Offshore-Onshore Port Systems

A framework for the cost evaluation of container port systems

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A framework for the cost evaluation of container port systems

by

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Preface

The thesis is completed under the supervision of the Department of Hydraulic Engineering of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology.

This thesis is performed in collaboration with Royal HaskoningDHV. I would like to thank Royal HaskoningDHV for offering me the opportunity to work on my thesis at the office in Rotterdam. Furthermore, I would like to thank all colleagues of the Maritime & Aviation division for their support when needed.

Next, I would like to take this opportunity to thank the people that have supervised me during this thesis. Firstly, I would like to thank Mark van Koningsveld, the chair of my committee, for his endless enthusiasm and support concerning the model development. Because of this, I have become more proficient with advanced modelling concepts. Moreover, I would like to express my gratitude to Menno Mooij and Joost Lansen of Royal HaskoningDHV for their substantive support. I have experienced their guidance as very pleasant and enjoyed my time with them. Besides, I would like to thank Bart Wiegmans for providing me with very useful feedback, especially on how to set up and structure the report.

H.W.B. (Hugo) Stam
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Executive Summary

The size of container ships is constantly growing over recent decades due to a continuous search for economies of scale by shipping lines. The growth of the container ships has necessitated ports to adapt, e.g. by increasing the water depth requirements. Many of the conventional *onshore ports* (Figure 1) cannot receive larger ships without dredging activities due to depth restrictions. A considerable amount of dredging is necessary to create an access channel to reach deep waters. The costs for the capital and maintenance dredging may be equal to more than 60% of the total costs, as found in this research.

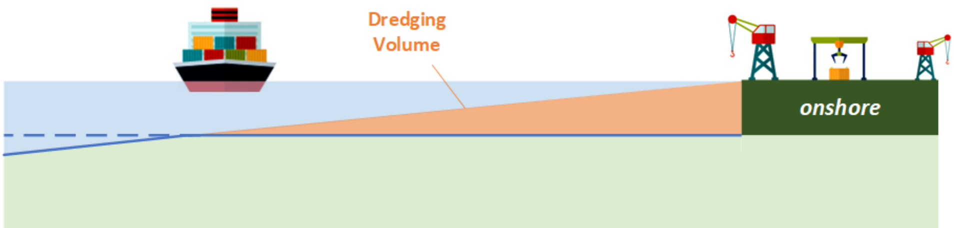
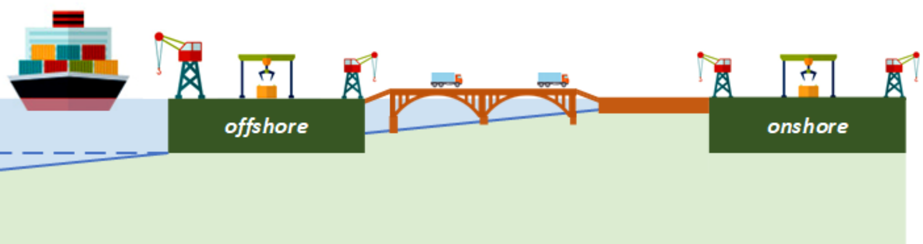


Figure 1: Onshore port with deepwater access after dredging the indicated dredging volume

The development of *offshore-onshore port systems* (Figure 2) can be a huge opportunity for coastal zones with an extensive shallow foreshore to limit the channel dredging costs. However, offshore-onshore port systems involve additional costs and operational challenges compared to conventional onshore ports, due to the partially double container handling at both the terminals and the transport link between the offshore and onshore terminals. The required storage capacities of both the offshore and onshore terminals depend on the operational reliability of the transport link which depends, amongst others, on the environmental conditions like wave conditions.

(a) Offshore-onshore port system with a waterway transport link for barge transport



(b) Offshore-onshore port system with a fixed infrastructure link (e.g. a bridge/causeway combination) for truck transport

Figure 2: Offshore-onshore port systems

Port authorities and governments should be able to evaluate the design of various types of port systems early in the design process. In reality, the methodology for evaluating the design of innovative solutions, like offshore-onshore port systems, is limited compared to the evaluation of conventional onshore port designs. The following gaps in the literature are identified:

1. the clarification of the differences between various types of port systems and an assessment of the port system characteristics;
2. a method to assess the relationship between the operational reliability of the transport between the offshore and onshore terminal and the required storage capacity of both the offshore and onshore terminals; and
3. the cost-based evaluation of the major logistical trade-offs regarding various types of port systems.

A framework, including the cost-based evaluations, could serve as a reference to make more deliberate and integral choices in the design of port systems. Therefore, the objective of this research is to evaluate the trade-offs regarding port system design for container handling and transport based on costs. The cost-based evaluations will set the *framework* - a collection of concepts - concerning the logistical trade-offs. The gaps in the literature are addressed by answering sub-questions. Next, in line with the with sub-questions, the research question is stated as follows:

"How can the cost-based evaluation of the major logistical trade-offs regarding various types of port systems for container handling and transport be framed for future port system concept design?"

Three port system alternatives, including the associated characteristics, are introduced: i) an onshore port system, ii) an offshore-onshore port system with a waterway transport link and iii) an offshore-onshore port system with a fixed infrastructure link, illustrated by Figure 1, 2a and 2b, respectively.

After this introduction, the port system characteristics are assessed. The assessment is presented as a list of advantages and disadvantages for each port system alternative (see Table 1). For the sake of clarity, the three port system alternatives are called Alternative Onshore, Alternative Barge and Alternative Bridge.

Table 1: Assessment of the various types of port systems

Assessment of the port system alternatives			
Advantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	Single container handling at the onshore terminal (time- and cost-effective)	Limited dredging activities required for deepwater access and the waterway transport link	Limited dredging activities required for deepwater access
		The ability of the shuttle barge fleet to be easily phased in line with changes in demand	The operational reliability of the transport link is barely affected by environmental conditions
Disadvantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	Possibly enormous dredging volumes required to guarentee deepwater access	Additional cost components for the construction of the offshore terminal	Additional cost components for the construction of the offshore terminal and the fixed infrastructure link
		Partially double container handling at both the terminals (additional operational costs and cycle time)	Partially double container handling at both the terminals (additional operational costs and cycle time)
		The operational reliability of the transport link is highly affected by weather conditions	The fixed infrastructure can hardly be phased gradually in line with changes in demand

Next, two *characteristic design variables* are identified to specify the *design scenarios*: i) the capacity of the design vessel and ii) the distance between the offshore and onshore terminal. These two variables represent the most fundamental design decisions. The capacity and the corresponding dimensions of the design vessel affect the ocean transport rates, the required channel dimensions and the vessel distribution over time and, therefore, the required storage capacity at the offshore terminal. The *offshore distance* affects the required logistical operations, channel dredging volume and island reclamation volume for Alternative Barge and Alternative Bridge and the length of the fixed infrastructure link for Alternative Bridge. Although the offshore distance only concerns the offshore-onshore port systems, the design variable is identified as one of the two characteristic design variables. Other important parameters like the bathymetry and the annual demand are determined by site conditions and economic studies and therefore, not by design decisions.

Table 2: Design scenarios

Design scenarios		Offshore-onshore distance		
Design vessel	Capacity	20 km	40 km	60 km
Panamax	6,000 TEU	scenario 1	scenario 4	scenario 7
New-Panamax	12,500 TEU	scenario 2	scenario 5	scenario 8
ULCS	21,000 TEU	scenario 3	scenario 6	scenario 9

A method is developed to quantify the logistical trade-offs by generating cost estimates for the design scenarios using a parametric model (see Figure 3). The model comprises two parts, and both include a simulation. The first part is developed to determine the required *port system elements* and to make the corresponding *cost estimates* for the specified design scenarios (see Table 2), for all three port system alternatives. The second part is developed to address the logistics of the offshore-onshore port system with a waterway transport link (Alternative Barge), as the relationship between the operational reliability of the waterway transport link and the required storage capacities of both the offshore and onshore terminals is identified as the second gap in the literature.

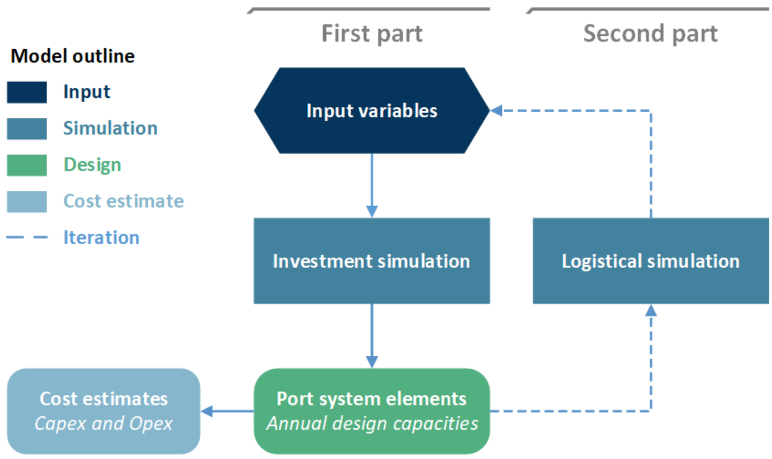


Figure 3: Model outline

Both simulations need to be evaluated. The evaluation of the model consists of two phases: i) verification and ii) validation, as shown in Figure 4. The verification phase addresses the correctness of the model operation according to its stated operating specifications. The correct operation of both simulations is ensured by various model tests.

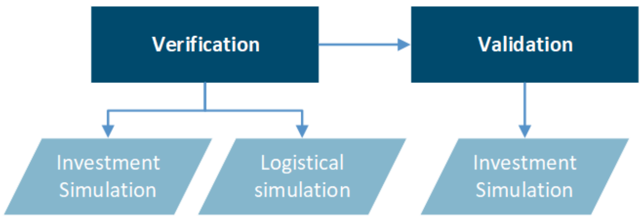


Figure 4: Phases of the model evaluation

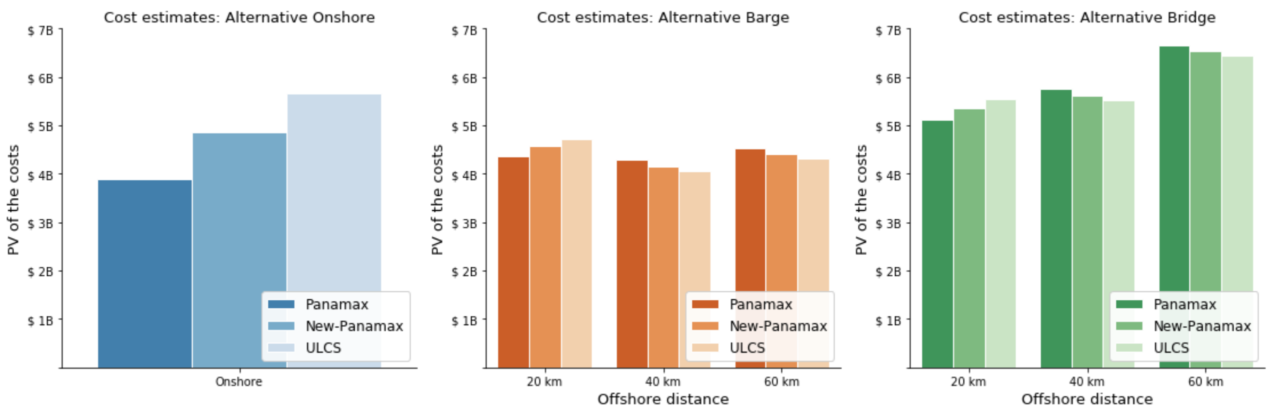
The validation phase addresses the validity of the investment simulation output. Therefore, the port system capacities are compared with design and performance benchmarks. Benchmarks are well-known and often-used standards in the maritime trade industry to evaluate the performance metrics to industry bests. Table 3 presents the results of the comparisons with the benchmark data. The metrics of the investment simulation resembles with the benchmarks.

Table 3: Comparison between the metrics of the investment simulation output and the capacity and performance benchmarks by Drewry (2010)

Benchmark study			
Berth performance	Investment simulation metrics	Benchmarks	Unit
Quay line	720 - 950	850 - 1,200	TEU per meter per year
Ship-to-shore crane	142,860	130,000 - 140,000	TEU per crane per year
Yard capacity and performance (RTG)			
Offshore operational area design capacity	1,200	1,455	TEU per ha
Offshore total terminal area performance	35,180	30,000	TEU per ha per year
Onshore operational area design capacity	1,200	1,455	TEU per ha
Onshore total terminal area performance	35,890	30,000	TEU per ha per year

Next, a case study is performed to evaluate the generation of the port system elements and the corresponding cost estimates. The case study covers the concept design of the master plan for Payra Port in Bangladesh. The master plan includes offshore-onshore port systems handling various types of cargo, including containers. Only the design of the container terminals is addressed for the validation. The total cost estimate generated by the investment simulation is 13% lower compared to the concept design of Payra Port. The difference in costs is considered as limited, and the most notable differences in costs can be explained. Therefore, the investment simulation is evaluated as a valid model.

Following the verification and validation of the *investment simulation*, the model correctly generates the port system elements and the cost estimates for the design scenarios. Hereby, the characteristic design variables will be evaluated. Figure 5 presents the cost estimates of the port system alternatives for the specified design scenarios. The cost estimates show clear trends with the capacity of the design vessel for the offshore distance clusters. The results show that the cost estimates of *offshore-onshore port systems* can be less costly compared to the cost estimates of *onshore port systems* for specific design scenarios. Notably, the cost estimates of Alternative Barge are less costly for the design scenarios that include the New-Panamax compared to the cost estimate of Alternative Onshore. Furthermore, the cost estimates of Alternative Bridge are slightly less costly for the design scenarios that include the ULCS for an offshore distance of 20 and 40 km compared to the cost estimate of Alternative Onshore.



(a) Alternative Onshore (b) Alternative Barge (c) Alternative Bridge

Figure 5: Cost estimates of the port system alternatives for the specified design scenarios

A more in-depth analysis is given by the generation of categorised cost estimates per design vessel. Figure 6 presents these categorised cost estimates for the design scenarios that include the ULCS. The segments in the bars represent different categories of the cost estimates. The colours indicate the category (e.g. dredging) and the tint indicate the type of costs (e.g. capital dredging or maintenance dredging).

Hence both offshore-onshore port systems offer less costly alternatives compared to the onshore port system for specific design scenarios. From this, we can conclude that Alternative Barge, as well as Alternative Bridge, will be considered more frequently in the future, as the size of container ships is still growing.

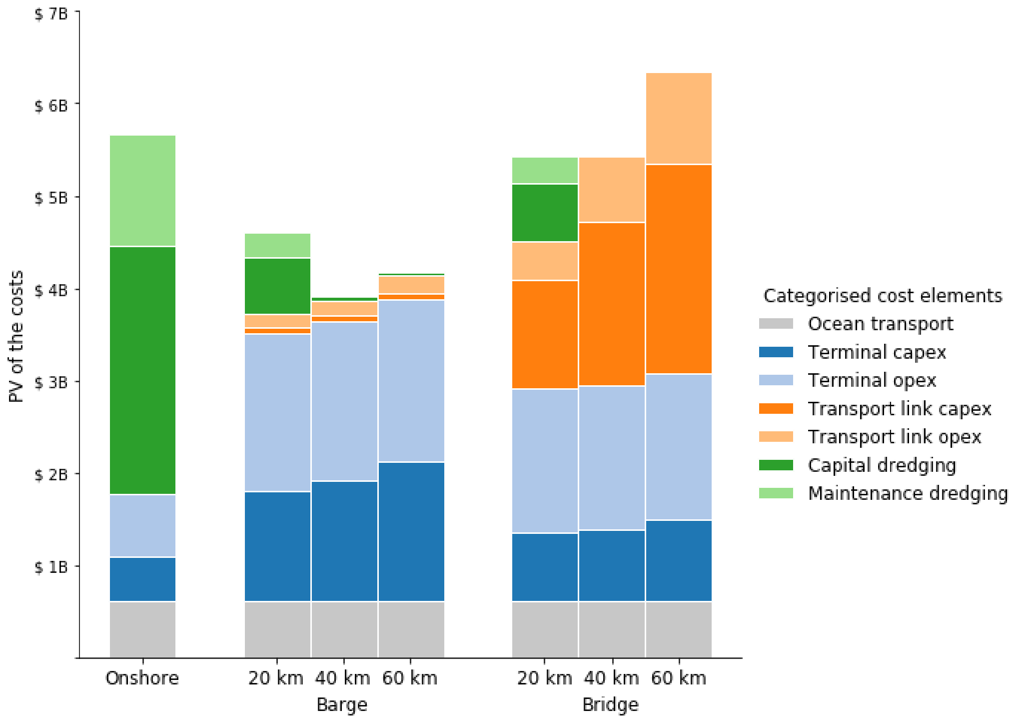
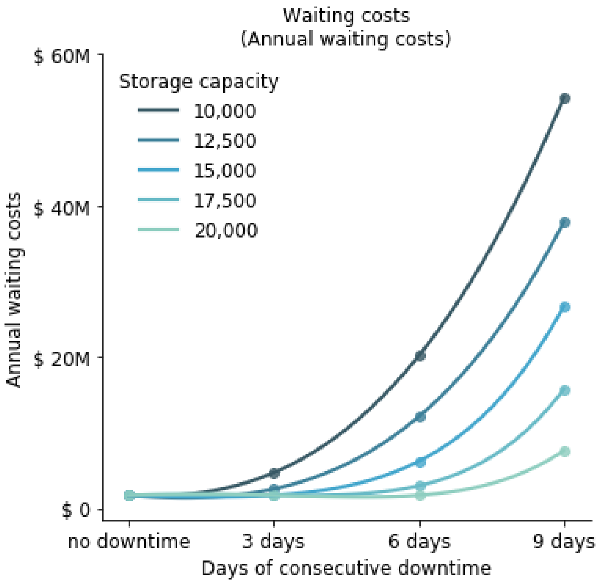


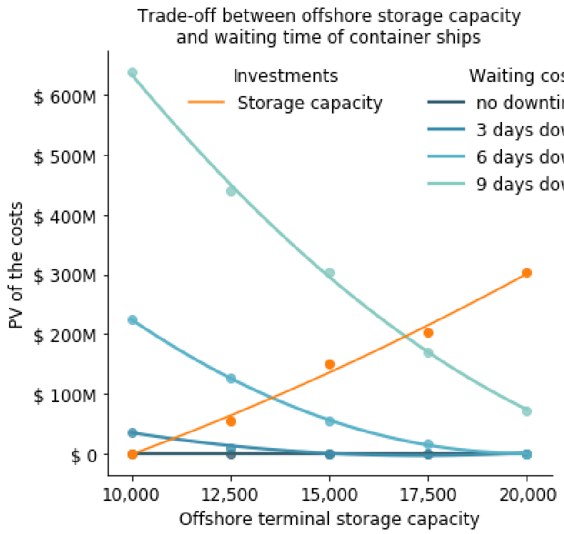
Figure 6: Categorised cost estimates for the design scenarios that include the ULCS

The findings with regard to the characteristic design variables are strengthened by sensitivity analyses for a specific design scenario (i.e. design scenario 5). The scenario comprises the New-Panamax and an offshore distance of 40 km. The sensitivity analyses discuss the variables that are not affected by the design decisions, but with a notable impact on the cost estimates. These variables concern the annual demand and the bathymetry of the foreshore.

Following the verification of the logistical simulation, the model correctly establishes the relationship between the operational reliability of the waterway transport link and the waiting events of container ships (see Figure 7a). Depending on the frequency and length of the periods of downtime of the barge transport, the trade-off can be made between the costs related to the offshore storage capacity and the annual waiting time of container ships (see Figure 7b). Therefore, the most cost-effective solutions can be found for specific downtime scenarios.



(a) Annual waiting costs related to the length of periods of consecutive downtime



(b) Trade-off between offshore storage capacity and waiting time of container ships

Figure 7: Assessment of the relationship between the operational reliability of the waterway transport link and the required storage capacities

The cost-based evaluations of the logistical trade-offs conclude the framework for future port system concept design. Four major logistical trade-offs are identified.

1. The first logistical trade-off concerns the choice between onshore port systems and offshore-onshore port systems, based on the bathymetry of the foreshore. The cost estimates for onshore port systems are highly affected by the slope and shape of the foreshore, contrary to the offshore-onshore port systems. This results in a trade-off between the dredging costs for onshore port systems and cost related to additional container handling, storage and transport and the reclamation costs for offshore-onshore port systems.

2. The second logistical trade-off concerns the choice between port system alternatives of which the cost estimates are significantly related to the demand (i.e. the offshore-onshore port system with a waterway transport link) and port system alternatives of which parts of the design are hardly related to the demand (i.e. the onshore port system and the offshore-onshore port system with a fixed infrastructure link). This results in a trade-off between alternatives with primarily capex and alternatives with primarily opex. Depending on the expected demand at the end of the life cycle, port system alternatives of which large components are hardly related to the demand may offer cost-effective alternatives.

3. The third logistical trade-off concerns the location of the offshore terminal in the case of an offshore-onshore port system with a fixed infrastructure link. The dredging costs of the access channel for the ocean-going vessels depend on the offshore terminal location, the draught of the design vessel and the bathymetry of the foreshore. The costs for the construction of the fixed infrastructure link depend on the offshore location as well. This results in a trade-off between the costs related to the dredging of an access channel and the construction of the fixed infrastructure link.

4. The fourth logistical trade-off, only concerning the offshore-onshore port system with a waterway transport link, is the trade-off regarding costs related to downtime of the shuttle barges. Depending on the frequency and length of the periods of downtime of the barge transport, one could make the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships.

Finally, the research question is answered.

"How can the cost-based evaluation of the major logistical trade-offs regarding various types of port systems for container handling and transport be framed for future port system concept design?"

A framework is a collection of concepts to give a better understanding of a given problem. The problem was stated as a lack of methodology to evaluate the logistical trade-offs between various types of port systems, including offshore-onshore port systems. The framework results in a better understanding of the logistical trade-offs between different type of port systems for container transport and handling.

The major logistical trade-offs are framed based on the evaluation of the characteristic design variables, the results of the sensitivity analyses and the assessment of the relationship between the operational reliability of the waterway transport link and the required storage capacities. The cost-based evaluations of these trade-offs could serve as a reference to make more deliberate and integral choices between various types of port systems.

Using the parametric model, the logistical trade-offs are quantified by the generation of cost estimates for the port system alternatives. The developed investment simulation is the first method generating offshore-onshore port system designs, including the corresponding cost estimates. In addition, the developed logistical simulation is the first method to relate the container ship and shuttle barge transport with the terminal operations using agent-based discrete-event simulations. These logistical simulations evaluate the cost related to the shuttle barge downtime. Depending on the frequency and length of the periods of downtime, the most cost-effective solutions are found for specific downtime scenarios.

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Acronyms

Capex	Capital Expenditures
CD	Chart Datum
LIGTT	Louisiana International Gulf Transfer Terminal
OGV	Ocean Going Vessel
Opex	Operational Expenditures
PV	Present Value
RMG	Rail Mounted Gantry (Crane)
RTG	Rubber Tyred Gantry (Crane)
SSBT	Semi Submersible Barge Transporter
ULCS	Ultra Large Container Ships
VOOPS	Venice Offshore Onshore Port System
VPA	Venice Port Authority

Glossary

agent-based simulation	Simulates the actions and interactions of autonomous agents (both individual or collective entities) to assess their effects on the system as a whole.
cargo projection	A long term projection of the cargo flows that are expected to be handled in the port. Cargo projections are conducted by a transport economist at the beginning of the masterplan project.
deepwater port	Port that provides for the accommodation of large ocean-going vessels for loading or unloading cargo. Deepwater ports are also defined to be any port which has the capability to accommodate a fully laden Panamax ship.
discrete-event simulation	Models the operation of a system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system.
modality	Mode of transport, various terms are used to refer to the combining of transport modes, such as multimodal, intermodal, modal split and modal shift.
nearshore port system	Port system positioned in the region relatively close to the shore.
offshore distance	The distance between the offshore and onshore terminal.
offshore terminal	Terminal facility at a certain distance from the coast in the sea/ocean. The terminal can be constructed as an artificial island protected by breakwaters or a more exposed platform with dynamic controlled mooring and fender systems.
offshore-onshore port system	Port system consisting of a combination of an offshore and onshore terminal with at least partly double container handling at both the terminals.

onshore port system	Port system only consisting of an onshore terminal.
port system	Collective term including all types of port layouts and covers offshore, nearshore and onshore types of terminals and combinations of these types, such as the offshore-onshore port system.
port system element	An entity of a part of the port system.
ship-to-shore crane	Type of large dockside gantry crane found at container terminals for loading and unloading intermodal containers from container ships.

1
Introduction

1.1. Background: developments in container transport

The containerised trade is the fastest-growing segment of the global seaborne trade. The trade volumes have increased with 8.1% annually over nearly four decades on average. Figure 1.1 presents the trade volumes and annual growth rates from 1996 until 2018. The volumes are expected to grow further with an annual growth rate of 6.0% until 2023 (United Nations Conference On Trade and Development (UNCTAD), 2018).

Another well-known trend is the constantly growing size of container ships over recent decades due to a continuous search for economies of scale by shipping lines. Nowadays, cost savings from bigger container ships are decreasing and supply chain risk related to mega-container ships are rising according to Merk, Busquet, and Aronietis (2015). Though, liner shipping alliances benefit from the efficiency gains of the increasing size of container ships[1].

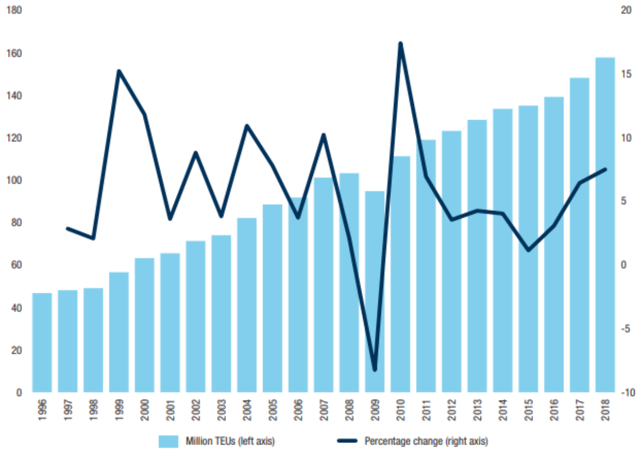


Figure 1.1: Global containerised trade, 1996–2018 (United Nations Conference On Trade and Development (UNCTAD), 2018) *Data for 2018 are projected figures.*

These large shipping alliances have great bargaining power and influence in the relationship between container shipping lines and ports (United Nations Conference On Trade and Development (UNCTAD), 2018). Three global liner shipping alliances[2] collectively account for 93 per cent of the deployed capacity, resulting in an order book capacity by ships of over 14,000 TEUs of two thirds (Merk, Lucie, & Salamitov, 2018). The growth of the container ships has increased the requirements for ports to adapt, such as more technologically advanced handling equipment and increasing water depth requirements, due to the increased draught of container ships over the years (see Figure 1.2).

As a result of the constantly growing container ship sizes, the demand for deepwater access will increase. Many of the conventional (onshore) *deepwater ports* are physically limited in terms of size and water depth to make the required changes to accommodate larger ships (Pluijm, 2014). In order to guarantee the increasing water depth requirements in onshore *deepwater ports*, dredging costs are supposed to grow.

In case of conventional *deepwater port* development, the coastal system is affected by the required dredging activities in terms of sediment balance, currents and waves. The local morphological disruptions can negatively impact the river- and delta ecosystems. Furthermore, onshore ports are confronted by a growing scarcity of prime locations and limited space for sustainable expansion (Schipper et al., 2015).

[1]Although the container shipping lines are the main beneficiaries of the economy of scale, the mega container ships have fuelled ship overcapacity depressing freight rates and profit margins of shipping lines (Merk et al., 2015)
[2]2M, Ocean Alliance and THE Alliance

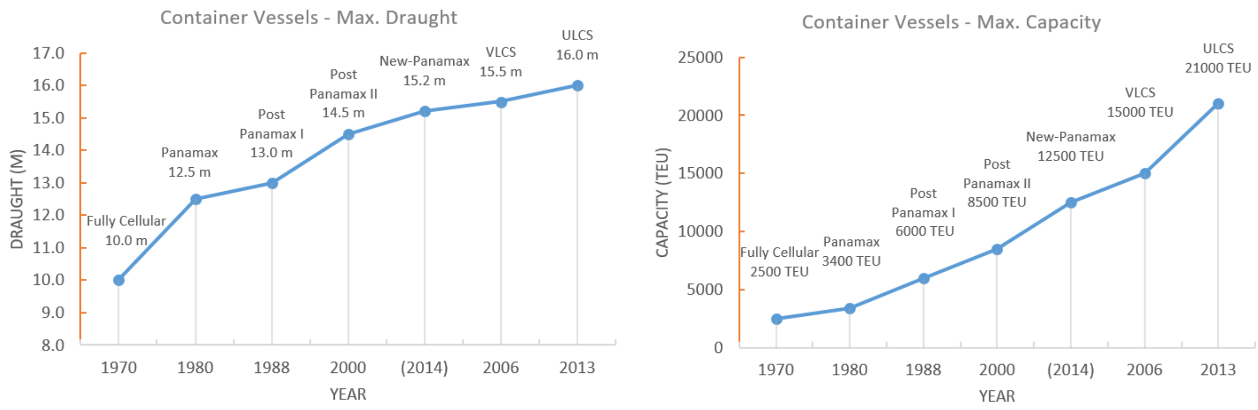


Figure 1.2: Development of container ship draught and capacity, data obtained from Rodrigue, Comtois, and Slack (2016)

The realisation of *offshore-onshore port systems*[3] can be a huge opportunity for coastal zones with an extensive shallow foreshore. In case of onshore *deepwater ports*, the dredging costs largely depend on the bathymetry of the coastal zone. Alongside large parts of the African coast, e.g., particularly in West and East Africa, distances of 10 - 15 km from the coast are required to reach a water depth of 20 m (Pluijm, 2014). A considerable amount of dredging activities will be necessary to create an access channel to reach natural deep waters. Furthermore, *offshore-onshore port systems* could be the future's energy-efficient and eco-friendly port systems due to overall energy efficiencies on the vessel side (Kurt, Boulougouris, & Turan, 2014).

1.2. Problem statement: gaps in the literature

Ideally, port authorities and governments should be able to evaluate the performance of various types of *port systems* early in the design process (W. S. Kim & Kim, 2019). Innovative solutions, like *offshore-onshore port systems*, can be developed to flexibly respond to the emergence of large container ships and the increase in port trade volume (Pluijm, 2014). The idea regarding *offshore-onshore port systems* is quite simple; if the ship is not able to come to the port, the port has to come to the ship.

In reality, the methodology for evaluating the performance of *offshore-onshore port systems* is limited compared to the evaluation of *onshore port system* performances. Most and best-known literature related to *offshore terminal*[4] development concerns floating terminals (Ali & Ligteringen, 2005; J. Kim & Morrison, 2012; Baird & Rother, 2013; Klusen, 2016; W. S. Kim & Kim, 2019). These floating applications are, however, only appropriate for limited capacities and the risks associated with the development of large floating terminals are difficult to quantify (Pachakis, Beamish, & Menegazzo, 2016). Kurt, Boulougouris, and Turan (2015) performed a cost-based analysis of *offshore-onshore port systems* for container shipment; however, exclusively floating container platforms are considered based on the research of J. Kim and Morrison (2012), and no comparison with *onshore port systems* is made. Moreover, currently operational static[5] port systems including an 'offshore' terminal are better classified as *nearshore port systems* since they are more like extended onshore terminals connected to land by a fixed infrastructure link without double container handling.

[3] Port systems consisting of a combination of an offshore and onshore terminal. Offshore-onshore port systems are defined as systems with at least partly double handling at both the terminals.
[4] The offshore part of the offshore-onshore port system.
[5] Non-floating, land reclamations

The development of *offshore-onshore port systems* has been considered lately as port authorities and governments are faced with increasing dredging volumes to meet the demand for deepwater access (Pachakis et al., 2016). Besides, onshore port development encounters increasing environmental constraints, a growing scarcity of prime locations, limited space for sustainable expansion, uncertain impacts of climate change and technological developments and increased security concerns (Schipper et al., 2015).

Offshore-onshore port systems involve additional costs and operational challenges compared to conventional onshore ports. The double container handling at both the offshore and onshore terminals results in a more extensive supply chain and, even more critical, the operational reliability of the infrastructure linking the offshore and onshore terminal highly affects the entire *port system*. The required storage capacities of both the offshore and onshore terminals largely depend on the operational reliability of the transport link which depends, amongst others, on the environmental conditions.

Port authorities and governments should be able to evaluate major logistical trade-offs between *offshore-onshore port systems* and *onshore port systems* early in the design process. The cost-based evaluations of these trade-offs for various port system designs could serve as a framework to make more deliberate and integral choices between various types of port systems.

The gaps in the literature are:

1. the clarification of the differences between various types of port systems and an assessment of the port system characteristics;
2. a method to assess the relationship between the operational reliability of the transport between the offshore and onshore terminal and the required storage capacities of both the offshore and onshore terminals; and
3. the cost-based evaluation of the major logistical trade-offs regarding various types of port systems.

1.3. Research objective: research question and sub-questions

The objective of this research is to evaluate the trade-offs regarding port system design for container handling and transport from a logistical perspective. Therefore various port systems will be evaluated based on costs. Cost estimates of various port system layouts will be generated to compare conventional onshore ports and offshore-onshore port systems in terms of costs. In addition, a method is developed to assess the logistical challenges involved with the offshore-onshore port systems. The cost-based evaluations will set a *framework* - a collection of concepts - concerning the logistical trade-offs.

The research question is stated as follows:

"How can the cost-based evaluation of the major logistical trade-offs regarding various types of port systems for container handling and transport be framed for future port system concept design?"

In order to formulate an answer to the research question, two sub-questions have to be answered.

i. What are the differences between and the advantages and disadvantages of various types of port systems?

ii. What are the major logistical trade-offs regarding various types of port systems based on costs?

1.4. Research scope

Cargo This research will study the greenfield development of static offshore-onshore port systems for container handling and transport. Currently operational static *offshore-onshore port systems* and *nearshore port systems* predominantly handle containers as described in Appendix A. Furthermore, some interesting handling and storage requirements relate to container terminals; the loading or unloading of containers require calm water and extensive areas for intermediate storage as the container flow is bidirectional. Therefore, the export containers have to be stored in advance of the arrival of the *Ocean Going Vessel* (*OGV*) and, due to inspection regimes and import containers may require additional time on the terminal (Pachakis et al., 2016).

The research focuses exclusively on container handling and transport. However, efficiencies may be achieved formed by a variety of types of cargo[6]. Offshore loading and unloading mechanisms for dry bulk and liquid bulk cargo are already well-known. Offshore buoy moorings, floating storage units, and transfer stations with self-unloading vessels are common arrangements to perform these operations. However, these type of arrangements barely resembles with static high capacity offshore container terminals. The parallel between container terminals and dry bulk terminals may be interesting, due to efficiencies achieved by the variety of types of cargo. Liquid bulk rather differs from other types of cargo in terms of transport and storage. Therefore, the parallel between liquid bulk transport and containers is less interesting. Other types of cargo, like general cargo and Ro/Ro, are also excluded because the ship sizes are substantially smaller and are unlikely to increase in the future (Merk et al., 2015).

Supply chain An offshore-onshore port system is part of a larger supply chain (see Figure 1.3). This research studies the ocean transport, the transport between the offshore and onshore terminal and the hinterland transport. The ocean transport will describe the transport from an overseas port towards the offshore terminal and vice versa. The hinterland transport will describe the transport from the onshore terminal towards an inland terminal and vice versa. The shipping projections are input parameters expressed by ocean transport and hinterland transport volumes and vessel distributions.

Figure 1.3: Demarcation of the nautical supply chain

Modalities The offshore-onshore port system is on the one hand considered as a partly closed system with internally operating means of transport, whereby only containers enter and leave the port. On the other hand, depending on the hinterland characteristics, particular *modalities* may be capable of transporting containers between the offshore terminal and inland destinations directly. This will result in the opportunity, for at least a share of the throughput, to transport containers directly to the inland destinations. The hinterland modes of transport are assumed not to constitute design capacity limitations.

Structural design Since the research addresses the concept design phase, no structural designs will be included. The research focuses exclusively on the concept design from a logistical point of view.

Environmental conditions The considered environmental conditions comprise the following components; bathymetry, wave conditions and water levels. Currents, meteorological conditions, sediment characteristics and sediment transport are not taken into account. Although these components may be critical in specific cases, they are excluded here for the set up of a generic framework.

[6]Economies of scope

Cost estimates The expected revenues generated by the port system are not included since container revenues highly fluctuate per region. The objective of the research is to evaluate cost estimates, not to explore positive business cases. Furthermore, the expected revenues mainly depend on the demand, and the demand is equal for all port system alternatives.

Cost estimates will be presented for various port system alternatives. These alternatives will differ in the ratios between the different port system components and, therefore, in the shares for governmental authorities, port authorities, contractors and engineering firms. There is, however, no intention to increase or decrease the share of one of the businesses. The cost estimates are evaluated on a system level, as defined by the supply chain demarcation.

Social costs, such as resettlement costs, are not taken into account. Additionally, environmental costs, according to the environmental full-cost accounting method[7], are excluded. An example of environmental costs is the 'full' costs of the construction of a causeway by negatively impacting the ecosystems as a result of morphological disruptions. Although social and environmental constraints can hugely impact the design, the involved costs are excluded.

1.5. Report outline

The outline of the report is presented in Figure 1.4. The sub-questions will be answered in Chapter 2 - 5. Chapter 2 introduces the offshore-onshore port systems. Subsequently, a description of the model development and validation is given in Chapter 3 and 4, respectively. In Chapter 5, the cost estimates of the port systems for specified design scenarios are presented. Additionally, the impact of multiple other parameters, such as the annual demand and the environmental conditions, are presented by cost-based sensitivity analyses related to a specified base design scenario. Eventually, based on the aforementioned chapters, the study will be discussed, and the research question will be answered in Chapter 6.

The appendix comprises six chapters. A. Reference projects, gives an overview of the currently operational or planned offshore and nearshore ports worldwide. B. Container ship characteristics, presents an overview of the used container ship classes. C. Port system elements, describes the required dimensions and the number of elements of the port system elements. D. Port element characteristics, presents the default values related to the port system elements. E. Results of the investment simulation, presents the results of the port system designs. F. Results of the logistical simulation, presents the results of the method developed to assess the logistical challenges involved with the offshore-onshore port systems. G. Code archive, comprises links towards the developed codes and includes the documentation.

[7] Environmental full-cost accounting (EFCA), also known as true-cost accounting, is a method of cost accounting that traces direct costs and allocates indirect costs by collecting and presenting information about the possible environmental, social and economical costs and benefits or advantages for each proposed alternative.

