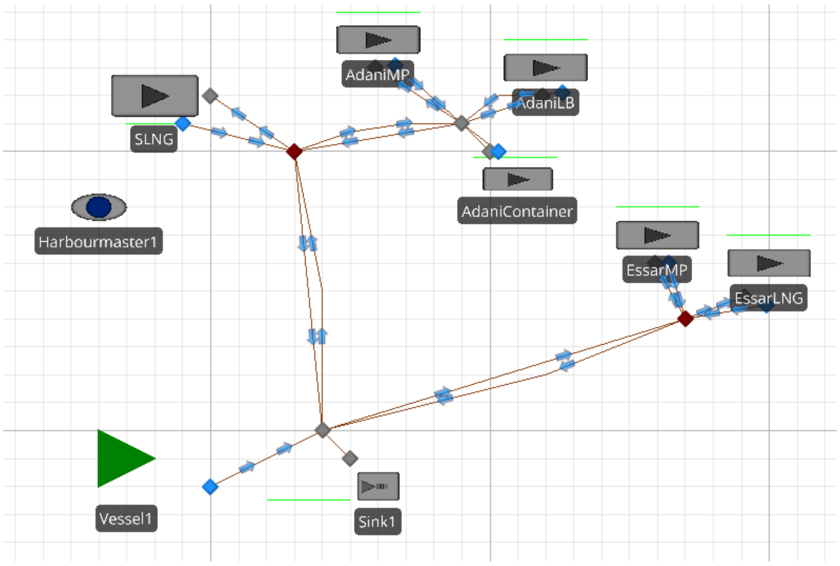


Figure 4.2: Example of the facility view

Table 4.3: Characteristics of a vessel type

Characteristic	Description
Limiting wave height	Threshold significant wave height for sailing (m)
Limiting wind speed	Threshold wind speed for sailing (m/s)
Priority	Priority number
Encounter	Allowed to encounter other vessels (yes/no)
Safety Distance	Minimum spacing (per ship length)

4.3.3. Weather conditions

Depending on the data available and the wishes of the user, a certain amount of input parameters can be entered in order to correctly model the weather conditions at the port. It is important to note that the model is also capable of running without any weather or tidal data, making it adequate for relatively simple set-ups. The following parameters can be specified:

- Weather data: both wind speeds and significant wave heights as a time series with a constant time interval. Other weather conditions (e.g. fog and ice) can be easily added into the model.
- Tide: the harmonic constituents should be justified to simulate the tidal variation.
- Climate change: effects of climate change can be incorporated by applying a certain amount of sea level rise or factor to generate an increase in wave heights and wind speeds. This can be a fixed number or an expression that changes over time. These factors are set to zero by default.

4.4. Run stage

Once the input stage is completed, the run stage starts. At this point, the simulation model is initiated.

4.4.1. Run utilisation

Upon initialisation, the input parameters specified in the previous stage are implemented into the simulation environment. Furthermore, the vessel generation and weather conditions are triggered, which will run during the entire model run.

Vessel Generation

Upon initialisation of the model, a resource, named the Harbourmaster, generates vessels based on the amount and type of arrivals specified in the input stage. In Simio, vessels will be modelled as entities. Upon creation, a vessel is assigned a specific type as well as general information on the dimensions of the ship. An overview of the characteristics that are assigned to vessels can be seen in table 4.4. The Harbourmaster determines the inter-arrival times of the vessels based on the amount of calls per year for each arrival type. Once the arrival time of a vessel is reached, it is send to the entrance of the access channel where it will evaluate whether it can proceed towards the berth. This process further described in section 4.4.2.

Table 4.4: Vessel charateristics

Characteristic	**Description**	**Unit**
Type	Type of vessel	-
Company	Company for which the vessel is sailing	-
LOA	Length of the vessel	m
Width	Width of the vessel	m
Draught	Draught of the vessel	m
Sailing speed	Sailing speed of the vessel	m/s
Priority	Priority of a vessel	-
Safety Distance	Minimum spacing	per ship length

Weather

Upon initialisation, the model triggers a process that determines the weather conditions in the port during the model run, as shown in figure 4.3. The weather conditions are determined based on the input table provided by the user. Once a new wave height and wind speed has been determined, the model will check the level of overtopping and wave transmission through the breakwater. Following this calculation, the model fires an event which will notify all vessels to check the new conditions with respect to their thresholds. The quays will also check whether the amount of overtopping and wave transmission causes the operations to be delayed or trigger the departure of vessels from the berth.

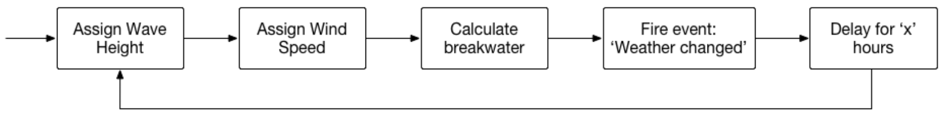


Figure 4.3: Example of a situation with different priorities

4.4.2. Vessel Arrival

Once a vessel has been generated by the model and made eligible to request authorisation to sail towards the port, it must first determine which berths it is allowed to use. This is done by checking which berths accept both the type of cargo and company assigned to the vessel.

Once this is done, the incoming vessel has to check the 'Reservation queue' for other vessels currently waiting for one of the destinations to become available. In case that there are no destinations available, the vessel will be added to the 'Anchorage queue' and wait for the status of one of the destinations to change. If one or more destinations are eligible, the vessel will be moved to the 'Reservation queue'.

Once a vessel has been added to the 'Reservation queue' it can start searching for a quay with sufficient quay length (see equation 3.2) and capacity. If this is not the case it will have to wait for the quay to be released. Once a quay is available, the vessel has to check whether the weather conditions are adequate. This is done by comparing the current weather conditions and the limiting values which depend on the given vessel type. If the conditions are not sufficient, the vessel will have to wait for the conditions to change. Otherwise it can add itself to the list of vessels using the selected berth and assign it as his destination.

Once the destination berth has been assigned, the vessel can determine the route it will have to sail in order to reach the berth. Once this is done a timetable will be constructed which will determine the sailing times for the vessel.

Routing

Whenever a vessel has received clearance to access the port (quay is available and weather conditions are adequate), it will have to determine the route it will take in order to reach the destination. Within Simio, paths can be added to a network. Entities can map their route from an origin to a predefined destination through paths that are contained within a network, based on the shortest path available. By using this functionality, vessel can dynamically select their route. As a result, the layout of a port can easily be changed without having to change the routing logic of vessels. Furthermore, multiple networks can be implemented, making

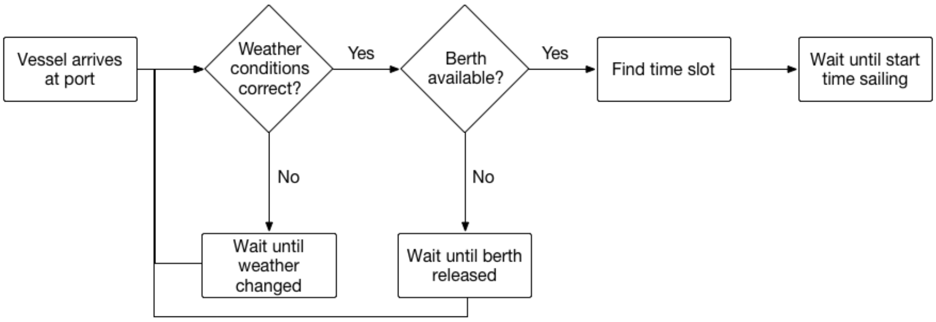


Figure 4.4: Process upon vessel arrival

it possible create specific routes for different type of vessels when certain sections of a port have restrictions placed on the type of vessel allowed.

