The impact of high sea-level rise (1-5 m) on mainport hinterland transport networks

MSc Thesis

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A method for assessing adaptive sea-level rise scenarios on container port competition; a case study for the port of Rotterdam

by

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Preface

This 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. It marks the end of the path for obtaining the title of Master of Science in the field of Hydraulic Engineering.

This thesis is performed in collaboration with the Port of Rotterdam Authority, the world-famous port of the Netherlands. I would like to extend my gratitude to the Port of Rotterdam Authority for their guidance and letting me attribute to their continuous quest of strengthening their competitive position. It has been an absolute delight to work with my colleagues of the Corporate Strategy Department. It is regrettable that our collaboration was abruptly interrupted by the pandemic and that we had to continue from home.

In addition, I would like to extend my gratitude to my commission for their advice and instructions. A special thanks to Mark Voorendt for his rapid feedback and to Mark van Koningsveld for his help and enthusiasm for the model we have built. Further acknowledgements to my family and my girlfriend for their (mental) support throughout my study and during this thesis. Lastly, I would like to thank Sander de Jong for helping me securing the internship at the Port of Rotterdam Authority.

Z.Z.E. (Zilver) de Iongh
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Abstract

Climate change & sea-level rise
It is well-known that the Netherlands is susceptible to sea-level rise. Half of the country is situated below sea level and in an estuary. Previous measures of the Dutch against the threat of inundation have resulted in the closure of estuary branches, decrease in the length of primal flood defences and the world-renowned Delta Works. The Nieuwe Waterweg is kept open for economic reasons, in order to provide unhindered access to the port of Rotterdam, the largest deep sea port in Europe. However, the rise in sea level poses a threat to the accessibility of the port.

Sea-level rise adaptation scenarios for the Netherlands
There are various scenarios conceivable for the Netherlands to adapt to sea-level rise. The main scenarios are “Open protection”, “Closed protection”, “Seaward” and a “Retreat” scenario. Each scenario brings its own set of challenges and benefits. There are many strategies to implement these scenarios for future landscape and sea-level rise adaptations.

Currently, there are around 180 sea-level rise adaptation strategies for the Netherlands, as collected by Deltares. Only a handful actually include the effects on modality networks, port activities and shipping. Furthermore, all strategies use the same method which uses multiple models and has a lead time which stretches over multiple weeks to determine the effects on waterborne supply chains. Moreover, this method is not compatible for the retreat scenario. This forms the knowledge gap of the thesis.

Proposed method & model
This thesis therefore sets out to mitigate that gap by developing a first-order method to quantify the consequences of large sea-level rise projections, landscape changes and hinterland modality network changes of a deep sea port and to provide the results in a comprehensive manner.

Therefore, we propose and create a method and a model to quantify the consequences on spatial sea-level rise adaptation strategies on hinterland container port competition, by enforcing modality network changes and being able to easily adjust boundary conditions of the model. This thesis brings forth the method and model and subsequently applies it to the Netherlands and the port of Rotterdam as a case study. The ports of Antwerp and Hamburg are additionally taken into account to model the port competition. The method and model can account for any number of deep sea ports and countries.

Conclusions & recommendations

- This thesis shows that currently, the majority of the sea-level rise adaptation strategies do not take their effects on waterborne transport and port activities into account. Furthermore, the strategies that do currently all use the same method, which cannot account for a retreat scenario. Furthermore this existing method uses four models which results in a total cycle time in the order of weeks. These existing models cannot account for landscape or network changes.

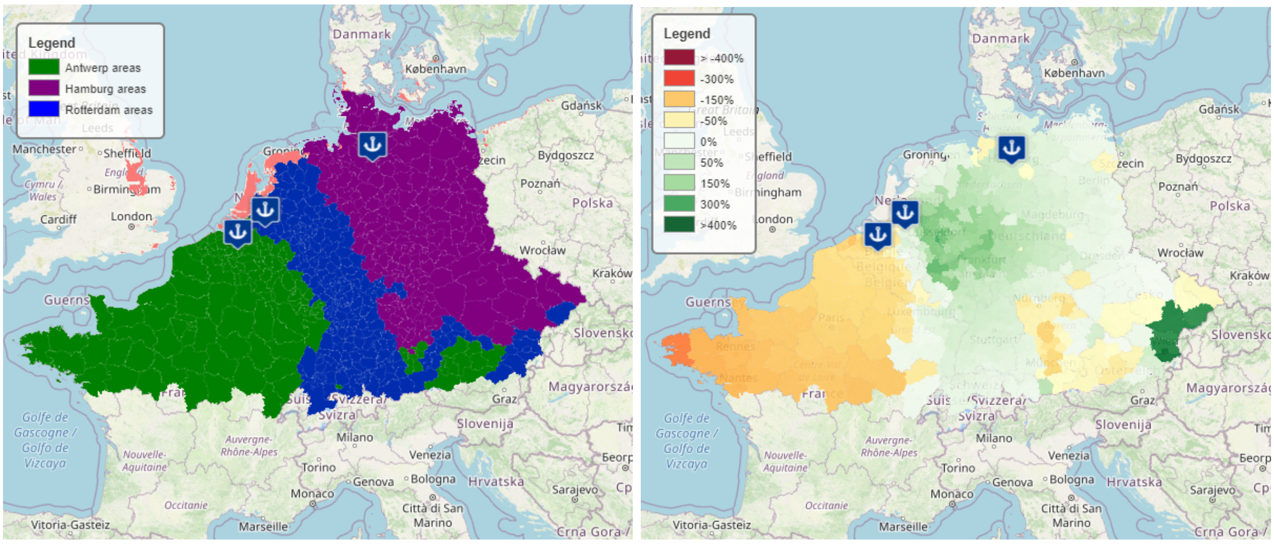
- The proposed method shows that current port operations for Rotterdam are no longer viable at +3 m sea-level rise and a retreat scenario. Two options for are suggested for the port of Rotterdam: relocate the port to the new coastline or transform the current port in a deep sea terminal in combination with inland terminals at the new coastline.

- The proposed method further shows that Belgium and Germany experience less inundation at +3 sea-level rise and a retreat scenario. Moreover, the ports of Hamburg and Antwerp are less susceptible to the inundation and do not have to resort to the extreme measures as the port of Rotterdam.

- The model shows that by locating the port more inland and in close proximity to (current) modality networks, the competitive position of the port of Rotterdam increases, whilst losing the advantages the port presently enjoys over Antwerp and Hamburg, as the modalities are now closer to the hinterland destinations. This is most notable for the road modality.
- Following the model, it can be concluded that new port locations have to be chosen with care as the results suggest a large decrease of hinterland areas for two locations (-51% and -88%), whilst the (other) two locations only show a slight increase in hinterland port areas (+3% and +16%). Table 1 shows the results for the different new port locations. The model suggests that the most promising new port location is Tiel, of which the results of the model are depicted in Figure 1.
- The proposed model only accounts for the container commodity, other commodities, such as dry bulk and liquid bulk, could give different results and it is therefore recommended that further research is done based on the other commodities.
- It is further recommended to improve the model by adding a common starting point, China for example. Currently, the model starts at the quay, when the containers are unloaded from the deep sea vessels. This would give the option to add (dis)advantages of ports, such as increased relative distances, a tidal window, or container dwell times.

Table 1: Number of competitive hinterland areas for different port locations which are cheapest to reach from a respective port and percentage of areas lost or gained for that port in respect to the current situation. *The figures and percentages are adjusted to the new number of areas excluded in the landscape outline.

Location	Current situation		Zwolle		Huizen		Tiel		Bergen op Zoom	
Rotterdam areas	212	195*	201	+3%	95	-51.3%	227	+16%	24	-87.6%
Antwerp areas	141	137*	159	+16%	241	+75.9%	131	-4%	301	+113.5%
Hamburg areas	234	234*	206	-12%	230	-1.7%	208	-11%	241	+4.3%
Total hinterland areas	587	566*	566	-3.6%	566	-3.6%	566	-3.6%	566	-3.6%



(a) Results port hinterland area distribution of the Tiel port location for the port of Rotterdam.

(b) Results areas which are more (red), or less expensive (green) to reach from the new port location in respect to the base case.

Figure 1: Results deep sea port location at Tiel, Gelderland at +3 m seal level rise and a retreat strategy.

Contents

Glossary

ArcGIS	A geographic information system for working with maps and geographic information maintained by the Environmental Systems Research Institute
inundation	For this thesis the term “inundation” is applied when dry areas become permanently wet, in contrary to flooding when dry areas become temporarily wet, periodically or episodically (Flick, Chadwick, Briscoe, & Harper, 2012)
location	A location is used in this thesis to define a site for a new deep sea port
NUTS	Nomenclature of Territorial Units for Statistics is a geo code standard by Eurostat for referencing the subdivisions European countries. NUTS 0 regions are major socio-economic regions, i.e. countries and NUTS 3 regions are the smallest regions, i.e. municipalities
scenario	A scenario is a consequence of sea level rise (adaptation) on an entire country. In this thesis, applied either for open protection, closed protection, seaward or a retreat scenario
strategy	A strategy is a plan for sea level rise adaptation on a smaller scale than a scenario. An example is the Maeslant Barrier for Rotterdam
TEN-T	Short for Trans-European Transport Network, it is an initiative from the European Commission to improve the core corridors and supply chains across and beyond Europe

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Introduction

1.1. Context

The Netherlands can be translated to “lower countries”, due to its topography. It is mostly flat and part of it is below sea level. The country is situated in a river delta which discharges in the North Sea. A characteristic of a delta system is the balance between land, sea and rivers. The result is an ever-changing landscape due to floods of the sea, (changing) flow of the rivers and sediment discharge of both the rivers and the sea. This can be seen when comparing the situation of Rotterdam around 1850 (Figure 1.1) and the current situation (Figure 1.2). This dynamic characteristic resulted in a battle with the sea lasting centuries, shaping and reshaping the Netherlands in the process.

In the wake of the disastrous floods of 1953, the decision was taken to reduce the coast(line) by 700 km and make it static, resulting in, amongst other interventions, the famous Delta Works. The country was safe against the perilous sea and would be in the forefront of hydraulic engineering for decades to come. Nevertheless, the water problem for the Netherlands has returned, in threefold: sea-level rise, fluctuating river discharge and subsiding land (Haasnoot et al., 2019)

Due to the relationship the Dutch have with the sea, they have always been world-renowned sailors and traders. The connection with the Rhine and the Meuse river systems, giving the Dutch an excellent hinterland connection, resulted in a hub function for European and world trade, accumulating in the port of Rotterdam earning the title of largest port in the world, from 1962 until 2004. Besides a transport hub, it is also a chemical and energy hub. Today, it is still the largest port in Europe. Figure 1.2 depicts the different commodities that are traded in the port of Rotterdam.

Via the inland waterways, most of Central and Eastern Europe can be reached, as evident in Figure 1.3 (Kriedel et al., 2019). In 2018, the port of Rotterdam (un)loaded 123,859 inland vessels and had the largest market share of the Hamburg- Le Havre range with 36.7%, followed by the port of Antwerp at 18.6% and the port of Hamburg at 10.6%. As these ports are connected to the same waterway network and have an open connection to the sea as well (the port of Antwerp has a partially open connection), competition is fierce between the ports.

Figure 1.1: Situation Rijnmond, South Holland circa 1850

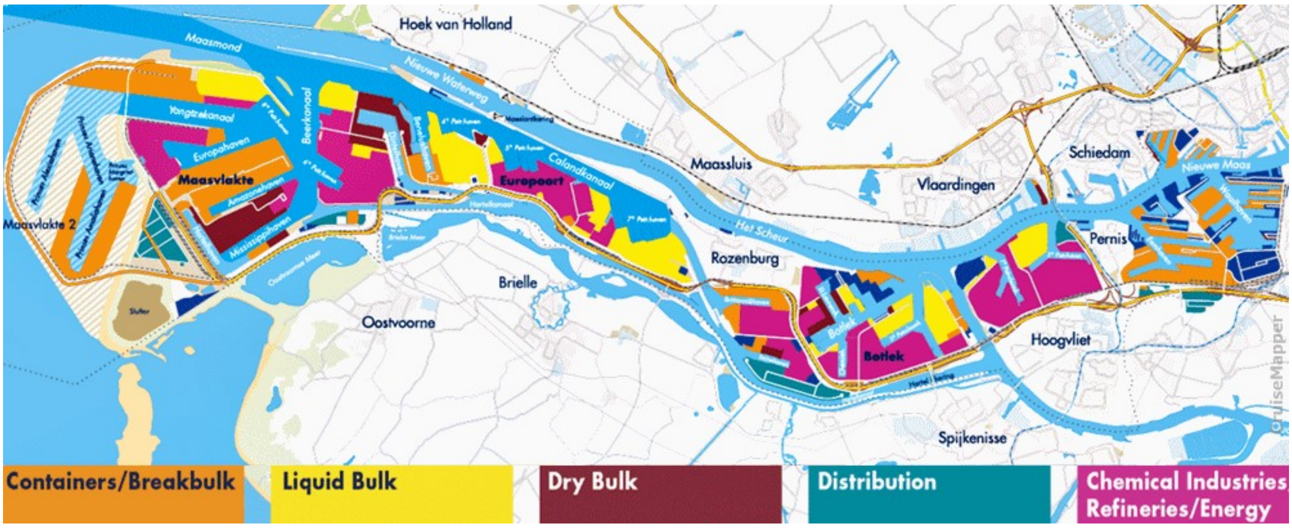


Figure 1.2: Commodities of the port of Rotterdam (blue areas are other activities) (Port of Rotterdam Authority, 2018).

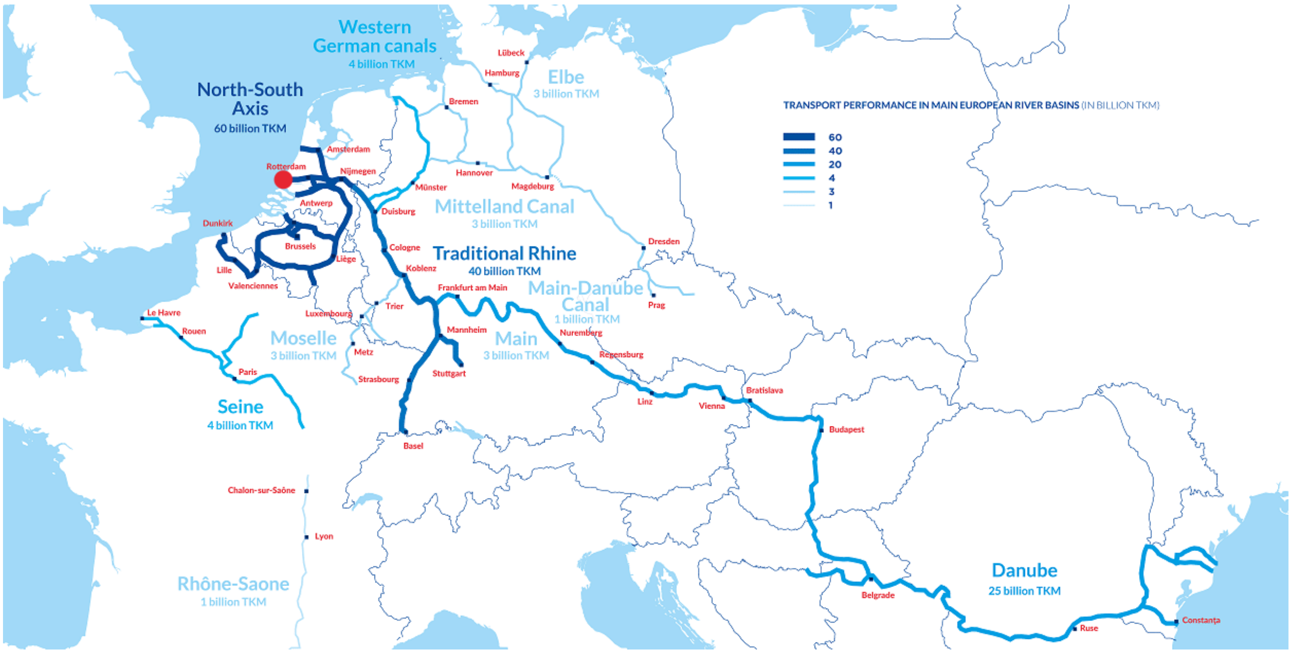


Figure 1.3: Transport Performance main European waterways. Adapted from (Kriedel et al., 2019).

1.2. Problem analysis

Rising average global temperature

The emission of greenhouse gasses result in a concentration increase of the gasses in the atmosphere. The heat rays of the sun bounce bounce back to the earth due to these gasses and subsequently warm the average global temperature. The increased temperature causes the earths ice to melt, including the land ice and glaciers and cause thermal expansion of the oceans. These processes (amongst others) result in a rising sea level. Forecasts and projections of the rising average global temperature can differ widely and depend on the actions societies and governments take. Recent reports state a significant faster rise in global temperature of +3 °C is possible in the next 60 years (Sherwood et al., 2020).

Rising sea level
According to the 2019 International Panel for Climate Change (IPCC) report of the UN, the sea level is rising, and even quicker than previously thought. In the report is stated that, for the Netherlands, the sea level will rise in between 35 - 85 cm by 2100, and that it will rise even faster after that (Gruber et al., 2019). These estimations are challenged by other authorities, stating a faster sea-level rise. In 2018, Deltares presented a report examining what happens if the average global temperature rises with +2 ^{o}C (as stated by the Paris Agreement) and +4 ^{o}C (if that agreement fails) (Haasnoot et al., 2019). They estimated that until 2050 there will not be an increase in the acceleration of sea-level rise. That acceleration is most likely to set in after 2050.

Sea-level rise adaptation scenarios
The current sea-level rise adaptation strategy of the Netherlands is viable until 2100 or +1 m sea-level rise. After the current strategy there are four possible scenarios for the Netherlands. An open protection, a closed protection, a seaward or a retreat scenario. For the first three scenarios the status quo is more or less retained, whereas for the retreat scenario, large scale landscape changes are implied.

1.3. Problem statement

Current literature shows that very few sea-level rise adaptation strategies focus on the consequences for shipping and port activities. The majority focuses on small scale sea-level rise (<1 m) and keeping the status quo, none focus on large scale landscape and hinterland modality network changes. The problem, therefore, is that there is no method which can (quantitatively) examine the consequences of these changes for shipping and port activities. This forms the knowledge gap of this thesis.

1.4. Objective, scope & questions

1.4.1. Objective

The objective of this thesis is to create a first-order method to quantify the consequences of large sea-level rise projections, landscape changes and hinterland modality network changes of a deep sea port and to supply the results in a comprehensive manner. Subsequently, this method is applied on the port of Rotterdam as a case study.

1.4.2. Scope

This thesis focuses primarily on the influence of non-status quo effects of sea-level rise on water-borne supply chain transport. Other aspects which can be influenced by sea-level rise, such as salt intrusion, freshwater intake points, the ecology and agriculture are not considered. Subsiding of the land and dikes can also have an impact on the port and the surrounding land and will increasingly become a problem for the Netherlands. However, as it is difficult to quantify and predictions are lacking, especially for the timeline of when the plans for this thesis come into play, these aspects are not specified. The same holds for the piping underneath the dikes.

Subsequently, this thesis focuses on the port of Rotterdam primarily as it is used as a case study, secondary focus lays on the ports of Hamburg and Antwerp. Nevertheless, other ports can also be examined using the methodology of the thesis as explained in Section 1.5. The port handles in three commodities, besides the two functions of chemical hub and distribution. This thesis, however, concentrates on the container logistics. This is because of the three commodities, the future container trade projections either remain constant or increase, whereas dry bulk and liquid bulk tend to have more negative trends (Havenbedrijf Rotterdam N.V., 2011).

1.4.3. Main question and sub-questions

To reach the objective set in Section 1.4.1, this thesis sets out to answer the question:

> "*How can the impact of extreme sea-level rise (+3 m) on container transport networks be assessed?*"

As the central question is complex and can be broadly interpreted, several sub-questions are asked. These sub-questions are further explained in Section 1.5 below.

1. *What are the possible scenarios to adapt to sea-level rise for the Netherlands and what consequences do they impose?*
2. *What is the current method of calculating the effects of sea-level rise strategies on shipping and port activities and are there shortcomings in those methods?*
3. *How can adaptive container port competition be modelled and which parameters are needed?*
4. *Does the model comply to its requirements and how accurate is it compared to reference data?*
5. *What are the options to adapt to sea-level rise for the three largest ports in Northwest Europe and the changes in their hinterland networks in case of +3 m sea-level rise and a retreat scenario?*
6. *Which new port location for the port of Rotterdam can be considered most promising, in regard to the number of competitive hinterland areas?*

1.5. Methodology

This thesis is essentially a hybrid between a research thesis and a design thesis. They are combined using a technical design cycle of an adapted flow chart which is based on the model proposed by Roozenburg and Eekels (1995) (Fig. 1.4). This flowchart uses six steps. Steps one and two cover the research part where the subsequent steps cover the design part.

1.5.1. Analysis of current and future climate change and sea-level rise strategies

In the first step, a literature study is used to answer the first sub-question. Therefore, the projections and uncertainties of sea-level rise are analysed. This gives an overview of how fast the sea level is rising and in what terms high sea-level rise can be expected. Subsequently, the options for the Netherlands to tackle sea-level rise are explored. This is done based on a report from Deltares in which they analyse four main adaptation scenarios to tackle sea-level rise. These scenarios are the extremes from which can be chosen, and will probably be executed in a milder form. However, it is important to know these extremes for the model. For each scenario, the future situation and implications for the Netherlands are given in three parts; a description of the effects on waterborne transport of the Netherlands generally, subsequently for the rivers and their surrounding areas and finally for the port of Rotterdam specifically.

1.5.2. Analysis of current literature and methods

To answer the second sub-question, current literature is further examined and analysed in more detail to determine if and how it includes the impact of the interventions imposed by the plans on shipping and port activities. In order to accomplish that, around 180 adaptation plans, collected by Deltares, are screened on if they actually help against the threat of sea-level rise and if they quantitatively take shipping or port activities into account. From the plans that consider these aspects, the methods are examined. It is thereby noted how the methods work, which programs they use and which gaps and shortcomings they have. The most important and prudent gaps are subsequently further examined and analysed. These gaps form the centre of the forthcoming model.

1.5.3. Developing of a hinterland container port competition model

Following the previous step in which the research part is finalised, the design part commences. In this step, a model is devised and built to examine the missing elements following sub-question two. To that extent, this step answers the third sub-question. The aim of the model is to be easy to use and to adjust, to be widely applicable and to have relevant outcomes which are comprehensible. A model is made which uses maps to alter the landscape and modality networks and to depict the results.

1.5.4. Evaluating the model

After the model is developed, it is verified by checking if it is built according to the requirements that were set in advance. The parameters of the model are calibrated and the resulting output is validated based on external data of the current situation. The simulation of the current situation can then be used as a basis to compare with future plans.

1.5.5. Exploration of the retreat scenario on shipping and port activities

From Section 1.5.2, it can be concluded that there currently is a method to explore three of the four scenarios. However, for the fourth one, the retreat scenario, current literature does not explore the consequences on shipping and port activities. In addition, the method cannot include changing networks and landscapes. Therefore, these aspects are explored and analysed in this step to answer the fifth sub-question, using the port of Rotterdam as a case study. Therefore, possible new locations for the port of Rotterdam are explored. These are used in the model.

1.5.6. Evaluating the changes

In the final step, the new port locations, changed landscape and altered networks are simulated in a model, thereby answering sub-question six. The model is a hinterland container port competition model, developed for this thesis. After the development of the model, it is verified by checking if the model is build according to the requirements set in advance. The parameters of the model are calibrated and the resulting output is validated, both based on external data of the current situation. The simulation of the current situation can then be used as a basis to which future plans can be compared to. Subsequently, the new port locations and landscape changes are simulated and evaluated, from which the most acceptable new port location for the port of Rotterdam follows.

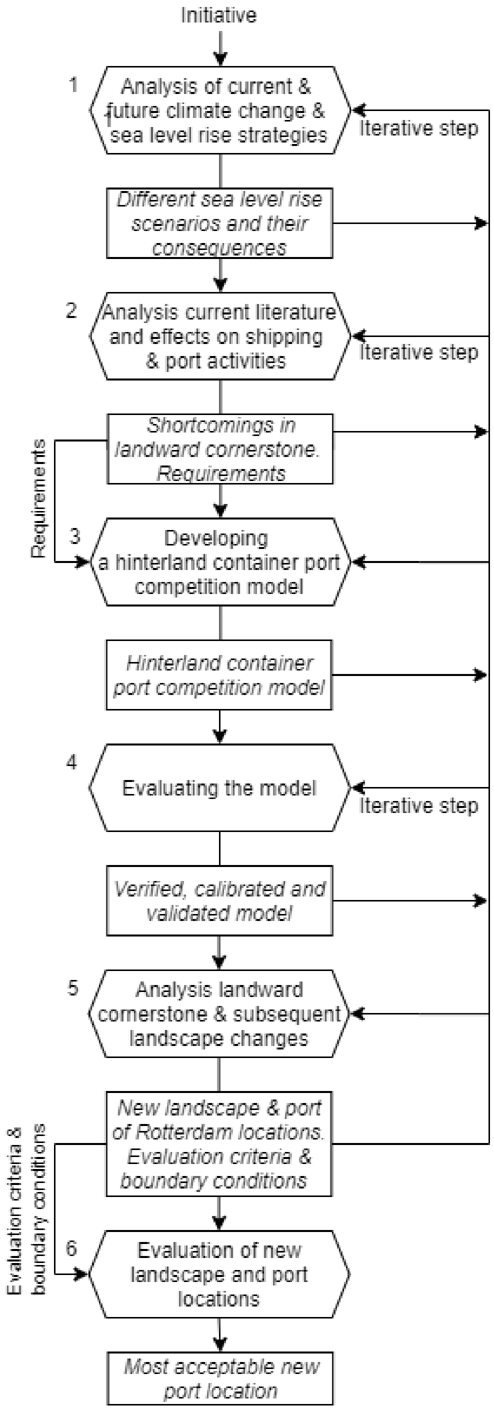
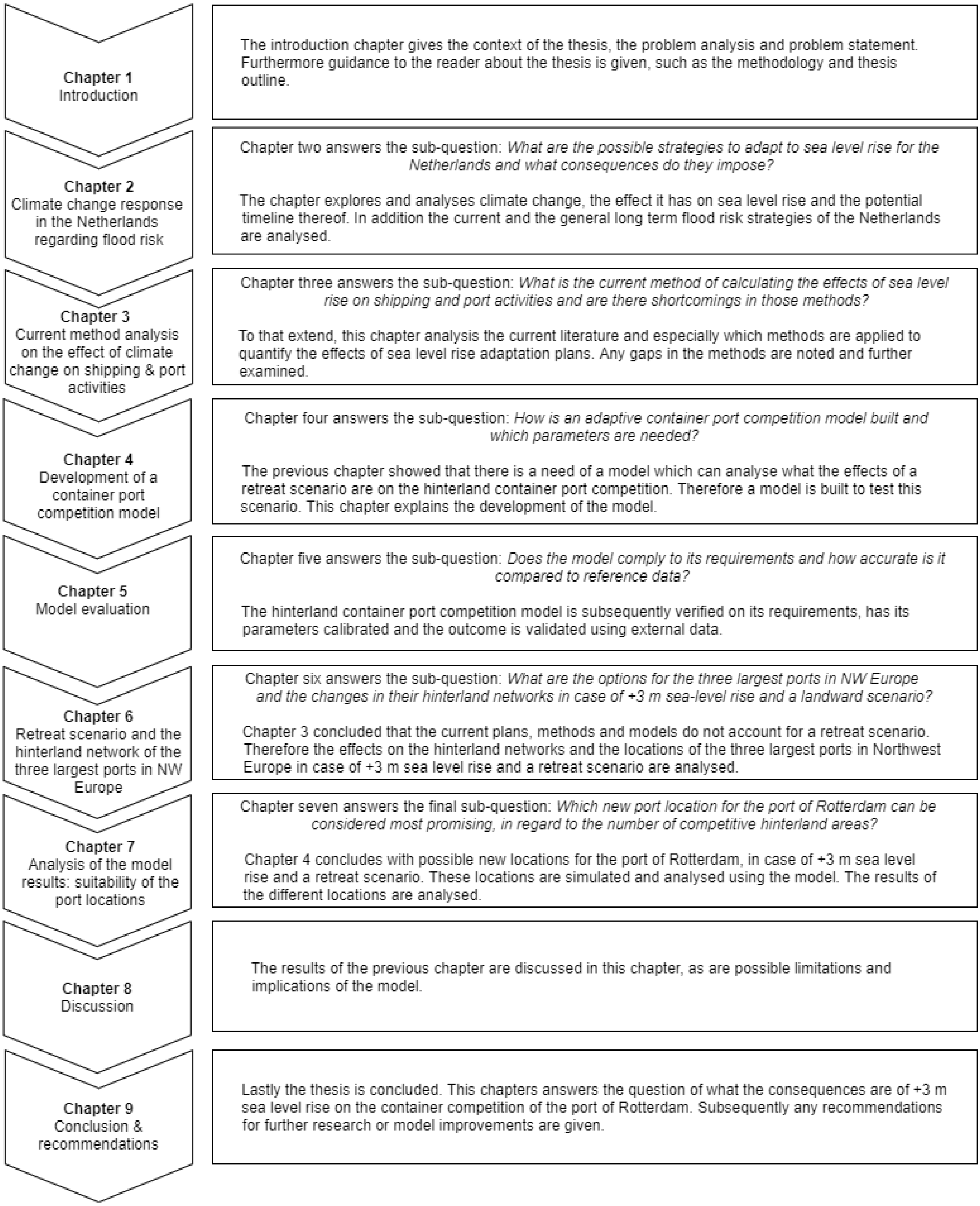


Figure 1.4: Altered model, based on the model proposed by (Roozenburg & Eekels, 1995)

1.6. Thesis outline

The thesis is split into nine chapters of which chapters one to four cover the research section and answer the first three sub-questions. Chapters five to seven handle the design section and answer the last three sub-questions. The final two chapters conclude the thesis. The chapters are outlined according to the methodology, as described in Section 1.5. Figure 1.5 gives an overview and a short summary of the chapters.



Chapter 1
Introduction

The introduction chapter gives the context of the thesis, the problem analysis and problem statement. Furthermore guidance to the reader about the thesis is given, such as the methodology and thesis outline.

Chapter 2
Climate change response in the Netherlands regarding flood risk

Chapter two answers the sub-question: *What are the possible strategies to adapt to sea level rise for the Netherlands and what consequences do they impose?*

The chapter explores and analyses climate change, the effect it has on sea level rise and the potential timeline thereof. In addition the current and the general long term flood risk strategies of the Netherlands are analysed.

Chapter 3
Current method analysis on the effect of climate change on shipping & port activities

Chapter three answers the sub-question: *What is the current method of calculating the effects of sea level rise on shipping and port activities and are there shortcomings in those methods?*

To that extend, this chapter analysis the current literature and especially which methods are applied to quantify the effects of sea level rise adaptation plans. Any gaps in the methods are noted and further examined.

Chapter 4
Development of a container port competition model

Chapter four answers the sub-question: *How is an adaptive container port competition model built and which parameters are needed?*

The previous chapter showed that there is a need of a model which can analyse what the effects of a retreat scenario are on the hinterland container port competition. Therefore a model is built to test this scenario. This chapter explains the development of the model.

Chapter 5
Model evaluation

Chapter five answers the sub-question: *Does the model comply to its requirements and how accurate is it compared to reference data?*

The hinterland container port competition model is subsequently verified on its requirements, has its parameters calibrated and the outcome is validated using external data.

Chapter 6
Retreat scenario and the hinterland network of the three largest ports in NW Europe

Chapter six answers the sub-question: *What are the options for the three largest ports in NW Europe and the changes in their hinterland networks in case of +3 m sea-level rise and a landward scenario?*

Chapter 3 concluded that the current plans, methods and models do not account for a retreat scenario. Therefore the effects on the hinterland networks and the locations of the three largest ports in Northwest Europe in case of +3 m sea level rise and a retreat scenario are analysed.

Chapter 7
Analysis of the model results: suitability of the port locations

Chapter seven answers the final sub-question: *Which new port location for the port of Rotterdam can be considered most promising, in regard to the number of competitive hinterland areas?*

Chapter 4 concludes with possible new locations for the port of Rotterdam, in case of +3 m sea level rise and a retreat scenario. These locations are simulated and analysed using the model. The results of the different locations are analysed.

Chapter 8
Discussion

The results of the previous chapter are discussed in this chapter, as are possible limitations and implications of the model.

Chapter 9
Conclusion & recommendations

Lastly the thesis is concluded. This chapters answers the question of what the consequences are of +3 m sea level rise on the container competition of the port of Rotterdam. Subsequently any recommendations for further research or model improvements are given.

Figure 1.5: The outline of the thesis per chapter

2

Inundation risk management in relation to waterborne transport

Chapter outline

This chapter answers the first sub-question: "What are the possible scenarios to adapt to sea-level rise for the Netherlands and what consequences do they impose?"

The chapter examines the problems, uncertainties and consequences of climate change and sea-level rise. An explanation is given about the different processes driving sea-level rise and the various projections of when certain levels can be reached. Subsequently, the current adaptation strategy of the Netherlands and the port of Rotterdam is explained, and the possible duration of that strategy. Lastly, the adaptation scenarios of the Netherlands are explored. First for the waterborne supply chain of the Netherlands in general, followed by the consequences for the rivers and then the consequences for the port of Rotterdam.

2.1. Climate change, sea-level rise and the uncertainty thereof

2.1.1. Main driver sea-level rise

Due to the emission of greenhouse gasses, the concentration of gasses in the atmosphere increases. These gasses bounce the heat rays back to earth, thereby increasing global temperature and changing the climate. The oceans absorb 90% of the extra heat, of which the Southern Ocean absorbs the largest part. The absorption causes thermal expansion of the oceans which, in turn, increases the volumes of the oceans (Trenberth & Fasullo, 2010). A change in mass balance is observed due to the melting of glaciers, sea and land ice, groundwater extraction and human-made reservoirs. Between 1994 and 2017 the earth has lost 28 billion tonnes of ice, which is only set to increase (T. Slater et al., 2020).

The regional sea-level changes have spatial variations due to gravitational effects of the ice caps on local sea level, atmosphere and ocean circulations and land subsiding and raising (Haasnoot et al., 2017). The International Panel for Climate Change (IPCC) makes estimations on the future average global sea-level rise using climate models. However, in these models, the changing ice mass balance of Antarctica is a very uncertain factor.

2.1.2. Relative sea level rise

For the countries surrounding the North Sea, the sea level is rising relatively slower than the global average. This is due to the shallow depths of the North Sea and the proximity to the (northern) ice caps. Due to the shallow water depths, the amount of water to (thermally) expand is limited, thus thereby restricting the local sea-level rise. Large masses, in this case water/ice, have a gravitational effect. These large masses pull water towards them, thereby increasing the local sea level. As these masses decrease, less water is pulled towards them, and the sea level drops, albeit locally. This is most effectively until 2.200 km from the masses. Between 2.200 and 6.700 km the effect is still present, although less effectively. The Netherlands is situated approximately 3.000 km away from Greenland, therefore profiting slightly from this gravitational effect (Aan de Burg, 2019; Bosboom & Stive, 2015).

The contribution of Antarctica to sea-level rise can be much larger than previously expected. This is because Antarctica has both sea and land ice. If the sea ice melts, the mass balance of the ocean does not change as the ice is already contributing to the sea level, albeit in another state. However, that same sea ice holds the Antarctic land ice in place. This land ice, ranging in thickness from 2 to 5 km, will contribute to the sea level, as it is not in the mass balance of the ocean. This process is called “Ice Cliff Instability” and is irreversible once it starts. This process is expected to start after 2050 (DeConto & Pollard, 2016). In addition, the gravitational effect will have a negative role. The water masses attracted to Antarctica will flow towards the Netherlands, thereby raising the local sea level.

2.1.3. Uncertainties in climate change and sea-level rise projections

In 2015, the Paris Agreement was signed. This agreement states that the average global temperature may not rise with more than 2 degrees Celsius compared to pre-industrial levels, and efforts should be pursued to limit the increase to 1.5 degrees (“Paris Agreement”, 2015). This is adapted to the Representative Concentration Pathway (RCP) 4.5 projection. In this projection, the radiative forcing is stabilised at 4.5 W/m^2 in the year 2100, without ever exceeding that value (Thomson et al., 2011). However, a recent study suggests a global rise of +3 degrees Celsius in 60 years due to the emission of CO_2 gasses (Sherwood et al., 2020) and does not exclude a 4 degree increase.

This is incorporated into the RCP 8.5 projection (Gruber et al., 2019). As these projections are uncertain, bandwidths are taken with a median and lower and upper percentiles (5% and 95% respectively). The results for the average sea level rise is depicted in Table 2.1.

Table 2.1: Sea level rise according to different projections, compared to the 1990 benchmark year (in cm). These results are specifically for the Dutch coast and differ from the projections of the Delta program (Haasnoot et al., 2017)

	RPC4.5 projection			RPC8.5 projection		
Year	Lower percentile	Mean	Upper percentile	Lower percentile	Mean	Upper percentile
2050	7	24	41	9	29	47
2100	29	108	192	75	194	317

Due to the high uncertainty of the projections, we must look at the extremes of the projections too. The upper value of the RCP4.5 projection matches the average value of the RCP8.5 projection in 2100 of 190 cm sea-level rise. At the moment, the Delta program estimates a maximum value of +85 cm sea-level rise for 2100, which is approximately half of the upper value and median value of the RCP4.5 and RCP8.5 projections, respectively. Climate change does not only pose a threat to the oceans; it affects the hinterland connection as well. As seaports are vital factors of the hinterland connection, they pose a vulnerable threat to the connectivity, if affected by sea-level rise (Nugroho, 2016). Furthermore, due to more considerable seasonal differences, the rivers in the hinterland are more susceptible to droughts and floods, which hinders the flow of goods (Van Meijeren, Groen, & Vonk Noordegraaf, 2011; Levermann, 2014; Sperna Weiland, Hegnauer, Bouaziz, & Beersma, 2015). This all threatens the position of the inland water transport in the modal split. Lower water levels caused by drought tend to have a larger impact on the inland water transport network than floods, as they tend to last longer (Fischer et al., 2015). However, this poses mainly a threat on the dry bulk trade, less on the container trade (Kievits, 2019; Volker & Volker, 2015).

2.2. Current adaptation strategy concerning the risk of inundation

2.2.1. Triggering flood event for current strategy

After the floods of 1953, the fist Delta program was set up. Chosen was that most of the Dutch coast had to be protected using soft protection, i.e. sandy dunes, with some exceptions of hard protection, i.e. dams and storm surge barriers. A shortened coastline was created to decrease the length of the primary flood defences with around 700 km. This meant that the riverine outlets and estuaries would have to be closed, except for the Nieuwe Waterweg and Western Scheldt as they lead to the port of

Rotterdam and port of Antwerp, respectively. To keep the surrounding land and its inhabitants dry, dikes were constructed on the banks of the rivers and the land side of the terminals. Thus resulting in directly accessible terminals from the sea whilst protecting the surrounding citizenry. Halfway the eighties of last century it turned out that the dikes protecting the south of South-Holland were not adequate enough to protect the surrounding lands. As raising and widening the dikes was not an option due to the expenses and availability of land, another option was chosen. In 1987 the plan was made to construct the Maeslant barrier and in 1997 Queen Beatrix took it into commission (Stadsarchief, n.d.). The Hartel barrier was made in the Hartelkanaal around the same time as the Maeslant Barrier and together they form the Europoort barrier. An overview can be seen in fig. 2.1.

The Maeslant barrier closes when the sea level is at +3.0 m above NAP at Rotterdam and +2.9 m at Dordrecht. Although the barrier has been closed a few times in the past, these were test closures or closures whereby the closure level was lowered. The barrier has yet to be closed for the +3.0 m storm surges (Rijkswaterstaat, 2013, 2018). When closed, the barrier protects the inhabitants of South-Holland from flooding, although its failure probability is disputed due to its design (Groote & Verhoef, 2006). As the Hartel barrier is situated about 15 km inland of the Maeslant barrier, wind and wave set-up can heighten the water level in the Hartelkanaal. This can result in flooding the Botlek and Europoort from the southern side, where the latter can also be flooded from the northern side. To remedy this problem, the Botlek and Europoort are constructed at a higher level than the protected areas, making flooding them less flood-prone. Maasvlakte 1 and 2 are entirely exposed to storm surges but are also built at a higher level. Although Rijnmond-Drechtsteden area is thus protected, this is only the case in extreme high water level events, when the storms surge barriers are closed. This means that a few areas are still prone to flooding in case of high water levels, which fall below the point of closure of the Maeslant barrier.

Figure 2.1: Left; Maeslant barrier, right; Hartel barrier and in red the dike protection of the Nieuwe Waterweg

2.2.2. Mixed adaptation strategy on a national and regional level

The current strategy to protect the coast of the Netherlands is a mix of open protection (i.e. free-flowing river outlets, heightened dikes) and closed protection (i.e. closed off river outlets with dams and locks). The open protection can be combined with structures which can close off the river outlets during storm conditions, such as the outlet of the port of Rotterdam. This means that the port of Rotterdam can always be reached, except in the case of extreme storm conditions. This also means that the port operations are directly influenced by sea-level rise, as a higher (mean) sea level means that the (current) point of closure of +3 m at Rotterdam is reached more rapidly, as can be seen in Figure 2.2. The current closure frequency is at around once every ten years and is expected to increase to 3 times per year in 2100. At +2 m sea-level rise, the (current) point of closure is reached daily. A maximum closure frequency of 3 times per year is advised; however, this has to do with the strain on the barrier, not with the accessibility of the port (Kind et al., 2019). The link between sea-level rise and increased frequency and severity of storm surges is still debated (Wahl, 2017). Nonetheless, there are models and papers which indicate that these connections do exist for the European coast (Vousdoukas et al., 2016).

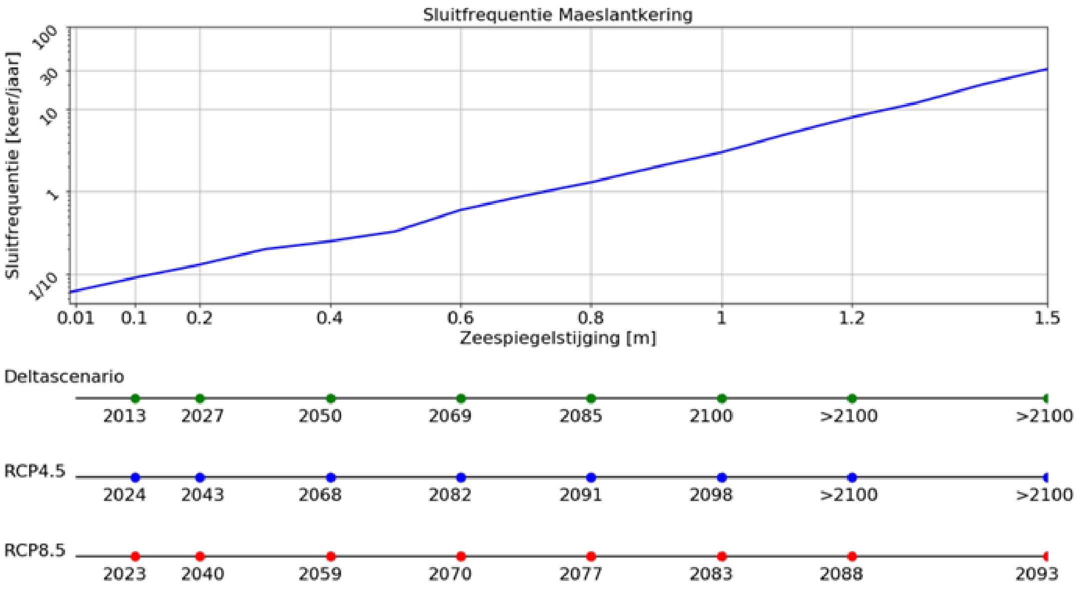


Figure 2.2: Frequency of closure Maeslant barrier (per year) for increasing sea level rise, with different projections (Haasnoot et al., 2017)

2.2.3. Adaptation strategy of the port of Rotterdam

The Port of Rotterdam Authority is currently assessing all areas in its possession to determine which terminals are prone to flooding. Per area, terminal, company or asset owner, an adaptation strategy is created to provide protection against flooding in the long term. The present adaptation strategy is based on the well-known multi-layer model, which can be seen in Figure 2.3. The layers are (bottom to top):

1. *Preventive measures*
   Lowering the possibility of flooding by raising dikes, quays and terrains;
2. *Spatial adaptation measures*
   Lowering the consequences of flooding by making terminals or critical equipment waterproof;
3. *Crisis management measures*
   Lowering the consequences of flooding by having preemptive plans to evacuate the terminals and plans to have the terminals swiftly back in operation.

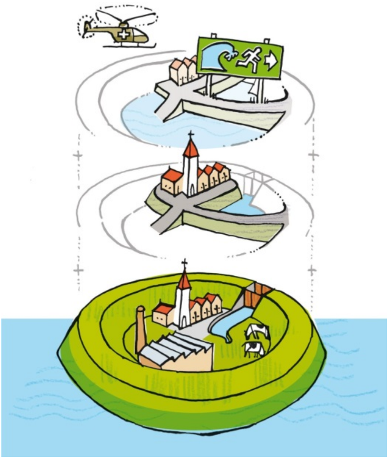


Figure 2.3: Multi-layer protection model

The port handles sea-level rise projections of +0.15 m to +0.35 m by 2050 and +0.35 m to +0.85 m by 2100 (Eisma, van Ledden, & van de Visch, 2017). Each area of the port is assessed to determine which areas are most vulnerable and which complication may come to play. To that extent, four categories are applied for the evaluation:

- *Risk to life*
  Casualties resulting from a flood event;
- *Social disruption*
  Disruption to shipping of cargo and loss of service from critical infrastructure;
- *Environmental damage*
  Damage to tanks containing hazardous materials;
- *Economic damages*
  Direct consequences of inundation of terminals, assets and infrastructure and consequences on shipping.

For the case study of the Botlek area, the main risks were the economic damages, comprising of damages to buildings, systems and infrastructure. What was noted was that the risk of flooding happens from the Hartelkanaal, not the Nieuwe Waterweg. The preventive measures contrived were raising the quays and ground level, thus making a flood defence system. Elevating the vulnerable infrastructure, thereby reducing the damages in case of flooding was listed as a spatial adaptation measure, and as a crisis management measure, emergency barriers were considered. These barriers can be placed when flooding is imminent. An interesting result of the case study was the interconnectivity of the Botlek area with other areas, terminals and industries. Suppose a system fails in the Botlek area. In that case, a chain reaction can occur, whereby other areas which are connected or dependent on the Botlek area might fail, enlarging the economic damages throughout the Netherlands.

