Measures for the reduction of CO_2 emissions, by the inland shipping fleet, on the Rotterdam-Antwerp corridor

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by

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Executive summary

The main aim of this research was to establish which measures are significant in reducing the CO_2 emission levels on the waterways between Rotterdam and Antwerp. The main research question has therefore been defined as follows:

What measures can contribute to the reduction of the CO_2 emissions, by the inland shipping fleet, on the Rotterdam-Antwerp corridor, in specific the Zuid-Beveland and Scheldt Rhine route?

The measures have been divided in two main categories which are in turn subdivided in three options.

1. Infrastructural modifications
    (a) Increase of the bridge heights on the Scheldt-Rhine canal
    (b) Conversion Bathse sluice into a lock
    (c) Removal Kreekrak locks
2. Fleet scenarios
    (a) Fleet with high-cube containers
    (b) Standard vessels and departure slots
    (c) Sea level rise

Rijkswaterstaat is aiming to have her infrastructural networks energy neutral by 2030 and zero emission networks by 2050. At the moment, no research has been conducted on the entire emission levels produced by inland shipping fleets. This research tries to contribute to the emission goals of Rijkswaterstaat by providing a tool that gives insights on the entire emission levels of the fleet, on the Rotterdam-Antwerp corridor, and shows the effects of implementing the above stated measures on the emission levels.

Different steps have been taken to answer the research question. First an analysis of the corridor and her fleet has been conducted. It became clear that for the emission calculations the encountered vessel resistance and the emission factors are most important. The vessel resistance during sailing has been divided into three main resistance classes, namely friction, residual resistance and resistance by limited water. For the resistance calculations fleet and waterway characteristics have been obtained. The calculated resistance has been multiplied with sailing speeds (resulting in the requested engine power) and sailing times to obtain the energy consumption. The translation from energy consumption to CO_2 emissions has been made by multiplying the energy consumption with the fuel dependent emission factors. In the end, total sailing times of the entire fleet (and therefore the sailing patterns) needed to be obtained, to be able to determine emission levels on the corridor. Between the Volkerak locks and Antwerp vessels have two sailing options, namely the Zuid-Beveland and Scheldt-Rhine canal. The choice of route is based on destination and on the height restrictions on the Scheldt-Rhine route.

Second, a model has been developed based on the above analysis. The developed tool provides insights in the emission levels, sailing patterns and congestion points on the waterways between the Volkerak locks and the port of Antwerp. A discrete event model has been developed in order to properly simulate where, when and how much CO_2 is produced. Vessels can be in different propulsion stages and the requested engine power can therefore differ between these stages. The route choice of the vessels on the network is determined based on destination and height of the vessel. A lock selection component has been implemented in the model to simulate the dynamic behaviour of vessels at locks. In order to reproduce the traffic flows, congestion patterns and with this the emission levels, generated vessels should be able to calculate their route, move over the chosen waterway and queue before locks and bridges. These requirements have been met by applying graph theory and queuing theory. The open-source NetworkX package from Python has been used to build a network (graph) based on the shapefiles (geographical coordinates) of the waterways between the Volkerak

locks and the port of Antwerp. Generated vessels use the algorithms of the NetworkX package to calculate their route. The open-source package SimPy has been used to simulate queue formation in front of locks and movable bridges.

Third, the developed model has been validated and calibrated. First the internal model components have been validated by individually checking fleet functioning, lock functioning and the emission calculations. Afterwards the capability of the model, to simulate the functioning of the fleet on the Rotterdam-Antwerp corridor, has been calibrated. Three cases have been tested, first the Base case followed by two Null-scenarios. The Base case represents the fleet in 2017. The simulation results of the Base case have been compared with IVS-90 data from Rijkswaterstaat and this shows that the model properly simulates the fleet on the corridor in 2017. The two Null-scenarios represent the situation on the corridor in 2030, for both a high and a low economic forecast. The Null-scenarios have been based on the economic forecasts of WLO (Toekomstverkenning Welvaart en Leefomgeving) developed by the Dutch PBL (Planbureau voor de Leefomgeving) and the CPB (Centraal Planbureau). The sailing patterns and the experienced congestion in the model (for both Null-scenarios) coincide with the expected situation in 2030, indicating that the model properly simulates the possible situations in 2030.

Finally, the measures have been implemented into the model. Changes in emission levels, after the implementation of the measures, resulted in changes in sailing patterns and waiting times in front of locks and bridges. The model shows that changes in sailing patterns towards the shorter Scheldt-Rhine canal influence the emission levels way more than reductions in waiting times. This results in some measures being very efficient in reducing the waiting times but not necessarily in reducing the CO_2 emission levels.

Conversion of the Bathse sluice to a lock shows promising results. Changing sailing patterns of the fleet results in a large reduction of the emission levels on the corridor. Additionally, the capacity problems at the Krammer and Kreekrak locks disappear almost completely. Implementation of this measure in the high Null-scenario resulted in a 35% CO_2 emission reduction. Additionally, waiting times decreased with 28% on the Scheldt-Rhine canal and with 48% on the Zuid-Beveland route.

The implementation of three standard vessels and time slot sailing shows immense changes in emission levels and waiting times. In this measure the fleet consisted out of three vessel classes which were generated over 24 hours evenly. This takes away the peak arrival rates of vessels during the afternoon and reduced the number of vessels on the corridor significantly. The results of all implemented measures are presented in Table 1.

Table 1: Emission level reduction for all measures

Situation:	**Bridge height increase** [%]	**Bathse lock** [%]	**Kreekrak lock removal** [%]	**High cube containers** [%]	**Standard vessels and time slots** [%]	**Sea level rise** [%]
Null-scenario low	1.3	16.5	3.5	0.18	80.8	0.66
Null-scenario high	8.25	35	1.6	0	68	0.31

Some limitations of this study should however be mentioned. The graph (network) that has been built in this study includes the waterways between the Volkerak locks towards the port of Antwerp. The fairways between Rotterdam and the Volkerak locks and the fairways towards Gent, Terneuzen and Vlissingen are not implemented.

Another limitation is the number of vessels generated in the model. The number of vessels generated each day is an average of the total number of vessels in 2017. This means that peak days are not represented in this study and model. High intensity days may show longer waiting and sailing times than presented.

Additionally, the Krammer lock has been implemented into the model in its current state. Meaning that the new salt/fresh water separating system has not yet been implemented. If the new system is implemented, the operating times at the Krammer lock could be lower than used in this study.

Preface

This research is my final step in obtaining a masters degree in Hydraulic Engineering at the TU Delft. This research has been done in collaboration with Rijkswaterstaat. Within Rijkswaterstaat multiple departments have provided intensive guidance and support in order for me to complete this project to the best of my ability. Rijkswaterstaat has given me the opportunity to work with people specialised in the hydraulic engineering field and has shown me the magnitude of hydraulic projects conducted in the Netherlands.

Throughout my studies I have faced a lot of hurdles and difficulties which I needed to overcome. One of the most challenging has definitely been this research. There have been moments where I honestly questioned myself if the completion of this thesis could be done in the given time. However, with the help of my family, friends, colleagues and supervisors I have overcome these challenges and I have now completed this thesis. I would like to express my thanks to all the people that have supported me throughout this process the last 9 months.

First, I would like to thank my daily supervisor from the TU Delft, ir. Henk Verheij. From the first day of my thesis Henk Verheij has supported and guided me throughout the process. First by getting my project from the ground, till the point where not only thesis support but also mental support was needed.

Second, I would like to thank my professor, Mark van Koningsveld, who helped me out with coding problems and kept me sharp during the entire project. The intense feedback has been overpowering at times but at the same time I could not have had a more committed and dedicated professor.

Third, I would like to thank my third supervisor from the TU Delft, ir. Rob Stikkelman, who gave me a complete different view on my project at a later stage. These insights have helped me very much with the actual writing of my thesis.

Moreover, I want to thank my supervisor from Rijkswaterstaat, Pieter Jonker, who guided me throughout the project both content wise as mentally. Who gave me the opportunity to speak with people throughout the entire organisation and get all the information I needed to complete this project.

Additionally, I would like to thank Joris den Uijl, who helped me with many of my coding problems no matter what time of the day it was. Finally, I would like to thank my parents and roommates who have motivated and supported me throughout the entire project and studies.

Leonore Vehmeijer
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1 Introduction

1.1. Background

The 2015 Paris agreement, signed by 174 countries, stimulates its participants to work towards climate neutral economies. In other words energy and emission neutral economies. Within the European Union the transport sector is aiming at a CO_2 emission reduction of 54 to 67 % in 2050. Although, transport by water was originally not part of the Paris agreement, the reduction of energy consumption and CO2-emissions by the inland shipping fleet is a growing policy. As such Rijkswaterstaat aims for its transport networks to be energy neutral by 2030 and aims for zero emission networks by 2050.

One of the main transport axis in the Netherlands is the Rotterdam-Antwerp corridor. Transportation of goods and raw materials between Rotterdam and Antwerp occurs via rail, road, pipeline and water. The focus of this research lies on the fairways in this corridor. With congestion on roads becoming an increasingly large problem and inland shipping a seemingly good and cleaner alternative, for transport of goods, a better insight in emission levels and energy consumption, on the fairways between Rotterdam and Antwerp, can be very useful.

The fairways between Rotterdam and Antwerp comprise two main canals for commercial shipping: the Scheldt-Rhine and Zuid-Beveland canal. The Zuid-Beveland canal is the oldest of the two and connects the Oosterschelde and Westerschelde. In the twentieth century this was one of the busiest canals of Europe until Antwerp insisted on a better connection between the Port of Antwerp and the Rhine. This resulted in the construction of the Scheldt-Rhine canal which opened in 1975. In Figure 1.1 the Zuid-Beveland route and Scheldt-Rhine route are highlighted. Starting at the Volkerak locks all the way towards the port of Antwerp.

Scheldt-Rhine route

The Scheldt-Rhine canal is tide free, and is characterised by one lock (Kreekrak lock) and eight fixed bridges. These fixed bridges result in an air draught of 8.7 m. The shorter Scheldt-Rhine route was originally meant to become the most important transport route for commercial shipping from Antwerp to the Rhine and Rotterdam. However, because of the height restrictions on the route, large 4-layer container vessels are forced to take the longer Zuid-Beveland route. In 2017, 68,500 vessel passages where counted on the Scheldt-Rhine canal of which about 15% where container passages (Rijkswaterstaat, 2017a). The large share of container vessels in this part of the fleet is mainly caused by the fact that Rotterdam and Antwerp are both important containers ports in the area. Research shows that about 5% of container vessels, with destination or origin Antwerp, is forced to take the longer Zuid-Beveland route because of the height restriction on the Scheldt-Rhine route (Arcadis, 2016).

In 2016, Arcadis performed a social cost-benefit analysis (SCBA-2016) on the increase of the bridge heights on the Scheldt- Rhine canal and of the Moerdijk bridges. Practically, all discussed scenarios resulted in a negative advise for the increase of the bridge heights. However, for the Global Economy forecast in combination with the scenario where the Moerdijk bridges are excluded from the calculations, the cost-benefit analysis turned out positive (Arcadis, 2016). The Moerdijk bridges are out of the scope of this research but shown in in Figure 1.1.

This SCBA-2016 was based on the previous WLO 2006-2010 scenario's. The SCBA-2016 was superseded by a new SCBA-2018, based on the WLO-2015 scenarios. Herein all bridge-height-increases in all economic growth scenario's resulted in hefty negative results.

Apart from the height restriction on the Scheldt-Rhine route, the Kreekrak locks are becoming increasingly problematic for the inland shipping fleet. The waiting times are on average 20 minutes and passage times have become around 36 minutes. Research shows that for high economic scenarios the Kreekrak locks will have waiting times of 30 minutes and higher by 2030 (Rijkswaterstaat, 2017a). Currently the Kreekrak locks consist of two lock chambers. Extension to a third lock chamber is possible, there are however other options. The main function of the Kreekrak locks is to prevent the salinisation of the Zoommeer. If an alternative is found for the prevention of the salinisation of the Zoommeer, the entire removal of the Kreekrak locks could be an option which takes away the expected capacity problem.

Relevant to mention is that parallel to the Scheldt-Rhine canal, the Bathse canal and sluice are located. The canal and sluice are currently not in use for shipping but function as flushing canal for the salt water surplus from the Zoommeer. Research has been conducted on the conversion of the Bathse sluice to a full shipping lock. This research concluded that in order to reduce the expected capacity problem at the Kreekrak locks the development of the Bathse lock is an interesting alternative, which could reduce the transported weight at the Kreekrak locks by 22% (Gideonse, 2008). Additionally, this research concluded that in depth study on durability and emissions is necessary for final decision making.

Zuid-Beveland route

The Zuid-Beveland route consists of three movable bridges and two locks (Krammer and Hansweert locks). On the Scheldt-Rhine canal there are no tidal influences but the Zuid-Beveland canal does experience the influence of the tide. The Zuid-Beveland route is mainly used for transport of bulk and general cargo between Rotterdam and Vlissingen, Gent and Terneuzen. However, because of the height restriction on the Scheldt-Rhine route more and more large container vessels have to take this longer route towards and from Antwerp. In 2017, there where 40,000 commercial vessel passages on the Zuid-Beveland route of which about 5% container passages (Rijkswaterstaat, 2017a).

The Hansweert locks provide fast passage, and are expected to do so in the future as well, the Krammer locks have capacity issues. The Krammer locks have a salt/fresh water separating system in their lock operation resulting in operating times of 30 minutes (Bückmann, 2009). This results in average waiting times of 30 minutes and passage times of 60 minutes (Rijkswaterstaat, 2017a).

Where the Scheldt-Rhine canal has fixed bridges, the bridges on the Zuid-Beveland canal are movable. Most 4-layer container vessels are currently able to pass the bridges even when they are closed. The new, high-cube containers are however expected to replace most containers that are currently in use (Brolsma Advies, 2015). This will result in more vessels having to wait before the bridges on the Zuid-Beveland canal to be opened before passage is possible.

Figure 1.1: Research area with traffic routes

1.2. Problem description

Rijkswaterstaat aims for its transport networks to be energy neutral by 2030 and aims for zero emission networks by 2050. In order to reach energy neutrality, there should be proper understanding of the energy consumption of the entire fleet. Additionally, the importance of factors influencing the energy consumption should be known. Until now, no research has been conducted on energy consumption patterns of the entire fleet on the Rotterdam-Antwerp corridor.

Energy neutrality can be achieved by assuring that the energy consumption of a network equals the amount of renewable energy generated. On the Dutch waterways, large contributors to the energy consumption are the vessels sailing over the networks. In reaching energy neutrality a good understanding of where, when and how much energy is consumed is important. The in Section 1.1 mentioned developments and changes in corridor layout can influence the sailing patterns and sailing times of the fleet. In order to become energy neutral and a zero emission corridor by 2050, proper understanding of emission patterns and therefore fleet behaviour on this corridor is necessary.

Until now, no research has been conducted on measures (that can be implemented in the corridor or fleet) that could reduce the energy consumption and therefore the emission levels of the fleet on the Rotterdam-Antwerp corridor. The lack of data makes it more difficult for Rijkswaterstaat to work towards energy neutral and zero emission operating networks.

1.3. Objective and scope

1.3.1. Objective

The main objective of this research is to establish which measures are significant in reducing the CO_2 emission levels on the waterways between Rotterdam and Antwerp, in particular the Zuid-Beveland and the Scheldt-Rhine routes. A model will be developed that simulates the sailing patterns and congestion points on the corridor. This tool should provide better understanding of the energy consumption and subsequently emission levels of the fleet on the Rotterdam-Antwerp corridor. By implementing different measures into the developed model, insights can be obtained on what measures could significantly reduce the emission levels on the corridor. Additionally, the implementations of the measures can provide insight on what factors are most important in reducing CO_2 emission levels on the corridor.

1.3.2. Scope

The fairway between Rotterdam and Antwerp has an important bifurcation just after the Volkerak locks. This allows vessels to take the Scheldt-Rhine or Zuid-Beveland route. This is the only point on the corridor that allows shippers to make a choice for a certain route. As the aim of this research is to identify sailing patterns and the influence of these patterns on the production of CO_2 emissions, the bifurcation point is relevant. This means that the geographic area of this study starts at the Volkerak locks, continues via the two routes (Scheldt-Rhine and Zuid-Beveland) and ends at the port of Antwerp (Berendrecht locks).

1.3.3. Limitations study

Measures

The measures in this study are divided into two categories, namely the infrastructural modifications and the fleet scenarios. The latter category contains scenarios related to trends which influence the fleet. It should however be noted that all scenarios, related to cleaner engine developments or alternative fuels, are not part of this research.

Model

The simulation model describes the corridor in discrete events. Fairway characteristics such as width, depth and flow of the water are assumed to be fixed for each event on the corridor. Vessel characteristics are implemented into the model via vessel classes, assuming that all vessels in a certain vessel class have exactly the same characteristics. In the model the inland shipping fleet has been implemented, so excluding pleasure crafts. Data on the number of pleasure crafts entering the model is scarce and not very reliable. Next to this, most locks in this model that do encounter pleasure crafts have separate locking chambers for pleasure crafts.