Once the route has been mapped out, the vessel will have to reserve a timeslot for every section it has to sail through. This is done by the 'reservation process' which is explained in the next section.

Reservation

Before proceeding towards the port, a vessel has to check the availability of the waterways. During this process, a vessel must check the sailing times of other vessels and determine whether it can proceed or must delay his voyage.

Whenever a vessel is checking whether it can sail through a certain section, it will check the following aspects:

- The width of encountering vessels.
- Sailing rules of the section (one- or two-way traffic).
- Restrictions of vessels encountered.
- Sailing distance with preceding vessels.
- Tidal elevation.

Figure 4.5 shows the main algorithm for finding the correct sailing window for a section of the port. Once a suitable time slot has been found, it must be checked that the entry time into the section co-insides with the exit time of the previous section. Whenever this is not the case, the vessel must check whether it can stay for a longer time in the previous section without obstructing other vessels. If this is possible, the exit time of the previous section will be changed to equal the entry time of the next section, otherwise new reservation will have to be made for the previous section with a delayed entry time, which leads to an iterative process until a complete sailing window has been found.

Additionally, once a vessel has found a suitable timeslot to sail through a section, it will check whether the tide is sufficient in order to permit sailing. The required tide for a vessel is described by equation 4.1. If this is not the case, the vessel will have to find the start time of the next tidal window and restart the reservation process.

$$h_T = D + s_{max} + a - h_{gd} \tag{4.1}$$

in which:
h_{gd} = guaranteed depth (with respect to a specified reference level) (m)
D = draught of the vessel (m)
h_T = tidal elevation above reference level, below which no entrance is allowed (m)
s_{max} = maximum sinkage (fore or aft) due to squat and trim (m)
a = vertical motion due to wave response (m)

Although the process of finding a timeslot is based on a first-come-first-serve principle, the user of the model can assign priority rules and allows pre-scheduling in order to make the process more dynamic.

Priority

As stated before, certain vessels may have priority over other vessels. This means that a vessel should be able to change the reservations made by vessels with a lower priority.

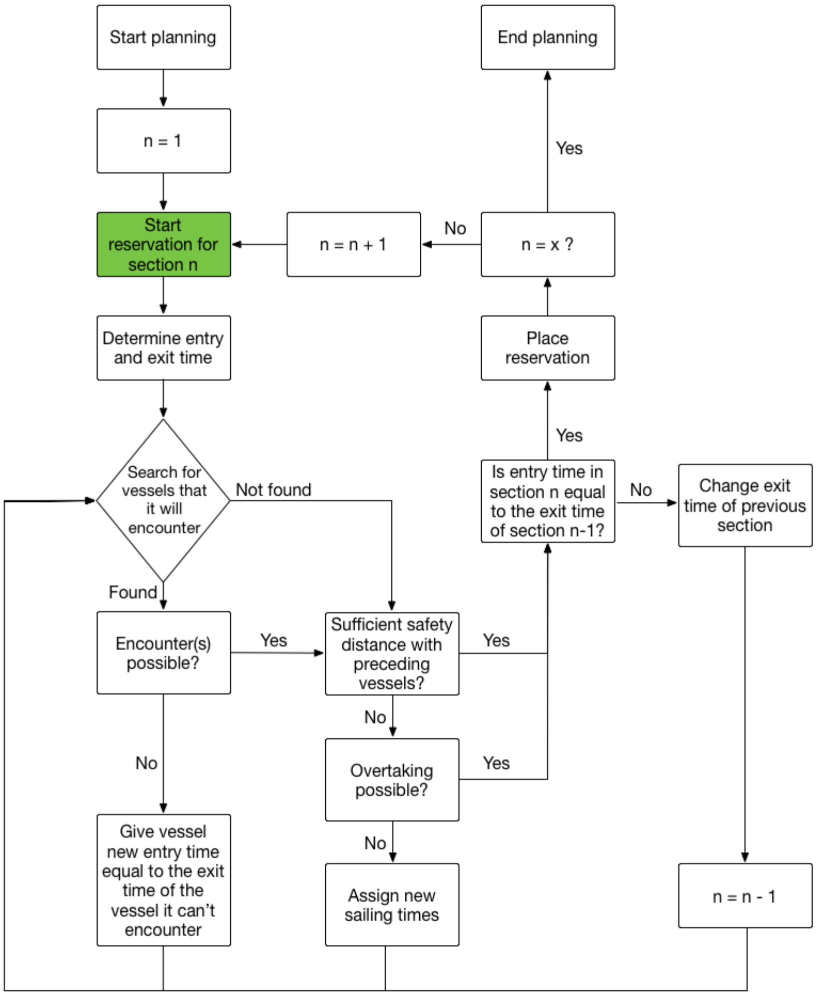


Figure 4.5: Algorithm for placing a reservation for 'x' sections

As a result, a vessel will check the current reservations made by other vessels. Depending on both the current location and the priority level of the vessels found, the reservations may be temporarily removed. The vessel with the higher priority can then complete the reservation process. Once this process is finished the lower priority vessels reschedule their route accordingly, taking into account the higher priority vessel.

Before removing the reservation of a vessel there are two parameters that have to be checked. First of all, the priority of the vessel that has already made the reservation must be lower than the priority of the vessel that is requesting a new reservation. Secondly, the vessel with the lower priority should not be located along the path that the higher priority vessel will follow. An example of this can be seen in figure 4.6, where ship A arrives at the port and has to reach the berth located at point 3. At same time ship B and C are leaving the port, but have a lower priority than ship A. In theory, both outgoing ships should wait and let vessel A proceed. However, ship B is currently located on the path that ship A will take. In order to prevent a deadlock, ship B will keep his original time schedule, while ship A has to check where an encounter with ship B is possible and plan his route accordingly. The route of vessel C will be rescheduled, taking into account the reservation made by both vessel A and B.

Pre-scheduling

Depending on the specifications of a terminal and the wishes of the user of the model, vessels may already plan their route a certain amount of time before arriving at the port or leaving the berth.

By default, vessels can notify the system of their arrival 4 hours prior to their arrival at the port. Furthermore, vessel can plan their outgoing travel two hours prior to leaving the berth. Both parameters can be customised depending on the type of vessel and berth.

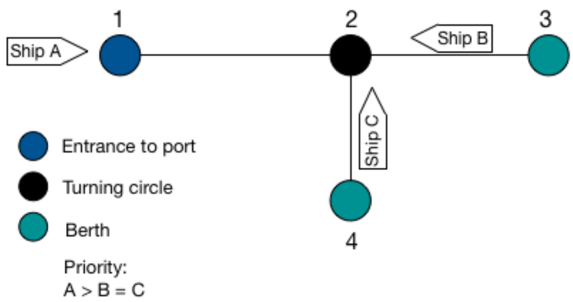


Figure 4.6: Example of a situation with different priorities

Once a vessel has found a suitable time slot for sailing towards its destination, it can start navigating towards to berth. Upon entry into a section, the vessel adjusts its speed to follow the timetable made during the reservation process.