When the contract of a company expires, the quays and ground level can be heightened. However, an entire area, such as the Botlek, cannot be “lifted” at once as there are multiple companies and industries with different backgrounds on the area. This is because the contracts of the various companies expire at different times, and the companies use the terminal for different applications. Therefore, when major maintenance on the quays or the embankments or the areas must be done, it is essential to take the preventive measures against sea-level rise into account. At the moment, the port applies a strategy which is projected to hold until 2100. This strategy includes maximum projections of the Deltascenario of +0.85 m to +1.0 m sea-level rise. At that point, the closure frequency of the Maeslant barrier will be three times per year. The areas and terminals in its possession can handle the sea level rise up until that point, albeit with spatial adaptation or crisis prevention measures. No plans exist yet for a sea-level rise of more than one meter, although there is a preference to continue the current strategy.

2.3. Future strategies for the Netherlands: the Deltares scenarios

The question arises, what are the options for the Netherlands to tackle (high) sea-level rise? Deltares presented a report in which the question was not raised *when* a certain sea-level rise will be reached, but what happens *if* it does. They took an arbitrary sea level rise of +2 m to +4 m and looked at the options which the Dutch have (Haasnoot et al., 2019). They formed four possible (extreme) scenarios for the Netherlands to cope with sea-level rise, of which general summaries are given below. These scenarios are analysed to explore all implications for the Netherlands and the (container) transport network. Illustrative overviews of the four scenarios are given in Figures 2.4 and 2.5. An overview of how the scenarios could be detailed can be found in Appendix A.

2.3.1. General implications Deltares scenarios for the Netherlands

There are some general implications, independent of the scenarios. Currently, $12 \cdot 10^6$ m^3 of sand needs to be dredged for beach nourishment on a yearly basis, to keep the coastline static at the present location. Sea level rise increases coastal erosion (Leatherman, Zhang, & Douglas, 2000). Therefore the dredging volume is expected to increase 4-5 times in 2100. For a higher sea level rise, this factor is predicted to be more in the range of 20 that of the current sand nourishment. The western part of the Waddensea will be constantly inundated due to sea-level rise. The eastern part of the Waddensea is more resilient to sea-level rise and therefore less prone to complete inundation.

All plans will bring tremendous costs and challenges. The Delta Works thus far have cost almost 5 billion euros, and some of the following scenarios will cost far more, especially when the economic damages are taken into account. This thesis mainly looks at the competition of Rotterdam in the Le-Havre - Hamburg range. What has to be taken into account is that the Netherlands are not the only country in this range which has challenges with sea-level rise. Other countries and ports will have to make similar decisions and sacrifices. Below the four sea-level rise adaptation scenarios, as conceived by Deltares, are presented (Haasnoot et al., 2019). In addition, the respective consequences they have on the waterborne supply chain of the country in general, on the rivers and on the port(s) are explained. This view is an adaptation of the view of the report by Deltares. However, the facts and conclusions match that of the report by Deltares.

2.3.2. Closed protection - dams, dikes, sediment, wetlands and foreshores

General consequences

Perhaps the most straightforward scenario is to close off the access to the sea, fortifying the Netherlands against the sea. The coast is protected using soft or hard protection or an combination of the two. The dunes and dikes safeguard the country against flooding are substantially raised and widened. River(arms) are closed off by locks and dams in order to shorten the primal dike defence system. The world-renowned Eastern-Scheldt barrier was constructed specially to maintain the tidal flow in the Eastern-Scheldt.

Consequences rivers

If the sea level rises to the degree that at low tide the mean water level of the river is lower than the sea level, river drainage using gravitational flow is no longer possible. Large pumps have to be installed to discharge the riverine water into the sea. These pumps will also have to be able to handle the peak discharges, or storage lakes have to be created where the water can be stored temporarily. The dams in Kreekrak and Volkerak will become redundant as they will no longer have to separate salt and freshwater. These areas, plus the Eastern-Scheldt, could then be used as storage lakes. The construction of locks and dams also means that the river dikes inland of the locks and dams have to be raised to prevent flooding. Low water levels in the rivers mean that inland vessels can take on less cargo and high water levels could mean that container vessel no longer have enough clearance to sail under bridges which cannot open. The absence of the tidal effect could also mean that the discharge distribution of the rivers can alter, which in turn affects the sedimentation distribution in the delta, possibly resulting in (high) dredging costs for the inland waterway transport.

Consequences port

The construction of locks is expensive, especially if one takes into account the capacity needed to handle the flow of vessels through the port of Rotterdam. The critical question is where the locks are placed. If the locks are placed at the mouth of the port, the locks have to have a larger capacity to accommodate the deep sea vessels than if the locks are placed more inland. The problem which then arises is that during storms, high water levels will occur in front of the locks due to wind and wave set-up. This has an effect that the port can experience downtime as vessels might choose to anchor outside of the port or even divert to other ports. In addition, the terminals and nearby land can inundate due to the set-up. This can be partly subverted by raising the terminals, but this cannot happen in phases. The terminals have to be raised before the construction of the locks are completed or still inundation and downtime. At the other side of the locks, the inland terminals can experience the same difficulties, however. At low and high river discharges, the water level can no longer be compensated or easily discharged without an open connection to the sea. This means that problems can arise when (un)loading cargo with fixed crane heights. The port can lose its market position to nearby ports which are not situated behind locks, although if the Western Scheldt is closed off too, the port of Antwerp will face the same problems. The locks in the Schelde-Rijn canal, which directly connects the port of Antwerp and port of Rotterdam, become redundant, thereby improving the sailing time between the two ports.

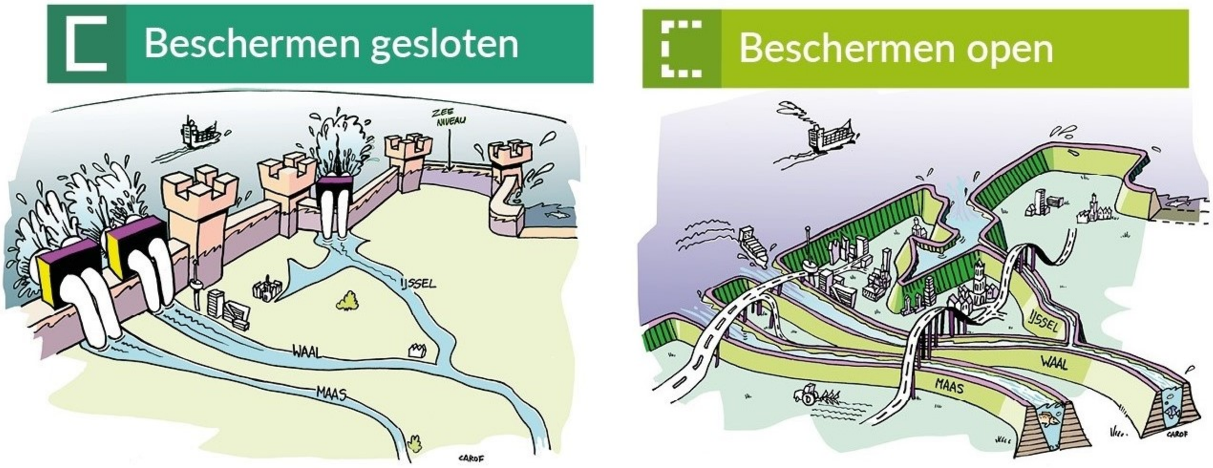


Figure 2.4: Closed and open protection adaptation scenarios for high sea level rise of the Dutch Delta. (©Beeldleveranciers-Carof commissioned by Deltares)

2.3.3. Open protection - Storm surge barriers, river dikes, sediment and foreshores

General consequences

The rivers are kept open to the sea, however the option remains to be closed off during storm conditions with storm surge barriers. To also maintain dry feet during normal conditions, the river dikes are raised to keep the water levels of the sea and rivers equal when the sea level rises. This enables the rivers to discharge the riverine water into the sea with gravity flow.

Cities and polders will continue to sink, which means an increasing of relative sea-level rise. The infrastructure and connections between dike rings can become a problem as the dikes need to be raised, and the polders keep sinking. This scenario has a lot of variation in how to be executed. If the vision of Deltares of Figure 2.4 is to be believed, the IJsselmeer is reopened to the sea, which means constructing costly sea dikes around the IJsselmeer.

Another version is to reopen the estuaries of the province of Zeeland to bring back the tidal effects there. This scenario also comes close to the current situation whereby the Western Scheldt and the Nieuwe Waterweg are kept open, as described in Section 2.2. For the Western Scheldt, either the primary dikes have to be heightened or a storm surge barrier, such as the Maeslant barrier, can be made. As there is less urban development on the embankments of the Western Scheldt, the primary dikes can be raised with more ease, as opposed to the Nieuwe Waterweg. However, the Western Scheldt is at its smallest point, at the border between Belgium and The Netherlands, 2 km wide, in contrast to the width at the Maeslant barrier of approximately 360 m. Constructing a barrier there will not be easy. Elevating the land and thereby raising the dikes or placing a barrier which closes during storm conditions is more difficult for the Nieuwe Waterweg. That card has already been played but is still an option for Antwerp and Hamburg. Raising the level of the terminals might be less complicated than raising the quays/dikes along the inland part of the Nieuwe Waterweg, the Lek and the Noord, as those areas are more urbanised and populated.

Consequences rivers

Raising the dikes will be a costly operation but can be done in phases as high sea-level rise will not occur at once. This contrasts the previous scenario where when a lock is constructed, the surrounding dikes and terminals have to be raised beforehand. However, more kilometers of dikes have to be raised than the previous scenario. At +3 m sea-level rise, this length will be approximately 30 km inland of the current location where the border between the sea and the river is situated. Not all dikes can be easily raised and widened. Where the rivers are positioned in close proximity to urban areas, there is a lack of space to raise the dikes in a traditional manner.

Peak river discharges in combination with closed storm surge barriers can still impose the threat of flooding on the country, albeit from the rivers. Inland shipping can also experience difficulties are bridge clearance can become an issue. If the sea level rises faster than the rivers can supply sand, the rivers will start to erode. This can cause problems at locations with fixed bed levels, at areas with underground infrastructure and at bridges with columns in the river. This in turn can cause problems for shipping and road transport.

Consequences port
Construction of a new Maeslant barrier is expensive, as is raising the undulations, quays and terminals. However, the costs for the new barrier would be accounted for by the government, whereas the undulations, quays and terminals would be paid for by the port. Container and dry bulk terminals are more easily raised as important infrastructure, which has to be removed, is limited. Liquid bulk is already more expensive as the silos have to be removed before the terminals can be raised. Although shipping will experience downtime, especially when the new Maeslant barrier is constructed, delay time on the long run will be limited. This scenario would be most beneficial for unhindered entrance to the port, if the Maeslant barrier problem is solved.

2.3.4. Seaward - Barrier islands with or without barriers, seaward polders

General consequences
The third scenario is to move seaward, go against the sea and to shape a barrier of islands in front of the coast. These can either be interconnected or detached. If they are connected, the idea is to create offshore new land, above sea level, to protect the delta. If not, the islands will act as giant breakwaters, with calmer waves behind them. The latter version does not tackle more than one meter sea-level rise; however, as the sea is still free to move in and out. The amount of sand needed for this scenario is estimated at 100x the amount that was required for the Second Maasvlakte. However, sand is not an infinite resource (Peduzzi, 2014). In addition, the islands are situated in the areas where sediment is currently being dredged for beach nourishment, and offshore wind parks are constructed. Next to the expenses of the construction of the islands, the construction of the barriers and locks between the island will add to the costs.

An important question is to where the islands extend. Belgium faces many of the same problems the Netherlands have; thus they might be interested in expanding the idea to their coast. Do the barrier islands connect to the Wadden Islands at the northern end? The positive side of the barrier islands is that they can be built in phases and that the barriers and locks in between do not have to be constructed at the same time. The barrier islands can firstly act as giant breakwaters, diminishing wind and wave set-up at the (current) coastline and when the sea level rises, the island can be closed.

Consequences rivers
As with the first scenario, at higher sea-level rise, gravitational discharge of the rivers is no longer possible. On the plus side, the lakes created between the islands and the current coast can act as giant storage lakes for the riverine water. Although the storage lakes can manage the peak river discharges, overall large pumps still need to be created to discharge the daily flow. Low river discharges can cause problems for inland waterway shipping because of a lack of depth. The absence of tides can halt the creation of current scour holes in the river, but these can relocate towards the area of the pumps because of the high flow velocities there. Although less significant than the previous scenario, river dikes still need to be improved.

Consequences port
With interconnected barrier islands, the port is well protected against sea-level rise and storm surges. The accessibility of the port will probably decline; however, the consequences for the port differ for the options from which can be chosen.

If one or more barrier islands can be used as deep sea terminals, where the goods can be transshipped onto other modalities as rail and road transport, fewer vessels have to travel through the locks, resulting in smaller locking capacity needed. Current port terminals can be reused for housing or other functions. If it is not possible to construct deep sea terminals on the islands, the current port layout can be kept. This will have the disadvantage of locks before entering the port. These locks will have to accommodate the massive deep sea vessels and have to have a high capacity. A small canal can also be constructed between two barrier islands, such as the Hartelkanaal in the current port layout. It is situated outside the primal sea defence system, which means that the surrounding dikes and terminals have to be raised significantly. Either this canal will have to have a very high capacity to accommodate all vessels or some vessels will still have to enter separately through locks. Wind and wave set-up also add to the problems in this canal. Every option has its pros and cons. The best solution for shipping is probably a combination of the three.

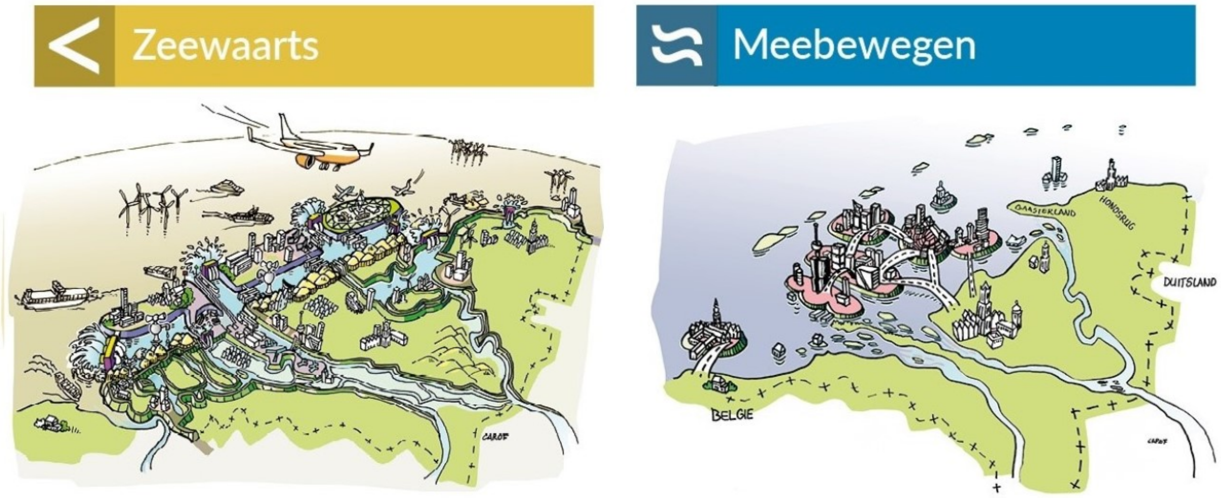


Figure 2.5: Seaward and retreat adaptation scenarios for high sea level rise of the Dutch Delta (©Beeldleveranciers-Carof commissioned by Deltares)

2.3.5. Retreat - Raised/floating buildings, raising the land, migration

General consequences

The final scenario is to live with and adapt to sea-level rise. This scenario has many versions and levels of adaptation as well, such as living in raised houses, floating or raised cities, retreating to higher ground and give the low lying areas back to the sea. The Dutch have a history of living with the sea, ranging from living on mounds to fleeing to the attics if the land is inundated. These are cheap options as the land does not have to be protected for the most severe storms. The problem is that the modern landscape is not suited to be inundated from time to time as it would be an expensive task to repair the infrastructure connecting the mounds and polders. It might be possible in less densely populated areas, not for the conurbation of Western Holland. Therefore, for this scenario, the situation is examined where the low lying land is given back to the sea, and the new shoreline is shifted in the Eastern part of The Netherlands, where the ground level is above sea level. This can be in combination with floating cities or cities on mounds.

When large parts of The Netherlands has to be given back to the sea, real estate and lands will become valueless, mortgages will have no backing, and the economy will suffer. Although this seems very unlikely to be chosen as a scenario, it can be triggered by flooding of an important area with casualties as a consequence. People might move on their own incentive to the eastern part of The Netherlands or West Germany. A phased and planned migration by the government can ease the impact on the economy, which has to be done with coordination with the German government too.

Consequences rivers

The location of the mouth of the rivers will move inland, to where the new shoreline is located. This will have a significant impact on the upstream water levels and distribution of the rivers. Sediment distribution will also change, and new branches can be formed. Current upstream structures will become too narrow, too high or useless at all as a river might choose another path. Inland ports may become redundant. A new delta can be created altogether. Although these changes will not happen overnight, critical shipping infrastructure must be present when a river or a branch changes course. A large part of the European inland waterway network could be affected and with it, inland shipping.

Consequences port
The current port layout and its operations will no longer be the same. Either the entire port will move to the new shoreline, or it will be divided into a deep sea part for the large seagoing vessels and an inland part, at the new shoreline. New deep sea terminals must be constructed, or the current Maasvlakes could be used if the berthing capacity and berthing circumstances are still adequate. If the migration and inundation are planned beforehand, the port could save costs by buying the land for the inland port and completing the infrastructure in phases. The entire inland port could be made 'in the dry', as opposed to having to dredge the terminals, which saves money. The amount of area of deep sea terminals and inland port will be dependent on the expected throughput. Companies and industries can choose to go to a different port for the transition phase but can also benefit from the cheap inland port terminals if they are early. An important question is also what the supply route will be between the deep sea terminal and the inland port. A bridge could be the solution, such as the Donghai Bridge in Shanghai. An inland waterway could also be challenging as the newly created sea could be teeming with obstacles not removed before the migration.

2.4. Concluding

There is large uncertainty in sea level rise and especially its timeline. However, most signs and scientist suggest that it is impending. Following the sub-question of the chapter:

> *What are the possible scenarios to adapt to sea-level rise for the Netherlands and what consequences do they impose?*

Concluded can be that there are four adaptation scenarios to be chosen from, as imagined by Deltares. These are “Open protection”, “Closed protection”, “Seaward” and “Retreat”. These scenarios are divers, and each gives different challenges for the country, the Dutch economy and the port of Rotterdam. Scenarios “Open protection” and “Closed protection” need tremendous amounts of sediment if soft protection is maintained, “Seaward” even to a greater extent, imposing large investments. “Retreat” is least desired as a (large) part of the country would be lost. It is most likely to happen because of an incidental dike breach in an important area or when it is not economically viable anymore to keep protecting certain areas.

The current strategy of the port of Rotterdam is to raise the port terminals when contracts end, thereby growing with the sea level rise. This strategy is set to hold until 2100 or +1 m sea-level rise. After that, other scenarios are explored. “Closed protection” and “Seaward” imply that (large) locks need to be placed in order to keep the Dutch ports accessible, although, for the latter scenario, locks can be placed at a higher sea-level rise. Scenarios “Open protection” and “Retreat” result in that ports can still be accessible, although port terminals need to be raised. In addition, “Open protection” implies that parts of densely populated areas have to be raised too. For shipping, these scenarios mean the least impact on shipping and port activities.

This chapter examined the adaptation possibilities to sea level rise in a broader sense. The following chapter examines actual strategies which are more detailed—thereby exploring if shipping and port activities are accounted for in the strategies and what methods are used to do so.

3

Current literature analysis on the effect of climate change on shipping & port activities

Chapter outline

This chapter answers the sub-question: "What is the current method of calculating the effects of sea-level rise strategies on shipping and port activities and are there shortcomings in those methods?"

In the previous chapter, the general influences of sea-level rise on shipping and port activities are analysed. In this chapter, we will examine how and if current adaptation strategies and landscape visions take those aspects into account and what their shortcomings are. The current literature is studied by analysing landscape visions and adaptation strategies. These strategies are obtained from Deltares and the Delta Programme. Deltares has combined almost 200 visions and strategies for the Dutch coast in a blog named Kust Wiki Idee (Coast Wikipedia Idea) (Deltares, 2020). In addition, the Delta Programme is investigating the options available for the Rijnmond-Drechtsteden area, and these will also be included.

These visions and strategies from Deltares and the Delta Programme have a wide range of different impacts on the landscape. Therefore they are first tested if they have an actual impact against sea-level rise. The strategies that do are then further investigated. Next, these strategies are examined in detail if they take influences on shipping and port activities into account. From the strategies that do consider shipping and port activities, with detailed figures, the method is analysed. This is done based on the steps taken, the computer models used and possible errors and shortcomings of the method. The chapter is concluded with what can be improved and further analysed in this thesis.

3.1. Examining current strategies on sea-level rise adaptation

174 strategies collected by Deltares are tested and two from the Delta Programme, totalling 176 strategies. The strategies are assessed by subjecting them to two sets of criteria. The first set is the examine if they actually have an influence against sea-level rise and if there is a technical report with details of the strategy. The remaining strategies are subjected to a second set of criteria, to investigate if and how they include shipping and port activities and which method they apply to analyse these aspects.

3.1.1. First selection: analysis based on sea-level rise and technical reports

The first set of criteria are given below. From the 176 strategies, 161 are dropped based on these criteria. In total, fifteen strategies remain. This means that of the 176 investigated strategies, 9% include strategies that account for sea-level rise and include a technical report. An overview of the strategies and the criteria why they are dropped can be found in Table B.1 in Appendix B.

1. Does the strategy include spatial sea-level rise adaptation?
   Some strategies have an influence on the coast or the landscape but do not give a solution to sea-level rise. Other strategies which only give energy or food solutions are also not considered.

2. Has the strategy a large scale impact?
   Several strategies have only local effects, in part of the country which does not have major influences on the central coast of important parts of the Netherlands, such as the North and South Holland or other important regions.

3. Is the strategy outdated?
   There are strategies on the website of Deltares which are either already executed or other versions are executed whereby the strategies become void.

4. Is there is a technical report available of the strategy?
   The website of Deltares gives a summary of the strategies. However, if a strategy ticks all the boxes above, but there is no report available about it, the strategy cannot be examined in detail and thus will still be dropped.

3.1.2. Second selection: analysis based on inclusion of shipping and port activities

Subsequently, the fifteen remaining strategies are examined in detail. This is done using a second set of criteria. The aim is to determine if there are existing comprehensive methods to quantify the influences of on shipping or port activities. The criteria are given below. Table 3.1 gives an overview of the strategies and if and how shipping or port activities are mentioned. Following these criteria, three strategies remain. Section 3.2 further analysis these strategies.

1. Are shipping and/or port activities influenced by the strategy?

2. Are the influences on shipping and port activities taken into account?

3. If this is the case, are these influences qualitatively or quantitatively taken into account?

4. If quantitatively, are those figures detailed or estimations?

Table 3.1: fifteen strategies evaluated on the above criteria

Name strategy	Year	Author	Shipping or port activities
Nieuwe Hollandse Zeelinie	2001	ir. W. Bos	Nothing mentioned
Nederland Omhoog	2004	Deltares, Provincie Zuid-Holland	No influence
Terpen van baggerspecie	2004	Rijkswaterstaat	No influence
De mooiste en Veiligste Delta 2010-2100	2007	RWS, Deltares, TNO	Qualitatively mentioned
Nederland Later	2007	Milieu- en Natuurplanbureau	Nothing mentioned
Superdijk	2011	Deltares	No influence
Deltaprogramma Rijnmond -Drechtsteden	2012	Deltaprogramma	Quantitatively mentioned, in detail
Wisselpolders	2013	IMARES, WUR	No influence
Plan Sluizen	2014	Deltares	Quantitatively mentioned, in detail
Drijvende stad	2014	F. Boogaard, R. de Graaf, M. Dionisio Pires	No influence
Hackathon Retreat Scenario	2017	Deltares	Nothing mentioned
Plan New Netherlands	2018	G.J.M. van der Meulen	Qualitatively mentioned
Plan Beaufort - Haakse Zeedijk	2018	Adviesgroep Borm & Huijgens	Qualitatively mentioned
Invloed Zeespiegelstijging Rijn-Maas Delta	2019	Deltares	Quantitatively mentioned, in detail
Natuurlijke toekomst voor Nederland in 2120	2020	WUR	Qualitatively mentioned

3.2. Analysis of the three selected strategies

3.2.1. Method of analysis

As can be seen from Table 3.1, three strategies give quantitative, detailed, results about the influence the strategy has on shipping and the port of Rotterdam. The results of these strategies stretch over multiple reports, over a period of years and include multiple companies for calculations and expert sessions. These strategies are further analysed using the following set of questions.

1. Which steps do the strategies take?
2. What is the input and output of the steps?
3. Which computer models do the strategies use and what is their output?
4. What are the benefits of the method?
5. What are the shortcomings of the method and computer models used?

3.2.2. Analysis of the three strategies

Deltaprogramma Rijnmond-Drechtsteden | mogelijke strategiëen (2012)

In 2011, a preliminary study was suggested to examine the possible flood protection strategies for the Rijnmond-Drechtsteden area, in which the port of Rotterdam is situated. The Department of Waterways and Public Works (Dutch: Rijkswaterstaat) tasked Deltares to examine the consequences of +0.85 m sea-level rise for different areas and aspects. Deltares, in turn, tasked Ecorys with the calculations of the effects of flood protections measures on shipping and port activities. This strategy has the most resemblance of “Closed protection” and “Open protection” of the Deltares scenarios. In the final report, five main strategies and three extra sub-strategies were examined (Ecorys, 2012):

1. Optimising the current strategy;
2. Closed seaward side;
    (a) Locks on the seaward side;
    (b) Locks on the seaward side in combination with a ring of locks in rivers;
3. Open Haringvliet;
    (a) Complete removal Haringvliet barrier;
    (b) Complete removal Haringvliet barrier in combination with a ring of locks in rivers;
4. Less discharge over the river Lek during peak discharges;
    (a) Reroute discharge over the river IJssel;
    (b) Reroute discharge over the river Waal with a ring of closable river barriers.

In the proposal for the approach to calculate the effects, the strategies are compared to the reference situation, which is the continuation of the current strategy (Ecorys, 2011). Then the climate projections are explored. These projections are possible scenarios for global warming and sea-level rise, ranging from the lower expected percentile to the upper expected percentile. From those projections, adaptation strategies follow, whereby it is noted that the suggested strategies will probably not match with the strategies which will eventually be calculated. From these strategies, the hydraulic structures follow, such as locks, weirs, (increased) closure frequency storm surge barriers and bridges. Subsequently, the projections for the social-economic growth and throughput of the port are explored. These projections are translated to the number of vessels movements through the port and inland waterways via in inland shipping model.

An iterative process is applied to determine the effects on the accessibility of locks in combination with the strategies. In this cycle, three models are used. A lock simulation model, which gives the waiting time and locking times of the locks based on lock dimensions, a container modal shift model which includes port competition results and a bulk commodity modal shift model. The purpose of the latter two models is to examine the effects of a lock and its capacity on the modal and port shifts if the waiting time is too long. Different lock dimensions give different waiting times which result in varying modal and port shifts.

The results are the throughput of the port, which is then translated to the direct economic consequences. These include higher transport costs for the receiving party, a negative effect on reliability and the effects on port revenue and infrastructure. These translations are made using key figures. As the port of Rotterdam has an influence on the entire Dutch economy, the (indirect) consequences are also calculated. These include the labour and housing markets, the reduced demand on industry and terminals, effects on the safety of shipping and effects on spatial development and living environment. An overview of the steps is given below and in Figure 3.1. Appendix B gives a more detailed overview of the effects studied, how they are determined and in which units.

1. Set the reference situation, which is the continuation of the current, preferential strategy of the Rijnmond-Drechtsteden area. Make projections for the throughput through the port and over the inland waterway network for the reference situation. Determine the closure frequency of the current protection measures, which are the Maeslant barrier, the Hartelkering and the Hollandse IJsselkering;

2. Compare that to the new strategies and note the changes in closure frequency and duration of the barriers. Plus the location, dimensions and number of new locks which have to be built;

3. Determine the hindrance of these strategies on shipping and port accessibility. Calculate the expected and unexpected waiting times and analyse possible limitations for ship dimensions;

4. Determine the change in the modal split and shift to other ports due to the hindrance. Do this iteratively in combination with the waiting times of the locks. Note the optimum throughput versus the costs of certain lock capacities of the different strategies;

5. Translate the remaining waiting times to the direct economic effects using key figures and access the future effects on transport costs;

6. Estimate the indirect and extreme effects using key figures and expert sessions.

Motie Geurts/Plan Spaargaren/Plan Sluizen (2014)

The second is Motie Geurts, otherwise knows as Plan Spaargaren or Plan Sluizen (Plan Locks). The motion was asked in parliament in 2014 by Mr Geurts (Tweede Kamer der Staten-Generaal, 2014), in which locks would be placed in the Nieuwe and Oude Maas, near the Benelux tunnel and compared with the current, preferential strategy to keep the port protected with a storm surge barrier (Van Waveren, Kors, Labrujere, & Osmanoglu, 2015). Although comparable to the former study, a separate study was conducted to compare the two strategies. This strategy also has the most resemblance of “Closed protection” and “Open protection” of the Deltares scenarios. The same method by Ecorys was applied to determine the influences on shipping and port activities. However, more funds were available (as it was now backed governmental research) and some corrections were made which resulted in large differences between results the reports:

1. A larger number of passages of ships through the port of Rotterdam was applied for the projections, as new counting methods by the Port of Rotterdam Authority showed that more ships pass through the port than previously thought;

2. The economic growth projections for future predictions were lowered

3. Accounting for a sea-level rise of 0.85 m, the closure frequency for the Maeslant barrier, Hartelkering and the Hollandse IJssel kering were set at 6.5, 6.5 and 65 times per year, respectively;

4. The key figures to translate the time factors to monetary values were actualised and strongly differed from the key figures from the previous report;

5. The previous report used passage costs which were substantially higher than the actual costs, which was adjusted in this report.

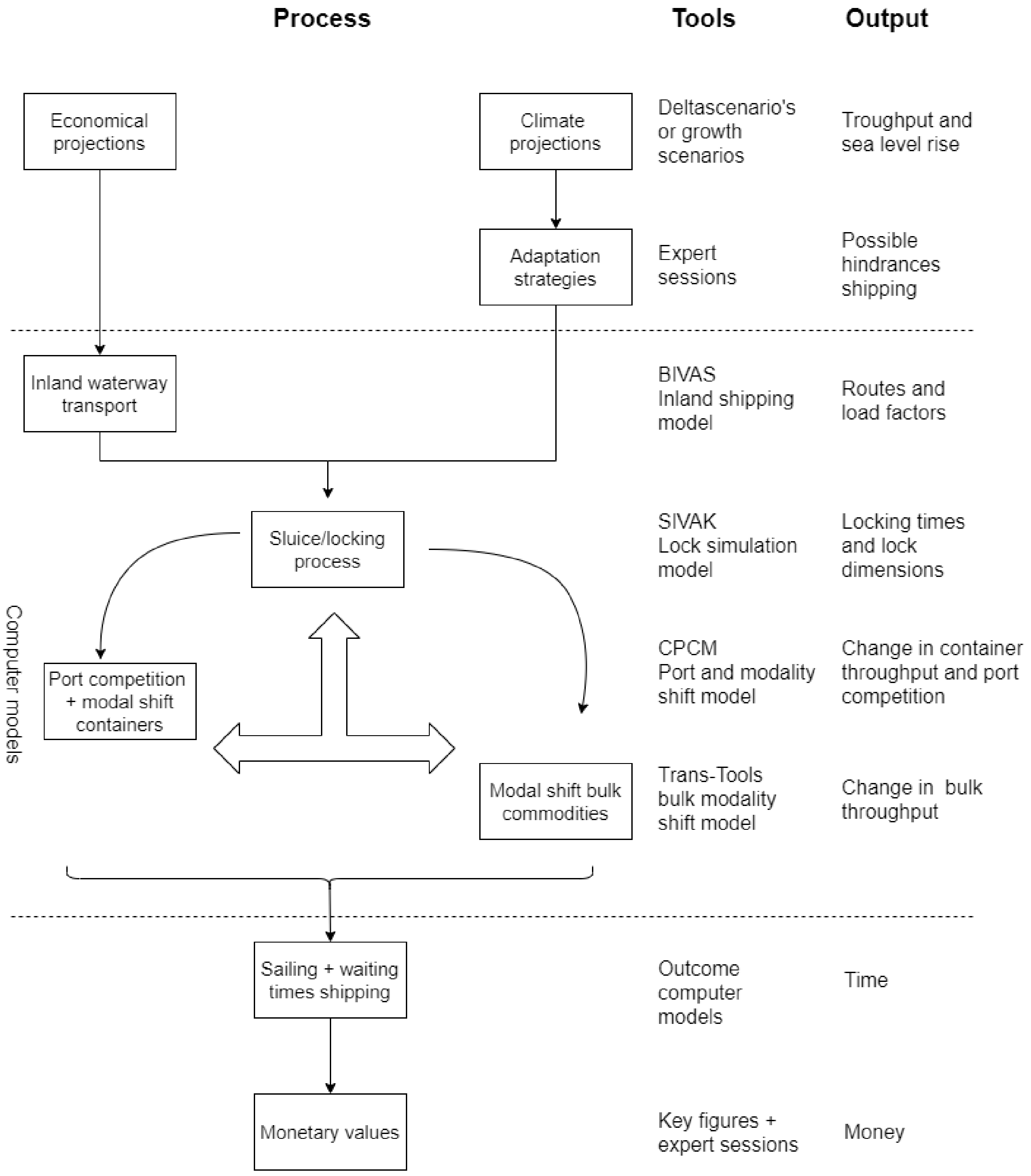


Figure 3.1: Schematic overview of the current method process to analyse the effects of climate change on shipping and port activities. Adapted from (Ecorys, 2011).

Three steps were taken to calculate the costs on shipping. First, the number of shipping passages per lock unit was determined. Using model simulations, the time per passage of a lock was assessed. Secondly, the costs per lock unit were calculated and combined for different years and growth projections. Lastly, the results were calibrated for the effects on the competitive position of the port resulting from the locks and uncertainties on passage times, the value of time and the projections of the number of deep sea vessels which would pass through the locks in the Nieuwe Maas.

The report stated that the resulting figures were not stable and reliable enough to draw any informed conclusions for increased costs for passages through locks, especially for the projections of the year 2100. Recommended was that due to the high uncertainties of the key figures used and the large differences in the results compared to the previous report, further research must be done about the extra yearly passage costs for shipping in 2100. As the same methodology was used, Table B.2 can be assumed identical for this report, albeit with different key figures.

Invloed Hoge Scenario's voor Zeespiegelstijging voor Rijn-Maas Delta (2019)
In recent reports, both studies are combined in the options for the Rijnmond-Drechtsteden area, where Plan Sluizen is used synonymously for closing the seaward side with locks. The latest report is one made by Deltares in which the effects of higher sea-level rise is examined for the current, preferential, strategy and introducing locks in the Maas (Kind et al., 2019). The effects were studied again as recent studies had shown that sea-level rise was the most important influence for the long term strategy of the Rijnmond-Drechtsteden area. In this report, the effects of +1, +2 and +3 m sea level rise were investigated for the preferential strategy (renewed Maeslant barrier) and +1 m sea-level rise for Plan Sluizen. However, the consequences on shipping and port activities were copied from the previous report, of Motie Geurts/Plan Sluizen thus, and no new results were obtained. Emphasised is that the estimations, assumptions, projections, key figures and effects on port competition were uncertain and unstable.

3.2.3. Conclusion of the current strategies

From Section 3.1, it can be concluded that there is a wide range of strategies to adapt to sea-level rise. Of those strategies, only three quantitatively consider their influence on shipping and port activities. The three strategies use the same method, as conceived by Ecorys, and two even use the same results. In this section, the shortcomings of the method are analysed. First, the general problems of the method are given; subsequently, the computer models used in the method are discussed and lastly the method is analysed per Deltares scenario. The analysis of the "Closed protection" and "Open protection" scenarios are combined.

3.3. Shortcomings adaptation methods used for current strategies

3.3.1. General shortcomings strategies

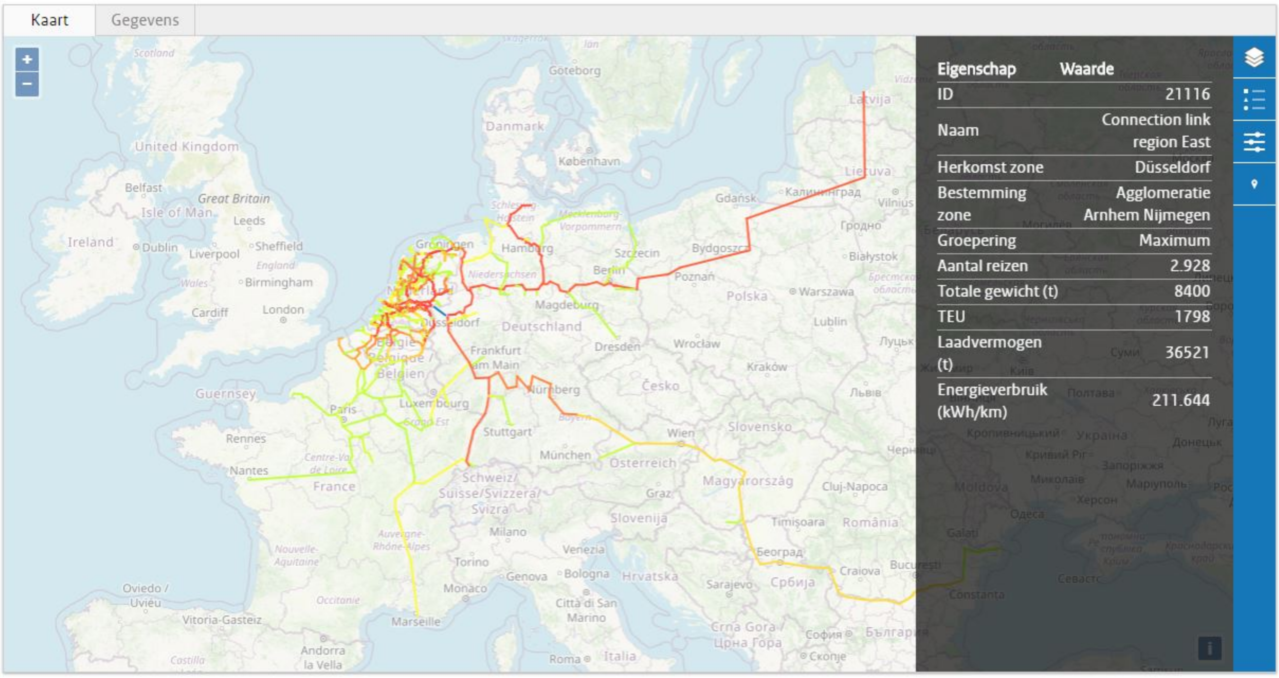
The current method has two main problems. Firstly, it lacks the ability to adapt to the network and landscape to significant changes in the landscape due to sea-level rise. Secondly, several expert sessions need to be held, and four computer models need to be used in order to reach a result, making it cumbersome. As one iteration over the entire process is time-consuming and expensive, multiple iterations over the entire process are less likely to happen when alterations are made. Knowledge and insight are needed about the use and results of the models, which takes time. Other problems are clarity, uniformity and reliability of the figures used. This starts in the economic and climate projections. These already differ for the report Deltaprogramma Rijnmond-Drechtsteden and the report Motie Geurts. If current projections were used, different results would be obtained yet again. Although this is obvious, the result is that the reports cannot be compared. Furthermore, the key figures used to translate shipping- and waiting times likewise keep changing as more insight and accuracy of the figures is acquired. Different closing levels and frequencies were used in the reports, which further complicates the comparison between reports. Lastly, only a sea-level rise of +0.85 m was applied in the method.

3.3.2. Shortcomings computer models used in the strategies

The four computer models used are examined in this section in further detail. Per model, an introduction is given about how it works, what the input and output of the model are and then what the drawbacks and shortcomings are. In doing so, the “black box” effect is minimised. This is the effect when one uses computer models and does not know precisely what the models do internally. The models used can be related to the implementations; however, they were designed for other specific applications.

BIVAS

Binnenvaart analyse systeem, or `BIVAS` in short, is a computer model developed by the Dutch Department of Public Works (Rijkswaterstaat). It has the ability to analyse the (current) inland waterway network of Northwest Europe and the Netherlands specifically. The model consists of a network of nodes and arcs. The nodes are the beginning and endpoints of an arc, and an arc can be a stretch of waterway, a lock, a weir or a bridge. Characteristics are given to the arcs which can form hindrances for the network. Then traffic projections are introduced to the system which takes as input the departure date, origin, destination, vessel dimensions and characteristics of the freight. Lastly, discharge conditions, flow velocities and water depths are implemented. It then calculates if a trip can be made or if alternate trips or if varying loads are more suitable. As output, it gives a network of waterways coloured on the intensity of the desired output, such as total weight or trips. To examine a particular river(stretch), the stretch can be selected to examine the possible outputs. An example is given in Figure 3.2.



Eigenschap	Waarde
ID	21116
Naam	Connection link region East
Herkomst zone	Düsseldorf
Bestemming zone	Agglomeratie Arnhem Nijmegen
Groepering	Maximum
Aantal reizen	2.928
Totale gewicht (t)	8400
TEU	1798
Laadvermogen (t)	36521
Energieverbruik (kWh/km)	211.644

Figure 3.2: Output example of the computer model BIVAS (Charta Software B.V., 2019)

The computer model has several shortcomings. These are identified by Van Meijeren and Groen (2010) and by Prins (2017), whereby the latter report used historic input to compare to actual historic data. An overview is given below:

- As the computer model uses a fixed network, it cannot (easily) include changing river courses. If due to sea-level rise the downstream conditions of a river change, the backwater curve can alter the flow conditions and river course. Likewise, if a new stretch of river is dug, it is difficult to add that change in the model. This is a large issue when modelling for sea-level rise and changing boundary conditions. Alterations in the network can only be made by the developers of the model in updates of the model;

- The model has no limits in the number of vessels in the fleet. If due to draught a vessel can only take one-third of its load, the model generates two more vessels. However, a limitation to the number of vessels cannot be set; thus, an infinite number of vessels can be created, which is not realistic. The model does not simulate the vessel travelling from destination A to B; it only checks if that trip is possible. The model does not include that the fleet is already in use and that there are no vessels available;

- When low or high water level occurs, it does not consider that the usage of (specific) weirs or locks are employed, which can cause obstructions and result in waiting times and trips over different routes. Furthermore, during low water level conditions, it selected the use of the river Waal, as opposed to the use of the Neder-Rijn and Lek, where weirs control the water levels;

- The calibration of the model can be off. When a simulation with historic input was made, it showed that the model routed trips via other waterways than the actual ones used. When manually calibrating the issues, an improvement of 25% was found. In addition, it was found to select illogical routes and vessel speeds;

- The model takes as input for the river dimensions the maximum vessel class it can handle. With this input, it calculates the wet cross-section of the river, as opposed to the actual wet cross-section. It thereby does not take the level of service of a waterway into account. This means that if a river is narrower (due to drought for example) or busier, the sailing speed and overtaking abilities of vessels diminish;

- A collection of other problems the models do not consider: the tides, ability of a shipper to wait to make a trip, not choosing different routes as it is more difficult or out of habit, not choosing routes due to uncertainty in waiting times at locks and bridges and the extra fuel usage for a different trip.

SIVAK II

The computer model `SIVAK II` (SImulatiemodel voor de Verkeers-Afwikkeling bij Kunstwerken II) simulates nautical and road traffic at locks, bridges and constrictions in an inland waterway network. This gives the user insight into the traffic handling at inland waterway bottlenecks. It takes as input a network, vessels and road traffic (if needed). As output, it provides tables of figures for bridges, locks, vessels and road traffic (Rijkswaterstaat, 1998; Chen, Ligteringen, Chen, Mou, & Ligteringen, 2013; ten Hoven & Bilingska, 2015). Figure 3.3 gives a schematic overview of an example network with input and output of the model. One can use this model to study what the optimum dimensions of a lock or bridge are in order to minimise waiting time and costs. The output is then used in the `BIVAS` model. The model has two main drawbacks, according to Lamboo (2014), which are stated below. It must be noted that construction engineering company Witteveen+Bos is developing a new version of `SIVAK II`.

- Human factors are difficult to simulate. Most locks are operated by a lock keeper, which makes their influence hard to simulate. However, it is an important factor to the efficiency of a lock;

- Lock capacity depends on dimensions of the vessels passing through it. If the future dimensions of the vessels and fleet composition increases and change, the capacity of the lock will reduce. As the future dimensions and composition of the fleet are unknown, it is difficult to make estimations about lock capacities and congestion. Assumptions made now can be invalid in future results.