Resistance calculations

The energy consumption by vessels on the corridor is determined by calculating the resistance they encounter during sailing. The encountered resistance depends on the fairway and vessel characteristics. Vessels are incorporated into the model under vessel classes. However, each vessel has its own specific characteristics and each vessel therefore has its own specific resistance. It is assumed that using representative vessels, in the form of vessels classes, leads to a good approximation of the resistance. Additionally, the water depth plays an important role in determining the resistance. On the Zuid-Beveland route tide plays a role and thus the water levels and subsequently the water depths on this route are continuously changing and influencing the resistance encountered. The resistance for this route has been determined using average water levels and does not incorporate the dynamic effect of the tide on the resistance.

1.4. Research question

After defining the problem and establishing the scope and objective, the following research question is defined:

What measures will contribute to the reduction of the CO_2 *emissions, by the inland shipping fleet, on the Rotterdam-Antwerp corridor, in specific the Zuid-Beveland and Scheldt Rhine route?*

To find an answer to the research question multiple sub questions are defined. The sub questions are listed below:

1. **Characteristics and data:**

   What information on fleet, corridor and emission data is needed to be able to determine the CO_2 emission levels on the Rotterdam-Antwerp corridor?

2. **Model setup:**

   How can a model be developed that simulates the traffic flows on the Rotterdam-Antwerp corridor in the current state, possible future states and have the ability to determine the accompanied emission levels?

3. **Base case (2017) and economic fleet forecasts 2030 (Null-scenarios):**

   Can the levels of CO_2 emissions for the Base case and the Null-scenarios be simulated and what are the corresponding levels of CO_2 emissions?

4. **Measure implementation:**

   What are the effects of implementing measures on the CO_2 emission levels and what are the impacts of these implementations?

1.5. Methodology

To fulfill the main objective of this research, this section outlines the method of approach. Each item mentioned below is carried out to first answer the sub questions of this research after which the main research question can be answered.

1. **Data collection:**

   Analysing energy consumption and emission patterns is only possible if information on how they can be defined and calculated is obtained. Information should therefore be gathered on fairway and fleet characteristics. Sailing patterns and characteristics of the fleet should be defined. Additionally, information should be obtained about the functioning of objects such as locks and bridges on the corridor. This should all be done for the current situation and the expected situation in 2030.

   Once this information has been obtained, the energy consumption of individual vessels can be determined. Literature study should therefore be done on what components are most important in determining the energy consumption and emission levels of vessels. Completing this section will results in answering sub question 1 of this research.

2. **Model setup:**

   In order to determine the emission levels of the entire fleet a model will be built. First existing model concepts should be evaluated after which appropriate concepts can be found for this study. Once the concepts of the model have been defined, the requirements the model should fulfill should be elaborated. The model should be able to represent the current situation and that in 2030. The base cases implemented into the model can therefore be divided in the following categories.

   Base case: The case that simulates the corridor and the fleet in 2017.

   Null-scenario low: The case that simulates the corridor and the expected sailing patterns of the fleet in the low economic scenario for 2030.

   Null-scenario high: The case that simulates the corridor and the expected sailing patterns of the fleet in the high economic scenario for 2030.

By developing a tool that can simulate the activities on the corridor and the related emission levels, the second sub question of this research is answered.

3. **Calibration and validation:**

   Once the model is built the Base case and the Null-scenarios should be validated. This can be done by first validating the functioning of individual components in the model. After which the simulation results of the Base case can be compared with the IVS-90 measuring data of Rijkswaterstaat. Additionally, Rijkswaterstaat has performed studies on the expected size, congestion and sailing patterns of the fleet in 2030 (for a high and low economic scenario). The results of these studies will be compared to the simulation results of the Null-scenarios in order to check whether the model simulates the possible situations in 2030 properly. Once this is done the third sub question of this research can be answered.

4. **Application:**

   To answer the last sub question of this research the measures that might influence the emission levels on the corridor should be implemented and analysed. The measures that should be implemented into the model are presented below.

   (a) Infrastructure modifications
      i. Increase of the bridge heights on the Scheldt-Rhine canal
      ii. Conversion Bathse sluice into a lock
      iii. Removal Kreekrak locks

   (b) Fleet scenarios
      i. Fleet with high-cube containers
      ii. Standard vessels and departure slots
      iii. Sea level rise

   Once all the measures are implemented into the model the effects of the measures on the emission levels can be analysed. Additionally. the results should provide insights on which factors play an important role in reducing the emission level of an entire fleet. This section therefore answers the fourth sub question of this research.

1.6. Contribution to science and practice

This research makes a contribution to science and its field of practice in multiple ways. First, until now no research has been done on the emission levels and patterns of an entire fleet. There is some research on how to determine the energy consumption of individual inland vessels (Bolt, 2003) and what happens with the emission production when vessels are in lock and bridge areas (Hulskotte, 2011). However, the combination of the above proposed research to a full emission model and fleet analysis is new.

Second, the developed tool supports the decision making on what measures could contribute to the reduction of emission levels and congestion on this corridor. Additionally, the tool helps in getting a better understanding on what factors play a role in reducing emission levels. This can provide guidance for traffic management decisions made by Rijkswaterstaat.

Until now, Rijkswaterstaat has two models that can analyse the fairways, namely SIVAK and BIVAS. SIVAK has its focus on traffic settlement at objects such as locks and bridges and BIVAS focuses on network analysis. The tool that is developed in this research is easy accessible, adaptable, universal and thus usable for any fairway one chooses. BIVAS has integrated emission calculation formulas in her model. However, the model is written in difficult and a bit outdated programming language and implementing new scenarios and features is therefore difficult and can take a lot of time. Next to this the model developed in this research focuses on emission patterns whereas both BIVAS and SIVAK have other priorities. The developed tool can therefore provide new inputs for the already existing tools at Rijkswaterstaat.

1.7. Reading guide

The report is divided in 6 Chapters which are in turn divided into Sections and Subsections. Every Chapter answers one of the sub questions from Section 1.4. Chapter 2 answers the first sub question by analysing and outlining all the data needed for the emission calculations. Chapter 3 analysis the possible model types and concepts based on the requirements the model should fulfill. After which the base cases, Section 1.5, of this study are implemented. Chapter 4 validates individual model components and calibrates the simulation outcomes of the base cases implemented. Chapter 5 analyses the results of the measure implementation into the model. This Chapter thereby answers the final sub question of this research. Chapter 6 answers the research question by giving a conclusion on the findings of this study, discussing limitations and by giving recommendations for future studies. In Figure 1.2 below the reading guide is presented.

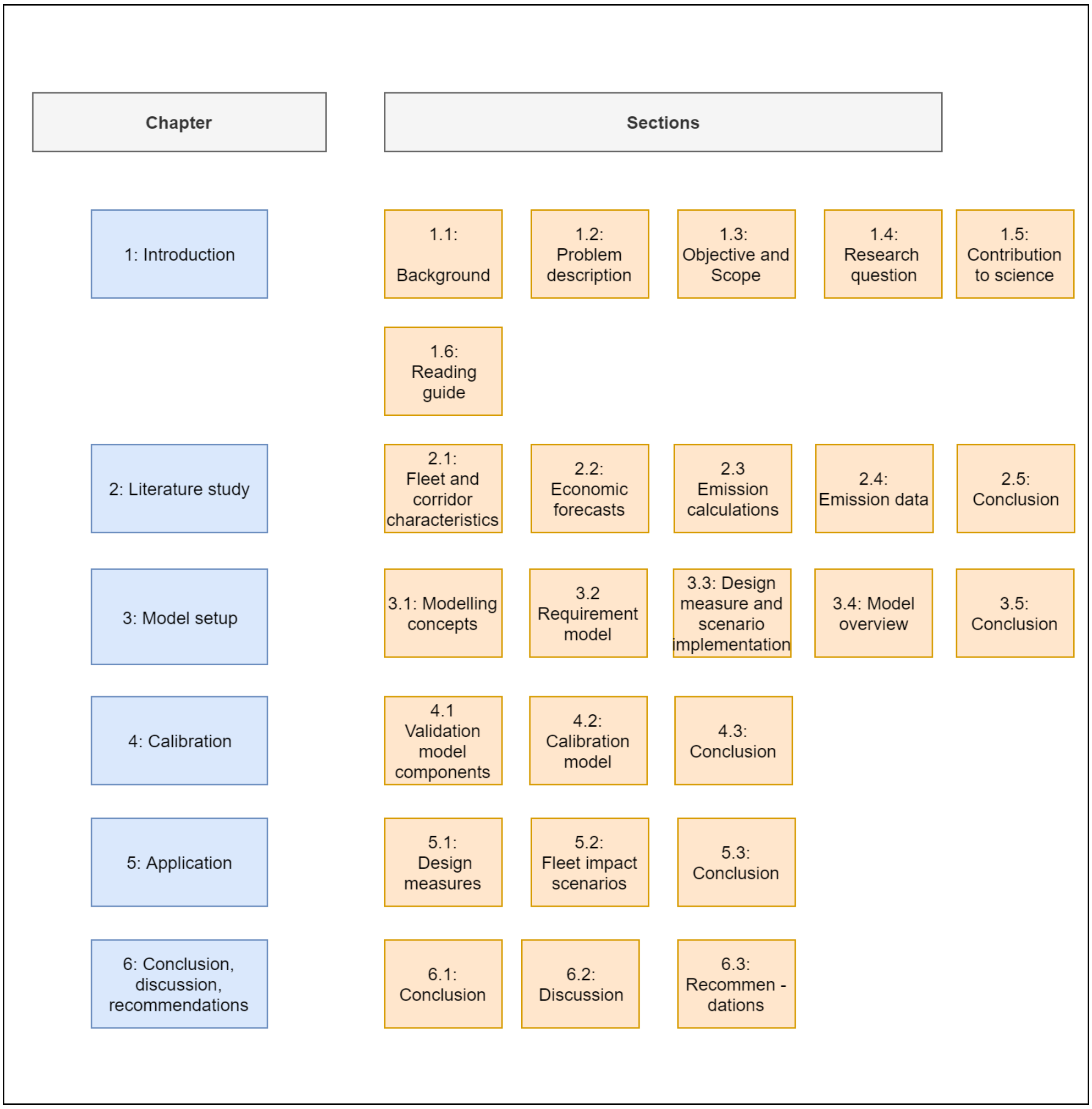

Figure 1.2: Reading Guide

2

Data collection

This Chapter answers the first sub question of this research:

What information on fleet, corridor and emission data is needed to be able to determine the CO_2 emission levels on the Rotterdam-Antwerp corridor?

To answer this question the Chapter is divided into 5 main Sections. Section 2.1 analysis the characteristics of the fleet and the corridor, that influence the emissions produced by the fleet. Section 2.2 analysis the economic forecasts of the corridor in 2030. Section 2.3 and 2.4 focus on the actual energy consumption and emission Equations for single vessels. Section 2.5 finalises this Chapter by answering the first sub question of this research.

2.1. Fleet and corridor characteristics

This Section outlines the characteristics, of the fleet and the corridor, that determine the emission levels produced by the fleet. Two important parameters in determining CO_2 emissions are the sailed distance and the speed with which vessels sail (Hulskotte & Bolt, 2012). From this it follows that to determine the emission levels of an entire fleet the size, type and sailing patterns of vessels should be known. Total distance and sailing times also depend on fairway characteristics such as available routes and objects such as locks and bridges. The network characteristics and fleet characteristics of this corridor should therefore be known.

Subsection 2.1.1 analysis the fairways on the corridor and Subsection 2.1.2 outlines all the important fleet characteristics.

2.1.1. Fairway characteristics

As has been mentioned in Chapter 1 the focus of this research lies on the commercial fairways between Rotterdam and Antwerp. In specific the fairways between the Volkerak locks and the port of Antwerp. In Figure 2.1 the fairways studied are shown. The two main routes are the routes via the Scheldt-Rhine canal and the Zuid-Beveland canal which are both VIb canals (Rijkswaterstaat, 2013). Meaning that both canals should be able to provide passage to the largest inland vessels in the CEMT or RWS (as used in this research) classification. In Section 2.1.2 the specific characteristics per vessel class are explained in more detail.

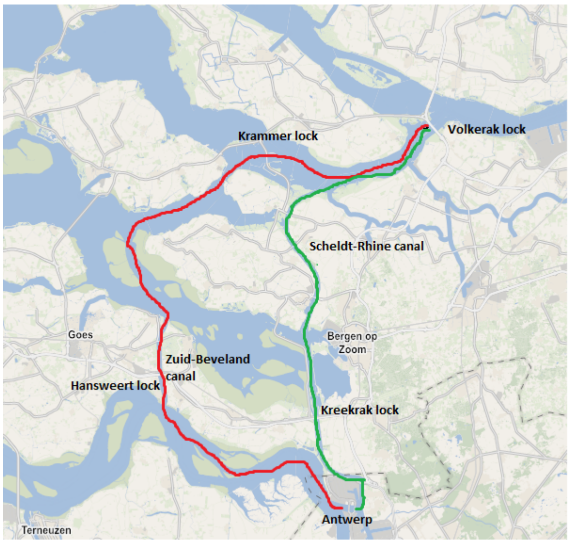

Figure 2.1: Fairways between Volkerak locks and Antwerp

Zuid-Beveland route

The Zuid-Beveland route is the longest of the two routes studied. From the Volkerak lock about 80 kilometers have to be covered to reach to port of Antwerp. Other than the Scheldt-Rhine route the Zuid-Beveland route is only partially a canal. The Zuid-Beveland canal itself connects the Westerschelde with the Oosterschelde. The other parts of the route have varying characteristics. The first part of the route lies between the Volkerak locks and the Krammer locks, named the Volkerak. This part of the route is tide free and has a fixed water level during the year. The Oosterschelde and Westerschelde, which are also crossed taking this route, do feel the influence of the tide. The tide causes changes in water depth on this part of the route. The dynamic water depth however does not create a tidal window for specific vessels forcing them to wait for high tide to continue their journey. In extreme cases the water depth on the route becomes 4.75 m. This navigable depth is enough for the largest vessels in the fleet the pass the route without hindrance. Other effects of the tide on the research will be discussed in more detail in Section 2.3.

The Zuid-Beveland route contains two locks and three movable bridges. Both locks on the Zuid-Beveland route have two lock chambers for commercial shipping. Other than the Hansweert lock the Krammer lock has a separate lock chamber for pleasure crafts, completely separating commercial shipping from pleasure crafts. In Table 2.1 the data of the locks and bridges on the Zuid-Beveland route are presented.

Table 2.1: Characteristics Zuid-Beveland route (Rijkswaterstaat,2018)

Object or fairway	Width [m]	Depth [m]	Air draught [m]	Lenght [m]
Volkerak	-	6	-	-
Krammer lock (2)	24	4.8 - 6.5	-	280
Oosterschelde	-	4.8 - 6.5	-	-
Zuid-Beveland canal	200	4.8 - 6.5	-	9000
Post bridge (N670)	200	4.8 - 6.5	9.10	10
Vlake bridge (N289)	200	4.8 - 6.5	9.10	10
Vlake railbridge(A58)	200	4.8 - 6.5	9.10	10
Hansweert lock (2)	24	4.8 - 6.5	-	280
Westerschelde	-	4.8 - 6.5	-	-

The two locks mentioned in Table 2.1 have the same capacity but have different waiting and passage times. The number of commercial passages per year at both locks are however almost the same. The difference is due to the fact that the Krammer locks has a salt and fresh water separation system in its lock operation. This results in longer operating times and thus longer waiting and passage times for vessels. A new salt and fresh water separating system will most probably be installed at the Krammer locks and it is expected that this will reduce the passage times at the Krammer locks with about 16 minutes, taking away the growing capacity problem at the Krammer locks (Poortvliet & Boeters, 2014). In Table 2.2 the waiting and passage times of the Hansweert and Krammer locks are given. The numbers between brackets show the expected passage and waiting times. at the Krammer locks, with the new salt and fresh water separating system in place.

Table 2.2: Passage and waiting times at locks on Zuid-Beveland route

Name	Average waiting time [min]	Average passage time [min]
Krammer locks	30 (17)	60 (33)
Hansweert locks	12	23

The model should be ably to simulate the general functioning of the Krammer and Hansweert locks. Consequently, it should be able to express the different operating and therefore the different waiting times correctly.

Scheldt-Rhine route

The Scheldt-Rhine route is the shorter route of the two and from the Volkerak about 50.5 kilometers need to be covered to reach the port of Antwerp. The Scheldt-Rhine canal itself is about 38 kilometers long and is completely tide free (Rijkswaterstaat, 2018). The route consists of eight fixed bridges and one lock, the Kreekrak locks (Brolsma Advies, 2015).

Bridges on Dutch fairways for commercial shipping are expected to meet the requirements set by Structuurvisie Infrastructuur en Ruimte (SVIR). The SVIR states that main fairways (connecting seaports to hinterland) should be able to provide passage to vessels in Va vessel classes and 4-layer container vessels. This results in minimum width, depth and height requirements for main waterways. The minimum air draught requirements are based on the CEMT classification of bridge heights from 1992. This classification states that bridges should have a minimum air draught of 9.1 meter, if the fairway allows 4-layer container vessels to pass. The Scheldt-Rhine canal is a VIb canal and should, according to the SVIR, have fixed bridges with an air draught of at least 9.1 meter (Ministerie van Infrastructuur en Milieu, 2012).