4.4.3. Quay

In the model, quays are represented by servers. When a vessel arrives at a quay, it will enter the server. At the server, the vessel will occupy a virtual quay length and berth. Upon entering the server, the vessel will be delayed for the processing time that was assigned to this vessel. Once this delay is finished, vessels will start planning the route to their next destination. Vessels will only release the berth once the start time for sailing has been reached. Depending on the quay, a vessel may already plan the route to the next destination a certain time before finishing (un)loading to limit the waiting time at the server.

During the model run, the quays will monitor the weather conditions. Each time the event 'Weather changed' is fired (see figure 4.3), the quays will check whether overtopping and wave transmission does not exceed the thresholds values. Depending on the threshold that is exceeded, the quay may halt operations or force vessels to leave the port. If the operations are halted, the server will simply interrupt the delay-step of the vessels being processed and only resume when the event 'Weather changed' is fired and that the thresholds are no longer exceeded. In case the vessels must leave the port, the processing will be interrupted and the vessels will be sent to the anchorage until the thresholds are no longer exceeded. In this case, vessels do not release the server where they were being processed. In other words, newer vessels will not be able to claim the berth when the conditions improve.

4.5. Output stage

In Simio, text files are used to write out simulation results. In order to produce the output described in section 3.16, the model keeps track of the time a vessel spend performing a certain task (e.g. waiting, processing or sailing). Instead of writing out the results of every individual vessels, which considerably increases the run time of the model, the results are first logged in different matrices in Simio. Once the simulation run is finished, the model will compute total and average values, construct histograms and cumulative probability distribution functions.

Each vessel has a matrix which keeps track of the time it has spent performing a task. The matrix contains the following information:

- Waiting time due to port availability: waiting time caused by the vessel arriving outside the opening hours of the port.
- Waiting time due to quay availability: waiting time caused by the quay not being available for a vessel.
- Waiting time due to weather conditions: waiting time caused by bad weather conditions.
- Waiting time due to tidal windows: waiting time caused by tidal windows.
- Waiting time due to waterways availability: waiting time caused by the waterways not being available.
- Total waiting time: summation of the all the waiting times.
- Processing time: time spend (un)loading at the berth.

Whenever there are two aspects that are simultaneously causing the delay of a vessel (e.g. the quay is not available and the weather conditions are bad), the model will log the waiting time under the cause that has the highest hierarchical order. By default, the hierarchy is as follows (from high to low): quay availability, weather conditions, tidal windows and waterways availability.

Once a vessel has left the system, the waiting times will be classified under three different categories: type of vessel, destination and company. The time a vessel has claimed a quay is logged whenever a vessel leaves a quay. This makes it possible to differentiate between multiple destination whenever a vessel serves multiple quays.

Once the simulation is finished, a process is triggered which writes to a text file the average waiting times as well as the utilisation of the different quays. Furthermore, histograms and cumulative distribution functions.

4.6. Scenario Navigator

Simio uses text files in order to read input data and produce output data. Given that the input data can only contain the values for one scenario at the same time and that the output is overwritten each time a model run is executed, it is hard to keep track and compare different scenarios. As a result, Systems Navigator as produce a software, Scenario Navigator, which can communicate with Simio.

Within Scenario Navigator, dashboard have been created which guide the user through the different input parameters and keeps track of the model results for different scenarios. This enables users with limited Simio knowledge to easily use the model and run multiple experiments.

4.7. Conclusion

In conclusion, this chapter has shown how the verbal model has been implemented into a functional simulation environment. The algorithm has been designed in such a way that user can easily change the layout of the port without having to make any changes to the model. Vessels can independently determine the route they have to follow and find a suitable time slot for sailing while taking into account the behaviour of other vessels in the system.

Given that the model is considered to include all relevant processes, it is now important to validate the proper functioning of all the features of the model and check whether the model produces the correct results.

5

Model verification

The previous section, the main processes that drive the simulation model have been introduced. The next step consists of verifying the correct behaviour of the model. The model verifications take place in two stages. The first, described in section 5.1, considers features separately and triggers a specific behaviour of the model in order to check the correct implementation of the features. To verify the cohesion between all the features, a theoretical port is set-up and compared with theoretical results from Queuing Theory. Once all the features have been checked the model may be deemed to work as expected. The second stage consist of comparing the model results with AIS data. This stage is intended to test the performance of the model against a real situation and determine effect of the assumptions that were made in the design process.

5.1. Verification of the model features

The first stage in the verification process consists of checking the correct behaviour of the features introduced in section 4.4. Specific situations will be triggered to force the model to show a certain behaviour. The main aim of the verification process is to check whether to model correctly implements the input parameters and that vessels follow the correct navigational rules.

First of all, the implementation of the weather conditions and behaviour of the quays is checked. Secondly the behaviour of vessels is tested. It is important the make sure that vessels can find their destination through different port layouts. Furthermore, the behaviour of vessels with respect to traffic rules (encounters, sailing speed and restrictions) are checked.

5.1.1. Weather

The process that determines the weather conditions is triggered upon initialisation of the model. After a predefined interval, the model has to update the conditions based on a table and notify all entities and objects in the system of the changes. This feature was visually checked by comparing the conditions with the input values.

Once the weather conditions have been updated, the model has to determine the amount of overtopping and wave transmission. The calculation has been checked by comparing the values adopted by the model with the expected values made by hand calculations, in accordance with appendix 3.5.2. Given that no abnormal values were found, the breakwater and the associated features are deemed to be working correctly.

5.1.2. Quay

Each quay has a specific length and capacity. This puts restrictions on the size and number of vessels that serve a quay at the same time. In order to check the proper implementation of the physical characteristics of the quay, multiples tests were conducted to show that the total amount of ships using a quay at the same time does not exceed the maximum amount of vessels allowed or available quay length. Given that this did not occur, it was concluded that this the physical characteristics of quays have been properly implemented.

Every time the weather conditions are updated and new values for overtopping and wave transmission have been calculated, the quay must check whether it has to halt operations or force vessels to leave the berth. Both situations have been triggered in the model and the correct response of both the quay and the vessels have been visually checked.

5.1.3. Vessel behaviour

One of the most complex processes taking place in the model is the algorithm that finds a suitable time slot for a vessel to sail to towards the assigned destination. During the verification, the routing of vessels as well as the proper implementation of traffic rules (encounters, sailing speed and restrictions) are checked.

Routing

The model has been built in such a way that vessels can find their route through a port based on an origin and destination and find an appropriate time slot for sailing. This feature has to work for any layout and deadlocks should not occur. To verify this feature, numerous port layouts have been implemented and tested while over-loading the system with vessels. By including a check in the algorithm that verifies upon entry and exiting of a section that the planned sailing times are followed, the routing process was found to be working for all the tested layouts.

Now that is has been established that vessels can find their route and create a timetable that determines the entry and exit time for each section of the port that will be visited, it is important to determine whether the right sailing rules and restrictions have been followed.

Encounters

When a ship arrives at the port, it will schedule the route it will take in order to reach the berth. When performing this process, the vessel checks if encounters will occur with other vessels and whether these are possible. In principle, vessels may only encounter each other when two-traffic is allowed and that there is sufficient channel width available. There may be three reasons why vessels cannot encounter each other: the waterway only allows one-way traffic, the waterway has insufficient width or one of the vessels is not allowed to encounter other vessels. In order to verify the correct behaviour, a limited model was set-up where vessels were generated at two sides of a waterway.