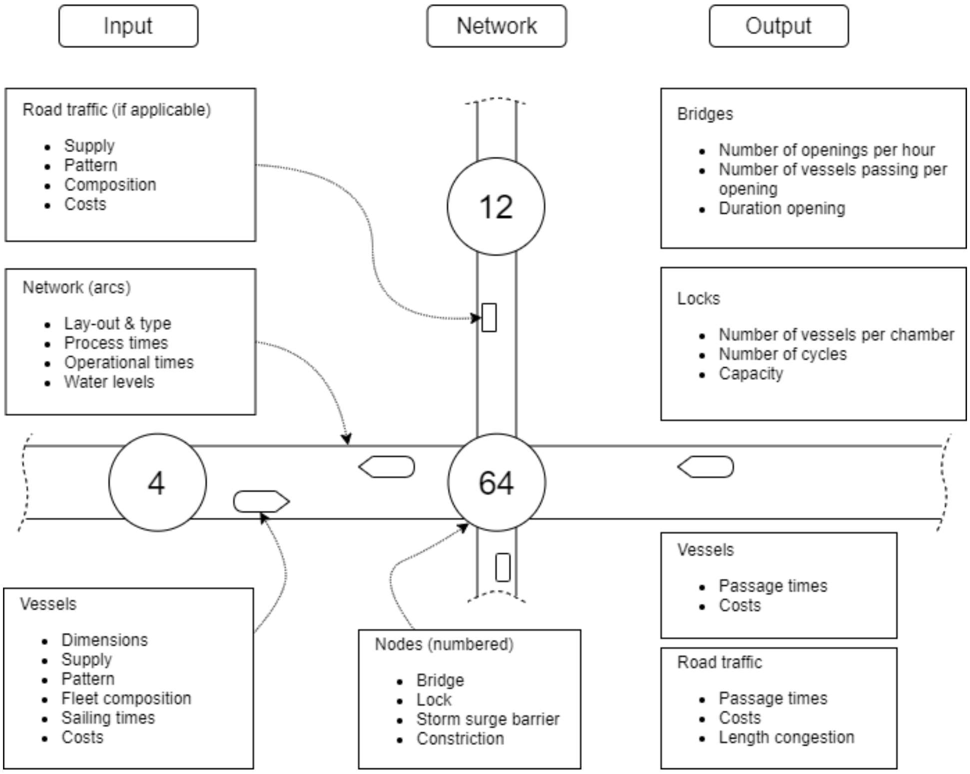


Figure 3.3: SIVAK II model with input and output parameters. A fictive projection is depicted in which a road (vertical) crosses a waterway (horizontal).

CPCM

Ecorys developed, together with the Netherlands Bureau for Economic Policy Analysis (CPB), a market share model for Western European container ports: Container Port Competition Model (`CPCM`) (Veldman & Bückmann, 2003; Macharis, Haezendonck, Veldman, Bückmann, & Van der Flier, 2004). With this model, the competitive position of port and hinterland modalities is determined on the basis of the considerations of the customers/shippers in the hinterland over the entire container transport chain between customers/ shippers and seaports. The weighting is explained on the basis of cost and quality factors of the different seaports and hinterland modalities, as experienced by the users. The model was initially developed to examine the increase in port competition of the port of Antwerp if the accessibility of the Western-Scheldt would be increased.

A container can be imported from China to a certain region or exported to a certain region to China using different routes whereby different ports and modalities can be used. The model selects the route with the highest value, whereby a trade-off is made between quality and pricing. The quality is based on the transport time and frequency of which the route is used. A higher value of a route implies a higher chance that a shipper will actually use the route. For pricing, key figures are used for the costs per modality for a given distance. Using historical data, the port competition and hinterland modality competition per region are replicated. The model uses the following aspects:

- The Northwest European hinterland: dividing Germany, Belgium, Luxembourg, the Netherlands and France in 70+ regions;
- Feeder function: to the U.K., Ireland, Norway, Iceland, Sweden, Denmark, Finland and other Baltic Sea ports;
- Deep sea ports: Le Havre, Zeebrugge, Antwerp, Rotterdam, Bremen and Hamburg;
- Hinterland modalities: road, rail and inland waterway.

The choice to use a port is made using a logit model which applies formula 3.1. For a specific region r, the probability P is calculated that a particular route is chosen from all possible routes. In the calculation, a combination is made between a modality m and a port p. Per route is denoted which port is chosen, which results in the port competition. The model and coefficients are calibrated with a regression analysis using historic data of 1997 and 2001.

$$P^r_{m,p}(m = 1, \dots, M, p = 1, \dots, P) = \frac{e^{U^r_{m,p}}}{\sum\limits_{m=1}^{m=M} \sum\limits_{p=1}^{p=P} e^{U^r_{m,p}}} \tag{3.1}$$

where:

$U^r_{m,p}$ = The utility for a given route in region r;
M = The total number of modalities, three (road, rail and inland waterways);
P = The total number of ports, six (Hamburg, Bremen, Rotterdam, Antwerpen, Zeebrugge and Le Havre.

with:

$$U_{m,p} = \alpha_{m,p} D_{m,p} + \alpha_1 C_{m,p} + \alpha_2 T_{m,p} + \alpha_3 F_{m,p} + \alpha_4 W_p + \alpha_5 M_p \tag{3.2}$$

where:

$D_{m,p}$ = Dummy variable indicating preference for a route;
$C_{m,p}$ = Shipping costs of a route for one TEU, including the freight rate, handling charges, land transport costs, etc.;
$T_{m,p}$ = Transit time for a route;
$F_{m,p}$ = Frequency of a route;
W_p = Routing resistance of a port, limited depth, tidal window, etc;
M_p = Capacity or volume of a port;
$\alpha_{m,p,1 \dots 5}$ = Coefficients of the utility function.

A schematic overview of the model can be seen in Figure 3.4. The model mainly consists of equation 3.1 which uses (static) data of the transport time and distances to reach specific regions using different modalities. This means that if landscapes, river courses or port locations change, this model cannot be used as is does not generate its own data. The data it uses is obtained from the ETISplus program database, which is short for European Transport policy Information System. The aim of this program is to provide a transport database using official statistics and figures. The program ended in 2012 (CORDIS European Commission, 2019). This means that if the model where to be used again, the coefficients would have to be updated for current figures. The model has several drawbacks, as described by Mueller (2014):

- Similar pricing is used throughout Europe. The labour and equipment costs can differ per country, whilst homogeneous figures are used;
- Although the model does include many factors, some are missing: port reliability, port efficiency and port service;
- The model only includes trips between Asia and Europe, whilst there is also trade with other continents;
- It does not include capacity constraints of hinterland infrastructure, such as railway or inland barge capacity;
- The model only focuses on the container trade; it is not suitable for other commodities.

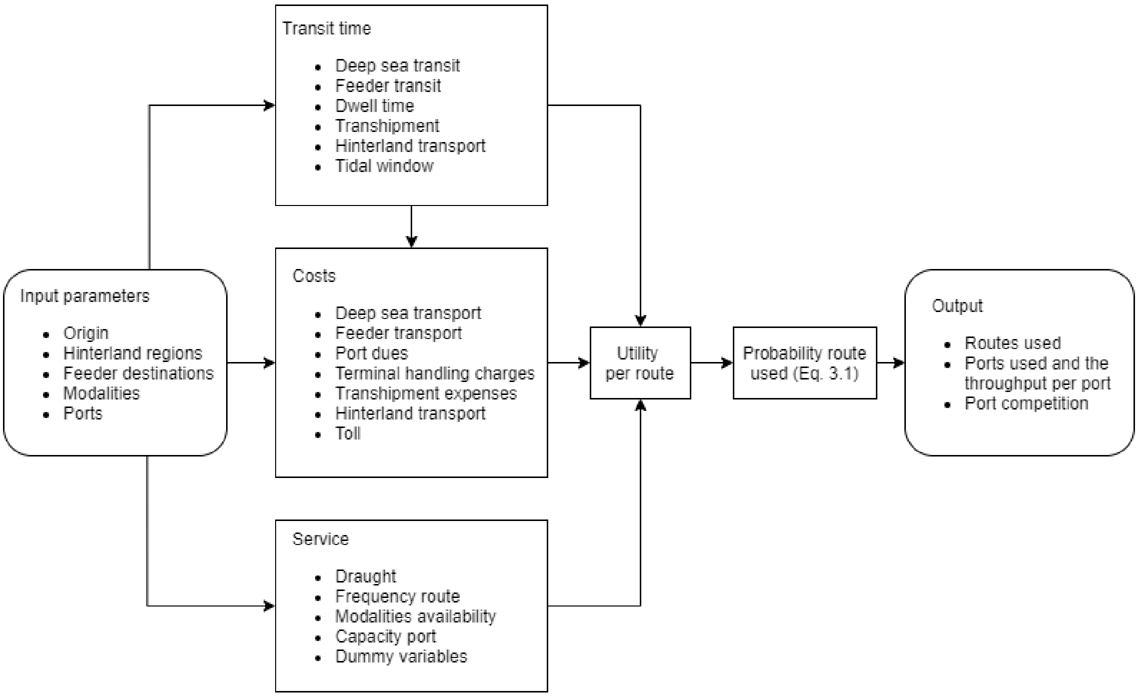


Figure 3.4: Schematic overview the CPCM, modified from (Mueller, 2014)

Trans-Tools

Trans-Tools is a European transport network model. It is developed by TNO and commissioned by the European Commission (Burgess et al., 2008). Although similar to the `CPCM`, it is more extensive. It does not only focus on container cargo but includes other commodities (dry bulk, liquid bulk, RoRo), passengers and air travel. However, for the purpose of the method as described in Section 3.2, the model is only used to examine the shift in bulk commodity transport. Similar to the `BIVAS` model, it uses the layout of the European transport networks to simulate the flow of different modalities. Contrarily, the Trans-Tools model incorporates all of Europe and all three modalities, instead of only the inland waterways.

Trans-Tools is a multi-modal network model, which covers the EU-25 member states plus links to external zones. A reference year (2000) is used as a base case to simulate the movement of passengers and freight. The population density of standard statistical European regions, NUTS 3 regions is used to determine the transport demand. This demand responds to changes in infrastructure, transport costs and times. In addition, the model takes congestion, indirect transport effects and environmental impacts into consideration. ArcGIS can be used to visualise the output of the model and make changes in the network by the user. For the network, it uses the TEN-T and main national network links.

The model uses five sub-models, a freight demand model, a passenger demand model, an assignment model, an economic model and impact models. The sub-models are linked using conversion routes which allows feedback between the sub-models. This results in an equilibrium between supply and demand. As input, the model takes a preset projection and altered projection(s) by the user. Changes to that projection can be the projection year, the network, databases, GDP growth rates, other projections, etc. From that base case, projections are made to the desired year, which can be compared to the user's projections. Each of the sub-models gives several outputs which can be viewed dependent on the users requests. Output examples are the increase in tonnages per country, freight modal-split per country of origin or passenger transport performance. The output can be compared to the base case, reference projection and (multiple) user projections. These results and changes to the reference projection can be viewed in Microsoft Access and ArcMap. In ArcMap the results are shown per network or in NUTS regions. Fig. 3.5 gives a schematic overview of the model.

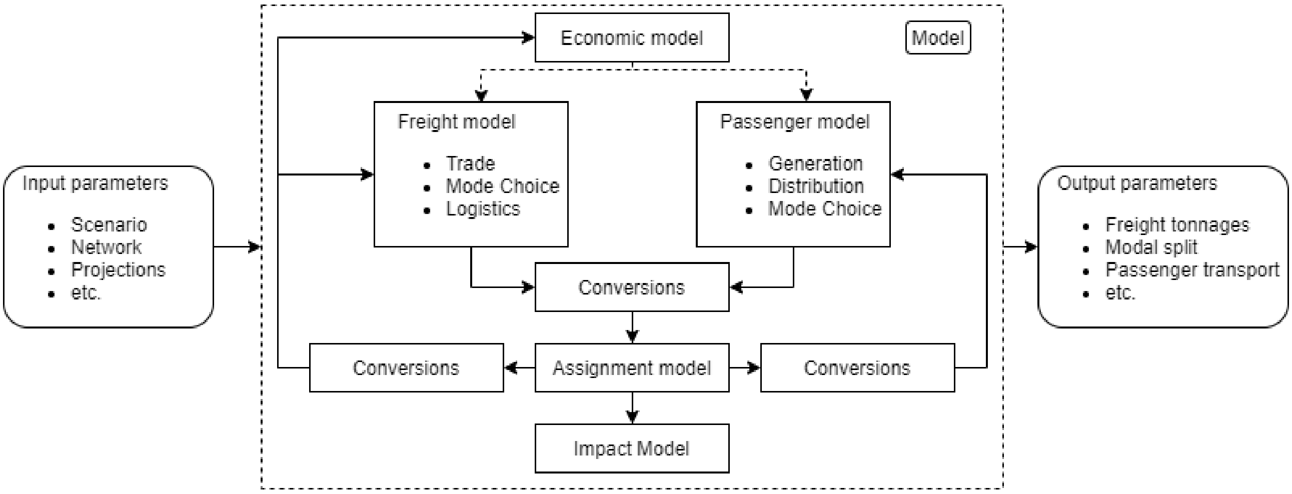


Figure 3.5: Schematic overview of the Trans-Tools model, adapted from (Burgess et al., 2008)

Several weaknesses in the model can be identified (Burgess et al., 2008; Van Meijeren & Groen, 2010; Ecorys, 2011). It must be noted that there is a new version: Trans-Tools 3. This description is about Trans-Tools 2 however, as was applied in the method examined in Section 2.2. The shortcomings are explained below:

- Advised is to use a dedicated computer for the model as the run time of the model is three days. This makes multiple simulations for different models less attractive;
- Capacity problems in other transport modes. If a shift in modalities occurs, the model assumes that there is an immediate and infinite supply of other transport vessels, as trucks and railway wagons;
- The model does not consider intra-zonal traffic, the exchange of freight and passengers between zones on a local scale. This exchange can amount up to 50% in some cases for passenger movements;
- The model produces around 3.5 GB of output data per run. The user cannot preselect the desired output data in order to minimise the output size or if more detail is wished about a component;
- Some input parameters cannot be changed by the user, such as unitary costs components, fixed times, etc. E.g. fuel is not a separate component. Thus fuel taxes cannot be implemented in the model;
- For future predictions, it is unclear what the increase in capacity will be of the modalities. If a projection after, say 2100, is chosen, there is large uncertainty in what the capacity of a modality will be. Thus no accurate predictions can be given;
- Furthermore as an energy transition is expected in the (near) future, the trend of flows of energy sources and thus raw materials and resources can break;
- This model is primarily focused on the flow of goods through Europe. The port of Rotterdam handles an intercontinental flow of goods, which is not included in the model;
- Port competition is not an element of the model.

3.3.3. Shortcomings for Deltares adaptation scenarios

With the shortcomings of the method and models used are known, the shortcomings for the Deltares scenarios specifically are explored. As the Open and Closed projection are similar in layout, they are combined.

Open and Closed protection scenarios

The current implementation of the method to examine the consequences of sea-level rise on container logistics mainly focuses on the "Open" and "Closed protection" scenarios of Deltares. Therefore the method is quite suitable for these scenarios. As it uses four computer models, the results of the method are elaborate en detailed. However, it is also time-consuming and expensive to run if the calculations are made by a third party. Therefore multiple iterations over the full method are less likely to be made. Another shortcoming is the inability to change the layout of the Dutch and European landscape, inland water network or port locations in the `BIVAS` and `CPCM` models. If one would, as an example, dig a new port entrance 20 km above the current one or a port outside mainland Europe was chosen, it could not be modelled.

Seaward scenario

For inland water transport, option "Seaward" is quite similar to options "Open protection" and "Closed protection" and can be examined using the same method, although facing the same problems as stated above. The main differences between this option and the former two are that the position of the coast has changed and that there are object/barriers in the sea, which can impose challenges for shipping. The objects in front of the (current) coast can mean that ships must follow an access channel in which wind and wave conditions can hinder the sailing velocity. The new coastline and (possible terminals) imply that the `BIVAS` model cannot be used as there are new boundary conditions, limits and shipping lanes.

Retreat scenario

For this scenario, the most problems with the current model arise. If (parts of) countries are flooded, the upstream course of the rivers alter. Ports possibly have to be relocated and locations where goods flow to disappear. As the current inland waterway network shall change, making the use of the `BIVAS` and `CPCM` models unfounded. This will not only have an effect on the Netherlands but on a broader European scale as other countries will also have implications due to sea level rise.

3.4. Concluding

In total 176 strategies were examined of which 161 were dropped based on the account of not having an influence on sea level rise projection and not having a technical report to analyse. Of the remaining fifteen strategies (9%), three strategies give quantitative results about their consequences on shipping and port activities influences are. All three strategies use the same method (albeit with a updated key figures). With this we can answer the first part of the chapter's sub-question:

> *What is the current method of calculating the effects of sea-level rise strategies on shipping and port activities?*

There is currently one method, contrived by Ecorys, which can give quantitative results of the effects of sea-level rise strategies on shipping and port activities. This method is complicated as it uses four models and the time to complete one entire cycle of the method is in the order of weeks. The models need economic, and climate projections as the different envisioned sea level rise strategies. The output is the costs for the Dutch economy.

The shortcomings of that method were analysed in three steps. The general shortcomings of the method, the shortcomings of the computer models and the shortcomings per adaptation scenario. The shortcomings are summarised below. However, there are two main shortcomings, to which the second part of the sub-question can be answered:

What are the shortcomings of the current method of calculating the effects of the sea level rise strategies?

The main shortcomings of the current method are that it does not include the retreat scenario and thus that it lacks the ability to calculate the effects of that scenario. Furthermore, only the consequences on the Netherlands and the port of Rotterdam are examined, not the consequences on neighbouring countries and their competitive ports.

General shortcomings:

- The current method used, as described in Section 3.2, is extensive and inclusive, it is also time-consuming, expensive, and require knowledge about the individual models. Generally, it is run once completely and then based on the outcome. Alterations are made for intermediate input variables, using expert judgement;
- The models use economic and sea-level rise projections as input. These projections are difficult and uncertain to make in themselves, resulting in large bandwidths. When combined, the uncertainty and bandwidths only increase. The horizon when certain levels of sea-level rise are reached is highly debated. If the general consensus of +1 m sea-level rise around 2100 is to be believed, accurate projections about throughput, global trade and economic growth can be ambiguous;
- Climate change also has an impact on the discharge regimes and water levels of the rivers and inland waterways. Low water levels mean vessels cannot take on as much cargo as usual, for fear of running aground. In addition, the method only assume changes in the landscape of the Netherlands and discard possible influences and changes on competing ports;
- A general ability to adapt to changing landscapes, inland waterways and port locations is missing in the current method. Moreover, it only assumes there are consequences of sea-level rise for the port of Rotterdam, the consequences for neighbouring ports are not included.

Model shortcomings:

- The models used are extensive and well designed when used for their specific purposes. For the purpose of the examined method, they are less suited, especially when combined. There seems to be a general lack of a hydraulic model, accounting for changes in river water levels due to global warming. Most models only focus on the (inland waterway) networks and the hinterland. Only the `CPCM` gives specific results for port competition;
- The `BIVAS` model network cannot be changed by the user. This implies that the model cannot account for changes in the landscape, river courses and port locations. In addition, there is no limit to the number of vessels it can generate, whereas in reality, the number of available vessels is finite. Its output only depicts the consequences on the inland waterway network, not for other modalities or a regional scale;
- The Trans-Tools model seems to be the most extensive and can simulate the entire trade in Europe for all commodities and modalities. The network can be adapted by the user, and the output data can be easily visually represented on maps (networks or NUTS regions) or in lists. However, it does not include port competition or intercontinental trade. In addition, the runtime of the model is three days and gives 3.5 GB of output data per iteration. The model can simulate container trade but is only used for bulk trade;

- The `CPCM` does account for port competition and intercontinental flows but does not simulate flows. It uses precalculated transit distances and times to and from specific regions and calculates which routes and ports have the highest probability to be used. Historical data is then applied to calibrate the variables in the equation. This results in accurate predictions of the near future, however for the far future the calibrations are more ambiguous. The model assumes that there is an instant capacity availability to transport freight over other modalities, whereas this is not always possible. It takes time to increase the capacity of railways and roads. This also applies to the port competition. Ports possibly perform near-maximum capacity and cannot handle a sudden large increase in throughput. By extension, it is difficult to assume what the future port capacities will be if there is enough room for port expansion. The model is only applicable for container trade, not for other commodities;
- The `SIVAK II` model is quite suitable in its application. The only shortcoming is the uncertainty in future fleet dimension. As the dimensions of the deep sea vessels and inland vessels change over time, accurate predictions for future lock capacities are problematic to make.

Deltares adaptation scenarios shortcomings:

- For the "Open" and "Closed protection" scenarios the methods work quite well, as it was specifically designed to compare the two. The general problems are the uncertainties in the long term economic and sea-level rise projections and the key figures used to translate the shipping and waiting times to economic values;
- The networks of the different modalities, the locations/layout of the ports and the landscapes may be changed for the "Seaward scenario". The use of the `BIVAS` model, with its static network, and the `CPCM`, where precalculated travel times and distances are needed, inhibit these changes to be modelled. The general problems of the former scenario also apply here;
- Whereas for the former scenario the network, port location and landscape changes can be limited, these are essential for the "Retreat scenario". As all future options and adaptation scenarios for sea-level rise need to be examined, this scenario seems to be least applicable for the current method. In addition, the possibilities for the event of this scenario for neighbouring countries need to be examined.

There is currently a method to examine sea-level rise, although this method has its problems, as can be read above, it is an extensive method and is suitable for the first two scenarios, "Open protection", "Closed protection" and possible for the "Seaward scenario" when no adaptations to the networks and port locations need to be made. Else it falls in line with the fourth scenario, "Retreat". For "Retreat", the method is not applicable as major network, landscape and possible port location changes need to be made. No studies have been done to examine the consequences of a retreat scenario on the port of Rotterdam in detail. Therefore, this scenario seems to have the most potential to be studied.

To examine said scenario, a new method and model are needed. A model in which networks, landscapes and port locations can be easily adjusted by the user. An open-source model with low run-time, with limited data output and is easy to use. One which has a comprehensive visual output of port competition and of which the input and output parameters can be chosen by the user. The model is developed in the following chapter.

The locations of flooded areas and (new) coastlines, not only for the Netherlands but also for other European countries, are unknown and will have to be examined. Assumptions have to be made however—assumptions such as the rise of the sea level, the consequences on ports and possible relocation thereof. Inherently there will be flaws and unrealistic outcomes in the method if assumptions are made for these factors. Therefore it is chosen to focus on port competition of the hinterland, which areas in Europe are best reached from which port whilst adapted to +3 m sea-level rise. The method to examine this is developed and applied in Chapter 6.

4

Development of a container port competition model

Chapter outline

This chapter answers the sub-question: "How can adaptive container port competition be modelled and which parameters are needed?"

The previous chapter concluded that there is a need for a new method and model to examine the retreat scenario. In this chapter, the model is developed. First, the model outline is given: the objective, structure and concept of the model with subsequently the general description of what the model does. Next, the used input data is described and explained, followed by an explanation of the distance to costs conversion and the results of the model.

4.1. Model outline

The model simulates the port competition of Northwest Europe in current and changed landscape conditions. Although the model was specifically developed for this thesis, it was developed in a manner that others may also test their landscape visions and examine the consequences thereof on the port competition. Hence, the model was constructed such that features can be easily added or removed.

4.1.1. Model objectives and requirements

Following Chapter 3, a method to examine the retreat scenario is missing. In order to examine the scenario, it was chosen to simulate port competition in a model. To that extent, the model was built using the following objectives and requirements, additionally obtained following Chapter 3.

- The primary objective of the model is to give a clear depicting of the shift in container port competition of North-west Europe in case of +3 m sea-level rise and changing conditions. Conditions such as landscape, modality networks and port locations, implying that parts of the landscapes and networks can be removed and excluded and new locations for deep sea ports can be chosen;
- The model is easy to use and has simple output results. It has low run-time and limited data output, thus multiple iterations can be run in a limited time span. The output must be easily and comprehensively visually depicted. At a glance, the user ought to be able to understand the results and be able to derive conclusions from it;
- The model is reproducible and open source, which means it can be freely used and tinkered with. The data it uses is freely available and only adjusted in the model. The conditions and features of the model can be adjusted by the user. Simple rules are used and applied: on different distances, different modalities are more competitive;
- The main output of the model are the distances of the modalities. These distances are converted to costs, however the conversion can be subjective. The conversion applied in the model is therefore conditional and gives a close approximation to the real-world situation. Therefore the user can implement their own conversion in the model.

4.1.2. Model structure

The model is split into two parts in order to be able to compare the effects of a scenario on port competition. The first part is setting the base case, to compare the results to. The base case reflects the current situation, without any sea-level rise or landscape changes. The second part is introducing scenario changes. To obtain the desired results, the user can alter the input variables of the model. To that extent, the input of a scenario case is structured in three steps, each step adding, removing or defining parameters. A detailed step-by-step overview of how to obtain and use the model can be found in Appendix D. Figure 4.1 shows a schematic overview of the model second part of the model. The steps are applicable to both the base case and the scenario cases.

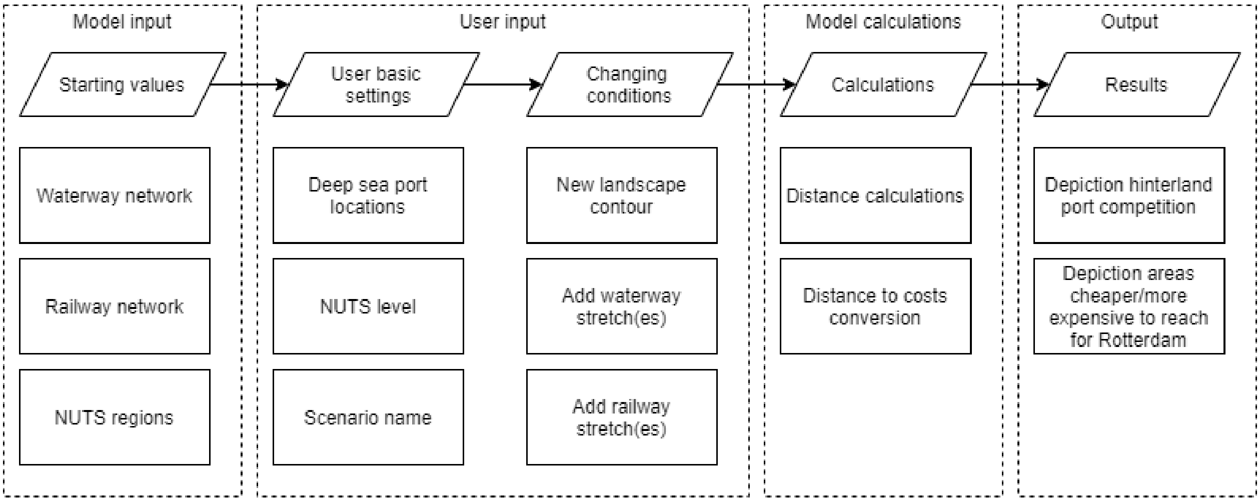


Figure 4.1: Schematic overview of the model scenario changing part. Left dashed box are the variables the user can change, right box is what the model automatically calculates and depicts.

4.1.3. Model assumptions

In order to build and create a port container competition model, some assumptions have to be made. These assumptions mostly follow from simplifications made in order to construct the model within the available time span and simply because one cannot model the entire complexity of the container supply chain. When interpreting the results, the following assumptions have to be kept in mind:

- *Port competition of Antwerp, Rotterdam and Hamburg*
  The model only includes the deep sea ports of Antwerp, Rotterdam and Hamburg to portray the port competition of Northwest Europe. To that extent, only their competitive hinterland areas are (roughly) used. Although there are more deep sea container handling ports in this region, for simplicity the largest three ports are included. It should be noted that the model can, in fact, include any number of (European) deep sea ports;

- *Container import*
  The model only simulates the import of goods. The manufacturing and export of goods are not taken into account for simplicity reasons. To that extent, a uniform demand for goods, and thus containers, is assumed for the hinterland destinations. In addition, the model only simulates what happens with the containers once they are unloaded from the deep sea vessels and picked up from the storage yards. The disadvantages as tidal windows or the ability of only half laden vessels to enter the port are not included;

- *No changes to the road modality network*
  The model does not account for changes to the road network, as opposed to the rail and waterway networks. This is assumed because the Google Directions API is used for the road network and the network is fine-mashed and therefore has many alternative routes available;

- *Uniform capacity modalities*
  Two assumptions are made about the capacity of the modalities. Firstly a uniform container capacity for the transportation devices. This implies that every transport of each modality has the same capacity to transport containers, whereas in reality there are different capacities. Secondly, continuing on the previous assumption, a uniform capacity over the modality roads, railways and waterways are assumed. This entails that there are no size restrictions over the modalities and the respective velocities are also uniform;
- *Instant availability*
  This assumption, again, is two-fold. The model assumes that there is instant and infinite availability of transport devices for the modalities, whilst in reality, this is not the case. In addition, an instant increase in capacity for when a modal shift occurs to another modality is assumed;
- *Uniform pricing modalities*
  As the pricing per modality is set, the model assumes uniform pricing throughout (the selected part of) Europe. Whereas, normally the pricing may differ per country or region due to the wage difference.

4.1.4. Modelling concept

Model set-up

The model is written using the Python programming language. This is an open-source, general-purpose programming language (Van Rossum, 2007). Jupyter Notebook, from the Anaconda Navigator package is used as the graphical user interface to write the code and simulate the model itself (Kluyver, Ragan-Kelley, Perez, Granger, & Bussonnier, 2016). The model and its data can be found in the Network Competitiveness GitHub repository from the civil engineering faculty of the TU Delft.

The model simulates the flow of goods from deep sea ports to hinterland destinations. For each hinterland destination is calculated what the distance, transit time and cost are from each respective port for the three modalities. The Python package NetworkX is used to simulate the flow of goods over the three transport modes. NetworkX is a flexible network analysis tool to study the structure, dynamics and functions of complex networks (Hagberg, Schult, & Swart, 2008). The modalities are road network, inland waterway network and the rail network, for which the latter two are combined with the road modality for the “last mile” (Rodrigue, Comtois, & Slack, 2009).

Hinterland modality distances

For the road network, the Google Directions API from Google Maps is used. This function finds the shortest path from a given origin point to a given destination point and returns the respective distance. It automatically finds the closest point on the (road) network to connect to for the given origin and destination. These distances represented the road modality.

For the inland waterway and rail modalities, the Google Directions API cannot be used. There is no inland waterway function of the Google Directions API, as the transit of people via inland waterways is very limited. To that extent, the the Google Directions API for the rail modality cannot be used as it does not use freight network, but rather the public transit network. Therefore separate data is used to simulate the inland waterway and freight rail networks. These networks are transformed into graphs using the NetworkX package.

Each graph consists of nodes and edges. The nodes consist of latitude and longitude coordinates and properties as names and specifications. The edges are the lines between the connected nodes. These edges can be given a weight. A weight can be viewed as a resistance parameter. The input for the weight is the ellipsoidal distance between the nodes. Using Dijkstra’s algorithm from the NetworkX package, the path with the least weight, i.e. distance, is chosen to a point over the graph. Dijkstra’s algorithm chooses the path with the least weight between nodes of a given graph or network (Floyd, 1962). If the weight between a set of nodes is increased or decreased, the algorithm can choose a different path as there is possibly a new path with the lowest weight.

Modality switch
Thus to calculate the length between the begin node and an arbitrary node in the hinterland, two steps have to be taken. The distance between the begin node and a graph node with a waterway/railway attribute, plus the distance between the graph node with a waterway/railway attribute and the hinterland point. A schematic overview of the principle can be seen in Figure 4.2. To reduce run-time over multiple iterations, the results of the trips are stored locally on the user's computer. This means that when a new iteration is made, it only calculates the paths which are not created and stored by previous iterations.

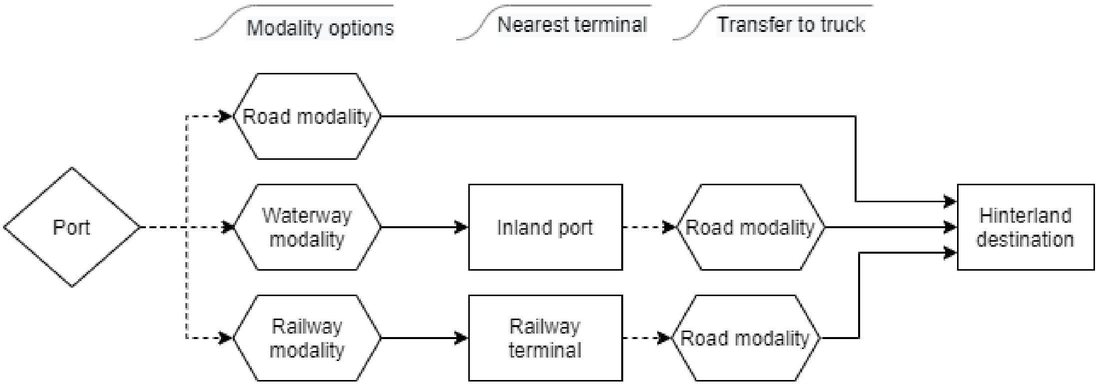


Figure 4.2: Schematic overview of container transport using different modalities with inter modal transport

To find the closest waterway/railway node to an arbitrary point in the hinterland, the shortest distance from an inland port or railway terminal to that point is calculated. As the graphs are only one dimensional, these ports and terminals do not lay directly on the networks and cannot be selected as destination nodes for the network. However, these ports and terminals do lay in close proximity to the networks. Therefore representative points on the networks are used to pose as these destination nodes. This is done by finding the closest network node to a respective destination node and adding an attribute to that node. Subsequently, the model can only select the closest nodes with the right attributes.

However, not all waterways in Europe are connected to each other. To that extent, an inland port can be selected, as an example, which is closest to the hinterland destination, whilst that stretch of waterway is not connected to the network of the origin port. Consequently, the model selects a node to which the network is not selected, and the transport cannot occur. To overcome this problem, first, a depth-first-search (DFS) from the begin node (deep sea port) is applied. DFS is an algorithm (from the Networkx package) which explores all arbitrary paths as deep as possible from a start node in a network, before backtracking to the first node (Tarjan, 1972). Thus the algorithm returns the nodes to which the start nodes are connected. The model can subsequently select the closest representative inland port or terminal node it is connected to. The last remaining part of the trip is done using the road network.

Lastly, the deep sea ports themselves can be defined. A function is made in which the name of the desired terminal, port or city can be passed. The user can choose any arbitrary name, as accepted by the OpenStreetMap database it uses (Haklay & Weber, 2008). The function then finds the nearest node to the respective networks and selects those as the starting points for the deep sea ports.

Calculations
From the NetworkX package, the respective distances for each modality to the hinterland destinations follow. These distances are subsequently converted to costs in order to depict the advantages or disadvantages the modalities have with respect to each other. A modality can be faster, however, when a large quantity of containers have to be transported, a larger capacity can be more advantageous. These calculations are collaborated upon in Section 4.3.

Results
The results are depicted in an interactive of hinterland destinations with the colour of the port of which that destination is the cheapest to reach. NUTS regions, or hinterland regions, of the European countries represent the destinations. These regions will be further explained in Section 4.2.1. The central points, or centroids, of the NUTS regions are used as the destination points. The user can select the desired NUTS region level, or detail level. For each region, the distance and related costs are calculated from each port for each modality. The results are compared and the combination port + modality with the lowest desired costs for that region is depicted. The output is a choropleth map of the port competition of Europe, created using the Python Folium package (Journois, Story, Gardiner, & Rump, 2020). The map can be saved as an interactive web page map, as the results are stored on the map.

4.2. Input data

In this section, the used input data is explained and accounted for. In principle, the user of the model can modify the input values or even insert their own data files, albeit with minor changes would to the code. The aim is to use open-source data which has not been altered, making the model reproducible. If alterations have been made to the source data, it is noted below. The first section discusses the data for the general input data, the destination areas and coordinate reference system. The subsequent section explains the data sources of the hinterland modalities. Then the changes the user can make to the system. Lastly, the values which are chosen to convert the distance to time and monetary values.

4.2.1. General input

Coordinate system
In order to properly project the model, a coordinate reference system was needed (Soler & Hothem, 1988). Several coordinate systems have been developed and revised over the years. The most commonly used system is the World Geodetic System 1984 (WGS 84 or EPSG:4326) which was in part developed by the US Department of Defense (J. A. Slater & Malys, 1998). It has an accuracy of 2 cm (Lemoine et al., 1998). As such, it is applied as the standard coordinate system in GPS.

NUTS regions
Chosen was to use the NUTS regions of the respective countries as hinterland destinations. NUTS regions are subdivisions of countries, referenced as geocodes. The NUTS regions are used by the European Commission to give statistical information at a more detailed level. It was first introduced in 2003, after which revisions have been introduced (European Commission, n.d.). NUTS regions are divided into four levels. For smaller countries, such as Luxembourg, the NUTS area are the same at every level. In Table 4.1 a summation is given for the distinction between the levels. Figure 4.3 gives a visual overview, excluding level 0. The model uses the NUTS 2016 data, retrieved as a shapefile at a scale of 1:1 million (European Commission, 2019). Overseas territories were excluded in the model as they are not connected to the European hinterland system. These are the NUTS regions from France, Spain and Portugal, denotes as “FRY”, “ES7” and “PT2/PT3” (depending on the selected NUTS level), respectively.

Table 4.1: Overview characteristics NUTS regions (European Commission, 2019)

NUTS level	Characteristic	Population
NUTS 0	Countries	Entire population
NUTS 1	Major socio-economic regions	3,000,000 - 7,000,000
NUTS 2	Basic regions for the application of regional policies	800,000 - 3,000,000
NUTS 3	Small regions for specific diagnoses	150,000 - 800,000

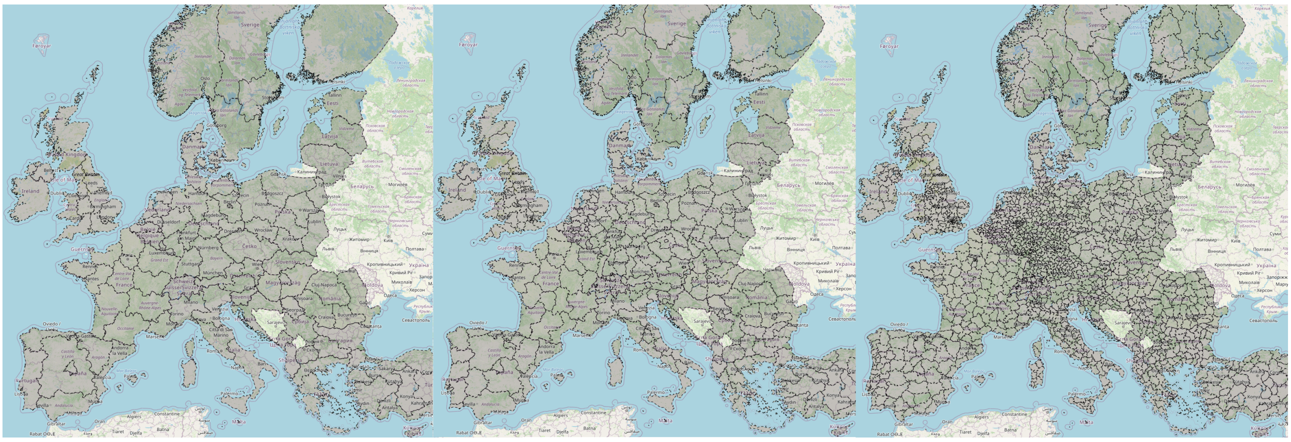


Figure 4.3: From left to right examples of NUTS levels 1, 2 and 3. Data retrieved from (European Commission, 2019)

Hinterland area
As stated in Chapter 6, the model focusses on the Hamburg-LeHavre range. More specific, the ports of Antwerp, Rotterdam and Hamburg. It is therefore important to distinguish their combined hinterland port competition area. This was accomplished using Figure 4.4. The orange area symbolises the Hamburg-LeHavre range, which included roughly the north of France, Belgium, Luxembourg, the Netherlands, Germany and parts of Austra, Switzerland, Spain and the Czech Republic. However, as Le Havre is not included in the model, a smaller area of France was used in the model.

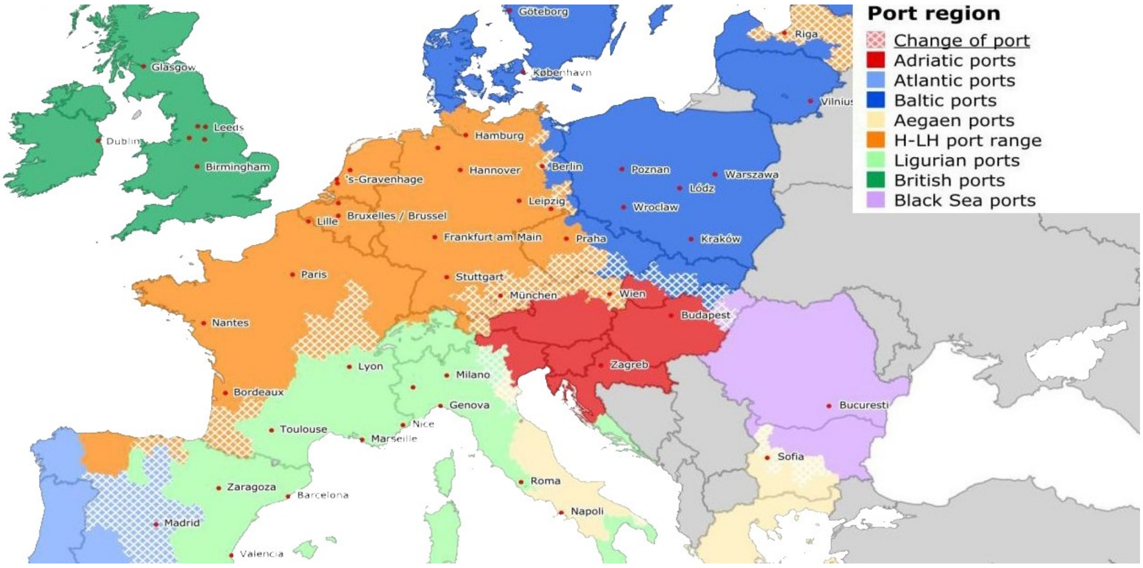


Figure 4.4: Competitive hinterland areas corresponding to given port regions (Port of Rotterdam Authority, 2016)

4.2.2. Modality networks

Road transport - Google Maps
For the road network, Directions API function from Google Maps was applied. The function calculates the distance from a given point to a given point. It lets the user choose the mode (driving, walking, bicycling and transit), what to avoid (ferries, highways, tolls and certain waypoints) and in which units the results are expressed (metric or imperial) (Wang & Xu, 2011). It should be noted that the user has to have a Directions API key for the model. The key can be obtained at the developers

page of Google. Per iteration a fee is asked, however, the first €300,- is free (Google, 2020). It was assumed that there are no dedicated truck freight terminals needed to unload the containers. Instead assumed was that the containers could be unloaded anywhere at the desired destinations.

Inland waterways

Per request at the Sustainable Transport Division of the section Transport Networks & Logistics from the United Nations Economic Commission for Europe (UNECE), inland waterway, inland port and lock data files were obtained (UNECE, 2020). However, after examination of the waterways, some stretches appeared not to be connected. Either because waterway stretches were missing or because at inland locks, the locking chambers were not distinguished as waterways. Therefore another source was used for the inland waterways. The ETISPlus program, although ended in 2012, still provides inland waterway data (CORDIS European Commission, 2019; Demis, 2017). Figure 4.5 depicts the waterways in blue. Appendix D further explains which choices were made when altering the networks and terminals.

Inland ports

Both UNECE and ETISPlus supply data files containing port locations (443 versus 1024, resp.) (UNECE, 2020; Demis, 2017). Chosen was to use the data from UNECE, because it does not include small coastal ports and it contains more information about the inland ports. These are cargo handling capacity, railway connection and the type of products transshipped at the port, as an example. The run-time of the model was further decreased by choosing one of these characteristics. Unfortunately, the information of the type of products transshipped was minimal and contained only a few container terminals. Therefore the intermodal ports were chosen by selecting the ports with rail access. This method brought the number of inland ports to 260. An overview of the inland port location can be seen in Figure 4.5 as red dots.

Figure 4.5: Map of Europe depicting the waterways (Demis, 2017) in blue and inland ports (UNECE, 2020) as red dots

Railways

As UNECE only supplied inland waterway data, the ETISPlus data was utilised for the railway network (Demis, 2017). The data contains both passenger and freight railway networks, which overlap. Not all railway lines are used for container transport. In addition, the data cannot be sorted on container transport or only freight transport. However, the data could be sorted for the railways where freight transport has priority. The resulting network can be seen in Figure 4.6 in black.

Railway terminals

The ETISPlus data contains over 1000 railway terminals (Demis, 2017). These range from coal to agricultural terminals. To differentiate between the terminals, only the ones named container terminals and have a terminal capacity larger than 100,000 TEU were applied (Wiegmans, 2003; Limbourg & Jourquin, 2009). 154 terminals remained by applying this method. The terminals are depicted in Figure 4.6 as purple dots.

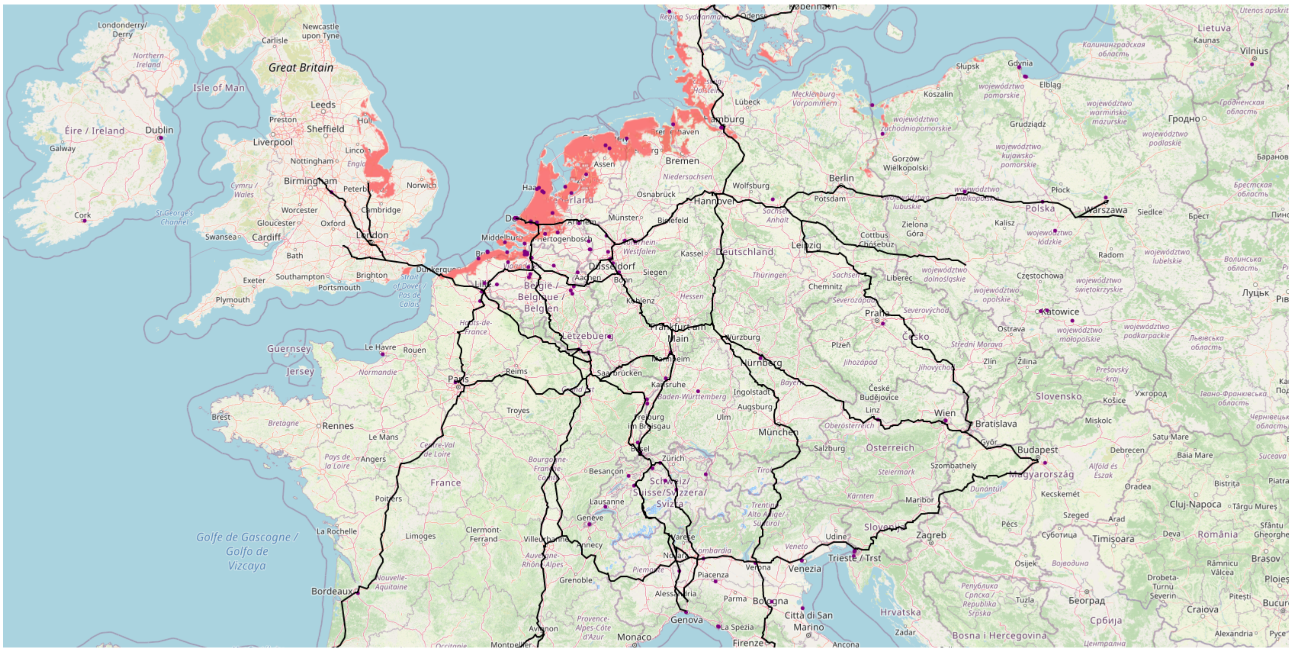


Figure 4.6: Map of Europe depicting the railways (Demis, 2017) in black and railway terminals (Demis, 2017) as red dots

4.2.3. User input

Landscape contours

The user can choose a new outline for Europe in order to incorporate the influence of sea-level rise in the model. The draw function of the Folium Python package allows the user to define the landscape contours and the desired parts of Europe. In addition, the new contour line changes the modality networks by excluding the stretches outside the line. This does not apply for the road modality, as the Google Maps network cannot be adjusted.