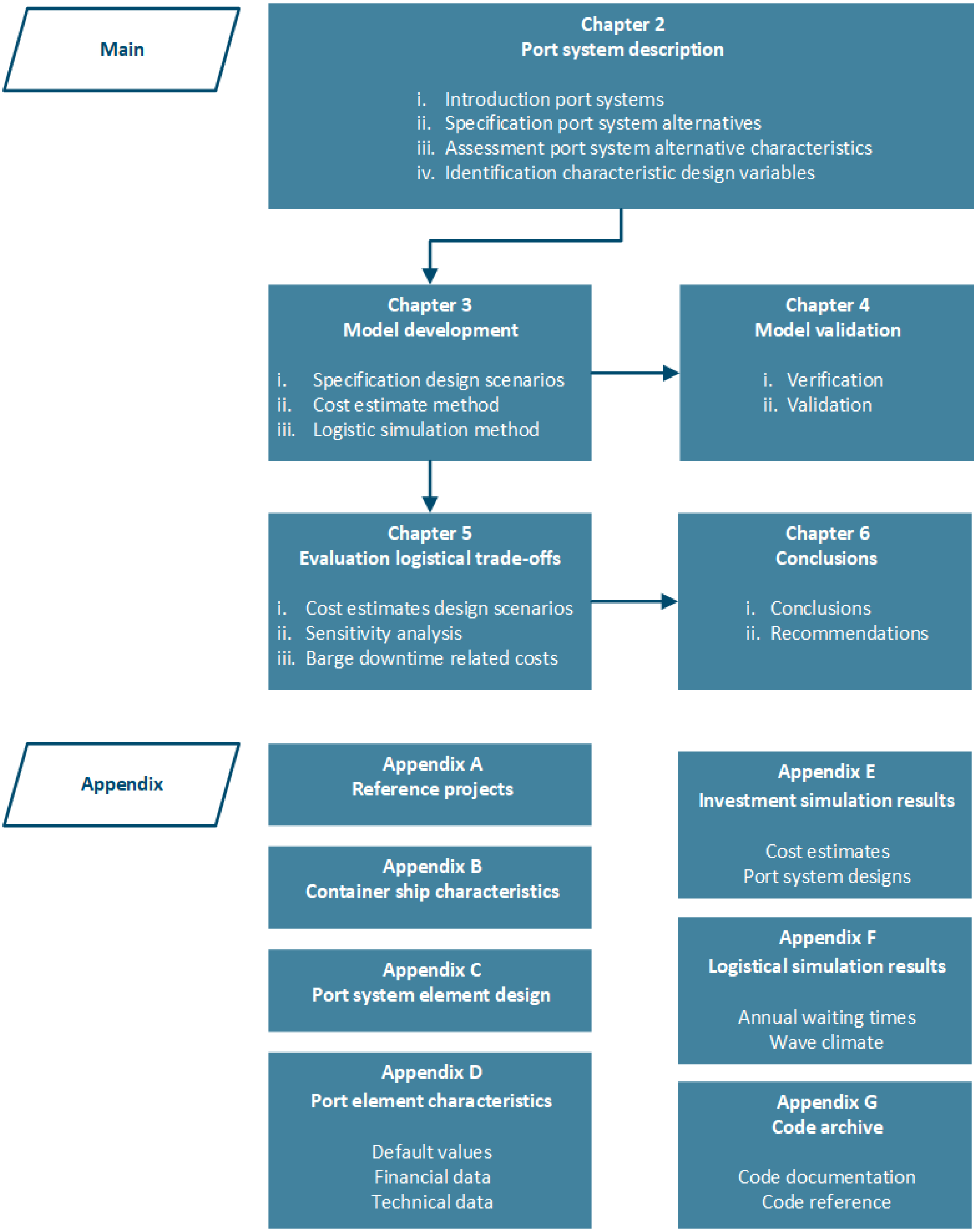


Figure 1.4: Report outline

2
Description of the port system alternatives

This chapter introduces the port systems and addresses the first sub-question:

> *"What are the differences between and the advantages and disadvantages of various types of port systems?"*

In order to answer the first sub-question, various types of port systems are defined. Therefore, the following items are discussed:

- a general introduction to port systems (Section 2.1);
- the description of the three types of port systems (Section 2.2); and
- the assessment of the characteristics of the port system alternatives (Section 2.3).

2.1. General introduction to port systems

Port systems include all types of port layouts and covers offshore, nearshore and onshore types of terminals and combinations of these types, such as the offshore-onshore port system. A port system links deepwater with the hinterland as depicted in Figure 2.1.

Figure 2.1: Scheme of the port system connectivity

2.2. Port system alternatives: three types of port systems

Three types of *port systems* are introduced:

I. an onshore port system;
II. an offshore-onshore port system with a waterway transport link; and
III. an offshore-onshore port system with a fixed infrastructure link.

The first type of port system forms the starting point for the comparison between the different port system alternatives. The port system alternatives are initiated with similar hinterland connectivity capabilities. The containers can be transported by barge, rail and road from the onshore terminal towards the inland destinations and vice versa. This part of the transport network is therefore not further discussed with the introduction of the port system alternatives.

2.2.1. Onshore port system

A conventional deepwater port fulfils the requirements for deepwater access onshore. The onshore terminal requires an access channel to link the turning circle in front of the *Ocean Going Vessel* (*OGV*) berth with deepwater. The required dredging volumes largely depend on the dimensions of the design vessel and the bathymetry of the foreshore. The dredging activities are required for the creation of an access channel. They mainly depend on the extent of the shallow foreshore, as depicted in Figure 2.2.

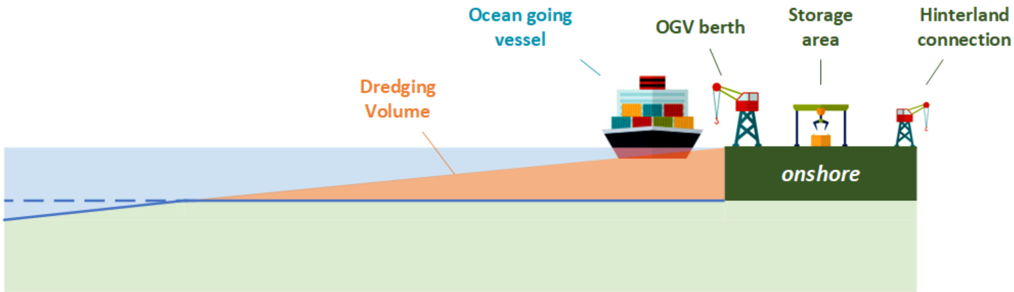


Figure 2.2: Onshore port system

2.2.2. Offshore-onshore port system with a waterway transport link

The second port system alternative is an *offshore-onshore port system*, including a waterway transport link between the offshore and onshore terminals. The *offshore terminal* will include berths schematically on both sides to accommodate the ocean-going vessels and the shuttle barges. In reality, berths for ocean-going vessels and shuttle barges could be shared. The container transport between the terminals is arranged by barges with a limited draught. Besides the transfer of containers to other *modalities* at the onshore terminal, a share of the barges may sail directly from the offshore terminal towards inland destinations.

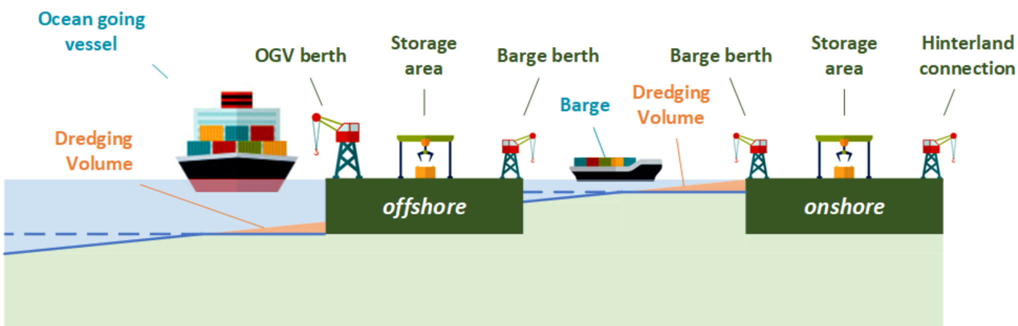


Figure 2.3: Offshore-onshore port system with a waterway transport link: the offshore terminal is located such that dredging is required in front of the OGV-berth

To fulfil the requirements for deepwater access, the offshore terminal may need an access channel to link the turning circle in front of the *OGV*-berth with deepwater, as shown in Figure 2.3. The required dredging volumes largely depend on the dimensions of the design vessel, the location of the offshore terminal and the bathymetry of the foreshore. The offshore terminal may be located such that no dredging activities are required for an access channel, as shown in Figure 2.4. In addition, a waterway transport link between the offshore and the onshore terminal is required.

A waterway transport link between the offshore and onshore terminal can offer the flexibility to route to several different onshore locations, the ability to be easily phased in line with an increase in demand by enlarging the shuttle barge fleet as well as likely environmental benefits (Venice Newport Container and Logistics, 2012).

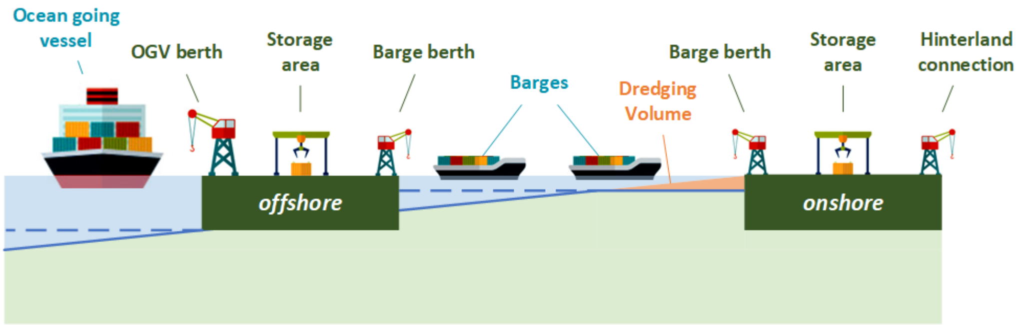


Figure 2.4: Offshore-onshore port system with a waterway transport link: the offshore terminal is located such that only dredging for the waterway transport link is required

One major disadvantage is that the operational reliability of the waterway transport link largely depends on the weather and wave climate. Besides, double handling of containers makes the operations more expensive compared to conventional onshore container operations.

2.2.3. Offshore-onshore port system with a fixed infrastructure link

The third port system alternative is an *offshore-onshore port system*, including a fixed infrastructure link between the offshore and onshore terminals. The container transport between the terminals can be arranged by rail or road transport by a bridge, causeway or tunnel, or a combination of these types of fixed infrastructure. Besides the transfer of containers to other *modalities* at the onshore terminal, a share of the trucks may drive directly from the offshore terminal towards inland destinations.

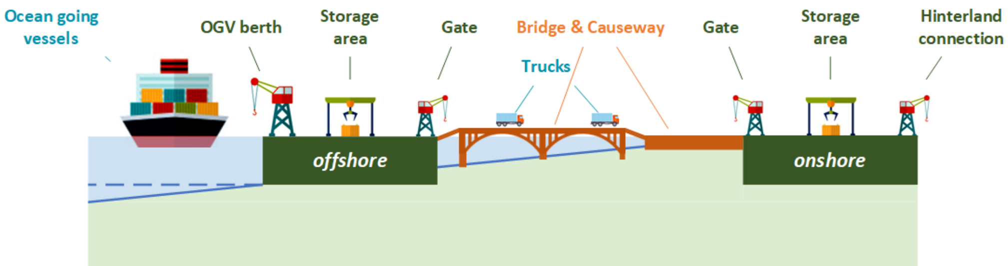


Figure 2.5: Offshore-onshore port system with a fixed infrastructure link: the offshore terminal is located such that no channel dredging is required

In order to fulfil the requirements for deepwater access, the offshore terminal may need an access channel to link the turning circle in front of the OGV-berth with deepwater (see Figure 2.5). The required dredging volumes largely depend on the dimensions of the design vessel, the location of the offshore terminal and the bathymetry of the foreshore. Similar to the second port system alternative, the offshore terminal may be located such that no access channel is required.

The operational reliability of the fixed infrastructure link may be barely affected by harsh environmental conditions. Besides this particular relevant logistical advantage for all types of fixed infrastructure links, the combination of a causeway and a bridge brings in financial and environmental opportunities and benefits. Causeways are less expensive in shallow waters, and the construction of a bridge is less costly in deep waters compared to a causeway construction, and bridges will affect the coastal sediment balance less compared to causeways, though marine habitats can flourish along causeways.

One main disadvantage of this concept is that the fixed infrastructure link can hardly be phased gradually in line with the demand, as a completely new connection to the mainland is required for operation. Moreover, additional infrastructure is required to route the containerised cargo to several onshore terminals.

2.3. Assessment of the characteristics of the port system alternatives

2.3.1. Advantages and disadvantages of the port system alternatives

After the introduction of the port systems, the characteristics of these port systems are assessed. The assessment is presented by a list of advantages and disadvantages for all port system alternatives (see Table 2.1). As this research discusses the logistical trade-offs, the characteristics related to these trade-offs are selected to include in the framework. These characteristics are indicated by a checkmark. The characteristics without the indication of a checkmark are not related to the research question and, therefore, classified as out-of-scope for the remainder of this research. The first gap in the literature is filled by the assessment of the port system characteristics.

Table 2.1: Overview of the main advantages and disadvantages of the port system alternatives

Assessment of the port system alternatives			
Advantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	Conventional port system, widely applied	✓ Limited dredging activities required for deepwater access and the waterway transport link	✓ Limited dredging activities required for deepwater access
	✓ Single container handling at the onshore terminal (time- and cost-effective)	✓ The ability of the shuttle barge fleet to be easily phased in line with an increase in demand	✓ The operational reliability of the transport link is barely affected by environmental conditions
		The flexibility to route easily to several different onshore locations	The combination of a bridge and a causeway can offer a cost-effective and relative environmental friendly alternative
		Limited onshore channel dredging activities resulting in environmental benefits	
Disadvantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	✓ Possibly enormous dredging volumes required to guarentee deepwater access	✓ Additional cost components for the construction of the offshore terminal	✓ Additional cost components for the construction of the offshore terminal and the fixed infrastructure link
	Channel dredging activities may highly affect the coastal sediment balance	✓ Partially double container handling at both the offshore and onshore terminals (additional operational costs and cycle time)	✓ Partially double container handling at both the terminals (additional operational costs and cycle time)
	Physically limited in terms of size and water depth	✓ The operational reliability of the transport link is highly affected by environmental condition	Negatively impacts the coastal sediment balance (in case of a causeway construction)
	Limited space for sustainable expansion		✓ The fixed infrastructure can hardly be phased gradually in line with the demand
	Growing scarcity of prime locations		Additional infrastucture is required to route to several onshore terminals

After the assessment and the classification of specific characteristics out-of-scope, only a bridge is considered as fixed infrastructure from now on. For the sake of clarity, the port system alternatives are called Alternative Onshore, Alternative Barge and Alternative Bridge for the remainder of the research.

2.3.2. Identification of the characteristic design variables

Two major characteristic design variables are identified to specify the design scenarios. These two variables represent the most fundamental design decisions. The first characteristic design variable is the capacity of the design vessel. The capacity and the corresponding dimensions of the design vessel affect the ocean transport rates, the required channel dimensions and the vessel distribution over time and, therefore, the required storage capacity at the offshore terminal.

The second characteristic design variable is the distance between the offshore and the onshore terminal. The offshore-onshore distance affects the required logistical operations, channel dredging volume and island reclamation volume for Alternative Barge and Alternative Bridge and the length of the fixed infrastructure link for Alternative Bridge.

Although the offshore-onshore distance only concerns the offshore-onshore port systems (Alternative Barge and Alternative Bridge), the design variable is identified as one of the two most fundamental and relevant parameters for the overall comparison between the port system alternatives. Multiple other parameters are extremely relevant such as the bathymetry and the annual demand. However, these parameters are determined by the site conditions and by the economic study.

Table 2.2 presents the setup for the design scenarios, which is further specified in Chapter 3.

Table 2.2: Overview of the specified design scenarios based on the characteristic design variables

Scenarios	*Offshore-onshore distance*		
Design vessel	a.	b.	c.
A.	1	4	7
B.	2	5	8
C.	3	6	9

3

Model development rationale: method to quantify the logistical trade-offs

In Chapter 2, the port system characteristics are identified, and three *port system alternatives* for container transport are defined. Furthermore, the characteristics related to the logistical trade-offs to include in the framework are selected, and the two *characteristic design variables* are defined to specify nine *design scenarios*.

Next, a method is developed to quantify the logistical trade-offs. These trade-offs are cost-based as a practical problem is addressed. To quantify these trade-offs, cost estimates are generated for the *design scenarios* by a parametric model. The model comprises two parts, and both include a simulation. This chapter elaborates on the model development, therefore, the following items are discussed:

- the general model outline (Section 3.1);
- the rationale of the first part of the model: cost estimates using investment simulations (Section 3.2);
- the rationale of the second part of the model: the logistical simulation and the feedback on the investment simulation (Section 3.3).

3.1. General model outline

The model comprises two parts, both include a simulation. The first part is developed to determine the required *port system elements* and to make the corresponding *cost estimates* for all three port system alternatives. The second part is developed to address the logistics of Alternative Barge, as the relationship between the operational reliability of the waterway transport link and the required storage capacities of the offshore and onshore terminals is addressed as one of the gaps in the literature. Figure 3.1 presents the model outline, which is further explained in more detail in the following sections.

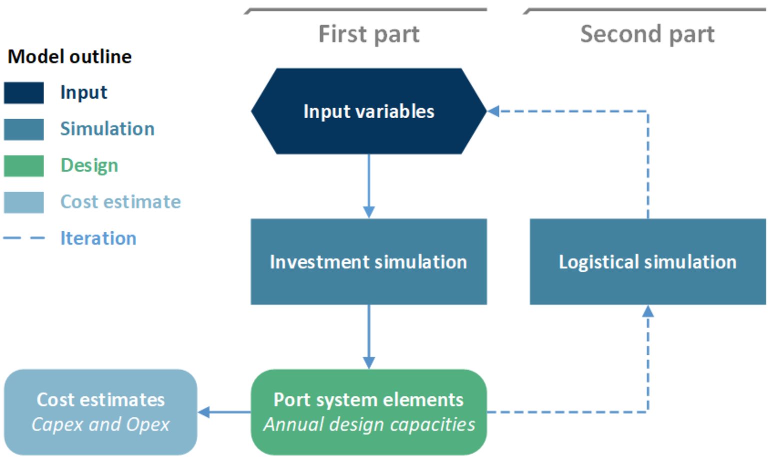


Figure 3.1: General model outline

3.2. Investment simulations to estimate the costs of the port systems

3.2.1. Objective of the investment simulations

The objective of the first part of the model is to determine the required *port system elements* and to make the corresponding *cost estimates* of the port systems. The investment simulation is developed to evaluate the cost estimates of individual design assumptions, such as the port system alternative and the design scenario. Based on a predefined *work method*, the model is capable of translating a *cargo projection* into a port system design. The cargo projection can either be developed as fixed volumes or as growth in demand over time. Figure 3.2 presents an example of a cargo projection with a growth in demand over time.

Besides, the figure shows an example of the translation of the annual demand into the port system capacity. This translation is called capacity planning. A lag capacity planning strategy is applied where capacity is added in response to an increase in annual demand. The vertical parts of the port system capacity graph indicate the increase in port system capacity after the investment in additional port system elements.

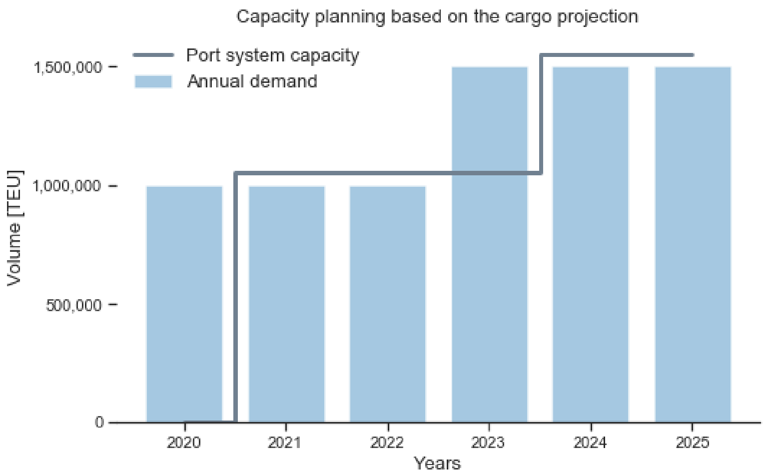


Figure 3.2: Example of the capacity planning including the cargo projection with an increase in demand

The port system design consists of a combination of various *port system elements* (e.g. berths, ship-to-shore cranes and stack equipment). The required number of port system elements depends on the port system capacity, and therefore, the annual demand. If the annual demand increases, the occupancy and utilisation rates of the port system elements increase. The work method prescribes, amongst others, the allowable occupancy or utilisation rates of the port system elements. If allowable occupancy or utilisation rates are exceeded, an investment of the element is triggered. These allowable rates are referred to as *investment triggers*. Figure 3.3 presents an example of the investment triggers for ship-to-shore cranes based on the allowable berth occupancy rate. If the berth occupancy rate exceeds the allowable berth occupancy rate, as a result of the increasing annual demand, additional ship-to-shore cranes are required. The number of added ship-to-shore cranes ensures that the berth occupancy rate is no longer above the allowable berth occupancy rate.

Besides the required number of ship-to-shore cranes, multiple other port system elements are required (e.g. the required number of berths and the required number of stack equipment). Figure 3.4 illustrates an example of the required port systems elements for Alternative Barge. The figure shows all port system elements included in the design of the offshore and onshore terminals. The number of port system elements is in line with the port system capacity. For example, the number of ship-to-shore (STS) cranes at the offshore terminal increases after the increase in capacity. All the calculations are based on yearly averaged capacities of the port system elements.

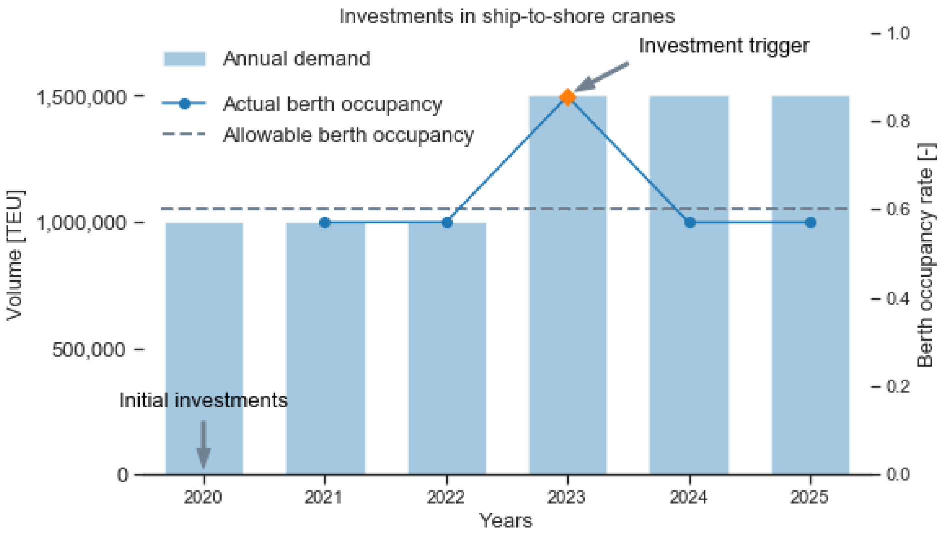


Figure 3.3: Example of the investments in ship-to-shore cranes including the cargo projection with an increase in demand

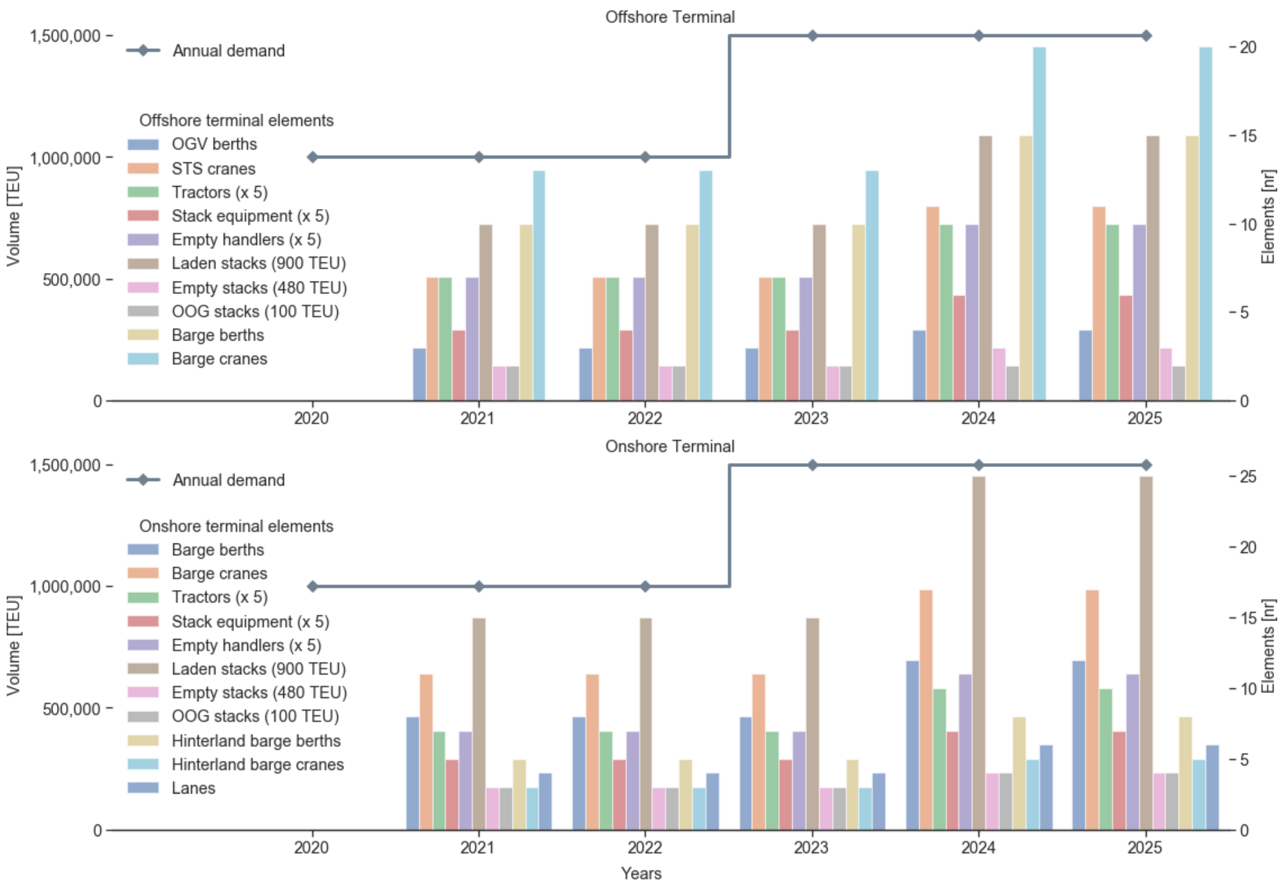


Figure 3.4: Example of the number of offshore and onshore terminal elements for Alternative Barge in line with the port system capacity (abbreviations in figure: OGV (ocean going vessel), STS (ship-to-shore) and OOG (out of gauge))

The *cost estimates* are determined based on the number of port system elements and the corresponding implementation of these elements. The costs are grouped into two categories. The first category consists of *Capital Expenditures* (*Capex*), related to the acquisition and reinvestment of the terminal elements, capital dredging and the transport link. The second category consists of *Operational Expenditures* (*Opex*), related to the annual costs due to the terminal operations, maintenance dredging, transport link operations and ocean transport. The cost estimate is expressed as the summation of the capex and opex while considering the time value of money. This value is called the *Present Value* (*PV*) of the costs.

Figure 3.5 shows the time series of the annual costs corresponding to the port system elements of the example of Alternative Barge, as shown in Figure 3.4. The investments in (additional) port system elements in 2020 and 2023 are indicated as *Capex*. The *Opex* are related to the port system capacity[1] and increase after the investments in 2023. Additionally, the effect of the time value of money is illustrated as the opex reduces over time.

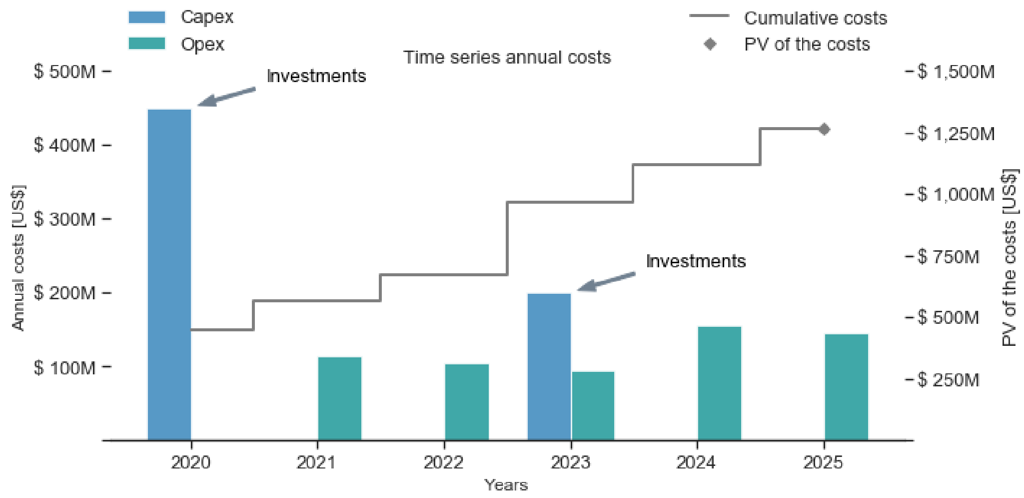


Figure 3.5: Example of the annual costs (capex and opex) corresponding to the port system elements for Alternative Barge

3.2.2. Modelling concept of the investment simulations

The applied model concept is the *Open Source Terminal Investment Simulation* (OpenTISim) which is available at the GitHub of the Hydraulic Engineering department of the Delft University of Technology (van Koningsveld, 2019). The method automatically generates investment decisions, parametrically derived from demand trends and a number of investment triggers, and is, therefore, able to generate cost estimates for various design scenarios. OpenTISim is a *Python* package for the evaluation of investment decisions and is further developed by multiple MSc students for various types of terminals (i.e. agribulk terminals (IJzermans, 2019), hydrogen import terminals (Lanphen, 2019) and container terminals (Koster, 2019)).

[1] In reality, the opex are partly related to the annual demand (e.g. energy costs) and partly related to the capacity (e.g. maintenance costs).

3.2.3. Model outline: investment simulation

Figure 3.6 depicts the detailed model outline of the investment simulation in line with the first part of Figure 3.1. The model outline gives an overview of all the processes of the model and how they are linked to each other. The first row (*defaults*, *work methods* and *boundary conditions*) indicates the types of input parameters. The input parameters and processes are discussed in the subsections below.

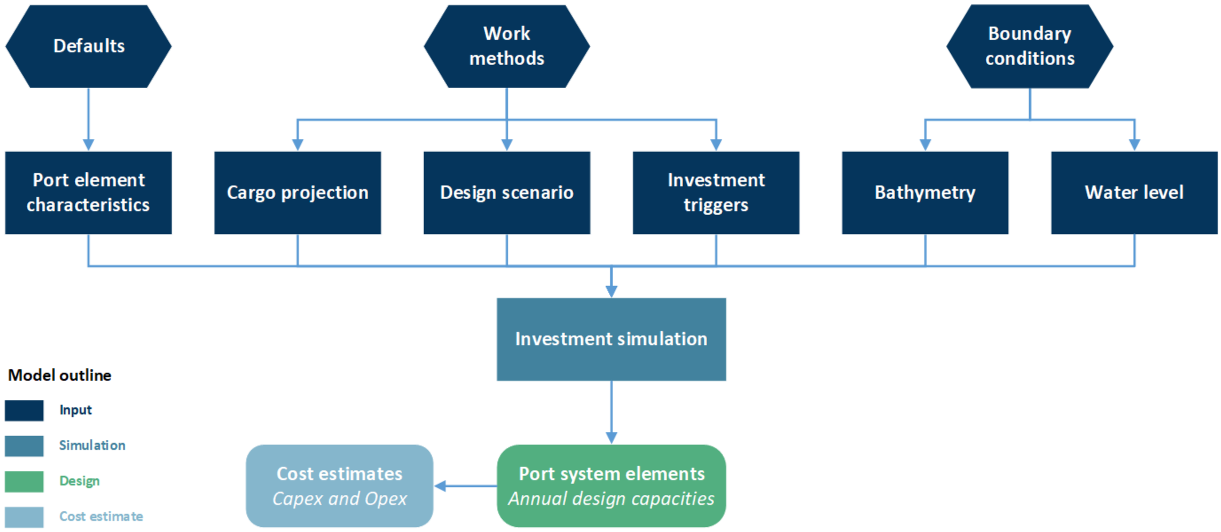


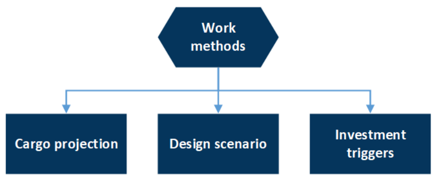
Figure 3.6: Model outline: investment simulation

3.2.4. Defaults

The *port elements characteristics* are default[2] input parameters composing the various port system elements. Appendix D gives an overview of all the default values used for the port system design.

3.2.5. Work methods: cargo projection, design scenarios and performance triggers

A work method consists of a cargo projection, a design scenario and a set of performance triggers. The individual parts of the work method are described below.



Cargo projection

The investment simulation generates cost estimates based on the cargo projection, the long term projection of the annual demand. For the calculation of the cost estimates of the port system alternatives in Section 5.1, an annual demand of 1,000,000 TEU is specified. A specification of the annual demand is necessary to compare the cost estimates for all port system alternatives equally. Subsequently, the sensitivity analysis in Section 5.2 evaluates: i) to what extent a variation of the fixed annual demand affects the cost estimates and ii) to what extent an increasing demand over time affects the cost estimates of the port system alternatives.

[2] A default refers to the value of a setting that is assigned to a program. Such settings are also called presets.

Design scenarios

The design scenarios are defined by the *characteristic design variables* as identified in Section 2.3.2. The two characteristic design variables are: i) the capacity of the design vessel and ii) the distance between the offshore and onshore terminal. Three values are specified for both the characteristic design variables resulting in nine design scenarios. The choice for three values per characteristic design variable is advantageous for the following two reasons: i) a limited number of simulations required and ii) allows for non-linear (curved) relationships of the cost estimates between the design scenarios[3]. The specification of the nine design scenarios is presented in Table 3.1.

Table 3.1: Design scenarios

Design scenarios		Offshore-onshore distance		
Design vessel	Capacity	20 km	40 km	60 km
Panamax	6,000 TEU	scenario 1	scenario 4	scenario 7
New-Panamax	12,500 TEU	scenario 2	scenario 5	scenario 8
ULCS	21,000 TEU	scenario 3	scenario 6	scenario 9

i) **Capacity of the design vessel**
As the ever-growing container vessels are one the main drivers for offshore-onshore port system development, three large container vessels, three large container ship classes are selected: *Post Panamax I*, *New-Panamax* and *ULCS* with capacities of 6,000 TEU, 12,500 TEU and 21,000 TEU, respectively.

ii) **Offshore-onshore distance**
The range of the offshore-onshore distance is based on the offshore-onshore port system concept of Payra Port, as described in Appendix A and used for the case study in Section 4.2.2. An offshore terminal located 60 km from the coast is considered for the development of Payra Port in Bangladesh. The coastal area of Bangladesh surrounding Payra Port can be considered as one of the most extensive shallow foreshores, reaching natural deep waters of 16 meters water depth located 60 km offshore. Therefore, the maximum offshore-onshore distance in this study is set at 60 km. Since three values are desired, distances of 20 km and 40 km offshore are set to complete the range. Figure 3.7 illustrates the effect of the offshore-onshore distance on the required channel dredging volume for Alternative Barge.

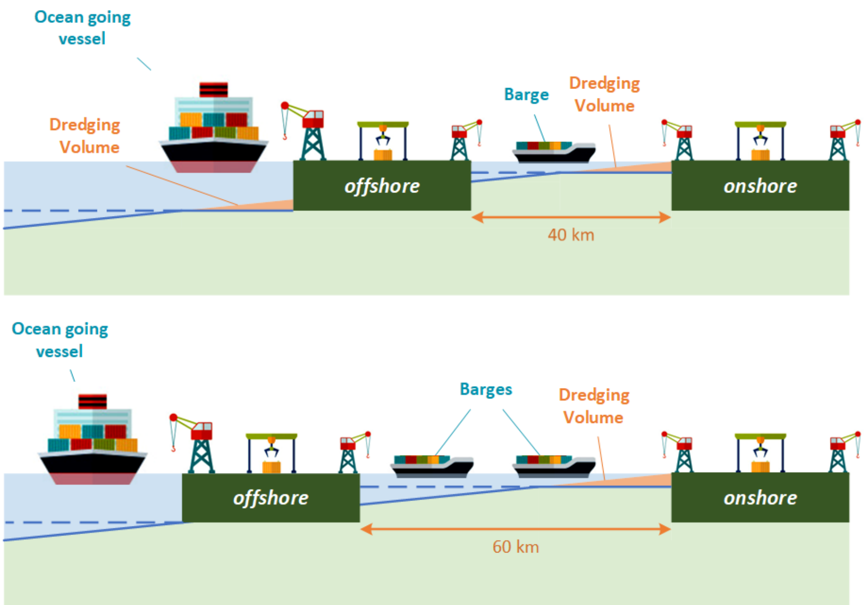


Figure 3.7: Illustration of the variation in the offshore-onshore distance for Alternative Barge

[3] In contrast to plots of only two values per characteristic design variable

Investment triggers

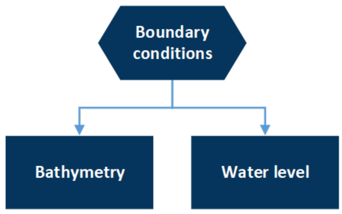
The investment triggers are listed below (see Table 3.2).

- The allowable OGV berth occupancy is the investment trigger to determine the required number of berths and cranes. The allowable barge berth occupancy forms the investment trigger for the determination of the number of shuttle barge berths and barge cranes at the offshore and onshore terminals.
- The allowable barge utilisation rate is the investment trigger for the number of shuttle barges to include in the barge fleet.
- The allowable stack occupancy rate is the investment trigger for the number of laden, empty and OOG stacks.