In the case of a two-way access channel, where encounters and overtaking is permitted, vessels must check whether the width of the channel permits an encounter or an overtaking manoeuvre. When determining if an encounter is possible, the model has to take into account the safety coefficient determined by PIANC (2014). Figure 5.1a shows the combined widths of encountering vessels as a portion of the total width of the channel, while figure 5.1b shows the encounters that were rejected by the model. From these figures, it can be concluded that the model correctly rejects encounters when the width of vessels, including the PIANC coefficients, is larger than width of the channel. Furthermore, the correct calculation of the PIANC coefficient was checked by hand for specific encounters.

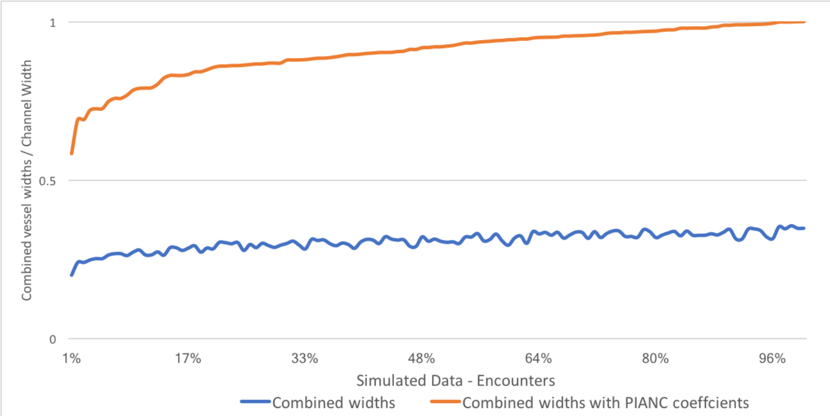
In case of a one-way channel, where encounters and overtaking is not permitted, the channel may not be simultaneously used by incoming and outgoing traffic. In order to check this feature, the waterway was given an infinite width and two-way traffic was turned off. The infinite width means that all vessel can technically encounter, as enough width is available, and will therefore only be rejected due to the one-way limitation of the waterway. Figure 5.2 shows the amount of ships using the one-way channel at any time. From this figure, it can be seen that whenever a ship is using the channel in one direction, the other direction is not utilised. This has also been checked by multiplying the number of incoming vessels with the number of outgoing vessels, which should always amount to zero.

The same process was undertaken for a model set-up with a two-way traffic and an infinite waterway width, while not allowing the vessels generated from one side to encounter other vessels. This resulted in the same type of figure as figure 5.2.

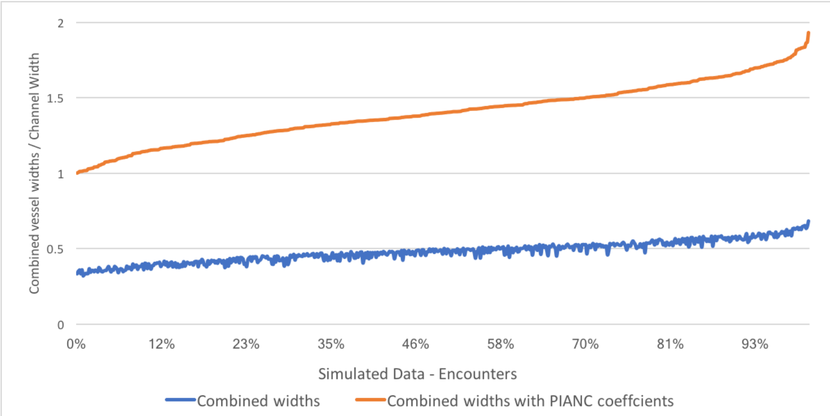
Given the results for both one and two-way traffic we can conclude that the encountering of vessels has been verified works properly.

Sailing speed

Whenever a ship cannot overtake another ship due to lack of space or sailing regulations, the vessel trying to overtake should decrease his speed and maintain sufficient safety distance with his predecessor. In order to test this feature, a one-way channel was implemented with ships receiving different speeds upon creation. The spacing between ships was checked upon leaving the access channel. For testing purposes, the minimum spacing possible was set to five minutes. The results of this test can be seen in figure 5.3. The result show that vessels never arrive with less than five minutes between each other. The feature is therefore considered to be checked.



(a) Accepted encounters



(b) Rejected encounters

Figure 5.1: Combined width of encountering vessels as a portion of the total channel width

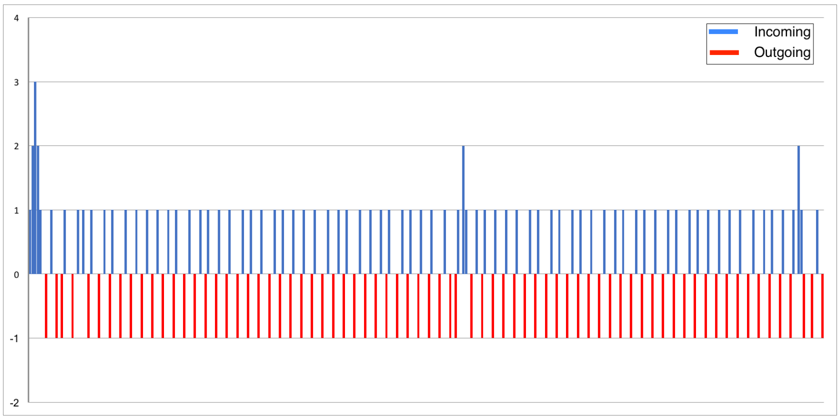


Figure 5.2: Number of vessels using a one-way channel

Weather conditions

Vessels may be forbidden of navigating due to the weather conditions. Depending on the type of vessel, different thresholds apply. The proper implementation of this feature has been visually checked by checking that vessels stopped sailing during extreme weather conditions and restarted whenever the conditions improved. As this was the case, this feature is deemed to be working properly.

Given that tidal windows may apply for certain vessels it is important to check that vessels only sail when sufficient depth is available. In order to check this feature, vessels were given the same draught as the waterway and the underkeel clearance was recorded upon entry into a waterway. Given that safety margin was set

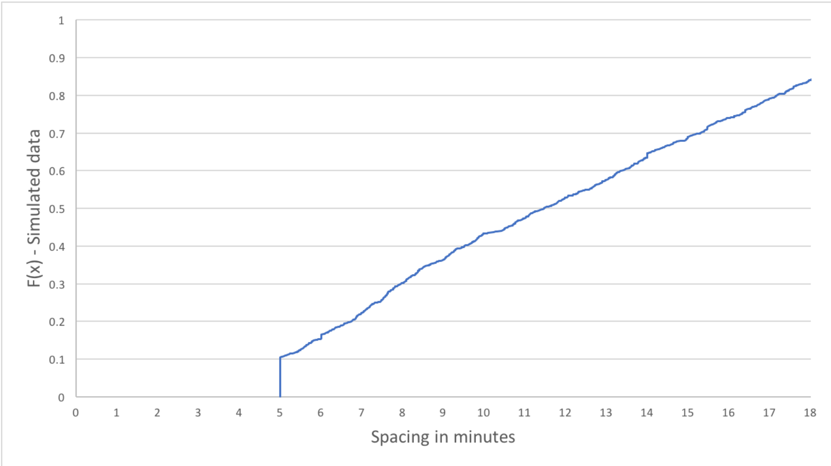


Figure 5.3: Spacing between vessels (minimum spacing set to 5 minute)

to 0.5 m, the clearance should never be less than 0.5 m. Figure 5.4 shows the result of this verification process. Given that the line never drops below 0.5 m, the tidal windows are considers properly implemented.