Deep sea port location

New coastlines can also mean new deep sea port locations. Therefore the model is constructed that the user can insert the name of the new location or city. The model automatically finds the nearest connections to the modality networks as starting points. The default deep sea port locations are the “Maasvlakte” for the port of Rotterdam, “Container terminal Tollerort” for the port of Hamburg and “Haven van Antwerpen” for the port of Antwerp. Locks are not incorporated in the model.

Adding network stretches

As stated in the landscape contour section above, network stretches can be removed by drawing new landscape contours. However, the model also allows adding network stretches if the user wishes to keep a deep sea port outside the new contour lines or wants to add new network sections. Using the same draw function, stretches of a network can be added by the user. Again, this only applies for the inland waterway and rail modalities as the Google Maps network is not modifiable. An overview of the user input can be seen in Figure 4.7.

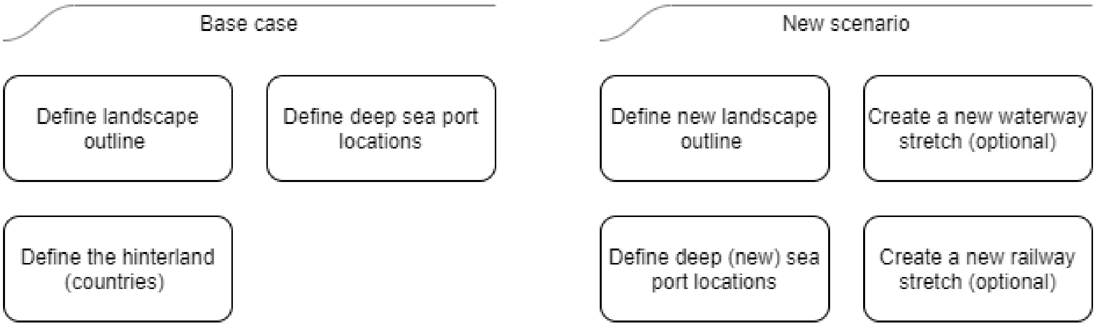


Figure 4.7: User input for the base case and new scenario

4.3. Distance to time to costs conversion for different modalities

4.3.1. Modality characteristics and advantages

Each modality has its advantages and disadvantages due to the characteristics it has. These characteristics come to play at certain distances. For example, the truck modality has a capacity of two TEU and therefore a minor loading time. For limited distances, it has an advantage over the inland vessel and train modalities, as their loading time is subsequently increased due to their larger capacity and their more complex loading procedure. However, as the distance increases a single voyage by train or vessel can be cheaper. The characteristics and their differences per modality are discussed below. An overview of the advantages and disadvantages per characteristic per modality can be seen in Table 4.2. With these characteristics, equation 4.1 can be applied. Distance is transformed to time using the (un)loading times and the transport time.

$$T_{transport} = N_{trips} \cdot \left[C_{modality} \cdot (T_{load} + T_{unload}) + \frac{L_{trip}}{v_{modality}} \right] \tag{4.1}$$

where:

N_{trips} = The number of trips needed;
$C_{modality}$ = The capacity per modality transport device;
T_{load} = The loading time per modality transport device;
T_{unload} = The unloading time per modality transport device;
L_{trip} = The distance over the modality;
$v_{modality}$ = The average speed of the modality transport device.

4.3.2. Distance to time conversion

Equation 4.1 can be split into three parts, the number of trips a modality has to make, the loading and unloading times of the containers and the time it takes to transport the containers to their destinations. These three parts are explained separately below. Section D.3 explain the actual figures used for the variables in more detail. The steps below are done twice for the waterway and railway modalities. First for these modalities themselves, secondly for the last part of the trip, via the road.

Number of trips

Equation 4.1 starts with the number of trips a modality has to make in order to transport the total number of containers. This part therefore depends on the capacity characteristic and differs strongly per modality and even within modalities. Equation 4.2 depicts the formula for the number of trips.

$$N_{trips} = \frac{N_{TEU}}{C_{modality}} \tag{4.2}$$

Loading and unloading times
The first part of the equation inside the square brackets consist of the time it takes to load and unload the containers to and from their respective modalities. Each modality has its advantage or disadvantage when it comes to loading and unloading. This reflects in their loading and unloading times.

Equation 4.3 gives a simplification of the (un)loading time. The number of TEU which needs to be transported times the loading and unloading times results in the total (un)loading time. Equation 4.1 rewrites the number of TEU to the number of trips times the capacity of the modality to incorporate changing capacity conditions. An example of this are low water conditions on the waterways.

$$T_{(un)load} = N_{TEU} \cdot (T_{load} + T_{unload}) \tag{4.3}$$

Trip time
Trip time is the time it takes to transport all the containers to their destinations. First, the length of a single trip is calculated. This length automatically follows from the NetworkX package. Subsequently, the number of trips the modality has to undertake are calculated by dividing the number of containers which need to be transported by the capacity of the modality. The trip length and the number of trips give the total trip distance of the respective modality. When this number is divided by the average velocity of the modality, the total trip time is obtained.

4.3.3. Time to costs

The last step is to convert the found transport time of equation 4.1 to costs. This is done using the operating costs, however it should be noted that the user is free to implement their own respective distance to cost conversion formulae. . The operating costs are the costs it takes to run a modality day to day. The operating costs are chosen because they do not incorporate the profit margins and therefore better combine with the real world variables described above.

Several overlapping costs can be found between the modalities, such as fuel, maintenance, depreciation, salaries and third party services (van Essen, Faber, & Wit, 2004). These costs can be added and translated to daily costs and subsequently multiplied with the total (un)loading and transport time subsequently. The results are the total costs. Figure 4.8 gives the percentage of the (un)loading costs versus the travel costs for a certain distance.

There are however, differences between the costs of the modalities. A truck is normally operated by one driver, whereas inland vessels and trains tend to need more crew to operate. In addition, inland vessels need to pay port fees and trains have to pay fees to use railways, whereas trucks do not have to pay these fees (in Europe). Thus the capital costs of inland vessels and trains are far higher than that of a truck. However, on the other hand, the inland vessel and train can carry more containers. Thereby decreasing the capital costs per container it transports. Figure 4.9 displays the costs of a modality for a certain distance. As can be seen at certain distances a modality becomes cheaper than the other two and therefore more competitive. The daily operating costs are found at €1,440, €3,550 and €3,000 for the truck, inland vessel and train respectively (van Essen et al., 2004; Konings, Kreutzberger, & MaraŠ, 2013; Flóden, 2011).

Table 4.2: Overview advantages and disadvantages of the modality properties

Modality	Capacity	(Un)loading time	Velocity	Costs (per device)	Costs (per TEU)
Road	– –	++	+	+	–
Waterway	++	–	– –	– –	++
Railway	+	– –	++	– –	++

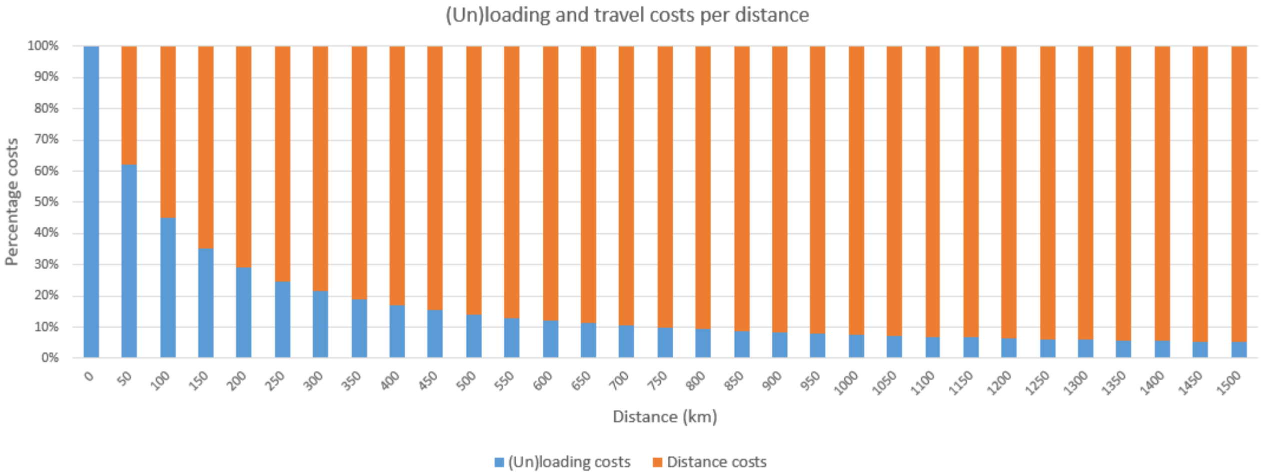


Figure 4.8: The percentage of the (un)loading costs and the travel costs of the total costs per distance

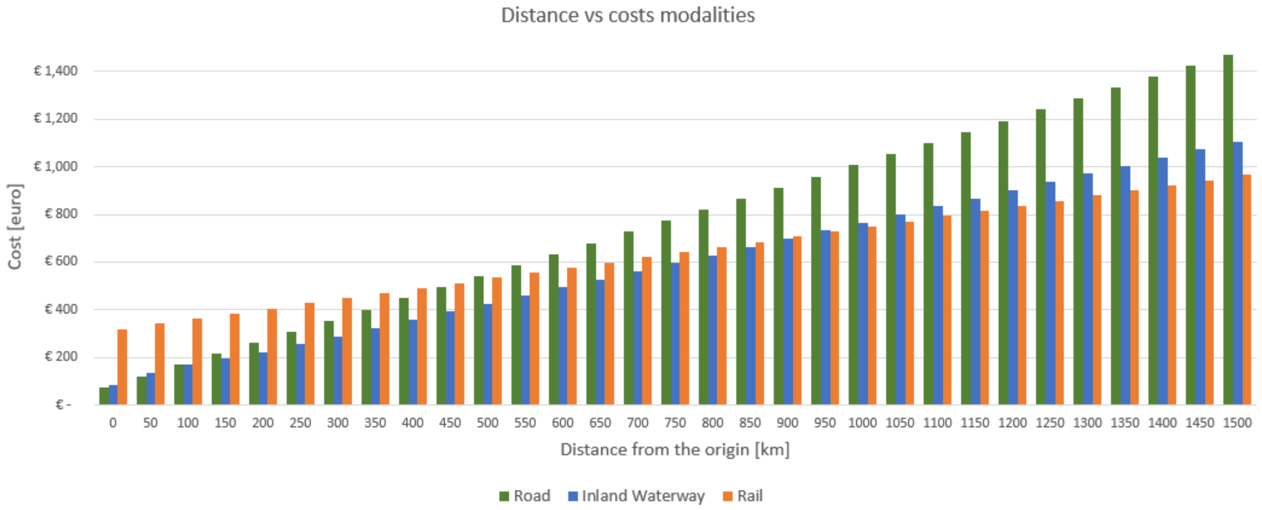
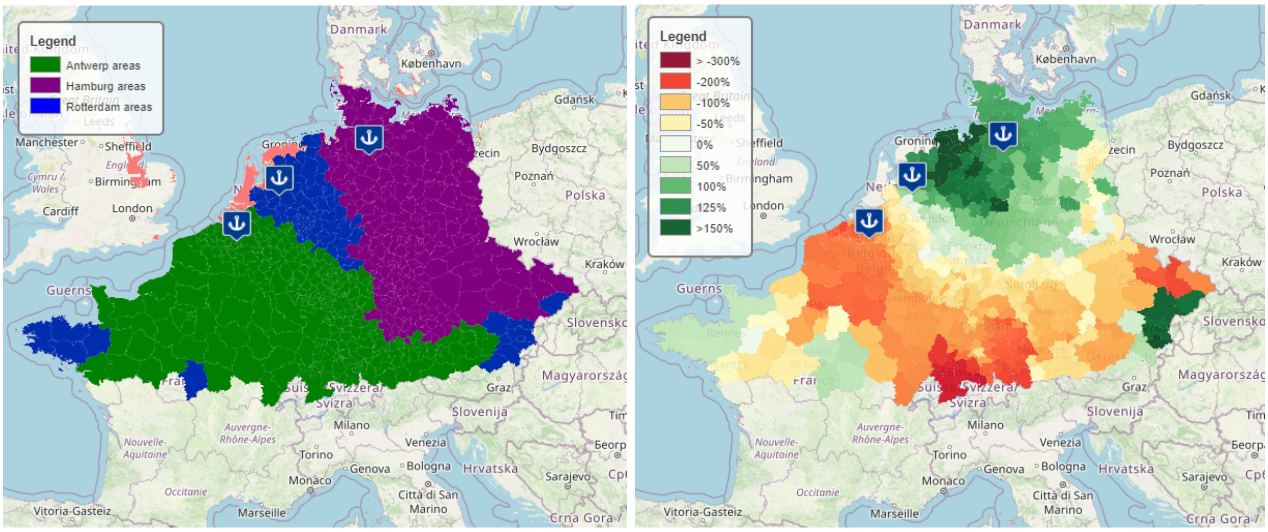


Figure 4.9: Costs per modality over the distance. Lowest costs means that the respective modality is most competitive on the given distance. Data used is fictional.

4.4. Description of the output

To compare different scenarios for new possible locations for the port of Rotterdam, a base case is set first. The base case implies the current port competition distribution of the hinterland, or a different case, set by the user. Next, the new scenarios are introduced and calculated. These are then compared to the base case to identify, for the port of Rotterdam, the hinterland areas which have become more expensive or cheaper to reach. The cheaper and more expensive areas are subsequently depicted in a choropleth map. Figure 4.11 depicts both output figures of a fictive port situation. Figure 4.10 provides a link to the resulting model notebooks and Appendix D.1 provides more details as how to download the model.

Figure 4.10: Github link to the model notebooks



(a) Results port hinterland area distribution of a new fictive location for the port of Rotterdam.

(b) Results areas which are more (red), or less expensive (green) to reach from the new port location in respect to a base case.

Figure 4.11: Output for a new fictive deep sea port location for the port of Rotterdam

4.5. Concluding

This section concludes the chapter. To that extent the sub-question of the chapter is answered:

> *How is an adaptive container port competition model built and which parameters are needed?*

The model is based on the principle that transport modalities are competitive at different distances from the origin. At certain distances from the origin, a shift in modality will occur. This can be explained by the characteristics of the modalities. These characteristics are used to calculate the costs of transporting the containers over a certain distance. The cost to reach a hinterland area for the different modalities are calculated by transforming the distance to transport time and subsequently to costs.

Chapter 3 concluded that an adaptive and easy-to-use model is missing. A model in which landscapes, modality networks and port locations can readily be changed. One which is open-source and comprehensible. These objectives of the model are achieved by developing a port competition model in Python programming language. The user first chooses a base case in which some parameters as port locations, detail level, the desired hinterland area. Next, the future scenarios can be set by drawing a polygon around the non-inundated areas on a map. This automatically excludes the areas, waterway stretches and railway stretches which fall outside the drawn polygon. New port location(s) can be set and new waterway and/or railway stretches can be drawn on another map. The competitive areas which are gained or lost due to the scenario change are depicted in another map.

5

Model evaluation

Chapter outline

This chapter answers the sub-question: "Does the model comply with its requirements and how accurate is it compared to reference data?"

The chapter sets out to verify, validate and, if needed, calibrate the model described in the previous chapter. As there is only a limited number of container port competition models available, part of the validation is done in the calibration process. During calibration and validation, the results are compared to known cases. The main difference between the two processes is that during calibration, the input variables are adjusted, such that the results give a better approximation of the known cases. Of the current port competition models, the outcomes are not widely available, and indeed the real European port competition is unknown. As such, the complete model cannot be compared directly. However, parts of the expected outcomes are known and can be compared. In addition, the used base networks can be directly compared and validated. Noted must be that this model and subsequent method are a first attempt to tackle these issues using simple rules. The container supply chain is a complex mechanism which is not easily simplified.

5.1. Model verification

5.1.1. Verification method

The model is verified in order to check if the model is built according to the requirements set in advance. These requirements are in dependent from each other and can be tested separately. The main requirements set in Chapter 4 are:

1. Origin - Destination paths;
2. Adjustable model conditions;
3. Model difficulty and run-time;
4. Comprehensive output.

Test 1: Origin - destination

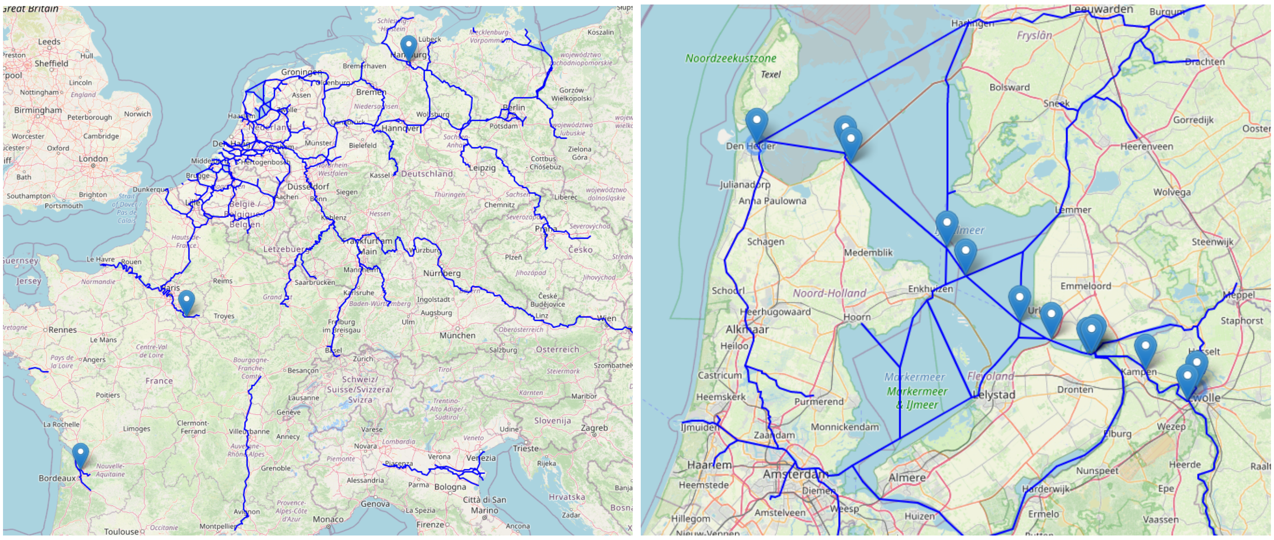
The first requirement is that the model can simulate and calculate the length of a different network path from a given origin to a given destination. To that extent, the requirement can be split into two parts. Automatically finding the closest network nodes to the origin and destination, connected to the same network stretch and finding the shortest path between those two nodes.

These two parts are examined. The former one is checked by selecting Hamburg as the origin and Bordeaux as the destination for the inland waterway. The river Garonne meanders through the city of Bordeaux but is not connected to the Rhine or Elbe waterway systems. It is however included in the overall waterway network. This means that there are (waterway) nodes surrounding Bordeaux which are not connected to the river system surrounding Hamburg. If the model works correctly, it should return a path to a node which is on the outskirts of the Hamburg system (as Hamburg is selected as the origin). Else the model has selected one of the Garonne nodes and returns an error.

The model returns a path to node 7. This node is located on the river Seine, near Fontainebleau in France. Figure 5.1a depicts the respective locations and waterway networks. This appears to be the closest node to Bordeaux. As the same code is used for the railway modality, works for both the waterway and railway networks.

The path from Den Helder to Zwolle, over the inland waterway, is tested to examine if the model actually picks the shortest path from the origin to the destination. This path is chosen as multiple routes can be chosen to reach Zwolle. Figure 5.1b shows the multiple routes available to Zwolle. In addition, the nodes which the model uses to reach the Zwolle are depicted with the markers. As can be seen from the figure, the model chooses the shortest path to Zwolle whilst the chosen nodes numbers are not sequential. Further details can be found in Appendix D.5.

The railway network does not have such a clear example of multiple paths to a destination where the differences are minute, as can be seen from Figure 5.8. However, it uses the same code as the waterway network. As such, both the waterway and the railway network choose the shortest paths.



(a) Check if the model chooses the node which is closest to the destination but still connected to the network of the origin. Top marker shows the origin (Hamburg), bottom marker shows the destination (Bordeaux) and the middle marker shows the closest point to the destination which the model returns.

(b) Check for the shortest path. Den Helder (top left marker) is used as origin whereas Zwolle (outer right marker) is used as the destination. As can be seen multiple routes can be chosen to reach Zwolle. The markers between the origin and destination depict which nodes and thus which route is used to reach Zwolle.

Figure 5.1: Origin - destination check of the waterway network (in blue)

Test 2: Adjustable conditions

The second requirement is the easily adjustable conditions. Port locations, network alterations and landscape changes must be adaptable by the user as to implement their respective visions on the consequences of sea-level rise. These conditions can all be adjusted and are discussed below. However, there are three things we were not able to incorporate in the model. These are addressed first. Appendix D gives a walk-through of how to change the conditions in the model.

- Locks, deep sea terminals in combination with inland ports
  There were two things which we were not able to incorporate in the model. Navigation locks in front of the ports or in the waterways and deep sea terminals in combination with inland terminals. The reason for the former flaw is that one would have to know the time loss due to the (individual) locking process. The latter flaw is because the deep sea terminal with inland port combination would always give worse results than only deep sea terminals due to the added travel distance and handling time. The real trade-off between deep sea terminals and deep sea inland ports are the concessions in dredging costs, which is out of the scope of this thesis.

- Fully reproducible model
  The last flaw is that the railway network file was altered outside the model in order to connect the freight priority stretches. Any attempts to alter the properties inside the model failed. Therefore the model can be considered not fully reproducible. However, the alterations made to the network are noted in Appendix D.4.

- Port locations
  The origin nodes, or port locations, can be adjusted by typing the name of the desired city or port at the top of the model. Thus in that respect, the port locations are changeable. If an offshore deep sea port is planned, it cannot readily be chosen as there is no nearby city to select it from. However, this can be overcome by knowing the coordinates and small changes in the code.

- Network alterations
  The networks can be changed in two ways. Firstly by selecting the outline of (Northwest) Europe, thereby excluding the river stretches which are outside the outline. Secondly, the user can add stretches (e.g. to a new port location) by simply drawing them on the respective network maps and adding them to the existing network. In that respect, the networks can be altered. However, if a user wants to exclude a specific network stretch, it can only be done in an external model. In addition, the road network cannot be altered as the Google Maps API is used. Although it can be swapped for a road network similar to the railway and waterway networks.

- Landscape changes
  The inundated landscape is excluded in the same manner as the networks by selecting the non-inundated areas of Northwest Europe. The model then excludes the NUTS regions which are (for the large part) excluded by the new outline.

Test 3: Model difficulty and run-time

The third requirement is that the model is easy to use and has a low run-time. Although difficulty and if the duration of the run time is low enough are subjective matters, we can quantify them and compare them to the models discussed in Chapter 3. This does not give the difficulty of an action. To set the base case, twelve actions have to be taken. To set a scenario, an additional twelve actions have to be taken. These actions are explained step by step in Appendix D. Thus in total 24 actions have to be taken to run the model.

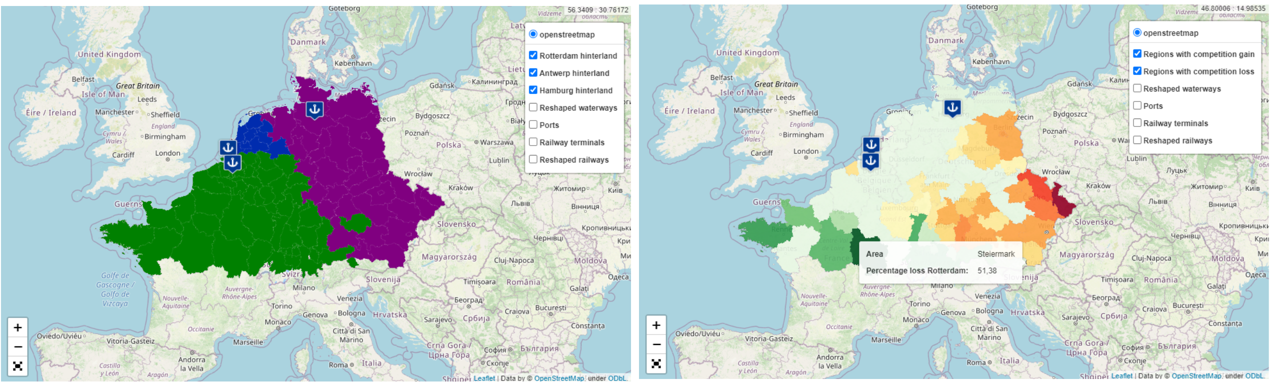
The current method used in literature (as discussed in Section 3.2) uses four different models, thereby far exceeding the 24 actions of the model. That being said, the method is far more extensive than the model, and the model is by all means not a complete replacement for the method. Therefore the number of actions of the individual models used in the method are also compared. As the definition of an action is ambiguous, and the number of actions depends on the usage of the models, the order of magnitude of the actions are given and compared. They are obtained from the literature used in Chapter 3. The results are shown in Table 5.1.

In addition, the run time is compared. The total (iterative) time to complete the method is in the order of magnitude of months. However, as discussed above, this is not comparable to the model developed in this thesis. Therefore the run time of the individual models is also compared and given in Table 5.1. The run times exclude the learning curve to use the models. The run time of the developed model can vary between one to five minutes, depending on how different the scenario is to the base case. The developed model is similar to the `BIVAS` model in the number of actions and run time. As for the other models, the actions and run time of the developed model are lower. Notably, the Container Port Competition Model (`CPCM`), which is similar to the developed model has more actions and a higher run time. The developed model can implement changes more efficiently on a larger scale and has fewer variables, thereby reducing the number of actions and run time.

Table 5.1: The amount of actions and run times of the different models used in the current method compared to the model of this thesis. Figures are in order of magnitude.

Model	BIVAS	SIVAK II	CPCM	Trans-Tool	Model thesis
Actions [number]	10^1	10^1	10^2	10^2	10^1
Run time [minute]	10^0	10^1	10^2	10^2	10^0

Test 4: Comprehensive output
The final requirement is regarding the output of the model. The output should be comprehensive, visually understandable and easy to draw conclusions from. In other words, the output data must be readable. Again, this is a subjective matter and cannot readily be quantified. The output of a fictional scenario is depicted in Figure 5.2. Figure 5.2a on the left depicts which competitive areas belong to which port. Figure 5.2b depicts the areas in which Rotterdam is more or less competitive when compared to the base case. As previously stated, the readability is subjective, however the resulting output is what the developers set out to obtain.



(a) Results model which hinterland areas can be contributed to each port

(b) Results model of a scenario compared to a base case. Depicts which areas Rotterdam has lost or gained competitiveness (hover over an area to see detailed figures)

Figure 5.2: The output of the model for a fictional and non-calibrated scenario.

5.2. Model calibration

The calibration process involves the specification of the correct values of the parameters in order to provide realistic answers. To calibrate the model, data is needed to which the results can be compared. Two data sets are used for this process: tipping points and competitive hinterland areas.

5.2.1. Comparing the tipping points of the modalities

As described in Section 4.3, at specific distances from the origin a modality can be more advantageous than the other two modalities. As such there are distances at which one modality is as advantageous as another before one surpasses or falls behind the other. Those distances are known as tipping points. Figure 5.3 gives an example of the tipping points for the road, waterway and rail modalities. These tipping points can be used as calibration points.

Based on figures from (CBS, 2016) and (Jonkeren, Francke, & Visser J., 2017), the tipping points can be determined and compared. These points can be expressed in different ways, such as costs over distance or percentages over distance. However, the tipping points remain at the same distance as the ratios remain the same. The output of the model data is costs over distance, following from eq. 4.1. The data to which these results are compared is expressed in percentages over distance.

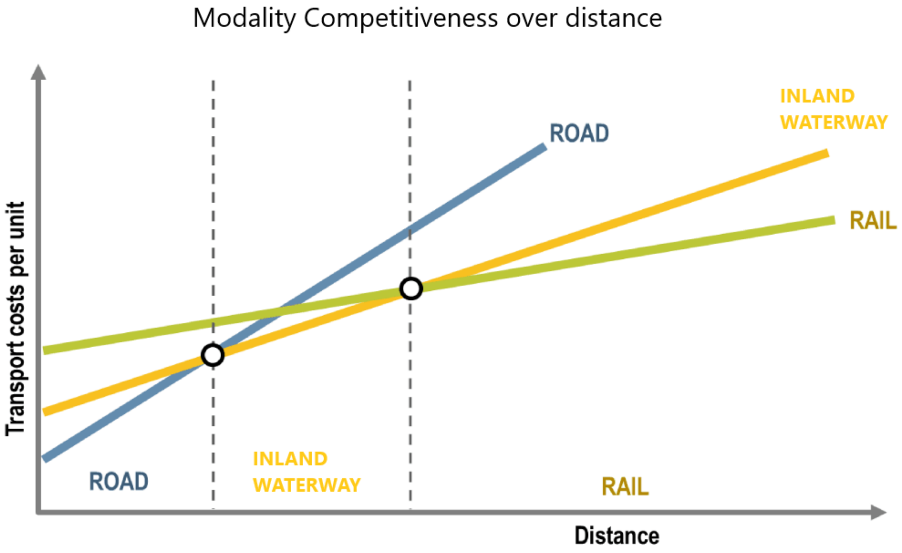


Figure 5.3: Example of modality competitiveness and tipping points (white dots). Adapted from (Rodrigue, 2020).

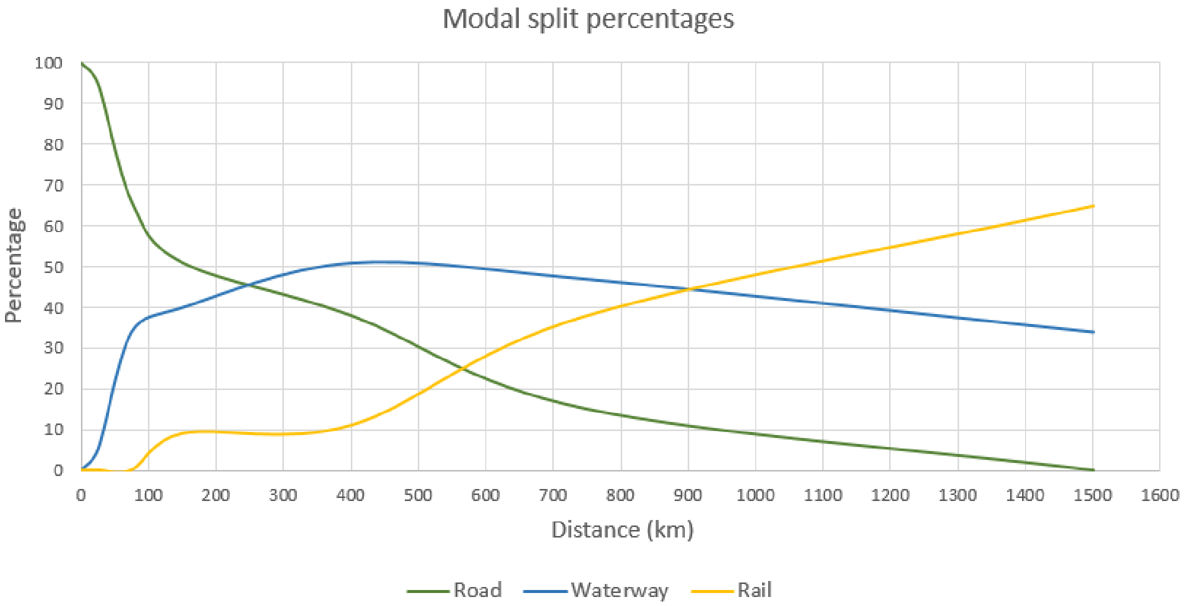


Figure 5.4: Figures from (Jonkeren et al., 2017); percentage modal split over distance. Tipping points at 250 km and 900 km.

Figure 5.4 gives the modal split and the tipping points from (Jonkeren et al., 2017). Figure 5.5 gives the costs per modality over the distance, as described in Section 4.3. The tipping points of the former figure lay at around 250 km and 900 km, whilst the latter only has one tipping point, at around 200 km. It can be concluded from these figures that either the input variables used in equation 4.1 or the equation itself is not correct.

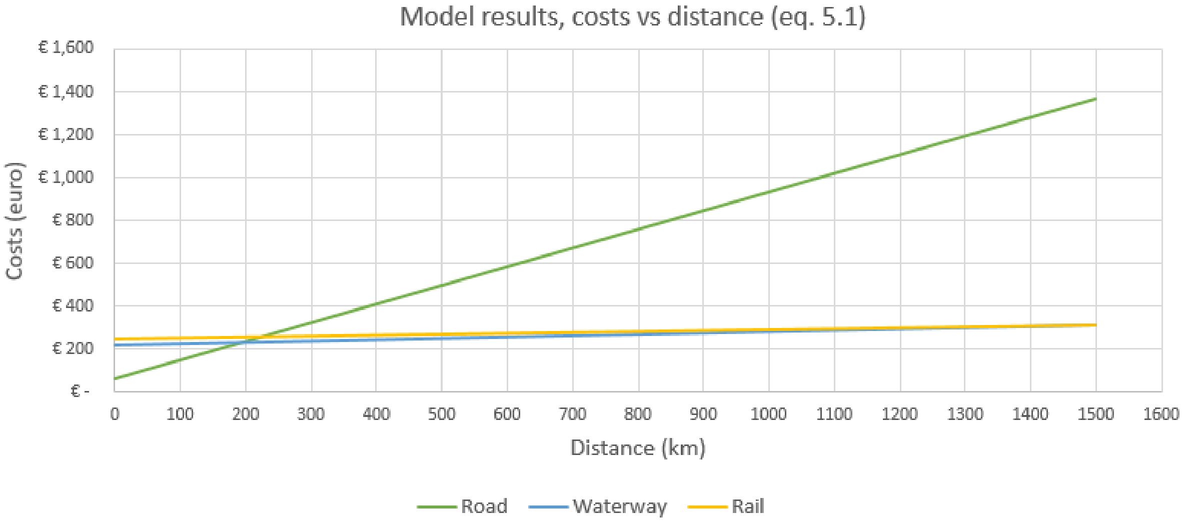


Figure 5.5: Results model based on equation 4.1; costs over the distance. Figures used as described in Section 4.3 and 15 TEU. Only one tipping point from road to waterway at 200 km.

Simplification to fixed and variable costs

When a single modality is closely examined for its costs following equation 4.1, a distinction can be made between the costs of loading and unloading the containers and the travel costs. Figure 4.8 shows this visually. This distinction of (un)loading costs and travel costs can also be simplified to the fixed costs and variable costs per distance unit. This approach may not give the exact costs it would take to operate a modality, it does, however, give the ratios between the modalities and the tipping points of when a certain modality becomes more competitive than the others.

Following this method, van Kersbergen (2018) proposed a fixed rate, in which the fees and (un)loading time costs are represented and a variable rate per km. The variable rate includes the fuel, depreciation, salaries etc. By taking a linear regression of quotes for certain distances of the modalities, costs functions can be derived. The functions are:

$$\begin{aligned} \text{Road modality:} &\ = €76.22 + €0.93/km \\ \text{Waterway modality:} &\ = €86.19 + €0.68/km + €600 \cdot \exp(-0.029 \cdot km) \\ \text{Rail modality:} &\ = €320.13 + €0.43/km \end{aligned} \tag{5.1}$$

However, as can be seen, this approach is not watertight. The added €600.- serves as a penalty which diminished over distance, as to discourage the use of inland water transport over short distances. Furthermore, the fixed rate for the train is found to be €102.74. Fees are added which represent the extra handling costs of transhipment in the storage yard (two times €80.-) and a fee for the added dwelling time of the containers (€57.39).

It should be noted that by applying this method, specific problems do arise. The black box effect of the model is increased as the individual variables as loading time and capacity are no longer adaptable by the user. If the available capacity of an inland vessel drops due to low water conditions, the formula cannot incorporate this. A low water fee could be added; this however, only increases the black box effect.

Figures 5.6 and 5.4 show the results of eq. 5.1 and from (Jonkeren et al., 2017), respectively. The orders between the modalities, when a modality certain modality is the most advantageous, is the same for both figures. The tipping points of the model can be found at 150 km for the road to waterway switch and at 900 km for the waterway to rail switch. The tipping points, according to Jonkeren et al., can be found at 250 km for the road to waterway switch and 925 km for the

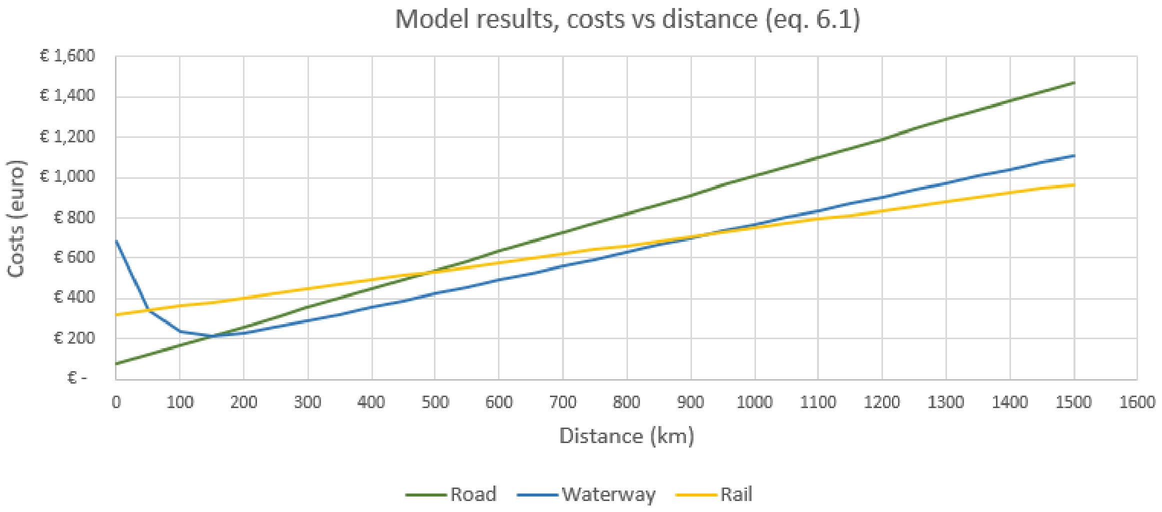


Figure 5.6: Results model based on equations 5.1; costs over the distance. Tipping points at 150 km and 925 km.

waterway to rail switch. This implies a difference of 100 km for the former switch, whereas the latter switch is off by 25 km.

This can be explained by the possible exclusion of the “last mile” costs, for which the costs of the remaining distance per truck from an inland port or terminal is added. Furthermore, Jonkeren et al. use straight distances, as the crow flies. They do not calculate the network distances, which further strengthens the former statement. This results in a negative shift of the tipping points; they occur at a shorter distance. Therefore it can be concluded that the tipping point of the road to the waterway of the model roughly matches that of the comparison data, whereas the tipping point of the waterway to rail is somewhat off. This results in a negative bias for the rail modality and an overall positive bias for the waterway modality.

5.2.2. Comparing the hinterland competitive areas of the ports

The actual (costs) results from the model for the base case, or current situation are compared to internal Port of Rotterdam Authority data and calibrated. Two steps are taken to achieve this. First, the individual modalities per port are roughly calibrated. Secondly, the overall hinterland areas per port are examined and compared.

Modalities

For the base case, the model gives as output the hinterland areas, which can be attributed to each port. However, it can also produce for each port which modality is most competitive for each port within their respective hinterland. Using this output, we can check and calibrate certain modalities if they are absent or false. Section D.6 gives more details about the calibration.

This is the case for both the waterway modalities of Antwerp and Rotterdam. The waterway modality for Antwerp is absent altogether and the Rhine area is underrepresented. To calibrate this result, the results of the waterway costs are decreased by 12% for Antwerp and 7% for Rotterdam. The waterway results of Hamburg appears to be sufficiently accurate, as are its other modalities, except for one waterway area. This is explained in more detail in Section D.6.3.

Port hinterland areas

Although the individual modalities for each port are now calibrated, the hinterland areas of each port must be calibrated too. This is really only the case for the hinterland of the port of Rotterdam, which has only a handful of competitive areas, as can be seen from Figure 5.2a

This can be explained by the absence of some of the advantages the port of Rotterdam has over the other two ports. As the supply chain of the model begins when the containers are loaded from the quays to the hinterland modalities, it skips the part where the deep sea vessels offload the containers on the quay. This is actually the part where Rotterdam gets its advantage as it can be reached 24/7 by the deep sea vessels. In contrast, deep sea vessels have to wait for the tidal window to reach the port of Antwerp and have to pass through a lock before berthing. To reach the port of Hamburg, the deep sea vessel can only approximately be partially loaded.

Therefore a 6% decrease in the costs for the hinterland modalities is applied. This gives a (close) approximation to the current situation. However, these advantages are, of course, eliminated when a future scenario is applied. Hence the 6% decrease only applies for the base case, to which the future scenarios are compared. Figure 5.7 depicts the resulting base case.

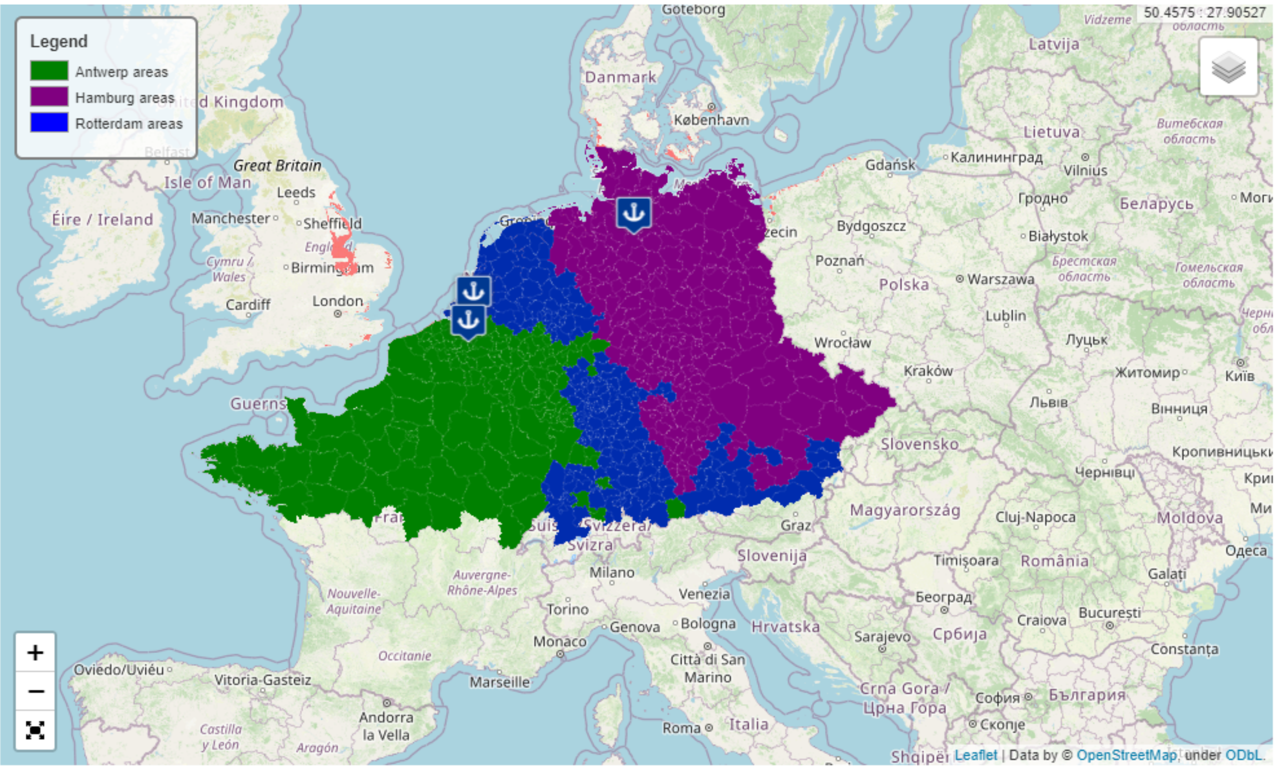


Figure 5.7: Result port hinterland competitiveness after calibration. The results used NUTS level 3.

5.3. Model validation

Lastly, the model is validated. In contrast to verification, validation is done based on external data. In contrast to the calibration, the model variables are not adjusted to reflect realistic results better; the results are purely compared to known cases. The validation is done based on three aspects: the networks used in the model, the inland port and train terminals and the resulting distances from the origin to destinations.

5.3.1. Network simplification

The modality networks are simplified in the model to reduce the run time. With the simplification, the run time is around four minutes, without it is around 24 hours. The network is simplified by reducing the number of nodes on a modality stretch to just the outer two. This means that there are fewer nodes the inland ports or railway terminals can choose from to match their location. The result is that the relative distances the modalities travel before switching to the road modality can differ. Section D.4 in Appendix D explains this in more detail. The difference in results is found to be negligible as other assumptions can result in a difference of the same order of magnitude.

5.3.2. Modality networks

The networks play a considerate role in the model. It is therefore essential that the networks used in the model reflect the correct transportation networks. This section visually compares the networks of the model with the networks of the Trans-European Transport Network (TEN-T) program (European Commission, 2020). Unfortunately, their data is not freely available to use in the model.

Road network

The inland waterway network and railway network, inland port locations and rail to road terminals are compared to those of the TEN-T program. The road network, however, is not. This is because to reach the (random) hinterland destinations, the road modality needs to be fine-mashed. The road network of TEN-T only includes the larger motorways. Therefore the “last mile” would still pose a problem. This could be solved by attributing the nearest node of the road modality to a hinterland destination. However, when NUTS level 3 is selected, the same node could be used for neighbouring regions due to the smaller density of the network—thereby returning the same result for different regions, defeating the purpose of the model.