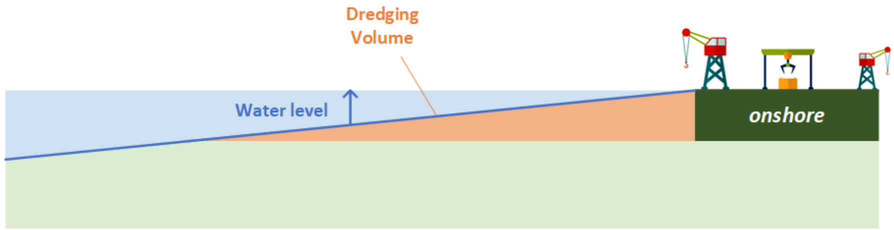
Table 3.2: Investment triggers

Investment triggers		
Allowable rates	Values	Source
OGV berth occupancy	0.60	Groeneveld, 1993, Table IX
Barge berth occupancy	0.80	Groeneveld, 1993, Table IX
Barge utilisation	0.80	RHDHV
Laden stack occupancy	0.80	RHDHV
Empty stack occupancy	0.70	RHDHV
OOG stack occupancy	0.90	RHDHV

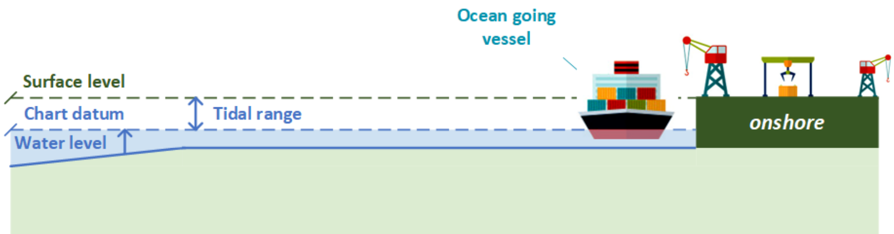
3.2.6. Boundary conditions



Two types of boundary conditions (i.e. bathymetry and water level) are included in determining the required dredging volume and retaining height of the quays. The surface levels of the terminals are set at the maximum water level. Next, the bathymetry of the foreshore is simplified as a straight slope starting from the surface level as depicted in Figure 3.8a. The required water depth and, therefore, the required dredging volume is determined by the draught of the design vessel and the tidal range above *Chart Datum* (*CD*). Figure 3.8b illustrates the boundary conditions during low water for Alternative Onshore. The typical tidal range in the open ocean is about 0.6 meter (Davis & Fitzgerald, 2004). Closer to the coast, this range may be much higher. Coastal tidal ranges vary globally and can differ widely.



(a) Boundary conditions during high water



(b) Boundary conditions during low water after capital dredging

Figure 3.8: Illustration of the boundary conditions for the investment simulation

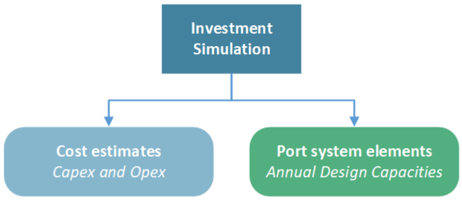
3.2.7. Design starting points

To conclude the input parameters of the investment simulation, a combination of default values, design assumptions and boundary conditions is listed. This list forms the starting points for the port system design (see Table 3.3).

Table 3.3: Starting points for the port system design

Starting points	
General	**Value**
Demand (TEU)	1,000,000
Onshore percentage	100%
Transshipment ratio	0%
Modal split hinterland	50%
Laden percentage	80%
Reefer percentage	10%
Empty percentage	7.5%
OOG percentage	2.5%
Life cycle (years)	20
Operational hours	8640
Slope of the foreshore (km/m)	2.00
Bathymetry factor	0.50
Average parcel size (TEU)	1,500
Average barge size (TEU)	250
Storage equipment	RTG
Offshore dwell time (days)	2

3.2.8. Output of the investment simulation



The investment simulation generates the *port system elements* based on the default values, work methods and boundary conditions for the three port system alternatives.

Moreover, according to the corresponding capex and opex of the port system elements, the investment simulation is able to estimate the PV of the costs. Appendix E presents all the results of the investment simulations for the different design scenarios.

3.3. Logistical simulations to evaluate the cost related to shuttle barge downtime

Following the first part of the model (i.e. the investment simulation), the second part of the model includes the logistical simulation. The logistical simulation is developed to address the logistics of the offshore-onshore port system with a waterway transport link.

3.3.1. Objective of the logistical simulation

The maritime transport between the offshore and onshore terminal involves additional operational challenges and uncertainties. If the barges are non-operational, they become the bottleneck for the container transport of the port system. In case of harsh environmental conditions, such as an extreme wave climate, downtime of the barges may occur. Depending on the length of the period of downtime, this may have a significant impact on the sport system operations.

The import containers from scheduled liner ships have to be stored at the offshore terminal. When the container level reaches the storage capacity, the container ships have to wait, and demurrage[4] is charged. Similarly, the export containers have to be stored at the onshore terminal.

The storage capacity at the offshore terminal should be designed depending on the frequency and the length of (consecutive) periods of downtime. The objective of the logistical simulations is to evaluate the trade-off between extensive offshore storage capacities and annual waiting times of container ships based on costs. This objective is in accordance with the second gap in the literature: the relationship between the operational reliability of the waterway transport link and the required storage capacities of the offshore and onshore terminals.

[4] Compensation to shipping lines for delays which lasts longer than the agreed laytime.

3.3.2. Modelling concept of the logistical simulations

The applied model concept is the *Open Source Complex Logistics Simulation* (OpenCLSim) which is available at the GitHub of the Hydraulic Engineering department of the Delft University of Technology (van Koningsveld, den Uijl, Baart, & Hommelberg, 2019). OpenCLSim is a *Python package* for rule-driven scheduling of cyclic activities for an in-depth comparison of alternative operating strategies. The simulation is a combination of *discrete-event simulation* and *agent-based simulation*. OpenCLSim continues on the SimPy discrete-event simulation package. The package is further developed by multiple MSc students for various types of logistic simulations (i.e. den Uijl (2018), Van Der Bilt (2019), Kievits (2019) and Halem (2019)).

Various software packages are appropriate for nautical logistic simulations. The choice for a purposely-built simulation model based on the OpenCLSim package is mainly based on the adaptability of the model concept, the possibility to collaborate with other students (i.e. (Kievits, 2019)) and the similarity in programming language as the model concept of the investment simulation (OpenTISim). Although the model concept comprises most of the relevant features, some of them are very high-level. The model should be further developed to reach the same level of detail as other well-known simulation software. Table 3.4 gives an overview of some selected features to compare the simulation software.

Table 3.4: Nautical simulation software selection.

	SCM Globe (SC Sim)	InterDynamics (Planimate)	AnyLogic (Container Line)	Talumis (FlexSim)	Python - OpenCLSim
Concept					
Discrete-event	✓	✓	✓	✓	✓
Agent-based	✓	✓	✓	✓	✓
Object-oriented	✓	✓	✓	✓	
3D animations	✓	✓	✓	✓	
Commodities					
Containers	✓	✓	✓	✓	✓
Facilities					
Operational costs	✓	✓	✓	✓	✓
Storage capacities	✓	✓	✓	✓	✓
Multiple resources per facility		✓	✓	✓	✓
Modalities					
Operational costs	✓	✓	✓	✓	✓
Capacity	✓	✓	✓	✓	✓
Routes					
Graphs	✓	✓	✓	✓	✓
Environmental conditions			✓	✓	✓
Simulation					
Random arrivals/departures	✓	✓	✓	✓	✓
Weather induced downtime			✓	✓	✓
Other					
Adaptable entities		✓	✓	✓	✓
Python*					✓
Costless			✓		✓

3.3.3. Model outline: logistical simulation

Figure 3.9 presents the model outline of the second part of the model, including the logistical simulation in line with the general model outline (Figure 3.1). The model outline shows an overview of the *objects* used in the agent-based discrete-event simulations.

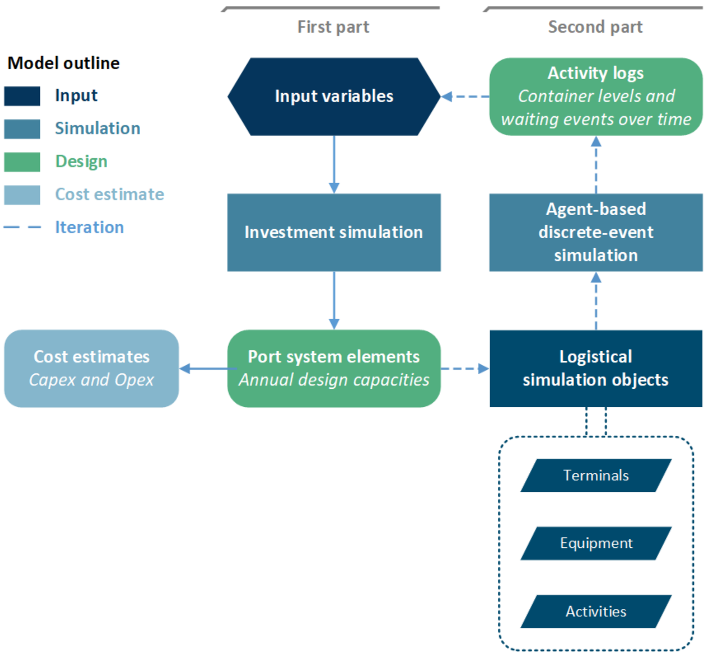


Figure 3.9: Logistical simulation model outline

3.3.4. Input parameters for the logistical simulation

The following parameters are used in the same way as used in the investment simulation, as described in Section 3.2.4 and 3.2.5:

- the annual demand;
- the offshore-onshore distance;
- the dimensions of the design container vessel and the average parcel sizes;
- the offshore and onshore terminal handling times; and
- the offshore and onshore terminal dwell times.

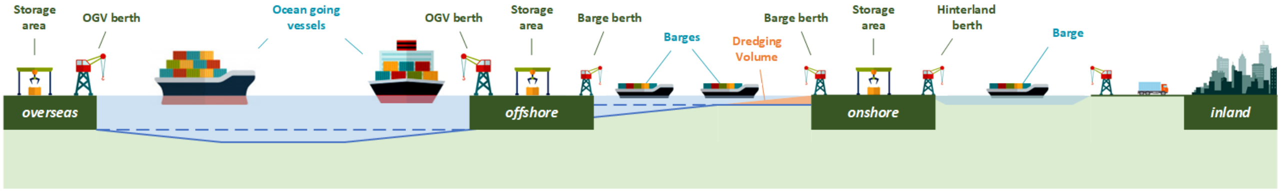
The following output of the investment simulation is used as input parameters for the logistical simulation, as described in Section 3.2.8:

- the number of berths at both the offshore quays (i.e. the container ship berths and the barge berths) and the number of barge berths at the onshore terminal;
- the number of cranes per berth and the crane (un)loading rates;
- the storage capacity of both the offshore terminal and the onshore terminal; and
- the number of shuttle barges and the barge properties (handling rate, sailing speed, utilisation rate).

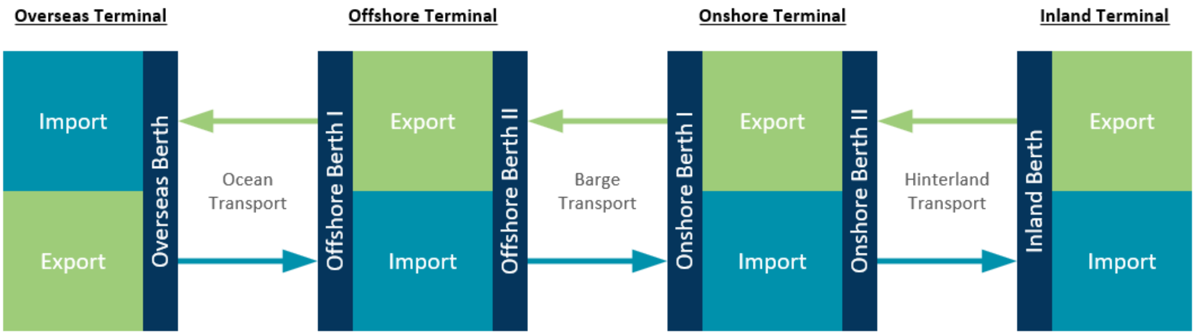
Next, additional variables are initiated for the logistical simulation. The input of the applied model concept (OpenCLSim) is categorised into objects called *terminals*, *equipment* and *activities*, as shown in Figure 3.9. Two figures are presented to give a better understanding of these objects.

Figure 3.10a shows an illustration of the offshore-onshore port system (i.e. Alternative Barge) located between an overseas and inland terminal. The overseas terminal represents a generator for import containers, and the inland terminal represents a generator for export containers. These terminal objects are only initiated to generate import and export containers and are not part of the offshore-onshore port system.

Figure 3.10b shows a schematisation of the offshore-onshore port system and the terminal objects generating the import and export containers. The offshore and onshore terminals consist both of two berths and a storage area for import and export containers. Ocean transport, barge transport and hinterland transport indicate the *activities*. The berths indicate the *equipment* and the storage areas indicate the *terminals*.



(a) Illustration of Alternative Barge and the overseas and inland terminals



(b) Schematisation of Alternative Barge and the overseas and inland terminals

Figure 3.10: Illustration of Alternative Barge (incl. overseas and inland terminals) and the corresponding schematisation for the logistical simulation

The ocean transport covers scheduled liner ships. In order to simulate container ships arriving non-uniform over the year, a normal (random) vessel distribution is defined. Figure 3.11 depicts an example of such a vessel distribution, showing the arrival deviation in comparison with uniformly arriving container ships at the offshore container terminal. The probability of vessels arriving earlier, or later than uniformly arriving vessels, is more frequent around the mean, as normal distributions prescribe[5].

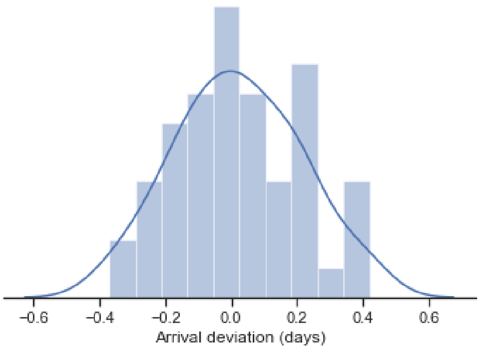


Figure 3.11: Vessel distribution

[5]A normal distribution, also known as the Gaussian distribution, is a probability distribution that is symmetric about the mean, showing that data near the mean are more frequent in occurrence than data far from the mean.

The last type of input required for the simulation is a trigger of downtime for the shuttle barges. To simulate this effect of downtime, a set of maximum values of significant wave height data between the offshore and the onshore terminal is generated. Besides, an operational threshold value is assigned to the barges. When the significant wave height value exceeds the operational threshold value, a period of downtime is induced. Therefore, the significant wave height over time functions as a trigger for periods of downtime. Figure 3.12 shows an example of a set of maximum values of significant wave height data between the offshore and the onshore terminal.

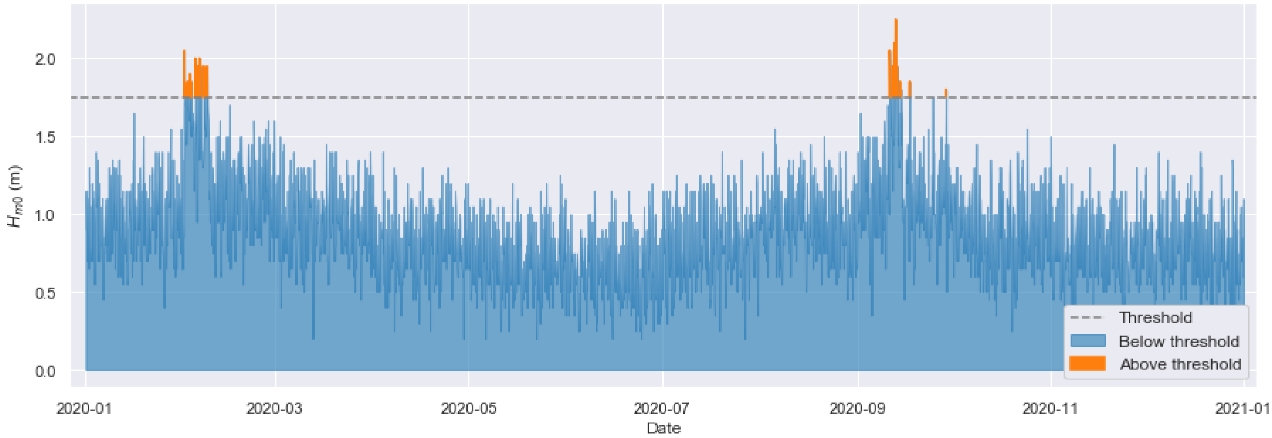


Figure 3.12: Example of a maximum significant wave height (H_{m0}) pattern between the offshore and the onshore terminal. The periods indicated in orange are periods with a significant wave height above the operational threshold value of the barges, resulting in downtime.

A remark is made regarding the definition of the downtime of ocean-going vessels. The potential downtime of these vessels is covered by the irregularities of the vessel distribution (see Figure 3.11). Therefore, the correlation between the downtime of ocean-going vessels and shuttle barges is excluded.

3.3.5. Output of the logistical simulation

By running the logistical simulation, agent-based activity logs are generated for the container ships, the barges, the terminal storage and the berth equipment. The activity logs vary per object depending on the assigned properties. By the translation of these activity logs, multiple results can be achieved.

In Section 4.1.2, the model operation is verified by various model tests, whereby the output of the logistical is illustrated. The illustrations include, amongst others, a vessel planning, terminal storage levels over time, throughput figures and waiting events of the container ships.

4
Evaluation of the model: verification and validation

In Chapter 3, the methods to quantify the logistical trade-offs are described. The cost estimates are generated by a parametric model consisting of two parts, both including a simulation. Next, the simulations need to be evaluated. The evaluation of the model consists of two phases: i) verification and ii) validation, as shown in Figure 4.1.

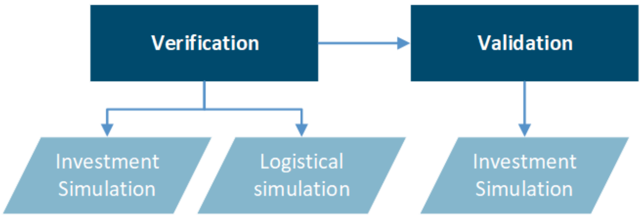


Figure 4.1: Phases of the model evaluation

The verification phase addresses the correctness of the model operation according to its stated operating specifications. This is done by various model test. The validation phase addresses the validity of the model output. Therefore, the capacities and cost estimates are compared with benchmarks and evaluated by a case study. This chapter describes the evaluation phases of the parametric model. Therefore, the following items are discussed:

- the verification of the investment simulations (Section 4.1.1);
- the verification of the logistical simulations (Section 4.1.2);
- the validation of the investment simulation based on a comparison of the capacities with benchmarks (Section 4.2.1);
- the validation of the investment simulation based on the case study: Payra Port (Section 4.2.2).

4.1. Verification of the model operations

This section evaluates the operation of the model according to its stated operating specifications. These operating specifications are evaluated by model tests. Firstly, the operation of the investment simulation is evaluated and, secondly, the operation of the logistical simulation is evaluated.

4.1.1. Verification of the investment simulation

The following model tests evaluates the correctness of the investment simulation:

i. the determination of the required port system elements;

ii. the phasing of the port system elements; and

iii. the assignment of the *Capex* and *Opex*.

The determination of the required port system elements

The first model test evaluates if the number of port system elements is determined correctly. In order to illustrate the determination of the required port system elements, the determination of the number of berth infrastructure is explained. The required number of berths and *ship-to-shore cranes* depends on the annual demand, the vessel specifications and the allowable berth occupancy. The berth occupancy is considered as the investment trigger, as explained in Section 3.2.1. When the allowable berth occupancy is exceeded, berth infrastructure is added.

An example is given where the annual demand is equal to 500,000 TEU, the offshore terminal accommodates New-Panamax vessels, and the allowable berth occupancy is equal to 0.6 (Groeneveld, 1993, Table IX). All steps of the investment simulations are listed. Figure 4.2 shows the steps of the investment simulation concerning the berth infrastructure of the first year of the simulation.

```
Simulate year: 2020

  Start analysis:
     Berth occupancy planned (@ start of year): inf
     Berth occupancy online  (@ start of year): inf

  *** add Berth to elements
     Berth occupancy planned (after adding Berth): inf
     Berth occupancy online  (after adding Berth): inf

  >>> Number of OGV berths: 1
     >> The length of the design vessel is 366 m
     >> The length of the quay is 396 m
     >> The water depth at the quay is 19 m

  *** add Quay to elements
     Berth occupancy planned (after adding Quay): inf
     Berth occupancy online  (after adding Quay): inf

  *** add STS crane to elements
     Berth occupancy planned (after adding Crane): 1.669
     Berth occupancy online  (after adding Crane): inf

  *** add STS crane to elements
     Berth occupancy planned (after adding Crane): 0.946
     Berth occupancy online  (after adding Crane): inf

  *** add STS crane to elements
     Berth occupancy planned (after adding Crane): 0.705
     Berth occupancy online  (after adding Crane): inf

  *** add Berth to elements
     Berth occupancy planned (after adding Berth): 0.593
     Berth occupancy online  (after adding Berth): inf

  >>> Number of OGV berths: 2
     >> The length of the design vessel is 366 m
     >> The length of the quay is 853 m

  *** add Quay to elements
     Berth occupancy planned (after adding Quay): 0.593
     Berth occupancy online  (after adding Quay): inf

  *** add STS crane to elements
     Berth occupancy planned (after adding Crane): 0.473
     Berth occupancy online  (after adding Crane): inf

     STS cranes online            (@ start of year): 0
     STS cranes planned           (@ start of year): 4
     Horizontal transport online  (@ start of year): 0
     Horizontal transport planned (@ start of year): 0

  *** add Tractor Trailer to elements
```

Figure 4.2: Investment simulation: determination of the berth, quay and crane elements

At the start of the simulation, no berth infrastructure is present. In order to accommodate container ships, *berth elements* are added. A single berth element enables the addition of a *quay element* and *crane elements* with a maximum of three cranes per berth. The berth occupancy reduces by the addition of cranes. After the addition of four cranes, the allowable berth occupancy is not exceeded anymore. Two berths (and quays) are required to facilitate a number of four cranes. Therefore, sufficient berth infrastructure is planned, and the next investment trigger is considered. The next investment will cover the number of tractor-trailers, as this is related to the number of cranes.

Note: The *port system elements* are objects where all properties are stored. An object is a collection of data (variables) and methods (functions) that act on those data.

The phasing of the port system elements

The second model test evaluates if the port system elements are phased correctly over time. All the port system elements include a specified delivery time (see Appendix D). To illustrate the phasing of the port system elements, the phasing of the berths, cranes and tractor-trailers are explained in line with the example of the first model test. Following to the simulation of the first year, two berths, two quays and four cranes are planned. Figure 4.3 shows the steps of the investment simulation concerning the berth infrastructure and tractor-trailers in the second and third year of the simulation.

```
Simulate year: 2021

  Start analysis:
     Berth occupancy planned (@ start of year): 0.473
     Berth occupancy online  (@ start of year): inf

     STS cranes online            (@ start of year): 0
     STS cranes planned           (@ start of year): 4
     Horizontal transport online  (@ start of year): 0
     Horizontal transport planned (@ start of year): 20
```

```
Simulate year: 2022

  Start analysis:
     Berth occupancy planned (@ start of year): 0.473
     Berth occupancy online  (@ start of year): 0.473

     STS cranes online            (@ start of year): 4
     STS cranes planned           (@ start of year): 4
     Horizontal transport online  (@ start of year): 20
     Horizontal transport planned (@ start of year): 20
```

Figure 4.3: Investment simulation: phasing of the berth, crane and horizontal transport elements

The delivery time (or construction time) of the quay elements is set at two years. The delivery time of the cranes and tractor-trailers are both equal to one year. The phasing of the cranes and the tractor-trailers is defined such that the elements come online in the same year as the latest berth element. Therefore, although the delivery time of the cranes and the tractor-trailers is just one year, they should come online in the third year of the simulation. Figure 4.3 shows that the timing for these elements to come only is correct.

The assignment of the costs

The third model test evaluates if the costs associated with the port system elements are assigned correctly. In order to illustrate the assignment of the costs, the capex and opex associated with the quays, cranes and tractor-trailers are explained. For reasons of consistency, the example is in line with the example of the first two model tests.

The capex for elements with a delivery time of two years should be assigned for 60% to the first year and 40% to the second year of delivery (or construction). The opex that may include maintenance, insurance and labour, should be assigned to the years when the elements are online.

```
Simulate year: 2020

  Start analysis:
     Berth occupancy planned (@ start of year): inf
     Berth occupancy online  (@ start of year): inf

  *** add Berth to elements
     Berth occupancy planned (after adding Berth): inf
     Berth occupancy online  (after adding Berth): inf

  >>> Number of OGV berths: 1
     >> The length of the design vessel is 366 m
     >> The length of the quay is 396 m
     >> The water depth at the quay is 19 m

  *** add Quay to elements
```

	Year	Offshore Capex	Offshore Maintenance	Offshore Insurance
0	2020	28785033.6	0.00	0.00
1	2021	19190022.4	0.00	0.00
2	2022	0.0	405250.56	405250.56
3	2023	0.0	405250.56	405250.56
4	2024	0.0	405250.56	405250.56

```
     Berth occupancy planned (after adding Quay): inf
     Berth occupancy online  (after adding Quay): inf
```

```
*** add STS crane to elements
```

	Year	Offshore Capex	Offshore Maintenance	Offshore Insurance	Offshore Labour
0	2020	0.0	0.0	0.0	0.0
1	2021	11695500.0	0.0	0.0	0.0
2	2022	0.0	305100.0	101700.0	687500.0
3	2023	0.0	305100.0	101700.0	687500.0
4	2024	0.0	305100.0	101700.0	687500.0

```
   Berth occupancy planned (after adding Crane): 1.669
   Berth occupancy online  (after adding Crane): inf

*** add Tractor Trailer to elements
```

	Year	Offshore Capex	Offshore Maintenance	Offshore Labour
0	2020	0.0	0.0	0.0
1	2021	114000.0	0.0	0.0
2	2022	0.0	11300.0	125000.0
3	2023	0.0	11300.0	125000.0
4	2024	0.0	11300.0	125000.0

Figure 4.4: Investment simulation: assignment of the costs for the quay, crane and tractor-trailer elements

Figure 4.4 shows the assignment of the costs for the quay, crane and tractor-trailer elements. The capex of the quay element, indicated as "Offshore Capex", shows the correct assignment. The capex of the crane and tractor-trailer elements show the correct assignment as well. Lastly, the opex are also assigned correctly.

Conclusion regarding the verification of the investment simulation

Based on the model tests, the investment simulation operates according to the stated operating specifications. The investment simulation is, therefore considered as verified.

4.1.2. Verification of the logistical simulation

The following model tests evaluate the correctness of the logistical simulation:

i. the generation of the arrival pattern of container ships and hinterland modalities;

ii. the offshore terminal storage level over time;

iii. the container ship waiting times as a result of the berth occupancy;

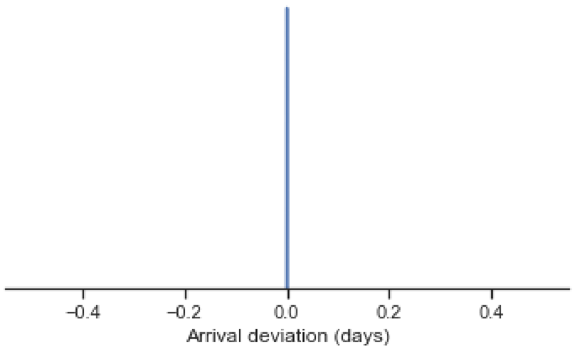
iv. the impact of harsh environmental conditions on the shuttle barge operations;

v. the container ship waiting times as a result of harsh environmental conditions on the shuttle barge operations; and

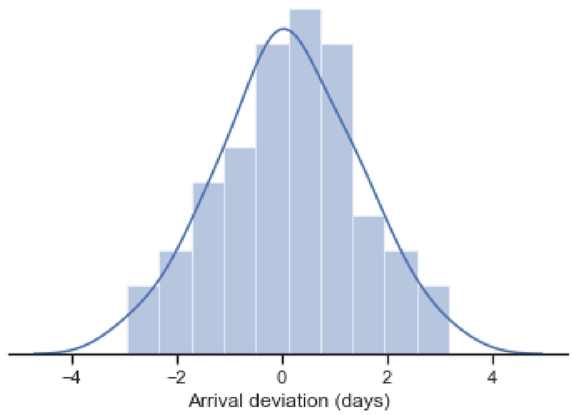
vi. the catch-up of the throughput after a period of downtime.

The arrival pattern of container ships and hinterland modalities

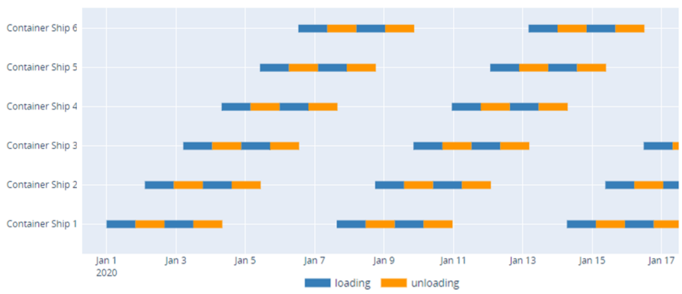
The first model test evaluates the correctness of the assigned arrival pattern of container ships (import) and hinterland modalities (export). The arrival pattern of the container ships at the offshore terminal is illustrated. To simulate randomly arriving container ships over the year, normal (random) distributed arrival deviations (Figure 4.5b) are added to a vessel planning uniform over time, without deviations in the arrival pattern (Figure 4.5a). The vessel plannings as a result of the arrival deviation patterns are presented in Figure 4.5c and 4.5d.



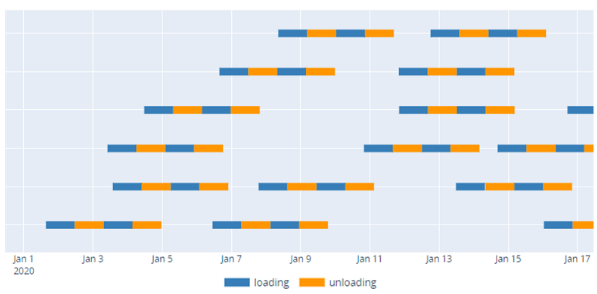
(a) No arrival deviation (singular)



(b) Random arrival deviation (normal distribution)



(c) Vessel planning - Uniform over time



(d) Vessel planning - Normal distributed over time

Figure 4.5: The arrival deviations in fig. 4.5a and fig. 4.5b correspond to the vessel plannings of fig. 4.5a and fig. 4.5d, respectively.

The offshore terminal container level over time

The second model test evaluates the correctness of the terminal container level over time when the barges are continuously operational. The offshore and onshore terminals both have a certain storage capacity that cannot be exceeded. Figure 4.6 shows the offshore container level over time for an offshore storage capacity of 10,000 TEU.

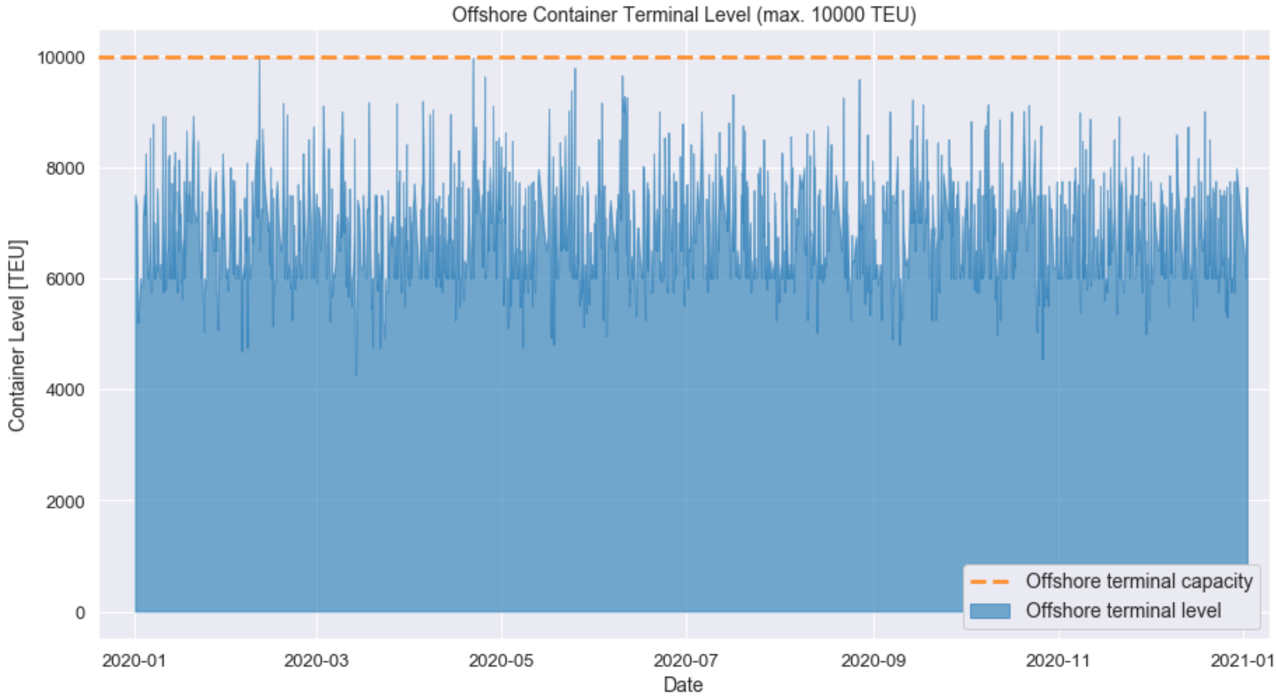


Figure 4.6: Offshore container level over time (normal distributed import and export over time)

The following observations indicate the correct model operation.

- The container level does not exceed the storage capacity.
- The container level varies over time, indicating the normal distributed import and export over time.

The container ship waiting times as a result of the berth occupancy

The third model test evaluates the waiting times of the container ships at the offshore berth, due to the berth occupancy. Figure 4.7 shows the waiting times at the offshore terminal when all berths are occupied.

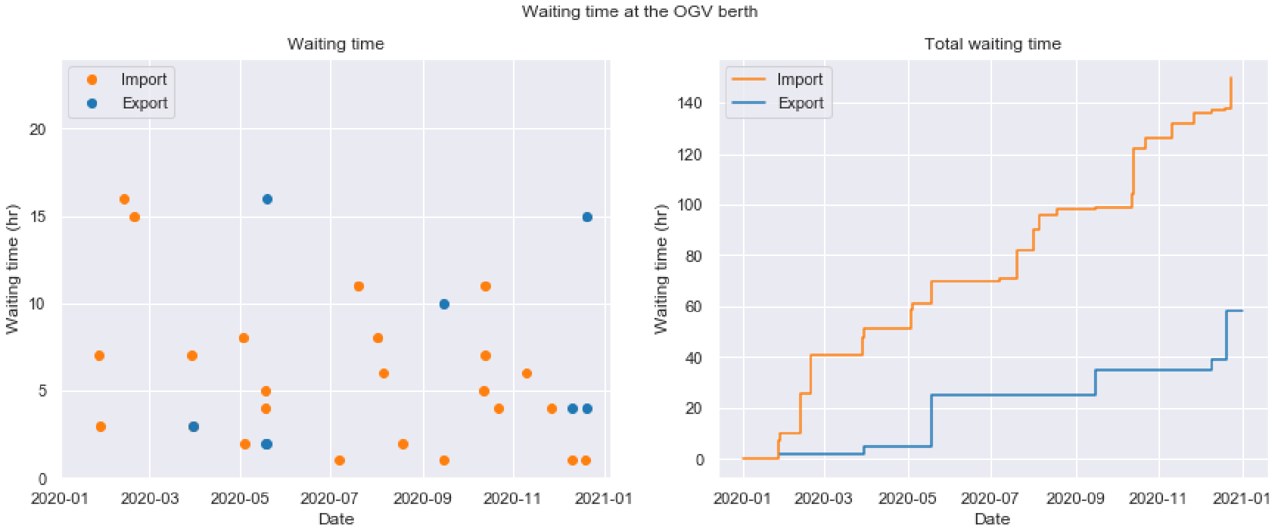


Figure 4.7: Container ship waiting times as a result of the berth occupancy. The waiting events are labelled based on the type of container transfer that causes the waiting time (*left*: individual waiting time events, *right*: cumulative waiting time over time)

Figure 4.8 shows the vessel planning in February. The offshore terminal used in the example contains three ocean-going vessel berths. The waiting events are indicated, when all berths are occupied.

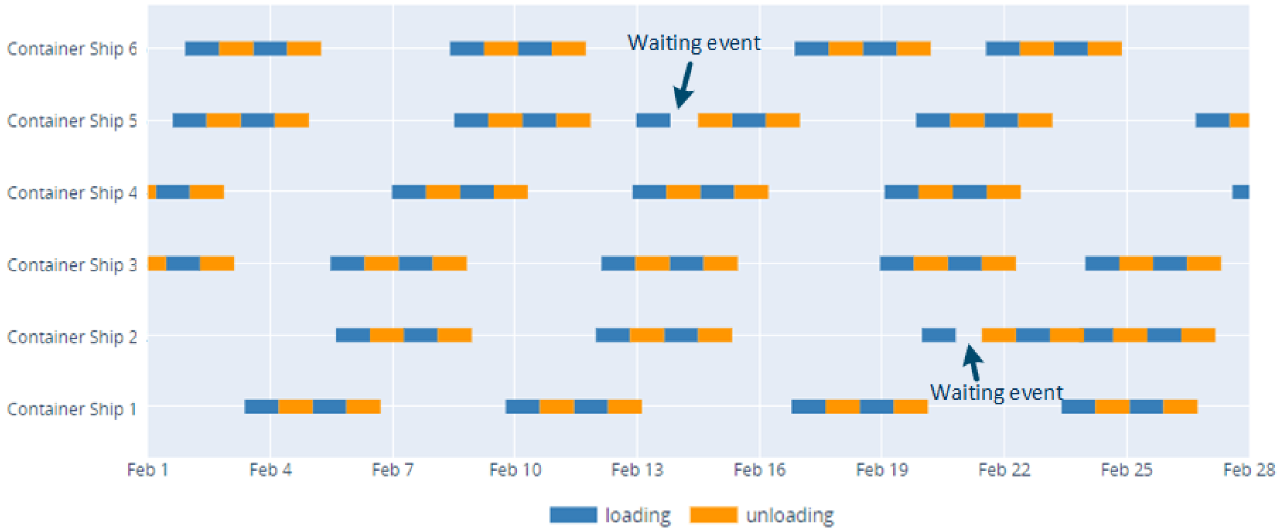


Figure 4.8: Example of the vessel planning in the month February, indicating the waiting events

No conclusions are drawn based on the acceptable levels of the waiting time as a factor of the service time stated by PIANC (2014) since different methods are applied.