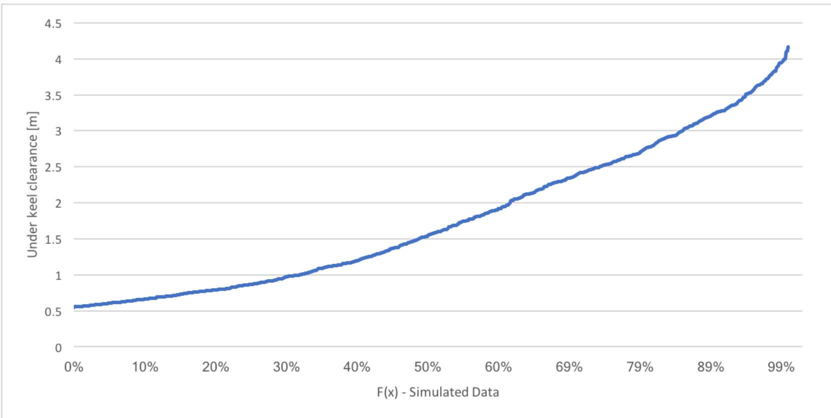


Figure 5.4: Underkeel clearance

5.1.4. Model testing

In order to verify the working the total model and check the reliability of the output, a fictional port has been implemented and waiting times have been compared with theoretical results from queueing theory. This fictional port consists of a single terminal and a two-way access channel to neglect the effects of congestion and making waiting times primarily dependent on the berth's availability. Both a scenario with a single berth as a scenario with two berth have been tested. Table 5.1 shows the characteristics of the test scenario's.

Table 5.1: Characteristics

Characteristic	Description
Number of terminals	1
Number of berths	1-2
Quay length	350-700 m
Ship length	300 m
Average service time	25 hours
Service time distribution function	2nd degree Erlang

The simulations were run over a period of 1 year. Every scenario is performed with a specific amount of calls per year, corresponding to a theoretical utilisation. For each scenario, 40 runs were performed in order to increase the accuracy of the results. The results of the runs for respectively one and two berths can be found in table 5.2 and 5.3.

Table 5.2: Comparison between queueing theory and model results for a M/E_2/1

Theory		Model		
Utilisation	Normalized waiting time	Calls / year	Utilisation	Normalized waiting time
0.1	0.08	35	0.10	0.08
0.2	0.19	70	0.20	0.19
0.3	0.32	105	0.31	0.32
0.4	0.50	140	0.41	0.50
0.5	0.75	175	0.50	0.78
0.6	1.13	210	0.60	1.17
0.7	1.75	245	0.70	1.69
0.8	3.00	280	0.78	2.98
0.9	6.75	315	0.88	6.65

Table 5.3: Comparison between queueing theory and model results for a M/E_2/2

Theory		Model		
Utilisation	Normalized waiting time	Calls / year	Utilisation	Normalized waiting time
0.1	0.01	70	0.10	0.01
0.2	0.03	140	0.21	0.03
0.3	0.08	210	0.31	0.08
0.4	0.15	280	0.40	0.15
0.5	0.26	350	0.50	0.25
0.6	0.43	420	0.59	0.42
0.7	0.73	490	0.69	0.75
0.8	1.34	560	0.79	1.35
0.9	3.14	630	0.89	3.06

For both the utilisation and waiting times the model the average difference with the theoretical values is around 2%. As a result, it can be concluded that the model simulates well the arrival and processing of vessels and results in proper waiting times.

5.2. Model validation

Given that the different features of the model have been verified, a validation process can be undertaken with available AIS data. As described in Piccoli (2014), validating a simulation model with AIS data is difficult as human interactions can differ widely from the expected, theoretical, behaviour. In addition, the simulation model will always have limitations and not all processes can be taken into account.

For the purpose of the case study, AIS data was made available for the Port of Hazira for the period March-May 2017. The model was set-up with the vessels registered in AIS and the weather data form the same period.

Table 5.4 compares the waiting times and quay utilisation form the AIS data and model results. The model produces approximately the same quay utilisation as the AIS data. However, the model underestimated the waiting times by approximately 30%. For the LNG, liquid bulk and container quay the error amounts to approximately 1 hour. Given that human interactions can cause extra delay compared to the model, this error is deemed acceptable. This means that only the Adani multi-purpose quay is showing abnormally high waiting times.

Given that the proper functioning of the processes which were included in the scope of this study has been verified, the difference in waiting times are expected to be caused by processes which have not been included in the scope. When analysing the AIS data, it became apparent that certain vessels, destined for the Adani multi-purpose quay, would stay at the anchorage whilst the berth was available and the tidal and weather conditions were adequate. An explanation for this is that the terminal is not ready to receive the vessel. In section 3, it was decided to assume that the terminals are continuously ready to receive vessels. To correct for this assumption, the option will be given to the user of the model to apply a correction factor to the waiting times based on the differences observed between the AIS data and the validation run.

Table 5.4: Comparison between AIS data and model results

Quay	Utilisation			Waiting Times		
	AIS	Model	Diff	AIS	Model	Diff
Adani MP	51%	51%	1%	25.7 hr	13.3 hr	48%
Container	27%	32%	18%	4.3 hr	4.99 hr	16%
ESSAR MP	93%	91%	3%	116.8 hr	110 hr	6%
LNG	14%	14%	2%	3.8 hr	2.52 hr	34%
Oil	37%	37%	1%	5.1 hr	4.06 hr	21%

5.3. Conclusion

In conclusion, the proper functioning of the different processes has been verified. Given that the model must work in a generic way, allowing for multiple case studies, many different layouts and combinations of input parameters have been successfully implemented and verified. Furthermore, the generated output concerning waiting times and quay utilisation match the theoretical values expected with queuing theory.

However, the validation with AIS data has shown that the model underestimates waiting times. It is expected that is mainly due to the assumption that the terminal is always ready to start (un)loading vessels, which is not necessarily the case and can increase waiting times. As a result, the user of the model will have the option of correcting the model output with a coefficient based on the differences found at terminals during the validations process.

Given that the model is deemed to be working properly, a case study is carried out to demonstrate the usefulness of this tool.

6

Case study: Port of Hazira

As stated before, a study of the Port of Hazira will be used to demonstrate the usefulness of the newly developed tool. This study is aimed to demonstrate the different features of the model and capabilities.

The Port of Hazira is planning to increase its throughput over the coming years. To maintain the same service levels, plans have been made to increase the available quay lengths and increase the depth of the access channel. The analysis is conducted in two phases: the first will consists of analysing the current situation in order to set a benchmark for other scenarios. The second phase consists of simulating the increase in throughput and changes in the infrastructure. Finally, the results of the different scenarios can be compared and can be drawn concerning the capacity of the Port of Hazira.