Rail network

Figure 5.8 indicates a denser TEN-T railway network than used in the model. The main railway lines and routes do match. However, the railway network of the model has fewer branches than that of the TEN-T program. The railway network of the model is chosen by selecting the railways which have freight priority. Appendix D further explains this and the criteria used for the other network and terminals. In addition, some railway stretches to deep sea ports are missing, to Bremen and Le Havre for example. However, the three deep sea ports used in the model are connected to the railway network.

However, there appears to be some railway connection included in the model which are not included in the TEN-T program. This can be explained by the fact that the TEN-T program only shows the freight corridors, indicated by the different colours. Connections between the corridors may not be included. Overall a negative rail modality bias can be expected in the model.

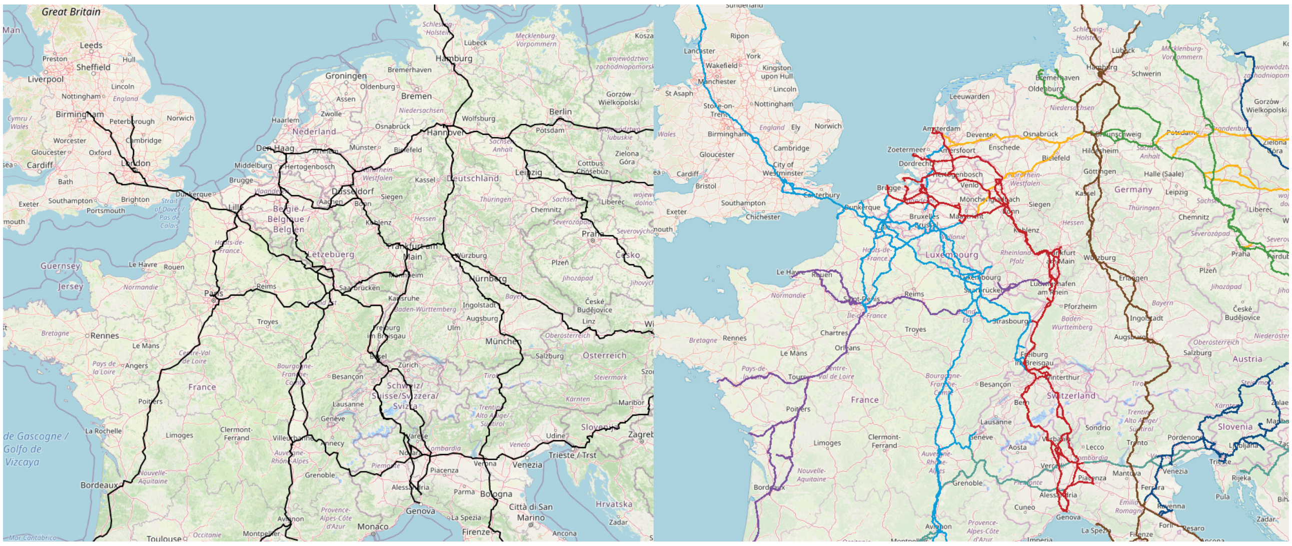


Figure 5.8: Left railway network used in the model, right TEN-T railway network (European Commission, 2020). The different colours indicate the different railway corridors.

Inland waterway network

As can be seen from Figure 5.9, the inland waterway network used in the model is a bit more extensive than that of the TEN-T program. Especially in the Netherlands and Belgium. Both networks only incorporate waterways with the capacity of accommodating for CEMT-IV to CEMT-VII class vessels. These are standard classifications for vessel sizes, ranging from CEMT-I class to CEMT-VII class (European Commission, 1992). However, it seems that some extra routes are defines in the network of the model. Some waterway bias may be expected.

On the other hand, the TEN-T network also seems to include some stretches of network that the network model does not incorporate, namely the dotted lines in France and Italy. These are waterway stretches which are not finished yet and are expected to be completed in 2025-2030 (European Commission, 2020). This is in line with the expected horizon of the +3 m sea-level rise. However, one could use the draw function of the model to include those stretches manually.

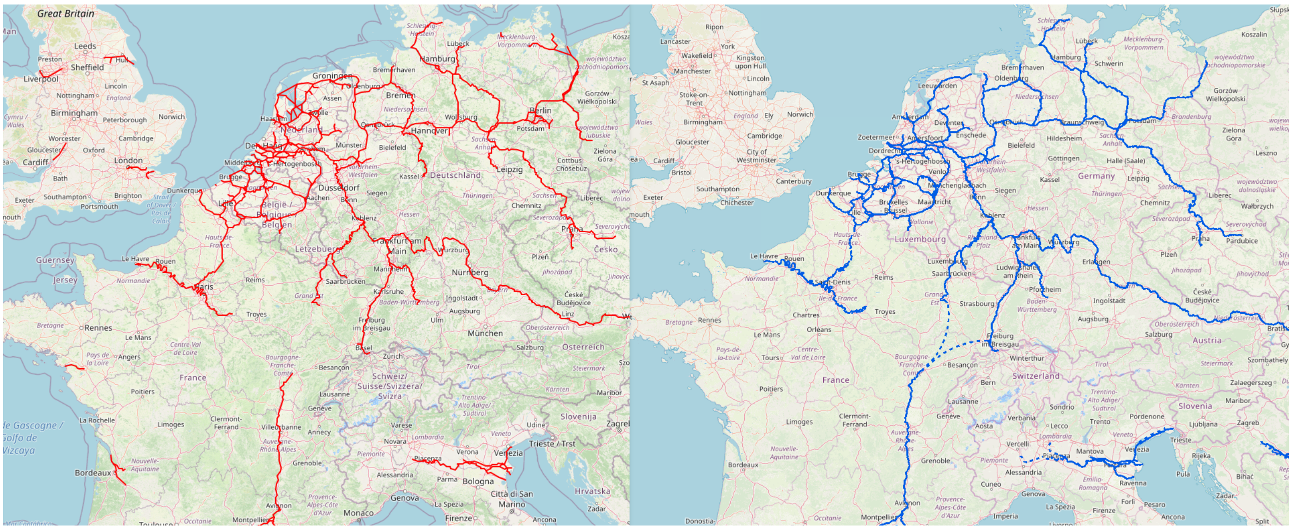


Figure 5.9: Left inland waterway network used in the model, right TEN-T inland waterway network (European Commission, 2020)

5.3.3. Inland ports and terminals

The inland ports and railway terminals form the points where the containers depart from their respective modality network onto the road network. It should be noted that the TEN-T program does not differentiate between container handling ports and terminals and non-container handling ports and terminals. Although contains are universal in nature, they do need special equipment to be loaded and unloaded from and to the different modalities. Therefore it is important to select the ports and terminals which are able to do so. However, one could make the argument that for the timeline used in this thesis/model, ports and terminals which cannot transship containers currently could be transformed to container handling terminals in the future.

Inland ports

Following Figure 5.10 he inland waterway ports applied in the model match relatively well when compared to the ports of the TEN-T program. The TEN-T program seems to have a few more ports in Belgium and the Netherlands. However, this could be attributed to non-container handling ports. Overall the inland ports of the model and of the TEN-T program align quite well.

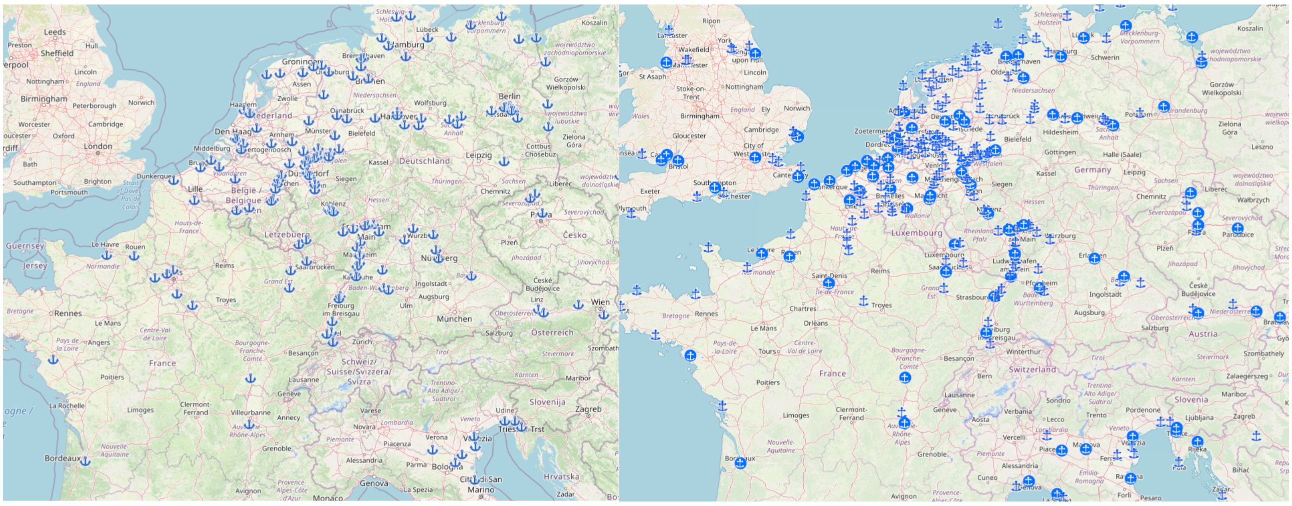


Figure 5.10: Left inland waterway ports used in the model, right TEN-T the inland waterway ports (European Commission, 2020). The encircled inland ports markers belong to the core inland port network whereas the normal anchors are of the comprehensive inland port network.

Railway terminals

The situation for rail to road terminals is quite different. When comparing the terminal locations of the model and the TEN-T program, Figure 5.11 does not give much overlap. The model includes more terminals in Belgium, the Netherlands and Switzerland, whereas there are notably fewer terminals in Germany, the Czech Republic and the Eastern Bloc.

This can be attributed to two criteria, which again follow from the manner the terminals are selected in the model (see Appendix D for more information). The terminals of the model are selected based on their name, if it includes “container” or a variation thereof. The TEN-T program can include the non-container handling terminals. In addition, the program could only include terminals with a certain capacity. The number of terminals does seem to match. However concluded can be that there can be a positive railway bias in Belgium, the Netherlands and Switzerland, whereas a negative railway bias can occur in the other countries.

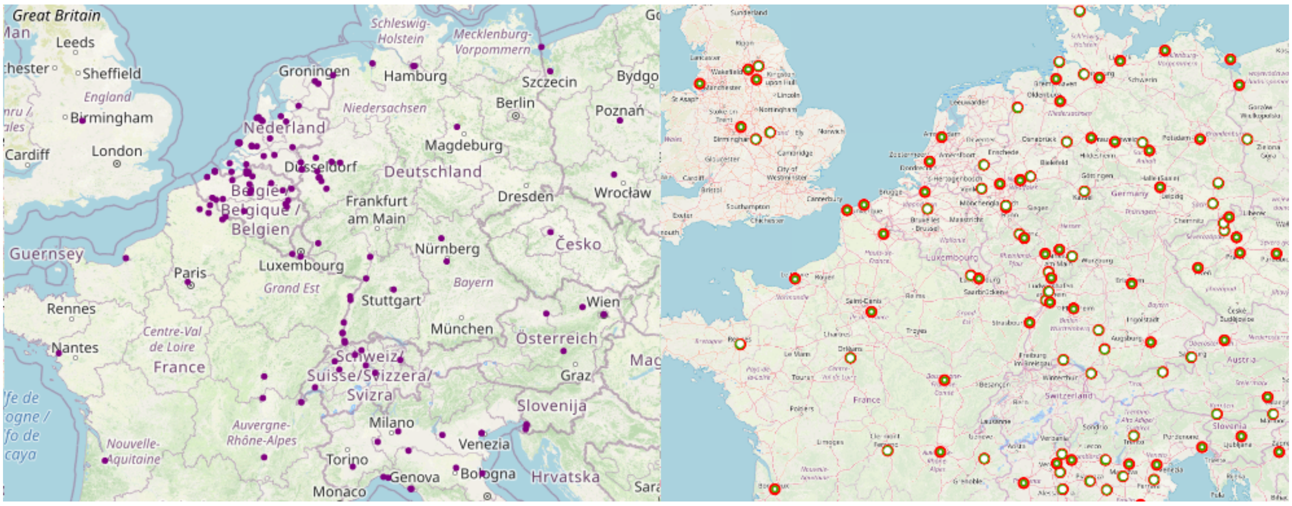


Figure 5.11: Left rail to road terminals used in the model, right TEN-T the rail to road terminals (European Commission, 2020). The markers displaying more green belong to the core railway terminal network whereas the markers displaying more white are of the comprehensive terminal network.

5.3.4. Comparing the distance results

Lastly, the distances between the origin(s) and the destinations are compared to validate the results. The model has to give proper distance results as the distances form the basis for the costs, which in turn used for the final output. Additionally, the user is free to implement their own distance to cost conversion formula; the distance formulae cannot be altered however. It is therefore paramount for the model to give correct results for the distances. Each modality is tested individually six times, two for each port. The results from the model are compared to control data, which is obtained from distance measurement tools for the modalities. Section D.7 gives more detail about these tools and results.

Table 5.2: Part of the distance regression results. Section D.7 gives more details.

Regression variable	Value
Multiple R	0.996
R-squared	0.993
Adjusted R	0.993
Standard Error	23.773
Observations	18

The distances of the model have an average deviation of 8.2%. The standard deviation is found at 10.0% and the R^2 value at 0.9929. Table 5.2 gives a part of the results of the regression analysis. The R^2 value is given a value close to 1, indicating a high correlation. The standard deviation of 10% can be explained by the starting points and networks of the model. Using the ports as starting points results can give trouble for the map function, as for the waterway network, as explained below. In addition, the (freight) railway network is less extensive than the existing freight network, which can cause a difference in the distances. Overall the results are found to be acceptable for the purpose of this thesis.

It was noted that using “Maasvlakte” as a starting point for the port of Rotterdam gives a (much) larger deviation than “Europoort”. This explains some of the negative bias Rotterdam experiences as discussed in Section 5.2.2 and is therefore adjusted accordingly.

5.4. Concluding

The sub-question this chapter answers is:

> *Does the model comply with its requirements and how accurate is it compared to reference data?*

The answer to this question is split in three and are listed below. The first answer revolves around if the model complies to its requirements, otherwise known as verification. The second part of the question, how accurate the model is compared to reference data, is split in the last to answers: calibration and validation. This is because they are similar in that they compare reference data, yet still distinct because in the calibration part, the model is adjusted whereas in the validation part the output of the model is only confirmed.

Verification

The verification is based on four requirements set in Chapter 4. The first test is two-fold, to check if the model finds the closest nodes to given points without choosing nodes which cannot be reached by the network and to check if the shortest path is chosen by the model to reach a given destination. Both are verified to be true. The second test is to see if the (boundary) conditions of the model (port locations, networks and landscapes) are adjustable. This is also true to the extend which is required for the model. New (offshore) created land and port locations cannot be added in the model.

The third test checks the model difficulty and the run time of the model. These are around 24 actions and two to five minutes, respectively. These figures are comparable to the `BIVAS` model and are lower than the other models. Lastly, the readability of the output is examined. Although the readability is subjective, the output is the desired output of the developers. Therefore it can be concluded that overall, the requirements of the model are verified.

Calibration

The model is calibrated on three aspects, the simplification of the networks, the tipping points of the modalities and the resulting hinterland competitive areas for each port. The simplification is necessary to decrease the run time of the model significantly. This simplification has a negligible influence on the result of the model, however.

The results of the distance to costs conversion formula are compared to the known points at which a modality becomes more or less advantageous than another modality. These are known as tipping points. The compared tipping points do not match the results from the formula used, as there is no tipping point between waterway and railway. Therefore other formulas are applied which do approximate the tipping points.

Lastly, the resulting competitive hinterland areas for each port are evaluated and calibrated using internal data from the Port of Rotterdam Authority. The hinterland area of the port of Rotterdam is increased overall by 10% as the non-calibrated areas of the port are too limited. In addition, a 7% and a 12% decrease in the costs for the waterway modalities of the Rotterdam port and Antwerp port are applied, respectively. The resulting respective competitive areas for each port is a close approximation of the real-world situation. However, the outset of the model is to give accurate distance results and to give the user the opportunity to implement their own distance to cost conversion formulae.

Validation

Validation is done based on external data. Three parts of the model are validated, the networks used in the model, the inland ports and railway terminals and the resulting distances between the origin and destinations. The road network is not validated as the Google Maps API is applied, which is assumed to be accurate. The TEN-T program networks of the European Union are used to compare the networks. For the waterway network, it is important to consist only of the larger class waterways. The railways are selected on the property to only transport freight. Both the railway and waterway networks match the TEN-T networks, although the railway does have fewer branches and is therefore in a slight disadvantage.

The inland ports and railway terminals too are compared to the TEN-T program. However, the ports and terminals of the TEN-T program are not distinctively for container transport. Therefore the results should be taken with a grain of salt. That being said, the inland ports do match the ports used in the model. This is, however, not the case for the railway terminals. Although some do match, in some countries there are too many terminals whilst in others to few. This can be attributed to the aforementioned lack of distinctive container terminals.

Control values are used to validate the distances resulting from the model. These values are obtained from respective modality distance tools. The R-squared value is found at 0.9929, indicating a high correlation between the control distances and the model distances. The standard deviation is found at 10.0%, which can be attributed to the difference in networks used in the model and control tools and the starting points. Overall the results are found to be sufficient.

6

Retreat scenario and the hinterland network of the three largest ports in NW Europe

Chapter outline

This chapter answers the sub-question: "What are the options to adapt to sea-level rise for the three largest ports in Northwest Europe and the changes in their hinterland networks in case of +3 m sea-level rise and a retreat scenario?"

Following Chapter 2, consequences on shipping and port activities are still relatively unknown, in case of a retreat scenario. Thence, this chapter examines the changes on the hinterland and its networks using a new method. First, the inundated landscapes of the Netherlands, Belgium and Germany are briefly assessed. Subsequently, the options for sea-level rise adaptation of the ports of Rotterdam, Antwerp and Hamburg are explored, as derived from the method. For the port of Rotterdam, future operations are evaluated, whereby strategic sites are determined to construct new (inland) port locations, with or without a deep sea terminal at the current port location. The guideline for the port locations is their proximity to the (new) coastline, keeping them accessible for shipping.

The results are different options for the three ports, which can be used as boundary conditions for the model. Lastly, the changes in the transport networks of the different ports and their respective modalities are shown, as influences by the new coastline. The logistical systems to and from the hinterland are depicted, including the different options for deep sea terminals and deep sea inland terminals, for the port of Rotterdam.

6.1. Creating a new method for analysing the retreat scenario

Following the development of the adaptive hinterland port competition model in Chapter 4, a method is devised to obtain the new boundary conditions at +3 m sea level rise and a retreat scenario. This method is subsequently applied in this chapter for the port of Rotterdam as a case study.

1. Assume a certain sea-level rise
2. Apply the sea-level rise to an inundation model to find new coastline
3. Examine the consequences of the sea-level rise on the (inundated) land
4. Examine the locations of the ports in respect to the inundated areas
5. Determine the options for the ports to adapt to the possible sea-level rise and inundation hindrances
6. If needed, find new port location(s) along the new coastline and in proximity to deep water and modality networks
7. Assume modality network stretches in the inundated areas to be redundant

6.2. The consequences of inundated landscape of Northwest Europe

To examine the landscape of Northwest Europe in case of +3 m sea-level rise and a retreat scenario, a "bathtub model" is assumed and utilized. This model is essentially an elevation map which utilizes the height differences of the landscape and the selected water level. If the model finds a point lower than the selected water level and connected to saltwater, the lower-lying land behind it fills up, as a bathtub. This creates an inundation map which marks the areas red that is connected to the sea when a particular water level is selected, in this case, +3 m.

As the water level fluctuates during the day and over a month, the "high tide line" is used. The high tide line is the water level at the mean higher high water level (MHHW). This is obtained by adding modelled tidal increments to recent historical data, using satellite measurements (Kulp & Strauss, 2018, 2019; Climate Central, 2020). Figure 6.1 depicts the inundated areas at +3 m sea-level rise and a retreat scenario for Northwest Europe.

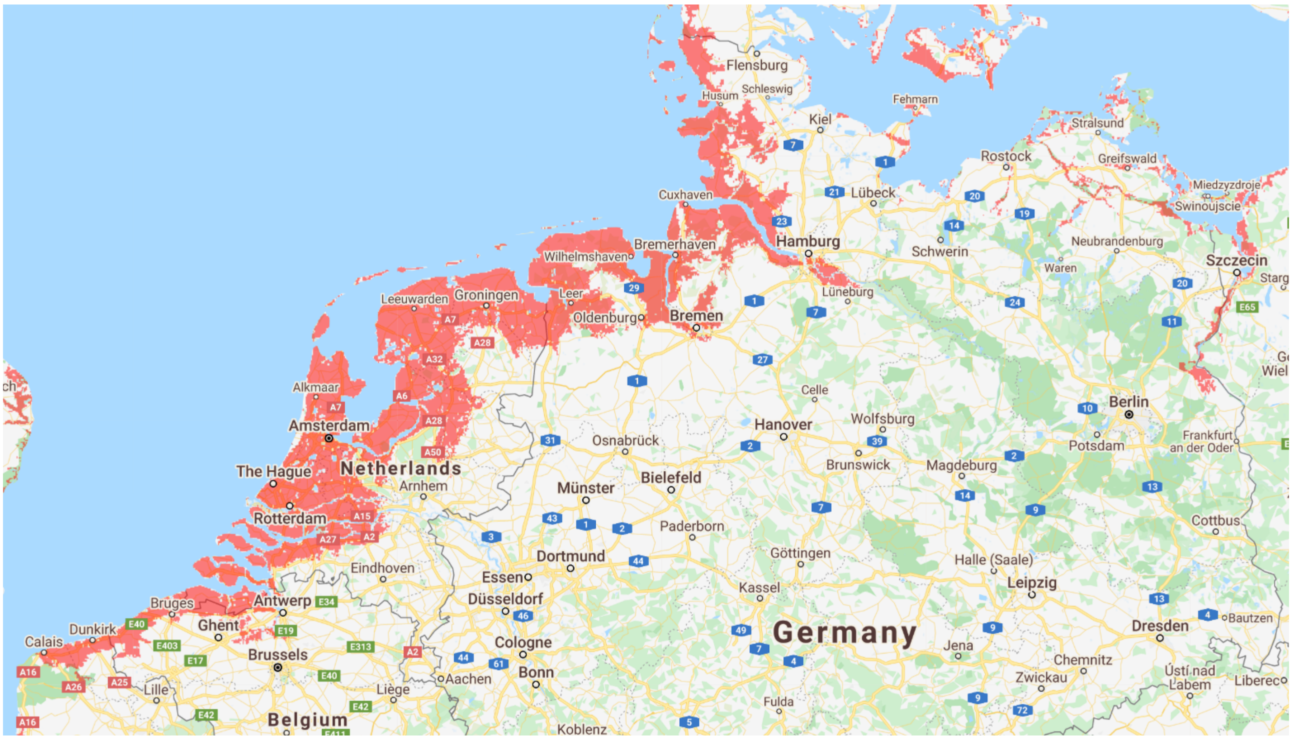


Figure 6.1: Map of Northwest Europe depicting the inundated land in case of +3 m sea-level rise (Climate Central, 2020)

6.2.1. Assumptions

Following the map of Figure 6.1 and the retreat scenario for the Netherlands, some assumptions have to be made. The assumptions, including explanation, are listed below. Subsequently, some drawbacks and notes on the bathtub model are given.

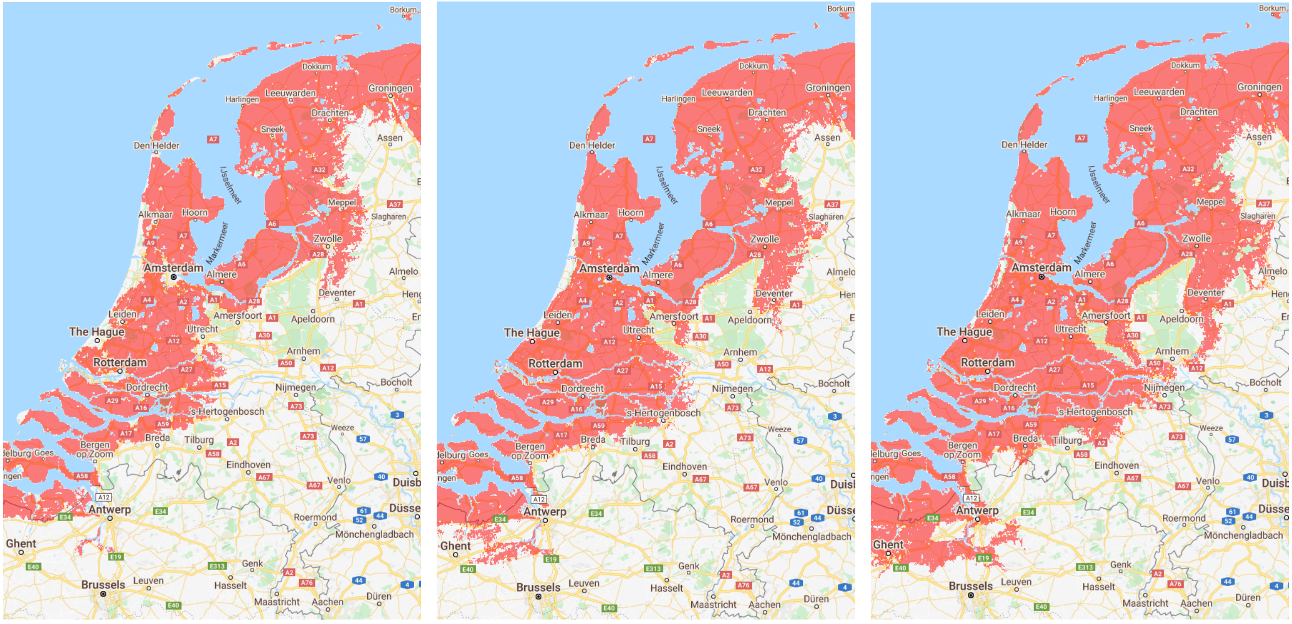
1. *"Sudden breach" at +3 m sea-level rise, not gradual*;
   Assumed is that the Netherlands can handle sea-level rise up until +3 m. Due to a relatively steep border between the low lying areas and higher land of the Netherlands, the amount of land which is inundated does not differs a lot at a lower or higher level than +3 m. Figure 6.2 depicts the difference. Therefore it is assumed that the governments are able to maintain the current strategy up until that point and a retreat scenario is chosen. However, due to planning the coastline at +3 m can be maintained even if the sea level rises above that level.

2. *Planned and constructed ports*;
   As the breach is planned at +3 m, new port locations have been gradually developed and constructed over time, thus at the moment of inundation, the ports are already in use, albeit in a smaller capacity. Therefore, investments and time to resume port operations are limited.

3. *New foreshore*;
   The large deep sea vessels, which need a waterway depth of around sixteen meters, cannot sail unhindered over the inundated land. The depth would be too shallow still. For some locations, new canals need to be dug and rails need to be placed in order to connect the ports to the networks. As the +3 m breach is anticipated, this can be done in advance, thus saving costs.

4. *Only the ports of Antwerp, Rotterdam and Hamburg are examined*;
   Although there are more (container handling) ports in Northwest Europe for simplicity of the thesis is chosen only to take Antwerp, Rotterdam and Hamburg into account. Nonetheless, these ports are the three largest in Europe and are in direct competition with each other.

5. *Population shift of and in the Netherlands*
   Around eight million people currently live in the to be inundated areas. The large majority of these people will have moved to the southern and eastern parts of the Netherlands and the western part of Germany.



(a) Inundation at +1 m sea-level rise (b) Inundation at +3 m sea-level rise (c) Inundation at +5 m sea-level rise

Figure 6.2: Inundated land of the Netherlands at different sea-level rise levels. Total difference of 4 meters between Figures (a) and (c) (Climate Central, 2020).

The bathtub technique is considered accurate for permanent sea-level rise, less so for incidental floods. However, some important factors are left out of scope. The inundated land is relatively shallow and induces friction on the inflowing water. Tidal and wave energy will largely be dissipated, resulting in overestimating of the total flood height. Likewise, the energy dissipation makes wave run-up and overtopping less critical for flood protection. In addition to the coastline and river mouths will retreat too, implying that sediment is discharged and deposited on the newly inundated land, forming a new delta and increasing the energy dissipation.

The model does not include flood protections, however. This decreases the accuracy of the bathtub model (Climate Central, 2020). For the purpose of this thesis, to give a crude estimate of a new location for the Northwest European coastline, the bathtub model considered sufficiently accurate.

6.2.2. Inundation consequences for the Netherlands and the port of Rotterdam

The Netherlands

Following the bathtub model and Figure 6.1, it can be concluded that the Netherlands is affected the most by the retreat scenario. Large parts of the country as we now know it are inundated and uninhabitable. As assumed in Section 6.2.1, these inhabitants have migrated to the parts of the Netherlands which are above (the new) sea level. From these assumptions, new possible port location can be identified. A list is given below, sorted north to south. An overview of the locations are given in Figure 6.3. They are chosen for their proximity to the sea and to the inland waterway network. Obviously, new port locations are not limited to the following examples, others may be chosen and applied in the model.

1. Hoogeveen
   Hoogeveen is connected to the west the sea via the IJsselmeer and has a limited inland waterway connection to the east via the Hoogeveense Vaart, connecting the port to the Eems river in Germany. As the inland waterway connections and capacity is limited, it is only considered as an inland port location which would be mostly used for the (remaining) north-east of the Netherlands.

2. Zwolle
   South of Zwolle lays a hill ridge, the Veluwe. This naturally higher lying area is situated 20 km upstream of the IJsselmeer, along the river IJssel. This river is connected to the Twenthekanaal to the east and the Rhine to the south. To the west, the location is connected to the IJsselmeer and Veluwemeer. Due to these connections, it can be considered as a deep sea port and an inland port location.

3. Huizen
   Situated at another small hill ridge, Huizen is directly connected to the IJsselmeer to the north. Fifteen km to the west, the Amsterdam-Rhine Canal, which ends in the Rhine, is located. To the northeast of the Netherlands, it is connected via the IJsselmeer and the Veluwemeer. These connections are not directly linked to the location however. The link to the IJsselmeer, which gives a direct connection to the sea. Therefore it is considered a deep sea port.

4. Tiel
   Following the current main hinterland waterway connections of the port of Rotterdam approximately 100 km inland are the rivers Waal, Nederrijn and Meuse. Tiel is located in the midst of these three rivers and at the crossing of the new coastline, making it suitable as a deep sea port and an inland port.

5. Bergen op Zoom
   Following Figure 6.1, the town of Bergen op Zoom is bordered to the west to the Eastern Scheldt, linking it in close proximity to the sea. The eastern inland waterway connection can be reached via the Scheldt-Rhine Canal in the north. To the south however, the port of Antwerp is in close proximity, a close competitor to the Port of Rotterdam Authority. Due to the connection to the Eastern Scheldt, this location is considered a deep sea port and an inland port.

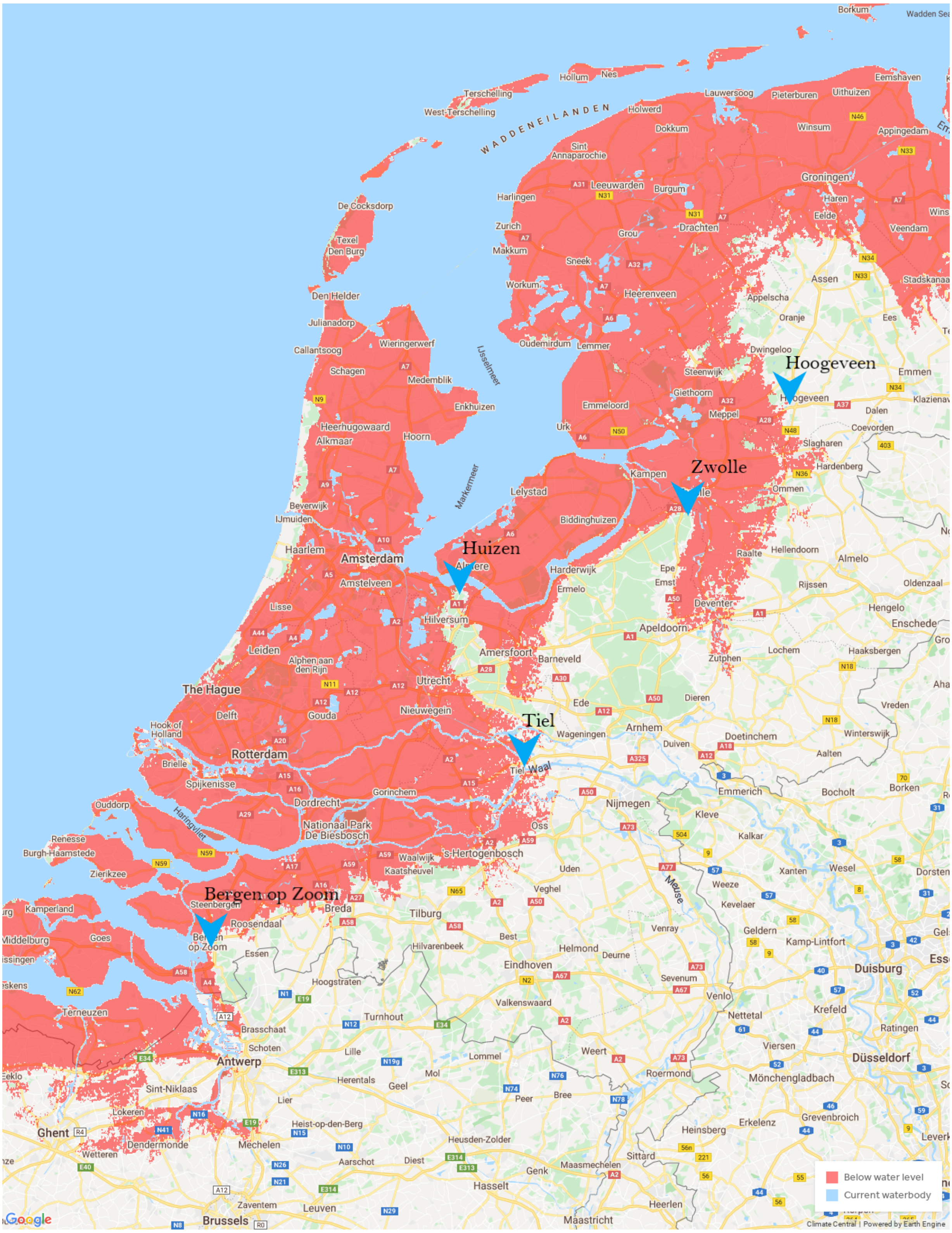


Figure 6.3: The Netherlands at +3 m sea-level rise and retreat scenario (Climate Central, 2020). Positions for possible future port locations are additionally depicted.

Port of Rotterdam

If we zoom in on the port of Rotterdam at +3 m sea-level rise, using Figure 6.4, some areas and terminals (at their current height) are still above sea level. The model uses an outdated map, thus it does not include the Tweede Maasvlakte. As the Tweede Maasvlakte is constructed at +5 m NAP, it would also mainly still be dry at +3 m sea-level rise. With this in mind, two options for the Port of Rotterdam Authority can be identified.

1. *Deep sea terminal at the current port location in combined with inland port(s) at the new coastline*
   If the current strategy of the Port of Rotterdam Authority is continued, to raise terminals when contracts end, more areas and terminals of the port can be expected not to be inundated at +3 m sea-level rise. This poses an option for the port of Rotterdam to continue the usage of the current terminals as deep sea terminals where the large sea-going vessels can dock. This option can be combined with inland ports at strategic locations along the new coastline via short sea trade and with the use of inland barges. This implies that the deep sea vessels do not have to travel up a canal or river to reach the new inland ports. This would save cost to dig or deepen a canal or river(stretch) and would mean that the sailing time of the deep sea vessels would be less. This would also be more beneficial for the short sea trade and the feeder container trade.

2. *A deep sea port directly at the new coastline, possibly in combination with a canal to ensure depth for the vessels*
   Another option for the Port of Rotterdam Authority is to relocate the entire port to the new coastline, enabling deep sea vessels to berth directly at that location. This has as an implication that a canal or inundated river stretch needs to be dredged in order to create the depth needed for the deep sea vessels. This signals extra cost, notably when maintenance dredging is considered. However it might be faster as containers would not have to be transshipped two times, first at the deep sea terminal and secondly at the inland port. Additionally, the containers can be shipped in large quantities on the sea going vessels, whereas the short sea and inland vessels have a much smaller capacity. These two qualities result in fewer trips that have to be made in a shorter time span.

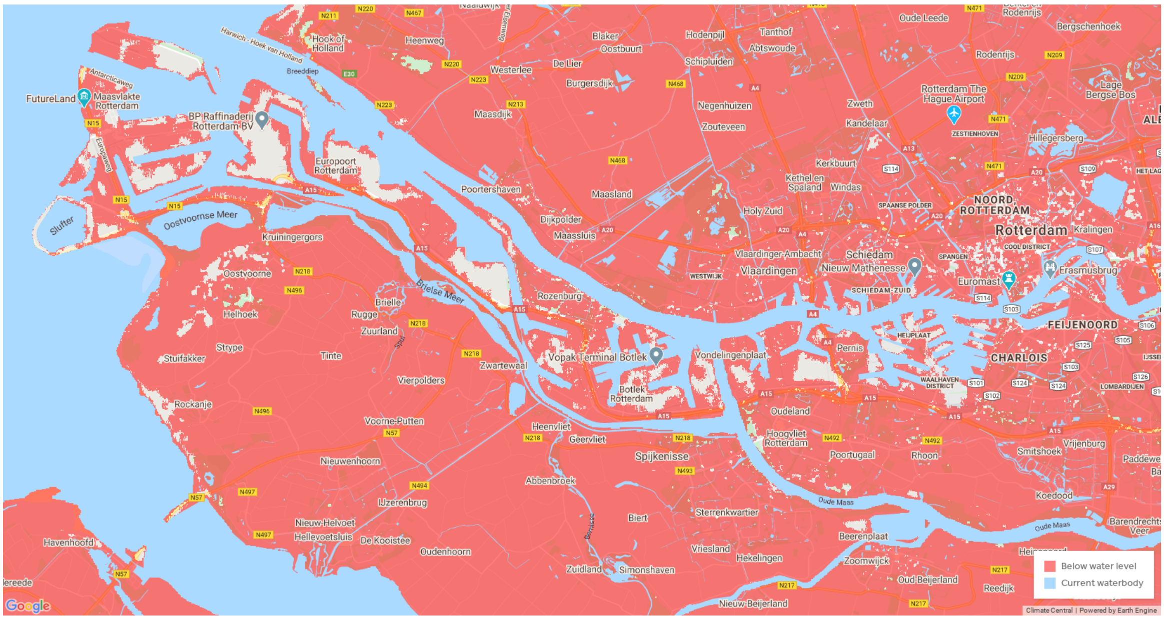


Figure 6.4: Inundated areas of the port of Rotterdam at +3 m sea-level rise. The Tweede Maasvlakte is not depicted. (Climate Central, 2020)

6.2.3. Inundation consequences for Belgium and the port of Antwerp

Belgium

The current adaptation strategy of the Belgium coast dates back to 2013. Similar to the current strategy of the Netherlands, the coast is protected via beach nourishment to keep level with the sea-level rise (Vlaams minister van Omgeving Natuur en Landbouw 2014-2019, 2013). To the northwest, Belgium is bordered by the North Sea and Zeeuws-Vlaanderen the southern part of the Dutch Zeeland province, which in turn is bordered by the North Sea. Most of the inhabitants live in the north by northwest part of the country, although relatively spread out (Eurostat, 2020). However, following Figure 6.1, those are the areas which inundate at +3 m sea-level rise when the bathtub model is applied. The rest of the country remains mostly unscathed.

Port of Antwerp

Following Figure 6.5, the port and the city of Antwerp are significantly less affected by the sea-level rise than Rotterdam. The port, therefore, does not need to be relocated or combined with inland port locations, contrary to the port of Rotterdam. To prevent future flooding of the port, terminals can be heightened, similar to the current adaptation strategy of the port of Rotterdam. This can be done in phases to ease expenses. Locks or a storm surge barrier are possibly needed to protect the city of Antwerp, which can hinder shipping. Parts of the port are currently behind locks, however, adding only a relative amount of waiting time to the transport chain. If higher sea-level rise is examined, +5 m for example, the port and the city of Antwerp are less able to withstand flooding. In that case, a relocation of the port would be advised. However, +5 m sea-level rise is beyond the scope of this thesis. Appendix C shows inundation maps of the ports at +5 m sea-level rise.

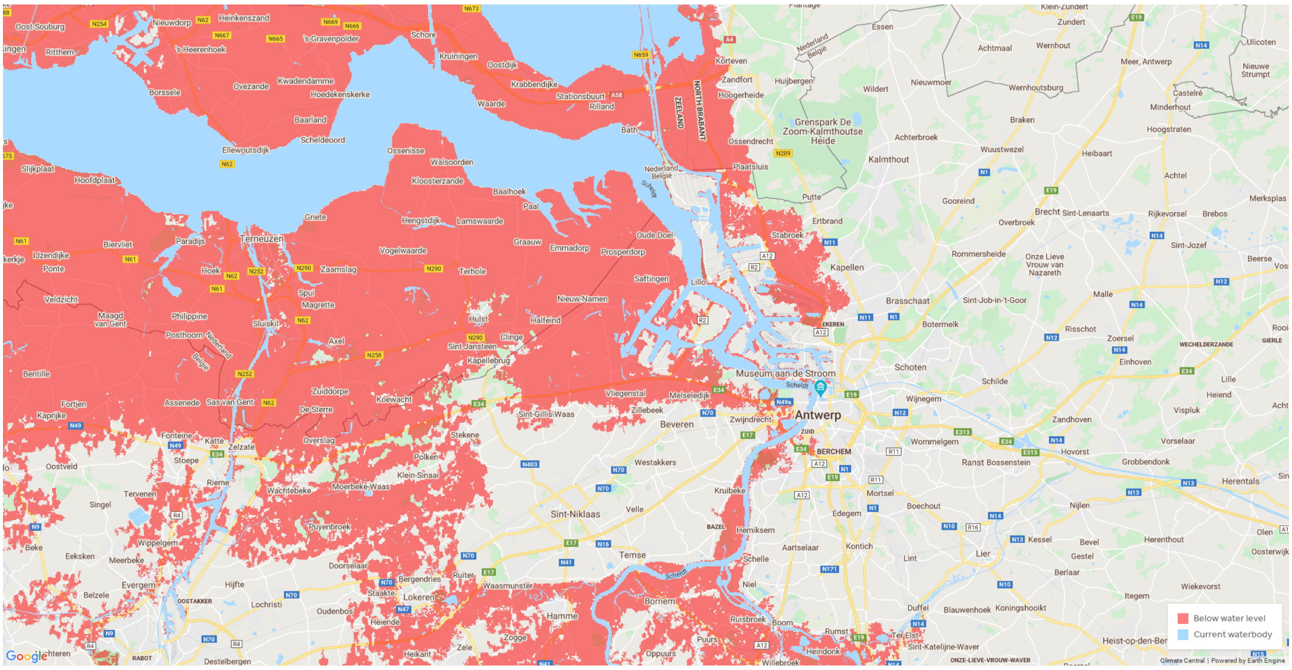


Figure 6.5: Inundated areas of the port of Antwerp at +3 m sea-level rise. (Climate Central, 2020)

6.2.4. Inundation consequences for Germany and the port of Hamburg

Germany

Germany is situated to the east of the Netherlands. The north of the country borders the North Sea and the Baltic sea which are divided by peninsula of Denmark. The German North Sea coast faces similar problems as the Dutch North Sea coast, as the Wadden Sea continues into Germany and onto Denmark (Sterr, 2008). The Baltic Sea coast seems to be more resilient against sea-level rise, following Figure 6.1. The coastal defence is not regulated centrally in Germany, in contrast to the Netherlands. The responsibility of coastal and sea-level rise protection lays with the respective state governments which border the coastline. Therefore there is no uniform strategy for the five neighbouring coastal states. Currently, the sea dikes are designed for +50 cm sea-level rise in 2100 (European Commission, 2009). Some states are already slowly exploring the options of giving farmland back to the sea, thereby reducing the protection costs (Correctiv, 2019).

As can be seen from Figure 6.1, only a relatively small part, in the northeast of Germany, experiences inundation at +3 m sea-level rise. This is an area with a low population density, except for the cities of Hamburg and Bremen. Coincidentally these cities are of importance to the German economy however (European Commission, 2009; Brinkwirth, von Wirth, & Berndt, 2019).

Port of Hamburg

Figure 6.6 below shows a zoomed-in depiction of the inundated areas at and leading to the port of Hamburg at +3 m sea-level rise. As can be seen, the city or of Hamburg does not inundate at +3 m sea-level rise, nor at higher sea-level rise. The port does experience some inundated areas. However, if they apply the same strategy as the current strategy of the port of Rotterdam, heightening the terminals, then the port could still be operational. Similar construction as the Maeslant barrier would be advised to ensure safety against storm surges. Safety would be maintained whilst the port accessibility would not be hindered.