The impact of harsh environmental conditions on the shuttle barge operations

Figure 4.9 presents a wave climate to test the impact of harsh environmental conditions on the shuttle barge operations. The operational threshold value is set at 1.75 m. When the significant wave height exceeds the operational threshold value, a period of at least two days of downtime is induced. The required time margin of two days is set at the time it takes for a single barge to complete a cycle (loading, sailing, unloading, loading, sailing and unloading).

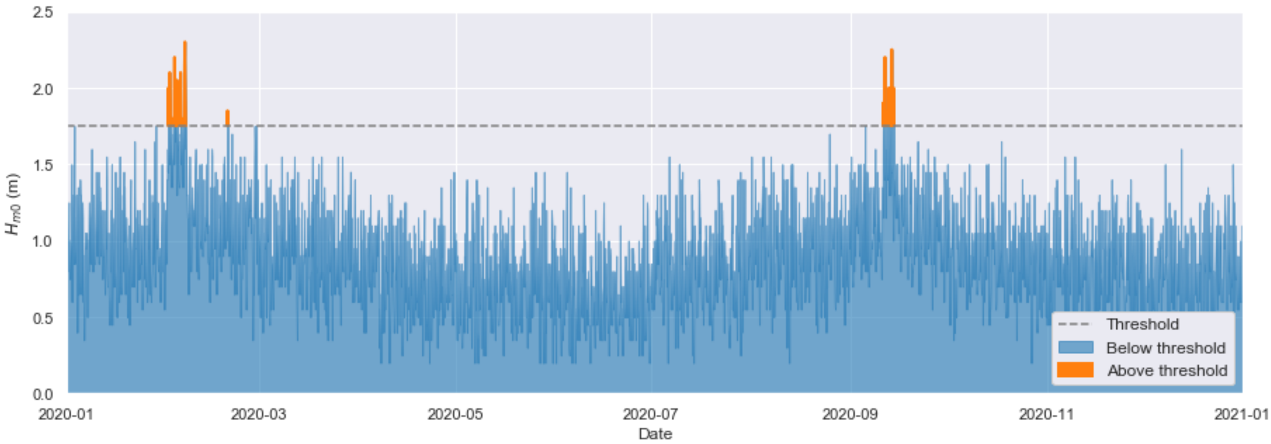


Figure 4.9: Wave climate scenario to evaluate the shuttle barge downtime. The scenario is a set of wave height values for every three hours.

The first downtime event starts at ”2020-01-26 03:00:00” and ends at ”2020-02-05 15:00:00”. The *vessel planning* illustrates the correct weather related downtime of the shuttle barges for this period (see Figure 4.10).

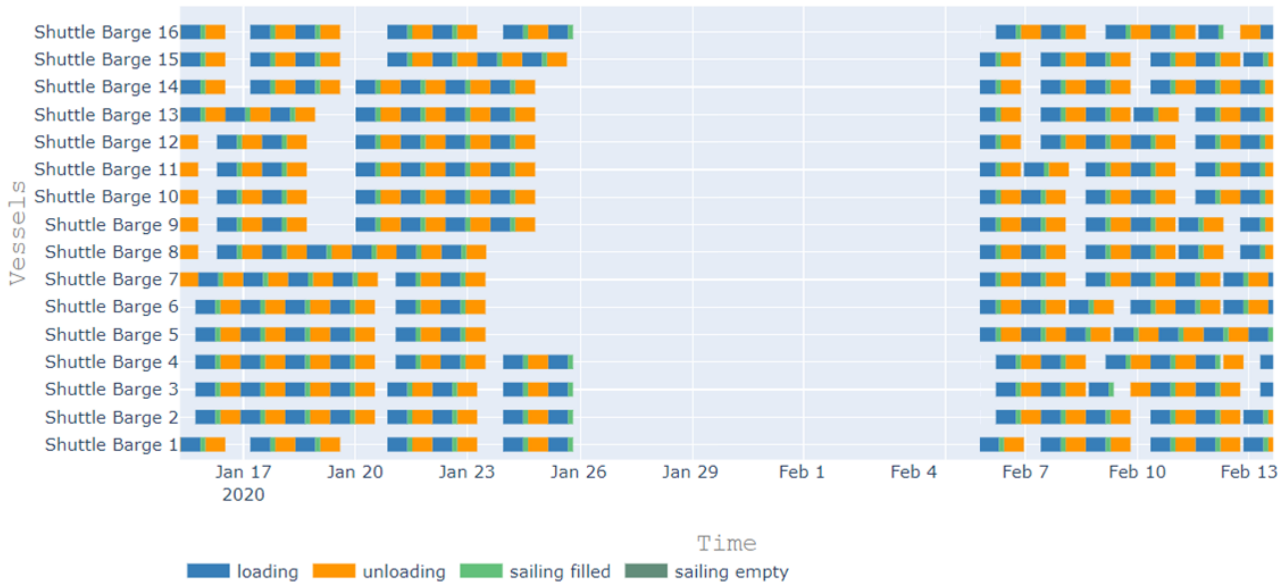


Figure 4.10: Vessel planning of the shuttle barges

The offshore terminal storage level over time for a specified downtime scenario

The fifth model test evaluates the correctness of the terminal storage level over time for a specified downtime scenario. Figure 4.11 shows the offshore storage level over time for the offshore storage capacity of 10,000 TEU for the specified downtime scenario.

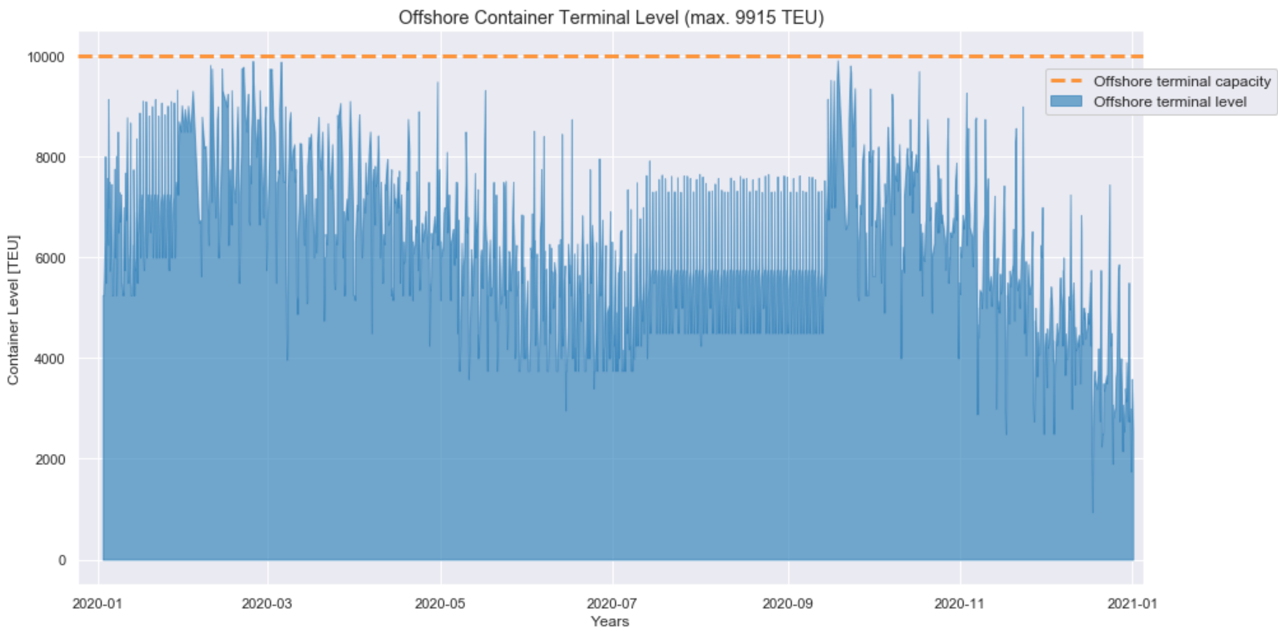


Figure 4.11: Offshore storage level over time for a specified downtime scenario

The following observations indicate the correct model operation:

- the container level does not exceed the storage capacity;
- the container level reaches the storage capacity during the periods of downtime (at the start of February and October); and
- the container level reduces after the period of downtime until it reaches 'steady state' (at the start of June).

The container ship waiting times as a result of harsh environmental conditions on the shuttle barge operations

The sixth model test evaluates the container ship waiting times as a result of harsh environmental conditions on the shuttle barge operations. Shuttle barge downtime may lead to container ship waiting times when the storage area of the offshore terminal is full, or the export storage level is insufficient. Figure 4.12 presents the waiting times of the container ships as a result of the shuttle barge downtime. The waiting events are labelled based on the type of container transfer that causes the waiting time. The figure shows a sharp increase labelled as *export*. This is since the export storage level appears to be more towards zero in the beginning of the period of downtime than the storage level towards the storage capacity.

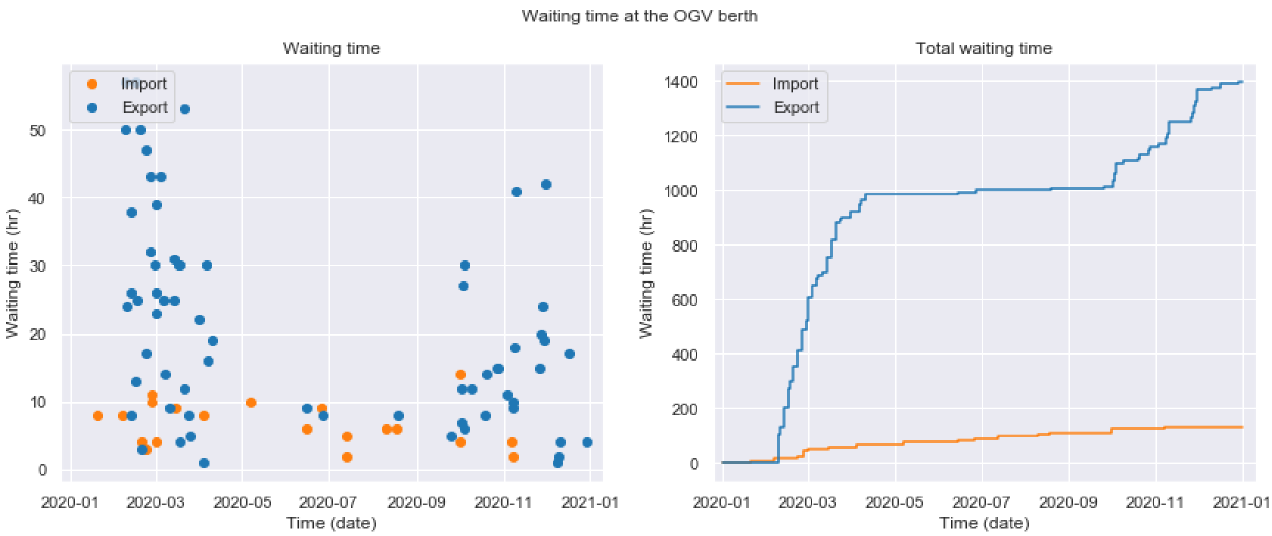


Figure 4.12: Container ship waiting times as a result of shuttle barge downtime. The waiting events are labelled based on the type of container transfer that causes the waiting time (*left*: individual waiting time events, *right*: cumulative waiting time over time)

The following observations indicate the correct model operation:

- the waiting events (below approximately 15 hours) as a result of the berth occupancy still take place;
- the additional waiting events start occurring at the begin of the periods of downtime (at the beginning of February and October); and
- the waiting time of these events reduces after the period of downtime.

The catch-up of the throughput after a period of shuttle barge downtime

The seventh model test discusses the catch-up of the throughput after a period of downtime of the shuttle barges. The impact of the environmental conditions as presented by the vessel planning in Figure 4.10 is evaluated.

The required number of shuttle barges is determined for an average utilisation rate of 0.8 (see Appendix D). This results in a surplus of the available shuttle barges when the operations are not limited, but is necessary to restore the throughput after a period of downtime. Figure 4.13 presents the throughput of the first half year of the simulation.

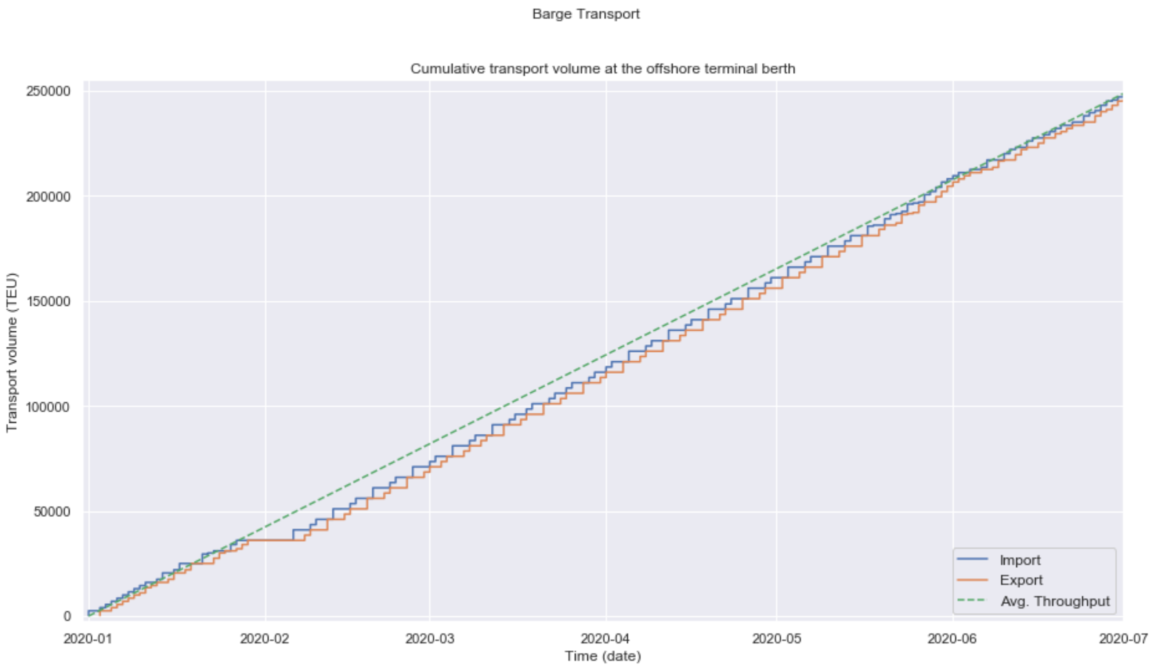


Figure 4.13: The catch-up of the throughput after a period of downtime of the shuttle barges

The following observations indicate the correct model operation:

- the throughput is in line with the yearly average throughput before the downtime occurs;
- the throughput stops at the begin of the period of downtime;
- the throughput gradually returns to the yearly average throughput after the period of downtime, due to the surplus of the available shuttle barges; and
- the throughput is again in line with the yearly average throughput after the period of downtime.

Conclusion regarding the verification of the logistical simulation

Based on the model tests, the logistical simulation operates according to the stated operating specifications. The model correctly establishes the relationship between the operational reliability of the waterway transport link and the storage level of the offshore terminal. The logistical simulation is, therefore considered as verified.

Note: The relationship between the operational reliability of the waterway transport link and the storage level of the offshore terminal may not be confused with the storage capacity of the offshore terminal, as indicated as the second gap in the literature.

4.2. Validation of the model output

The validation phase addresses the validity of the investment simulation output. The investment simulation generates the required port system elements. The corresponding port system capacities are compared to capacity and performance benchmarks. Benchmarks are well-known and often-used standards in the maritime trade industry to evaluate the capacity and performance metrics to industry bests. Additionally, the generation of the port system elements and corresponding cost estimates are evaluated by a case study.

4.2.1. Benchmark study to evaluate the generation of the port system design

The comparison with the capacity and performance benchmarks starts with the definition of the port system elements according to the starting points (see Section 3.2.7). The most relevant starting points for the benchmark study are listed to the right. Figure 4.14 illustrates all port system elements that are used for the comparison with the benchmarks. Only the design of the terminal accommodating the container ships is used for the comparison with the quay line and ship-to-shore crane benchmarks. The offshore and onshore terminals are used for yard operation benchmarks.

Benchmarks	
Starting points	**Value**
Demand (TEU)	1,000,000
Transshipment ratio	0%
Laden percentage	80%
Reefer percentage	10%
Empty percentage	7.5%
OOG percentage	2.5%
Storage equipment	RTG
Offshore dwell time (days)	2

The capacity and performance benchmarks of Drewry (2010) are used for the comparison. Therefore, the terminals of the port system are classified as *large terminals*, since the annual demand is above 750,000 TEU. An important distinction should be made between design capacity and operational capacity. The design capacity is used for the comparison with the capacity benchmarks, and the operational capacity is used for the comparison with the performance benchmarks. The percentages of time that the port infrastructure is used are taken into account for the operational capacity. These percentages are known as occupancy and utilisation rates.

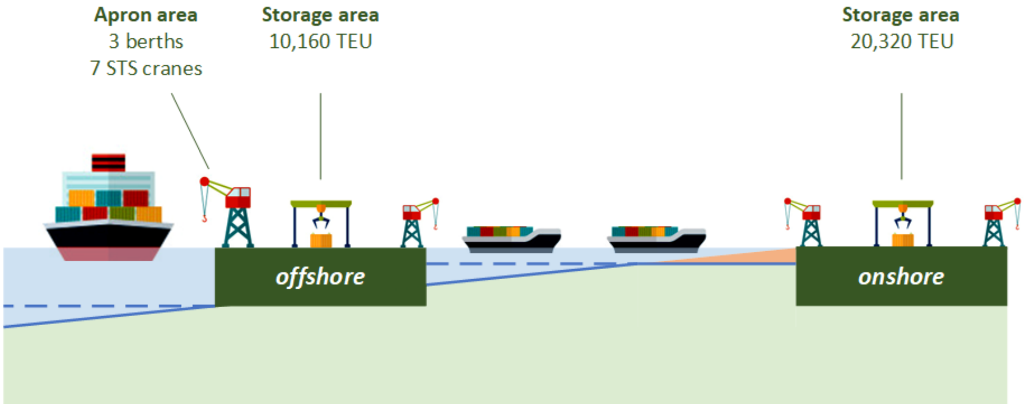


Figure 4.14: Illustration of Alternative Barge according to the starting points for the comparison with the benchmarks

Quay line metrics

The measurement of quay line capacity is defined as TEU per meter of quay per year (Drewry, 2010). The factors influencing the terminal capacities include the size of the terminal, the traffic mix, the tariff regulation and operation type.

According to Drewry (2010, Table 3.1), the quay line performance ranges from 850 TEU per meter of quay per annum for a large terminal with a mixed vessel arrival pattern to 1,400 TEU per meter of quay per annum for a large terminal with tightly scheduled ship arrivals and significant transhipment activity.

The output of the investment model is presented in Table 4.1. The relatively low performance of the quay line metrics are a result of the assumption that no transhipment takes place at the offshore terminal since the storage capacity is limited. The quay line performance of all terminals sampled by Drewry (2010) with an average annual throughput per terminal of 820,000 - 890,000 TEU equals 846 - 913 TEU per meter of quay per annum. These ranges resemble with the operational capacity metrics of Table 4.1.

Table 4.1: Quay line operational capacity metrics

Quay line metrics				
Design vessel	Capacity	Length	Occupancy	Operational capacity
Panamax	6,000 TEU	1,055 m	0.584	950 TEU/m/yr
New-Panamax	12,500 TEU	1,272 m	0.561	790 TEU/m/yr
ULCS	21,000 TEU	1,385 m	0.532	720 TEU/m/yr

Ship-to-shore crane metrics

The measurement of ship-to-shore crane capacity is defined as the number of moves or a TEU figure that can be achieved annually. According to Drewry (2010, Table 4.1), the ship-to-shore crane performance benchmarks range from 130,000 - 140,000 TEU annually per crane for large terminals.

The main factors affecting crane capacity are the availability, utilisation and moves per hour. The defaults values for these factors used in the investment simulation result in a ship-to-shore crane annual operational capacity of 142,860 TEU.

Yard operation metrics

The measurement of yard capacity is defined as the number of TEU per hectare (ha). The main factors affecting yard capacity are the type of equipment deployed, the dwell time and the operational limit. Generally, an operational capacity is between 70% and 80% of the maximum design capacity. An important note should be made when comparing the terminal areas. The following terminal areas are often provided.

i. The actual storage area
ii. The operational area
iii. The total terminal area

According to Drewry (2010, Table 5.4), the operational area capacity benchmarks range from 550 TEU per ha for straddle carriers to 2,850 TEU per ha for *RMG* cranes. In addition, the total terminal area capacity benchmarks are around 30,000 TEU/ha for large terminals with *RTG* or *RMG* cranes (Drewry, 2010, Figure 5.5).

The output of the investment model is presented in Table 4.2. The operational area design capacity depends on the type of stack equipment. It is equal to 1,200 TEU for both terminals. The total terminal area operational capacity of both terminals is above 35,000 TEU/ha.

Table 4.2: Yard operation metrics: operational area design capacity and total terminal area operational capacity

Yard operation metrics					
Terminal	Storage capacity	Area	Dwell time	Operational area	Total terminal area
Offshore	10,160 TEU	8.5 ha	2 days	1,200 TEU/ha	35,180 TEU/ha/yr
Onshore	20,320 TEU	17.0 ha	4 days	1,200 TEU/ha	35,890 TEU/ha/yr

Conclusions regarding the benchmark study

Table 4.3 presents the results of the comparisons with the capacity and performance benchmarks. The metrics of the investment simulation resembles with the benchmarks. However, a remark should be made regarding the offshore total terminal area performance. Since a dwell time of only two days is applied, a very high operational area performance is present. Therefore, a relatively small operational storage area is required compared to the throughput. This results in a high operational area performance. Nevertheless, due to the combination of a large apron and barge berth area, the offshore total terminal area performance is average compared to the benchmarks.

Table 4.3: Benchmark study overview

Benchmark study			
Berth performance	Investment simulation metrics	Benchmarks	Unit
Quay line	720 - 950	850 - 1,200	TEU per meter per year
Ship-to-shore crane	142,860	130,000 - 140,000	TEU per crane per year
Yard capacity and performance (RTG)			
Offshore operational area design capacity	1,200	1,455	TEU per ha
Offshore total terminal area performance	35,180	30,000	TEU per ha per year
Onshore operational area design capacity	1,200	1,455	TEU per ha
Onshore total terminal area performance	35,890	30,000	TEU per ha per year

4.2.2. Case study to evaluate the generation of the port system elements and the corresponding cost estimates

Introduction to the case: Payra, Bangladesh

Royal HaskoningDHV started feasibility and engineering design studies for a deepwater port in Bangladesh. Payra is located at the world's largest delta. The Ganges-Brahmaputra Delta in the Bengal region is exceptionally laden with sediments coming from the Himalayas upstream. The delta is very dynamic, since siltation, shifting of channels, the emergence of new islands and low tide elevations are common phenomena (Ahmed, 2016). These phenomena result in the hindrance of marine navigation regarding deep water access.

Payra Port is planned to become the third seaport of Bangladesh after Chittagong and Mongla. Since the deepwater access is troubled, an onshore port would result in significant dredging works. As an alternative, an offshore-onshore port system with an offshore terminal located 60 km from the coastline is considered.

The case study covers the concept design of the master plan for Payra Port in Bangladesh. The master plan includes offshore-onshore port systems handling various types of cargo, including containers. Only the design of the containers terminals is addressed for the validation.

Economic study and site specific conditions

The economic study for Payra Port assigns a New-Panamax of 5,100 TEU as design vessel. The average parcel size is equal to 3,060 TEU. Figure 4.15 depicts the annual demand for Payra Port until the year 2045. The bold line indicates the capacity planning of the port infrastructure, adapting to the increasing demand over time. Table 4.4 presents the other key input parameters for the case study.

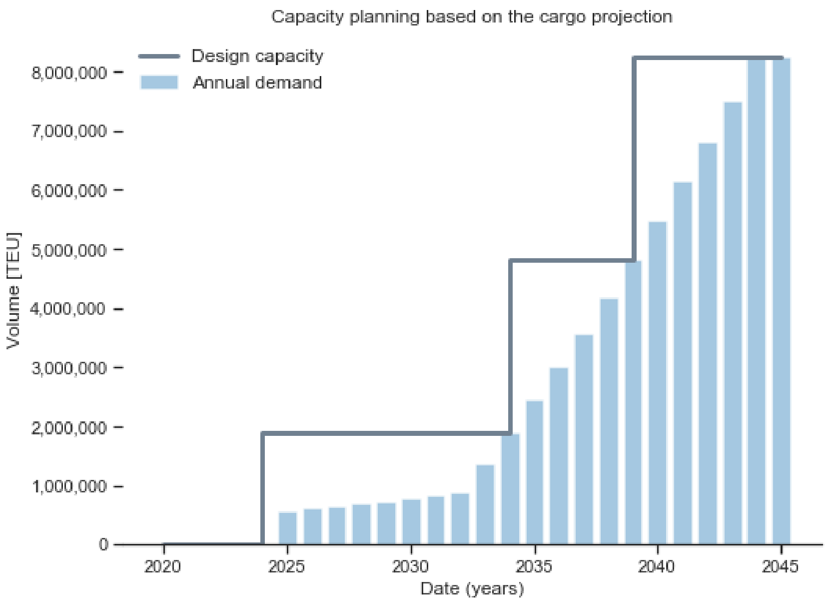


Figure 4.15: The annual demand for Payra Port

Table 4.4: Case study: Input parameters

Case study: input parameters	
General	Value
Demand (TEU)	8,250,000
Onshore percentage	75%
Transshipment ratio	-
TEU factor	1.62
Life cycle (years)	25
Operational hours	8322
Slope of the foreshore	3.75
Bathymetry factor	0.80
Average parcel size (TEU)	3,060
Average barge size (TEU)	225
Storage equipment	RTG
OGV berth parameters	
STS crane (MPH)	22
Efficiency	75%
Utilistation	90%
Cranes per OGV berth	3.0
OGV berth occupancy	0.7
Barge berth parameters	
Barge crane (MPH)	15
Efficiency	75%
Utilistation	90%
Cranes per barge berth	1.5
Barge berth occupancy	0.7

Comparison between the output of the investment model and the case study

Table 4.5 shows the cost estimates of the main components according to the specified input parameters (see Table 4.4). The ocean transport costs are excluded since they are not included in the cost estimates for Payra Port. *Remark:* limited details are shared due to confidentiality issues.

Table 4.5: Comparison based on the percentages of the cost estimates of the investment simulation and the container terminal design of Payra Port according to the stated input parameters

Validation - Percentages of the cost estimates			
Cost element	Simulation	Payra	Difference
Reclamation	5.1%	4.3%	+ 19%
Terminal Capex	38.0%	60.7%	- 37%
Terminal Opex	34.6%	22.7%	+ 53%
Capital dredging	1.4%	1.4%	- 3%
Maintenance dredging	1.0%	2.6%	- 62%
Barge capex	2.9%	5.8%	- 51%
Barge opex	4.1%	2.5%	+ 64%
Total	87.1%	100%	- 13%

Although the total costs differ with only 13%, some of the cost components differ significantly. The explanations of the most considerable differences in costs are listed below.

- The difference in terminal capex (-37%) is partly due to a difference in the number of ship-to-shore cranes. The default capacity and costs of the ship-to-shore cranes are too high for the design vessel of 5,100 TEU. Furthermore, the investment simulation determines the storage area in a different manner, resulting in less stacking equipment required at the offshore terminal. Although the investment simulation determines the storage area in more detail, it is difficult to indicate which manner determines the number of stacks, stack equipment and corresponding costs, the most 'correct'.
- The difference in terminal opex and barge opex (+53% and +64%) is due to local costs conditions, such as labour, energy and fuel prices. In Bangladesh, these costs are relatively low. The costs determined by Royal HaskoningDHV are more realistic for this specific case, where the investment simulation uses more average labour, energy and fuel prices.
- The difference in maintenance dredging costs (-62%) is due to the high rate of yearly sediment infill for Payra Port determined by Royal HaskoningDHV. The investment simulation uses a more average yearly sediment infill rate.

The total cost estimate generated by the investment simulation is 13% lower compared to the concept design of Payra Port. The difference in costs is considered as limited, and the most notable differences in costs can be explained. Therefore, the investment simulation is evaluated as a valid model.

5
The cost-based evaluation of the logistical trade-offs

In Chapter 4, both the model simulations are evaluated. The model operation is verified by various model tests, and the output is validated based on benchmarks and a case study. Following the verification and validation of the *investment simulation*, the model will correctly generate the port system elements and the corresponding cost estimates of the port system alternatives for all design scenarios. Accordingly, the characteristic design variables will be evaluated.

The findings with regard to the characteristic design variables will be strengthened by sensitivity analyses for a specific design scenario (i.e. design scenario 5). This scenario comprises a capacity of the design vessel of 12,500 TEU and a distance between the offshore and onshore terminal of 40 km. The sensitivity analyses address the variables that are not affected by the design decisions, but with a notable impact on the cost estimates.

Following the verification of the *logistical simulation*, the model correctly establishes the relationship between the operational reliability of the waterway transport link and the storage level of the offshore terminal. Next, the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships is evaluated.

This chapter describes the evaluation of the logistical trade-offs. The evaluations are a combination of the results and the corresponding discussion. The results are immediately discussed after presenting them. In summary, the following items evaluate the logistical trade-offs:

- the cost estimates of the port system alternatives for the design scenarios (Section 5.1);
- the sensitivity analyses of crucial variables, though unrelated to design decisions (Section 5.2);
- the assessment of the relationship between the operational reliability of the waterway transport link and the required storage capacities (Section 5.3);

To conclude, the second sub-question will be answered:

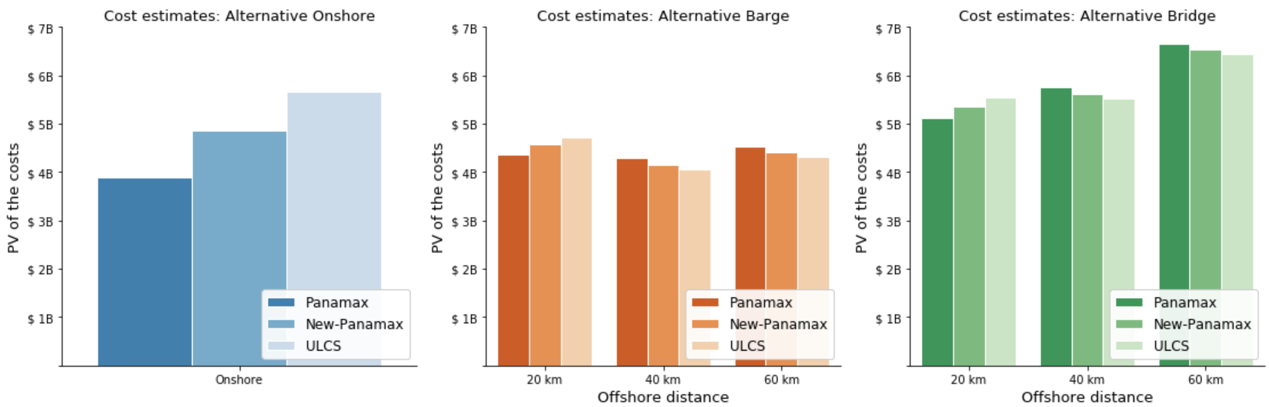
"What are the major logistical trade-offs regarding various types of port systems based on costs?"

The answer to this sub-question summarises the major logistical trade-offs.

5.1. Cost estimates of the port system alternatives for the specified design scenarios

The first results are the cost estimates of the port systems alternatives for the specified design scenarios. The design scenarios are related to the characteristic design variables. Therefore, the logistical trade-offs concerning the characteristic design variables are evaluated based on costs.

Figure 5.1 shows the cost estimates of the port system alternatives for the specified design scenarios. The cost estimates are expressed as the PV of the costs, considering the design starting points. Therefore, the findings only apply to the specified design assumptions and boundary conditions, as described in Section 3.2.7. For the onshore port system (Figure 5.1a), three cost estimates are generated based on the specified design vessels, since no offshore terminal is present. The exact values of the cost estimates can be found in Appendix E.1.



(a) Onshore (b) Offshore-Onshore Barge (c) Offshore-Onshore Bridge

Figure 5.1: Cost estimates of the port system alternatives for the design scenarios expressed as PV of the costs.

The results of Figure 5.1 show that the cost estimates of *offshore-onshore port systems* can be less costly compared to the cost estimates of *onshore port systems* for specific design scenarios. Notably, the cost estimates of Alternative Barge are less costly for the design scenarios that include the New-Panamax compared to the cost estimate of Alternative Onshore. Furthermore, the cost estimates of Alternative Bridge are slightly less costly for the design scenarios that include the ULCS for an offshore distance of 20 and 40 km compared to the cost estimate of Alternative Onshore.

A more in-depth analysis of the results is given from two perspectives:

- the cost estimates are analysed per offshore distance cluster (Section 5.1.1); and
- the categorised cost estimates are analysed per design vessel (Section 5.1.2).

5.1.1. Evaluation of the cost estimates regarding the offshore distance

The cost estimates of the onshore port system (i.e. Alternative Onshore) increase with the capacity of the design vessel. The differences in dredging costs outweigh the differences in ocean transport costs, as shown in the next section (Section 5.1.2).

The cost estimates of both offshore-onshore port systems show similar trends with the capacity of the design vessel for the offshore distance clusters (see Figure 5.1b and 5.1c). For an offshore distance of 20 km, the cost estimates increase with the capacity of the design vessel. In contrast, the cost estimates decrease with the capacity of the design vessel for offshore distances of 40 and 60 km.

These trends can be explained by the relation between the access channel dredging costs and the offshore distance. The access channel dredging costs depend on the location of the offshore terminal, the draught of the design vessel, the required net under keel clearance and the bathymetry of the foreshore (see Appendix C.1). These costs increase with the offshore distance until natural deep waters are reached. Following the design starting points, these distances are listed below. For all three design vessels, natural deep waters are reached at less than 40 km offshore. Therefore, the access channel dredging costs are constant for all offshore distances larger than 40 km.

- For the Panamax, natural deep waters are reached at 32.0 km offshore. A water depth of 16.0 m is considered as deep water for the Panamax with a draught of 13.0 m.
- For the New-Panamax, natural deep waters are reached at 36.4 km offshore. A water depth of 18.2 m is considered as deep water for the New-Panamax with a draught of 15.2 m.
- For the ULCS, natural deep waters are reached at 38.0 km offshore. A water depth of 19.0 m is considered as deep water for the ULCS with a draught of 16.0 m.

5.1.2. Evaluation of the categorised costs estimates

Figure 5.2, 5.3 and 5.4 presents the categorised cost estimates for the design scenarios that include the Panamax, New-Panamax and ULCS, respectively. The segments in the bars represent different categories of the cost estimates. The colours indicate the category (e.g. dredging) and the tint indicate the type of costs (e.g. capital dredging or maintenance dredging).

The categories represent the ocean transport costs, the terminal costs, the costs of the transport link between the offshore and onshore terminal and the dredging costs. The terminal costs include the costs for the construction and operations of the offshore and onshore terminals for the offshore-onshore port systems.

Categorised cost estimates: Panamax

Figure 5.2 presents the categorised cost estimates for the design scenarios that include the Panamax. Alternative Onshore shows the less costly alternative since the dredging costs are relatively low for the dimensions of the Panamax.

The cost estimates of Alternative Barge are not significantly affected by the offshore distance. The dredging costs at offshore distances of 40 km and 60 km are for the waterway transport link. Only the reclamation and construction costs of the offshore terminal (terminal capex) increase slightly.

The cost estimates of Alternative Bridge show a constant increase in costs with the offshore distance. The increase in the transport link costs is the most significant.

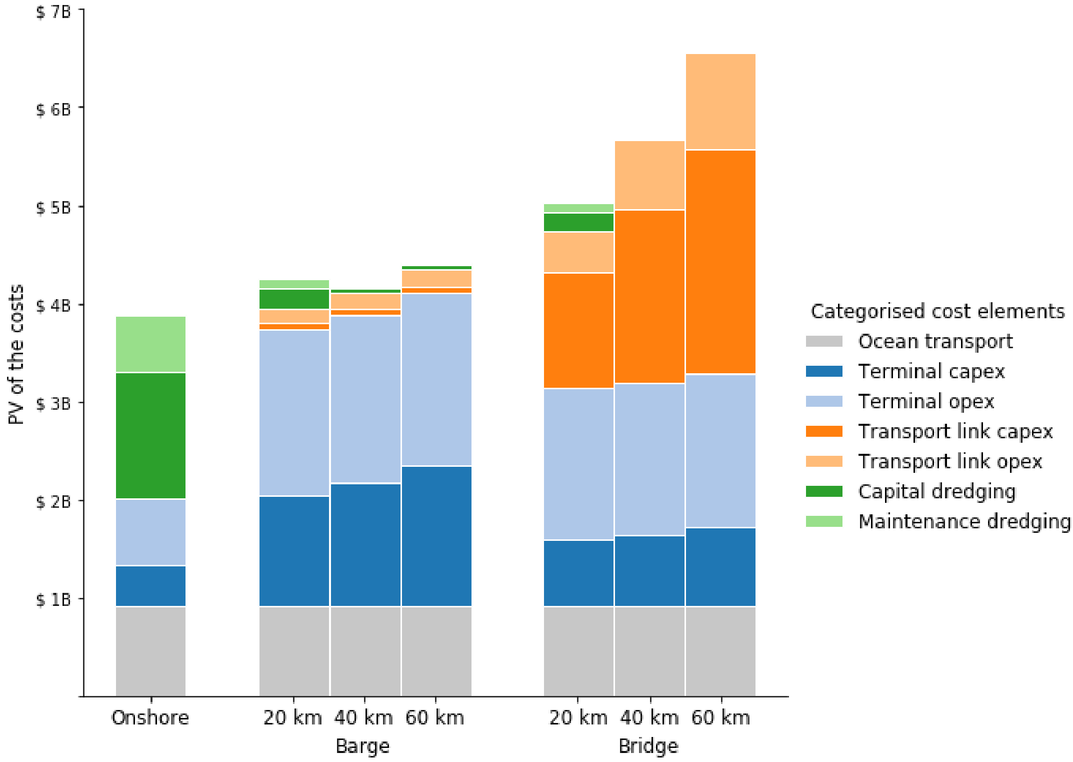


Figure 5.2: Categorised cost estimates for the design scenarios that include the Panamax

Categorised cost estimates: New-Panamax

Figure 5.3 presents the categorised cost estimates for the design scenarios that include the New-Panamax. Alternative Barge is the most cost-effective for an offshore distance of 40 km. This is a result of the increased dredging costs for Alternative Onshore. The reduction in ocean transport costs in comparison with the Panamax is hence outweighed for Alternative Onshore.