The Scheldt-Rhine canal can be separated into two parts. The first part is the one between the Volkerak locks and the Kreekrak locks. This part of the canal has three bridges with an air draught of 9.1 meter. This part of the canal meets the SVIR height requirements. Just before the Kreekrak locks this canal has a bifurcation point. This results in the Bathse sluice canal parallel to the Scheldt-Rhine canal. The Bathse canal is currently not used for shipping and is therefore not disscussed in more detail in this section. The second part of the canal lies between the Volkerak locks and the port of Antwerp. This part of the canal contains five bridges. The lowest bridge has an air draught of 8.7 meters. Therefore this part of the Scheldt-Rhine canal does not meet the SVIR requirements. In Tables 2.3 and 2.4 the characteristics of the Scheldt-Rhine canal are presented.

Table 2.3: Characteristics Scheldt-Rhine route (Rijkswaterstaat,2018)(Brolsma Advies, 2015)

Object or fairway	Width [m]	Depth [m]	Air draught [m]	Lenght [m]
Volkerak - Scheldt-Rhine canal	-	6	-	12500
Scheldt-Rhine canal upper part	120	6	9.1	24000
Scheldt-Rhine canal lower part	120	8	8.7	14000
Slaak bridge (N257)	120	6	9.1	10
Vossemeer bridge	120	6	9.1	10
Tholense bridge (N286)	120	6	9.1	10
Kreekrak lock (2)	24	6	8.9	320
Kreekrak bridges (N289)	120	6	8.7	10
Kreekrak railbridge	120	6	8.7	10
Kreekrak bridge (A58)	120	6	8.7	10
Bathse bridge	120	6	8.7	10
Noordland bridge	120	6	8.8	10

Table 2.4: Passage and waiting times at lock on Scheldt-Rhine route

Name	Average waiting time [min]	Average passage time [min]
Kreekrak lock	20	36

Lock capacities

To be able to determine the I/C ratio's (ratio Intensity-Capacity) of the locks on the corridor, the available capacity of the locks should be determined. The I/C ratio is a ratio that shows the level of used capacity in locks compared to the existing capacity of the lock. As a result, the hindrance the fleet experiences from passing the lock can be measured by the level of the I/C ratio. When this ratio increases the delay times will increase proportionally (Goffin et al., 2009). In practice this means that when the ratio exceeds the 0.5 problems can occur on short notice. A ratio of 0.5 (or higher) most probably will result in waiting times exceeding the maximum allowed 30 minutes. This number is based on the NoMo-/SVIR criterion (Rijkswaterstaat, 2017a).

To be able to determine the I/C ratios at the locks first the available capacity per lock should be determined. This is done by using the general equations for lock capacities (Ministerie van Verkeer en Waterstaat, 1999). Equation 2.1 shows the locking duration for both upstream and downstream direction.

$$T_d = T_i + T_b + T_u \tag{2.1}$$

T_d = locking duration upstream or downstream [min]
T_i = entry time = $t_l + \sum t_i$ [min]
T_b = operating time [min]
T_u = total leaving time = $\sum t_u$ [min]
t_l = loop time [min]
t_i = individual entry time [min]
t_u = individual leaving time [min]

Loop time represents the time that elapses between the moment that the last ship leaves the lock and the moment at which the first ship enters the lock (Ministerie van Verkeer en Waterstaat, 1999). The locking duration can be different for loaded and empty vessels. This is caused by the fact that loaded vessel often need more entry and leaving time than empty vessels. The locking duration can therefore be represented by Equation 2.2.

$$T_d = \lambda * T_{d.loaded} + (1-\lambda) * T_{d.empty} \tag{2.2}$$

λ = share of loaded vessels

The total cycle time of the lock operation consists of the lock duration upstream and downstream. The equation for the total cycle time of the lock operation is presented in Equation 2.3

$$T_c = T_{d.upstream} + T_{d.downstream} \tag{2.3}$$

T_c = total cycle time of lock operation [min]
$T_{d.upstream}$ = lock duration in upstream direction (including operating time) [min]
$T_{d.downstream}$ = lock duration in downstream direction (including operating time) [min]

Once the total cycle time of the lock operation is known, the capacity of the lock can be determined. There are two, often used, representations of the lock capacity. The capacity in vessels per hour and in loading capacity per hour. Equations 2.4 and 2.5 show how the capacity of a lock can be determined.

$$T_s = \frac{n * 2 * N_{max}}{T_c} \tag{2.4}$$

T_s = capacity lock [vessels/hour]

$$T_s = \frac{n * 2 * N_{max} * L_{loading}}{T_c} \tag{2.5}$$

T_s = capacity lock [ton capacity/hour]
$L_{loading}$ = average loading capacity vessels in fleet [ton]

n = number of chambers [-]
N_{max} = maximum number of vessels fitting in a lock chamber [-]

By using the above presented formulas the capacities of the locks on the corridor can be determined. Appendix A presents the data used to determine the capacities of the Krammer, Hansweert and Kreekrak lock. To determine the capacity in ton per hour the average loading rates of the fleet should be known. The average loading capacity on the corridor is 1630 ton per vessel. This will be further explained in the Section 2.1.2, fleet characteristics. The results of the capacity calculations are presented in Table 2.5.

Table 2.5: Capacity locks on corridor

Lock	**Capacity [vessels/ hour]**	**Capacity [capacity in ton/ hour]**
Kreekrak	20	32600
Krammer	9	14670
Hansweert	15	24450

Once the model is developed, the intensities at the locks can also be obtained. In combination with the capacities of the locks the I/C ratio's per lock can be determined. After implementation of the design measures and scenarios, the changes in I/C ratio's can be a useful analysing tool. It can not only provide better insights on changing waiting times but also show the effects of changing waiting times on the total emission levels on the corridor.

It can be concluded that, in order to determine the emission levels on this corridor, the model should be able to simulate the Zuid-Beveland and Scheldt-Rhine route and it should be able to simulate the lock operations on both routes. To get a proper understanding, of what factors influence the emission levels, it should additionally be possible to determine the intensities on both fairways from the model results. The intensities mainly depend on the fleet size and distribution and this is therefore further analysed in Section 2.1.2.

2.1.2. Fleet characteristics

The inland shipping fleet sailing on the corridor contains many different types of vessels carrying all kinds of cargo that need transportation. The vessels on the corridor are divided into vessel classes. These classes contain the standard vessel characteristics. Accordingly, the vessels sailing on the corridor are implemented into the model using these vessel classes. As has been mentioned in Section 2.1.1 both the Scheldt-Rhine and Zuid-Beveland route are classified as VIb fairways. On VIb fairways the largest vessel dimension allowed is 200 x 23.5 x 4.75 m (ECORYS, 2008). In total there are 28 vessel classes sailing on the corridor studied. The 28 vessel classes can be divided in loaded and empty vessels. This results in a total of 56 vessel possibilities on the Rotterdam-Antwerp corridor. In Table 2.6 the fleet characteristics per vessel class are presented.

Table 2.6: Vessel classes and characteristics (Rijkswaterstaat,2010)

Vessel class	Length[m]	Width [m]	Draught loaded [m]	Draught empty [m]	Height [m]	Height high cube containers [m]
BI	90	9.5	3	0.4	7	7.97
BII-1	110	11.4	3.5	0.4	7	7.97
BII-2b	145	22.8	4	0.4	9.1	10.42
BII-2L	190	11.4	4	0.4	9.1	10.42
BII-4	195	22.8	4	0.4	9.1	10.42
B01	55	5.2	2.6	0.4	5.25	5.36
B02	70	6.6	2.6	0.4	6.1	-
B03	80	7.5	2.6	0.4	6.4	-
B04	85	8.2	2.6	0.4	6.6	-
C1b	38.5	10.1	2.2	0.5	5.25	5.36
C1L	80	5.05	2.2	0.8	5.25	5.36
C2b	105	19	3.5	0.8	7	7.97
C2L	185	9.5	3.5	0.8	7	7.97
C3b	110	22.8	3.5	0.8	9.1	10.42
C3l	190	11.4	3.5	0.8	9.1	10.42
C4	185	22.8	3.5	0.8	9.1	10.42
M1	38.5	5.05	2.5	0.5	5.25	5.36
M2	55	6.6	2.6	0.6	6.1	-
M3	70	7.2	2.6	0.7	6.4	-
M4	73	8.2	2.7	0.7	6.6	-
M5	85	8.2	2.7	0.7	6.4	-
M6	85	9.5	2.9	0.8	7	7.97
M7	105	9.5	3	0.8	7	7.97
M8	110	11.4	3.5	0.8	9.1	10.42
M9	135	11.4	3.5	0.8	9.1	10.42
M10	110	13.5	3.5	0.8	9.1	10.42
M11	135	14.2	3.5	0.8	9.1	10.42
M12	135	17	3.5	0.8	9.1	10.42

Table 2.6 shows the heights for standard containers and for high-cube containers. These heights have been determined based on the loading rates of container vessels. Research and measuring data show that the loading rates of container vessels lie around 65% of the total capacity (Arcadis, 2016) resulting in the total heights presented in 2.6. The required air drafts have an exceedance rate of 1% per year relative to high water levels. The difference between the two container types is discussed in more detail in Chapter 3, Model setup.

As has been mentioned above the loading rates of container vessels equal 65% of the total capacity. Other vessels not carrying containers have higher loading rates. On the Rotterdam-Antwerp corridor the average loading rates, of a loaded vessel carrying bulk or general cargo, lies around 70 % . Apart from loading rates, vessels can also sail empty. 35% of the entire fleet sails empty and 65% sails loaded (Goffin et al., 2009). To properly simulate the fleet, vessel classes and the related loading rates should therefore be implemented into the model.

Next to loading rates and characteristics of vessel classes the size of the fleet on the corridor is important. Approximately 108500 vessels passed the Volkerak locks in 2017 (Rijkswaterstaat, 2017a). From the Volkerak locks the vessel can choose between the Zuid-Beveland route or the Scheldt-Rhine route. In this research, the choice for one of the two routes is based on the destination of the vessels and the height restriction on the Scheldt-Rhine route. The most important transport flows on the corridor are between the large ports in the area. The most important cargo flows are between Rotterdam and Antwerp, Rotterdam and Terneuzen/Gent and Antwerp and Germany. Container transport flows play the largest role on the Scheldt-Rhine canal as both Rotterdam and Antwerp are important ports for container transshipment in the area. Almost 15% of all passages at the Kreekrak locks are container vessel passages. Only 5% of all passages on the Zuid-Beveland route are container passages (Arcadis, 2016). Mainly caused by the maximum air draught of 8.7 meters on the

Scheldt-Rhine route which forces loaded 4-layer container vessels to take the longer Zuid-Beveland route. In Table 2.7 the total number of passages and the share of container passages at the Volkerak, Krammer and Kreekrak locks is presented.

Table 2.7: Total number of passages (Rijkswaterstaat,2017)(Arcadis,2016)

Location	Total number of passages [year]	Fraction of which container vessels [year]	Total number of passages [day]	Fraction of which container vessels [day]
Volkerak locks	108500	12467	297	34
Krammer locks	40000	2056	110	7
Kreekrak locks	68500	9834	188	27

Around 35% of the total amount of bulk and general cargo transported over the corridor has a destination or origin other than Rotterdam or Antwerp. The largest part of these vessels has origin or destination Terneuzen, Gent or Vlissingen. This part of the fleet chooses the Zuid-Beveland route (ECORYS, 2008). Taking into account the 5% container vessels on this route, around 40% of the entire fleet takes the Zuid-Beveland route (Rijkswaterstaat, 2017a). The other 60%, with destination or origin Antwerp takes the Scheldt-Rhine route. In Figure 2.2 below the cargo weight distributions over the corridor, together with the vessel distributions over the corridor is given.

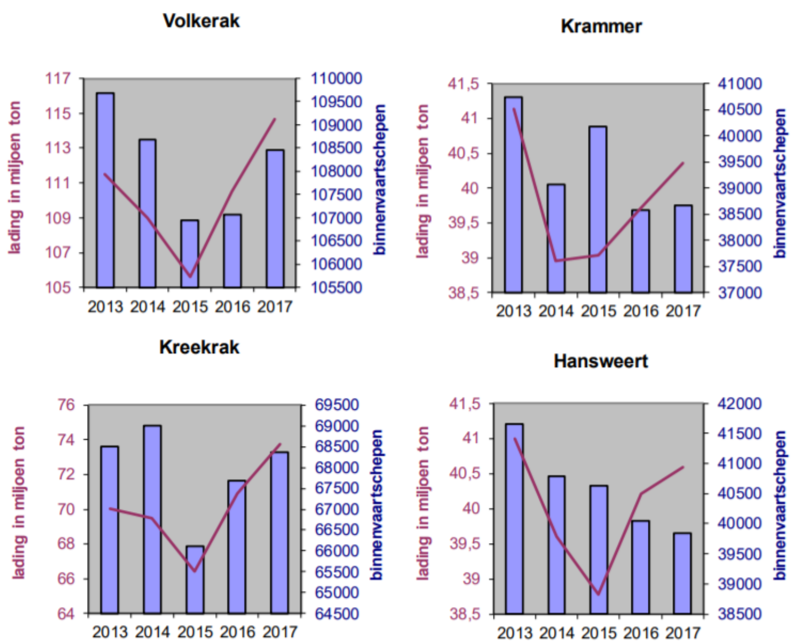

Figure 2.2: IVS-90 data for locks on Rotterdam-Antwerp corridor (Schefferlie,2017)

An observation that can made is that the number of vessels at the Krammer and Hansweert locks is quite similar. At the Krammer locks, 39,478 vessels passed in 2017 (Schefferlie, 2017). At the Hansweert lock 40,220 vessel passages are measures in 2017 (Schefferlie, 2017). This is a total difference of 742 vessel passages. This is a difference of 1.8 % on the total number of passages. The difference can be caused by measuring errors of the IVS-90 system or by vessels entering the corridor not using the Volkerak locks. This could be via the Roompot lock or the Grevelingen lock. As the difference is only 1.8 % and the essence of this study is to find the global CO_2 emission patterns of the fleet, assuming a closed-system on this part of the corridor seems an appropriate simplification.

Additionally, many commercial vessels passing the Volkerak locks also return to the Volkerak locks once they have reached Antwerp or other destinations such as Terneuzen. From the IVS-90 data it becomes clear that the vessel type and numbers are relatively stable over the year indicating that a large part of the fleet indeed sails back via the Volkerak locks. This can be explained by the fact that the research focuses on the Inland shipping fleet and as such the vessels of interest do not have many other opportunities than sail back via the Scheldt-Rhine or Zuid-Beveland canal.

Besides the vessel distribution over the fairway the arrival rates of vessels at the locks is important. To determine the emission levels around locks, the waiting times and passage times for each vessel should be known. In Chapter 4 the model is validated and an important aspect of this validation are the arrival rates at locks. If these rates do not fit the actual arrival rates, mistakes can be made in the emission calculations. To determine the actual arrival rates at the locks data obtained by IVS-90 is used. IVS-90 is a counting tool installed at all the important locations at fairways in the Netherlands. Although IVS-90 is not very accurate in providing specific information on vessel characteristics, it is accurate in counting vessel passages. Data of multiple days in 2017 have been combined to determine the arrival rates of vessels at the Volkerak, Krammer and Kreekrak locks in both directions.