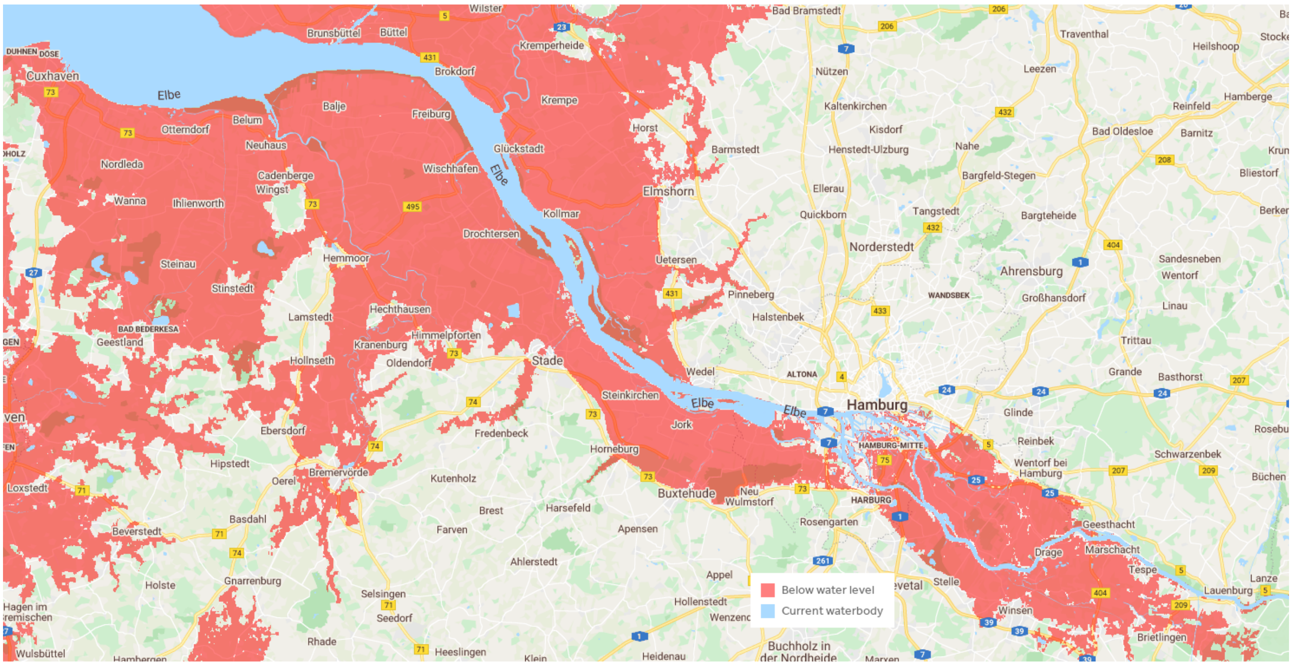


Figure 6.6: Inundated areas of the port of Hamburg at +3 m sea-level rise. (Climate Central, 2020)

6.3. Inundation consequences for logistics and network changes

Not only are the sea ports of the countries of Northwest Europe impacted by sea-level rise and a retreat scenario, but their respective logistic systems are also influenced, assuming the new coastline enforces network changes. These changes can be of important influence on the port competition as the hinterland connectivity plays an important factor (Meersman, Pauwels, Van De Voorde, & Vanelslander, 2008; Zondag, Bucci, Gützkow, & de Jong, 2010). To examine the network changes, the (current) hinterland modalities of Northwest Europe are depicted in combination with the results from the bathtub model. Therefore the data from Climate Central (2020), Demis (2017) and European Commission (2020) is combined.

6.3.1. Container logistics and supply chain

When a container is offloaded at a deep sea port, they are first stored at the terminal. After a few days (depending on the cargo and modality) they are transshipped and transported to their respective destinations. There are three possibilities for a container to reach a hinterland destination: via road, rail and inland waterway. Figure 6.7 depicts the intermodal container supply chain. Depending on the distance, destination and amount of containers, one modality can be more advantageous than the others. However, the rail and waterway networks are limited, whereas the road network can reach (almost) any destination. These limitations differ from port to port and therefore influence the port competition. The differences in the modalities and the (possible) changes of the network due to inundation at +3 m sea-level rise are discussed below.

Figure 6.7: Intermodal container supply chain from deep sea vessel (on the left) to the hinterland destination (on the right). Figures are not to scale.

6.3.2. Road network

Although each modality is affected by the inundation, it is assumed that there are no changes to the road network in the non-inundated areas. This is due to its close-knittedness nature of the road network and lack of major important corridors, as opposed to the rail and waterway network. For the road network, alternative routes are in close proximity and smaller roads can more readily be enlarged to serve as highways. That being said, the road corridor is an essential network for the ports (T. E. Notteboom & Rodrigue, 2005).

6.3.3. Rail network

With the TEN-T program, the European Commission is interconnecting Europe's core corridors systems. Among these systems is the freight railway network, depicted in Figure 6.8 in black. The passenger railway network in Europe is far more extensive but unsuitable for freight transport as the transport of passengers has priority. Therefore dedicated freight corridors are constructed which run to and through the deep sea ports. The railway network is important for the destinations which are far inland and not in close proximity to a waterway network. It is, however, an expensive modality to use (Witlox, 2006; Pieriegud, 2019).

In addition to the freight railway corridor, Figure 6.8 also depicts the inundated land at +3 m sea-level rise and the (current) deep sea port locations. Again, the port of Rotterdam is most influenced by the inundation. The railway connection between the ports of Rotterdam and Antwerp is no longer an option. This also limits the connectability of the port of Rotterdam. The railway connections to the south and east of Antwerp remain intact. Parts of the northern network of the port of Hamburg can inundate, however, the primary connection to the south is preserved.

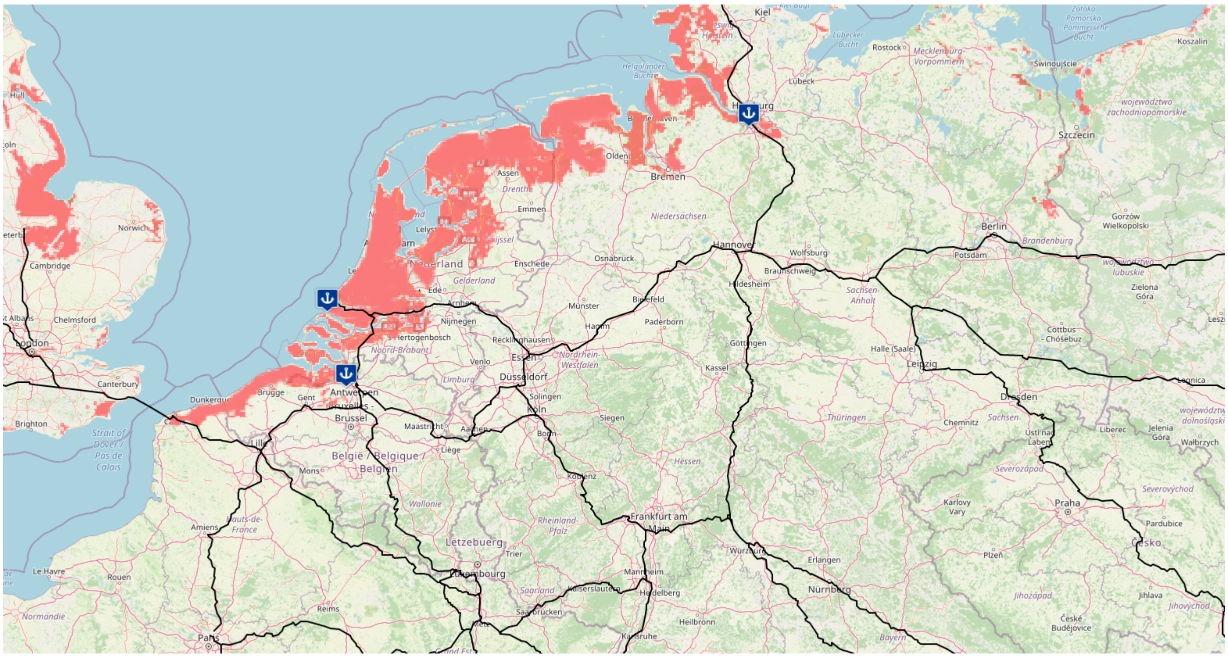


Figure 6.8: European rail freight corridors and inundated land at +3 m sea-level rise. From top to bottom, the ports of Hamburg, Rotterdam and Antwerp are depicted. Data combined from (European Commission, 2020; Climate Central, 2020).

6.3.4. Inland waterway network

The hinterland waterway connection is essential for the port of Rotterdam. Nevertheless, the ports of Antwerp and Hamburg are also connected to the waterway system. The port of Antwerp is connected to the Rhine system via the Scheldt-Rhine canal, dug to the north of Antwerp. It is an essential connection for the port, as it provides a competitive route to the West-Germany and Switzerland (De Vries, 2008). The waterway network of Hamburg is less closely-knit than that of Rotterdam and Antwerp. However, it serves a broader area.

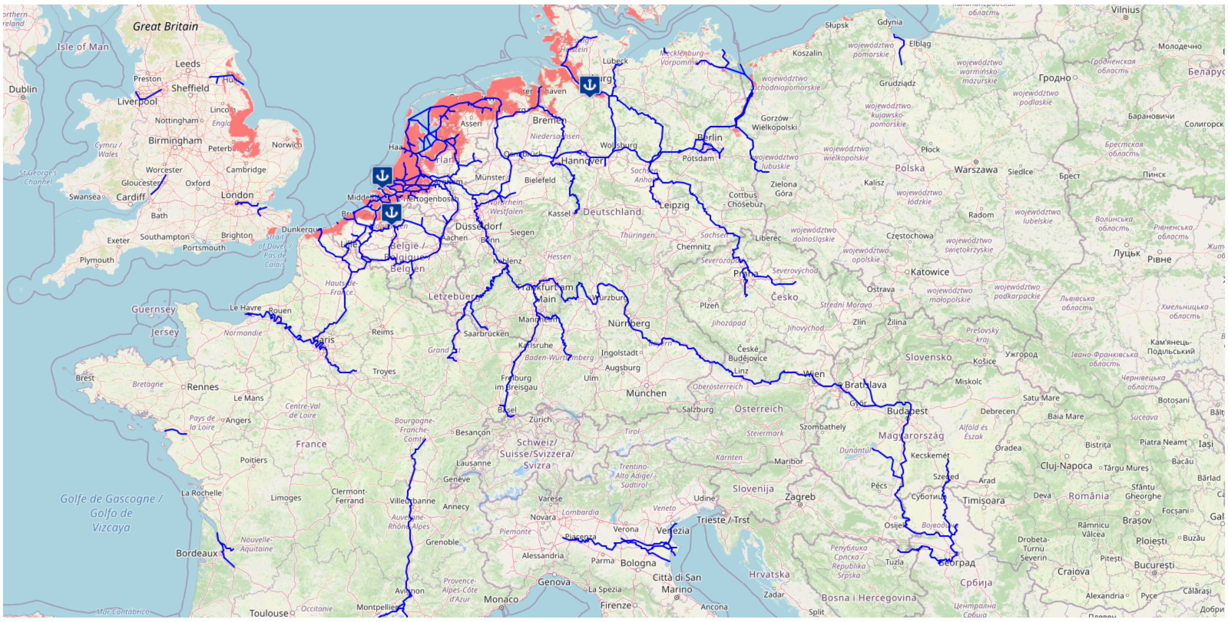


Figure 6.9: Northwest European waterway network (in blue) and inundated land at +3 m sea-level rise (in red). From top to bottom, the ports of Hamburg, Rotterdam and Antwerp are depicted. Data combined from (Demis, 2017; Climate Central, 2020).

Figure 6.9 depicts the waterway network and the inundated areas at +3 m sea-level rise. Most of the Dutch waterways their respective locks are affected, as are the waterways at the western coast of Belgium. Significantly, the Scheldt-Rhine canal, with its locks on either side, is also impacted, thereby rendering the connection of Antwerp to the Rhine unusable. The connection to the Meuse system and the remaining Belgium waterway system does remain intact. The waterways surrounding the port of Hamburg remain mostly unscathed, except for its connection to Denmark via the north. As stated in Section 6.2.2, the Netherlands is most affected. However, when moving more inland from Rotterdam, the connections to the Meuse and Rhine river systems remain intact, even bringing the rivers in close proximity to another.

6.3.5. Geography of the Netherlands and the flow of goods to the hinterland

There are two main corridors for the export in the Netherlands. The eastern corridor, via the Rhine, through Germany and onto central Europe and the southern corridor through Antwerp and onto Northern France. These corridors are depicted in Figure 6.10. The eastern corridor transports by far the largest amount of goods to the hinterland. As can be seen from the same figure, both corridors follow the low lying parts of the Netherlands, as they follow the rivers. This makes them more prone to inundation, supporting the conclusions from Sections 6.3.3 and 6.3.4. Subsequently, the competitive position of the port of Rotterdam can be affected.

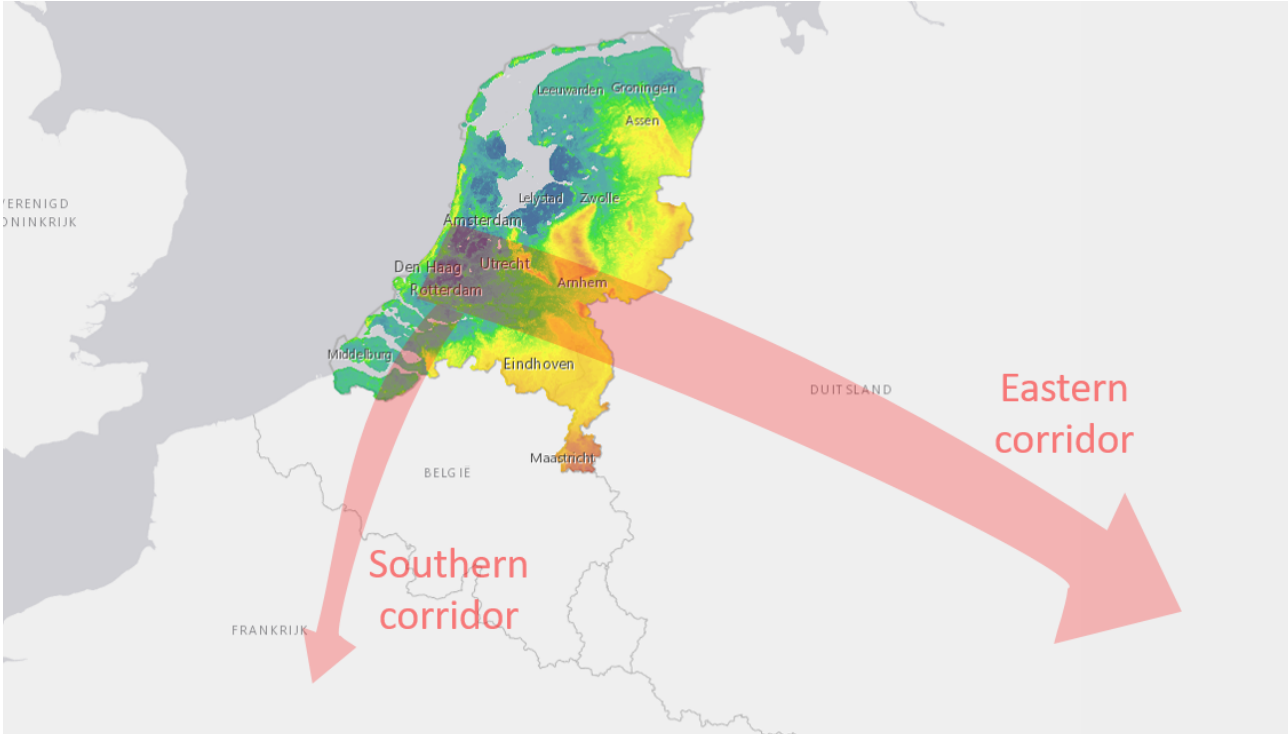


Figure 6.10: Flow of goods to the hinterland via the eastern and southern corridors combined with an elevation map of the Netherlands. Respective flows are to scale to another. Data from (AHN, 2019) and (Ministry of Economic Affairs, 2013).

6.4. Concluding

To conclude the chapter, the sub-question is answered:

> *What are the options for the three largest ports in Northwest Europe and the changes in their hinterland networks in case of +3 m sea-level rise and a retreat scenario?*

If we look at the inundated landscape of Northwest Europe, where the three largest ports of Europe are situated, the Netherlands are most affected at +3 m sea-level rise and a retreat scenario. The neighbouring countries of Belgium and Germany are also affected, however due to their mountainous and hilly landscapes, the overall effects on those countries are more moderate. The largest ports of those respective countries, Antwerp and Hamburg, lay on the new borders between inundated land and dry land. Their surrounding cities and lands are too substantially less affected around those ports than that of the Netherlands and the port of Rotterdam. This implies that far less drastic actions have to be taken for the ports of Antwerp and Hamburg to handle the sea-level rise and a retreat scenario. The ports can stay at their current locations, albeit with locks or storm surge barriers at their respective entrances.

For the port of Rotterdam, the situation is more grave. Some areas of the port remain dry, however most of the direct hinterland does not. Nonetheless, options remain for the future of the port. The options are divided in using a deep sea terminal where the current Eerste and Tweede Maasvlakte are situated or creating a deep sea port where the new coastline will form. Several strategic locations are selected and discussed, which are either dedicated deep sea ports or inland port or both. These options will be implemented and tested in the forthcoming model. Below the options for the different ports are summarized.

The port of Rotterdam:

- Deep sea terminal in combination with inland port locations at Hoogeveen and Tiel;
- Deep sea inland port, with possible locations at either Zwolle, Huizen, Tiel or Bergen op Zoom.

The ports of Antwerp and Hamburg:

- Lock(s) in front of the port, combined with pumps and storage lakes;
- Open connection to the North Sea, in combination with a storm surge barrier.

The changes to the networks of the different modalities are mostly limited to the Netherlands. From the three ports, the port of Rotterdam experiences the most hinder, as to be expected from the inundation figures. However, options for new locations of the port arise where modality networks converge. The southern rail connection of Rotterdam, via the port of Antwerp, is no longer usable, which can impact the competitiveness of the port in Belgium. The eastern connection does remain still.

For the port of Antwerp, the same railway connection to the port of Rotterdam is lost, however their southern and eastern connections remain intact. The most considerable impact due to the sea-level rise appears to arise due to the loss of the Scheldt-Rhine canal, connecting the port of Antwerp to the Rhine. The connection to the Meuse river system does remain unscathed.

The port of Hamburg seems to have the least impact by the sea-level rise. Although the railway and waterway connections to the peninsula of Denmark become infeasible, the (larger) hinterland area south of Hamburg is still reachable.

7

Analysis of the model results: suitability of the port locations

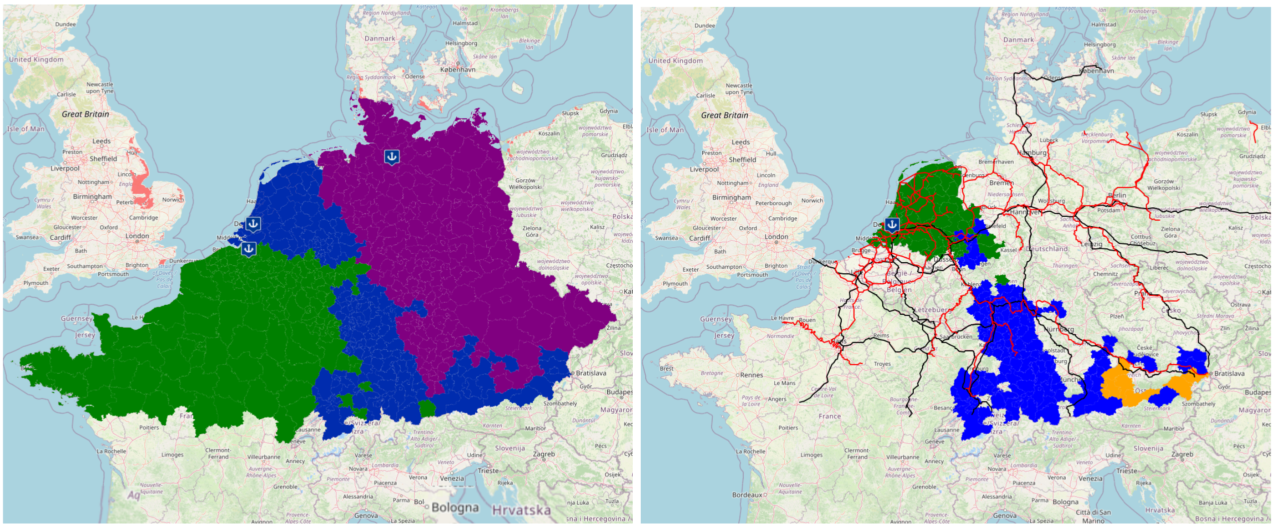
Chapter outline

This chapter answers the sub-question: "Which new port location for the port of Rotterdam can be considered most promising, in regard to the number of competitive hinterland areas?"

The retreat scenario, including the new locations for the port of Rotterdam which follow from Chapter 6 are analysed in this chapter. First, the base case is depicted to which the current situation to which the results are compared. Subsequently, the results of the new port locations are given, followed by an analysis of the results. The analysis is based on the two outputs of the model: port hinterland distribution and the areas which are more expensive or cheaper to reach from the new port location in respect to the base case. Noted must be that the results only apply for the container commodity.

7.1. Base case: approximating the current port competition

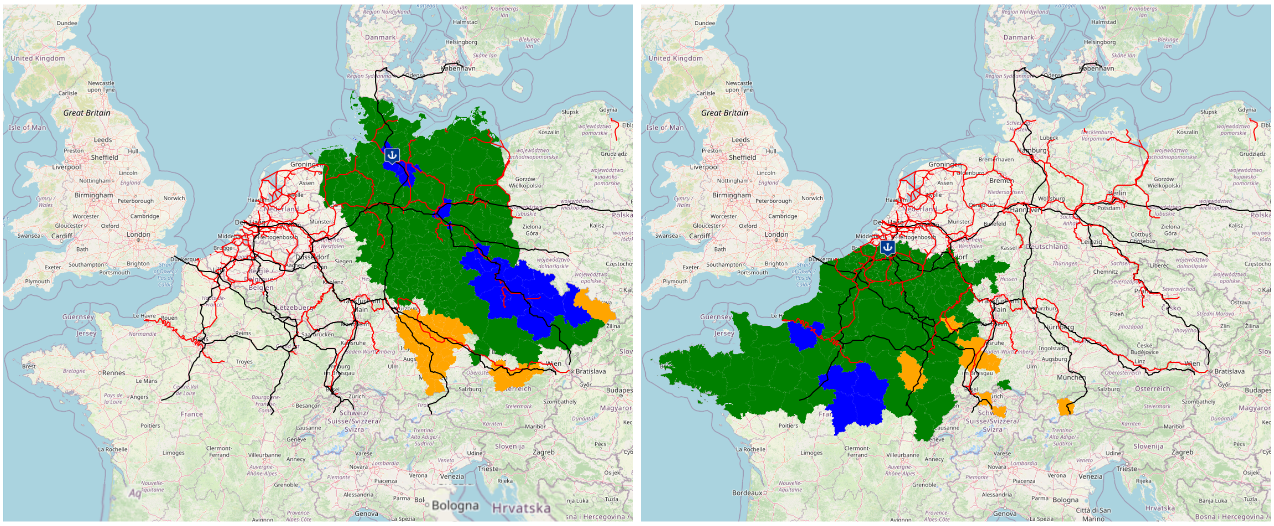
The current situation was simulated in the base case with the ports and coastline at their current locations. For Rotterdam a 6% cost decrease was applied, which was dropped for the new port locations, as discussed in Section 5.2.2. Figure 7.1a shows the results of the base case. Figures 7.1b, 7.2a and 7.2b depict the hinterland areas of the ports of Rotterdam, Hamburg and Antwerp respectively and include the waterway and railway networks. Of the total 587 hinterland areas, the ports of Rotterdam, Antwerp and Hamburg have 212, 141 and 234 hinterland areas, respectively.



(a) Results base case model. Green, blue and purple indicate the competitive hinterland areas for the ports of Antwerp, Rotterdam and Hamburg respectively.

(b) Results base case for Rotterdam. Green, blue and orange indicate the road, waterway and rail modalities respectively and the red and black networks represent the waterways and railways respectively.

Figure 7.1: Results base case for the ports of Antwerp, Rotterdam and Hamburg and for Rotterdam specifically.



(a) Results base case for Hamburg. Green, blue and orange indicate the road, waterway and rail modalities respectively and the red and black networks represent the waterways and railways respectively.

(b) Results base case for Antwerp. Green, blue and orange indicate the road, waterway and rail modalities respectively and the red and black networks represent the waterways and railways respectively.

Figure 7.2: Results base case for Hamburg and Antwerp.

7.2. Results for the new port locations

7.2.1. Selection method for port locations, network changes and landscape changes

It is assumed that the new landscape is drawn based on the inundated areas, depicted in red in Figure 7.3. The waterway and railway stretches which fall inside the inundated areas are assumed obsolete. However, if any links to the new port locations are missing, new waterway or railway stretches can be added. This is noted if need be. Furthermore, the ports of Antwerp and Hamburg remain at their current location and do not face any hinder, as was concluded from Chapter 6, except for waterway and railway stretches which are excluded due to the inundation. The NUTS level used in the model is level 3. The other variables are described in Chapter 4.

Figure 7.3 below depicts the outline of the non-inundated areas for the retreat scenario in blue. Due to the new outline, twenty-one hinterland areas are lost, of which three can be contributed to the Hamburg hinterland area and eighteen to the Rotterdam area.

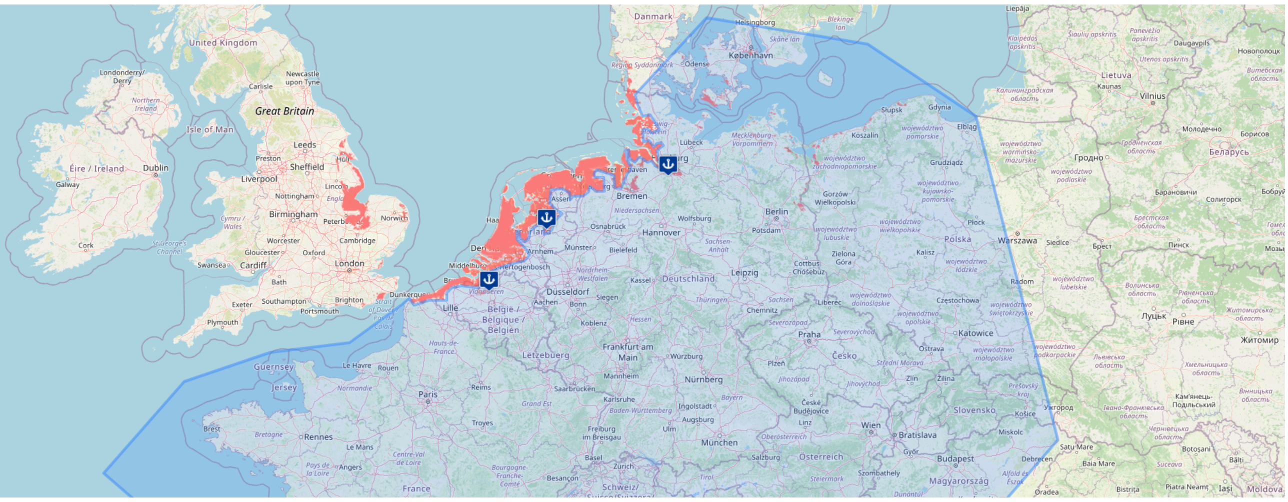
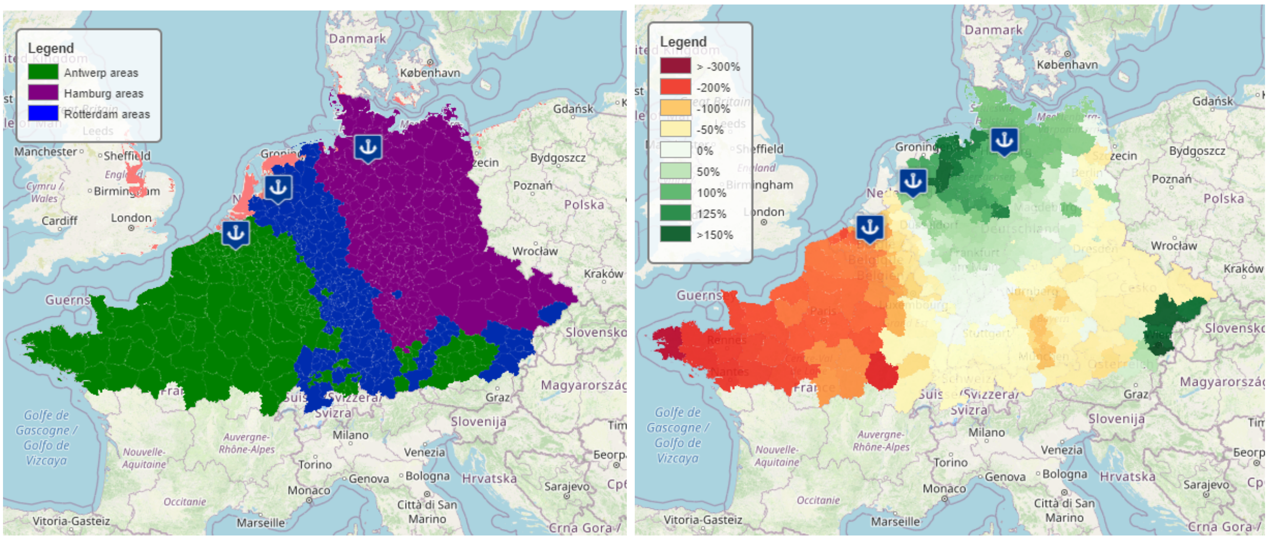


Figure 7.3: Outline of the non-inundated landscape of Northwest Europe in blue. Red depicts the inundated areas at +3m sea level rise.

7.2.2. Output model: results new port locations

The results of the simulation are shown in two figures—first the new distribution of the hinterland areas for the ports of Antwerp, Hamburg and Rotterdam. Secondly, the areas which are more expensive (in red) or cheaper (in green) to reach from the new port of Rotterdam location in contrast to the base case.

Deep sea port at Zwolle

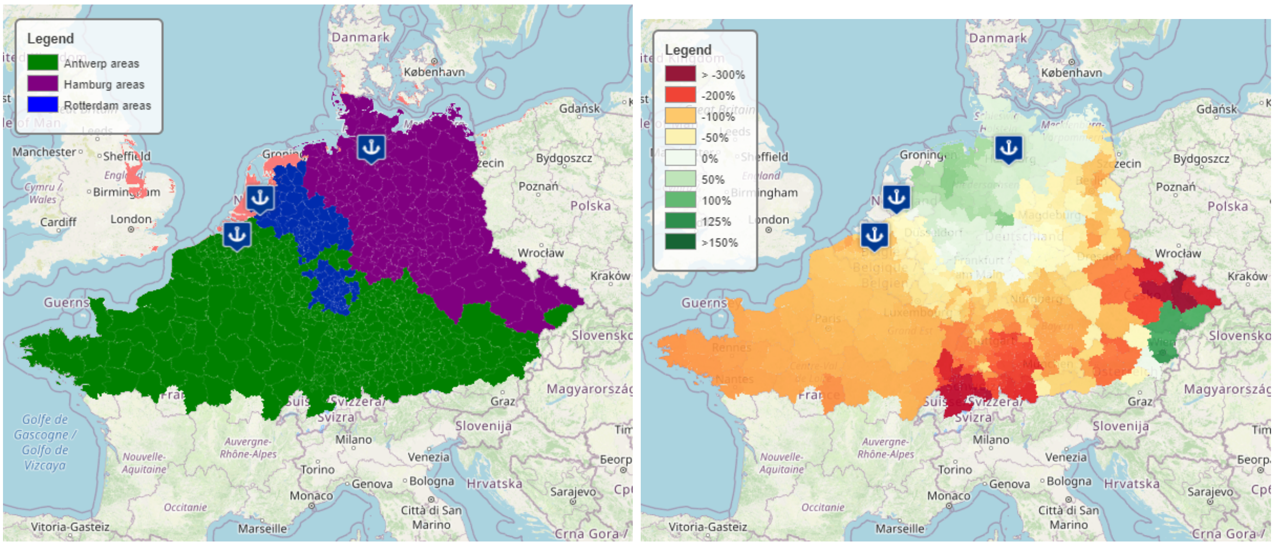


(a) Results port hinterland area distribution of the new location for the port of Rotterdam.

(b) Results areas which are more expensive (red) or cheaper (green) to reach from the new port location in respect to the base case.

Figure 7.4: Results deep sea port location at Zwolle, Overijssel at +3 m sea level rise and a retreat scenario.

Deep sea port at Huizen

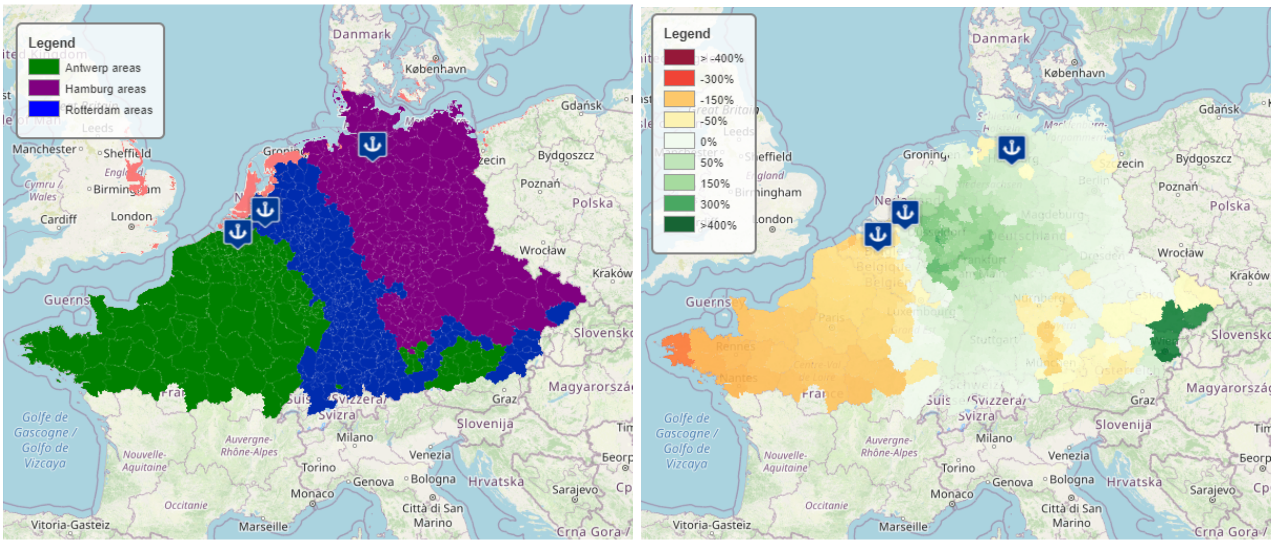


(a) Results port hinterland area distribution of the new location for the port of Rotterdam.

(b) Results areas which are are more expensive (red) or cheaper (green) to reach from the new port location in respect to the base case.

Figure 7.5: Results deep sea port location at Huizen, Noord-Holland at +3 m sea level rise and a retreat scenario.

Deep sea port at Tiel

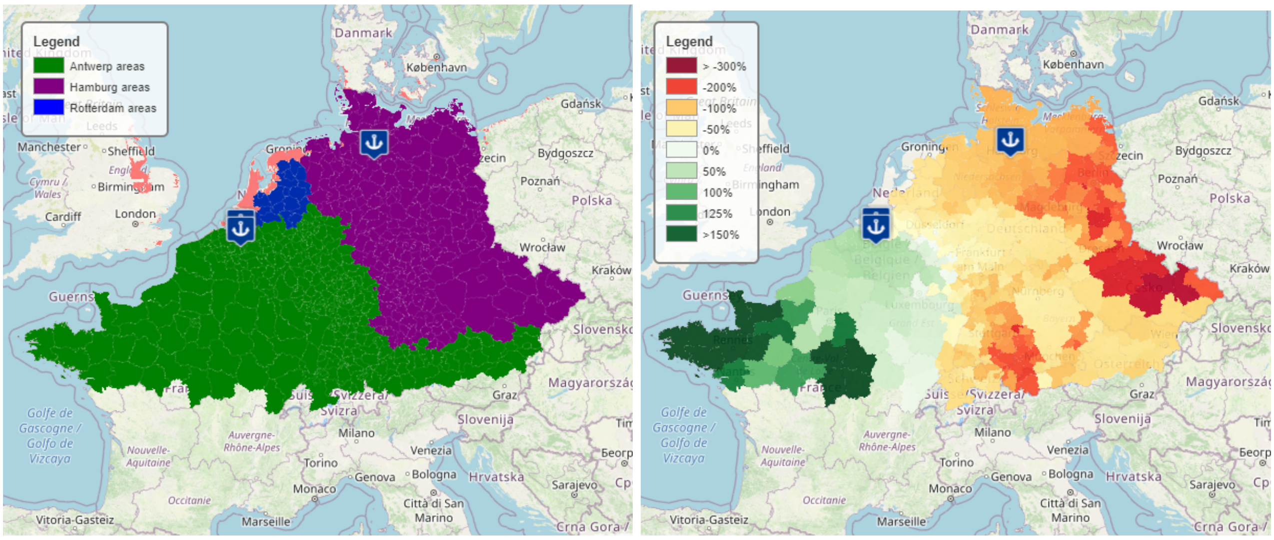


(a) Results port hinterland area distribution of the new location for the port of Rotterdam.

(b) Results areas which are are more expensive (red) or cheaper (green) to reach from the new port location in respect to the base case.

Figure 7.6: Results deep sea port location at Tiel, Gelderland at +3 m sea-level rise and a retreat scenario.

Deep sea port at Bergen op Zoom



(a) Results port hinterland area distribution of the new location for the port of Rotterdam.

(b) Results areas which are are more expensive (red) or cheaper (green) to reach from the new port location in respect to the base case.

Figure 7.7: Results deep sea port location at Bergen op Zoom, Brabant at +3 m sea-level rise and a retreat scenario.

7.3. Evaluation new port location results

7.3.1. Method of evaluation

The results of the new port locations are evaluated based on the output of the model. The output shows two types of result. First the (new) distribution of the hinterland areas per port and secondly the areas which are cheaper or more expensive to reach. For both the visual output data (the maps) is used. However, for the former, additional statistical data analysis is applied for the evaluation.

7.3.2. Hinterland port area distribution

As can be seen from the Figures 7.4a - 7.7a, two locations lose hinterland areas whilst the other two locations gain hinterland areas. If we examine the locations which gain hinterland areas, most areas are gained by Tiel, at +16%. The other location, Zwolle, gains +3%. The figures of the other two locations which lose hinterland areas are more substantial. The Huizen location loses -51.3% of its hinterland areas, which is only surpassed by the Bergen op Zoom location with a loss of -87.6%.

The port of Antwerp benefits most from the new distributions, with an increase in the number of hinterland areas ranging between +16% to +113.5%, only losing -4% for the Tiel location. The port of Hamburg more or less retains its number of hinterland areas, varying between -12% and +4.3%. Table 7.1 gives an overview of the figures.

Table 7.1: Number of hinterland areas for different port locations and percentage of areas lost or gained in respect to the base case. *The figures and percentages are adjusted to the new number of areas excluded in the landscape outline.

Location	Base case		Zwolle		Huizen		Tiel		Bergen op Zoom	
Rotterdam areas	212	195*	201	+3%	95	-51.3%	227	+16%	24	-87.6%
Antwerp areas	141	137*	159	+16%	241	+75.9%	131	-4%	301	+113.5%
Hamburg areas	234	234*	206	-12%	230	-1.7%	208	-11%	241	+4.3%
Total hinterland areas	587	566*	566	-3.6%	566	-3.6%	566	-3.6%	566	-3.6%

7.3.3. More expensive or cheaper areas to reach

In terms of areas which are more expensive or cheaper to reach from the new locations (Fig. 7.4b - 7.7b), the results from the Section 7.2.2 match. Tiel has the largest number of areas which are cheaper to reach (marked green) and the smallest number of areas which are more expensive to reach (marked red), followed by Zwolle. The contrast between more or less expensive areas is lowest for Tiel, which mostly can be explained by the fact that the Tiel location is in closest proximity to the current Rotterdam location and the current networks. Zwolle is located to the north, resulting in larger intensity of cheaper areas in Germany and a smaller intensity in France and the Alps.

The Huizen location has the smallest number of areas which are cheaper to reach and are predominantly found in (East) Germany. The intensity is similar to the Zwolle location. For the Bergen op Zoom location the results are reversed. Most locations which are cheaper to reach are located in France and Belgium, whilst the locations in The Netherlands, Germany, Switzerland and Austria are all more expensive to reach.

7.4. Conclusion

Of the four strategic new locations for the port of Rotterdam, at +3 m sea-level rise and a retreat scenario, the Zwolle and Tiel give a positive result whilst Huizen and Bergen op Zoom give a negative result. The number of hinterland areas lost is more severe in contrast to the number of hinterland areas gained. Choosing the right new port location is therefore important. Antwerp gains the most, in terms of hinterland areas, from the retreat scenario at +3 m sea-level rise. However, to answer the sub-question of the chapter:

Which new port location for the port of Rotterdam can be considered most promising, in regard to the number of competitive hinterland areas?

The deep sea port location at Tiel indicates the largest gain of hinterland areas (+16%) and can therefore be considered most promising out of the four locations.

8

Discussion

Chapter outline

In this chapter, the results, as presented in the previous chapter, are analyzed and discussed. Subsequently, any limitations and implications of the model are discussed.

8.1. Discussing the results

The results are discussed in three parts. First, a summary is given, subsequently, the results are interpreted to analyze what they mean and lastly, the implications of the results are given.

8.1.1. Summary of the results

Four new port locations for the port of Rotterdam were simulated in a hinterland port competition model. The model only incorporated the container trade. The port locations were chosen following a scenario to retreat to the new shoreline, in case of a +3 m sea-level rise. These locations are Zwolle, Huizen, Tiel and Bergen op Zoom.

The Zwolle and Tiel locations show an increase in hinterland areas, at +3% and +16% respectively with respect to the current situation. The other two locations, Huizen and Bergen op Zoom show a decrease in hinterland areas at -51.3% and -87.6% respectively. These lost hinterland areas of Rotterdam are mainly redistributed to the hinterland area of the port of Antwerp. The areas of the port of Hamburg do not differ noticeably from the current situation.

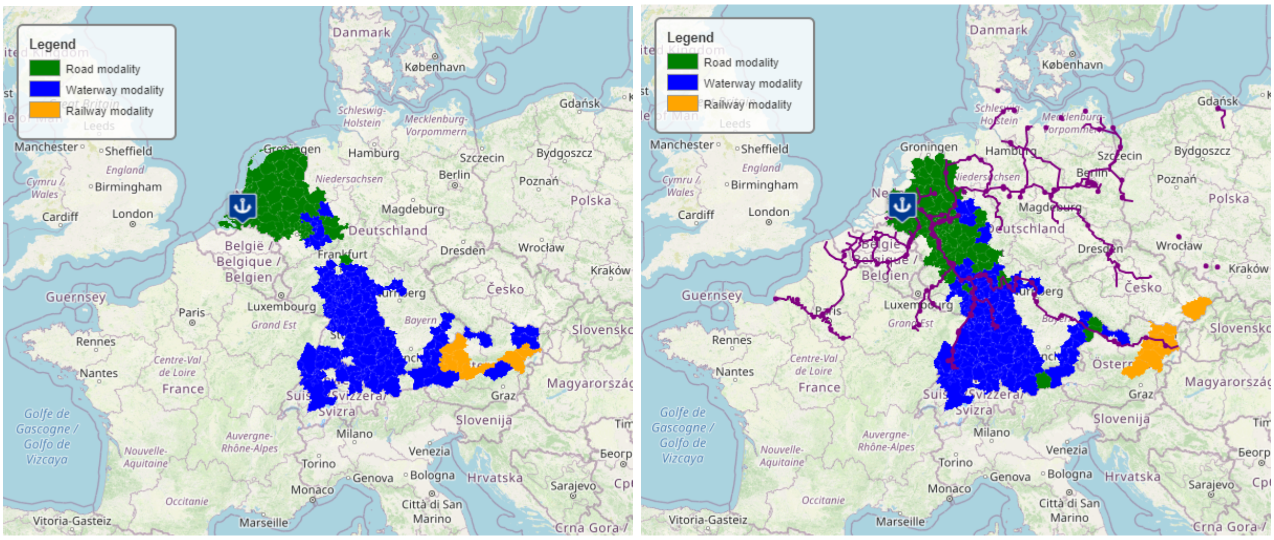
8.1.2. Interpretation of the results

A 6% cost reduction was applied to calibrate the base case for the current port hinterland distribution of the port of Rotterdam. The reduction can be seen as the advantages the port of Rotterdam currently has over the two other ports. These advantages are entry for fully laden vessels, no tidal window for large vessels and a limited sailing time from sea to terminal. As the model only focuses on the hinterland networks and thus starts at the quay when the deep sea vessels are unloaded, these advantages have to be incorporated artificially. Although some new port locations can have one of the previously mentioned advantages, it is not possible to be certain which advantages and how much they might account for. Therefore the advantages, or the 6% cost reduction, are not taken into account for the new port locations.

This is compensated for the Tiel and Zwolle locations by their respective movements to the east, closer to the hinterland destinations and their proximity to the current networks. The relocations even result in an increment of competitive hinterland areas for the two locations. Figure 8.1 depicts the current modality hinterland area distribution and that of the Tiel location.

The large decline in the number of hinterland areas of Bergen op Zoom (-87.6%) can be explained by the location of the port in respect to the modality networks and the port of Antwerp. Although the Bergen op Zoom location is connected to the same two modality networks as the port of Antwerp, the port of Antwerp is located after the Bergen op Zoom location on the networks. Therefore the distances from the Bergen op Zoom location will always be greater than the distances from the port of Antwerp, except for the road modalities.

Similar to the Bergen op Zoom location, the discrepancy in hinterland areas of the Huizen location versus the current situation can be explained by the less favourable position of the port and the networks in relation to the current location of the port. Thus in addition to the loss of port advantages described above, the modalities simply have to travel a greater distance, resulting in fewer competitive hinterland areas.



(a) Approximation of the hinterland modality distribution of the current port location. Results from the basecase notebook.

(b) Hinterland modality distribution of the Tiel port location including the waterway network. Results from the endgame notebook

Figure 8.1: Hinterland area distributions for the different modalities of the port of Rotterdam.

Interestingly, if we look at Figure 8.1b, several road modality areas can be identified in the Alpine regions in close proximity to the waterway modality regions. This is unexpected as these regions are at waterway or even railway modality distances from the origin location. However, if the results for the Alpine regions between the waterway and road modalities costs are compared to one another, the differences range in the order of 10%, whereas for the base case, the difference is larger.

This discrepancy in results can be explained by three factors. The first factor is the waterway modality network itself. Upstream from the Middle-Rhine river stretch, at the bifurcations, the waterways start to twist and meander. This results in an increase in length of the waterways over a relative short distance, whereas the road modality does not follow these twists and turns.

Secondly, the new port location is closer to the Alpine hinterland areas than the Rotterdam port location. Therefore the road modality will be more competitive in the Alpine regions, shifting the tipping point between the road and waterway modalities more inland, thereby accounting for the smaller difference in costs.

The last factor is related to the proximity of the regions to the waterway modality network and the inland ports connected to the network. Some regions are not in close proximity to the waterway network or an inland port where the switch to the road modality is made. Therefore the extra distance travelled from the nearest inland port to a region can be such that the road modality becomes cheaper, especially when combined with the second factor.