The cost estimates of Alternative Barge show the trade-off concerning the offshore distance. On the one hand, the dredging costs are higher at 20 km offshore than at 40 km and 60 km offshore and, on the other hand, the construction costs of the offshore terminal (terminal capex) and the barge operation costs increase with the offshore distance.

The cost estimates of Alternative Bridge show a constant increase in costs with the offshore distance. The increase in the transport link costs is the most significant.

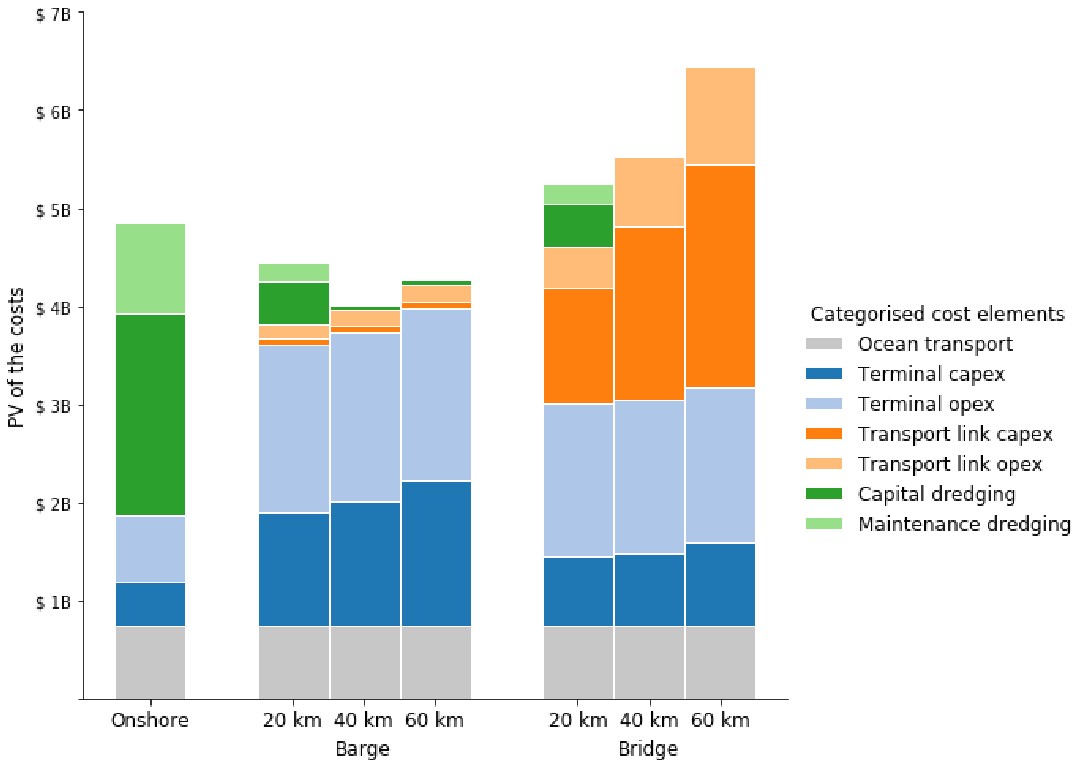


Figure 5.3: Categorised cost estimates for the design scenarios that include the New-Panamax

Categorised cost estimates: ULCS

Figure 5.4 presents the categorised cost estimates for the design scenarios that include the ULCS. Alternative Barge shows again the less costly alternative for an offshore distance of 40 km for the same reason as in the previous section.

The cost estimates of Alternative Barge show a similar trade-off concerning the offshore distance as for the New-Panamax. However, all cost estimates are slightly less costly compared to the cost estimates for the design scenarios that include the New-Panamax, due to the lower ocean transport costs.

The cost estimates of Alternative Bridge show comparable results for offshore distances of 20 km and 40 km. Moreover, Alternative Bridge is less costly compared to Alternative Onshore. This is a result of the dredging costs for an offshore distance of 20 km and the increase in transport link costs for an offshore distance of 40 km.

From this, we can conclude that Alternative Bridge, as well as Alternative Barge, will be considered more frequently in the future, as the size of container ships is still growing due to the continuous search for economies of scale by shipping lines.

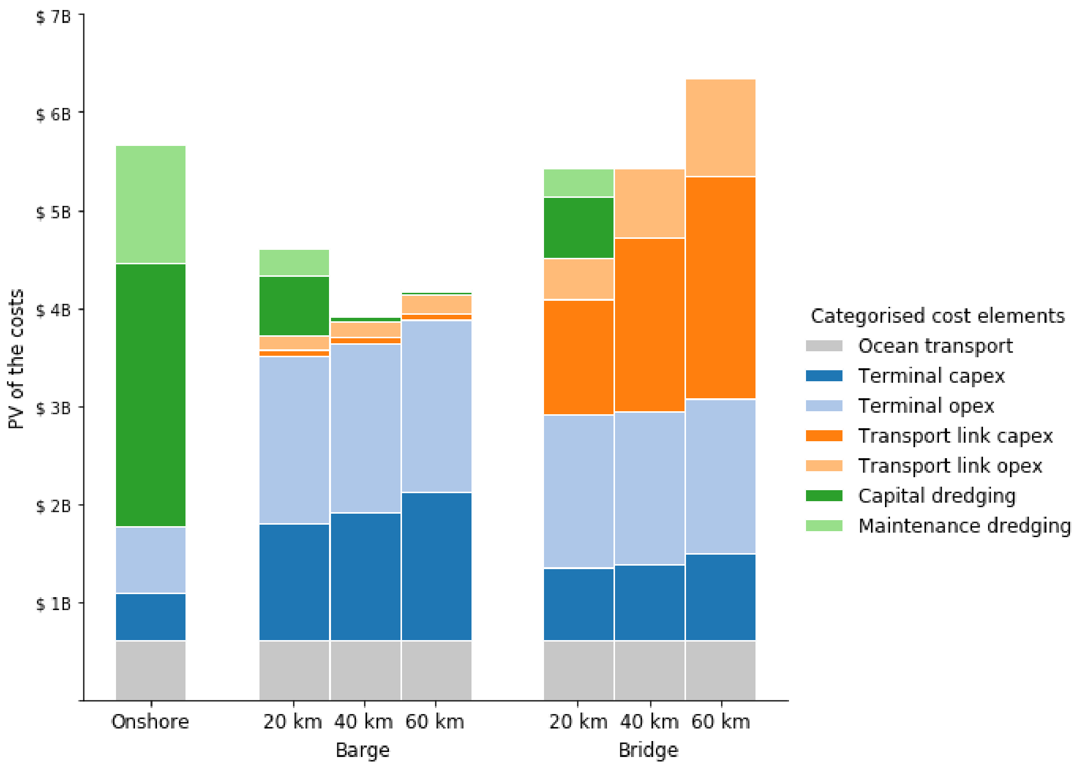


Figure 5.4: Categorised cost estimates for the design scenarios that include the ULCS

5.2. Sensitivity analyses for a specific design scenario: New-Panamax and 40 km offshore

The findings regarding the characteristic design variables will be strengthened by sensitivity analyses for design scenario 5. This scenario comprises a capacity of the design vessel of 12,500 TEU and a distance between the offshore and onshore terminal of 40 km. The sensitivity analyses address the variables that are not affected by the design decisions, but with a notable impact on the cost estimates.

In the sections below, various sensitivity analyses are shown to present the relationships between specific variables and the cost estimates. Table 5.1 shows an overview of the various sensitivity analyses. The sensitivities are illustrated by figures of the PV of the costs over the specified ranges of the variable. Furthermore, the relative changes in PV of the costs are presented. The exact values of the cost estimates can be found in Appendix E.3.

Table 5.1: Overview of the sensitivity analyses

Sensitivity analysis			Scenarios		
Variables	(base)	Unit	Low	Medium	High
Demand: fixed volume	1,000,000	TEU	500,000	1,000,000	1,500,000
Demand: growth over time	no growth	-	scenario 1	scenario 2	scenario 3
Bathymetry: slope of the foreshore	2.0	km/m	1.0	2.0	3.0
Bathymetry: shape of the foreshore	0.5	-	0.50	0.75	1.0

Before analysing the relationships between variables and the cost estimates for design scenario 5, the shares of cost categories for the specific design scenario are given. Figure 5.5 presents the shares of the categorised cost estimates, specifically for design scenario 5. The outer wedges represent the categorised cost, i.e. dredging costs, terminal costs, costs of the transport link between the offshore and onshore terminal and ocean transport costs. The terminal costs include the costs for the construction and operations of the offshore and onshore terminals for the offshore-onshore port systems. The inner wedges represent the corresponding capex and opex of the categorised costs. The colour palette is similar to those of Figure 5.2 - 5.4.

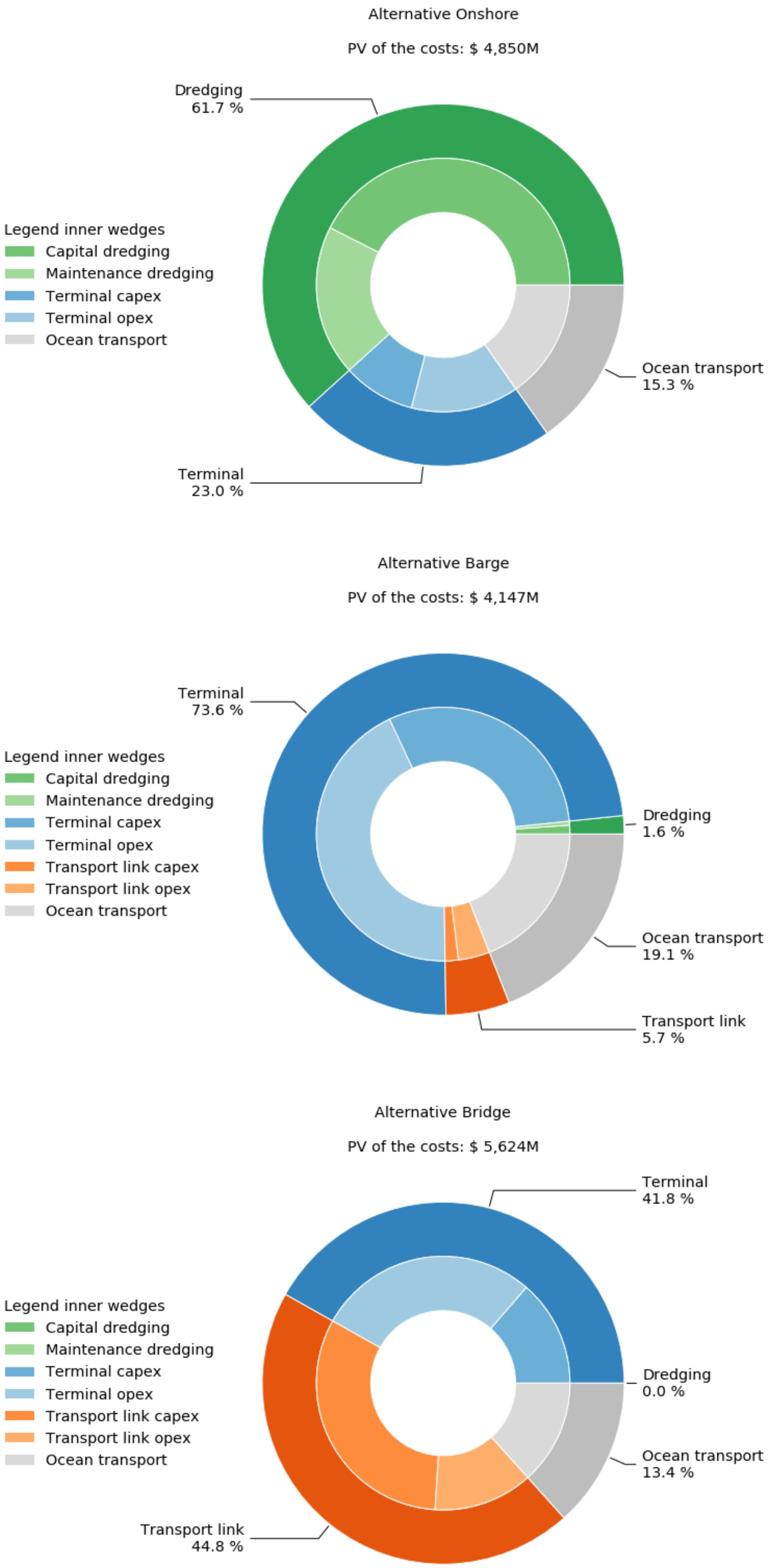
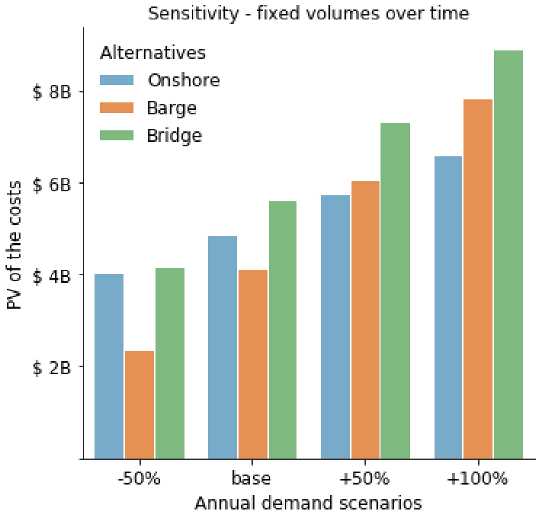


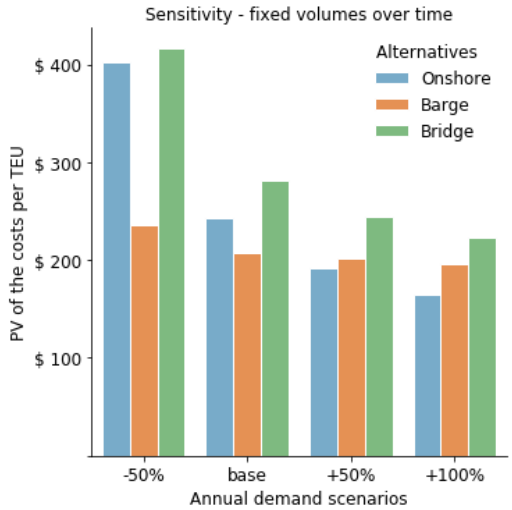
Figure 5.5: Shares of the PV of the costs for design scenario 5. The outer wedges represent the categorised costs, and the inner wedges represent the corresponding capex and opex.

5.2.1. Demand: fixed volume over time

The first sensitivity analysis addresses variations in annual demand. The annual base volume is 1,000,000 TEU. Figure 5.6 presents the sensitivity plot of the annual demand to fixed volume changes.



(a) Cost estimates over total container volume



(b) Cost estimates per TEU

Figure 5.6: Sensitivity plot to changes in fixed volumes over time

The analysis of the results is given below.

- The cost estimates of Alternative Onshore gradually increase for an increasing demand.
- The cost estimates of Alternative Barge show the most significant increase to the fixed volume changes.
- The cost estimates of Alternative Bridge gradually increase for an increasing demand.

The results of Figure 5.6a show that Alternative Barge is especially less costly for lower container volumes compared to the other port system alternatives. This difference can be explained by the shares of the fixed and variable costs. The shares of both the dredging costs for Alternative Onshore and the transport link costs for Alternative Bridge are fixed. The required dredging volume is, at least to a certain extent, not affected by the annual demand. Additionally, the capacity of the bridge hardly phases gradually in line with the demand, as a completely new connection to the mainland is required for operation.

The relative increase and decrease of the cost estimates of Alternative Barge are the most significant with a change of 88% (Table 5.2) for a doubling of the annual demand. This is a result of the relatively high variable costs (i.e. the costs for the berth infrastructure and the barge investment and operational costs), as shown in Figure 5.5. These cost increase nearly completely in line with the demand, as shown by Figure 5.6b, where the PV of the costs per TEU are presented.

Table 5.2: Relative changes in cost estimates for changes in annual demand

Demand: fixed volume over time (%)				
Port system	-50%	*base*	+ 50 %	+ 100 %
Alternative Onshore	- 17%	-	+ 19%	+ 36%
Alternative Barge	- 43%	-	+ 46%	+ 88%
Alternative Bridge	- 26%	-	+ 30%	+ 59%

5.2.2. Demand: growth over time

Capacity expansions are required to meet a growth in demand over time. Three scenarios are defined, called low, medium and high with annual demand growth rates of 3.3%, 6.7% and 10%, respectively. These annual demand growth rates are of a similar order of magnitude as the global average annual demand growth rate of 8.1% over the past four decades, as stated in Section 1.1 (United Nations Conference On Trade and Development (UNCTAD), 2018).

Figure 5.7 presents the specified scenarios. The first scenario is equal to the fixed volume of 1,000,000 TEU annually. The other scenarios are defined as increasing volumes over the life cycle.

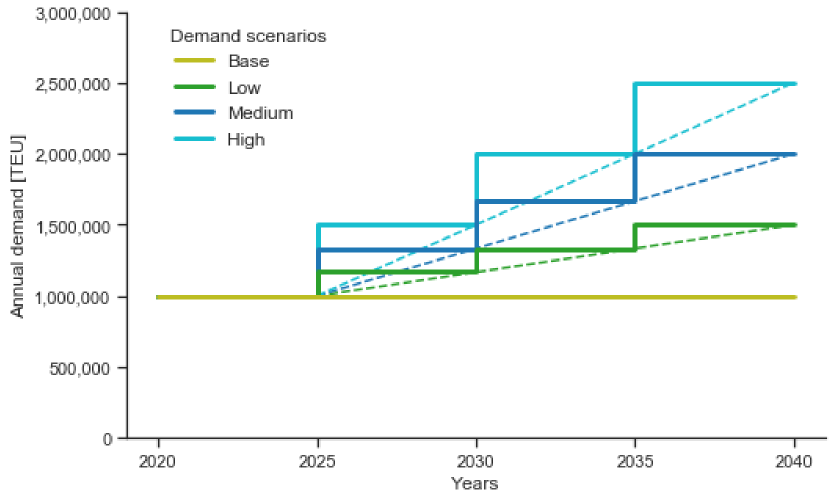
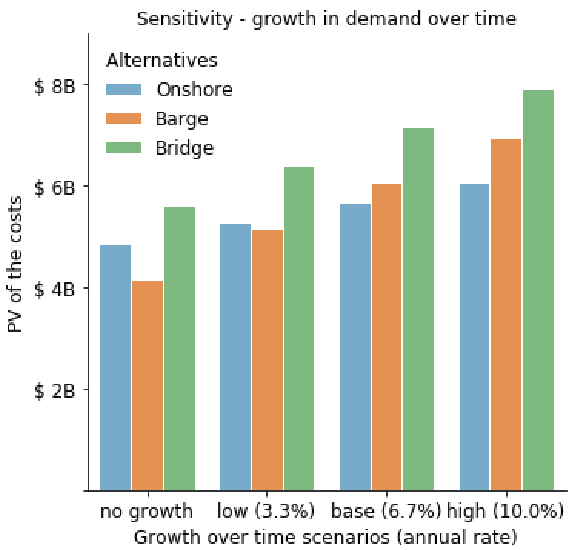
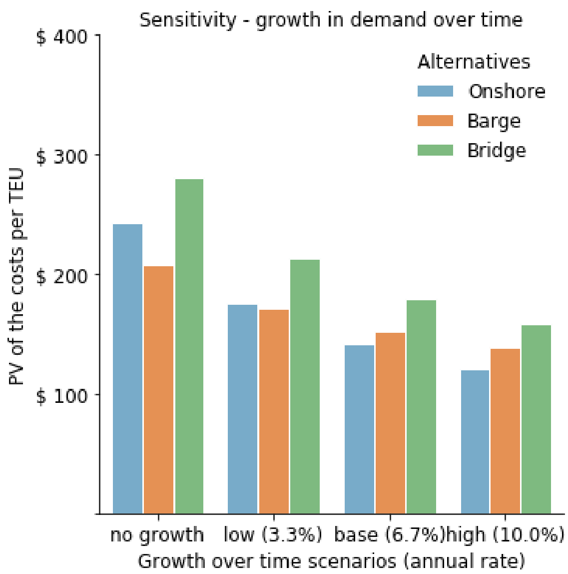


Figure 5.7: Demand growth over time forecasts and capacity planning scenarios

Figure 5.8 presents the sensitivity plot to the growth in demand over time.



(a) Cost estimates over total container volume



(b) Cost estimates per TEU

Figure 5.8: Sensitivity plot to a growth in demand over time

The analysis of the results is given below.

- The cost estimates of Alternative Onshore gradually increase for a growth in demand over time.
- The cost estimates of Alternative Barge show the most significant increase to the growth in annual demand over time.
- The cost estimates of Alternative Bridge gradually increase for a growth in demand over time.

The results of Figure 5.6a show that Alternative Barge is especially less costly for lower container volumes compared to the other port system alternatives.

The results of Figure 5.8 show Alternative barge is significantly less costly in case of no or limited growth. The cost estimates of Alternative Onshore show the lowest increase, with only +25% for the highest annual demand growth rate (Table 5.3).

Similar to the findings of changes in fixed annual volumes (Section 5.2.1), the increase of the cost estimates of Alternative Barge is the most significant. However, if an expansion of the fixed infrastructure may be required, the cost estimate of Alternative Bridge is likely to increase immensely.

Table 5.3: Relative changes in cost estimates for a growth in demand over time

Demand: growth in volume over time (%)				
Port system	*no growth*	low	medium	high
Alternative Onshore	-	+ 9%	+ 17%	+ 25%
Alternative Barge	-	+ 24%	+ 46%	+ 67%
Alternative Bridge	-	+ 14%	+ 23%	+ 41%

5.2.3. Bathymetry: the slope of the foreshore

The third sensitivity analysis addresses the bathymetry. The bathymetry affects the required dredging volume and retaining height of the quays, as explained in Section 3.2.6. Figure 5.9 presents the sensitivity plot of the bathymetry to changes in the slope of the foreshore.

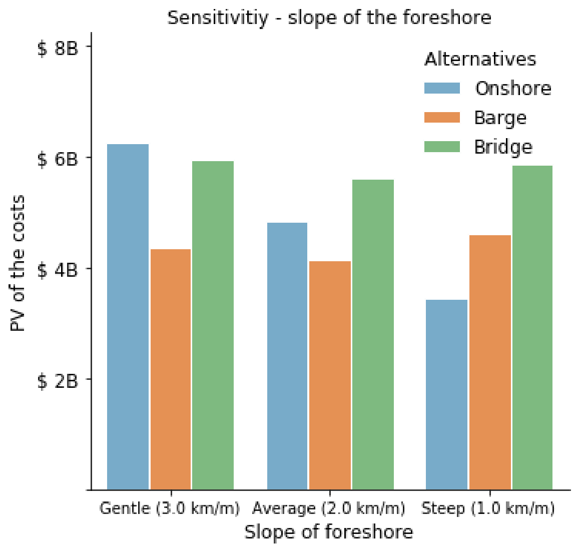


Figure 5.9: Sensitivity plot to changes in the slope of the foreshore

The analysis of the results is given below.

- The cost estimates of Alternative Onshore decrease significantly for a steeper slope of the foreshore.
- The cost estimates of Alternative Barge are limited affected by the changes in the slope of the foreshore.
- The cost estimates of Alternative Bridge are the least significant affected by the changes in the slope of the foreshore.

The results show that the cost estimates of Alternative Onshore are significantly affected by the changes in the slope of the foreshore. This can be explained by the share of the dredging costs for the onshore port system (see Figure **??**). The slope of the foreshore appears to be decisive for the question if an onshore port system alternative or an offshore-onshore port system alternative is the most cost-effective.

For the New-Panamax, natural deep waters[1] are reached at 36.4 km offshore for a slope of 2.0 km/m. Since the offshore terminal is located at 40 km offshore for design scenario 5, the dredging costs for the access channel do not reduce for a steeper slope. The decrease in dredging costs for the shuttle barge waterway is smaller than the increase in construction costs of the offshore terminal. Therefore, the cost estimates of the offshore-onshore port systems are slightly higher (below 7%, Table 5.4) for steeper and more gentle slopes.

Table 5.4: Relative changes in cost estimates for a change in the slope of the foreshore

Bathymetry: slope of the foreshore (%)			
Port system	gentle	average	steep
Alternative Onshore	+ 29%	-	- 29%
Alternative Barge	+ 5%	-	+ 11%
Alternative Bridge	+ 6%	-	+ 4%

5.2.4. Bathymetry: the shape of the foreshore

The fourth sensitivity analysis addresses the shape of the foreshore. Where the bathymetry of the foreshore was simplified as a straight slope until now, other shapes result in changes of the required dredging volume. This shape is defined by the bathymetry factor (see Figure 5.10). Figure 5.11 presents the sensitivity plot of the bathymetry for changes in the shape of the foreshore.

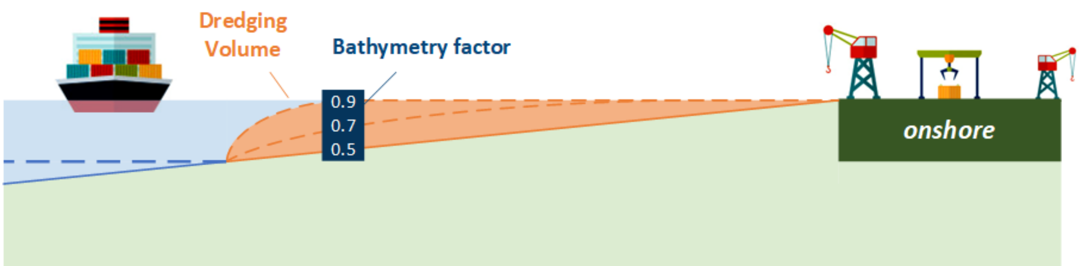


Figure 5.10: Illustration of the bathymetry factors used for the sensitivity analysis of the shape of the foreshore

[1]A water depth of 18.2 m is considered as deep water for the New-Panamax with a draught of 15.2 m.

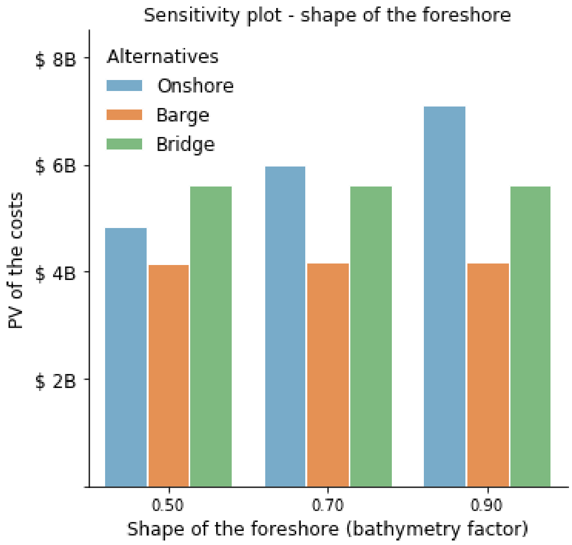


Figure 5.11: Sensitivity plot to changes in the shape of the foreshore

The analysis of the results is given below.

- The cost estimates of Alternative Onshore increase for an increasing bathymetry factor.
- The cost estimates of Alternative Barge are hardly affected by changes in the shape of the foreshore.
- The cost estimates of Alternative Bridge are not affected by changes in the shape of the foreshore.

The results show that the cost estimates of Alternative Onshore are significantly affected by changes in the bathymetry factor. Similar to the findings of changes in the slope of the foreshore, this is a result of the share of the dredging costs (see Figure 5.5). The cost estimates of Alternative Barge are hardly affected (+1%, Table 5.5), due to a small increase of the dredging costs for the waterway transport link.

Table 5.5: Relative changes in cost estimates for a change in the shape of the foreshore

Bathymetry: shape of the foreshore (%)			
Port system	0.50	0.70	0.90
Alternative Onshore	-	+ 23%	+ 47%
Alternative Barge	-	+ 1%	+ 1%
Alternative Bridge	-	+ 0%	+ 0%

5.3. Assessment of the relationship between the operational reliability of the waterway transport link and the required storage capacities

A method to assess the relationship between the operational reliability of the waterway transport link and the required storage capacities of offshore-onshore port systems is addressed as the second gap in the literature. The logistical simulation is developed to assess this relationship. The container ship and shuttle barge transport are related to the terminal operations using agent-based discrete-event simulations. These logistical simulations evaluate the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships. Although the evaluation of this trade-off is a sensitivity analysis, it is described separately from the previous section, as it only concerns the offshore-onshore port system linked by a waterway.

5.3.1. Introduction to the method for the assessment

Similar to the sensitivity analyses of the previous section, the assessment starts with the definition of the port system elements according to design scenario 5. The port system elements are determined by the investment simulation in line with the design starting points, as described in Section 3.2.7. Figure 5.12 illustrates the port system elements that are used for the logistical simulations. These port system elements are determined based on yearly averaged design capacities.

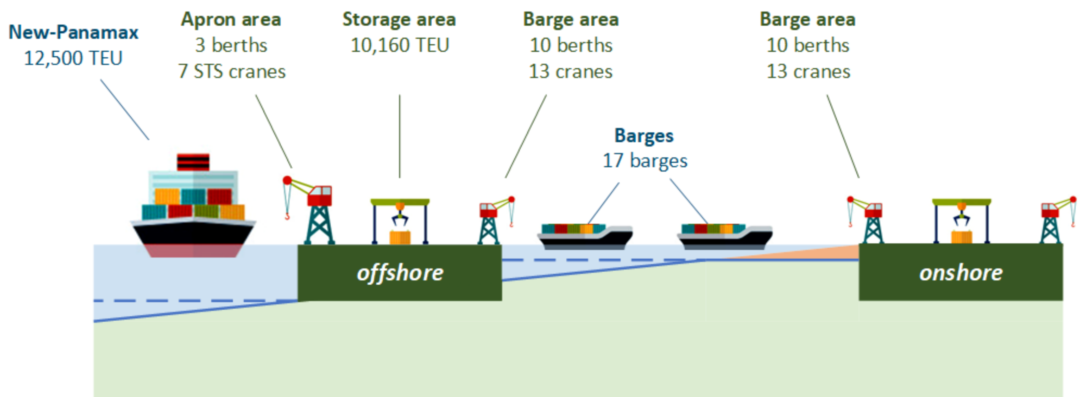


Figure 5.12: Illustration of Alternative Barge based on yearly averaged design capacities for design scenario 5.

Next, the relationship between the operational reliability of the waterway transport link and the required storage capacities is assessed. Therefore, the effect of downtime of the shuttle barges is evaluated from the following three perspectives:

1. the effect of various downtime scenarios on the offshore storage level that is reached in case of unlimited offshore storage capacity;
2. the effect of limited offshore storage capacity on the container ship waiting costs for various downtime scenarios; and
3. the effect of varying the offshore storage capacity on the cost estimates by including the costs for additional port infrastructure and annual waiting time.

Four downtime scenarios are defined in order to simulate the impact on the offshore terminal:

1. no downtime;
2. three days of consecutive downtime;
3. six days of consecutive downtime; and
4. nine days of consecutive downtime.

5.3.2. The effect of various downtime scenarios on the offshore storage level that is reached in case of unlimited offshore storage capacity

Figure 5.13 presents the effect of various downtime scenarios of the barge transport on the offshore storage level that is reached in case of unlimited offshore storage capacity.

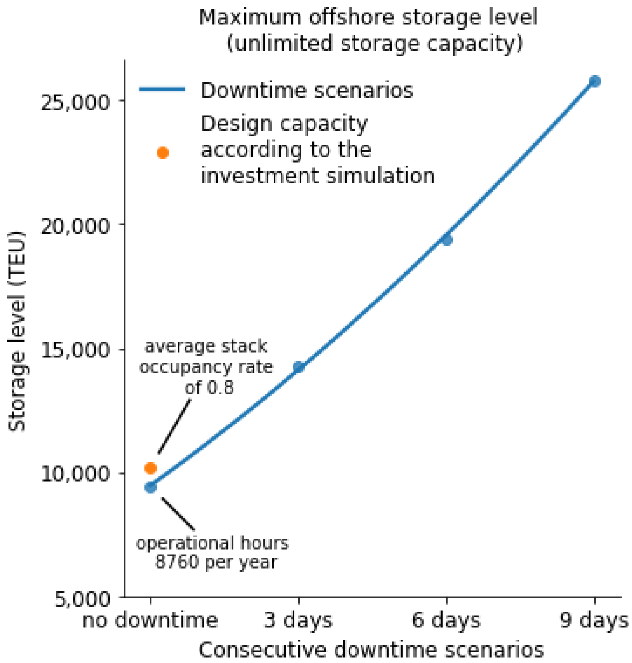


Figure 5.13: The effect of downtime on the offshore storage level that is reached in case of unlimited offshore storage capacity

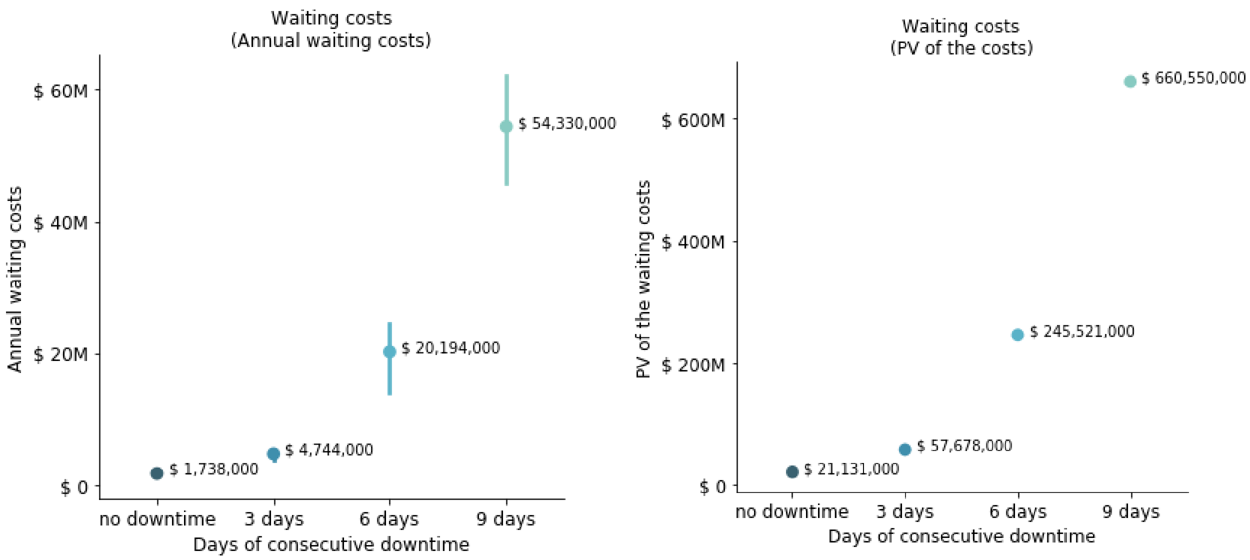
The scenario without downtime includes 8760 operational hours (365 days) and does not reach the level of the storage capacity of 10,160 TEU as described in the introduction of the chapter. The storage levels that are reached for the scenarios with periods 3, 6, or 9 days of consecutive downtime once a year, show a linear relationship with the length of the consecutive downtime period. The storage levels that are reached indicate the range of storage capacities to be studied in the following sections.

5.3.3. The effect of limited offshore storage capacity on the container ship waiting costs

This section addresses the offshore-onshore port system according to design scenario 5, whereby the offshore storage capacity is equal to 10,160 TEU as described in the introduction of the chapter.

The waiting costs are determined for periods of consecutive downtime of 0, 3, 6 and 9 days. Since the planning of the arriving container ships and hinterland modalities is normally distributed over time, the storage level at both the offshore and onshore terminals at the start of the period of downtime varies per run. The storage level at the start of the period of downtime, and therefore the timing, appears to be a significant factor affecting annual waiting costs.

Figure 5.14 presents the average waiting costs as a result of periods of consecutive downtime. A daily demurrage rate of 100 USD/TEU is applied since daily demurrage rates can typically range from 75 to 150 USD/TEU (PLS Logistics, n.d.). The vertical lines indicate the range in which the waiting costs differ (see Figure 5.14a). The PV of the waiting time costs is determined based on the average annual waiting costs over a life cycle of 20 years (see Figure 5.14b). The determination of the waiting times for the downtime scenarios is given in Appendix F.



(a) Annual waiting costs

(b) PV of the waiting costs over the life cycle

Figure 5.14: The effect of limited offshore storage capacity on the waiting costs

The analysis of the results is given below.

- The waiting costs increase exponentially over time since the length of the period of downtime defines the number of waiting container ships and the length of period of the catch-up after the barges become operational again, as explained in Section 4.1.2.
- The waiting costs in case of no downtime are a result of waiting events at the offshore terminal when all berths are occupied, as explained in Section 4.1.2.
- The waiting costs for the periods of consecutive downtime are a result of combinations of waiting events when all berths are occupied or when the storage area is full, or the export storage level is insufficient, as explained in Section 4.1.2.

5.3.4. The effect of varying the offshore storage capacity on the cost estimates

The objective of this section is to evaluate the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships. Offshore storage capacities ranging from 10,000 to 20,000 TEU are evaluated. The annual waiting costs are determined for the specified days of consecutive downtime, as presented in Figure 5.15. The annual waiting costs are determined similarly to the annual waiting costs as presented in Figure 5.14 following the design capacity according to the investment simulation.