For more information about this section, please contact Systems Navigator at info@systemsnavigator.com.

7
Evaluation of Simio

In this chapter, the use of Simio as a simulation tool in order to assess the effective capacity of the capacity of the wet infrastructure. As described in section 1.4, the software will be judged on the following criteria:

1. Implementation: Simio should be able to simulate adequately all the identified processes.
2. Genericity: Simio should allow the algorithm to be built in a generic way, avoiding any hard coding.
3. Flexibility: Simio should be flexible and allow for different input values in order to easily implement multiple scenarios.
4. Run time: the runtime should be kept at an adequate level.
5. Output: the KPIs should be easily derived from the model.

The evaluation of the criteria is discussed below:

1. Implementation: All the required features have been successfully implemented into Simio. However, new building blocks had to be created and default objects could be used to build up the simulation model. Overall, Simio is capable of simulating well the identified processes.
2. Genericity: Although the algorithm can run independently of the type of port layout, thus allowing the model to be reused for different case studies, some features did require hard coding. The size of matrix tables and vectors have to be predefined and cannot be dependent on an input value. As a result, all the matrices and vectors have been over dimensioned to cope with larger ports.
3. Flexibility: Although Simio allows input values to be imported from an excel file, it is difficult to keep track of the input values of different scenarios. This is due to the fact that the excel files used by Simio can only contain the values for one scenario at the time. However, Systems Navigator has developed a tool, Scenario Navigator, which helps to keep track of the input and output of different scenarios.
4. Run time: The simulation time of a model is related to the complexity of the layout of the port and the amount of vessels to be generated. In this study, the running of a scenario through Scenario Navigator, over a run time of 5 years, takes less than 5 minutes which is considered adequate.
5. Output: Although Simio logs numerous KPIs, none were found relevant for this study. As results, the algorithm had to be improved in order to keep track of the relevant KPIs for all the objects in the system. Furthermore, an algorithm had to be built to process all these KPIs once an object was removed from the system or the run was terminated.

Overall, Simio is considered to work well as a simulation tool to assess the effective capacity of the wet infrastructure of a port. The developed tool is capable of producing reliable results and can be relatively easily reused for different case studies. However, the developed algorithm is quite complicated and whenever a new user wants to make changes or add functionalities, a deep understanding of Simio is required.

8

Conclusions and recommendations

The main objective of this thesis is to produce a simulation tool which can assess the effective capacity of the wet infrastructure of a port in order to guide port authorities in their future investments. The usefulness of this tool should be demonstrated by means of a case study.

To complete this objective, research questions were established in section 1.3.3. In section 8.1, the answers to these questions will be presented, while section 8.2 considers the scientific contribution of the thesis. Section 8.3 presents the recommendation for future studies.

8.1. Research questions

In section 1.3.3, a list of research questions was established and investigated during the course of this MSc thesis. The answers to the research questions are presented in this section.

What is the definition of the capacity of a port?

During the literature study, different types of capacities were distinguished: physical capacity, effective capacity and economic capacity. The physical capacity is considered to be of limited interest as it does not consider enough factors, while the economic capacity is considered to be outside of the scope of this study. As this study aims to link the capacity of a port to the external factors effecting it, this study focusses on determining the effective capacity of a port, which is defined as: "the greatest possible capacity at which the structure can operate, taking into account the external circumstances in which the physical capacity is utilised" (Notteboom (2002)).

Which aspects of the wet infrastructure are of interest in order to respond to the demands of port planners?

To determine the effective capacity of a port, planners need to evaluate relevant indicators. In UNCTAD (2002), a list of indicators has been set-up to quantify the efficiency of a port: occupancy rate for each homogeneous group of berths, average time spent by ship at berth loading/discharging, ratio between the working time and the total turnaround time of vessels and average waiting time of a ship. As a result, the developed simulation model mainly focusses on producing the following performance indicators: occupancy rates, waiting times and processing times. In order to compare different berths and cargo types, the ratio between the waiting time and processing time will be calculated.

Which processes are necessary to implement into a simulation model in order to correctly asses the effective capacity of the wet infrastructure of a port?

Based on the finding of Bellsolà Olba et al. (2015), who analysed the implementation of simulations models to assess the performance of a port, the following processes have been deemed necessary in order to correctly asses the effective capacity of the wet infrastructure of a port: arrival at the port, waiting at the anchorage, navigating through the access channel towards the port entrance, navigating through the port, berthing, (un)loading, waiting at berth, navigation towards the exit of the port and leaving the port through the access channel.

Bellsolá Olba also stated that the tugs and pilots had to be properly simulated as well as the behaviour of vessels at the anchorage. However, the behaviour of these processes are specific for each port and therefore not suitable for a generic model. Furthermore, these processes are greatly dependent on the planning of port authorities and thus human interactions, which is considered to be outside the scope of this study and is therefore not included in this model.

What is the performance of the Port of Hazira for the current and projected throughput and what are the bottleneck?

For more information about this section, please contact Systems Navigator at info@systemsnavigator.com.

What are the effect of changes made to the wet infrastructure of the Port of Hazira?

For more information about this section, please contact Systems Navigator at info@systemsnavigator.com.

How adequate is Simio for the assessment of the wet infrastructure of a port?
In section 7 the use of Simio for simulating the wet infrastructure of a port was evaluated. The software was deemed to perform well. All the required features were successfully implemented and the model can be relatively easily used for different case studies. However, the handling of in- and output of different scenarios through Simio is not ideal. An additional software is required to process and compare scenarios.

Although the algorithm has been created in such a way that the user is not required to reprogram the code whenever a new case study is performed, additional feature might be requested. In such a case, the user would have to have a good understanding of Simio and fully understand the different steps undertaken by the model. Ultimately, seems that additional features will have to be done by the person that developed the model.

8.2. Scientific contribution

In conclusion, a generic simulation model has been developed which assesses the effective capacity of a port. Instead of building a model for a single case study, a new approach was used which enables the model to be applied to multiple case studies without having to make any major changes. This has been accomplished by creating an algorithm that can take into account any type of port layout.

Furthermore, an interface has been built to facilitate the use of the model by users that have a limited knowledge of Simio. This enables the model to be used by a broader public.

8.3. Recommendations

As a result of this study, the following recommendations are made for future research in the assessment of the effective capacity of the wet infrastructure of a port:

- Additional validation: The simulation tool developed in this study has been validated with limited AIS data available for one port. Ideally the model should be implemented for multiple ports and validated again in order to demonstrate the relevance of a generic model.

- Vessel behaviour: Currently the vessel movements are modelled at a high aggregate level. Further research is required to improve the sailing behaviour of vessels with respect to surrounding ships and weather conditions.

- Tugs boats: The behaviour of tug boats has not been considered in this study. The behaviour of tugs is greatly affected by the decisions taken by the port operators, which makes it difficult to determine a generic behaviour for the attribution of tug boats. Further research is required to create a generic approach to include the behaviour, in a generic way, of tug boats into port capacity studies.
- Weighted waiting times: In this study, no difference has been made between waiting times of different types of vessels. However, port authorities might grant more importance to the waiting times of a certain type of vessel. Further research is required to find an adequate KPI which can take into account the difference in importance of waiting times for different vessel types and cargo.

Bibliography

Adani Groups. Available at http://www.adaniports.com/ (13/02/2017).

AHPPL. Port & terminal information book v3.4. 2015.