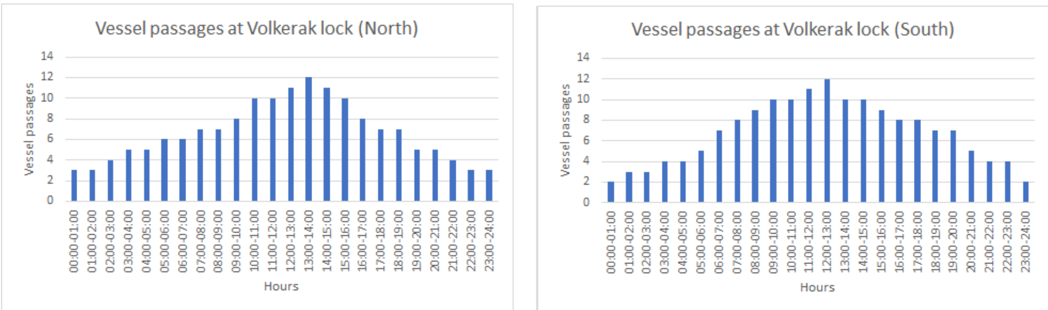

Figure 2.3: Arrival rates vessels Volkerak locks (IVS-90)

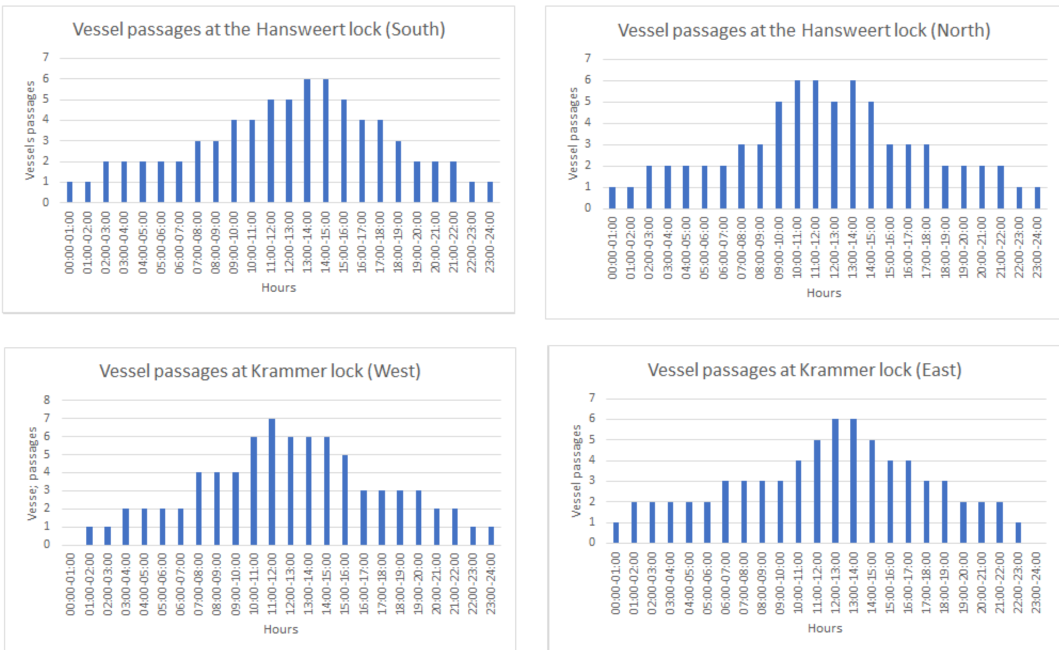

Figure 2.4: Arrival rates vessels at Krammer and Hansweert locks (IVS-90)

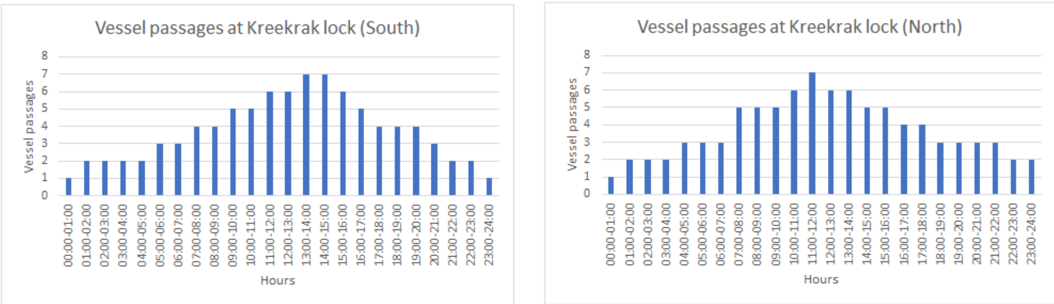

Figure 2.5: Arrival rates vessels at Kreekrak locks (IVS-90)

It can be concluded, that next to proper implementation of the vessel classes into the model, the model should represent the vessel distribution over the corridor correctly.

2.2. Economic forecasts fleet composition 2030

The measures, studied in this research, should be implemented into the corridor of 2030. Future fleet scenarios should therefore be implemented in the model. Where the Base case is used to simulate the corridor and fleet in its current state, the Null-scenarios should simulate the expected fleet size and corridor layout in 2030.

The Null scenarios represent the economic WLO (Toekomstverkenning Welvaart en Leefomgeving) forecasts developed by the Dutch PBL (Planbureau voor de Leefomgeving) and the CPB (Centraal Planbureau). These Nul-scenarios form the basic system for the implementation of the measures. The two null scenarios, namely high and low economic growth forecasts, are explained in this Section.

Based on the WLO forecasts of 2015, Rijkswaterstaat has developed two economic scenarios (high and low) for her fairways until 2040. As Rijkswaterstaat wants her transport networks to be energy neutral by 2030, 2030 is chosen as forecast year for this research.

In 2017, the total weight transported over the Rotterdam-Antwerp corridor was around 115 million ton. The 115 million ton was transported by approximately 108500 vessel passages at the Volkerak locks. In other words, 108500 sailing trips between Rotterdam and Antwerp are needed to transport this cargo size. The weight transported by the entire inland shipping fleet is expected to grow between 0.3 % and 0.8 %. The weight transported by containers is expected the grow between 1.5 % and 2.1 % per year (Rijkswaterstaat, 2017a). These numbers are based on the two WLO forecasts. It is assumed that there is a linear relation between the total increase of transported weight in the Netherlands and the transported weight on this specific corridor. The growth scenarios for this corridor until the year 2030 are given in the Table 2.8 below.

Table 2.8: Growth transported weight Rotterdam-Antwerp corridor (Rijkswaterstaat,2017)(Schefferlie,2017)

Type	**Weight 2017 (mln.ton)**	**Growth 2017-2030 low**	**Growth 2017-2030 high**	**Growth per year low**	**Growth per year high**	**Weight 2030 (mln.ton) low**	**Weight 2030 (mln.ton) high**
Container	13	21%	31%	1.5%	2.1%	16	17
Other	102	4%	11%	0.3%	0.8%	106	113
Total	115	6%	13%	0.4%	1%	121	131

The two economic growth scenarios can also be represented in fleet size. For the year 2030 the expected growth rates are expressed per route. The growth rates for the high and low economic scenarios are shown in Table 2.9.

Table 2.9: Growth number of vessels on Rotterdam-Antwerp corridor (Rijkswaterstaat,2017)

Cases:	Zuid-Beveland route	Scheldt-Rhine route	Vessels corridor
Base case	40000	68500	108500
Growth Null-scneario low	1.5%	0.5%	109700
Growth Null-scenario high	3%	1%	110500

The growth expected on the two routes results in a total fleet growth of 0.9 % in the low Null-scenario and a 1.8% growth in the high Null-scenario. The average load per vessel in the Base case is 1060 ton. Tables 2.8 and 2.9 show that the growth rates of transported cargo weight are higher than the growth rates of vessels on the fleet. Assuming that the loading rates of vessels stay the same this would indicate that the average vessel in 2030 will be larger than the average vessel size today.

2.3. Emission calculations

To be able to calculate the CO_2 emission levels on the corridor, multiple values for each vessel class need to be determined. The Equations leading to the CO_2 emission production per vessel, should therefore be implemented in the model. First, the final emission equation is studied after which the individual components needed for the CO_2 emission equation are determined.

2.3.1. $\mathbf{CO_2}$ emission calculations

There are multiple stages in which a vessel produces emissions and where the production levels of these emissions differ. Four stages are distinguished in this study. The acceleration, deceleration, stationary and average propulsion stage. In the average propulsion stage a vessels sails at its average speed. Every vessel class has a specific average speed in loaded and unloaded situations. To indicate the levels of CO_2 emissions on the corridor the produced emissions are represented in two ways. Namely, as the total amount of CO_2 produced in kg and the amount of CO_2 produced in gram per ton Km. These values can be obtained by using the following equations.

$$E = N * P_b * L/(V_v + V_w) * EF \tag{2.6}$$

E = CO_2 emissions per vessel class [kg]
N = number of vessels per vessel class [-]
P_b = requested engine power for this speed for this vessel class [kW]
L = length of route [km]
V_v = average vessel speed in this ship class, distinction made between loaded en empty vessels [km/h]
V_w = flow velocity [km/h]
EF = emission factor per vessel class [kg/kWh]

When the flow velocities do not play a role and when the calculation is done for only one vessel the formula can be written in a simplified manner. The middle part of the formula can also be expressed as the time needed to travel a certain distance. The equation can now be written in the following simplified manner.

$$E = P_b * \Delta_t * EF \tag{2.7}$$

Where Δ_t stands for the time needed to cover a certain distance. The first part of the formula is equal to the energy consumption needed to cover a distance over a certain time. The last term of the formula expresses the emission factor. This factor is a combination of fuel consumption and the emissions produced at the given consumption rate. The derivation and characteristics of both terms will be explained in more detail in following Sections.

Representing the CO_2 emissions produced in gram per ton km is a specific way to define emissions. Emissions are not only produced when cargo is transported but also when vessels sail empty. To get an indication of the emissions produced in the entire process of transportation, the emissions produced during sailing unloaded also need to be taken into account. The CO_2 emissions in gram per ton km can be expressed as shown in equation 2.8.

$$E_{tkm} = \frac{E_t}{C * D} \tag{2.8}$$

E_{tkm} = CO_2 missions [kg/tkm]
E_t = total CO_2 emissions loaded and empty vessels [g]
C = weight of transported cargo [ton]
D = sailed distance by loaded vessels [km]

2.3.2. Resistance calculations

The requested engine power can be determined by calculating the resistance a vessel encounters when sailing with a certain speed. The total resistance a vessel encounters can be divided into three types of resistance. The friction, residual resistance and the resistance encountered by limited water. The three resistance types are explained in the Sections below.

Friction

The friction resistance depends on the velocity profile in the boundary layer of the vessel. This in turn depends on the Reynolds number and the roughness of the surface area of the hull of the vessel. The friction resistance can be calculated using the friction coefficient which depends on the above mentioned parameters. The friction coefficient is dimensionless.

$$Cf = \frac{Rf}{\frac{1}{2} * \rho * V_v^2 * S} \tag{2.9}$$

Rf = friction coefficient [N]
ρ = density water [kg/m^3]
V_v = vessel speed [m/s]
S = wet surface [m^2]

The Reynolds number can in term be determined by the kinematic viscosity, ship length and the speed.

$$Rn = \frac{V_v * L_s}{\nu} \tag{2.10}$$

L_s = Length vessels in certain vessel class [m]
ν = Kinematic viscosity = $1 * 10^{-6}$ [m^2/s]
V_v = vessel speed [m/s]

Because of the mutual dependence on speed the friction coefficient is proportional to V^n. n equals one for laminar flows (small objects) and 2 for large objects. For vessels the n lies between 1.83 and 2 (Bolt, 2003). Next to this another formula, based on empirical grounds, is used for seagoing vessels to determine the friction coefficient (ITTC,2002).

$$Cf = \frac{0.075}{(\log Rn - 2)^2} \tag{2.11}$$

Combining formulas 2.9, 2.10 and 2.11 results in the expression for the friction resistance, assuming ρ equals 1000 kg/m^3.

$$Rf = \frac{0.075}{(log\frac{V_v L}{\nu} - 2)^{-2}}\frac{1}{2}\rho V_v^2 S = 37.5(logV_v L + 4)^{-2} V_v^2 S \tag{2.12}$$

The wet surface S for inland shipping vessels can be determined by assuming the vessels have a tubular form.

$$S = LB + 2LT_{gem} \tag{2.13}$$

B = width vessel [m]
T_{gem} = average draught of vessel (average of draught bow and draught stern vessel) [m]

The actual wet surface area of the vessels will be a bit larger due to the curvature of the hull and the extra surface area of the rudder. This will increase the roughness of the hull and therefore an additional allowance is added. For inland vessels the size of additional surface area, caused by for example the rudder, is proportionally much larger than the extra surface area for seagoing vessels. The share of friction on the total resistance is larger for inland vessels than for seagoing vessels as well. Seagoing vessels have higher speeds, especially compared to their length, causing the residual resistance to be more important. In calculations done for seagoing vessels 20 percent allowance is added. Taking into account the above mentioned factors the additional allowance for inland vessels on the total friction is set at 40 percent. This results in the following friction formula (Bolt, 2003).

$$Rf = 52.5(logV_vL+4)^{-2} * (LB+2LT_{gem}) * V_v^2 \tag{2.14}$$

Residual resistance

The residual resistance contains both the resistance caused by the creation of waves and the residual resistance which includes the pressure resistance caused by not ideal currents. The residual resistance is more difficult to determine, however from experience it is known that the residual resistance is about equal in size as the friction for inland vessels. Next to this the pressure resistance is proportional to the hydrodynamic pressure (Bolt, 2003). This results in the following residual resistance.

$$Rp = C_p\frac{1}{2}\rho V_v^2 A_m \tag{2.15}$$

A_m = transverse vessel cross-section ($B * T_{max}$) [m^2]
Cp = residual resistance coefficient [-]

The residual resistance coefficient depends on the speed of the vessel. Within the inland shipping fleet the variation for the resistance coefficient is however not so large. A value of 0.15 corresponds to a size for the residual resistance that will be of the same order as the friction resistance (Bolt, 2003)

Resistance by limited water

Next to friction and residual resistance an additional resistance plays a role when an inland vessel sails on limited water. In limited water situations, the resistance for the vessel increases as the flow velocities next to the vessel, increase and extra pressure resistance is created. Examples of limited water are canals, where there is a limited width of the fairway, and situations where the depth of the water is very small compared to the width of the fairway. In the case of limited width, which is the case in this research as the focus lies on the commercial shipping canals between Rotterdam and Antwerp, the theory of Schijf can be used to calculate return currents. The return currents can be added to the vessel speed, this way the increased velocities, caused by limited water, can be added to the resistance. The return current can be determined by formula 2.16 given below.

$$u = \frac{\frac{A_m}{A_c}}{1-\frac{A_m}{A_c}-F_{nh}^2}V_v \tag{2.16}$$

u = return velocity [m/s]
A_m = transverse vessel surface: $B * T_{max}$ [m^2]
A_c = cross section canal [m^2]
V_v = vessel speed [m/s]
F_{nh} = Froude number based on depth: $\frac{V}{\sqrt{gh}}$ [-]
g = gravitational acceleration [m/s^2]
h = water depth [m]

The water level decreases at the point where the ship passes. This is caused by the pressure reduction caused by the locally increased flow velocities. The water level reduction can partially be seen as an extra hydrodynamic pressure term. This is caused by the fact that the water level behind the vessel cannot immediately return to its original level due to friction losses and disruptions caused by the propeller of the vessel. The water level reduction can be determined using the formula given below.

$$z = \frac{\frac{A_m}{A_c}}{1 - \frac{A_m}{A_c} - F_{nh}^2} F_{nh}^2 h \tag{2.17}$$

The additional resistance term, due to limited water, can now be written as shown in equation 2.18 below.

$$R_z = C_z * \rho * g * z * BT \tag{2.18}$$

C_z = water level reduction resistance coefficient [-]
B = width vessel [m]
T = draught vessel [m]

It is difficult to determine the value of C_z as it is very much depended on the shape of the stern of the vessel. The value of 0.2 is used in this research (Bolt, 2003).

The total resistance on the vessel can now be determined by adding all the resistances calculated above. Adding formula 2.14, 2.15 and 2.18 results in the total resistance which will be used to determine the engine power used by the vessels on the corridor.

$$R_{tot} = R_f + R_p + R_z \tag{2.19}$$

The results of the total resistance per vessel class are presented in appendix B Section B.1.

2.3.3. Energy consumption

The energy consumption of vessels can be determined once the required engine power is known. The required engine power can in term be determined once the total resistance a vessel encounters, for a given speed, is known. The derivation of the total resistance is explained in Section 2.3.2 and it is therefore now possible to determine the requested engine power. Combining vessel speed, total resistance and efficiency losses results in Equation 2.20 for the requested engine power (Bolt, 2003).

$$P_b = 1.8 * V_v * R_{tot} \tag{2.20}$$

P_b = requested engine power [Kw]
R_{tot} = total resistance [N]
V_v = vessel speed [m/s]

The total efficiency of the propeller is about 0.55 (Bolt, 2003) which results in the 1.8 in Equation 2.20. The calculated engine power, P_b can now be used to determine the energy consumption per vessel. Equation 2.21 shows the calculation for the energy consumption.

$$E_e = P_b * \Delta_t = 1.8 * V_v * R_{tot} * \Delta_t \tag{2.21}$$

E_e = energy consumption [kWh]

The related CO_2 emissions can be calculated once the relation between the energy consumption and fuel consumption is known. This is explained in more detail in Section 2.3.4.

2.3.4. Emission factors

To determine the emission levels the emission factor per vessel class should be known. The CO_2 emission factor is a fuel dependent emission factor and can be calculated by multiplying the fuel dependent emission factor with the specific fuel consumption of the engine(Hulskotte & Bolt, 2012) (Hulskotte, 2009). The fuel dependent emission factor is equal to the CO_2 produced in grams per kg diesel. Every vessel class has slightly different specific fuel consumption as these consumption's are based on the type of motors in a vessel class. Age of engines plays an important role just like the distribution of the manufacturing year of engines within a vessel class. The specific fuel use of diesel engines lies around 200 g diesel/ kWh. Where the new engines have lower values and the older ones higher. The fuel dependent emission factor equals 3.034 g per kg diesel (Otten, 't Hoen, & den Boer, 2017). By combining the emission factors based on the age of the engines and the age distribution in each class, the emission factors per vessel class can be determined. Appendix A shows two graphs with age distribution per vessel class and a Table with the emission factors based on age of engines. Appendix B Section B.2 shows the emission factor results per vessel class.

2.3.5. Emission stages

Distinction is made between four different stages in which vessels produce emissions. These stages are the acceleration, deceleration, stationary and average propulsion stage. The average propulsion stage is the stage where the vessels sail at the average speed which is in term based on sailing loaded or empty. The emissions produced during average propulsion can be determined by using the formulas explained in Section 2.3.1. All the other stages are determined based on the outcomes of the average propulsion state.

The stationary and deceleration stage have the same emission levels. Vessels often decelerate before arriving at locks and bridges by switching the engines to stationary mode and by this letting the vessel come to a stand still. The deceleration stage therefore equals the stationary stage in emission production levels. The emission production equals 15% of the emission per time unit under the average propulsion stage. This number is based on stationary engine use and occasional adjustments (Hulskotte, 2011).