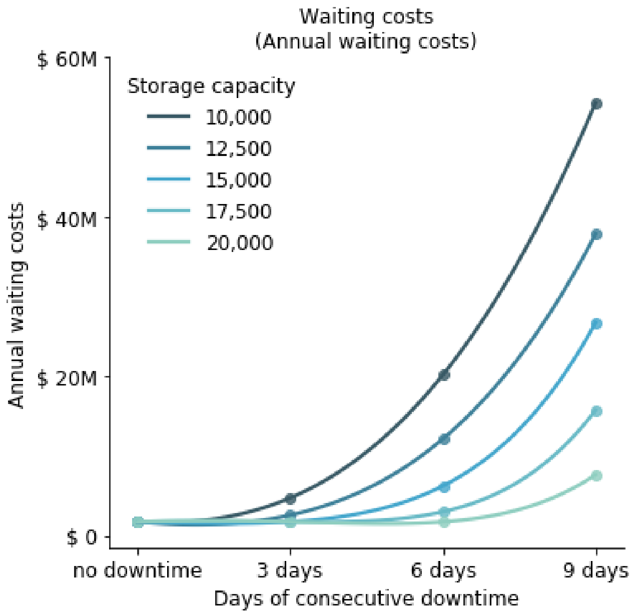
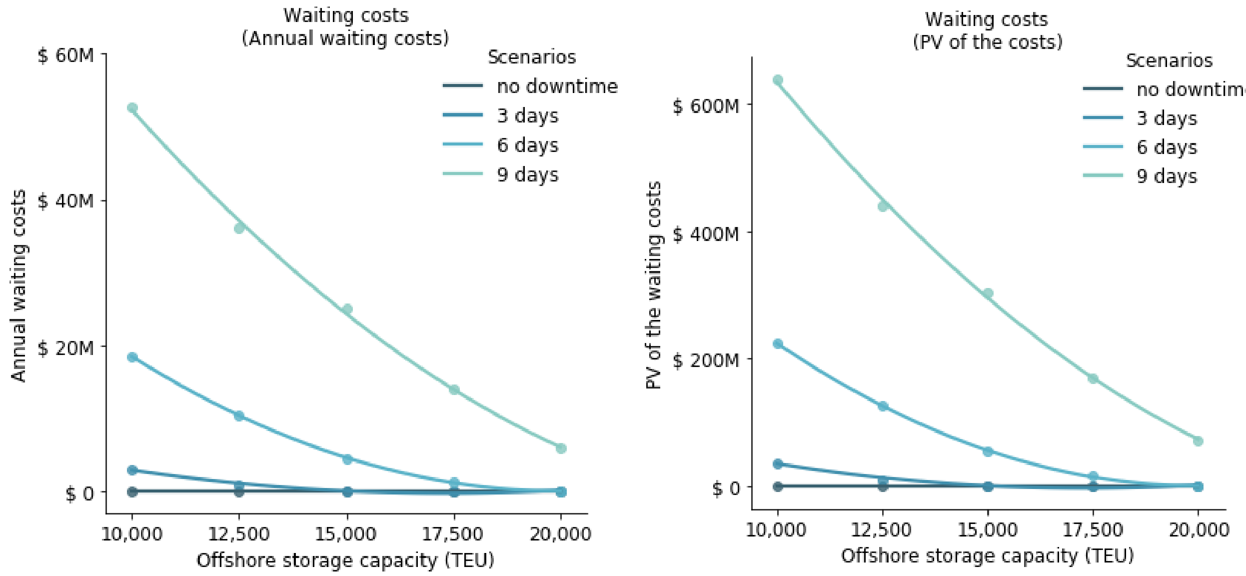


Figure 5.15: Annual waiting costs related to the length of the consecutive downtime periods

The terminal with a storage capacity of 10,000 TEU becomes full after a few days of consecutive downtime. The annual waiting costs increase exponentially with the length of the period of downtime. Considering the terminal with a storage capacity of 20,000 TEU, the capacity is sufficient for some days and becomes full after a longer period of downtime. Once the storage capacity is reached, the annual waiting costs increase similarly to the annual waiting costs of the terminal with smaller storage capacities.

In order to evaluate the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships, the waiting costs as a result of fully occupied berths are excluded. Furthermore, the storage capacity is placed at the x-axis, and the annual waiting costs are plotted for the specified periods of downtime (see Figure 5.16a).



(a) Annual waiting costs

(b) PV of the waiting costs over the life cycle

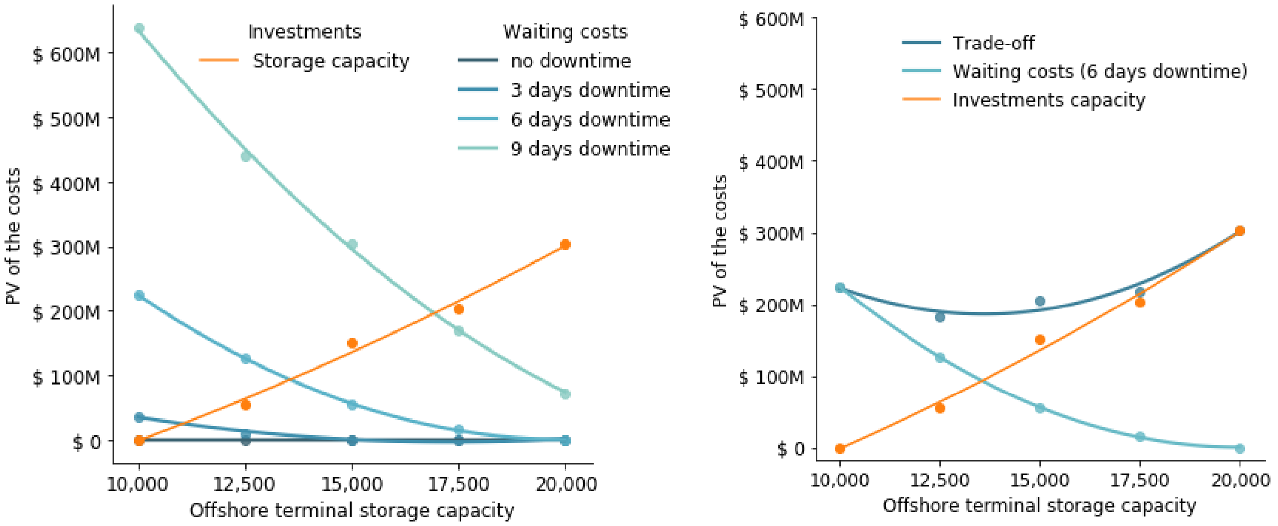
Figure 5.16: Waiting cost related to the offshore storage capacity for the downtime scenarios

Next, the PV of the cost for the expansion of the offshore terminal storage capacities are determined using the investment simulation. The costs for the expansions of the storage capacity compared to the storage capacity of 10,000 TEU are presented in Table 5.6. The storage capacities generated by the investment simulation include entire stacks. Therefore, the costs are related to the storage capacities of the second column.

Table 5.6: PV of the cost for the expansion of the offshore storage capacity compared to a storage capacity of 10,000 TEU

Storage area expansion costs		
Storage capacity*		Costs
10,000 TEU	10,160 TEU	$ -
12,500 TEU	12,860 TEU	$ 5,598,000
15,000 TEU	15,000 TEU	$ 150,428,000
17,500 TEU	17,040 TEU	$ 203,085,000
20,000 TEU	19,740 TEU	$ 304,186,000

Figure 5.17 presents the trade-off between the costs related to offshore storage capacity and the waiting time of container ships. Therefore, the most cost-effective solutions can be found for specific downtime scenarios. Depending on the frequency and length of the periods of downtime of the barge transport, the trade-off can be made between the costs related to the offshore storage capacity and the annual waiting time of container ships (see Figure 5.17b).



(a) Waiting cost related to the offshore storage capacity for the downtime scenarios

(b) Example of the trade-off for a period of consecutive downtime of 6 days

Figure 5.17: The trade-off between the costs related to the offshore storage capacity and the annual waiting time of container ships

Therefore, the objective to develop a method to assess the relationship between the operational reliability of the waterway transport link and the required storage capacities of offshore-onshore port systems is met. The method establishes the relationship between the container ship and shuttle barge transport with the terminal operations using agent-based discrete-event simulations.

5.4. Major logistical trade-offs

This section concludes on the cost-based evaluation of the logistical trade-offs. Therefore, the second sub-question will be answered:

"What are the major logistical trade-offs regarding various types of port systems based on costs?"

To answer this sub-question, a list, summarising the major logistical trade-offs will conclude the framework for future port system concept design.

Four major logistical trade-offs are identified. These are clarified below.

1. The first logistical trade-off concerns the choice between onshore port systems and offshore-onshore port systems, based on the bathymetry of the foreshore. The cost estimates of onshore port systems are highly affected by the slope and shape of the foreshore, contrary to the offshore-onshore port systems. This results in a trade-off between the dredging costs for onshore port systems and cost related to additional container handling, storage and transport and the reclamation costs for offshore-onshore port systems.
2. The second logistical trade-off concerns the choice between port system alternatives of which the cost estimates are significantly related to the demand (i.e. the offshore-onshore port system with a waterway transport link) and port system alternatives of which parts of the design are hardly related to the demand (i.e. the onshore port system and the offshore-onshore port system with a fixed infrastructure link). This results in a trade-off between alternatives with primarily capex and alternatives with primarily opex. Depending on the expected demand at the end of the life cycle, port system alternatives of which large components are hardly related to the demand may offer cost-effective alternatives.
3. The third logistical trade-off concerns the location of the offshore terminal in the case of an offshore-onshore port system with a fixed infrastructure link. The dredging costs of the access channel for the ocean-going vessels depend on the offshore terminal location, the draught of the design vessel and the bathymetry of the foreshore. The costs for the construction of the fixed infrastructure link depend on the offshore location as well. This results in a trade-off between the costs related to the dredging of an access channel and the construction of the fixed infrastructure link.
4. The fourth logistical trade-off, only concerning the offshore-onshore port system with a waterway transport link, is the trade-off regarding costs related to downtime of the shuttle barges. Depending on the frequency and length of the periods of downtime of the barge transport, one could make the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships.

6
Conclusion

This chapter concludes the research by answering the research question:

> *"How can the cost-based evaluation of the major logistical trade-offs regarding various types of port systems for container handling and transport be framed for future port system concept design?"*

6.1. Conclusions

The objective of this research is to evaluate the logistical trade-offs based on costs regarding various types of port systems for container handling and transport from a logistical perspective. Therefore, a framework, including the cost-based evaluations of various types of port systems, is developed. Cost estimates of various port system layouts are generated to compare conventional onshore ports and offshore-onshore port systems in terms of costs. In addition, a method is developed to assess the logistical challenges involved with the offshore-onshore port systems. In order to formulate an answer to the research question, two sub-questions are answered first. The first sub-question is:

> *"What are the differences between various types of port systems and the advantages and disadvantages of offshore-onshore port systems compared to conventional onshore ports?"*

The three port system alternatives, including the associated characteristics, are assessed. The assessment is presented as a list of advantages and disadvantages for each port system alternative (see Table 6.1).

Table 6.1: Assessment of the various types of port systems

Assessment of the port system alternatives			
Advantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	Single container handling at the onshore terminal (time- and cost-effective)	Limited dredging activities required for deepwater access and the waterway transport link	Limited dredging activities required for deepwater access
		The ability of the shuttle barge fleet to be easily phased in line with changes in demand	The operational reliability of the transport link is barely affected by environmental conditions
Disadvantages	Alternative Onshore	Alternative Barge	Alternative Bridge
	Possibly enormous dredging volumes required to guarentee deepwater access	Additional cost components for the construction of the offshore terminal	Additional cost components for the construction of the offshore terminal and the fixed infrastructure link
		Partially double container handling at both the terminals (additional operational costs and cycle time)	Partially double container handling at both the terminals (additional operational costs and cycle time)
		The operational reliability of the transport link is highly affected by weather conditions	The fixed infrastructure can hardly be phased gradually in line with changes in demand

The second sub-question is:

> *"What are the major logistical trade-offs between offshore-onshore port systems and onshore ports based on costs?"*

The cost-based evaluations of the logistical trade-offs conclude the framework for future port system concept design. Four major logistical trade-offs are identified.

1. The first logistical trade-off concerns the choice between onshore port systems and offshore-onshore port systems, based on the bathymetry of the foreshore. The cost estimates of onshore port systems are highly affected by the slope and shape of the foreshore, contrary to the offshore-onshore port systems. This results in a trade-off between the dredging costs for onshore port systems and cost related to additional container handling, storage and transport and the reclamation costs for offshore-onshore port systems.
2. The second logistical trade-off concerns the choice between port system alternatives of which the cost estimates are significantly related to the demand (i.e. the offshore-onshore port system with a waterway transport link) and port system alternatives of which parts of the design are hardly related to the demand (i.e. the onshore port system and the offshore-onshore port system with a fixed infrastructure link). This results in a trade-off between alternatives with primarily capex and alternatives with primarily opex. Depending on the expected demand at the end of the life cycle, port system alternatives of which large components are hardly related to the demand may offer cost-effective alternatives.
3. The third logistical trade-off concerns the location of the offshore terminal in the case of an offshore-onshore port system with a fixed infrastructure link. The dredging costs of the access channel for the ocean-going vessels depend on the offshore terminal location, the draught of the design vessel and the bathymetry of the foreshore. The costs for the construction of the fixed infrastructure link depend on the offshore location as well. This results in a trade-off between the costs related to the dredging of an access channel and the construction of the fixed infrastructure link.
4. The fourth logistical trade-off, only concerning the offshore-onshore port system with a waterway transport link, is the trade-off regarding costs related to downtime of the shuttle barges. Depending on the frequency and length of the periods of downtime of the barge transport, one could make the trade-off between the costs related to extensive offshore storage capacity and waiting time of container ships.

Finally, the research question is answered.

> *"How can the cost-based evaluation of the major logistical trade-offs regarding various types of port systems for container handling and transport be framed for future port system concept design?"*

A framework is a collection of concepts to give a better understanding of a given problem. The problem was stated as a lack of methodology to evaluate the logistical trade-offs between various types of port systems, including offshore-onshore port systems. The framework results in a better understanding of the logistical trade-offs between different type of port systems for container transport and handling.

The major logistical trade-offs are framed based on the evaluation of the characteristic design variables, the results of the sensitivity analyses and the assessment of the relationship between the operational reliability of the waterway transport link and the required storage capacities. The cost-based evaluations of these trade-offs could serve as a reference to make more deliberate and integral choices early in the design process.

The development of the parametric model was crucial for the evaluation of the port system alternatives. Using the parametric model, the logistical trade-offs are quantified by the generation of cost estimates for the port system alternatives. The findings regarding individual trade-offs in qualitative terms are very comprehensible. Nevertheless, the setup of the parametric model, comprising the investment and logistical simulation, allows for the complexity of generating all quantitative findings.

The developed investment simulation is the first method generating offshore-onshore port system designs, including the corresponding cost estimates. The method automatically adapts to changes in demand and responds flexibly to changes in phasing and design life cycle.

In addition, the developed logistical simulation is the first method to assess the relationship between the operational reliability of the waterway transport link and the required storage capacities of offshore-onshore port systems. The method establishes the relationship between the container ship and shuttle barge transport with the terminal operations using agent-based discrete-event simulations. These logistical simulations evaluate the cost related to the shuttle barge downtime. Depending on the frequency and length of the periods of downtime, the trade-off can be made between the costs related to the offshore storage capacity and the annual waiting time of container ships. Therefore, the most cost-effective solutions can be found for specific downtime scenarios.

A limitation of the methodology is that the quantitative findings are not generic. Although the setup of a parametric model is, in essence, generic, the output of the simulations is case-specific. The cost estimates of the port systems will always be according to specified design assumptions and boundary conditions.

6.2. Recommendations

Offshore-onshore port system development will be an option which will be considered more frequently in the future. Further research can improve the applicability and reliability of the developed methods. This section addresses the recommendations for further research.

Increase the applicability with other types of cargo

This research focuses exclusively on the development of offshore-onshore port systems for container handling and transport. The parallel between container terminals and dry bulk terminals may be interesting, due to efficiencies achieved by the variety of types of cargo (economies of scope). Furthermore, offshore loading and unloading mechanisms for liquid bulk are already well-known. Although, the study to the parallel between liquid bulk transport and containers is less interesting. The combination of these types of cargo may result in a better business case.

Add more port system alternatives

The definition of three port system alternatives was in favour of clear comparisons between the port system alternatives. A suggestion for further research is the addition of other port system alternatives. This can be done by combining the modalities and by adding floating applications.

Improve the level of detail of the transport links

The level of detail of the transport links is limited. In the case of the waterway transport link, only two-way channels are considered. The option of a one-way channel where the barges need to sail in convoy may offer a cost-effective alternative, as a more narrow channel will result in a reduction of the dredging costs.

In case of the fixed infrastructure link, only the construction of a bridge is considered. As described in Section 2.2, the combination of a causeway and a bridge may offer a cost-effective alternative. Causeways are often less costly in shallow waters, where the construction of a bridge is less costly in deep waters compared to a causeway construction.

Include a correlation between the downtime of ocean-going vessels and shuttle barges

The effect of downtime on the shuttle barges is simulated by a set of significant wave height data exceeding the operational threshold value for barge transport. Therefore, the significant wave height over time functions as a trigger for periods of downtime.

A remark is made in Section 3.3.4 regarding the definition of the downtime of ocean-going vessels. The potential downtime of these vessels is covered by the irregularities of the vessel distribution. Therefore, the correlation between the downtime of ocean-going vessels and shuttle barges is excluded.

In reality, the downtime of tugs, assisting the ocean-going vessels, and shuttle barges as a result of the wave climate are correlated. Further research should be done to the effect of this correlation on the trade-off between the offshore storage capacity and the annual waiting times on container ships.

Include the additional handling time as a consideration

In this research, the evaluation of the trade-offs is cost-based. However, the additional handling time can be an essential consideration as well. A suggestion for further research is to include the port system handling time as a secondary consideration. The logistical simulation should be capable of including the time consideration.

Vary the modal split and include direct transport between the offshore terminal and the hinterland

The starting points of an equal modal split (i.e. 50% road and 50% maritime) for all port system alternatives may be reconsidered. Since the assumption is made that all containers are handled by the offshore and onshore terminal, the impact of the modal split on the cost estimates is equal for all port systems. However, when including direct transport between the offshore terminal and inland destinations, the assumption concerning the modal split should be reconsidered.

For the offshore-onshore port system with a fixed infrastructure link, it is likely that a large share of the hinterland transport occurs by road. The same applies to the offshore-onshore port system with a waterway transport link in combination with a large share of maritime hinterland transport. Including direct hinterland transport results in less double container handling (container handling at both terminals) and, therefore, offer more cost-effective solutions since the required terminal infrastructure reduces.

Add hinterland characteristics

The hinterland characteristics are assumed not be a limiting factor in this research. By the addition of hinterland characteristics, other environmental conditions, such as limited river water depths, can be evaluated. These can result in downtime and therefore increase the storage capacity requirements. Furthermore, these site conditions can result in limitations of specific modalities.

Improve the determination of the demurrage

The determination of the demurrage is considerably simplified. The assumption is made that the relation between demurrage and the time the container ships have to wait is linear[1].

However, depending on the contract between the shipping line and the port authority, the daily charges typically range from 75 to 150 USD/TEU during the first days only. Usually, the charges become higher if the container ship has to wait longer. This may impact the cost-based evaluation of the trade-off between the offshore storage capacity and the annual waiting times of container ships.

[1] Not to be confused with the exponential relation between the container ship waiting time and the length of a period of consecutive shuttle barge downtime.

Perform an in-depth study on the relationship between the operational reliability of container transport and the required handling capacity for container stacking

Usually, engineers apply design guidelines (e.g. (PIANC, 2014)) for port master planning. These guidelines provide information and recommendations on good practice and should be seen as expert guidance. However, there is no single formula in the literature that connects the total throughput and the required stacking area. The approaches to calculate the handling capacity of a container stacking area generally apply a peak factor to account for peak conditions and average utilisation rates to account for potential downtime of port infrastructure.

The development of the logistical simulation is the first step in studying the relationship between the operational reliability of container transport and the required handling capacity for container stacking using agent-based discrete-event simulations. These logistical simulations evaluate the ocean-going vessel waiting cost related to the shuttle barge downtime. In combination with cost estimates for different storage capacities using the investment simulation, the most cost-effective solutions are found for specific downtime scenarios.

The logistical simulation shows promising results for a more generic connection of the throughput and the required stacking area. A recommendation for further research is to perform a more in-depth study on this topic.

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A

Reference projects

Offshore-onshore and *nearshore port systems* are currently operational in limited amounts worldwide. Most of them accommodate container terminals and few of them are combined with other types of cargo like dry bulk or general cargo. These ports are all connected to land via causeways for rail and road transport. Recently, more offshore-onshore port systems with various modes of transport are developed (e.g. the *Venice Offshore Onshore Port System* connected by a barge link). An overview of the *offshore-onshore port systems* and nearshore (concept) ports in Shanghai, Abu Dhabi, Moín, Venice, Vancouver, Louisiana and Hon Khoai and their relevant characteristics are given below.

Yangshan Port, Shanghai

Figure A.1: Yangshan Port

The Yangshan Port is an offshore *deepwater port* for container transport in the Hangzhou Bay south of Shanghai. The *deepwater port* is built on the islands of Greater and Lesser Yangshan and is connected to Shanghai's Pudong New Area by the Donghai Bridge, world's largest sea bridge with a length of 32.5 km. Yangshan Port is operational since 2004 and the operations are still expanding, due to the increase in maritime traffic passing through the port facility. The Donghai Bridge is a six-lane unimodal bridge for road transport, as there is no direct railway connection to the Yangshan Port (Song, 2008). The intermodal railway connection is located near the mainland end of the Donghai Bridge (Yangshan Customs, 2011).

Khalifa Port, Abu Dhabi

The Khalifa Port in Abu Dhabi with a project value of USD 5 billion started operating in 2012. The offshore port covers 270 ha, is situated 5 km offshore and is connected to land with a 4 km long causeway and a 1 km long bridge for road transport. The water depth at the terminals is 16.5 m at minimum and can therefore accommodate the *ULCS*.

The Khalifa Port Container Terminal (KPCT) has a capacity of 2.5 million TEUs and 12 million tonnes of general cargo annually (Abu Dhabi Ports Operating Company PJSC, n.d.). In 2018, Cosco Shipping Ports (CSP) launched the CSP Abu Dhabi Terminal of 27.5 ha with a design capacity of 2.5 million TEU annually. The total capacity is expected to increase from the current 5 million TEUs to 9.1 million TEUs, which also includes boosting capacity at the KPCT to more than 5 million TEUs (Abu Dhabi Ports, 2018).

Figure A.2: Khalifa Port

APM Terminals, Moín

Figure A.3: APM Terminals in Moin

The APM Terminals Moín in Costa Rica has opened in march 2019. The APM Terminals Moín will enable the shipment of products on transatlantic routes to European and Asian markets without transshipment. The terminal, built on a 80 ha artificial island 500 m offshore, represents a total investment of USD 930 million. The quay is 650 m long and with an access channel of 18 m deep, the terminal will be capable of handling container ships with a draught up to 14.5 m (8,500 TEUs). In later stages, the New Panamax (13,000 TEUs) will be able to be received. The container storage area has a capacity to hold 26,000 TEUs[1]. Moreover, a protected nesting area for sea turtles is set up[2].

Roberts Bank, Vancouver

The Roberts Bank Superport is a port facility with two terminals on the west coast of Canada. The Westshore Terminals is a coal terminal of 54 ha with a throughput capacity of 33 million tonnes (Westshore Terminals, n.d.). The GCT Deltaport is a container terminal of 85 ha with a throughput capacity of 3.6 million TEUs in 2019 after multiple expansions and a water depth of 15.9 m (GCT Deltaport, n.d.).

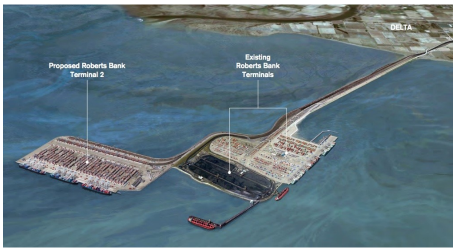

Figure A.4: Roberts Bank

The Roberts Bank Terminal II is a proposed new container terminal expansion project of USD 2 billion. A new three-berth container terminal of 108 ha and a widened causeway will be constructed (Vancouver Fraser Port Authority, 2018).

However, according to Environment and Climate Change Canada, the expansion project will impact hundreds of thousands of sandpipers [3] as ”potentially high in magnitude, permanent, irreversible, and, continuous.” Therefore, the plans of the port expansion currently encounter an obstacle [4].

Louisiana International Gulf Transfer Terminal

The *Louisiana International Gulf Transfer Terminal* (*LIGTT*) is envisioned to be the first offshore deepwater terminal of the United States to handle containers, bulk cargo and petroleum products. The deepwater transfer terminal will be located just east of the mouth of the Mississippi River where the Southwest Pass meets the Gulf of Mexico. The port is designed to accommodate the new Post-Panamax ships and Cape Size vessels. The suggested port site is located at a water depth of more than 20 m. All ports operating in the Gulf of Mexico are draught restricted in terms of accommodating Post-Panamax vessels. The project is currently in the permitting and pre-construction phase (LIGTT Midstream Holdings, 2019).

[1] https://www.apmterminals.com/en/moin/about/our-terminal
[2] https://magazine.vanoord.com/en_US/4033/63180/creating_societal_value_in_costa_rica.html
[3] Sandpipers are a large family of waders or shorebirds. The majority of these species eat small invertebrates picked out of the mud or soil.
[4] https://vancouversun.com/news/local-news/environment-canada-strikes-potential-death-blow-to-ports-2b-container-expansion-at-roberts-bank/

Venice Offshore-Onshore Port System

The *Venice Port Authority* (*VPA*) is planning an offshore container and oil terminal in combination with an onshore terminal at Porto Marghera, called the *Venice Offshore Onshore Port System* (*VOOPS*). The platform will be located 15 km from Malamocco Entrance of the Venice lagoon. The offshore terminal with a water depth of 20 m should be capable of handling *ULCS*s and will be protected by a 4.2 km outer embankment. An onshore *deepwater port* is not an option, due to the port characteristics and the regulatory and environmental constraints on the development of the navigation channels within the Venice Lagoon (Pachakis, Libardo, & Menegazzo, 2017).

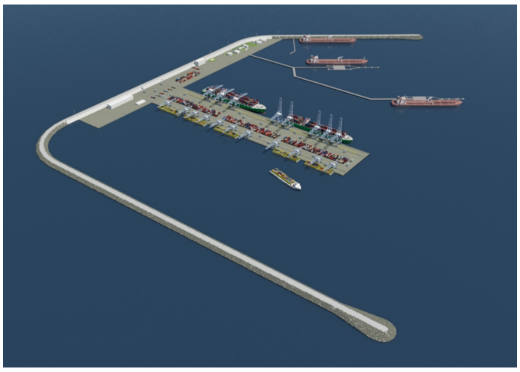

Figure A.5: Venice Offshore-Onshore Port System

According to The European Commission (n.d.), the *VOOPS* has high potential competitive advantage to reach Central/Eastern Europe markets, like saving up to EUR 389 per TEU and 5-6 days in order to complete the shipping considering the whole logistics chain. The estimated cost are EUR 2.2 billion (around USD 2.5 billion) in total.

Figure A.6: Semi Submersible Barge Transporter (SSBT)

The offshore and onshore facilities will be connected by a barge link. The *Semi Submersible Barge Transporter* (*SSBT*) (fig. A.6) is flexible to accommodate different types and sizes of barges up to 384 TEU [5], e.g. in addition to the barges going to Porto Marghera, narrow river barges (class V) can be carried by the barge carrier to serve the nearby river ports up to Mantova (Pachakis et al., 2017). They can withstand heavy seas and have a specially designed low wash hull form minimising wave impact to sensitive habitats and species in the Venice Lagoon [6].

Hon Khoai

Hon Khoai Port is a proposed *deepwater port* at Hon Khoai, an island 17 km off the coast of Ca Mau, in Vietnam. The estimated project value is up to USD 3.5 billion. A feasibility study is done by Bechtel Corporation and consist of 12 transhipment berths, half of which will be dedicated to coal imports and with two container terminal berths. The offshore port will be connected to the mainland by a railway bridge and will be capable of handling ships up to 250,000 DWT[7].

When completed, Hon Khoai Port is planned to be situated on a new sea route, which will be enabled by the proposed *Kra Canal project* in southern Thailand. The new route will reduce the sailing time by 72 hours and the travel distance by 1200 km for ships moving from the Andaman Sea and the Gulf of Thailand, as ships will be able to skip Singapore, Peninsula Malaysia and the Straits of Malacca. The Kra Canal is more than 100 kilometers long with a cost projection of about USD 28 billion. The feasibility of Hon Khai Port will largely depend on the completion of the Kra Canal[8].

[5] http://www.bmt-titron.com/portfolio.html
[6] https://www.royalhaskoningdhv.com/en-gb/smc/news-room/news/20141211pr-master-plan-major-efficiencies-port-of-venice-extension/3346
[7] http://bizhub.vn/news/vietnamese-port-infrastructure-needs-solutions-to-keep-pace-with-growth_310171
[8] https://www.straitstimes.com/opinion/new-viet-port-a-clue-to-kra-canal

B
Container ship characteristics

Table B.1 presents the container ship characteristics, including the capacity, vessel dimensions and average ocean transport costs per TEU (Rodrigue et al., 2016), that are included in the investment simulation. The ocean transport costs are based on global averages for a distance of 6,000 miles (i.e. the average between the distances of the Trans Pacific and Trans Atlantic routes). These costs only include the transport costs, not the handling costs.

Table B.1: Design vessels characteristics

Container ship characteristics					
Vessel type	Capacity [TEU]	Length [m]	Beam [m]	Draught [m]	Costs [USD/TEU]
Fully Cellular	2,500	215.0	20.0	10.0	200
Panamax	3,400	250.0	32.0	12.5	180
Panamax Max	4,500	290.0	32.0	12.5	170
Post Panamax I	6,000	300.0	40.0	13.0	150
Post Panamax II	8,500	340.0	43.0	14.5	140
New-Panamax	12,500	366.0	49.0	15.2	120
VLCS	15,000	397.0	56.0	15.5	110
ULCS	21,000	400.0	59.0	16.0	100

Figure B.1 presents the ocean transport costs used for three design vessels defining the design scenarios. *Note:* The characteristics of the *Post-Panamax I* is in the specification of the design vessels referred to as *Panamax*.

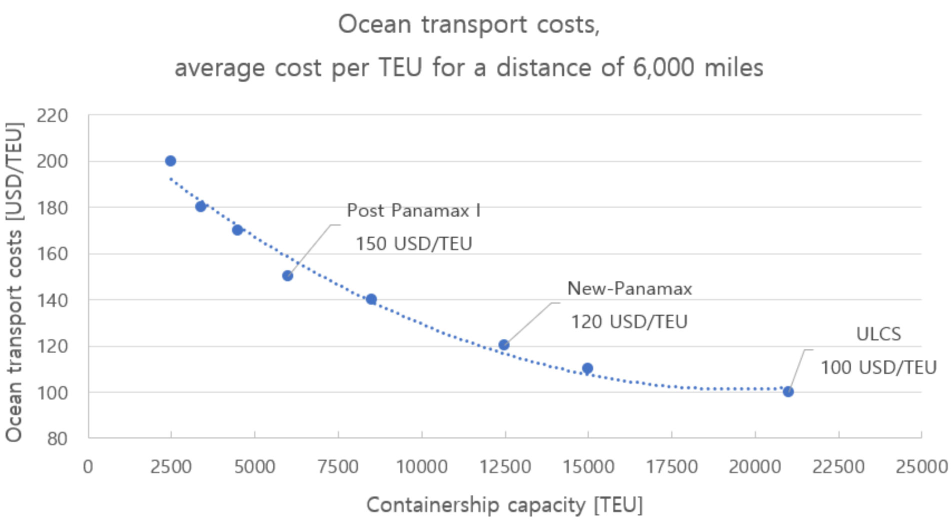

Figure B.1: Ocean transport costs used for the design scenarios, data obtained from Rodrigue et al. (2016)

C
Port system elements

This appendix addresses the design of the port system elements. The methods to determine the dimensions and the number of elements of the container terminals are already described by Koster (2019). Therefore, this appendix focuses on the access channel for the ocean-going vessels, the waterway transport link and the fixed infrastructure link. The method to design the access channel and the waterway transport link are the same. Consequently, only the method to determine the dimensions and costs of the access channel (Section C.1) and the bridge (Section C.2) are described.

C.1. Access channel

The access channel is the waterway linking the turning circle inside a port with deep water. According to PIANC (2014), the design parameters are the length of the manoeuvring area, width and depth. In this section, the method to determine the required width and depth of the access channel is explained. The length of the manoeuvring is excluded since the breakwater design is excluded as well.

C.1.1. Access channel width

Since a ship makes a sinusoidal track, a basic manoeuvring lane width (W_{bm}) of 1.5 times the beam of the design vessel is applied for container vessels (PIANC, 2014, Table 3.4). Additional widths ($\sum W_i$) are required for the effects of wind, current and waves and the lack of visibility and the type of cargo. Furthermore, additional width is required depending on the type of channel bank (W_b) and for passing distance (W_p). Equation C.1 describes the overall bottom width of the access channel for two-way traffic, according to PIANC (2014, eq. 3.4), since only two-way traffic is considered. The guidelines apply to a tidal range below 4 m.

$$W = 2 \cdot \left(W_{bm} + W_b + \sum W_i \right) + W_p \tag{C.1}$$

The additional widths ($\sum W_i$) to account for the environmental and navigation effects, according to (PIANC, 2014, p.87, Table 3.5), are listed below. These values are used as default values by the investment simulation.

- Vessel speed: 0.0 B for moderate vessel speeds
- Prevailing cross-wind: 0.4 B for moderate prevailing cross-wind
- Prevailing cross-current: 0.7 B for moderate prevailing cross-currents (open water)
- Prevailing longitudinal current: 0.1 B for moderate prevailing longitudinal currents
- Beam and stern quartering wave height: 0.5 B for wave heights between 1 m - 3 m
- Aids to navigation: 0.2 B for good aids to navigation
- Seabed characteristics: 0.1 B for smooth and soft bottom surfaces

- Depth of the waterway: 0.1 B for a moderate waterway depth to vessel draught ratio
- Cargo hazard: 0.0 B since container vessels do not contain hazardous loads

The additional width to account for the bank clearance depends on the type of channel bank (W_b) (PIANC, 2014, p.88, Table 3.6).

- Bank clearance: 0.5 B for sloping channel edges

The additional width to account for the passing distance in two-way traffic (W_p) depends on the vessel speed (PIANC, 2014, p.89, Table 3.7).

- Passing distance: 1.6 B for moderate vessel speeds

C.1.2. Access channel depth

The required depth of the access channel is determined by:

1. the draught of the design vessel;
2. the ship-related factors;
3. the water level; and
4. the channel bottom factors.

These factors are represented in the equation for the guaranteed depth (eq. C.2) (Ligteringen, 2017, p.117, eq. 5.12). For the concept design no tidal window is applied and the gross under keel clearance defaults are set at s_{max} = 0.5 m, z = $H_s/2$ and h_{net} = 0.5 m for a sandy bottom (see Appendix D).

$$h_{gd} = D - h_T + s_{max} + z + h_{net} \quad \text{(C.2)}$$

where:

D : draught design vessel
h_T : tidal elevation above reference level (= 0.0 m)
s_{max} : maximum sinkage due to squad, including dynamic trim (= 1.0 m)
z : vertical motion due to wave response ($H_s/2$)
h_{net} : net keel clearance (= 0.5 m)

C.1.3. Channel dredging costs

The default values for the determination of the dredging costs are listed in Appendix D.7. The capital dredging costs are equal to the capital dredging volume times the sum of the capital dredging rate (7.0 USD/m3) and the infill dredging rate (5.5 USD/m3). The infill dredging concerns the additional dredging during construction and is assumed to be equal to the capital dredging volume. The maintenance dredging costs are equal to the capital dredging volume times the annual maintenance percentage (10%) times the maintenance dredging rate (4.5 USD/m3). The (de)mobilisation costs of dredging vessels and pipelines are excluded.

C.2. Bridge

In order to estimate the construction costs of a bridge for the offshore-onshore port system with a fixed infrastructure link, a generic high-level unit rate needs to be specified. Table C.1 presents an overview of relevant reference cross-sea bridges and large river bridges to determine the unit rates. Figure C.1 presents the analysis of i) the total costs, ii) the costs per meter and iii) the costs per squared meter over the length and width of the bridges.