8.1.3. Implication of the results

The redistribution of the lost hinterland areas from the port of Rotterdam to the port of Antwerp implicates that the current competition is very competitive between the two ports, as simulated by the model. The competition between the port of Hamburg and Rotterdam, by contrast, is more robust and equally divided.

8.2. Discussing the limitations and uncertainties

In this section, the limitations and uncertainties are discussed. The uncertainties can be split into two parts, the uncertainties created by the assumptions made and the uncertainties of the model. Both are discussed below.

8.2.1. Limitations and uncertainties of the assumptions

No other implications due to climate change

The main uncertainty is the timeline of the +3 m sea-level rise and factor changes which can occur and have occurred by that time. These factor changes (political, ecological, medical) can have an impact on the global economy, of which the ports of Europe are dependent on. This is best illustrated by the current Covid-19 pandemic, which has an immediate effect on the throughput of seaports.

The assumption that climate change only affects the sea level is quite limited. We can already see changes and problems occuring in (inland) shipping due to low water conditions and more extreme and frequent storm conditions. Besides, other problems may arise, which we currently cannot imagine.

Population shift of the inundated areas

Assumed was that the population (around eight million people), which currently live in the areas that would inundate at +3 m seal level rise, would all be relocated to other areas without a problem. Not only will that number be significantly increased by the time the +3 m sea-level rise occurs, but such a population shift would also be a remarkable feat in itself, and therefore unlikely to occur without any complications. It would mean that the current spatial layout of where the people should be moved can be renounced and disposed of, which is improbable.

Adding to that, the regions to where the population would be relocated can have an influence on the import and export of those regions and thus on the importance of the locations. The model does not account for GDP, however it does account for population density as the NUTS regions are defined by a number of inhabitants. If the regions and figures are updated, the model includes the new distribution (see Section 4.2.1 for more detail).

Only container commodity

The method and model do not include the other commodities, such as liquid or dry bulk. Different results of hinterland competitiveness distribution can be obtained when accounting for or including the other commodities.

Changes to modality networks

To create the network changes, the waterway and railway networks which lay in the inundated areas disappear under the current assumptions. However, some might be of such importance that they would be saved. The waterway networks which are inundated might be usable still and even have an increased depth, thereby increasing the capacity.

In addition, the networks can be improved, or even complete new modalities can arise. Capacities, velocities and costs can change due to new improvements. The air modality, currently left out of the scope, can become competitive on the short distance, or disappear altogether due to the depletion of fossil fuels. The hyperloop, or a similar example, can become feasible and disrupt the current modal distribution.

Ports of Antwerp, Hamburg and Rotterdam

Only the ports of Antwerp, Hamburg and Rotterdam were included in the calculations and assumed to be the most important ports of (Northwest) Europe. Whilst there are more (container) handling ports in the area which are not included, global influence can also mean a shift in port importance. The port of Gdansk in Poland is expanding, and the Chinese are investing in ports in Italy to bypass European port fees. The Chinese are further investing in rail transport through Asia to Europe, which is known as the “Silk Railroad”. This railroad can have further influence on the European modal split. It is therefore unlikely that only the ports of Antwerp, Hamburg and Rotterdam are of importance in the future.

Furthermore, the results of the distribution of hinterland areas is biased towards Antwerp and Hamburg. This is because the entire hinterland area of Northwest Europe is used in the model, whilst the ports on the outer sides of Antwerp and Hamburg are not accounted for. This results in a larger number of areas which are normally attributed to different ports. However, as this thesis focuses on the hinterland of Rotterdam specifically, the effects are considered negligible.

No changes to the local and global economy
To accumulate the above assumptions, the assumption that the Dutch, European or even the global economy will not have changed due to the implication of +3 m sea-level rise, is improbable. To start on a local level, the loss of the inundated areas in the Netherlands would have tremendous implications on the Dutch economy. Houses, properties and cities will become valueless, and unemployment will ensue. This, in turn, has implications on the European economy. A global sea-level rise of +3 m (although it can variate locally) will influence other cities and countries too. The entire east and south coast of the U.S. is inflicted by inundated at +3 m sea-level rise (Climate Central, 2020).

Other possible sea level rise adaptation strategies
Two strategies were not taken into account but can also be considered. Doing nothing and removing the port altogether. The former option is always the cheapest as there are no capital costs needed, however for obvious reasons, not a possibility. With the latter option, the Dutch can import their goods via Antwerp or Hamburg, which saves investments of keeping the port accessible; however, it also means significant job loss.

8.2.2. Limitations and uncertainties of the model

To create a container port competition model, some assumptions had to be made. These assumptions were mainly simplifications in order to decrease the insecurities which came with more (input) variables and to prevent the model from becoming too confusing. These uncertainties are discussed below.

Model starts at the quay
The transport distance and thus transport time starts when the containers are loaded on the modalities, from the quays of the ports in Europe. Choosing this starting point for the model, however, skips essential parts of the container supply chain. When sailing from the origin, China, for instance, there is a difference in sailing time to the European ports. This can influence the goods transported, as the value of the goods can diminish over time. When arriving at the ports, each port can have advantages or disadvantages, respectively—demurrage, port downtime or tidal window, to name a few. At the terminals, the handling costs can vary between the ports and the dwell time of the containers can differ, which can influence the value of the cargo. None of these aspects are (physically) included in the model.

No locks included
The model does not include navigation locks. Not at the port entrances and along the waterways. These locks can have a significant influence on sailing time. These are, however, absent in the model, because the model starts at the quay. Thus the deep sea vessels already have passed through potential locks and are inside the port. In addition, the model cannot include (time) obstacles.

Only deep sea terminal option
Only the deep sea terminal options for the retreat scenario were simulated, not the combination of deep sea terminal (at Maasvlakte, e.g.) in combination with inland terminals. This is not because the model could not simulate the latter option; it is because it would always be longer and slower than the former option. Creating additional transport distance and transhipment points is not the

real differential between the two options, it is the dredging costs related to creating deep sea inland ports (Stam, 2020). However, including such capital costs over a long time period creates additional problems.

Road modality
For the road modality, the model uses the Directions API from the Google Maps function. Using this API has its advantages as it works very well for the “last mile” aspect as it has a dense network. However, it has also some limitations. Using the API means that the road modality cannot be adjusted according to the new landscape outline and prohibits the creation of additional routes.

Furthermore, it has no truck option, only a car option; thus height restrictions are not taken into account. No toll is included in the road modality, whereas that can be a considerate cost factor.

Train modality
The train modality now only includes the usage of freight railway stretches, whereas in reality some stretches might be shared between public transit and freight transport. Therefore the train modality might have a negative bias, as in reality the train modality can choose from more railway routes and stretches.

Waterway modality
Capacity is the main limitation for the waterway modality. As discussed above, low water conditions can create a limitation in the capacity which the inland vessels can transport. With the current formulae, the capacities of inland vessels cannot be altered. In addition, the waterway system sees a wide range of capacities of inland vessels. Currently, a uniform capacity is assumed. As discussed above, the absence of locks is also a limitation. The model now assumes a uniform velocity in which the occurrence of locks is included. However, on some (shorter) stretches, this can give a negative bias as there might be an absence of locks.

Single direction trips
The model simulates the transport of containers from deep sea ports to the hinterland. This creates two limitations. Firstly, it does not include the export of goods and containers over the networks. Secondly, the model assumes that there is an infinite supply of trucks, trains and inland vessels which can be used for transportation at the origins. In reality, that supply is limited, and the modalities have to travel back to the origins, which means a doubling of the transport distance and thus the costs.

Infinite capacities modalities
The model assumes that there is an infinite supply of trucks, trains and inland vessels and on the modality networks themselves, which was already touched upon above. Thus when a modality (stretch) becomes disposed of, the model assumes that the other modalities can immediately cope with the increase in demand. In reality, the rail modality as an example has a maximum capacity over its railway and a maximum supply of freight trains and therefore cannot immediately handle the increase in demand.

Hinterland area ratios
When the costs to reach a hinterland area are similar for two ports or modalities, both ports or modalities will have a share in the container transport. In the model, when one port or modality is cheaper by a cent, that hinterland area is directly attributed to the respective port or modality.

9
Conclusions & recommendations

9.1. Conclusions

The objective of this thesis is to create a first-order method to quantify the consequences of large sea-level rise projections, landscape changes and hinterland modality network changes on a deep sea port and to provide it in a comprehensive manner. Subsequently, this method is applied on the port of Rotterdam as a case study. To reach that objective, one central question and six sub-questions are asked. These sub-questions are answered below, concluded by the main question.

The first sub-question handles the literature study concerning the different sea-level rise projections for the Netherlands:

What are the possible scenarios to adapt to sea-level rise for the Netherlands and what consequences do they impose?

There are four main sea-level rise adaptation scenarios, identifiable for the Netherlands; “closed protection”, “open protection”, “seaward” and “retreat”. To choose a scenario is to choose the lesser of the four evils. This is only supported by the ambiguity of the timeline of sea-level rise, as there are many uncertain factors which can contribute to sea-level rise. It is therefore difficult to assess which scenario can be the most effective at which point in time. Subsequently, the second sub-question can be answered:

What is the current method of calculating the effects of sea-level rise strategies on shipping and port activities and are there shortcomings in those methods?

The current literature shows that for the first three sea-level rise adaptation strategies, there is one method to quantify the effects on shipping and port activities. This method is contrived by Ecorys, which uses four different models and results in negative effects on the Dutch economy.

Several drawbacks to the method can be identified. The main drawback is that the method cannot account for the retreat scenario and cannot give quantitative results to analyse the scenario. The method can primarily focus on the open protection, closed protection and seaward scenarios. In addition, the method does not include the effects of sea-level rise in neighbouring countries and ports, which form the competition of the port of Rotterdam. This leads us to the third sub-question:

How can adaptive container port competition be modelled and which parameters are needed?

The model is based on the principle that transport modalities are competitive at different distances from the origin. At certain distances from the origin, a shift in modality will occur. This can be explained by the characteristics of the modalities. The model uses modality networks; hinterland regions denoted as NUTS regions, and the Folium and NetworkX packages of the Python programming language. Together the desired new outline of Northwest Europe can be drawn; new port locations can be chosen by entering the name of the location and networks can be added by drawing them on maps in the model. Subsequently, the model calculates the different origin-destination distances and converts them to costs. Each hinterland destination which is cheapest to reach from a port is then attributed to that port and depicted on a map. To ensure the model gives accurate results, the fourth sub-question is asked:

Does the model comply with its requirements and how accurate is it compared to reference data?

The model complies with all its requirements, except for two items. No navigation locks can be added to the networks, which hinder shipping and increase shipping time and railway network data was altered outside the model, as to connect specific stretches of railway. As there is a minimal number of other hinterland container port competition models, no direct reference data could be found. However, the individual elements of the model could be compared.

It was found that the results of the Dutch and Belgium waterway networks had to be calibrated and the results for the port of Rotterdam as a whole, in order to approximate the current situation for the base case. This is because the model does not include the advantages the port currently has over the ports of Antwerp and Hamburg. The subsequent validation was shown to be accurate enough for the purposes of this thesis. With the model verified, calibrated and validated, the penultimate sub-question can be answered.

What are the options for the three largest ports in Northwest Europe and the changes in their hinterland networks in case of +3 m sea-level rise and a retreat scenario?

At +3 m sea-level rise, the largest rivals of the port of Rotterdam, the ports of Antwerp and Hamburg, can remain at their current locations without much adaptation and even resolving some of their current problems. The port of Rotterdam and its surrounding areas are much more prone to inundation and therefore cannot be maintained at its current location if a retreat scenario will be chosen. The port of Rotterdam would lose its main advantages it has over the other ports in that case. Therefore, to analyse the retreat scenario, four new deep sea port locations for the port of Rotterdam were chosen to see which location would result in the best outcome for the new distribution of competitive hinterland port areas. These locations are Zwolle, Huizen, Tiel and Bergen op Zoom and are chosen because of their proximity to the new coastline and existing networks. To test these locations, and a retreat scenario, a model had to be built. To that extent, the final sub-question is addressed:

Which new port location for the port of Rotterdam can be considered most promising, in regard to the number of competitive hinterland areas?

The Tiel and Zwolle locations show an increase in the number of competitive hinterland areas, whereas the Huizen and Bergen op Zoom locations result in a decrease in hinterland areas. Table 9.1 gives an overview of the results for the different locations with respect to the current situation. Concluded can be that the locations which gain hinterland areas in respect to the base case are positioned in closer proximity to the modality networks, closer to the hinterland and at a distance from rival ports. Noted is that the port of Antwerp mainly gains these areas which are lost by the port of Rotterdam, therefore adding to the already fierce competition between the two ports.

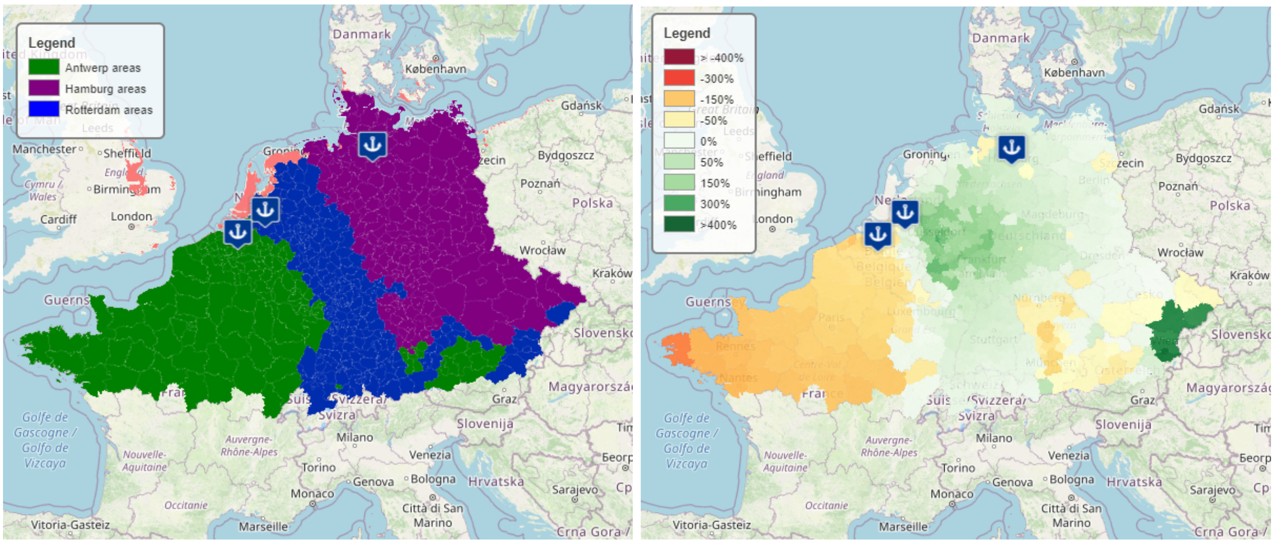
Table 9.1: Number of hinterland areas for different locations and percentage of areas lost or gained in respect to the base case. *The figures and percentages are adjusted to the new number of areas excluded in the landscape outline.

Location	Base case		Zwolle		Huizen		Tiel		Bergen op Zoom	
Rotterdam areas	212	195*	201	+3%	95	-51.3%	227	+16%	24	-87.6%
Antwerp areas	141	137*	159	+16%	241	+75.9%	131	-4%	301	+113.5%
Hamburg areas	234	234*	206	-12%	230	-1.7%	208	-11%	241	+4.3%
Total hinterland areas	587	566*	566	-3.6%	566	-3.6%	566	-3.6%	566	-3.6%

The Tiel location has the largest increase in hinterland areas, at +16% and can therefore be considered most promising. The results from the model are depicted in Figure 9.1. Tiel is situated approximately 100 km more inland of Rotterdam, in between the Rhine and Meuse rivers, which explains the increment of hinterland areas. However, if we closer examine the hinterland area results of the modalities, several road modality outliers can be identified in the Alpine region as can be seen in Figure 9.2. These outliers can be attributed to three factors:

1. Twisting nature of the waterway network in the Alpine regions;
2. Shift in tipping point from road to waterway modality due to the relocation of the port;
3. Location of the waterway network and the inland ports in respect to the regions.

In short, it can be concluded that the right position for a new port location is important for the hinterland area distribution. Finding the correct location in proximity to the modality networks and the hinterland is, thus, paramount when choosing a new port location.



(a) Results port hinterland area distribution of the new location for the port of Rotterdam.

(b) Results areas which are more (red), or less expensive (green) to reach from the new port location in respect to the base case.

Figure 9.1: Results deep sea port location at Tiel, Gelderland at +3 m seal level rise and a retreat scenario. Figures obtained from the endgame notebook.

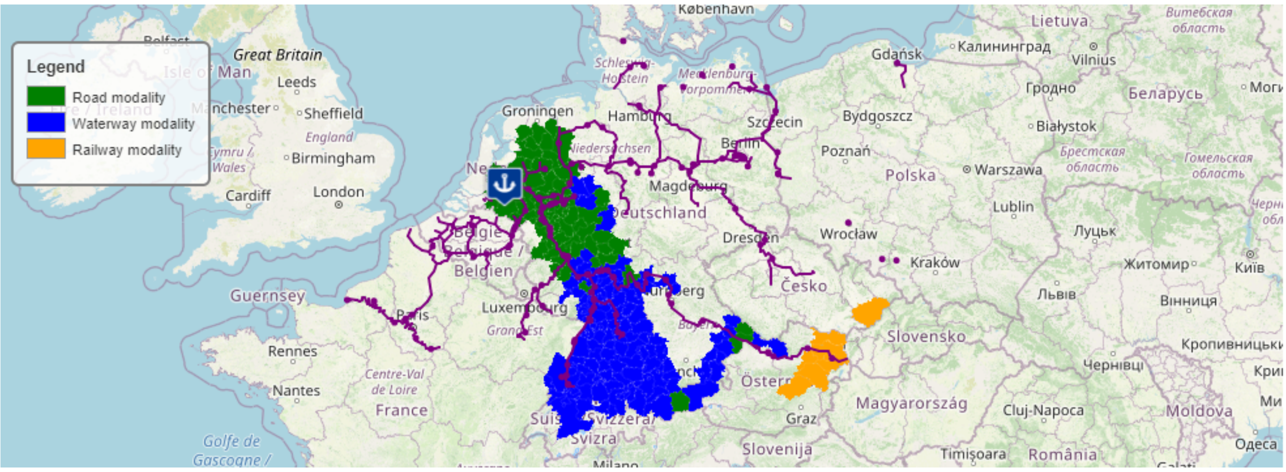


Figure 9.2: Hinterland modality areas of the new distribution due to the port location at Tiel. The waterway network is displayed in purple. Figures obtained from the endgame notebook.

With the sub-questions answered, we can answer the main question of the thesis:

> "*How can the impact of high sea-level rise (+3 m) and a retreat scenario on hinterland container transport networks be assessed?*"

The consequences of high sea-level rise and a retreat scenario on hinterland container transport networks can be assessed in several steps. First a certain sea level rise is chosen. That level is applied to a bathtub model which examines the areas which inundate. From the inundated areas, a new coastline can be derived and the consequences on the modality networks. The inundated landscape enforces hinterland modality network changes as the inundated networks become redundant and are cut-off from the remaining modality networks. Following from the new coastline, new port location(s) can be chosen if needed.

Subsequently the remaining networks and new port locations are applied to a hinterland port competition model which simulates the flow of goods from the (new) deep sea port location over the networks to hinterland destinations. For each modality the distance over the respective network is noted. For the waterway and railway networks, a switch is made to the road modality for the "last mile" stretch to the destination. The distances can then be converted to costs using conversion formulae. This gives an overview which hinterland destination is cheapest to reach from which port and results in the competitive port hinterland area distribution. Using the current situation, the results can be compared to examine which new landscape or port location is most optimal. Except for the bathtub model, these steps are combined in the developed model.

9.2. Recommendations

During this thesis recommendations were noted for improvements on the model, to be able to test for a broader range of scenarios and plans and to give more accurate and insightful results. In addition, this section gives recommendations for further research. These recommendations are summarised below.

Add a common starting point to model

Better results would be obtained if a central starting point for all (three) ports is chosen. Calais could be an option as all deep sea vessels pass through the English Channel; however, the relative distance between the ports would still be significant. A better solution would be to start in China to remove the significance in the relative distance. This would, however, significantly improve the run time of the model.

Add the (dis)advantages of ports

By applying the aforementioned starting point, the respective port advantages and disadvantages could be incorporated. A tidal window, half laden capacities, container dwell times and port fees can all be included in the formulae to calculate the costs.

Incorporate the percentages of port competition

The current model calculates the costs for the modalities for the different ports. These costs are used to examine which hinterland area is cheapest to reach from which port and the area is attributed to the respective port. However, in reality, there can be multiple ports which have a share in supplying the hinterland area. Therefore to get a better picture of what the share of a hinterland area is, the costs can be converted to percentages.

When the percentages are combined with the number of containers which are shipped to the hinterland areas, it can be calculated how many containers each port handles. Not only is this an interesting result to obtain, it can also be used as another benchmark to calibrate the model, as the current distribution is known. The information about how many containers are shipped to each hinterland area is unknown, however and calculating or obtaining that information can be a study in itself. An example could be to divide the number of yearly imported containers by the GDP or population density of each hinterland area.

Add more ports to the simulations

To give a better view of the port distribution of (Northwest) Europe, more ports should be added in the model. Although this is no problem for the model itself, for the purpose of this thesis, the model simulations were limited to the ports of Rotterdam, Antwerp and Hamburg. The hinterland distribution for the latter two ports now gives a convoluted picture. In reality, their respective hinterland areas are more limited. The addition of more deep sea ports would give a better sense of the distribution. Ports such as Genoa and Gdansk could form a threat to the established order.

In addition, it could be interesting to look what the most optimum port location would be if Europe would plan a single deep sea port or even a single port in the Netherlands.

Compare deep sea terminals vs deep sea inland ports
In the event of a retreat scenario, the option to keep the Maasvlaktes as deep sea terminals and combine them with inland terminals is currently not taken into account. The reason is that the combination is slower than a deep sea inland port location as there is an extra transhipment moment and an increased trip distance. As stated in the previous chapter, the options can best be compared when combined with a dredging cost research between the two options. Stam (2020) proposes such a model which can be applied to calculate the dredging costs and the influence on the sailing time between the two options.

Add the ability to examine closed protection and retreat scenarios
Currently, the model can give results for the open protection retreat scenario. By adding the ability to include navigation locks in front of the ports, a more comprehensive range of scenarios can be simulated by the model. In addition, if new landscape can be created in the model, the retreat scenario can be completely included.

More research about beach nourishment
To build on that, it would be interesting to see how much potential sediment is available in the North Sea and at what depths. The North Sea is being filled with wind parks at the shallow parts of the sea bed to reduce the costs. However, these shallow parts are also the cheapest locations to dredge sediment for beach nourishment. Dredging at greater depths and further off the coast increases the costs. Therefore a comparison is interesting between how much sediment is available, at what depths and distances versus how much sediment is needed, not only for the Dutch coastline but also for the European coastline.

Road modality improvements
For the road network, the model uses the Google Directions API. As this API is created by Google, it gives an accurate approximation of the real road network layout. This induces the accuracy of finding the correct distances to the different hinterland destinations, especially at a detailed level. However using this API inhibits the ability to alter the network, as can be done for the waterway and railway modalities. It can therefore be recommended to implement a fine-knitted road modality network from a file. However, this increases the run time of the model.

Waterway and railway modality improvements
One goal of the model is to be reproducible and therefore, the alterations of the network layouts and inland port and terminals locations are kept to a minimum. However, this creates the problem of the inaccuracy of the real-world situation of the networks. Currently, the model filters the railway network for the freight priority characteristic, however, when compared to data from the European Commission, discrepancies can be found. This also applies for inland ports and railway terminals which have to be filtered on the ability to handle containers. Further research into the exact locations of container handling inland ports and terminals and freight networks is advised.

Adding other modalities
The model mainly focuses on the hinterland of Europe and the potential landscape and network changes due to sea-level rise. Therefore only the road, waterway and rail modalities are included. However, to give a better approximation of the container supply chain, other modalities can be added. Between (deep) sea ports, containers are transported via short sea shipping. These are smaller sea vessels which sail the coastal seas, such as the North Sea. Airfreight can be an addition as it moves

goods which can have a high depreciation and are therefore interesting to transport via air. As stated in the discussion, China is building a railroad to Europe via Asia; if the starting point of the model is chosen to be in China, this railroad should be included in the model. Lastly, the addition of new modality networks, such as the hyperloop is interesting. However, in the current model new networks can be easily added.

Add a hydraulic model rivers
The last few years low water conditions have had an impact on inland shipping. Therefore it would be interesting to implement a hydraulic model for the rivers, to see what low water conditions would implicate for the modal split and port competition as it influences the capacity of the waterway modality. This can however, significantly add to the run time of the model.

Add agent based simulation
To be able to better simulate the (reduction in) capacity of the modalities, agent-based simulation can be added in the model. By applying this type of simulation, dedicated modality vessels or vehicles can be appointed to which a finite amount can be attributed. If all the vessels or vehicles of a modality are used, the model must choose from a different modality.

Include export next to import
Agent-based simulation is substantiated by applying both the import and export of goods and containers. The current model only assumes the import of containers and a one way trip of the modalities. In reality, a modality has to travel back to the origin, doubling the price of a trip. However, the price of transporting a container to a hinterland can be reduced by choosing a hinterland which also exports containers. The vessel or vehicle does not have to travel back empty-handed, and the trip costs can be reduced.

Depicting the best/cheapest routes
The “black box” level of the model is reduced as much as possible by applying input data which has not been altered outside the model, or at least kept to a minimum and noted what the alterations are. However, the model does not depict the routes it chooses to a hinterland destination, and for the rail- and waterway modalities, where the transhipment happens. Although for these two modalities, the nodes can be found which the model uses to reach the hinterland destination. The locations of the nodes can be plotted, and a route can be found. This is not the case for the road modality as it uses the Google Directions API.

A great addition to the model would be if it could show which route it takes to which destination and where the transhipment happens. Currently, if a new stretch of waterway or railway is added but not properly connected, the results for that modality can be quite off. The model works in such a way that it will always find a route, however it is not visible which route. This could be further improved by adding a heat map function, which colours the area or network stretch according to the intensity of its use, giving insight to which routes are used the most.

Getting a more accurate timeline on sea-level rise
Another significant improvement would be to get more clarity as to when certain levels of sea-level rise can be expected. Currently, there are multiple models and forecasts from various institutions which all predict different scenarios. The uncertainties and bandwidths within these models only add to the ambiguity. However, climate change and sea-level rise is dependant on many different factors, of which some humanity controls. Therefore one clear prediction of future sea-level rise will be unlikely.

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A
Sub-scenarios

This appendix explores the possible sub-scenarios for the different Deltares scenarios, thus to give an idea how these scenarios would be implemented.

A.1. Sub-scenarios

Each scenario, drafted by Deltares, can be conceived in different ways. In this section the different alternatives per Deltares scenario are explored. These alternatives are called sub-scenarios. Some of these sub-scenarios have only implications the Rijnmond-Drecht- steden area, others have implications for the Netherlands altogether. For the purpose of this thesis, these broader sub-scenarios are distilled to the impact on the Rijnmond-Drechtsteden area and its inland waterway connections. To easily name and differentiate between the different sub-scenarios, each main scenario has a number and each sub-scenario a letter.

A.1.1. Closed protection

The main layout of the port remain the same in this scenario. The difference for the sub-scenarios is where and if a combination of locks are placed. As there are a lot of variations, four are chosen. If storage lakes are appointed, the terminals do not have to be raised in case of peak river discharges, else the terminals can still inundate.

A sub-scenario where inland locks are placed in the Lek, Spui, Dordtse Kil and Beneden-Merwede to create a closed ring and regulate the waterlevel of the Rijnmond-drechtstede area is not taken into account. This sub-scenario would decrease the frequency of flooding of the areas outside the flood defence system, such as Dordrecht. However this scenario is not taken into account, as the costs would increase significantly with the addition of four lock complexes and the problem of inundation would only shift to the areas behind the locks.

1. Closed protection
    (a) *Locks directly in front of the port*
    Locks that can accommodate the largest deep sea vessels are placed at the entrance of the Nieuwe Waterweg. By doing so, only the outer protection of the Second Maasvlakte needs to be raised and strengthened, all terminals can remain the same height, if storage lakes are created to accommodate for peak river discharges.
    (b) *Locks after the entrance of the Maasvlaktes*
    The First and Second Maasvlakte are in direct contact with the sea and need to be raised to prevent inundation. Deep sea vessels do not have to pass through locks, which means that the dimensions of the lock can be smaller than the previous sub-scenario and because of modal split, less containers have to pass through the locks, thereby decreasing the capacity needed. The entrances of the Nieuwe Waterweg and Calandkanaal are closed off by the locks.
    (c) *Locks at the entrance of the Nieuwe Waterweg, no locks Calandkanaal*
    The locks are placed around 3 km inland than the previous sub-scenario, closing off only the Nieuwe Waterweg. The Calandkanaal is left open. This sub-scenario is similar to

the current scenario whereby the Maeslant barrier is replaced by a lock. The terminals bordering the Calandkanaal need to be raised in order to accommodate for sea level rise.

   (d) *Locks at Benelux tunnel*
   Locks are placed about 18 km inland of the entrance of the port, near the Benelux tunnel. In addition , locks are constructed at the mouth of the Old Meuse. This sub-scenario is based on Plan Spaargaren, a solution devised by ir. Spaargaren. The Botlek area will remain in direct contact with the sea, reducing waiting time for the industry there. The dikes and terminals at the sea side of the locks have to be raised however, which increases the costs significantly if when the locks are constructed at the entrance of the Nieuwe Waterweg.

A.1.2. Open protection

Similar to the closed protection scenario, the port layout will remain the same. The variations are in the location of the Maeslant barrier, of which two are chosen and if a combination with inland locks is made. The closure frequency of the barrier could also be chosen as a variable. A smaller closure frequency is preferred, although, the costs will increase significantly as the dikes and land need to be raised more to prevent flooding. However, the difference for the model would not differ much and in order to limit the number of sub-scenarios, only one closure frequency is chosen. It is set at three times per year which means that the river dikes to not have to be raised until +1 m sea level rise. The frequency of three times per year is chosen as the corresponding downtime is still acceptable and it is also used in other studies (Kind et al., 2019) (Haasnoot et al., 2019).

2. Open protection
   (a) *No storm surge barriers, only raised dikes*
   The removal of the Maeslant, Hartel and the Hollandse IJssel barriers would mean that there are no obstructions for shipping and no protection for storms. Inland dikes would have to be improved to be primal defence dikes to be able to protect against 1/10.000 to 1/100.000 storms. Although the costs for shipping would decrease, the costs for the dike improvements would increase dramatically.
   (b) *Renewed Maeslant barrier at same location + raised dikes, closing freq. = 3 times/year*
   The Maeslant barrier is replaced around 2100 with a new design, significantly improving the failure probability of the barrier. The location will remain the same, thereby keeping the First and Second Maasvlakte and Calandkanaal open. These areas and terminals will have to be raised more than the other terminals and dikes, as wind and wave set-up will increase storm surges even more at those locations.
   (c) *Renewed Maeslant barrier at port entrance + raised dikes, closing freq = 3 times/year*
   A renewed Maeslant barrier is placed at the entrance of the port, thereby closing of the entire port if a storm occurs. This would mean that the downtime of the port would spread to the entire port, as opposed to the previous sub-scenario. In reality (sea-going) ships might prefer to lay outside the port during storm conditions and wait out the storm, as damage to a vessel is more likely when moored at a quay.
   (d) *Renewed Maeslant barrier at same location + locks v1 (Ecorys modellen)*
   In order to decrease the amount of dikes which have to be raised and improved behind the Maeslant barrier, inland locks can be constructed. The location the the locks is in the New Meuse, between the Hollandse IJssel and the bifurcation of the Lek and Noord. The Hollandse IJssel barrier in combination with a lock, as the current situation, is maintained.

A.1.3. Seaward

The current layout of the port is for a large part maintained. The difference between the sub- scenarios is how the port is connected to and with the barrier islands. As unconnected barrier islands cannot withstand +3 m sea level rise, it is assumed that dams, locks and barriers are placed in between the islands.

3. Seaward
    (a) *Deep sea terminals on the barrier islands*
    The loading and unloading of deep sea vessels only happens at the barrier island(s). A portion of the containers is transshipped to road and rail at the islands. Due to the usage of the barrier islands as terminals, the port area increases. In principal vessels do not use locks to depart from or enter the port. All commodities are handled at the barrier island(s). This means that the capacity and quay lengths of the island(s) have to be adequate to handle the projected throughput.
    (b) *Shipping through the locks between the barrier islands*
    The barrier islands are used for other functions than transshipment for the port. Deep sea vessels will have to pass through locks in order to reach the port. The capacity and dimensions of the locks need to be able to handle the largest deep sea vessels, which means that the locks will be expensive. The areas in between the barrier islands and current shoreline can be used as storage lakes to accommodate peak river discharges. This sub-scenario is similar to sub-scenario 1a, the difference is that the port can more easily expand as wave conditions behind the barriers is limited.
    (c) *Open canal to port behind barrier islands + locks between barriers*
    A small canal is kept open in between two islands. It is comparable to the size of the Hartelkanaal, thus the amount of water which can pass through the islands is kept at a minimum. The canal is only connected to terminals of the port and does not form a threat to nearby residents. The surrounding terminals have to be raised in order to prevent flooding from sea level rise and storm surges. As dimensions of the canal are to small in order to handle the throughput of the port, a large fraction of the throughput still passes through the locks between barrier islands at the Nieuwe Waterweg. The new canal only serves for limited, dedicated, terminals. The price for these terminals would be higher than the terminals behind the locks.
    (d) *Deep sea terminals + locks between barrier islands*
    A portion of the deep sea vessels can (un)load at the more expensive terminals on a barrier island. The remaining vessels can pass through locks between barrier islands, leading to the Nieuwe Waterweg. This is a combination between sub-scenarios 3a and 3b. Commodities where delays are less important, as break and dry bulk, can use the locks or container terminals which offer lower prices for transshipment.

A.1.4. Retreat

Chosen is to abandon the lands below mean sea level and move east. Assumed is that the throughput of Northwestern Europe would still pass through the Netherlands, thus a new port of Rotterdam needs to be created. This can be done in advance of the retreat, thereby being able to construct the port “in the dry”. This saves costs and can keep economic damages to a minimum.

4. Retreat
    (a) *Only new port*
    The current port of Rotterdam is abandoned and demolished. All port activities are moved to a new location at Tiel. At Tiel, the new port is created at the new shoreline. A new canal, or prolonged Hartelkanaal, is dug to reach the new port from the old shoreline, such that deep sea vessels can reach the new port. This can partly be done in the dry and is partly dredged. Around 80-90 km of canal needs to be created, with an considerable width in order to have enough capacity. The development of such a canal is expensive. From the new port, containers and other commodities are transferred to road, rail and inland vessels.
    (b) *Deep sea port at current Maasvlakten + new port connected by barges*
    To solve the problem of having to create a costly canal, a deep sea port can be created at

the current coastline. The current First and Second Maasvlakten can be maintained and heightened. Deep sea vessels can moore at the terminals with minimum need for dredging. At Tiel, a new port is created where the industries and refineries can settle. To transfer the containers and other commodities to the new port, barges are used. These barges have considerable less draught than deep sea vessels, thus dredging is kept to a minimum. The downside is that the loading and unloading of the separate barges takes longer than if the cargo is unloaded from one large deep sea vessel.

(c) *Deep sea port at current Maasvlakten + new port connected by a bridge*
This sub-scenario is largely the same as sub-scenario 4b, however, instead of transferring the containers onto barges, it is transferred onto trucks and trains. A bridge is created to connect the deep sea terminals to the mainland and to the new port. By using trucks and trains, the time to transfer the goods from the deep sea terminals to the mainland is lowered. However, the construction of such a bridge is costly. At the mainland, the containers can still be transferred onto inland vessels. An example of this sub-scenario is the deep sea port of Shanghai.

B

Adaptation strategies

This appendix gives more detail about the strategies obtained from Deltares and on what grounds they fail. In addition an overview table about the method of Ecorys is given.

Table B.1: Plans collected by Deltares plus the reason of failure (Deltares, 2020)

#	Name adaptation plan	Reason plan failed
1	Naar zee!	No impact against sea-level rise
2	Zee_delijkheid - het land verwatert en de zee verlandt	No report available
3	Urgenda	No impact against sea-level rise
4	Duurzaam leven aan zee - de Nederlandse kust in 2080	No report available
5	Nova Delta	No report available
6	Plan B - Nederland 2200	No report available
7	Delta 21	No impact against sea-level rise
8	De Tulp	No impact against sea-level rise
9	Deltawerken van de Toekomst	No report available
10	Luwte Parken	No impact against sea-level rise
11	Holland - Bolland	No impact against sea-level rise
12	Groningen Adaptatie 2100 - Nieuwe Wadden	No report available
13	Evoluerende Blauwe Eilanden	No impact against sea-level rise
14	Eiland voor één seizoen	No impact against sea-level rise
15	Industrie-eiland	No impact against sea-level rise
16	SeaWing	No impact against sea-level rise
17	Atollen in de Noordzee	No report available
18	Plan Emergo	No report available
19	Drijvend Schiphol	No impact against sea-level rise
20	Plan Waterman	No large scale impact
21	Segmentatie Hollandse Kust	No report available
22	Not afraid of Red, Yellow and Blue	No large scale impact
23	Inrichten van klimaatbesteding Nederland	No report available
24	Kustlocatie Bhalotra	No report available
25	Randstad 2040	No impact against sea-level rise
26	Brede Kuststrook	No report available
27	Geleidelijk aangroei Hollandse en Zeeuwse kust	No report available
28	Plan West-Holland	No large scale impact
29	Aanleggen van Nieuwe Kust	No report available
30	Een binnenzee en nieuw land voor de kust	No report available
31	De zuidwestelijke Delta 2200	No large scale impact
32	Plan Boorsma	No impact against sea-level rise
33	Een ander IJsselmeer	No large scale impact
34	Plan Waterlely	No report available
35	Schetsplan Waterlely	No large scale impact
36	Extra spuicapaciteit in de Afsluitdijk	No large scale impact
37	Toekomst van het waterrijk	No impact against sea-level rise

#	Name adaptation plan	Reason plan failed
38	Drijvende Kassen	No impact against sea-level rise
39	Zeestad	No impact against sea-level rise
40	Elastocoast	No impact against sea-level rise
41	Kunstriffen	No impact against sea-level rise
42	Ecobeach	No impact against sea-level rise
43	Bodemverhoging door Gipsmethode	No large scale impact
44	Dynamisch handhaven kustlijn en kustfundament	No report available
45	Compartimenteren en ophogen van laag Nederland	No report available
46	Wetlands lifting	No report available
47	Duinwonen in de droogmakerij	No report available
48	Verstuiving in de duinen	No impact against sea-level rise
49	Vorming washovers en slufters	No impact against sea-level rise
50	Zwakke Schakels	No report available
51	Deltadijk - Terpdijk - Klimaatdijk	No report available
52	Overslagbestendige dijk	No impact against sea-level rise
53	Geen stilte voor de storm	No large scale impact
54	Waker en Slaper	No impact against sea-level rise
55	COMCOAST	No impact against sea-level rise
56	IJkdijk	No impact against sea-level rise
57	Zachte superdijk	No large scale impact
58	Kunstriffen voor de afsluitdijk	No large scale impact
59	Noortzee en Zuyderzee afscheyden	Outdated
60	Overschelde	No impact against sea-level rise
61	Open afsluitdijk	No large scale impact
62	De Noordzeedijk	No report available
63	Met Rotterdam in zee	No report available
64	Eilanden in de monding van de Westerschelde	No impact against sea-level rise
65	Zomerpolders omzetten in kwelders	No impact against sea-level rise
66	Nieuwe duinen - Groese Duintjes en Cletemspolder	No large scale impact
67	Duincompensatie Tweede Maasvlakte	No report available
68	Het tij geleerd	No report available
69	Verlagen van het Verdronken Land van Saeftinghe	No large scale impact
70	De Kerf	No impact against sea-level rise
71	Zeegras transplantatie	No impact against sea-level rise
72	Vogelvriendelijke verlichting op olie- en gasplatforms	No impact against sea-level rise
73	Plan Turelaar	No impact against sea-level rise
74	Zandhonger Oosterschelde	No report available
75	Doorlaatmiddel in de Philipsdam	No impact against sea-level rise
76	Doorlaatmiddel Veerse Meer	No impact against sea-level rise
77	Ontzilting van zeewater	No impact against sea-level rise
78	Drinkwater uit Oosterschelde	No impact against sea-level rise
79	Vijfeilandenplan	Outdated
80	Dijkstad	No report available
81	Amfibisch wonen	No large scale impact
82	Floodproof woningen	No report available
83	Stad op zee	No report available
84	Getijdenstad	No report available
85	Drijvend Paviljoen Shanghai	No report available
86	Compartimentering Dijkring 14	No impact against sea-level rise
87	Klimaatbestendig Schouwen Duivenland	No report available
88	Terug naar de Kust	No report available
89	Wieringerrandmeer	No impact against sea-level rise

#	Name adaptation plan	Reason plan failed
90	Generating Dune Scapes	No impact against sea-level rise
91	The Dutch Mountains	No impact against sea-level rise
92	Gebiedsontwikkeling Perkpolder	No large scale impact
93	Waterdunen	No large scale impact
94	Catamaranstad	No impact against sea-level rise
95	Innovatielocaties Deltatechnologie en Klimaat in de Zuidwestelijke Delta	No impact against sea-level rise
96	Wonen op de Afsluitdijk	No impact against sea-level rise
97	Fryske Fiersichten	No impact against sea-level rise
98	Afsluitdijk als icoon voor duurzame energie	No impact against sea-level rise
99	Ontwikkelingsvisie Eemsdelta	No large scale impact
100	Risicobewust bouwen op de zeekering	No impact against sea-level rise
101	Alternatieven voor ontpoldering langs de Westerschelde	No large scale impact
102	Kaap de Goede Hoek	No impact against sea-level rise
103	Ontwerpatelier Ter Heijde	No report available
104	Projectontwikkeling aan de kust bij Scheveningen	No impact against sea-level rise
105	Stadshavens Rotterdam	No impact against sea-level rise
106	Zeejachthaven Katwijk	No impact against sea-level rise
107	Marina Petten	No impact against sea-level rise
108	Bergse Haven	No impact against sea-level rise
109	Sluis aan Zee	No impact against sea-level rise
110	Esonstad	No impact against sea-level rise
111	Drijvend toerisme aan het waterfront	No impact against sea-level rise
112	Dongtan Ecocity - Greenport Shanghai	No impact against sea-level rise
113	Smart soils	No impact against sea-level rise
114	Blauw Bloed	No report available
115	Innofisk	No impact against sea-level rise
116	Happy Shrimp	No impact against sea-level rise
117	Zeeuwse Tong - De Zilte cascade	No impact against sea-level rise
118	Zeecultuurpark	No impact against sea-level rise
119	Zilte botanie, landgoed en proeftuin	No impact against sea-level rise
120	Zilte landbouw in Zeeland	No impact against sea-level rise
121	Zilte landbouw op Texel	No impact against sea-level rise
122	Biosaline agro forestry	No impact against sea-level rise
123	Zeecultuurpark - de getijdennatuurpolder	No impact against sea-level rise
124	Bollenmeer - zuinig omgaan met zoet water	No impact against sea-level rise
125	Watervoorziening in de Delta	No impact against sea-level rise
126	Maasvlakte 2	No impact against sea-level rise
127	Derde Maasvlakte	No impact against sea-level rise
128	Nieuwe Zeesluis IJmuiden	No large scale impact
129	Haven in Zee (IJmuiden)	No impact against sea-level rise
130	Nieuwe zeesluis voor Kanaal Gent - Terneuzen	No large scale impact
131	Flyland, onderzoek Luchthaven in Zee	No impact against sea-level rise
132	Schiphol in zee	No impact against sea-level rise
133	Vliegveld voor de kust	No impact against sea-level rise
134	Hub-eiland voor de kust	No impact against sea-level rise
135	Plan Schiphol IJpoort	No impact against sea-level rise
136	Westerschelde container terminal	No impact against sea-level rise
137	Plan T	No impact against sea-level rise
138	Costa due	No impact against sea-level rise
139	Energy Park Eemshaven	No impact against sea-level rise

#	Name adaptation plan	Reason plan failed
140	Blue Energy	No impact against sea-level rise
141	Energie uit stroming	No impact against sea-level rise
142	Energie uit getijdenstroming	No impact against sea-level rise
143	Golfenergie	No impact against sea-level rise
144	Torcado	No impact against sea-level rise
145	Drijvende windmolens	No impact against sea-level rise
146	Windmolens op drijvende platforms	No impact against sea-level rise
147	Akkers van wieren	No impact against sea-level rise
148	Zeewierplantage	No impact against sea-level rise
149	Zeewater warmt Scheveningse huizen op	No impact against sea-level rise
150	LNG terminal op zee (FPSO)	No impact against sea-level rise
151	Offshore regas faciliteit	No impact against sea-level rise
152	Drijvende LNG terminal	No impact against sea-level rise
153	Energie-eiland in de Noordzee	No impact against sea-level rise
154	Energie-eiland in het Markermeer en de Noordzee	No impact against sea-level rise
155	Bioport	No impact against sea-level rise
156	Poseidon	No impact against sea-level rise
157	Schoon fossiel en CO2 opslag in de Noordzee	No impact against sea-level rise
158	Gate Terminal - LNG op de Maasvlakte	No impact against sea-level rise
159	MERA Park Delfzijl	No impact against sea-level rise
160	Spray Turbine	No impact against sea-level rise
161	Schoon fossiel en CO2 opslag in W-Australië	No impact against sea-level rise
162	Zandmotor	Outdated

Table B.2: Overview effects, units, economical translations and source (deltaprogramma RMD) (Ecorys, 2011)

Effect	How to determine	Unit	Translation into economical value	Source
Closure frequency barriers	Deltascenarios	Numbers per year	-	-
Expected waiting time new locks	SIVAK model	Transporation time in hours	VOT load and ships	Key figures, literature
Reliability new locks	Storage waiting time	Hours per year	VOT load and ships	Key figures, literature
Unexpected delays new locks	Deltascenarios	Hours per year	Losses industry and trade	EUR-study
Shift to other ports	CPCM, Trans-Tool, experts	Added transport costs and time	VOT load and ships	Key figures, literature
Modal shift	CPCM, Trans-Tool	Added transport costs and time	VOT load and ships	Key figures, literature
Transport costs due to lock dimensions	Calculations	Added transport costs and ships	Factor costs per shipping clas	Key figures, literature
Port revenues	Number of ships or cargo	€ per shipping type per ton	-	Havenbedrijf Rotterdam N.V.
Indirect effects	Storage direct transporteffects	€	-	15%
Effects safety	Regarding shipping	Accidents per year	Qualitative	-
Effects emissions	Regarding cars/ shipping/trains	Emissions per vehicle kilometer	Qualitative	-
Spacial development	-	-	Qualitative	-

C

Inundation maps

This appendix gives more detailed maps of the inundation at +3 m sea-level rise and a retreat scenario to supplement Chapter 6.