X. Bellsolà Olba, W. Daamen, T. Vellinga, and S.P. Hoogendoorn. An approach to port network capacity. 2014.

X. Bellsolà Olba, W. Daamen, T. Vellinga, and S.P. Hoogendoorn. Simulating the port wet infrastructure: Review and assessment. 2015. ISSN 2352-1465.

BMT Argoss. Available at http://www.waveclimate.com/ (2/03/2017).

H. Ligteringen and H. Velsink. Ports and Terminals. 2012.

T Notteboom. Current issues in port logistics and intermodality. 2002.

PIANC. Harbour approach channels: Design guidelines, PIANC report n° 121. 2014.

C. Piccoli. Assessment of port marine operations performance by means of simulation. Master's thesis. Department of Hydraulic Engineering, Delft University of Technology. 2014.

S. Rayo. Development of a simulation model for the assessment of approach channels - The Taman Seaport case. Master's thesis. Department of Hydraulic Engineering, Delft University of Technology. 2013.

H. Scott, D. McEvoy, P. Chhetri, F. Basic, and J. Mullett. Climate change adaptation guidelines for ports. 2013.

P. Taneja, W.E. Walker, H. Ligteringen, M. van Schuylenburg, and R. van der Plas. Future scenarios: Implications for port planning. 2009.

P. Taneja, W.E. Walker, and H Ligteringen. Flexibility in port planning and design. 2012.

UNCTAD. Port statistics. 2002.

A
Design guidelines

General guidelines for the design of approach channels can be found in PIANC (2014). These guidelines provide an in-depth analysis of the required vertical and horizontal dimensioning of access channels. An approach channel is defined as any stretch of waterway linking the berths of a port and the open sea. A difference is made between outer channels, located in open water and exposed to wave action, and inner channels, which are relatively sheltered from waves. The design procedure uses the concept of a design ship, which should be chosen to ensure that the channel design allows it, and all other ships to navigate safely. An obvious choice could be to choose the largest ship. However, tidal windows could be used to permit deep-draught vessels with infrequent calls to access the channel.

A.1. Required depth

Figure A.1 shows an overview of the different factors that determine the required channel depth. In most cases, the static draught of a ship is known. One must pay particular attention to the factors which influence the Gross under keel clearance (UKC). According to the PIANC report the Gross UKC is composed of six factors including (a) allowance for static draught uncertainties, (b) change in water density, (c) ship squat and dynamic trim, (d) dynamic heel, (e) wave response allowance and (f) Net UKC.

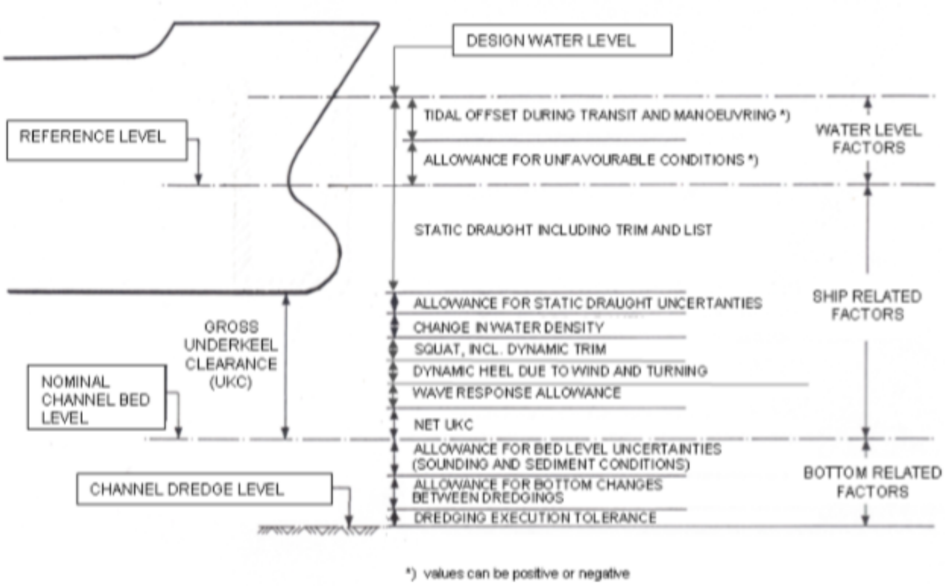


Figure A.1: Channel depth factors (PIANC (2014))

According to Ligteringen and Velsink (2012), the required depth by a vessel can be described by equation

A.1.

$$h_{gd} = D - h_T + s_{max} + a + h_{net} \tag{A.1}$$

in which:
h_{gd} = guaranteed depth (with respect to a specified reference level) (m)
D = draught design ship (m)
h_T = tidal elevation above reference level, below which no entrance is allowed (m)
s_{max} = maximum sinkage (fore or aft) due to squat and trim (m)
a = vertical motion due to wave response (m)
h_{net} = remaining safety margin or net UKC (m)

The value for the vertical motion due to wave response can be estimated as the amplitude related to the significant wave height and h_{net} depends on the type of soil along the channel (0.3 m for soft mud, 0.5 m for a sandy bottom and 1.0 m for a hard soil or rock). Equation A.2 gives a general formula for the sinkage of a ship.

$$s = 3.98 * \frac{C_B}{30} * k^{0.81} * v_s^{2.08} \tag{A.2}$$

in which:
s = squat (m)
v_s = vessel speed (m/s)
C_B = block coefficient (-)
k = blockage coefficient (=A_s/A_{ch}) (-)

A.2. Channel width

Besides the depth of the channel, the width is also important. According to PIANC (2014), the width of a channel can be described as follows:

$$W = W_{bm} + 2W_b + \Sigma W_a \tag{A.3}$$

when a two-way channel sections is considered, a additional separation distance is added between the lanes. This results in the following equation:

$$W = 2 * (W_{bm} + W_b + \Sigma W_a) + W_p \tag{A.4}$$

The coefficients for these equations can be found in table A.1

A.3. Breakwater

Depending on the weather conditions, a port may have to halt its activities or even shut down completely and force ships to temporarily leave the quay. Different types of weather thresholds can be distinguished. Certain thresholds can be directly linked to the current weather conditions, such as the threshold wind speed. However other thresholds, such as the wave height within the harbour or the amount of overtopping, are more complex to determine.

Both wave transmission into the harbour and amount of overtopping are dependent on the dimensions of the breakwater and the combination of wave height and water level. Due to climate change, sea level rise may put under threat the operational windows of harbours by rendering breakwaters less efficient. The model should evaluate the amount of water going over the breakwater and the wave energy that is being transmitted through the breakwater in order to estimate the downtime of a port due to the weather conditions. The required calculations are explained below.

A.3.1. Overtopping

When waves hit a breakwater, a certain amount of water will flow over the crest. This is often defined as a specific discharge per meter along the crest. This phenomenon is referred to as overtopping and it's amount is dependent on the wave characteristics, geometry of the slope and crest and the wind. When the amount of overtopping becomes too high, damage can occur to nearby structures and potentially dangerous for human activities may occur. For a port, this can cause damage to terminals or ships and halt operations at the terminal. The expected damages caused by a certain amount of overtopping can found in appendix B.