Bridge cost rate estimation												
Name	Country	Type	Length [m]	Width [m]	Lanes*	Tracks*	Modality	Year	Total costs	Costs per m	Costs per m²	Source
Padma Bridge	Bangladesh	Bridge	6,150	18.1	2	0	Road	2020	$ 1,421,831,502	$ 231,200	$ 12,770	[1]
Donghai Bridge Shanghai	China	Bridge	31,500	31.5	3	0	Road	2005	$ 1,501,272,265	$ 47,700	$ 1,510	[2]
Jiaozhou Bay Bridge	China	Bridge	42,500	35.0	3	0	Road	2011	$ 2,108,905,852	$ 49,600	$ 1,420	[3]
Hangzhou Bay Bridge	China	Bridge	35,600	33.0	3	0	Road	2008	$ 1,500,000,000	$ 42,100	$ 1,280	[4]
King Fahd Causeway	Bahrain - Saudi Arabia	Bridge	25,000	23.0	2	0	Road	1986	$ 800,000,000	$ 32,000	$ 1,390	[5]
Kacchi Dargah–Bidupur Bridge	India	Bridge	9,760	-	3	0	Road	2021	$ 483,337,329	$ 49,500	$ -	[6]
Bogibeel Bridge	India	Bridge	4,950	-	3	2	Road/Rail	2015	$ 774,025,974	$ 156,400	$ -	[7]
Digha–Sonpur Bridge	India	Bridge	4,550	10.0	2	2	Road/Rail	2003	$ 194,805,195	$ 42,800	$ 4,280	[8]
Jintang Bridge	China	Bridge	26,540	24.5	2	0	Road	2009	$ 1,800,000,000	$ 67,800	$ 2,770	[9]
Runyang Yangtze River Bridge	China	Bridge/Viaduct	35,660	39.2	3	0	Road	2005	$ 902,000,000	$ 25,300	$ 650	[10]
Bangabandhu Bridge	Bangladesh	Bridge	4,630	18.8	2	2	Road/Rail	1998	$ 696,000,000	$ 150,300	$ 8,000	[11]
Sultan Abdul Halim Muadzam Shah Bridge	Malaysia	Bridge	24,140	-	2	0	Road	2008	$ 1,200,000,000	$ 49,700	$ -	[12]
East Bridge	Denmark	Bridge	6,760	31.0	2	1	Road	1998	$ 950,000,000	$ 140,500	$ 4,530	[13]
Confederation Bridge	Canada	Bridge	12,900	11.0	2	0	Road	1997	$ 1,000,000,000	$ 77,500	$ 7,050	[14]
Vasco da Gama Bridge	Portugal	Bridge	12,345	30.0	4	0	Road	1998	$ 1,285,000,000	$ 104,100	$ 3,470	[15]
	Averages		**20,899**	**25.6**	**2.7**					**$ 76,447.06**	**$ 2,962.35**	

Table C.1: Reference bridge construction costs *Source*: footnotes at next page

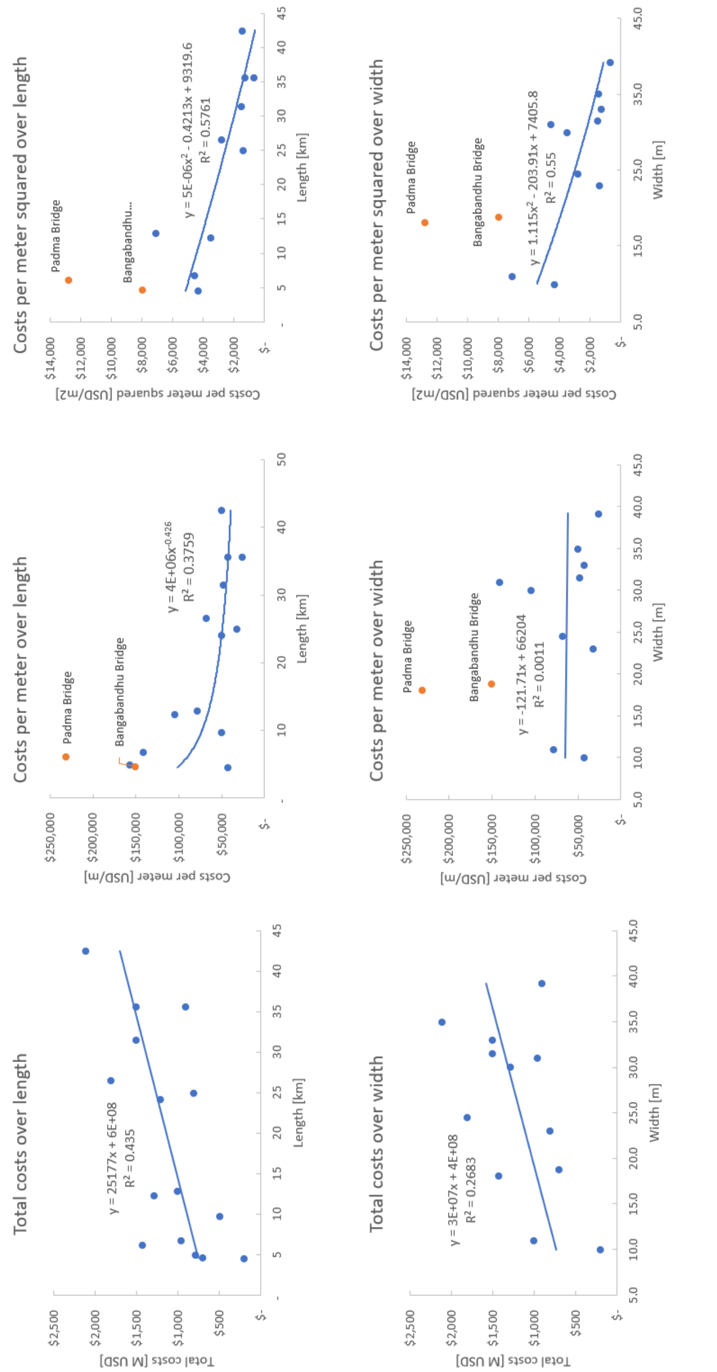

Figure C.1: Analysis of the bridge construction costs over the length and width of the bridges as listed in Table C.1

Considering the case study of Payra Port, Royal HaskoningDHV used a rate of $ 100,000 per meter for the static infrastructure alternative. The analysis shows two outliers in both the cost per meter over length and width and the cost meter squared over length and width. These are the Padma Bridge and Bangabandhu Bridge, both located in Bangladesh. After excluding these two bridges, the relation between the costs per meter and the length of the bridge is used. Figure C.2 presents this relation.

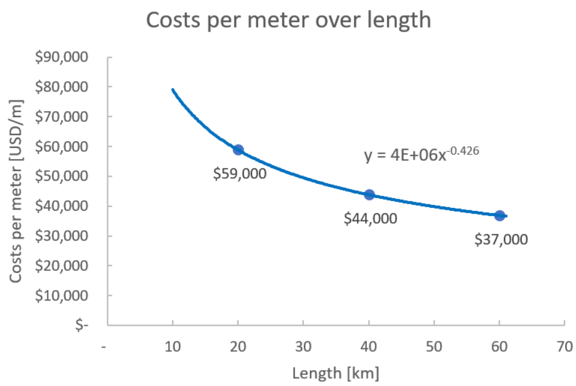

Figure C.2: Bridge construction unit rates

The applied construction rates, according to the offshore distances of the specified design scenarios, are shown in Table C.2. These rates are not related to the number of lanes, as this appears to be no main driver of the costs. The assumption is made that the capacity of the bridge is not a limiting factor since the Donghai Bridge includes three lanes in each direction for a throughput of more than 13.5 million TEUs.

Table C.2: Bridge construction unit rates

Bridge construction rates	
Length	Rate [/m]
20 km	$ 59,000
40 km	$ 44,000
60 km	$ 37,000

Table C.3: Conversion rates

Date	12/03/2020
Curency	Rate to EUR
EUR	€ 1.00
USD	$ 1.12
CNY	¥ 7.86
INR	₹ 83.42
BDT	95.55৳
DKK	7.47 kr.

Table C.3 shows the rates applied for the conversion of the local currencies of the sources as indicated in Table C.1[1-15].

[1] https://en.wikipedia.org/wiki/Padma_Bridge
[2] http://people.bath.ac.uk/jjo20/conference2/2008/SONG%20PAPER%2021.pdf
[3] https://www.straitstimes.com/world/longest-bridges-over-water-in-the-world
[4] https://www.straitstimes.com/world/longest-bridges-over-water-in-the-world
[5] https://www.straitstimes.com/world/longest-bridges-over-water-in-the-world
[6] https://en.wikipedia.org/wiki/Kacchi_Dargah-Bidupur_Bridge
[7] https://www.quora.com/How-much-did-it-cost-to-build-Bogibeel-bridge-in-Assam
[8] https://wiki2.org/en/Digha-Sonpur_Bridge
[9] https://en.wikipedia.org/wiki/Jintang_Bridge
[10] https://en.wikipedia.org/wiki/Runyang_Yangtze_River_Bridge
[11] https://en.wikipedia.org/wiki/Bangabandhu_Bridge
[12] http://straits-design.com.my/sultan-abdul-halim-muadzam-shah-bridge/
[13] https://www.storebaelt.dk/english/bridge
[14] https://en.wikipedia.org/wiki/Confederation_Bridge
[15] https://www.roadtraffic-technology.com/projects/vasco-da-gama/

D
Port element characteristics

This appendix provides an overview of the *port element characteristics* introduced in Section 3.2.4. The default input parameters are listed per *port system element*. Most of the data is obtained by Koster (2019), design guidelines (e.g. PIANC) and expert knowledge of Royal HaskoningDHV (RHDHV).

D.1. Quay wall

Table D.1 shows the default container ship quay wall data.

Table D.1: Quay wall defaults

Element: Quay wall				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years		Koster, 2019
lifespan	50	years		Koster, 2019
mobilisation_min	$ 2,500,000	USD		Koster, 2019
mobilisation_perc	2%	-		RHDHV
maintenance_perc	1%	-		RHDHV
insurance_perc	1%	-		RHDHV
berthing_gap	15	m		PIANC, 2014, p. 98
freeboard	4	m		Koster, 2019
Gijt_constant	$753.24	USD/m	1.0 EUR = 1.12 USD	J. de Gijt, 2011, Figure 2
Gijt_coefficient	1.2729	-		J. de Gijt, 2011, Figure 2
max_sinkage	0.5	m		Koster, 2019
wave_motion	0.5	m		Koster, 2019
safety_margin	0.5	m		Koster, 2019
apron_width	100	m		PIANC, 2014, p. 62
apron_pavement	125	USD/m^2		Koster, 2019

D.2. Berths

Table D.2 shows the default container ship berth data.

Table D.2: Berth defaults

Element: Berth				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years		Koster, 2019
max_cranes	3	-	STS cranes per berth	RHDHV

D.3. STS crane

Table D.3 shows the default STS crane data.

Table D.3: STS crane defaults

Element: Crane				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years		Koster, 2019
lifespan	40	years		Koster, 2019
unit_rate	$ 10,170,000	USD		RHDHV
mobilisation_perc	15%	-		RHDHV
maintenance_perc	2%	-		RHDHV
insurance_perc	1%	-		RHDHV
consumption	8	kWh		Koster, 2019
crew_per_shift	5.5	-	1.5 crane driver, 2.0 quay staff, 2.0 twistlock handlers	Koster, 2019
lifting_capacity	1.6	TEU/lift	TEU factor	RHDHV
hourly_cycles	25	cycles/hr		RHDHV
effectiveness_factor	1.0	lift/cycle		RHDHV

D.4. Barge quay wall

Table D.4 shows the default barge quay wall data.

Table D.4: Barge quay wall defaults

Element: Barge quay wall				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years		Koster, 2019
lifespan	50	years		Koster, 2019
mobilisation_min	$ 1,000,000	USD		Koster, 2019
mobilisation_perc	2%	-		RHDHV
maintenance_perc	1%	-		RHDHV
insurance_perc	1%	-		RHDHV
berthing_gap	15	m		PIANC, 2014, p. 98
freeboard	4	m		Koster, 2019
Gijt_constant	$753.24	USD/m	1.0 EUR = 1.12 USD	J. de Gijt, 2011, Figure 2
Gijt_coefficient	1.2729	-		J. de Gijt, 2011, Figure 2
max_sinkage	0.5	m		Koster, 2019
wave_motion	0.5	m		Koster, 2019
safety_margin	0.5	m		Koster, 2019
apron_width	50	m		PIANC, 2014, p. 62
apron_pavement	$125	USD/m^2		Koster, 2019

D.5. Barge berths

Table D.5 shows the default barge berth data.

Table D.5: Barge berth defaults

Element: Barge berth				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years		
max_cranes	1.3	-	cranes per berth	RHDHV

D.6. Barge crane

Table D.6 shows the default barge crane data.

Table D.6: Barge crane defaults

Element: Barge crane				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years		-
lifespan	40	years		-
unit_rate	$ 6,780,000	USD		RHDHV
mobilisation_perc	15%	-		RHDHV
maintenance_perc	2%	-		RHDHV
insurance_perc	1%	-		RHDHV
consumption	4	kWh		RHDHV
crew_per_shift	1.5	-	1.5 crane driver	Koster, 2019
lifting_capacity	1.6	TEU/lift	TEU factor	RHDHV
nom_crane_productivity	15	cycles/hr		RHDHV
utilisation	0.90	-		RHDHV
efficiency	0.75	-		RHDHV
handling_time_ratio	0.90	-	handling time to	RHDHV
peak_factor	1.1	-		RHDHV

D.7. Access channel

Table D.7 shows the default access channel data.

Table D.7: Access channel defaults

Element: Acces Channel				
Element defaults	Values	Unit	Description	Source
capital_dredging_rate	$7.0	USD/m^3		RHDHV
infill_dredging_rate	$5.5	USD/m^3		RHDHV
maintenance_dredging_rate	$4.5	USD/m^3		RHDHV
maintenance_perc	10%	-		RHDHV
insurance_perc	1%	-		RHDHV

D.8. Bridge

Table D.8 shows the default bridge data.

Table D.8: Bridge defaults

Element: Bridge				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years	*simplified*	-
lifespan	50	years		-
construction_rate_20	$59,000,000	USD/km	rate if length is 20 km	Appendix C
construction_rate_30	$50,000,000	USD/km	rate if length is 30 km	Appendix C
construction_rate_40	$44,000,000	USD/km	rate if length is 40 km	Appendix C
construction_rate_50	$40,000,000	USD/km	rate if length is 50 km	Appendix C
construction_rate_60	$37,000,000	USD/km	rate if length is 60 km	Appendix C
maintenance_perc	2.5%	-		RHDHV
insurance_perc	1.0%	-		RHDHV

D.9. Island reclamation

Table D.9 shows the default island reclamation data.

Table D.9: Island reclamation defaults

Element: Island reclamation				
Element defaults	Values	Unit	Description	Source
delivery_time	2	years	*simplified*	-
lifespan	50	years		-
reclamation_sand	$12.50	USD/m^3		RHDHV
maintenance_perc	1%	-		RHDHV
soil_improvement	$40	USD/m2		RHDHV
heavy_duting_paving	$100	USD/m^2		RHDHV
bed_protection	$1,900	USD/m		RHDHV
bank_protection	$12,500	USD/m		RHDHV

D.10. Revetment

Table D.10 shows the default revetment data.

Table D.10: Revetment defaults

Element: Revetment				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years	*simplified*	-
lifespan	50	years		-
revetment_rate	$180,000	USD/m		RHDHV
maintenance_perc	1%	-		RHDHV

D.11. Tractor-trailer

Table D.11 shows the default tractor-trailer data.

Table D.11: Tractor-trailer defaults

Element: Tractor Trailer				
Element defaults	Values	Unit	Description	Source
delivery_time	0	years		
lifespan	10	years		
unit_rate	$ 113,000	USD		RHDHV
mobilisation	$ 1,000	USD		RHDHV
maintenance_perc	10%	-		RHDHV
insurance_perc	1%	-		RHDHV
fuel_consumption	2.0	l	per box move	RHDHV
crew_per_shift	1	-		Koster, 2019
salary	$ 30,000	USD		Koster, 2019
utilisation	0.8	-		Koster, 2019
productivity	1.0	-		Koster, 2019
required	5	-	typical 3 - 6	PIANC, 2014, p. 58
non_essential_moves	1.2	-		Koster, 2019

D.12. Container

Table D.12 shows the default container data.

Table D.12: Container defaults

Element: Container				
Element defaults	Values	Unit	Description	Source
Laden				
teu_factor	1.60	-	TEU per container	All values from Koster, 2019
dwell_time	3	days	*default value	"
peak_factor	1.2	-		"
stack_occupancy	0.8	-		"
Reefer				
teu_factor	1.75	-	TEU per container	All values from Koster, 2019
dwell_time	3	days	*default value	"
peak_factor	1.2	-		"
stack_occupancy	0.8	-		"
Empty				
teu_factor	1.55	-	TEU per container	All values from Koster, 2019
dwell_time	10	days		"
peak_factor	1.2	-		"
stack_occupancy	0.7	-		"
OOG				
teu_factor	1.55	-	TEU per container	All values from Koster, 2019
dwell_time	4	days		"
peak_factor	1.2	-		"
stack_occupancy	0.9	-		"

D.13. Laden stacks

Table D.13 shows the default laden stack data.

Table D.13: Laden stack defaults

Element: Laden stacks				
Element defaults	Values	Unit	Description	Source
All stacks				
delivery_time	1	years		All values from Koster, 2019
lifespan	40	years		"
mobilisation	$ 50,000	USD		"
maintenance_perc	1%	-		"
pavement	200.00	m^2	*dummy*	"
drainage	50.00	m^2	*dummy*	"
household	0.10	-		"
digout_margin	1.20	-		"
reefer_factor	2.33	-		"
consumption	4.0	kWh	per activate reefer	"
reefer_rack	$3,500	USD		"
reefers_present	0.50	-	per reefer spot	"
RTG stack				
width	6	TEU		All values from Koster, 2019
height	5	TEU		"
length	30	TEU		"
capacity	900	TEU		"
gross_tgs	18.0	TEU	per groundslot	"
area_factor	2.04	m^2/TEU		"
RMG stack				
width	6	TEU		All values from Koster, 2019
height	5	TEU		"
length	40	TEU		"
capacity	1200	TEU		"
gross_tgs	18.67	TEU	per groundslot	"
area_factor	2.79	m^2/TEU		"
SC stack				
width	48	TEU		All values from Koster, 2019
height	4	TEU		"
length	20	TEU		"
capacity	3840	TEU		"
gross_tgs	26.46	TEU	per groundslot	"
area_factor	1.45	m^2/TEU		"
RS stack				
width	4	TEU		All values from Koster, 2019
height	4	TEU		"
length	20	TEU		"
capacity	320	TEU		"
gross_tgs	18.00	TEU	per groundslot	"
area_factor	3.23	m^2/TEU		"

D.14. Empty stacks

Table D.14 shows the default empty stack data.

Table D.14: Empty stack defaults

Element: Empty stacks				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years		All values from Koster, 2019
lifespan	40	years		"
mobilisation	$ 25,000	-		"
maintenance_perc	1%	-		"
pavement	200.00	m^2	*dummy*	"
drainage	50.00	m^2	*dummy*	"
household	1.05	-		"
digout_margin	1.05	-		"
width	8	TEU	TEU per container	"
height	6	TEU		"
length	10	TEU		"
capacity	480	TEU		"
gross_tgs	18.0	TEU	per grounslot	"
area_factor	2.04	m^2/TEU		"

D.15. Out of Gauge stacks

Table D.15 shows the default Out of Gauge (OOG) stack data.

Table D.15: OOG stack defaults

Element: OOG stacks				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years		All values from Koster, 2019
lifespan	40	years		"
mobilisation	$ 25,000	-		"
maintenance_perc	1%	-		"
pavement	200.00	m^2	*dummy*	"
drainage	50.00	m^2	*dummy*	"
width	10	TEU	TEU per container	"
height	1	TEU		"
length	10	TEU		"
capacity	100	TEU		"
gross_tgs	64.0	TEU	per grounslot	"
area_factor	1.05	m^2/TEU		"

D.16. Stack equipment

Table D.16 shows the default stack equipment data.

Table D.16: Stack equipment defaults

Element: Stack equipment				
Element defaults	Values	Unit	Description	Source
All stack equipment				
delivery_time	-	years		All values from Koster, 2019
lifespan	10	years		"
mobilisation	$5,000	USD		"
maintenance_perc	2%	-		"
insurance_perc	0%	-		"
Rubber tyred gantry (RTG)				
unit_rate	$1,400,000	USD	per unit	RHDHV
crew_per_shift	1	-		All values from Koster, 2019
salary	$50,000	USD		"
required	3	-	per stack	"
fuel_consumption	1.0	kWh		"
power_consumption	0.0	l	per box move	"
Rail mounted gantry (RMG)				
unit_rate	$2,500,000	USD	per unit	RHDHV
crew_per_shift	1	-		All values from Koster, 2019
salary	$50,000	USD		"
required	1	-	per stack	"
fuel_consumption	0.0	kWh		"
power_consumption	15.0	l	per box move	"
Straddle carrier (SC)				
unit_rate	$2,000,000	USD	per unit	RHDHV
crew_per_shift	1	-		All values from Koster, 2019
salary	$50,000	USD		"
required	5	-	per stack	"
fuel_consumption	0.0	kWh		"
power_consumption	30.0	l	per box move	"
Reach stacker (RS)				
unit_rate	$500,000	USD	per unit	RHDHV
crew_per_shift	2	-		All values from Koster, 2019
salary	$50,000	USD		"
required	4	-	per stack	"
fuel_consumption	1.0	kWh		"
power_consumption	0.0	l	per box move	"

D.17. Gate

Table D.17 shows the default gate data.

Table D.17: Gate defaults

Element: Gate data				
Element defaults	Values	Unit	Description	Source
delivery_time	1	years		All values from Koster, 2019
lifespan	15	years		"
mobilisation	$5,000	USD		"
maintenance_perc	2%	-		"
unit_rate	$30,000	USD	per gate	"
crew_per_shift	2	-		"
salary	$30,000	USD		"
canopy_rate	$250	USD/m^2	*dummy*	"
area	288.75	m2/TEU		PIANC, 2014
staff_gates	1	-		"
service_gates	1	-		"
design_capacity	0.98	-		"
exit_inspection_time	2	min		"
entry_inspection_time	2	min		"
peak_hour	0.1	-		"
peak_day	0.25	-		"
peak_factor	1.2	-		"
trucks_moves	0.75	-		"
operating_days	6.0	-		"
capacity	60			"

E

Results of the investment simulation

This chapter presents the results of the investment simulation in addition to Chapter 5.

E.1. Cost estimates

This section provides the cost estimates of the port system alternatives for the design scenarios, as described in Section 5.1.

Table E.1: PV of the costs of the port system alternatives for the specified design scenarios

Cost estimates ($M)		
Design vessel	Capacity	
Panamax	6,000 TEU	$ 3,888
New-Panamax	12,500 TEU	$ 4,850
ULCS	21,000 TEU	$ 5,672

(a) Alternative Onshore

Cost estimates ($M)		*Offshore-onshore distance*		
Design vessel	Capacity	20 km	40 km	60 km
Panamax	6,000 TEU	$ 4,393	$ 4,270	$ 4,440
New-Panamax	12,500 TEU	$ 4,602	$ 4,144	$ 4,318
ULCS	21,000 TEU	$ 4,769	$ 4,053	$ 4,226

(b) Alternative Barge

Cost estimates ($M)		*Offshore-onshore distance*		
Design vessel	Capacity	20 km	40 km	60 km
Panamax	6,000 TEU	$ 5,143	$ 5,746	$ 6,569
New-Panamax	12,500 TEU	$ 5,380	$ 5,721	$ 6,447
ULCS	21,000 TEU	$ 5,570	$ 5,530	$ 6,356

(c) Alternative Bridge

E.2. Port system design

This section provides the port system designs, as introduced in Section 3.2. The port system designs of the first 10 years of the life cycle, for the medium growth in demand scenario (6.7% annually) and with 25% of the containers transported directly to the hinterland are presented to illustrate the functionality of the investment simulation.