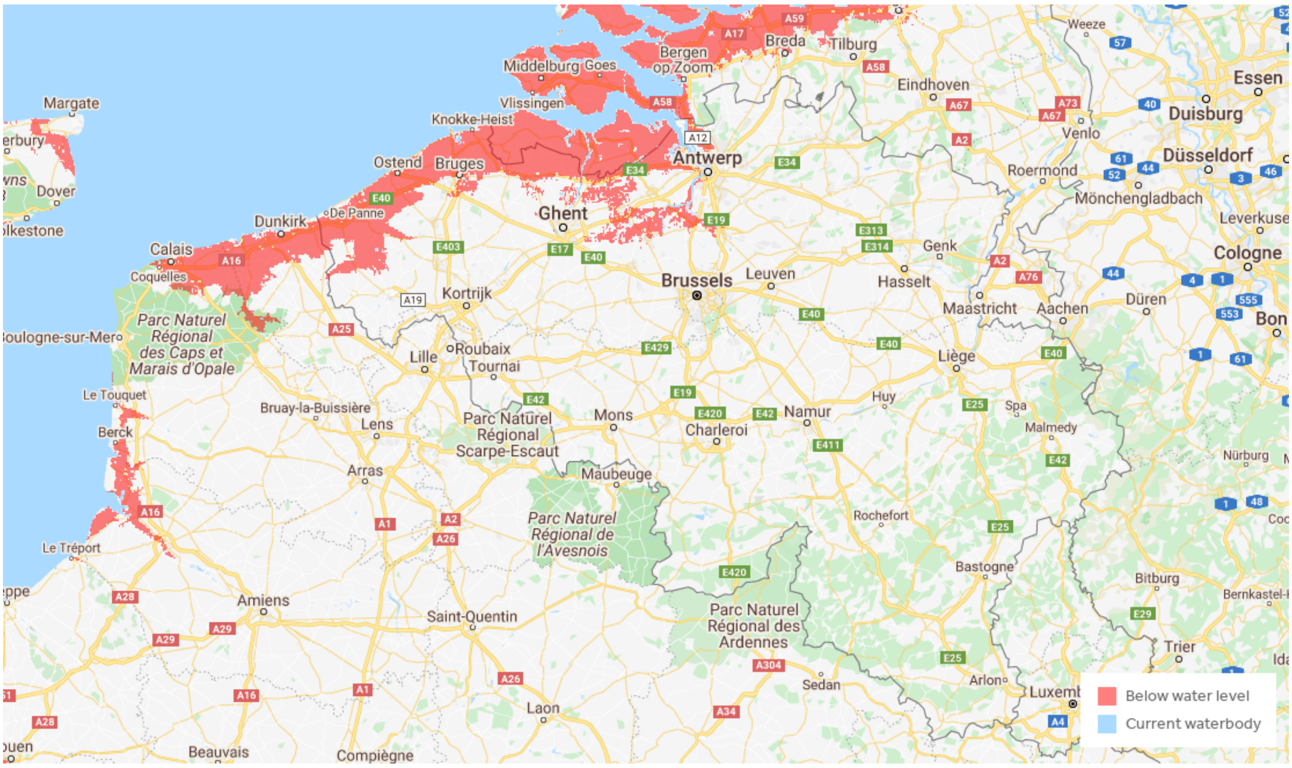


Figure C.1: Inundated areas of Belgium at +3m sea-level rise (Climate Central, 2020)

Figure C.2: Inundated areas of Germany at +3m sea-level rise (Climate Central, 2020)

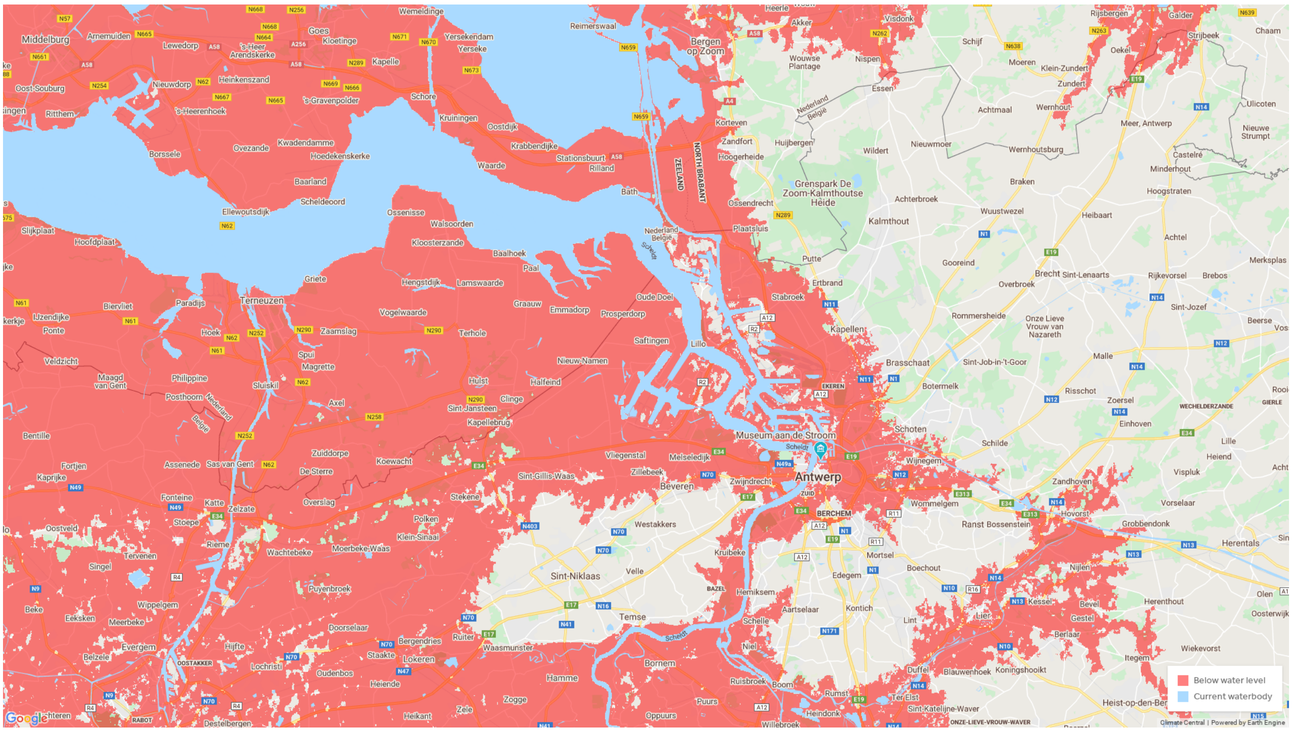


Figure C.3: Inundated areas of the port and city of Antwerp at +5 m sea-level rise. (Climate Central, 2020)

D
Model details

This appendix gives more information about the model, how to use it, which parameters it uses and what alterations are made.

D.1. Model download

1. Download Anaconda Navigator and install the Notebook option
2. Download the model notebooks by follow the QR-code link of Figure D.1 to the GitHub repository. Subsequently, open and download the “basecase” and “endgame” notebooks. To access the repository, permission has to be obtained by Mark van Koningsveld
3. Download the right packages (see example notebooks for more details)
   (a) Download GDAL package
      - Go to `https://www.lfd.uci.edu/~gohlke/pythonlibs/#gdal`
      - Download GDAL file for your os (x32 or x64) and your Python (3.5, 3.6, 3.7 etc) check Python version via `>>> python` in the command window
      - Copy the directory, including the file, example below `C:\Users\XXX\Downloads\GDAL-3.0.4-cp37-cp37m-win_amd64.whl`
      - Open command window as administrator: `>>> pip install C:\Users\XXX\Downloads\GDAL-3.0.4-cp37-cp37m-win_amd64.whl`

   (b) Download Fiona package
      - Go to `https://www.lfd.uci.edu/~gohlke/pythonlibs/#fiona`
      - Again, download file according to os and python version
      - `>>> pip install C:\Users\XXX\Downloads\Fiona-1.8.13-cp37-cp37m-win_amd64.whl`

   (c) Download GeoPandas package
      - Go to `https://www.lfd.uci.edu/~gohlke/pythonlibs/#geopandas`
      - `>>> pip install C:\Users\XXX\Downloads\geopandas-0.7.0-py2.py3-none-any.whl`

   (d) Install remaining packages using the command window
      - `>>> conda install shapely`
      - `pip install geocoder`
      - `pip install folium`

   (e) It is important to download the packages following this order. If an error occurs, best to uninstall Anaconda completely, install and try again.
4. Obtain a (free) Google Developers API Key and link it to your notebooks: `https://developers.google.com/maps/documentation/directions/get-api-key`

Figure D.1: Github link to the model notebooks

D.2. Model usage

1. Choosing the ports, countries and outline of the landscape

The user starts with passing in the names for the locations of the deep sea ports and the detail level of the NUTS regions. The locations ports of Antwerp, Rotterdam and Hamburg are selected as the default deep sea port locations. However the user can change the locations by entering the desired location name(s). The model automatically finds the new locations and depicts them on the map.

Subsequently the user introduced to an interactive map of Europe. Here the inundated areas at three meter sea level rise, as discussed in section 6.2, and the European waterways and railways are depicted. In the map, the the new outline on Europe can be drawn as envisioned by the user. When the user is content with the shape, which can be edited or removed, the outline can be exported. Next, the user can select the desired countries. It should be noted that the model then only incorporates the NUTS regions which are both in the new outline and in the selected countries. An example of a new outline around Northwest Europe can be seen in figure D.2.

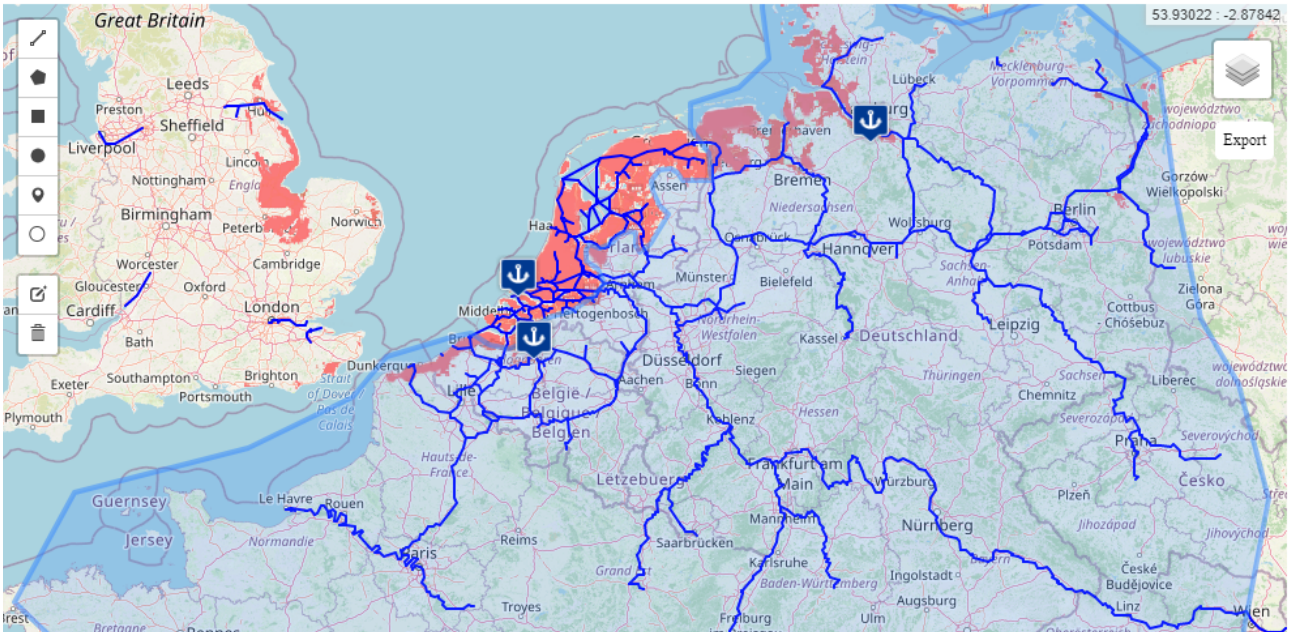


Figure D.2: First part of the model, selecting the new outline of North-west Europe. In red are the inundated areas at +3 m sea level rise.

2. Making changes to the modality networks

The new outline also deletes stretches inland waterway and rail networks which are not included within the outline. However a deep sea port connected to the inland waterway network or railway network can still be desired. As such, the user can draw on another interactive map missing or desired inland waterway or railway stretches. These are then added and combined to the networks in the new outline.

3. Calculating and depicting the results
Lastly the user runs the functions to calculate the distances and costs for the modalities from the different ports to the hinterland destination. The results are plotted on two interactive maps. The first depicting the (new) competitive hinterland distribution and the second which areas have become cheaper or more expensive for the port of Rotterdam in respect to the base case.

D.3. Equation variables

Capacity
The capacity is the amount of TEU a transport device can carry. More capacity means fewer trips, which can save costs. Having the capacity in the formula means that when water levels of the rivers change, due to draught for example, the effects can be quantified on the supply chain. Capacity is one of the advantages of the inland water transport. The amount TEU inland vessels can carry, can differ quite a bit. There are smaller vessels which carry 50 TEU, however push barge convoys exists with a capacity up to 500 TEU. These only serve on the Lower and Middle Rhine however. Generally a capacity between 96 and 196 TEU is assumed for inland water transport (Caris, Macharis, & Janssens, 2011; T. Notteboom, 2007).

Trucks can carry the smallest amount, two TEU or one FEU, which is twice the size of a TEU (Comer et al., 2010; S. Islam, Olsen, & Daud Ahmed, 2013). The train scores in between with an average of 74 TEU (D. Islam, Zunder, & Zomer, 2010; Woodburn, 2015). The relative trip distance per container thus smaller for an inland vessel as compared to truck and train.

(Un)loading times
The loading and unloading times of containers can differ from port to port and even between terminals in ports. It depends on the equipment used to transfer the containers and to which modality it is transferred. Trucks have the smallest loading and unloading times as they can collect the containers quite easily and swiftly by driving in the container storage yard. In addition, their small capacity means that the total (un)loading time is limited.

The loading and unloading of inland vessels and trains is more complicated. An inland vessel firstly has to dock next to the terminal and then collect the containers. Due to the manner the containers are stacked in and on the vessel, the loading and unloading times increase in respect to a truck (Konings, 2007). In addition, an inland vessel usually collects containers at multiple terminals in a port, before departing to the hinterland, whereas the truck can start its journey immediately.

For the train the loading and unloading operations are also more difficult than for a truck. However the main drawback is that the increased dwelling times of containers when transported by a train. The process can differ port to port. The containers are either firstly transferred to a collective storage yard from where the trains depart (thereby increasing the container dwelling time) or the train passes multiple terminals, in line with inland water transport (Konings, 2009). Concluded can be that the truck has an advantage over inland vessel and train as the loading, unloading and collecting procedures are more simple and the total (un)loading times are smaller because of its capacity. Train transport has the most disadvantage when it comes to loading and unloading.

Velocity
With the distances known, the modality velocities can convert the distances to transport time. Trucks are limited to a maximum velocity of 80 km/h in Europe. Due to congestion, refueling, eating and sleeping, the average velocity is in fact around 45 km/h (Pan-European Co-operation for Progress, 2006; Kim & Van Wee, 2009).

The average velocity of the waterway modality is the lowest at 10-12 km/h (Pan-European Co-operation for Progress, 2006). This is mainly due to the sleeping, water resistance, waiting time at locks and travelling upstream, against the flow of the river, when departing from deep sea ports. It is by far the slowest modality.

The average velocity of a freight train is around 60 km/h (Gattuso & Restuccia, 2014). Whilst the cruising speed of a train is much higher, it too has to stop. It has to stop to change personnel, locomotives at borders and to load or unload freight during the trip (Kim & Van Wee, 2009). It has however still the highest average velocity of the modalities.

D.4. Model changes

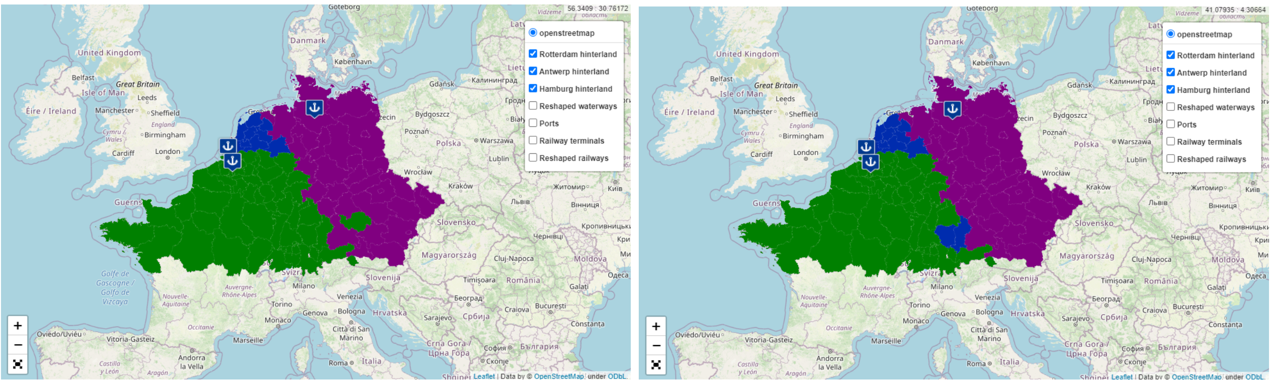
The raw data obtained for the model is changed to reflect the real world situation. To that extend, the data is selected on properties to accomplish the reflection. As one of the objectives of the model is that it is reproducible, the networks and port/terminal files are manually altered as little as possible. If manual adjustments have been made, these are documented below as to be reproducible still.

D.4.1. Networks

The files containing the networks are too detailed for the purpose of this thesis. They are too fine-meshed or simply do not reflect the truth. Below the inland waterway and railway network changes are discussed.

Simplified networks

The NetworkX package used in the (Python) model offers the function to simplify the network. It does this by removing the nodes of a line (i.e. stretch of waterway/railway) between the outer two nodes. Thereby reducing the number of nodes the model has to transform from the original data to a network. In addition it has to iterate over less nodes when finding the closest node of a network to an inland port or railway terminal. The result is a drastically reduced run time, a reduction from 24 hours to minutes, even to mere seconds if the refresh function discussed in section D.2 is off. The results can be seen in figure D.3 below.



(a) Results model with a non-simplified network

(b) Results model with a simplified network

Figure D.3: Results of non-simplified and simplified modality networks

As can be seen, there is a difference in results in the southern parts of the selected outline. We have to look at the networks to explain the results. The green region in figure D.3a can be attributed to the railway network of which a branch passes through there. The blue regions in figure D.3b can be attributed to the waterway network, namely the Rhine stretch which ends just before that region.

However the more interesting results is obviously the difference between the figures. Whereas the overall results are quite similar, the southern areas differ. This can be explained with the simplification function. If the network is simplified, there are less nodes or locations the inland ports or terminals can be attributed to. Therefore the “end” locations and thus the relative distances travelled per modality can differ. Especially at larger distances, the costs difference in a region between ports or modalities can be quite small. Therefore if there is a small difference between the inland port or terminal locations when the network is or is not simplified, the result can be a different port which is more competitive for that region.

Inland waterway

The inland waterway data is obtained from `https://ftp.demis.nl/outgoing/etisplus/datadeliverables/Additional/`. The raw data gives an inland waterway network which contains all CEMT class waterways. As a certain inland vessel container capacity is assumed, not all these classes are needed. In order to obain the ones that are, the data is selected on certain properties which are included in the data.

As only the waterways with CEMT classes IV, V and VI have the capacity for the inland vessels needed, the waterways with these properties are selected. This is represented in the data with the "class" property. In this case, the waterways containing the classes "40", "50" and "60" are selected, representing the IV, V and VI CEMT classes respectfully. They are selected using the following line of code, using the IV class as example: `waterways_gpd.Class.str.contains('40')`

Railway

As the waterway data, the rail data is obtained from `https://ftp.demis.nl/outgoing/etisplus/datadeliverables/Additional/` too. The data contains every raiway stretch in Europe, including all the passenger railways. Containers are (mainly) transported via the freight rail routes. Therefore, these railway stretches are selected for the model. This is accomplished by selecting the railway streches with freight priority property set to 1, as such: `railways_gpd.PriorityFr == 1`.

However, this comes with a problem. Some railway stretches do not have the freight priority but do connect the ones which have. This results in gaps between the selected railway stretches, which means that those gaps become the outer limits of the network, rendering the network invalid. In order to prevent this, manual changes have been made to the raw data. Using the ArcMap from ESRI, the networks can be altered manually. The stretches that have been altered by setting the `PriorityFr` from 0 to 1 can be found in table D.1.

Table D.1: Manually altered railway stretches

	Stretch	`PriorityFr`
ID	2502482	0 to 1
ID	2002516	0 to 1
ID	2502287	0 to 1
ID	2502366	0 to 1
ID	2501854	0 to 1

D.4.2. Inland ports and terminals

Both the inland ports and railway terminals data files contain over 1000 locations, respectfully. These files contain numerous types of ports and terminals, not all handling containers. If these ports and terminals would all be selected for the model, the run time would increase drastically and the results unreliably. Therefore the data is selected which does reflect a realistic amount of ports and terminals and their respective locations. However unlike the network data which has to be selected on the freight or class property, the port and terminal data has to be selected on containers specifically.

Inland waterway ports

The raw inland port data does not contain properties for which container cargo can be selected specifically. However it does contain some other properties. Among these properties is the property if rail access is available. Although this not guarantee containers, liquid and dry bulk are not easily transferred to rail due to the manner of transportation, which also holds for break bulk. When the results are compared to the TEN-T program in section 5.3.3, they match quite well. The following line of code is used: `inland_port_gpd.RAILACCESS.str.contains('Available')`.

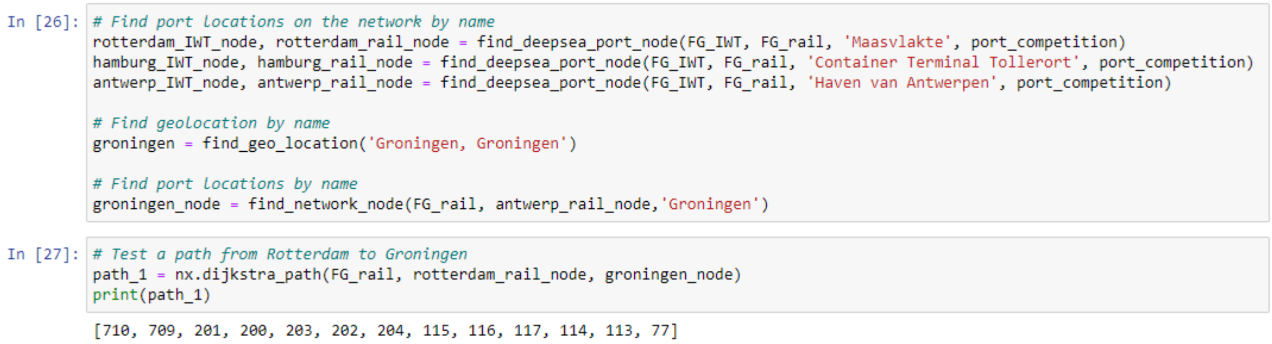
Rail to road terminals

As for the inland port data, the rail to road terminals data does not have a specific property for containers. It does have a property which states what types of cargo it handles, however for the vast majority of the terminal data, this is not specified. Therefore the terminal names are filtered if they contain the word “container” or a variant thereof or the world “intermodal”, following the same philosophy from the inland ports above. In addition the terminals are selected with a capacity over 1000. The following lines of code are applied:

```
[(rail_terminal_gpd.CapacityTE >= 1000)  |
(rail_terminal_gpd.TerminalNa.str.contains('Intermodal')) |
(rail_terminal_gpd.TerminalNa.str.contains('Container'))  |
(rail_terminal_gpd.TerminalNa.str.contains('container'))  |
(rail_terminal_gpd.TerminalNa.str.contains('Conteneur'))]
```

D.5. Verification

Figure D.4 depicts an example output for obtaining the node numbers used for the shortest path between Rotterdam and Groningen. Subsequently the latitude and longitude coordinates of each node are noted and plotted to obtain the route.



```
In [26]: # Find port locations on the network by name
         rotterdam_IWT_node, rotterdam_rail_node = find_deepsea_port_node(FG_IWT, FG_rail, 'Maasvlakte', port_competition)
         hamburg_IWT_node, hamburg_rail_node = find_deepsea_port_node(FG_IWT, FG_rail, 'Container Terminal Tollerort', port_competition)
         antwerp_IWT_node, antwerp_rail_node = find_deepsea_port_node(FG_IWT, FG_rail, 'Haven van Antwerpen', port_competition)

         # Find geolocation by name
         groningen = find_geo_location('Groningen, Groningen')

         # Find port locations by name
         groningen_node = find_network_node(FG_rail, antwerp_rail_node,'Groningen')

In [27]: # Test a path from Rotterdam to Groningen
         path_1 = nx.dijkstra_path(FG_rail, rotterdam_rail_node, groningen_node)
         print(path_1)

         [710, 709, 201, 200, 203, 202, 204, 115, 116, 117, 114, 113, 77]
```

Figure D.4: Model output snipped of the path from Rotterdam to Groningen. Numbers at the bottom indicate the nodes followed from the origin to the destination.

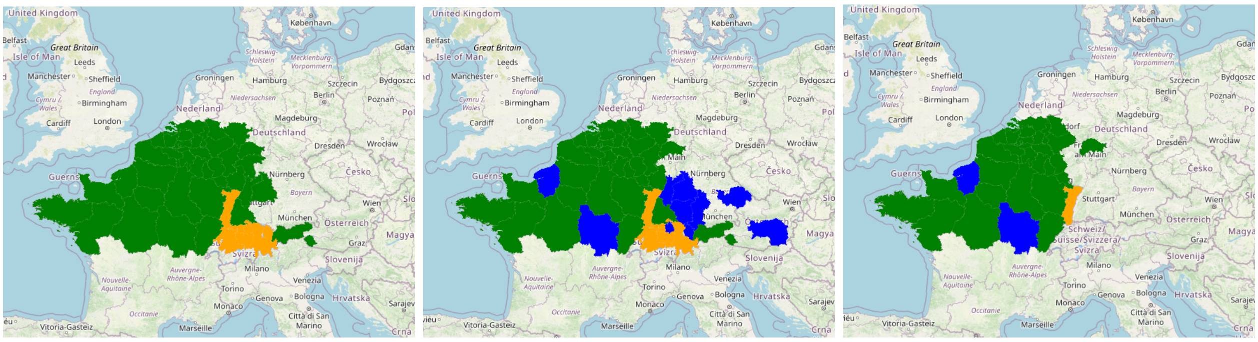
D.6. Calibration

In chapter 5 the (costs) results of the model are calibrated. This is further elaborated upon in this section. The figures below all give the results of the two calibration steps. The first figure gives the result before calibration, the second when the modalities are calibrated and the final when the ports themselves are calibrated.

D.6.1. Port of Antwerp

As can be seen in figure D.5a, the hinterland area of Antwerp lacks any competitiveness areas for the waterway modality, despite having a substantial waterway network. This network is however mostly close to the port itself and is therefore more expensive than the road modality. However, there are waterway stretches, such as the Seine, which are further away an connected to the port. Therefore a 7% cost decrease is applied for the waterway modality.

Figure D.5b shows the result of this 7% cost decrease. Although there is only a slight increase in waterway regions for the port of Antwerp, it is found to be sufficient. Fig. D.5c shows the resulting hinterland area and modality areas for Antwerp.



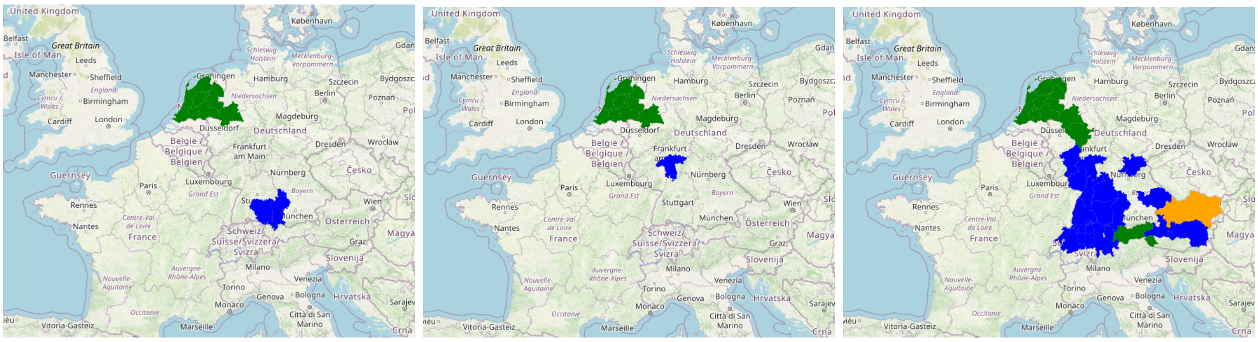
(a) Pre-calibration (b) Modality calibration (c) End result calibrations

Figure D.5: Competitiveness hinterland areas port of Antwerp for the calibration process of the model. Green, blue and orange areas represent the road, waterway and rail modalities, respectively.

D.6.2. Port of Rotterdam

The respective hinterland areas for the port of Rotterdam is very limited, as can be seen from figure D.6a. Therefore a 10% overall costs decrease is applied to the results of the port. This deficit can be attributed to the lack of advantages the port has in the real world, which are not included in the model.

An additional 6% waterway costs decrease is applied for the port. The Rhine area is a known competitive waterway area for Rotterdam. As such the modality is calibrated for better representation of this area. Figure D.6c gives the resulting hinterland area and modality areas for Rotterdam.



(a) Pre-calibration (b) Modality calibration (c) End result calibrations

Figure D.6: Competitiveness hinterland areas port of Rotterdam for the calibration process of the model. Green, blue and orange areas represent the road, waterway and rail modalities, respectively.

D.6.3. Port of Hamburg

The port of Hamburg is the only where no calibration is needed. However, as can be see from figure D.7, there is one outlier, the waterway area directly around Hamburg. This can be explained by the fact that the port node, which is also the start node of the waterway modality for the ports, is in very close proximity to the destination node. It is actually in such a close proximity that the model can skip the waterway path altogether and only calculates the second part of the trip, via the road modality. However this is still attributed to the waterway, due to the way it is coded.

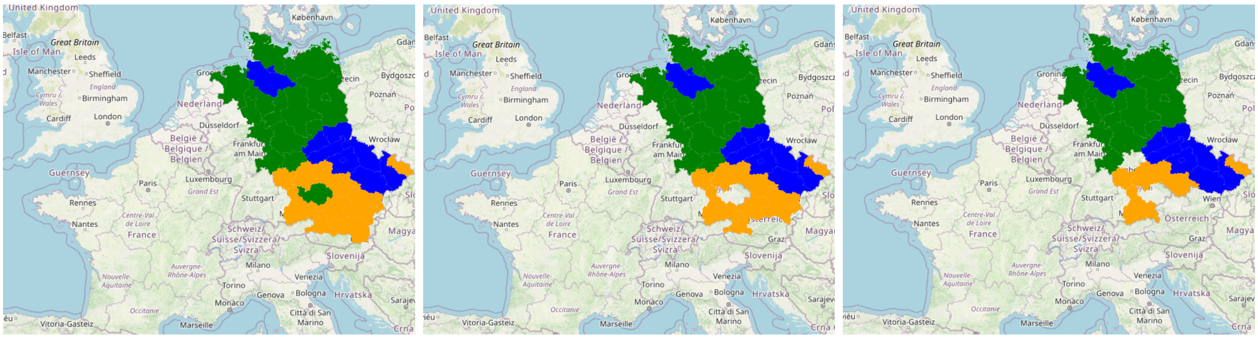

(a) Pre-calibration (b) Modality calibration (c) End result calibrations

Figure D.7: Competitiveness hinterland areas port of Hamburg for the calibration process of the model. Green, blue and orange areas represent the road, waterway and rail modalities, respectively.

D.7. Validation

To compare the distance results from model, different distance measurement tools are used. For the road modality the map function from Bing is used, as the model uses the Google Maps API. To test the waterway, inland shipping route planners are used for each country, as there is no single online route planner available. The same goes for the railway distances.

Excel is used to find the deviation, standard deviation and R-squared values. These are found to be 8.2%, 10.0 and 0.9929. Figure D.8 shows the distances of the model vs the distances of the control values.

Table D.2: Results of the distance validation test. The control data is obtained using distance measurement tools for different modalities.

Modality	Origin	Destination	Distance model [km]	Distance control values [km]	Deviation [%]
Road	Antwerp	Maastricht	129,5	130	0.3861
Road	Antwerp	Brussels	74,2	58	17.78976
Road	Rotterdam	Molenhoek	97,1	105	8.135942
Road	Rotterdam	Deventer	175,6	171	2.61959
Road	Hamburg	Berlin	293,8	288	1.974132
Road	Hamburg	Nürnberg	613,7	605	1.417631
Waterway	Antwerp	Maastricht	116,9	119,3	2.053037
Waterway	Antwerp	Brussels	70,2	67,1	4.415954
Waterway	Rotterdam	Molenhoek	103,5	125	20.77295
Waterway	Rotterdam	Deventer	167,5	153	8.656716
Waterway	Hamburg	Berlin	319,3	357,3	11.90103
Waterway	Hamburg	Nürnberg	1128,5	1267,3	12.29951
Railway	Antwerp	Hasselt	86,6	78	9.930716
Railway	Antwerp	Namur	114,9	99	13.83812
Railway	Rotterdam	Nijmegen	99,4	93	6.438632
Railway	Rotterdam	Roosendaal	52,7	50	5.12334
Railway	Hamburg	Berlin	421,0	388	7.83848
Railway	Hamburg	Nürnberg	583,5	603	11.97772

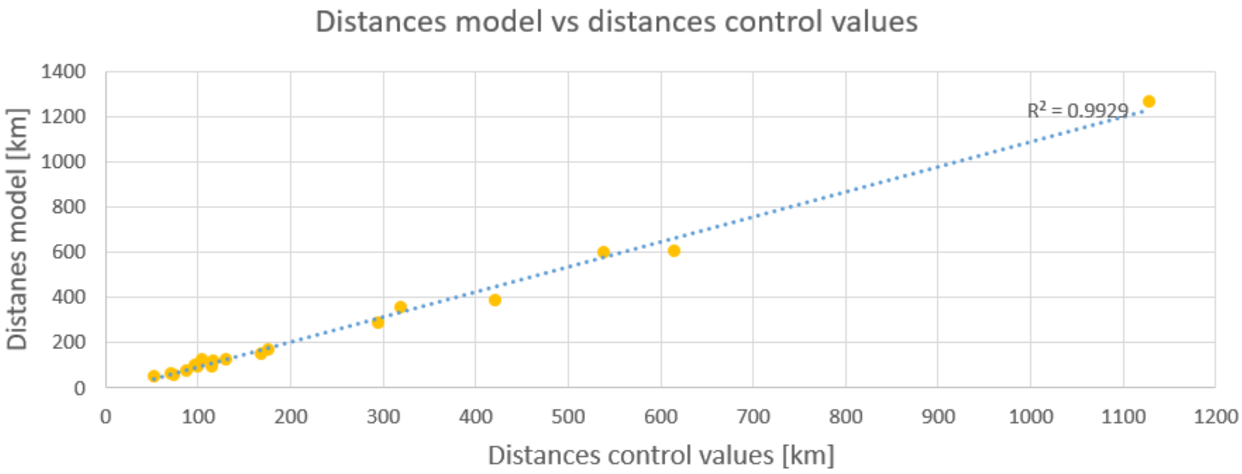
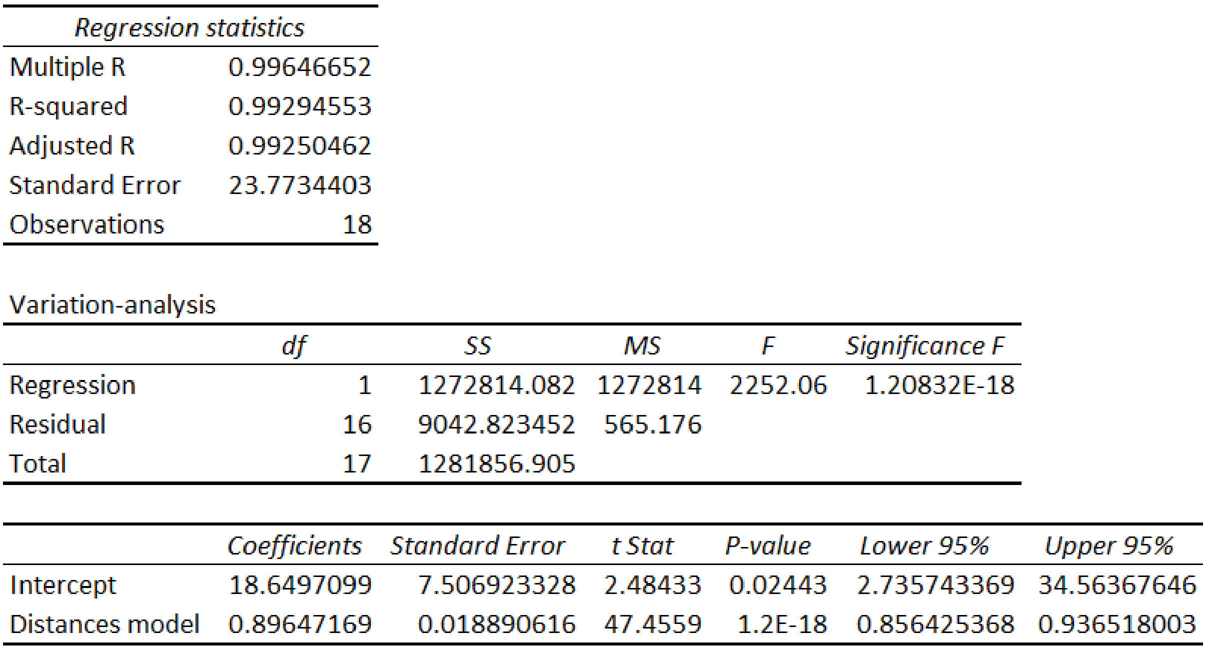


Figure D.8: Plot of the model distance values vs the control distance values



Regression statistics	
Multiple R	0.99646652
R-squared	0.99294553
Adjusted R	0.99250462
Standard Error	23.7734403
Observations	18

Variation-analysis

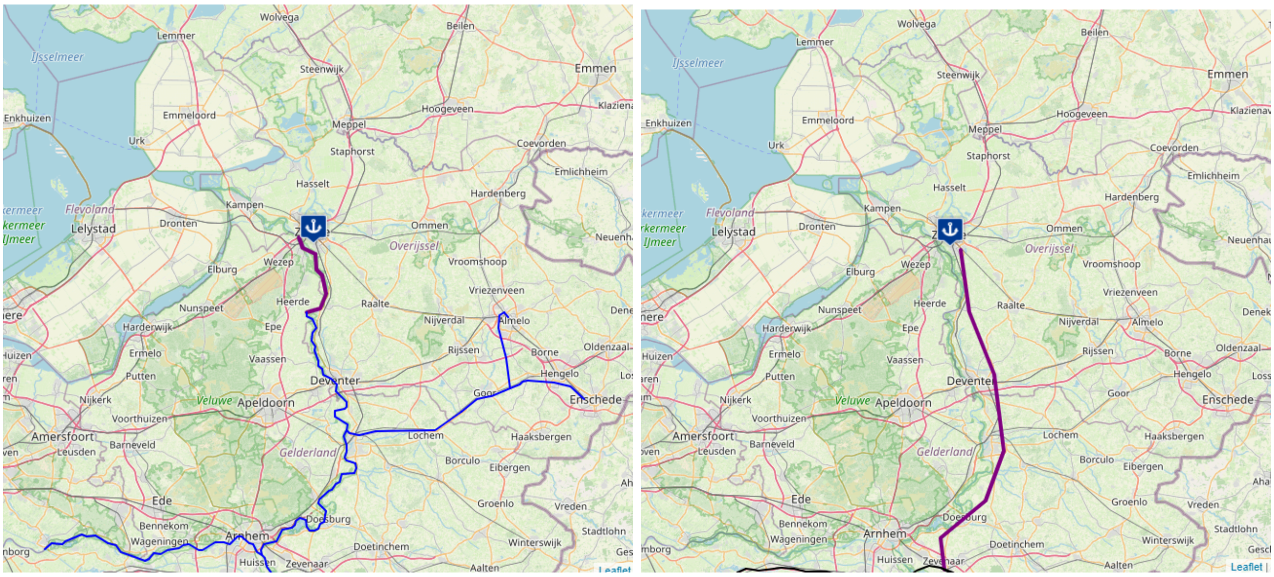
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1272814.082	1272814	2252.06	1.20832E-18
Residual	16	9042.823452	565.176		
Total	17	1281856.905			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	18.6497099	7.506923328	2.48433	0.02443	2.735743369	34.56367646
Distances model	0.89647169	0.018890616	47.4559	1.2E-18	0.856425368	0.936518003

Figure D.9: Complete result regression statistics model distance validation

D.8. Extra waterway and railway stretches model

Zwolle

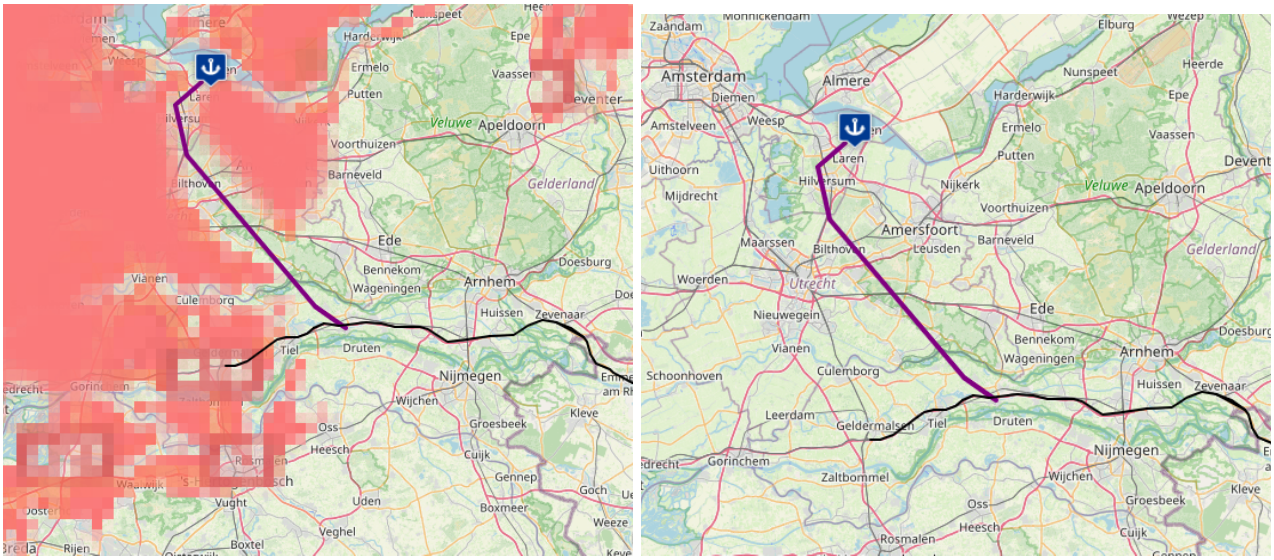


(a) Added waterway stretch.

(b) Added railway stretch.

Figure D.10: Added stretches for the location of Zwolle.

Huizen

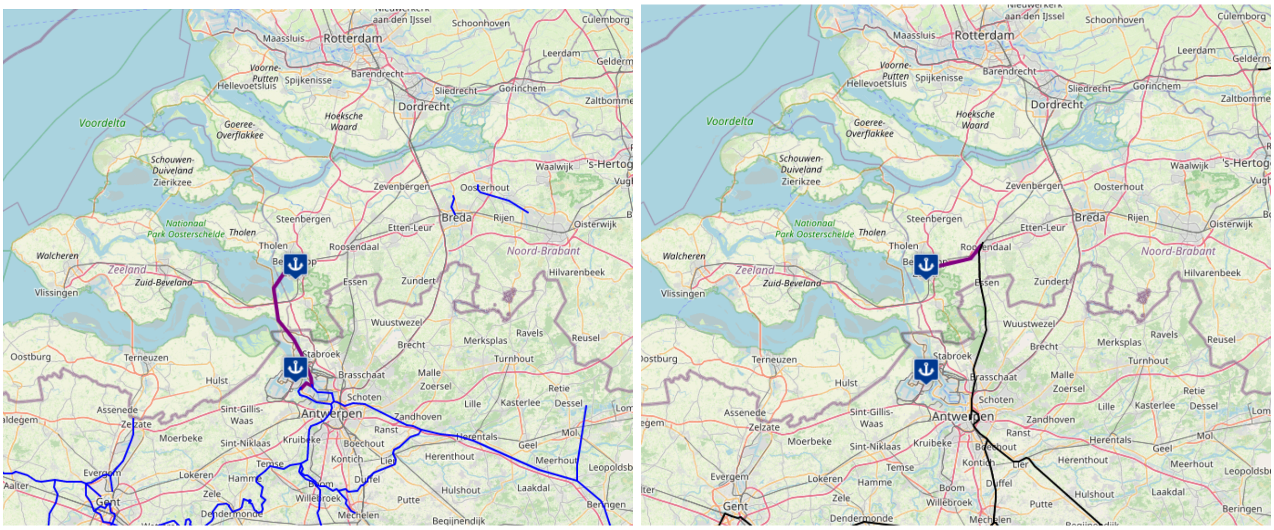


(a) Added waterway stretch.

(b) Added railway stretch.

Figure D.11: Added stretches for the location of Huizen.

Bergen op Zoom



(a) Added waterway stretch.

(b) Added railway stretch.

Figure D.12: Added stretches for the location of Bergen op Zoom.