Width (Wi)	Vessel speed	Outer channel (exposed to open water)	Inner channel (protected water)
(a) Vessel speed (kn)			
- Fast > 12		0.1 B	0.1 B
- Moderate > 8 - 12		0.0	0.0
- Slow 5-8		0.0	0.0
(b) Prevailing cross wind (kn)			
- Mild ≤ 15	all	0.0	0.0
- Moderate > 15 - 33	fast	0.3 B	-
	mod	0.4 B	0.4 B
	slow	0.5 B	0.5 B
- Severe > 33 - 48	fast	0.6 B	-
	mod	0.8 B	0.8 B
	slow	1.0 B	1.0 B
(c) Prevailing cross current (kn)			
- Negligible < 0.2	all	0.0	0.0
- Low 0.2 - 0.5	fast	0.1 B	-
	mod	0.2 B	0.1 B
	slow	0.3 B	0.2 B
- Moderate > 0.5 - 1.5	fast	0.5 B	-
	mod	0.7 B	0.5 B
	slow	1.0 B	0.8 B
- Strong > 1.5 -2.0	fast	0.7 B	-
	mod	1.0 B	-
	slow	1.3 B	-
(d) Prevailing longitidinal current (kn)			
- Low ≤ 1.5	all	0.0	0.0
- Moderate > 1.5 - 3	fast	0.0	-
	mod	0.1 B	0.1 B
	slow	0.2 B	0.2 B
- Strong > 3	fast	0.1 B	0.1 B
	mod	0.2 B	0.2 B
	slow	0.4 B	0.4 B
(e) Significant wave height Hs and length λ (m)			
- Hs ≤ 1 and λ ≤ L	all	0.0	0.0
- 3 > Hs > 1 and λ = L	fast	2.0 B	-
	mod	1.0 B	-
	slow	0.5 B	-
- Hs > 3 and λ > L	fast	3.0 B	-
	mod	2.2 B	-
	slow	1.5 B	-
(f) Aids to navigation			
- Excellent with shore traffic control		0.0	0.0
- Good		0.1 B	0.0
- Moderate with infrequent poor visibility		0.2 B	0.0
- Moderate with frequent poor visibility		≥ 0.5 B	≥ 0.5 B
(g) Bottom surface			
- If depth ≥ 1.5 D		0.0	0.0
- If depth < 1.5 D			
- Smooth and soft		0.1 B	0.1 B
- Smooth or sloping and hard		0.1 B	0.1 B
- Rough and hard		0.2 B	0.2 B
(h) Depth of waterway			
- Low		0.0	0.0
- Medium		~ 0.5 B	~ 0.4 B
- High		~ 1.0 B	~ 0.8 B

Table A.1: Channel width coefficients according to PIANC (2014)

According to Van der Meer, the maximum amount of overtopping is given by equation A.5. The effects of the slope roughness and the angular wave attack are taken into account by applying the reduction factors γ_f and γ_β. Theses factors depend on the type of breakwater and the materials applied on the slopes. Typical values van be found in appendix B.

$$\frac{q}{\sqrt{g{H_{mo}}^3}} = ae^{-b\frac{R_c}{H_{mo}\gamma_f\gamma_\beta}} \quad \text{with: } a = 0.2 \text{ and } b = 2.3 \tag{A.5}$$

A.3.2. Wave transmission

Another factor that puts the operations in a port at risk is the wave height inside the port. When the water inside the port basin become to 'brisky', vessel cannot be easily manoeuvred and kept in place. This can cause dangerous situation where both vessel and port infrastructure can be damaged. As a result, a port will close down and request ships to leave the harbour when wave become too high.

Breakwaters permit wave energy to be transferred into the area behind the breakwater. The amount of energy transferred through the breakwater is defined as the coefficient of transmission, as shown in equation A.6.

$$C_t = H_t/H_i = \sqrt{E_t/E_i} \tag{A.6}$$

For rubble mount breakwaters the coefficient can be calculated in the following way:

For narrow structures, B/H_i < 10:

$$C_t = -0.4\frac{R_c}{H_s} + 0.64(\frac{B}{H_s})^{-0.31}(1 - e^{-0.5\xi_p}) \tag{A.7}$$

with minimum and maximum values of Ct = 0.075 and 0.80 respectively.

For wide structures, B/H_i > 10:

$$C_t = -0.35\frac{R_c}{H_s} + 0.51(\frac{B}{H_s})^{-0.65}(1 - e^{-0.41\xi_p}) \tag{A.8}$$

with a minimum value of Ct = 0.05 and a maximum value depending on the crest width, B (m), of the structure. Given by:

$$C_{t,max} = -0.006B/H_s + 0.93 \tag{A.9}$$

B

Parameters

B.1. γ_f:

B.1.1. Rough slopes with non-permeable core

Structure type	γ_f for TAW method
Concrete, asphalt and grass	1.0
Pitched stone	0.80-0.95
Armourstone - single layer	0.70
Armourstone - two layers	0.55

Table B.1: Values for roughness reduction factor, γ_f, TAW (2002a)

Note:
For the TAW method, the roughness factor γ_f is only applicable for γ_f·xi m-1,0 < = 2.0. For larger values this factor increases linearly up to 1 for γ_f·xi m-1,0 = 10 and it remains 1 for larger values.

B.1.2. Rough slopes with a permeable core

Armour type or structure	No of layers	γ_f for TAW method
Rock	2	0.40
Cube	2	0.47
Cube	1	0.50
Antifer cube	2	0.47
Haro	2	0.47
Tetrapod	2	0.38
Dolosse	2	0.43
Accropode	1	0.46
Core-loc	1	0.44
Xbloc	1	0.45
Berm breakwater	2	0.40
Icelandic berm breakwater	2	0.35
Seabee	1	0.5
Shed	1	0.5

Table B.2: Values for roughness reduction factor, γ_f, TAW (2002a)

Note:
For the TAW method, the roughness factor γ_f is only applicable for γ_f·xim-1,0 < = 2.0. For larger values this factor increases linearly up to 1 for γ_f·xim-1,0 = 10 and it remains 1 for larger values.

B.2. γ_β

A description (see Equation 5.39) of a reduction factor for oblique waves is given by TAW (2002a), applicable to the TAW overtopping formulae, Equations 5.32–5.34:

$$\gamma_\beta = 1 - 0.0033|\beta| \qquad 0° \leq |\beta| \leq 80° \tag{B.1}$$

For angles of approach greater than 80°the result of β= 80°can be applied.

C

Tidal constituents for the Port of Hazira

Constituent	Name	Amplitude	Epoch	Speed	Node Factor	Equilibirum
1	M2	1.849369	2.828645396	0.505868046	1.032	4.995132318
2	S2	0.463194	3.528811383	0.523598776	1	0
3	N2	0.500600999	2.666089497	0.496366927	1.032	0.42062435
4	K1	0.605955	2.490249267	0.262516177	0.906	0.090757121
5	M4	0.948461	2.43404895	1.011736126	1.064	3.707079331
6	O1	0.421805	1.830729695	0.243351868	0.847	4.954989745
10	MN4	0.379633	1.987449389	1.002234938	1.064	5.415756669
23	MSF	0.519877999	0.871746426	0.017730727	1.032	1.288052988
24	MF	0.36474	1.126604533	0.019164293	0.696	4.508185457
37	MS4	0.521181	3.238042742	1.029466821	1.032	3.680899392

Figure C.1: Tidal constituents for the Port of Hazira