E.2.1. Alternative Onshore

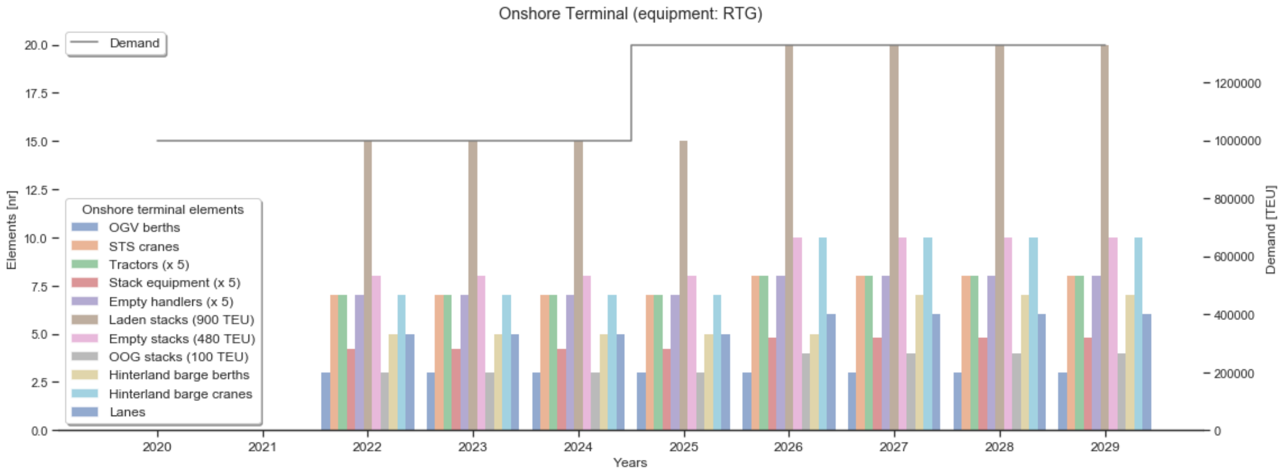

Figure E.1: Alternative Onshore: Terminal elements

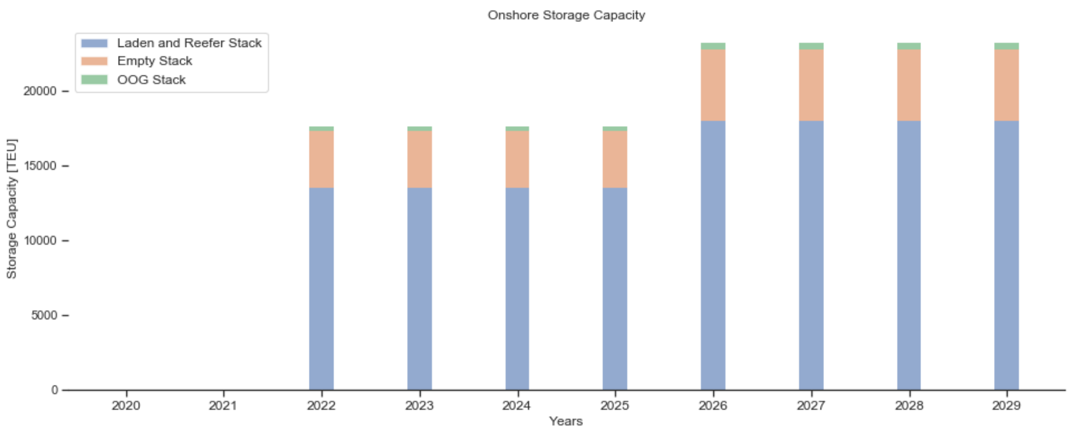

Figure E.2: Alternative Onshore: Storage capacity over the years

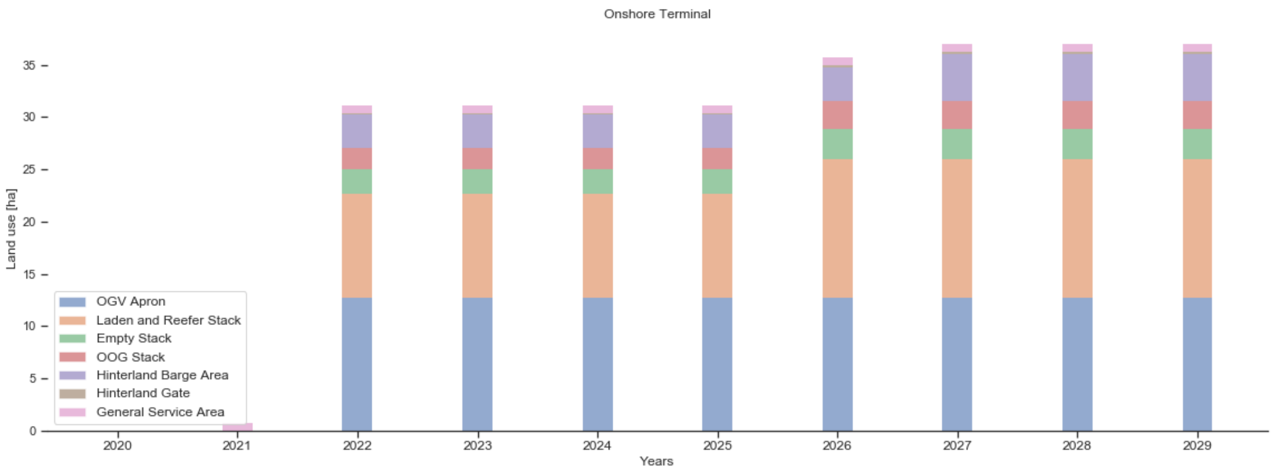

Figure E.3: Alternative Onshore: Land use over the years

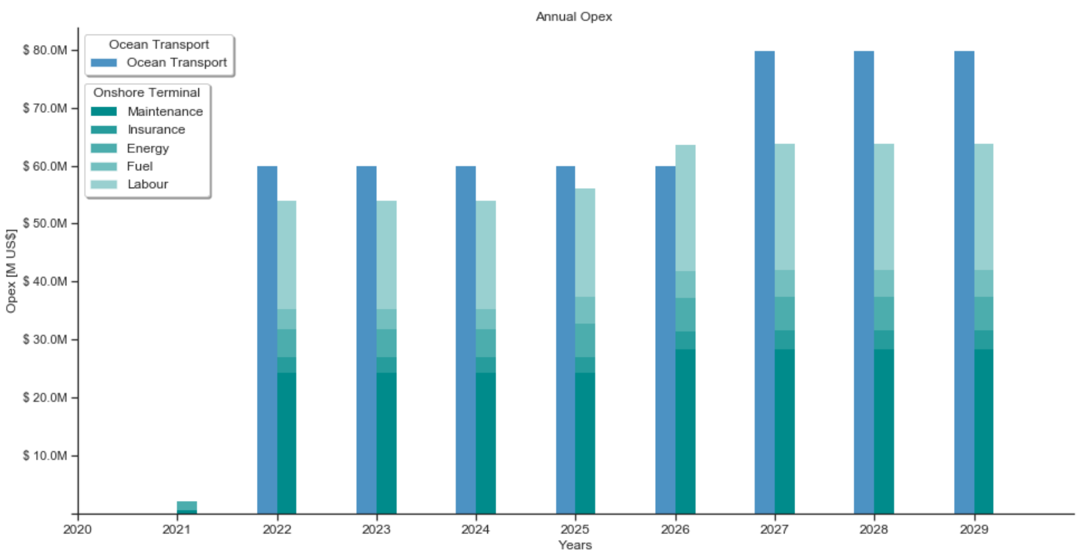

Figure E.4: Alternative Onshore: Annual Opex over the years

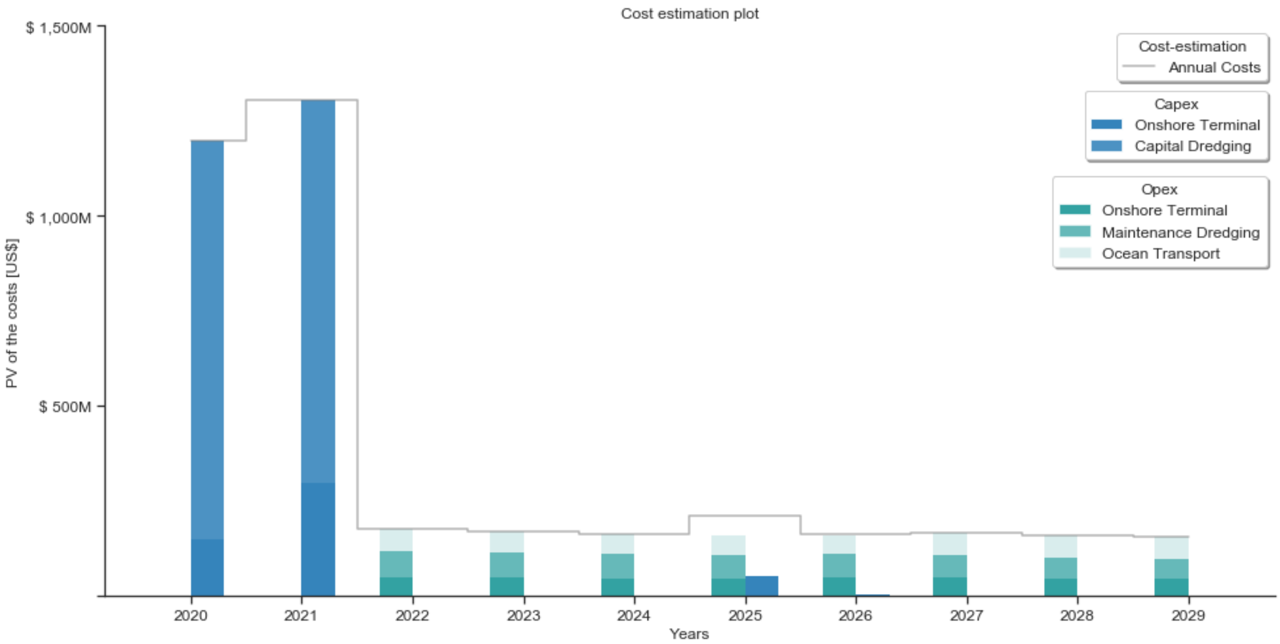

Figure E.5: Alternative Onshore: Cost estimate plot over the years

E.2.2. Alternative Barge

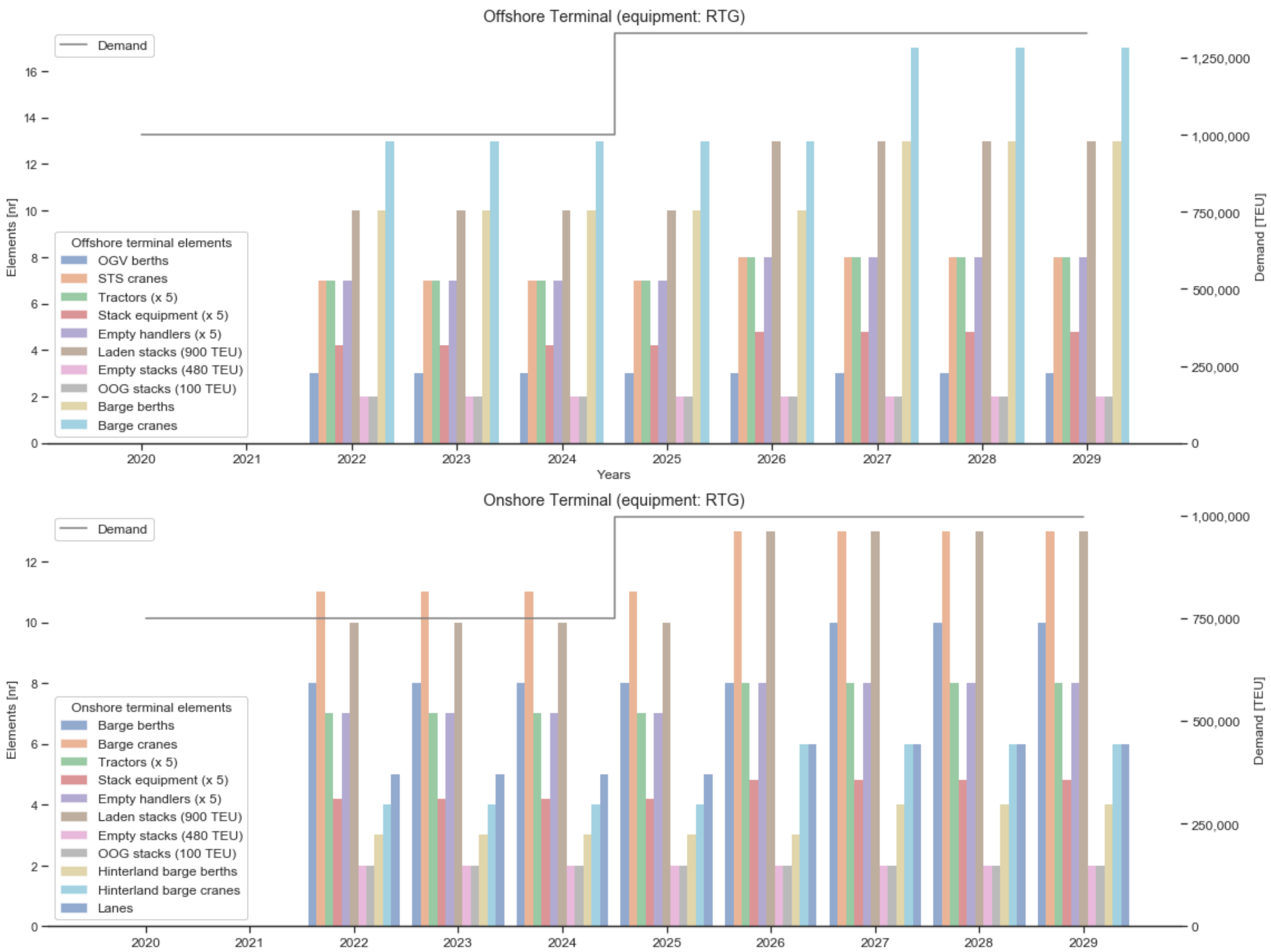

Figure E.6: Alternative Barge: Terminal elements

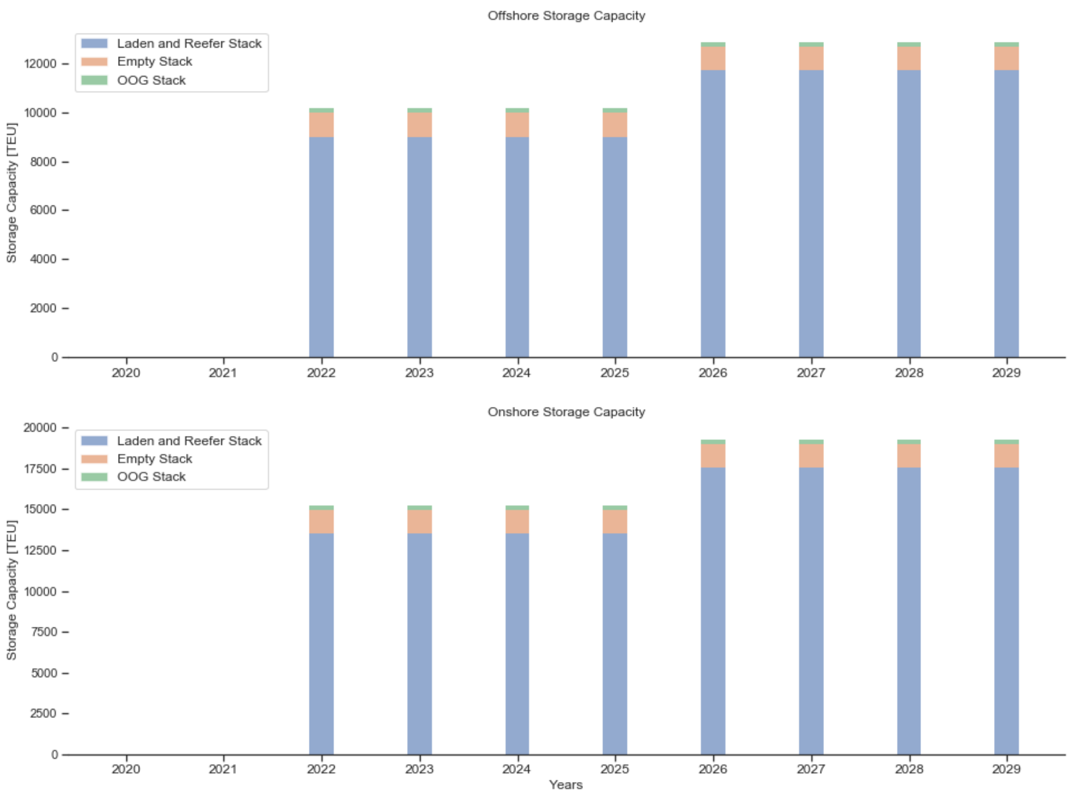

Figure E.7: Alternative Barge: Storage capacity over the years

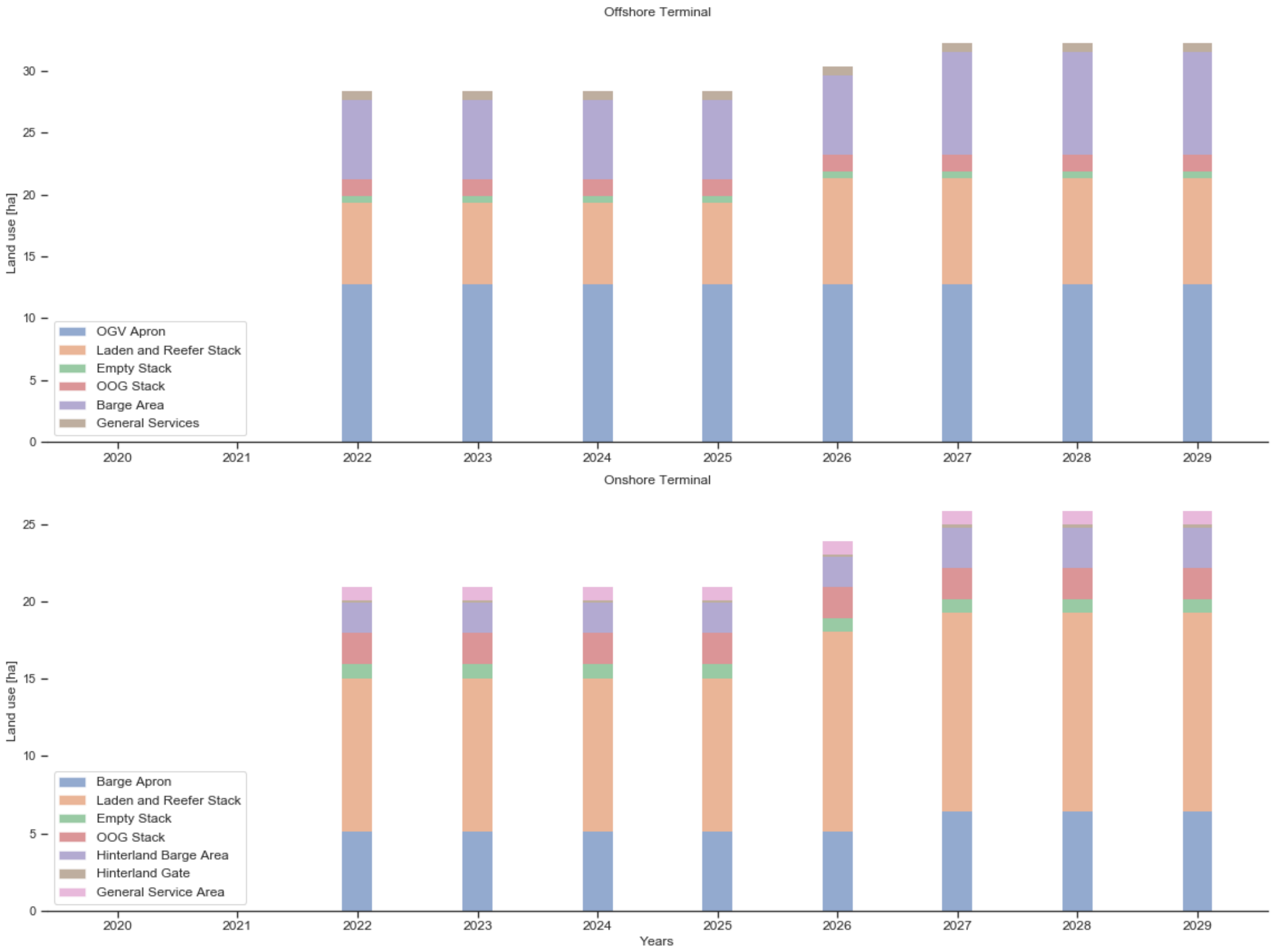

Figure E.8: Alternative Barge: Land use over the years

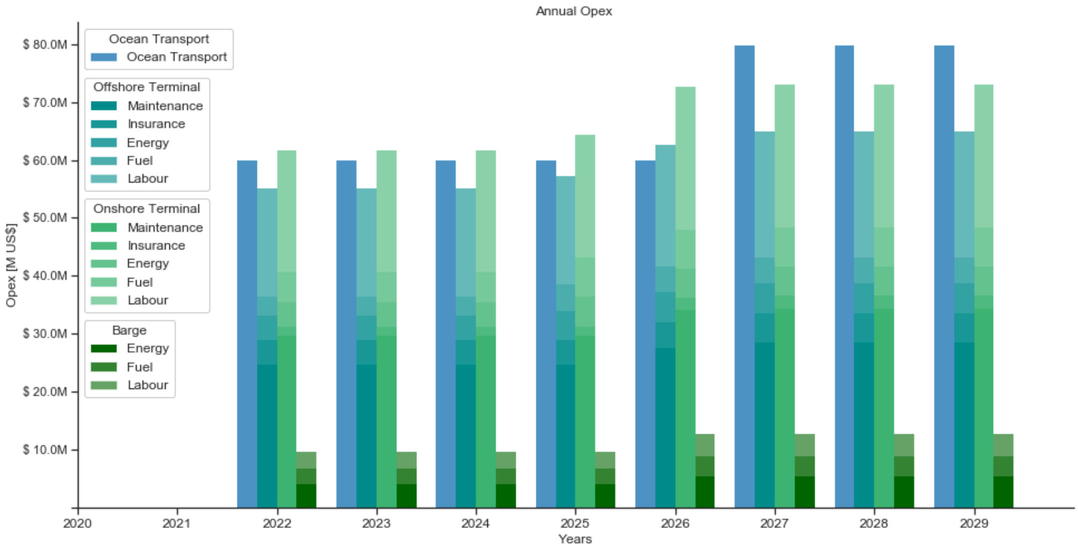

Figure E.9: Alternative Barge: Annual Opex over the years

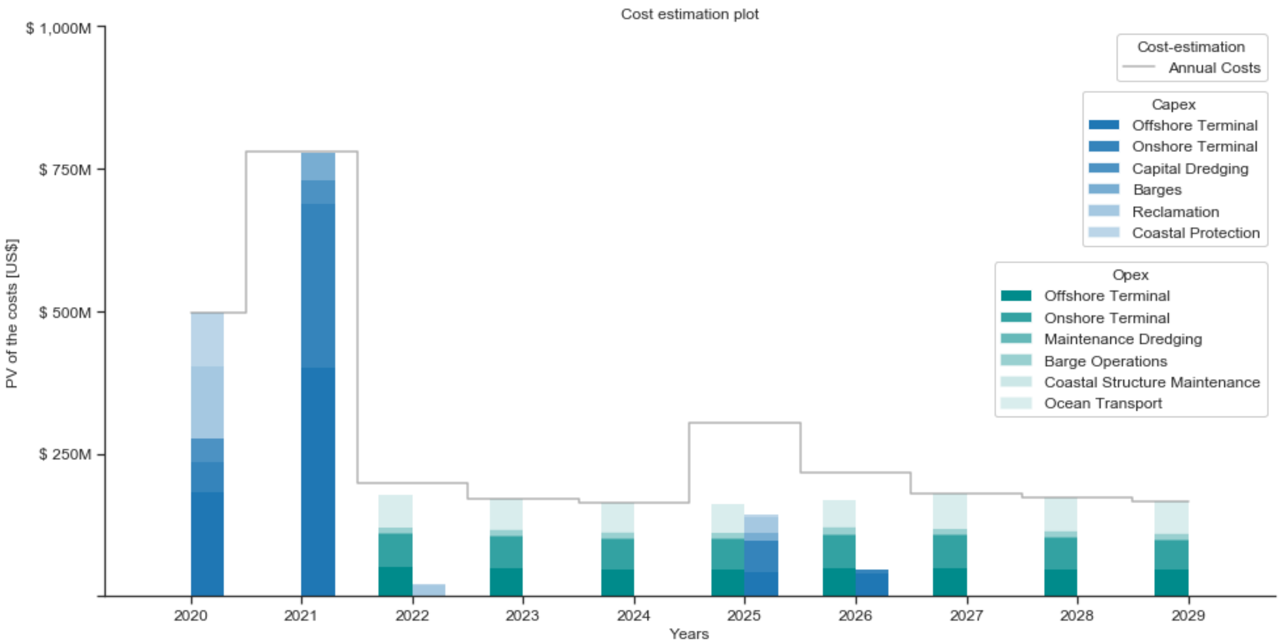

Figure E.10: Alternative Barge: Cost estimate plot over the years

E.2.3. Alternative Bridge

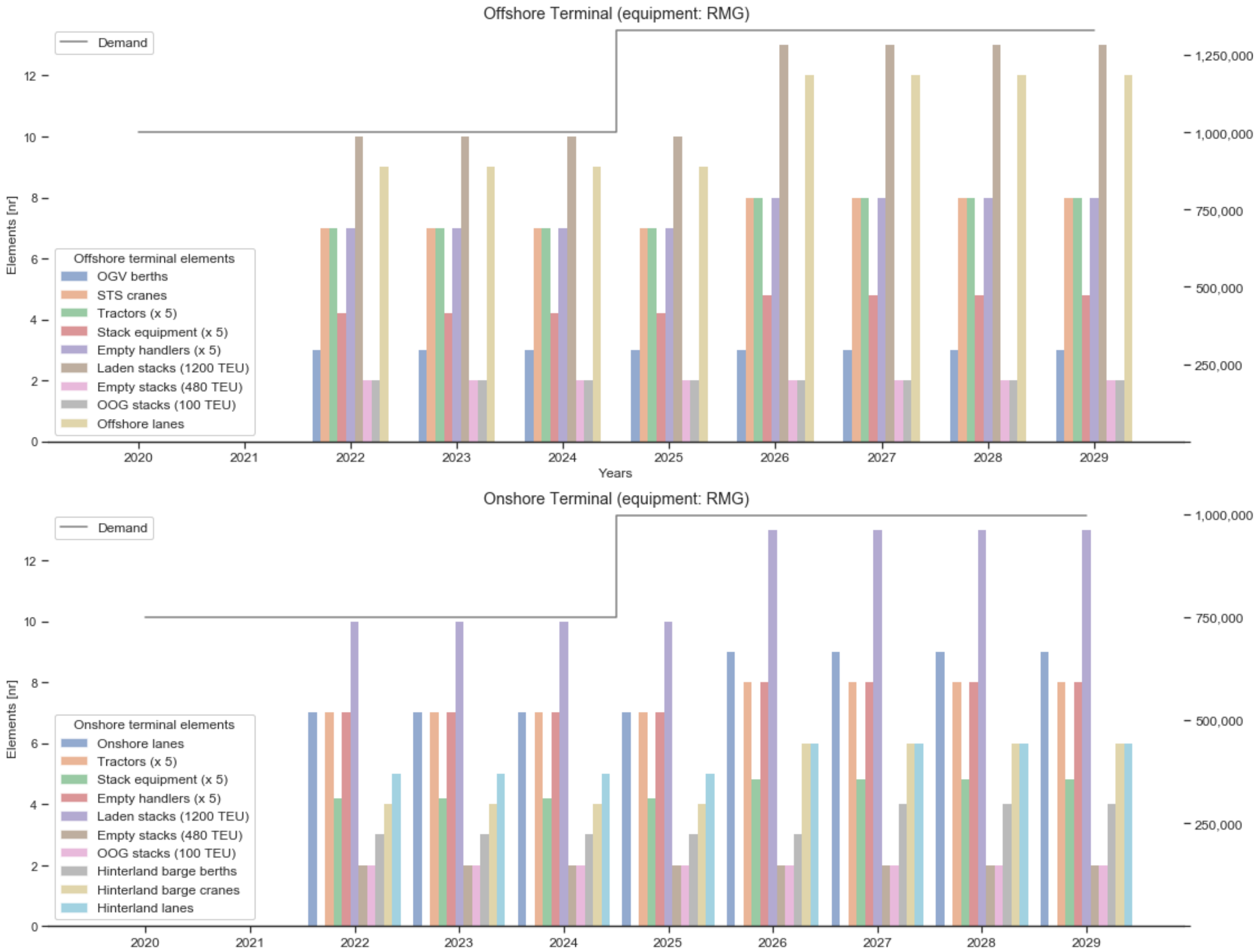

Figure E.11: Alternative Bridge: Terminal elements

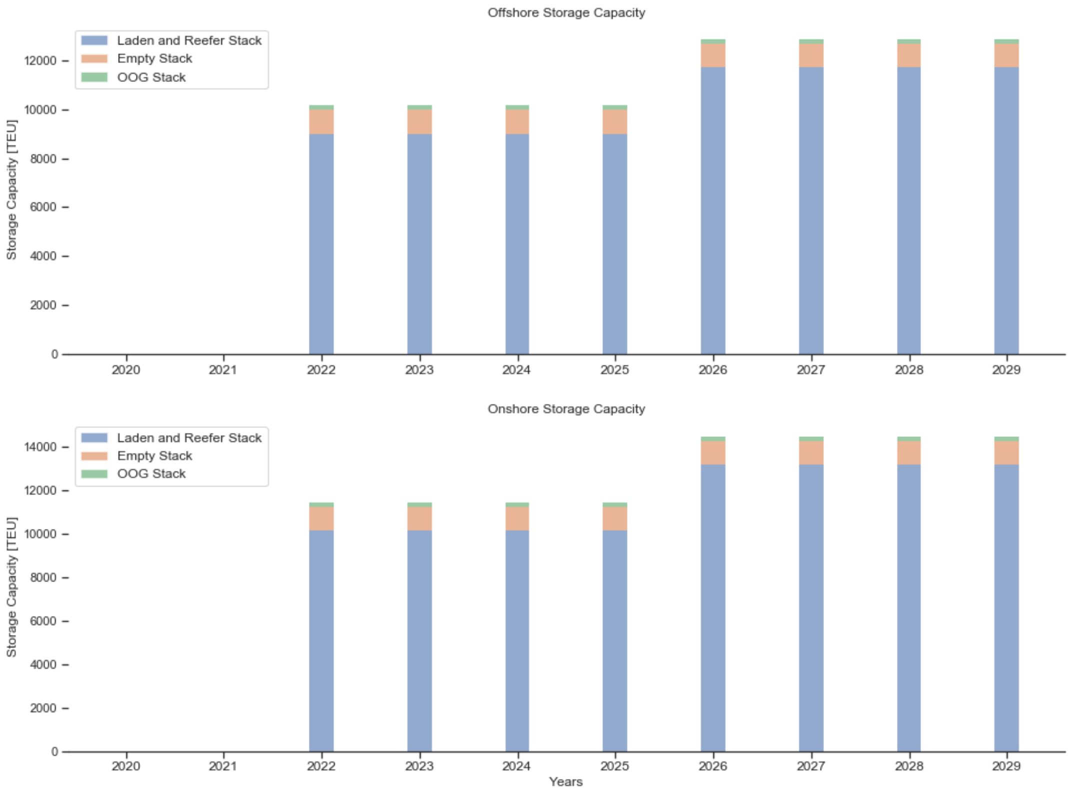

Figure E.12: Alternative Bridge: Storage capacity over the years

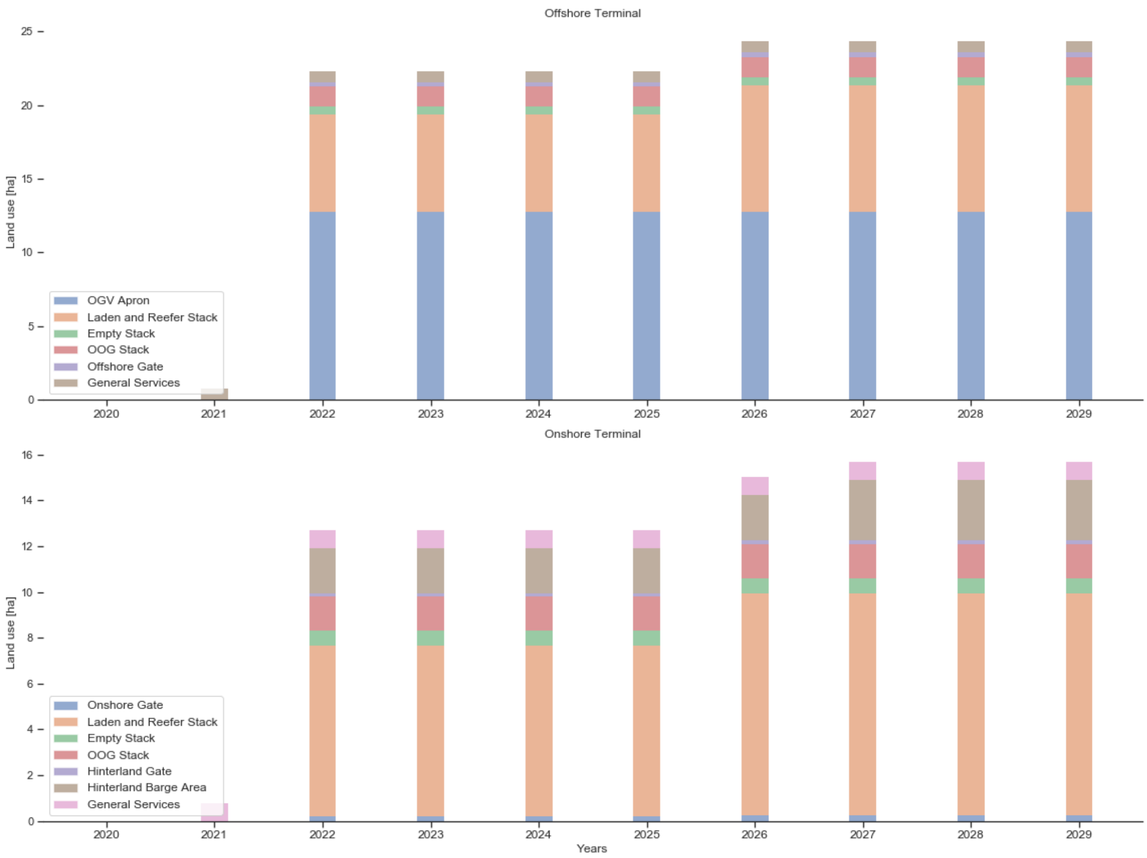

Figure E.13: Alternative Bridge: Land use over the years

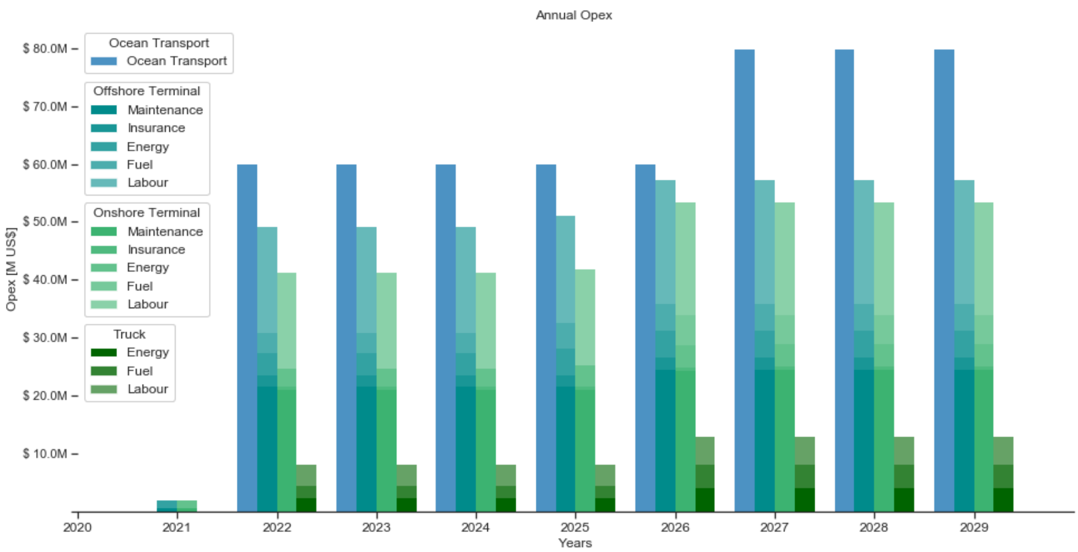

Figure E.14: Alternative Bridge: Annual Opex over the years

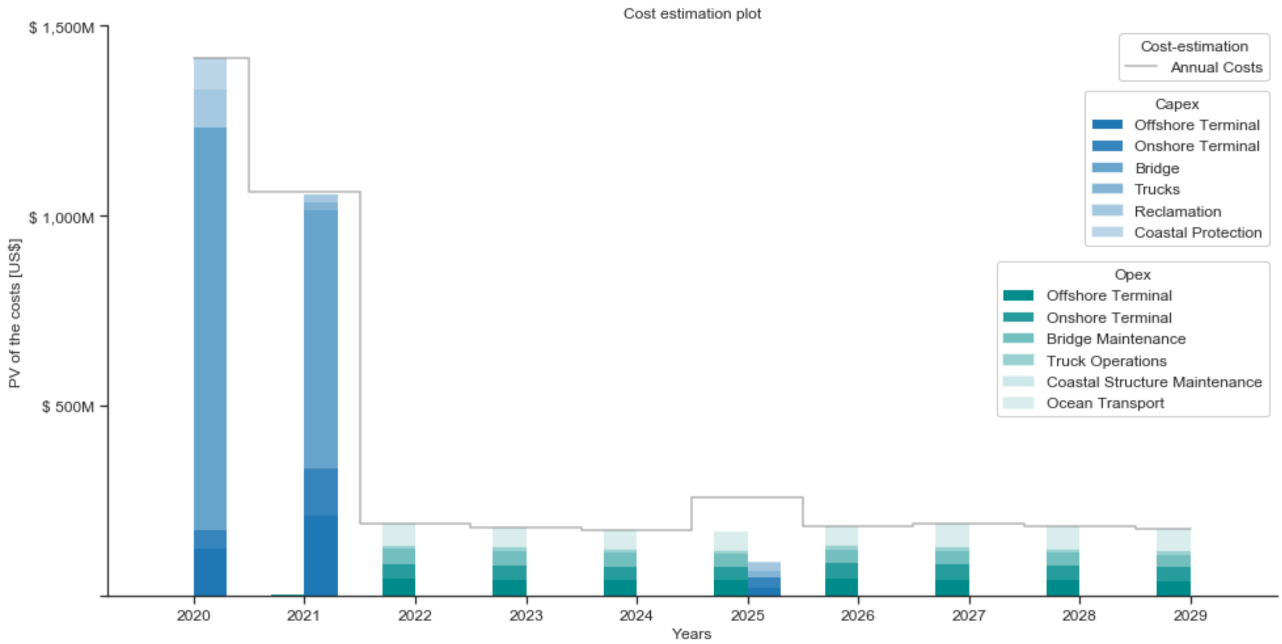

Figure E.15: Alternative Bridge: Cost estimate plot over the years

E.3. Cost estimates sensitivity analyses

This section presents the results of the investment simulation in addition to Section 5.2.

Demand: fixed volume over time ($M)				
Port system	-50%	*base*	+ 50 %	+ 100 %
Alternative Onshore	$ 4,022	$ 4,850	$ 5,758	$ 6,584
Alternative Barge	$ 2,356	$ 4,147	$ 6,062	$ 7,813
Alternative Bridge	$ 4,164	$ 5,624	$ 7,328	$ 8,916

(a) Demand: fixed volume over time

Demand: growth in volume over time ($M)				
Port system	*no growth*	low	medium	high
Alternative Onshore	$ 4,850	$ 5,274	$ 5,675	$ 6,059
Alternative Barge	$ 4,147	$ 5,142	$ 6,056	$ 6,935
Alternative Bridge	$ 5,624	$ 6,387	$ 6,935	$ 7,913

(b) Demand: growth over time

Bathymetry: slope of the foreshore ($M)			
Port system	gentle	average	steep
Alternative Onshore	$ 6,266	$ 4,850	$ 3,435
Alternative Barge	$ 4,361	$ 4,147	$ 4,611
Alternative Bridge	$ 5,947	$ 5,624	$ 5,869

(c) Bathymetry: slope of the foreshore

Bathymetry: shape of the foreshore ($M)			
Port system	0.50	0.70	0.90
Alternative Onshore	$ 4,850	$ 5,983	$ 7,115
Alternative Barge	$ 4,147	$ 4,169	$ 4,191
Alternative Bridge	$ 5,624	$ 5,624	$ 5,624

(d) Bathymetry: shape of the foreshore

Figure E.16: Cost estimates of the sensitivity analyses of the port system alternatives for design scenario 5

F

Results of the logistical simulation

This chapter presents the results of the logistical simulation in addition to Chapter 5.

Annual waiting time for downtime scenarios

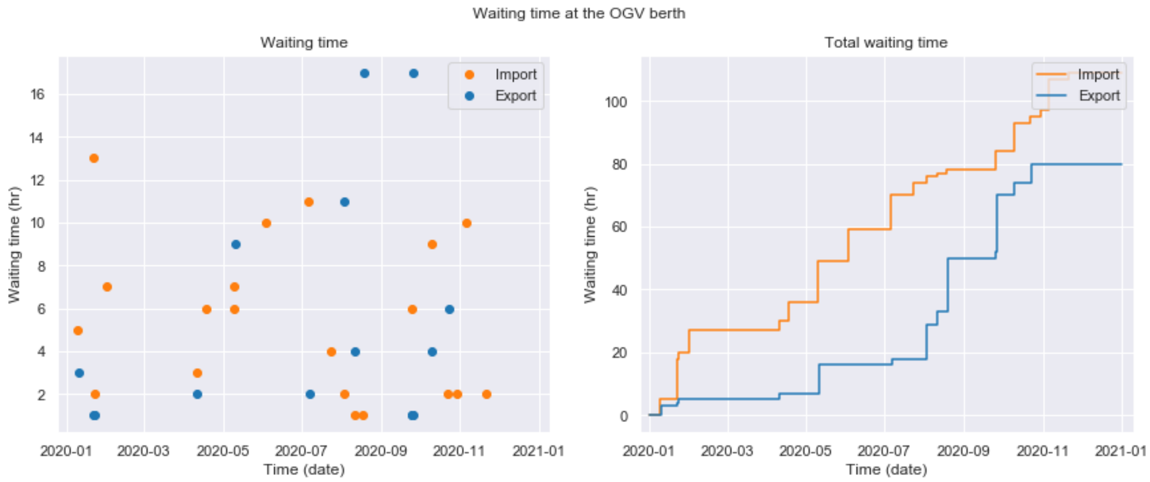

Figure F.1: Waiting time for downtime scenario: no downtime

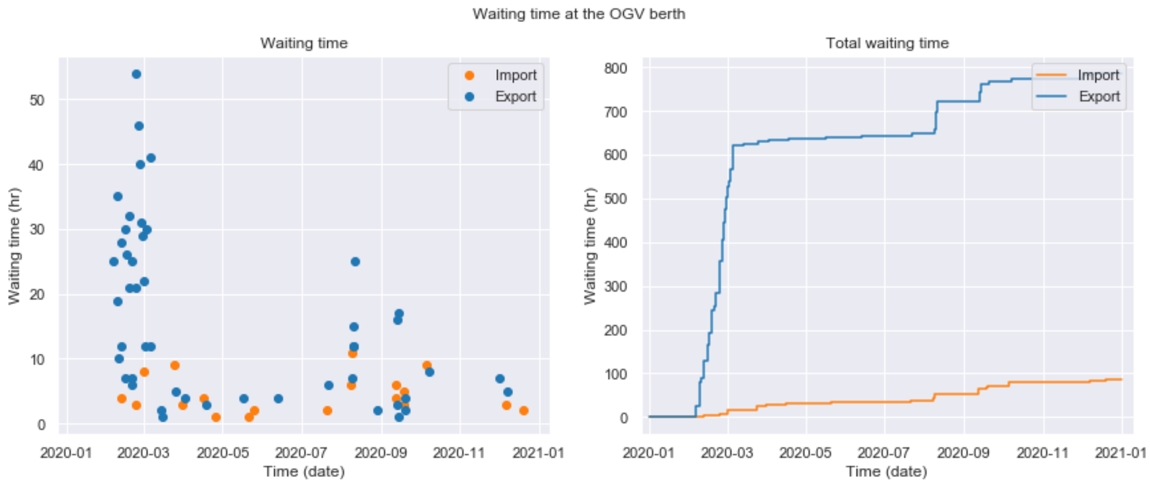

Figure F.2: Waiting time for downtime scenario: 3 days consecutive downtime

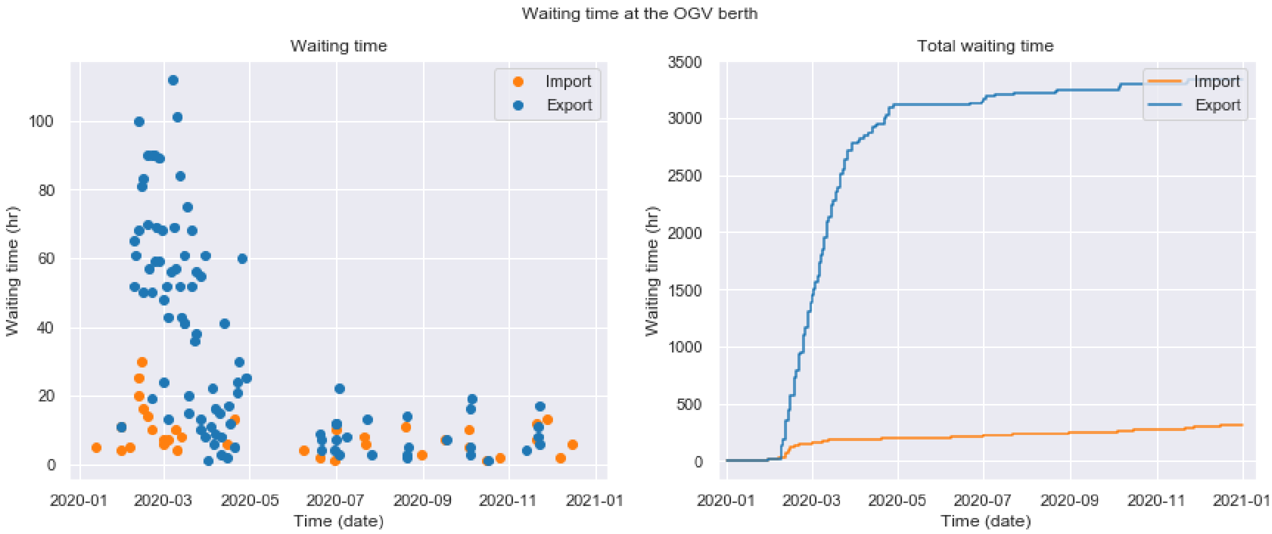

Figure F.3: Waiting time for downtime scenario: 6 days consecutive downtime

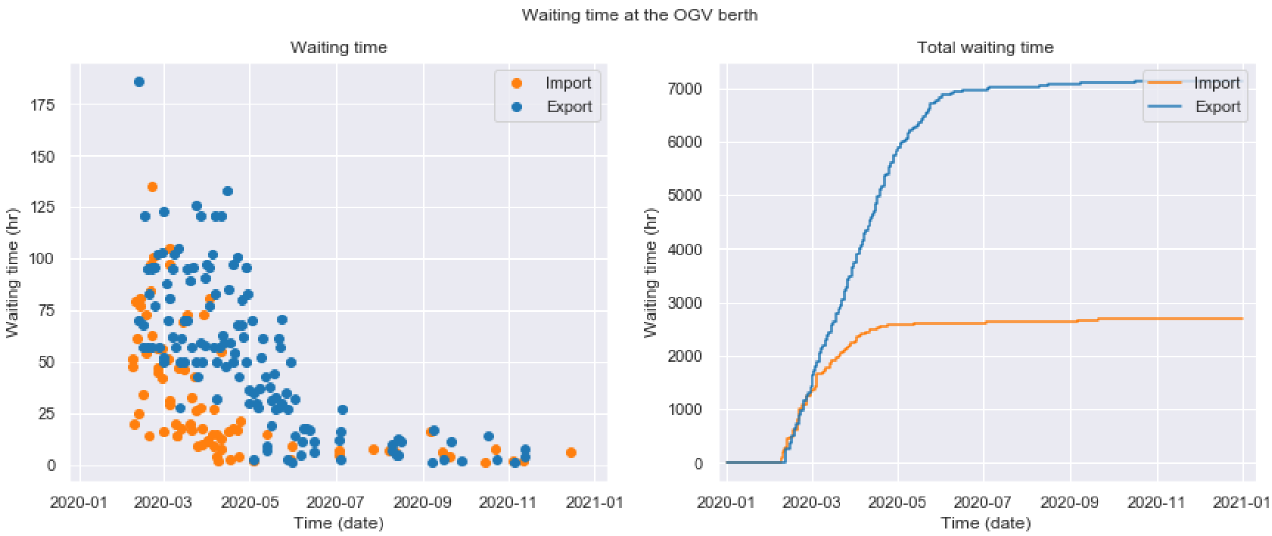

Figure F.4: Waiting time for downtime scenario: 9 days consecutive downtime

Annual waiting costs for downtime scenarios

Table F.1: Annual waiting cost related to the offshore storage capacity for the downtime scenarios

Annual waiting costs				
Storage capacity	no downtime	3 days	6 days	9 days
10,000 TEU	$ 1,738,000	$ 4,744,000	$ 20,194,000	$ 54,330,000
12,500 TEU	$ 1,742,000	$ 2,580,000	$ 12,150,000	$ 37,875,000
15,000 TEU	$ 1,736,000	$ 1,746,000	$ 6,250,000	$ 26,756,000
17,500 TEU	$ 1,740,000	$ 1,742,000	$ 3,005,000	$ 15,753,000
20,000 TEU	$ 1,738,000	$ 1,740,000	$ 1,742,000	$ 7,651,000

Table F.2 present the adjusted data.

Table F.2: PV of the waiting cost related to the offshore storage capacity for the downtime scenarios

PV of the waiting costs as a result of limiting storate capacity				
Storage capacity	no downtime	3 days	6 days	9 days
10,000 TEU	$ -	$ 36,522,980	$ 224,365,900	$ 639,395,300
12,500 TEU	$ -	$ 10,212,820	$ 126,566,000	$ 439,333,500
15,000 TEU	$ -	$ -	$ 54,833,110	$ 304,147,400
17,500 TEU	$ -	$ -	$ 15,380,020	$ 170,371,700
20,000 TEU	$ -	$ -	$ -	$ 71,866,630

Wave climate scenarios to simulate periods of consecutive downtime

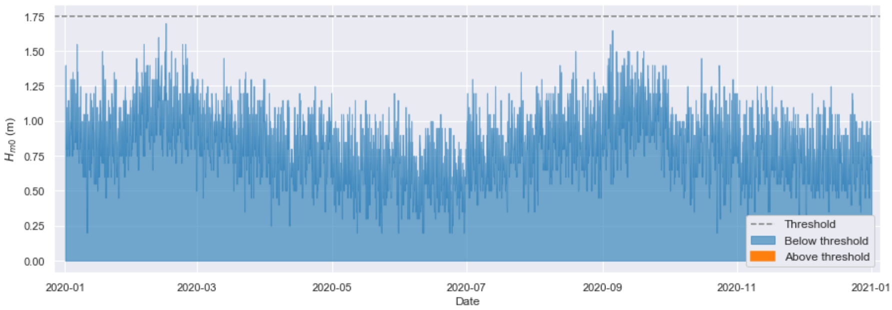

Figure F.5: Wave climate for downtime scenario: no downtime

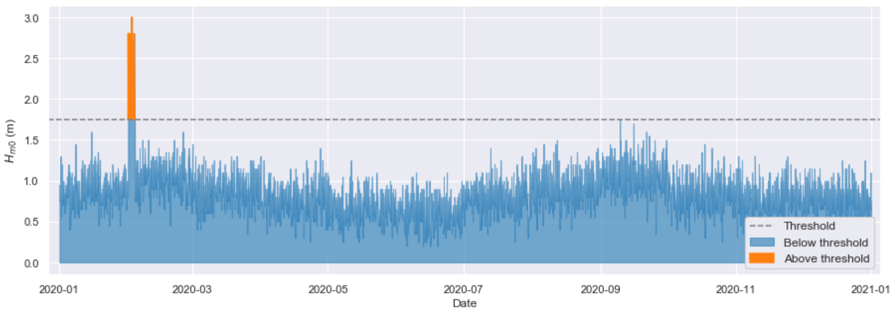

Figure F.6: Wave climate for downtime scenario: 3 days consecutive downtime

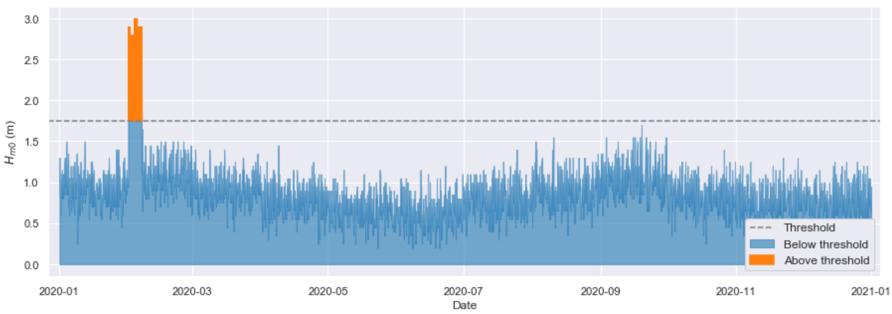

Figure F.7: Wave climate for downtime scenario: 6 days consecutive downtime

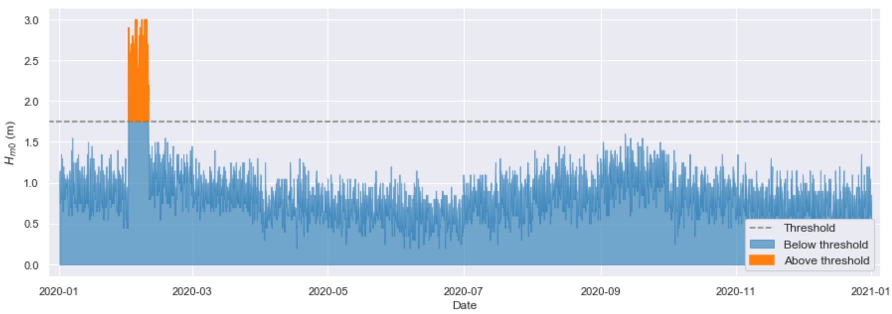

Figure F.8: Wave climate for downtime scenario: 9 days consecutive downtime

G
Code archive

G.1. Code documentation

Investment simulation

The applied model concept is the *Open Source Terminal Investment Simulation* (OpenTISim) which is available at the GitHub of the Hydraulic Engineering department of the Delft University of Technology (van Koningsveld, 2019). The method automatically generates investment decisions, parametrically derived from demand trends and a number of investment triggers, and is therefore able to generate cost estimates for various design scenarios.

Logistical simulation

The applied model concept is the *Open Source Complex Logistics Simulation* (OpenCLSim) which is available at the GitHub of the Hydraulic Engineering department of the Delft University of Technology (van Koningsveld et al., 2019). OpenCLSim is a *Python package* for rule-driven scheduling of cyclic activities for an in-depth comparison of alternative operating strategies. The simulations are a combination of *discrete-event simulation* and *agent-based simulation*. OpenCLSim continues on the SimPy discrete-event simulation package.

G.2. Code reference

Figure G.1 presents the links (QR-codes) to the model repositories applied in this thesis. All code is labelled with the tag *v_final_report*.

(a) OpenTISim repository
https://github.com/TUDelft-CITG/OpenTISim/tree/Afstuderen_HugoStam

(b) OpenCLSim repository
https://github.com/TUDelft-CITG/OpenCLSim-offshore-terminal-analysis

Figure G.1: Model repositories