In the acceleration stage the emissions production is highest. It is assumed that during acceleration vessels use all the engine power on board to reach their average propulsion stage as fast as possible. The acceleration speed can be determined by combining equations 2.22, 2.23 and 2.24.

$$F = m * a \tag{2.22}$$

$$P_b = F * V_v \tag{2.23}$$

$$a = \frac{P_b}{m * V_v} \tag{2.24}$$

F = force [N]
m = total weight vessel [kg]
a = acceleration speed $[m/s^2]$
P_b = engine power per vessel class [W]
V_v = speed [m/s]

The total weight of the vessel depends on the vessel being loaded or empty. Loaded vessels have a mass equal to the dead weight tonnage of the vessel class they belong to. This includes the own weight of the vessel and the weight of the load the vessel can carry. Empty vessels have a mass equal to their dead weight.

2.4. Emission data

In this Section data is collected on the current emission levels of the transport sector in the Netherlands. In appendix C Section C.1 the energy consumption levels of the traffic sector in the Netherlands and Zeeland are presented. Appendix C Section C.2 shows the CO_2 emission levels in the Netherlands. Distinction is made between the CO_2 emissions in ton and the CO_2 emissions in gram per ton km. The data is collected from the climate database from Rijkswaterstaat (Rijkswaterstaat, 2017b) and the database of the inland shipping fleet (CE Delft, 2016). The data explicitly shows that energy use and CO_2 emission caused by traffic by road is much larger than the numbers produced by the inland shipping fleet and pleasure crafts together.

2.5. Conclusion

The analyses done in this Chapter are done to be able to answer the first sub question of this research. The first sub question of the research can now be answered.

What information on fleet, corridor and emission data is needed to be able to determine the current CO_2 emission levels on the Rotterdam-Antwerp corridor?

The CO_2 emission levels on the corridor can be determined by calculating the emission productions of every vessel in the fleet separately. Emission production levels for individual vessels depend on multiple variables.

Important variables are emission factors and required engine power. Required engine power is in term dependent on the total resistance encountered by the vessel. The encountered resistance depends on the characteristics of the fairway and the typical characteristics of the vessel class in which the vessel is in. As such all the important data on the fleet and the fairways has been collected and the total resistance and emission factors have been determined per vessel class.

The sailing patterns of the fleet have been determined by the factors destination and restrictions on fairways. It is now possible to determine the entire sailing distance and sailing time. With this information the energy consumption per vessel can be determined. By multiplying the energy consumption with the calculated emission factors the CO_2 emission per vessel can in term also be determined.

Additionally, data is collected on the economic forecasts for 2030. Which makes it possible not only to derive the CO_2 emission levels for vessels in the Base case but also for vessels in the Null-scenarios. With all the information obtained it is now possible to build the simulation model and determine the total energy consumption and accordingly the total level of CO_2 emission for the Base case and the Null-scenarios.

3
Model setup

This Chapter will answer the second sub question of this research.

How can a model be developed that simulates the traffic flows on the Rotterdam-Antwerp corridor in the current state, possible future states and have the ability to determine the accompanied emission levels?

This is done by first evaluating the possible model concepts and determining which are applicable for this research in Section 3.1. Section 3.2 presents the model requirements. This Section focuses on all the aspects that the model must be able to simulate. Section 3.3 explains in detail which design measures and scenarios should be implemented into the model. Section 3.4 gives an overview of the model developed. Section 3.5 summarizes the Chapter and answers the second sub question of this research.

3.1. Modelling concepts

In this Section the model concepts used in the research are outlined. The simulation model needs to be able to simulate the sailing patterns of the commercial shipping fleet on the Rotterdam-Antwerp corridor. Besides this the simulation model should be able to simulate the different propulsion stages in which a vessel is in. The energy consumption and CO_2 emission formulas should be implemented in order to obtain the energy consumption and CO_2 emission levels of the entire fleet. The model should also be able to simulate the dynamics of transport flows and therefore the formation of queues in front of locks and movable bridges.

3.1.1. Discrete or continuous modelling

The fairways between Rotterdam and Antwerp are a form of a dynamic system where different components continuously interact with each other. Such systems are often modelled using simulation models. Within simulation modelling a distinction can be made between discrete and continues simulation models. The difference between the two can be found in the way they handle changing variables over time.

In discrete models the state variables change at a countable number of points in time. These points in time are the points where events occur or changes in state. A change in state is called an event. The independent variable time can be handled with two approaches. Namely, by time-slicing and by the next-event technique (Carvalho & Luna, 2002).

Time-slicing (Discrete time): The steps in a model are predefined by equal time intervals.

Next-event technique (Discrete event): The model is only examined and updated when it is known that a state or behaviour changes. The time moves from event to event.

In continuous models the state variables change in a continuous way and not abruptly from one state to another. The continuous model therefore has an infinite number of states. A continuous system can be modelled mathematically. Its variables, which represents the attributes, are then controlled by continuous functions.

In this research a discrete event model is used to simulate the sailing patterns on the fairways between Rotterdam and Antwerp. It is important that the simulation model can simulate the behaviour of the fleet over the network and shows the related emission production of the fleet. It is therefore important that the model is able to accurately simulate the different stages a vessel can be in, without the simulation time becoming to long.

With time-slicing a fixed time interval needs to be defined in the model (Chan et al., 2017). Which would result in unnecessary calculating time for the average propulsion stage (which have a long duration compared to the other stages) and too large time intervals in the stages around bridges and locks. Added to this, the choice of time step has a large effect on the accuracy of the discrete time model. In this study it would result in the average propulsion stages to be simulated over accurate and the stages around locks and bridges inaccurate. Additionally, in general the errors from discrete event simulations are smaller than that of discrete time simulations (Buss & Al Rowaei, 2010).

In discrete event modelling the model updates once a change in state occurs. In this research a change in state equals a change in emission state. Since the states of the vessels remain the same between events, it is not necessary to include this inactive time in the model. Additionally, 108500 vessels need to be simulated which would increase the simulation time immensely when time-slicing or continues modelling would be used.

The discrete event model is chosen as it can provide accurate representations of all the emission events distinguishable in this research. It can do so without simulation time becoming to large and inefficient.

3.1.2. Level of detail

Discrete event models are often modelled using a macroscopic, microscopic approach or with a combination of the two. The three different approaches are explained in this Section.

Macroscopic approach

In the macroscopic approach traffic is simulated by assuming conservation of the number of vehicles on the road. Therefore all macroscopic traffic models are based on the continuity equation. The approach is thus based on the deterministic relationships of the flow, speed, and density. All vehicles have the same speed and vehicles leave the road at fixed points (Helbing, Hennecke, Shvetsov, & Treiber, 2001). This approach is very suitable when large areas need to be covered, for example in the case of a highway. The fairways covered in this study cover a large distance and a macroscopic model seems suitable. However, because of this generic approach the emission calculations will also be generic. This will result in outcomes that are less accurate than when single vessels are analysed.

Microscopic approach

In contradiction to the macroscopic approach the microscopic approach focuses on the individual vessels. This approach simulates the movement patterns of the individual vessel based on lane-changing and car following theories. The two most used car following theories are the stimulus response and collision avoidance model (Chan et al., 2017). Microscopic models are suitable for situations with heavy congestion conditions and geometric configurations. The level of detail does cause this type of modelling to be very time consuming and difficult to calibrate. Another downside of the microscopic approach for this study is that we are dealing with sailing patterns of vessels which do not change lanes and in general do not immediately react to behaviour of the vessel in front of them. However, the ability to model congestion areas in a proper way is interesting for this research.

Mesoscopic approach

The mesoscopic approach is a combination of the macroscopic and microscopic approach. Individual vehicles can be followed but the overall flow is governed by macroscopic features (Chan et al., 2017). The mesoscopic modelling is therefore very suitable for this research. The emission calculations are done for every individual vessel, making it very important to be able to model and follow the individual vessels and monitor the queue formation at locks at specific moments in time. However, the overall flow on the corridor is generated by features and restrictions that are applicable for every vessel in the fleet. This suites the macroscopic features of the mesoscopic model. The mesoscopic approach is therefore used in this study.

3.1.3. Static and dynamic modelling

Another distinction that can be made is between static and dynamic modelling. This section outlines the difference between the two and explains which components of the model developed are static and which are dynamic.

A static simulation model is a representation of a system at a specific moment in time. A static model therefore represents the system in equilibrium and is time-invariant. Using this type of model for the simulation of transport flows limits the simulation possibilities. In a static model a vehicle, or in this case a vessel, determines its route choice at the start of the journey. The shortest route is determined at the start and is therefore not influenced by congestion during the trip. If, for example, one would simulate the transport flows of vehicles in a city this would not be very accurate. Most vehicles probably change their route based on congestion along the way.

Changing route choices over time can only be modelled with a dynamic model. In contradiction to the static model a dynamic model takes into account time-dependent changes. It can represent the behaviour and interaction of static components in the system. This allows vehicles in the network to change their route while travelling. Both, static and dynamic components should be used to simulate the fleet on the fairways between Rotterdam and Antwerp.

Other than the example used of vehicles in a city, there are only two route options for vessels sailing between Rotterdam and Antwerp. Choosing the Zuid-Beveland route or the Scheldt-Rhine canal does not depend on changes in congestion at locks over time. The route choice should be based on destination and the height restriction on the Scheldt-Rhine canal. For a given destination a vessel has a preference for one of the two routes and only takes the other route if the height restriction does not allow the vessel to take its preferred route. A static route choice, for the vessels at the start of the journey, will satisfy this requirement.

Once the route is chosen vessels should be able to choose the correct lock chamber when they arrive at a lock with a queue. Vessels should be able to determine which queue is shortest and change their route dynamically upon arrival. A lock selection component should therefore be implemented in the model to simulate the dynamic behaviour of vessels near locks.

3.1.4. Model language and packages

Now the choice for the model concept has been made, suitable model language and packages should be determined. As has been mentioned in the Section above the model is mesoscopic and discrete event steps are used to define different stages. The model is static but will also have dynamic components. Next to this the corridor should be visualised in a proper way. Taking into account these requirements results in the following choice for a programming language.

In order to build the model packages need to be found that can properly simulate the fairways and have vessels sail over these fairways. It should be possible to see the specific location and emission state of vessels at any moment in time. Next to this the packages should be able to properly simulate congestion at locks and bridges and therefore be able to simulate queues. Python is a programming language containing packages that can simulate all these requirements.

Graph theory is used to build the fairways on the Rotterdam-Antwerp corridor. Graph theory is a mathematical theory that studies and outlines graphs. The graph is build up from a collection of nodes and edges. Where nodes can be connected by the edges. Information can be attached to the nodes and edges to make the graph a more realistic display of reality. Nodes for example contain height constrictions and edges can for example carry lock data such as width and length. NetworkX is an open source package that can create, manipulate and study functions of complex networks such as the corridor studied in this research. This package allows shortest path calculations to be made according to fairway and fleet characteristics. Next to this Rijkswaterstaat has shape-files containing data of all the fairways in the Netherlands. With Networkx it is possible to implement these shape-files and immediately create a detailed outline of the fairways studied.

Another important requirement is the ability of the model to simulate queues and gather results using discrete event simulation. SimPy is an open source, process-based discrete-event simulation package. This package is very useful as it makes it possible to model active components like vessels. Next to this it is possible to model congestion points using SimPy. As just has been mentioned this is an important aspect of the model as this makes it possible to find the contribution of queue formation and delays to the total emission levels on the corridor.

All the above mentioned, Python is chosen as the programming language. Python offers extensive support libraries as standard tools limiting the length of the codes as often used programming tasks are built in. Next to this useful packages such as SimPy and NetworkX are available in Python which are very useful tools for discrete event modelling and visualising networks.

3.2. Requirements model

In this Section the requirements the model should fulfill are outlined. This is done with three basic principles. First the network requirements are explained as this is the basis for the entire system and should therefore work perfectly. After this the requirements related to the vessels and the simulation itself are outlined.

3.2.1. Network

To be able to model the sailing patterns of the vessels and their corresponding CO_2 emissions on this corridor the network needs to be build correctly. This is done with graph theory. Simply said, a graph (G) is an ordered pair of vertices and edges. Where the vertices (V), also be called nodes, are connected via edges (E), also called lines (Wilson, 1996). The important aspects and characteristics of this model related to these nodes and edges are highlighted below.

1. **Nodes:** When the shape-files from Rijkswaterstaat are implemented into the model it forms a very large network of nodes connected by edges. Nodes can carry all the information at that geographical location. To create the proper network suitable for this research some nodes need to carry specific information. Important information that should be attached to the nodes are bridge, lock and bifurcation points. Additional characteristics of bridges and locks such as height should also be added to the nodes. As the route choice of vessels on the corridor is determined by predefined restrictions, this should all be attached information to the nodes. Concluding, nodes carry important simulation information of that specific geographical location

2. **Edges:** Edges are the connections between two nodes. Just like nodes edges can contain information. In this research edges form the fairways between nodes. Characteristics such as distance between two nodes can be added. Another important aspect are the lock chambers. Lock chambers have dimensions which should also be added to the corresponding edges. This allows the locks in the model to handle the number of vessels that fit into the lock.

3.2.2. Vessels

Now the requirements for the network have been defined the requirements related to the vessels sailing over the network should be defined.

1. **Move on network:** Vessels should be able to sail from node to node. As the geographical location of each node is known, the distance between two nodes is also known. Each vessel should be able to sail from one node to the other with the speed that has been given to the vessel class to which the vessel belongs. As speed and distance are known the model should be able to log the sailing time between two nodes for each vessel class.

2. **Static route choice:** The choice for a specific sailing route is based on the destination of vessels and height restrictions on the routes. At the beginning of the simulation each vessel should be able to determine the shortest route to take based on destination and height restrictions.

3. **Dynamic route changes:** The main route should be predefined at the start but vessels should be able to change course when a queue develops at a lock. When a vessel arrives at a lock it should take the shortest route at that moment in time. in other words, the vessel should choose the shortest queue upon arrival.

4. **Follow route:** When the route choice has been determined the vessels should be able to sail the entire route from start to end node.

5. **Vessel classes:** All vessel classes and their characteristics should be implemented into the model and react to restrictions set on the network accordingly. This must result in vessel classes making different route choices based on their specific characteristics.

6. **Queuing before locks:** When a lock chamber is in operation and a vessel arrives it must understand that it should wait in line until it can enter the lock. Queue formation before a lock must thus be possible and vessels should switch to stationary mode while waiting. Vessels should additionally chose the waiting line that is shortest.

7. **React on node information**: The nodes before locks and bridges contain information that a lock or bridge is nearing. In the case of locks, every vessel should start decelerating after this node. For bridges, vessels higher than the clearance height should start to decelerate.

3.2.3. Simulation

This Section focuses on the functional requirements of the simulations in the model. All the important requirements related to the simulation itself are explained below.

1. **Duration simulation:** Although clear arrival peaks can be seen during the afternoon the commercial fleet sails 24 hours a day for seven days a week. To take away errors caused by vessels, starting the simulation but not finishing before the first 24 hours, the simulation duration should be set at one month (31 days).

2. **Vessel generation:** Vessels should be implemented into the model equally distributed over every hour. The number of vessels implemented each hour depends on the arrival rates of vessels at the Volkerak lock during the day. This arrival distribution per hour is known and can be seen in Figure 2.3. Each hour the given number of vessels arriving at the Volkerak lock should start sailing. The choice between vessel classes should be random.

3. **Discrete events:** The simulation should have four different discrete event stages. Namely, sailing at average speed (average propulsion stage), deceleration, acceleration and waiting (stationary).

4. **Emission stages**: The simulation model should be able to connect the different discrete events a vessel can be in with the related emission stages.

5. **Random destination assignment:** The destination of a vessel should not be based on information attached to the vessel class but should be generated for each vessel separately. This should be a random process.

3.3. Design measure and scenario implementation

The model must be generic in such a way that different design measures and scenarios can be implemented into the simulation model. In the following Sections the civil engineering design measures and fleet impact scenarios that should be implemented are explained in more detail.

3.3.1. Infrastructural modifications

This Section outlines the three choices for infrastructural modifications. The Section consists of three scenarios namely, the bridge height increase on the Scheldt-Rhine canal, conversion of the Bathse sluice to a lock and the entire removal of the Kreekraklocks.

Increase of bridge heights on the Scheldt-Rhine canal

The requirements for bridge heights on commercial fairways is included in the Structuurvisie Infrastructuur en Ruimte (SVIR).The SVIR states that the main waterways (connection seaports to hinterland) should be able to provide passage for ships of class VIb and 4-layer container vessels (Ministerie van Infrastructuur en Milieu, 2012). Both the Scheldt-Rhine canal and the Zuid-Beveland canal are main waterways and should thus be able to provide passage to vessel classes up to and including the VIb vessel class. The Zuid-Beveland canal meets this requirement by the fact that the canal has movable bridges, allowing all vessels that should be able to pass, pass the canal. The Scheldt-Rhine canal however, only has fixed bridges and therefore has height constrains.

The SVIR uses the CEMT classification for bridge heights from 1992 which states that bridges should be at least 7 meter and 9.10 meter high for respectively 3 and 4-layer container vessels (Brolsma Advies, 2013). The Schelde-Rhine canal is part of the main waterway system and should thus be able to provide passage to VIb and 4-layer container vessels. The minimum bridge height on the Scheldt-Rhine canal should therefore be 9.1 meter. Table 2.3 shows that from the nine height restrictions seven bridges do not meet the SVIR requirements. Not meeting the SVIR height requirements might imply that 4-layer container vessels, heading for Antwerp, are forced to take the longer Zuid-Beveland route. Increasing the bridge height in the model, eliminating these height constraints, can show what would happen with the CO_2 emissions on the corridor if the Scheldt-Rhine canal would meet the SVIR requirements.

Next to the fact that the bridges on the Scheldt-Rhine canal do not all meet the SVIR requirements there are trends that could even strengthen the effect of container vessels not taking the Scheldt-Rhine canal and thus taking the longer Zuid-Beveland route. With the increasing number of Ultra Large Container Carriers (ULCC) arriving in the port of Rotterdam the demand for immediate transportation towards the hinterland is increasing. Given the fact that ULCC's can carry around 10,000 TEU or more and the port of Rotterdam wanting these TEU's to be processed as fast as possible, it is expected that the the demand for large container vessels will continue to increase in the future (Brolsma Advies, 2013). The increase in container import/transport of around 5.8 % per year, as has been seen until 2010, will probably not be the case in the future but an increase of container transport of 2 % per year is still expected (Bus, Kuipers, & Saitua, 2016). Due to the fact that container transport is still increasing and initiatives for a model shift from land to water for container transport are made, it is expected that container transshipment, on the Rotterdam-Antwerp corridor, will lie around the high growth scenario of the gross domestic product. According to the Centraal Plan Bureau (CPB) this will be around 2 % in the high growth scenario and around 1 % in the low growth scenario.

The above mentioned trends can lead to more vessels not taking the Scheldt-Rhine canal because of height restrictions. The scenario of increasing the bridge heights is therefore included into the research to find the effects of this measure on the produced CO_2 emissions.

Conversion Bathse sluice into a lock

The excessive fresh water from the Volkerak and the Markiezaat lake can be discharged via the Bathse sluice. This sluice is located next to the village Bath and just north of the port of Antwerp. The system consists of an entrance canal, 140 meter wide and 7 meters deep starting at the Oosterschelde (Deltawerken, 2018). The canal lies parallel to the Scheldt-Rhine canal and is currently only used as a flushing canal for the salt water surplus from the Zoommeer.

The port of Antwerp has multiple container terminals where containers can be handled. Most of the container terminals can be reached via the Scheldt-Rhine canal or via the Berendrecht lock. However, recently DP World Antwerp announced that it will be expanding its container terminal at the Deurganckdok. This terminal is located at the west side of the port. This means that vessels coming from the Zuid-Beveland route do not have to take the Berendrecht lock but vessels sailing on the Scheldt-Rhine canal have to take the Berendrecht lock, making it less attractive to take the Scheldt-Rhine canal.

Turning the Bathse sluice into a lock able to handle vessels could be very interesting. No additional canal needs to be constructed as there is already a canal wide and deep enough to function as a VIb canal. Vessels with destinations other than Antwerp such as Terneuzen can now also take the Scheldt-Rhine canal without having to pay the port fees at Antwerp. Also all the vessels with destination the container terminal at the west side of the port can avoid the busy port of Rotterdam and the Berendrecht lock. It could be interesting to see what happens with the sailing patterns and so emissions of the fleet if this scenario would for example be combined with increasing the height of the bridges on the Scheldt-Rhine canal. This scenario is therefore implemented into the model as well.

Removal Kreekrak locks

The Scheldt-Rhine canal is a very busy canal and the largest part of the fleet chooses this route. In the current situation the Kreekrak locks still meet the capacity requirements. The average waiting time at the Kreekrak locks is about 20 minutes, which is still well below the maximum allowed 30 minutes waiting time. However the traffic flows on the Scheldt-Rhine (Antwerp orientated) route show larger growths than the traffic flows to Terneuzen, Gent and Vlissingen. In the high economic growth scenario (Null-scenario high) the average waiting times are expected to become 38 minutes(Rijkswaterstaat, 2017a). This exceeds the maximum allowable waiting time and will result in a capacity bottleneck.

Increasing the scale of the locks is an option but total removal of the lock could also be an option. The Kreekrak locks have been build to cover the water level difference between the port of Antwerp and the Volkerak and they prevent the salinization of the Zoommeer. There are however ideas on the removal of the Kreekrak locks and with this the expected capacity problems. By removing the Kreekrak locks it is clear that the capacity problems will be solved but what the effect would be on the CO_2 emission levels on this part of the corridor is still unclear. For this study it would therefore be interesting to see what happens after removal of the locks. This option is therefore taken into consideration as a design measure in this research.

3.3.2. Fleet scenarios

In this Section the fleet scenarios will be discussed. These scenarios are related to economical forecasts, which are in turn, related to the fleet composition and functioning. Therefore, this Section discusses three scenarios thought to be of importance on the emissions produced by the fleet.

High cube containers

An increasing number of high-cube containers are introduced in the container transport sector. These high-cube containers are expected to be a replacement for the standard 40 feet containers. High-cube containers are 9.5 foot high (2.896) which is one foot higher than the traditional 40 feet containers. This means that for the VIb canals, where 4-layer container vessels should be able to pass, a minimum height of 10.42 meter should be provided (this includes the 30 cm safety margin) according to the SVIR requirements. The 10.42 meter is based on the fact that on average the loading rate of a vessel is about 65% and 65% of the containers on the vessel is actually loaded.

In 2012 the market share of high-cube containers in the inland shipping industry was about equal to 20 % of the entire number of containers within the industry (Brolsma Advies, 2013). According to the two largest producers of containers world wide, the production of 40 feet high-cube containers has been increasing from 78% of the entire production in 2008 to 92% of the entire production in 2010 (Brolsma Advies, 2013). According to these firms the standard container in the future will be the 40 feet high-cube container. This can however still take a while before being reality. In general containers have a lifetime of 15 years and they are easy to repair (Brolsma Advies, 2015).

The possibility that high-cube containers will take over seems very realistic and the influence on the sailing patterns,caused by height restrictions, could influence the emissions produced on the corridor. It is therefore a scenario that is included in the model.

Standard vessels and departure slots

The inland shipping sector is a difficult industry which is not necessarily known for its innovative character. Inland vessels are robust and strong having extremely long lifetimes. In the past, there has often been a preference for transport over road as it is an easy way to get goods exactly at the places they should be. Where the road network is very developed,in most parts of Europe, the fairway network for transportation of goods, in most countries, is not. The Netherlands are however known for her good water transport networks including the fairways between Rotterdam and Antwerp. However, also the fairway networks between Rotterdam and Antwerp are experiencing problems with the number of vessels arriving at locks each day. Especially the Krammer and Kreekrak locks are reaching their maximum capacity . The maximum capacity is related to the criterion of Nota and Mobiliteit which states that waiting times at locks should not be longer than 30 minutes. When locks reach their capacity limits it becomes more difficult to guarantee reliable travel times. With reliability of time and money being two of the most important factors for shippers, solutions for these capacity problems should be found. In order to keep the inland shipping industry competitive with other transport possibilities and for stimulating a model shift towards inland waterways, the capacity problems should be solved.

One of the main reasons for the capacity problems at locks seems to be caused by the arrival pattern of vessels at the locks. Vessels tend to arrive in large numbers around a fixed number of hours during the day. This can be seen from the arrival rates in Figures 2.3, 2.4 and 2.5 in Chapter 2. Developing a system where vessels know exactly when to arrive at a lock could be a solution for a big part of the capacity problems. Multiple initiatives are currently made by different initiators to provide some sort of live location system that allows vessels to arrive at locks at when there is no or little waiting time. This allows vessels to adjust their speeds and travel programs in such a way that their journey is more reliable time wise and money wise. However, with a system like this the shipper is still making the decisions on where, when and what to do. Another possibility would be an entire fleet only consisting of three types of vessels. For example M8, C4 and the BII-4 vessel classes. These classes are all presenting different vessel types which are suitable to carry a large variety of cargo types. Next to this the dimensions of these vessels fit the current locks dimensions very well. This increases the efficiency rates of locks. This could be combined with assigned time slots for each vessel. This will assure the same arrival rates of vessels over the entire day and no peak arrival rates in the afternoon. A scenario like this could have a major impact on the emissions produced and therefore this scenario is also implemented into the model.

Sea level rise

The sea level rise in the Netherlands has been around 2 millimeters per year for about 120 years. There are however reasons to believe that the sea level rise will increase in the coming decades. The 2014 climate scenarios of the KNMI include a scenario where the sea level rise will reach 100 cm in 2100. Recent research from the the KNMI and University of Utrecht even predict a faster rise in sea level caused by the processes creating sea level rise. The ice on Greenland and Antarctica is melting much faster than predicted in the past. An even faster sea level rise scenario is therefore also possible. Studies have been done and are currently done for sea level rise scenarios between 1 and 6 meters in 2100 (Deltaprogramma, 2017).

Assuming a sea level rise of 1 meter could have especially large effects on the Zuid-Beveland route as this route is very much in contact with the sea and thus influenced by sea level rises. A rise of 1 meter combined with high tide could have effects on the passage possibilities for vessels underneath the bridges on the Zuid-Beveland canal. This could in turn lead to capacity problems on this route and influence the emissions produced. The scenario of 1 meter sea level rise is therefore included into the model.

3.4. Model overview

This Section explains how the model is built taking into account the above mentioned requirements.

3.4.1. Network

As has been explained in Section 3.2.1 the network is built with graph theory. On the corridor, vessels sail from Antwerp to Rotterdam and from Rotterdam to Antwerp and the graph is therefore undirected. In other words, the edges have no orientation and are bi-directional. For vessels to be able to calculate the shortest route to destinations edge attributes are used. Edge attributes contain information of that edge such as the length of the specific edge. When vessels are generated they calculate their route choice statically based on the shortest route towards their destination. Given the fact that a vessel only sails on an edge once, the shortest route can be calculated by adding all the distances attached to the edges. Next to this locks are also located on edges. Attributes can therefore also contain information on the dimensions of the locks. Additionally, information is attached to the nodes. Height restrictions, closures of nodes and approach of a lock or bridge. These specifics of a location are all attached to the nodes.

As has been mentioned in Section 3.1.4 the Networkx package is used to build, visualize and manipulate the graph. In Figure 3.1 the two possible routes from and towards Rotterdam and Antwerp is given.

Figure 3.1: Graphs of the two routes of the Rotterdam-Antwerp corridor

The simulation is modelled as a closed system. All the vessel are generated on two locations (Antwerp and Volkerak locks) and sail from their assigned start node to their assigned end node (Antwerp or the Volkerak locks). There is therefore no possibility for vessels to enter the model at other locations than the Volkerak lock and Antwerp.

3.4.2. Vessels

The vessels should be able to move over the graph build in Section 3.4.1. Each vessel class is modelled as an object containing specific information of that vessel class. Important information could be the average speed, experienced resistance, height, loaded or empty and emission factor. The route a vessel chooses entirely depends on the information attached to the vessel and the randomly assigned destination. After the graph is built the paths can be determined from start to end node. A path is an open trail where every node is passed only once. A trail can be defined as a sequence of edges where every edge is passed only once. Open revers to the fact the the system is not closed and the end note does not coincide with the start node. The paths studied in this research are open paths as the start and ending node differ.

In the Base case and the Null-scenarios there are three possible route choices for vessel classes. The functioning of route choice per vessel is explained in the flow chart shown in Figure 3.2.

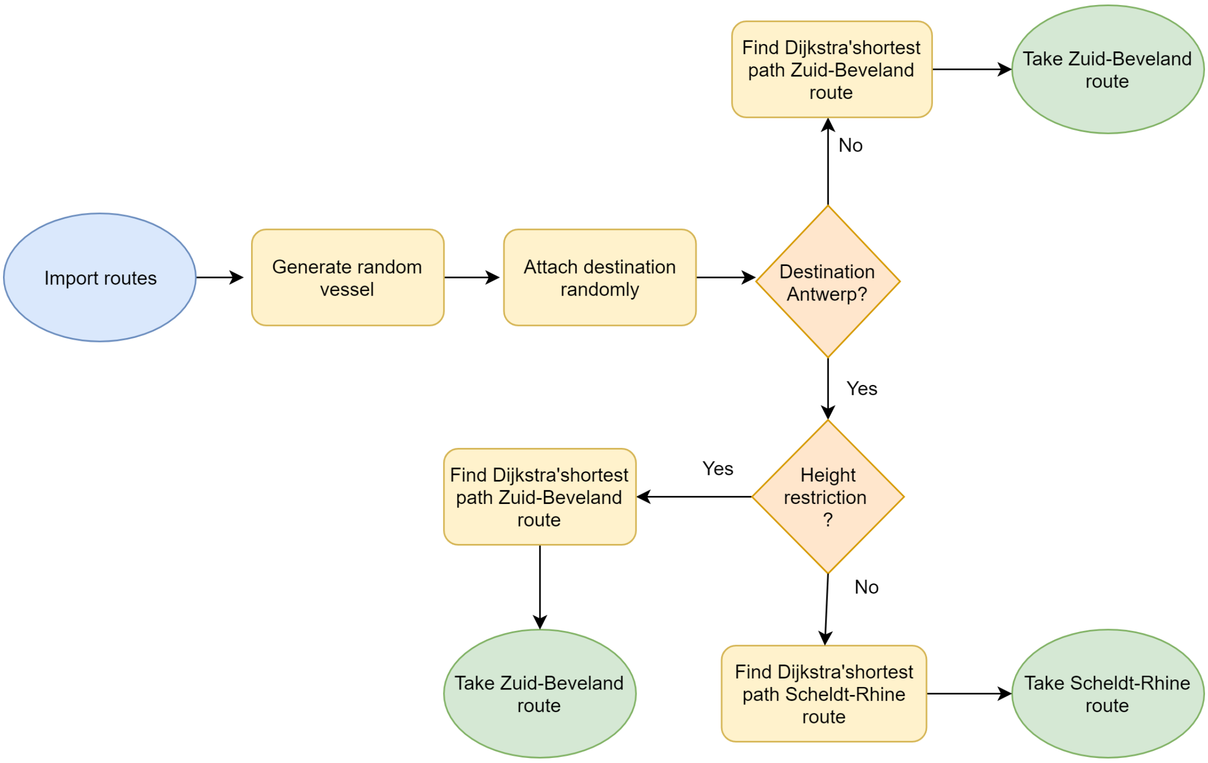

Figure 3.2: Static route generation of vessels

The flow chart in Figure 3.2 shows the static route choice made when the vessel is generated. In Section 3.4.3 this flow chart is shown again but with the dynamic route choice vessel can make during sailing. In the simulation Section the random destination attachment to vessels is explained in more detail.

3.4.3. Simulation

On the network, vessels can encounter bridges and locks. These encounters form the dynamic part of the routing. The accompanied behaviour and emissions are explained in more detail in this Section. First the vessel generation and random destination assignment is discussed.

Vessel generation and destination allocation

As has been mentioned in Chapter 2 the arrival rates of vessels per hour is known. At the starting point of the simulation (Kreekrak locks) the distribution known from the IVS-90 data is taken as main input parameter for the simulation. The simulation starts at 00:00 and the corresponding number of vessels for that hour can be implemented. The distribution of vessels within this specific hour is done with equal time intervals. If six vessels arrive within this hour the vessels will be generated each ten minutes. If four vessels arrive that hour every 15 minutes a vessel is generated. As not every vessel from a vessel class has the same destination the destination is attached to a vessel after it is generated. The allocation of destination is done randomly, where 40% of the fleet gets a destination allocated other than Antwerp and around 60% gets Antwerp as destination.

Movable bridge and lock encounters

After the path a vessel takes has been determined and vessels start sailing over the path they will encounter obstacles. When a vessel encounters a bridge or lock her sailing behaviour changes and in response her emission production changes too. When vessels encounter a queue on their path before a lock, they must check the other lock chamber an choose the shortest line. The simulation of the dynamic behaviour around locks and bridges is explained in with help of flow charts in Figures 3.3 and 3.4.

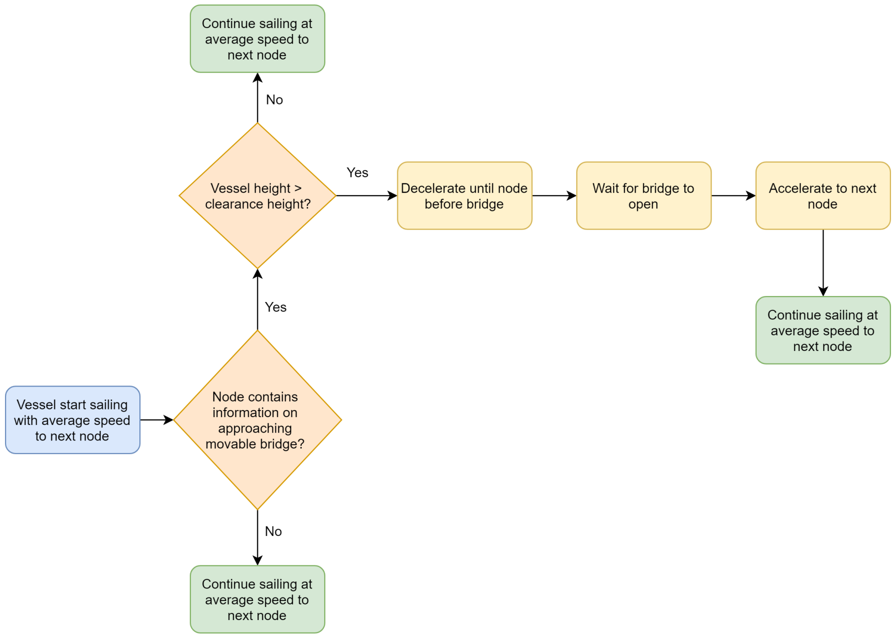

Figure 3.3: Bridge encounter

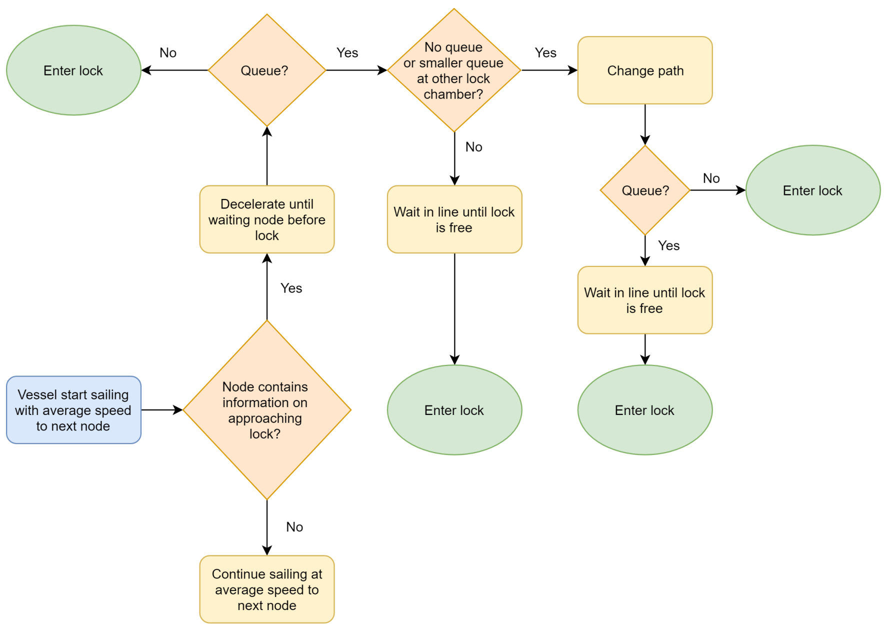

Figure 3.4: Lock encounter

Associated emission stages

Once the above situations can be simulated in a correct manner the emission stages should be added to the events vessels encounter. The energy consumption depends on the requested engine power and the demand for engine power differs in the discrete events distinguished in Figures 3.3 and 3.4. The four emission stages belonging to the discrete events are shown in Figure 3.5 below.

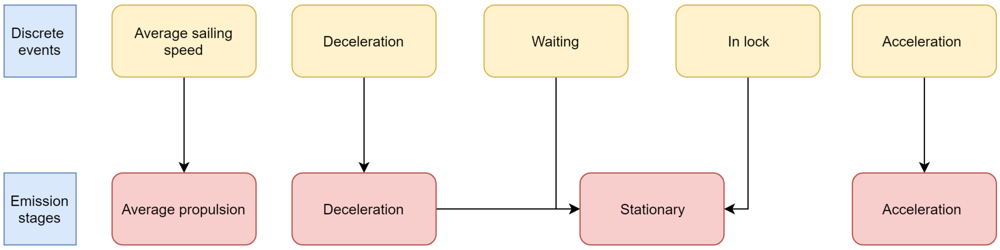

Figure 3.5: Discrete events and emissions stages

3.4.4. Measure implementations

The most measures can be implemented into the model by making small adjustments without significantly changing the graph and simulation steps vessels walk through. For the two design measures, bridge height increase and removal of the Kreekrak lock nothing will change in the core of the simulation. Vessels still walk through all the steps presented in Figures 3.2, 3.3 and 3.4. In the case of bridge height increase on the Scheldt-Rhine canal all the vessels will be able to enter the canal. The height restriction is still in place, only the height of this restriction has been adjusted allowing all vessels to pass. For the design measure Kreekrak lock removal everything stays the same except for the nodes and edges containing information on the Kreekrak locks. This information is removed and the vessels continue sailing at average speed where before they encountered the Kreekrak locks.

The simulations for the fleet scenarios sea level rise and high-cube containers have similar adjustments. Sea level rise will lower the clearance height of the bridges on the Zuid-Beveland canal and high-cube containers will result in higher vessels. Information on height of the vessels is adjusted in the vessel classes itself and the lower clearance heights can be adjusted on the nodes containing information on the bridges.

For the design measure Bathse lock and the scenario standard vessels this is however different. Implementing the Bathse lock into the model can change the choices vessels make significantly as a new fairway is opened which was closed before. Figure 3.6 shows the location of the Bathse canal.

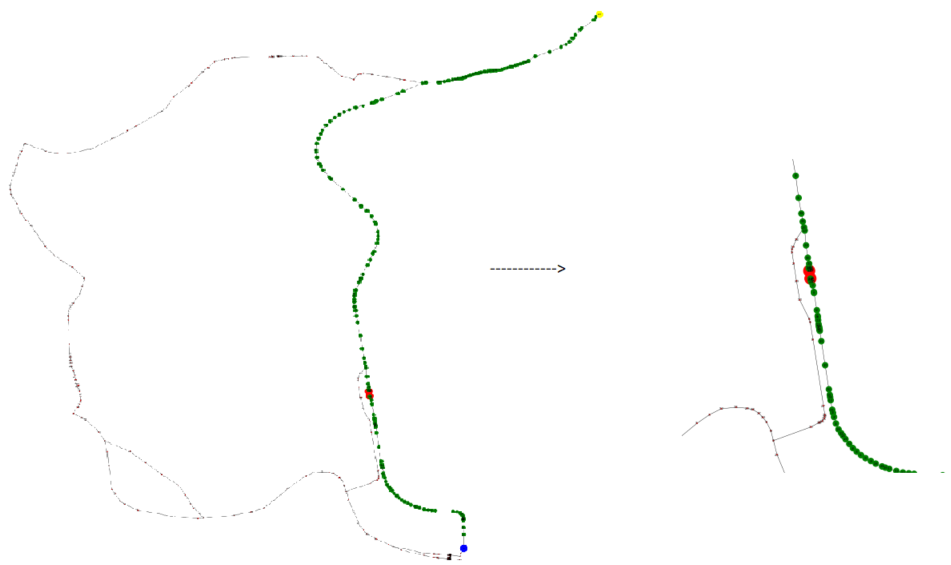

Figure 3.6: Graph with Bathse lock implemented

The opening of this route can influence the sailing patterns of the fleet significantly. All the vessels with destination Gent, Terneuzen and Vlissingen now have a shorter alternative for the Zuid-Beveland route. The main objective of shippers and their parent companies is a combination of time and money. Because of this the slightly shorter route is likely to become the preferred choice for many vessels. Not only the length of the route is important but also the expected waiting and passage times at the encountered locks. The Krammer locks have average passage times of 60 minutes and the Hansweert locks have average passage times of 23 minutes (Rijkswaterstaat, 2017a). This results in 83 minutes to pass the Hansweert and Krammer locks. The new build Bathse lock will probably have passage times not even close to those of the numbers on the Zuid-Beveland route. It may be assumed that the development of the Bathse lock takes into account the current and expected capacity demands on the corridor and will thus have much lower waiting and passage times. The static path generation will now look like the flow chart in Figure 3.7.

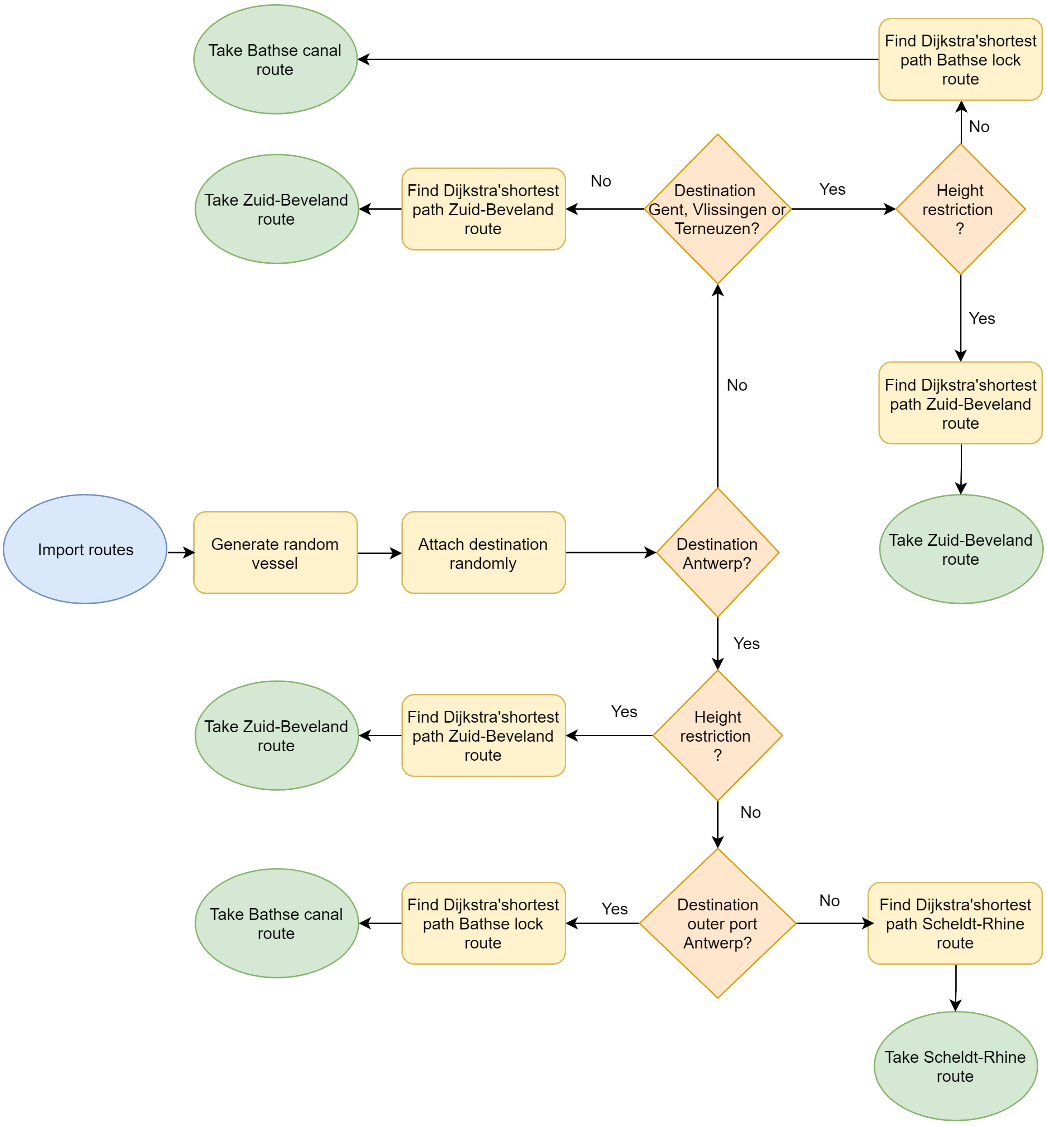

Figure 3.7: Static route choice when Bathse lock is implemented

For the scenario standard vessels, the vessel arrival rates and the amount of vessel classes changes. In this scenario only three vessel classes are generated in the model. Next to this all the vessels have time slots in which they are allowed to sail. This means that every hour the same number of vessels are generated. This can be done by adapting the arrival rate distribution in the model to an arrival distribution that is the same over the entire day. The three specified vessel classes that can sail in this scenario are defined as objects that can sail over the graph. All other vessel classes are taken out of the simulation.

3.5. Conclusion

This Chapter should answer the second sub question of this research.

How can a model be developed that simulates the traffic flows on the Rotterdam-Antwerp corridor in the current state, possible future states and have the ability to determine the accompanied emission levels?

To answer this question the model concepts that seemed applicable for a study like this have been discussed in Section 3.1. To accurately simulate the sailing patterns on this corridor static routing choices can simulate the choice between the Zuid-Beveland and Scheldt-Rhine canal. However to accurately simulate the sailing patterns around locks dynamic routing simulation is needed. To determine the emission levels on the corridor accurately the vessels sailing on the corridor should be examined individually and simulation of queues should be possible. A mesoscopic modelling approach is therefore chosen. Additionally, it is important to know when vessels change from emission stage. This can best be modelled using discrete event simulations.

Section 3.2 explained the functional requirements the model should fulfill to be able to simulate the Base case and the Null-scenarios. A model with these functional requirements should be able to simulate the current situation and situations expected in 2030 and thereby answers the first part of the sub question.

Section 3.3 explained the design measures and fleet impact scenarios in detail. This made it possible to determine which adjustments need to be made to the model to be able to simulate the design measures and scenarios in a proper way.

Section 3.4 gave an overview of the simulation model fulfilling the functional requirements and generic enough for implementation of the design measures and scenarios. Thereby answering the second sub question of this research.

4

Calibration

In this Chapter sub question three of this research should be answered:

Can the levels of CO_2 emissions for the Base case and the Null-scenarios be simulated and what are the corresponding levels of CO_2 emissions?

This is done by first internally validating individual components of the model. The network and the vessels are tested on the basic requirements they should fulfill. Additionally the emission outcomes for individual vessels are checked. This is done by manual calculation and by comparing model outcomes with data obtained in other studies. This is done in Section 4.1. In Section 4.2 the model is calibrated. This is done by comparing the simulation outcomes of the Base case and the Null-scenarios with measuring data(Schefferlie, 2017) and data obtained in other studies.

4.1. Validation model components

This Section outlines the validation of the individual model components. The Section is divided into three Subsections focusing on the functioning of the fleet, the locks and the emission calculations.

4.1.1. Fleet

There are three important components that need to be validated in order to determine if vessels sailing over the graph function as they should.

1. Check 1: Static route choice
2. Check 2: Waiting at locks and bridges
3. Check 3: Dynamic route choice
4. Check 4: Sailing times

Check 1: Static route choice

To check whether vessels take the correct routes, two vessel classes are evaluated. The two vessels evaluated are a M8 and BII-1 vessel. The height of the M8 vessel in loaded state is 9.1 meter. This should restrict the loaded M8 vessel to take the Scheldt-Rhine route as the clearance height on this route is 8.7 meter. The height of the BII-1 vessel in loaded state is below the 8.7 meter and this vessel should therefore be able to pass the Scheldt-Rhine route. In total, eight scenarios are tested where the vessels have different destinations and loading states. The first four scenarios given below are for the M8 vessel.

Table 4.1: Scenarios for a M8 vessel

Scenario	**Loaded**	**Destination**	**Height >clearance height**	**Route vessel should take**
a_M8	Yes	Antwerp	Yes	Zuid-Beveland
b_M8	Yes	Other	Yes	Zuid-Beveland
c_M8	No	Antwerp	No	Scheldt-Rhine
d_M8	No	Other	No	Zuid-Beveland

Table 4.2: Scenarios for a BII-1 vessel

Scenario	**Loaded**	**Destination**	**Height >clearance height Scheldt-Rhine**	**Route vessel should take**
a_BII_1	Yes	Antwerp	No	Scheldt-Rhine
b_BII_1	Yes	Other	No	Zuid-Beveland
c_BII_1	No	Antwerp	No	Scheldt-Rhine
d_BII_1	No	Other	No	Zuid-Beveland

All the above scenarios are simulated in the model. Validation has been done by letting the vessels visually indicate which path they take. Appendix D shows the paths taken with help of visual representation. All vessel scenario's result in the vessels taking the correct route. Indicating that the characteristics attached to the vessel classes are implemented correctly and vessels sailing over the graph notice restrictions set on the fairways. The simulation results for both the M8 and BII-1 vessel are shown in Table 4.3 below. In the simulation a 1.0 stands for loaded vessels and a 0.0 for empty vessels.

Table 4.3: Simulation outcome vessels M8 and BII-1

Scenario	**Loaded**	**Destination**	**Height >clearance height**	**Route vessel takes in simulation**
a_M8	1.0	Antwerp	Yes	Zuid-Beveland
b_M8	1.0	Other	Yes	Zuid-Beveland
c_M8	0.0	Antwerp	No	Scheldt-Rhine
d_M8	0.0	Other	No	Zuid-Beveland
a_BII_1	1.0	Antwerp	No	Scheldt-Rhine
b_BII_1	1.0	Other	No	Zuid-Beveland
c_BII_1	0.0	Antwerp	No	Scheldt-Rhine
d_BII_1	0.0	Other	No	Zuid-Beveland

Check 2: Waiting at locks and bridges

An important aspect of the corridor is the fact that vessels encounter locks and bridges which hinder their journey. It is therefore important to know if the vessels simulated recognize bridge and lock encounters and react the way they should. Lock encounters should result in vessels waiting before the lock. Vessel encountering movable bridges can either continue sailing or stop sailing if they are to high to pass. To test this the logs of different vessels during the simulation are checked. The first vessels take the Scheldt-Rhine route. This means the vessel should encounter one lock and react on this. Table 4.4 shows eight vessels arriving at the Kreekrak locks from both sides. There are two lock chambers at the Kreekrak lock which are both tested. The first four vessels take the first lock chamber and the second four the second lock chamber. The Kreekrak lock chambers are located between nodes 72-73 and 155-156. When a vessel arrives and there is no queue, it can immediately continue its journey into the lock. This is the case for generated vessels 0, 60, 243 and 156. When the vessel does encounter a queue it should wait. This is the case for generated vessels 113, 120, 85 and 112. As can be seen in Table 4.4 all the vessels notice the lock and respond as is expected. There is one more case a vessel can encounter. A vessel arriving at a lock where there is no queue but the water levels in the lock equals the water level on the other side. This case is explained in more detail in Section 4.1.2, locks. The results on the two locks on the Zuid-Beveland route are given in Appendix D Section D.4. These locks also pass the checks. The simulation logs from the model itself are given in Appendix D Section D.5 and Figure D.9.

Table 4.4: Lock recognition by vessels on Scheldt-Rhine canal

Generated Vessel:	**Arrival nodes**	**Lock chamber**	**Time after start simulation [s]**	**Message**	**Time after start simulation [s]**	**Message**	**Queue**
Vessel 0	71-72	1	3426	Sailing from node 71 to node 72 stop	3426	Sailing into lock start	No
Vessel 113	71-72	1	42145	Sailing from node 71 to node 72 stop	42145	waiting to pass lock start	Yes
Vessel 60	132-73	1	35233	Sailing from node 132 to node 73 stop	35233	Sailing into lock start	No
Vessel 120	132-73	1	51396	Sailing from node 132 to node 73 stop	51396	waiting to pass lock start	Yes
Vessel 243	154-155	2	74429	Sailing from node 154 to node 155 stop	74429	Sailing into lock start	No
Vessel 85	154-155	2	41366	Sailing from node 154 to node 155 stop	41366	waiting to pass lock start	Yes
Vessel 156	216-156	2	73247	Sailing from node 216 to node 156 stop	73247	Sailing into lock start	No
Vessel 112	216-156	2	41237	Sailing from node 216 to node 156 stop	41237	waiting to pass lock start	Yes

Additionally, vessels need to react on the movable bridges on the Zuid-Beveland canal when their height is larger than that of the bridges. In Table 4.5 the results for a vessel of 9.1m encountering a movable bridge are compared with the results of a vessel lower than 9.1m. The other two vessels take the Zuid-Beveland route. The first vessel is lower than the air draught on this route. This vessel should stop sailing when it encounters the Krammer and Hansweert lock but continue sailing when it encounters the two movable bridges. The last vessel is higher than the air draught on the Zuid-Beveland route and should therefore stop sailing at the two locks and the two movable bridges. The results are presented in Table 4.5. Node 340 corresponds to the Post bridge on the Zuid-Beveland route and node 103 corresponds to the Vlakke bridges on the Zuid-Beveland route.

Table 4.5: Movable bridge recognition Zuid-Beveland route

Generated vessel:	**Arrival node**	**Time after start simulation [s]**	**Message**	**Time after start simulation [s]**	**Message**
Vessel 1	341-340	16011	Sailing from node 341 to node 340 stop	16011	waiting to pass bridge start
Vessel 1	104-103	17485	Sailing from node 104 to node 103 stop	17485	waiting to pass bridge start
Vessel 4	341-340	15327	Sailing from node 341 to node 340 stop	15327	Sailing from node 340 to node 356 start
Vessel 4	104-103	15946	Sailing from node 104 to node 103 stop	15946	Sailing from node 103 to node 274 start

Table 4.5 clearly shows that the high vessel 1 recognizes the movable bridges and stops sailing before the bridges. The lower vessel 4 continues its journey without stopping in front of the bridges, indicating that the bridges and their height restrictions have been implemented correctly. The logs obtained from the model are presented in Appendix D Section D.5.

Check 3: Dynamic route choice

Vessels determine there route when they are generated. When arriving at a lock a vessel should however check which lock chamber has the shortest queue. The vessel should switch path if the lock chamber on the other path is shorter. The vessel should make a choice based on the traffic density when reaching the last shared nodes. These nodes are indicated in red in Figure 4.1. Figure 4.1 presents the general layout of a lock on the graph. The blue nodes correspond to the lock chambers.

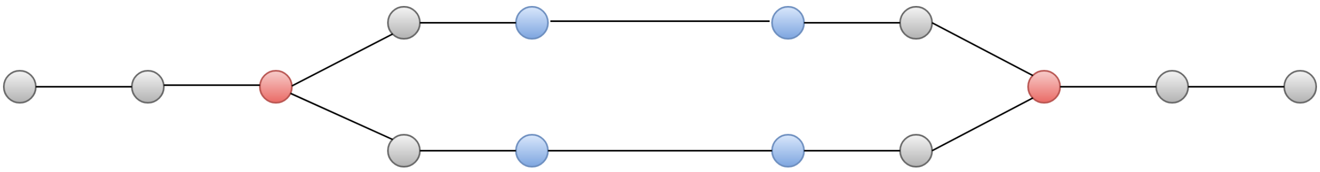

Figure 4.1: Lock layout based on edges and nodes

To test if vessels choose the correct routes the queues before the locks have been monitored and analysed. When a vessel arrives at one of the red nodes it logs the queue it chooses. This has been tested for all the locks on the network. The results of the tests for the Kreekrak lock are presented in Table 4.6. The results for the Krammer and Hansweert locks are presented in Appendix D, Section D.6.

Table 4.6: Queue formation at the Kreekrak locks

Time since start simulation [hr]	Queue lock chamber 1	Queue lock chamber 2
588.68	3	2
588.73	3	3
588.78	3	4
588.93	4	4
589.00	4	4
589.45	2	3
589.46	2	2
589.56	3	3

Table 4.6 presents one hour of vessels arriving at the Kreekrak locks. It clearly shows that vessels arriving choose the shortest queue. The vessels pass the check for dynamic route choice. Appendix D, Figure D.10 presents the simulation logs of these results. At the Krammer and Hansweert locks the vessels queue properly as well and therefore fulfill the dynamic route requirement.

Check 4: Sailing times

Now the static route choice has been validated and the individual components on the paths are recognized the travel times should be validated. Each vessel class has a specific sailing speed in loaded and empty stage. All vessels should sail over the paths with the speed attached to the vessel class they are in. From observations and measurements the average waiting times at locks are known. This can be combined with hand calculations using the given speed and covered distance. Additionally the calculating tool of the Blue Road Map can be used as another check of the total sailing times per vessel class (Bureau Voorlichting Binnenvaart, 2019). Two different vessel classes are used to check if the sailing times in the model coincide with those in reality. The same classes as have been used in check 1 are used in this check. Tables 4.7 and 4.8 shows the results of the hand calculations and the outcomes of the Blue Road Map tool together with the simulation results for the specific vessel classes. In Appendix D Section D.3 the extensive Tables and corresponding calculations are given.

Table 4.7: Sailing time results M8 and BII-1 vessels on Scheldt-Rhine route

Path: Scheldt -Rhine	Sailing time hand calculations [hr]	Sailing time Blue Road Map [hr] (Bureau Voorlichtingen Binnenvaart)	Sailing time Simulation [hr]
M8	3.82	3.8	3.90
BII_1	4.04	3.98	3.90

Table 4.8: Sailing time results M8 and BII-1 vessels on Zuid-Beveland route

Path: Zuid-Beveland	Sailing time hand calculations [hr]	Sailing time Blue Road Map [hr] (Bureau Voorlichtingen Binnenvaart)	Sailing time Simulation [hr]
M8	7.10	6.63	7.32
BII_1	6.84	6.79	7.01

The simulation outcomes are very close to both the hand calculations and the results from the Blue Road Map tool (Bureau Voorlichting Binnenvaart, 2019). The hand calculation results are closer to the simulation results than the ones of the Blue Road Map tool. This could be explained by the fact that different vessel speeds are used. The hand calculations use the same vessel speeds as have been implemented into the model. The vessel speeds used in the Blue Road Map tool are not known. This could be the reason why the results of this method differ the most from the simulation results. The hand calculations and simulation results are very similar indicating that the model is able to represent the real sailing times properly.

4.1.2. Locks

This Section focuses on the internal validation of the locks. Vessels recognize the locks and react on them but the locks should function properly as well. To validate this the Kreekrak lock is used as in example in this Section. The result for the Krammer and Hansweert locks is presented in Appendix D, Section D.7. There are two main checks that need to be done. First the general functioning of the locks is tested. When a vessel from one side sails into the lock and the lock starts its operation, the vessel arriving from the opposite direction should wait before it can enter the lock. Once the vessels sail out the lock, vessels from the other side can enter. The check whether this basic function is modelled correctly, the activity at the lock is analysed. A random moment of the simulation is picked and the messages of the lock are analysed. The nodes corresponding to the lock edges are 72-73 and 155-156 for the Kreekrak lock. Table 4.9 presents the lock messages at the Kreekrak lock for a random chosen point in time. Appendix D, Section D.5 presents the raw logs from the model.

Table 4.9: Lock message at Kreekrak locks

Generated vessel	Arrival nodes	Lock chamber	Sailing direction	Time since start simulation [s]	Message lock
Vessel:6	132-73	1	South	14861	Ship in lock
Vessel:6	132-73	1	South	16181	Ship out lock
Vessel:26	71-72	1	North	16621	Ship in lock
Vessel:26	71-72	1	North	17941	Ship out lock
Vessel: 19	154-155	2	South	26192	Ship in lock
Vessel: 19	154-155	2	South	27512	Ship out lock
Vessel: 57	216-156	2	North	27528	Ship in lock
Vessel: 57	216-156	2	North	28848	Ship out lock

Table 4.9 shows that when vessel 6 (sailing south) leaves the lock vessel 26 enters the lock. The same goes for lock chamber 2. When vessel 19 leaves the lock, vessel 57 enters the lock. This information alone does however not show the proper functioning of the lock. Without specific vessel information it is not clear if vessel 26 and 57 where actually waiting before the operating lock or just arrived when the lock operation finished and the doors where open on their side. The information of the individual vessels should therefore also be checked. For the same time frame, the vessel information is compared to the lock information. The results are presented in Table 4.10.

Table 4.10: Comparison vessel and lock messages at Kreekrak locks

	Vessel: 6	**Vessel: 26**	**Vessel: 19**	**Vessel: 57**
Message lock:	Ship in lock	-	Ship in lock	-
Time since start simulation [s]	14861	14861	26192	26192
Message vessel:	Sailing into lock start	Sailing from node 351 to node 320 stop	Sailing into lock start	waiting to pass lock start
Time since start simulation [s]	14861	14889	26192	26628
Message lock:	Ship out lock	-	Ship out lock	-
Time since start simulation [s]	16181	16181	27512	27512
Message vessel:	Sailing out of lock stop	Sailing from node 318 to node 60 start	Sailing out of lock stop	Sailing into lock start
Time since start simulation [s]	16181	16175	27512	27528

From Table 4.10 it becomes clear that indeed vessel 26 is not waiting in front of the lock when vessel 6 is in the lock chamber. Vessel 26 is sailing somewhere before the lock from node to node. The combination of these two vessels does therefore not show that the lock fulfills the basic requirement. Generated vessels 19 and 57 do however show the functioning of the lock. When vessel 19 is in the lock, this is confirmed by both the lock message and the activity message of the vessel itself, vessel 57 is waiting in front of the lock. This is confirmed by the fact that vessel 57 does not have a lock message at this point in time and has a vessel activity message stating that the vessel is waiting before the lock.

Another check that should be done for the locks is the check on the duration of individual components during the lock operation. To check this a Kreekrak lock encounter by a random vessel has been picked. The corresponding vessel activity messages around the lock are analysed and compared to the actual duration of these activities.

Table 4.11: Duration lock operation in simulation and in real time (Bückmann,2009)

Activity lock	**Time in simulation [sec]**	**Time from data [sec]**
Kreekrak lock		
Operating time chamber	600	600
Krammer lock		
Operating time chamber	1800	1800
Hansweert lock		
Operating time chamber	900	900

In Table 4.11 the closing times of the doors are incorporated into the operation time. Table 4.11 shows that the implemented data on operating time coincides with the times vessels encounter when sailing over the paths.

4.1.3. Emission calculations

This Section checks will check the individual components of the emission calculations and the related stages. This comprises two checks that need to be done.

1. Check 1: Individual resistance calculations
2. Check 2: Emission factors

The checks stated above are presented in the Sections below.

Check 1: Individual resistance calculations

To check if the requested engine power per vessel class can be determined in the correct way the results of the total resistance experienced per vessel class and average vessel speed needs to be checked. As the requested engine power is a multiplications of these variables. To validate this the resistance outcomes are checked in this Section. This is done by comparing the resistance results with another study. The calculated resistance, experienced per vessel class on this corridor, is compared to results of the report Schatting energiegebruik binnenvaartschepen (Bolt, 2003). The results of this study and the above mentioned study are presented in Table 4.12.

Table 4.12: Comparison resistance computations

Vessel class:	Calculated total resistance loaded vessels [kN]	Total resistance Estimation energy use inland vessels (Bolt,2003) [kN]	Calculated total resistance empty vessels [kN]	Total resistance Estimation energy use inland vessels (Bolt,2003) [kN]
M1	16.9	15.4	9.2	14.0
M2	28.8	29.4	17.5	27.6
M3	43.9	34.8	22.7	29.3
M4	50.6	48.0	28.8	38.1
M5	54.1	58.3	31.8	48.5
M6	70.8	68.9	44.7	55.0
M7	74.3	71.5	53.2	61.7
M8	106.5	137.1	61.5	83.9

The loaded resistances coincide quite well. The differences between most vessel classes is within the 10%, which is accurate when one takes into account the many variables that play a role in the resistance calculations. The only vessel classes that show larger differences are the M3 and M8 vessel class. Here the loaded resistance with about 25%. For the M8 vessel class this could be caused by the large difference in average vessel speeds used. Appendix D, Section D.8 shows the average vessel speeds used in both studies. The average vessel speed for the M8 vessel class in this research is considerably lower than the speed in the other study. An important factor in the resistance calculations is speed. It is therefore likely that the cause of the difference in resistance is caused by the difference in sailing speeds. The average vessel speed used in this research is based on the newest trends where certain vessel classes tend to sail with lower speeds, often called economical sailing (CE Delft, 2016). The estimated energy use inland vessels (Bolt,2003) uses sailing speeds until 2003 and these might therefore differ from the average sailing speeds today.

The vessel speed of the M3 vessel classes are almost equal in both researches, the difference is resistance can therefore not be caused by the vessel speed. The loaded draught for the M3 vessel classes differ in both researches. Where in this research a loaded draught of 2.6 m is used, the research of reference uses a smaller loaded draught. A larger draught generally results in a larger resistance and the difference in total resistance is therefore most probably caused by the difference in draught.

The calculated resistances for empty vessels have a larger deviation from the resistances in the comparison study (39% on average). This can again, likely be caused by the average vessel speeds of this research being lower than that of the comparison study. Next to this there are many variables that can be different. In the comparison study it is not stated what fairway dimensions have been used to calculate the resistance encountered. As this research focuses on large VIb canals it is likely that the dimensions used in the comparison study are smaller. This causes the resistance of the comparison study to increase as well. Large increases in the resistance by limited water can be expected for smaller fairway dimensions. Another factor could be the draughts of empty vessels. The empty draughts used in the comparison study are larger than those of this study. Which causes the resistance of the comparison study to be higher for empty vessels. The draught for empty vessels used in this study are based on the values of more recent studies of Rijkswaterstaat and TNO in 2013 (Hulskotte, 2013) which is most probably the cause of the observed difference.

It can be concluded that the calculated resistance values in this research fit the values of the comparison study well. The loaded vessels encounter resistances that fit the resistances of the comparison study very well. The empty vessels have larger deviations with the comparison study on resistance but do have very clear factors that can explain these differences. Now the resistance has been checked, the values of the requested engine power are also validated. The requested engine power being a simple multiplication of the resistance and the average vessel speed.

Check 2: Emission factors
The second important parameter in determining the CO_2 emissions are the emission factors. The emission factors have been calculated per vessel class based on the engine type and engine type distributions in each vessel class. As has been mentioned before, the results are given in Appendix B, Section B.2. On average the emission factor lies around 690 g/kWh in this research. This number is based on a combination of different studies on fleet distribution forecasts and measurements done by TNO (Hulskotte & Bolt, 2012) (Hulskotte, 2009). A more recent study shows an average emission factor of 622 g/kWh (Otten et al., 2017). This number is based on more recent measurements and indicated that the average age of engines in vessels has gone down faster than was expected.

With the resistance and emission factor values checked the individual components of the emissions calculations are validated. In Section 4.2, the total emission outcomes, for the entire fleet, will be checked.

4.2. Calibration model

The previous Section has validated individual components of the model. Now it is possible to calibrate the model and see if it can give a proper representation of reality. The calibration is done in two main Sections. The first Section focuses on the Base case. The second Section focuses on the two Null-scenarios. Both Sections are divided into multiple Subsections outlining the important outcomes of the simulation.

4.2.1. Simulation Base case

In this Section the Base case is calibrated. The Base case is the simulation that tries to simulate the current state of the corridor. In other words, it simulates the sailing patterns and the associated emission levels. To check whether the simulation of the current state works, multiple results are compared to the existing data and measurements on the corridor.

Fleet composition
The first calibration check is done on the fleet composition. The vessel generation in the model is based on the arrival rates of vessels on the corridor. The number of vessels in the model should coincide with the real number of vessels on the corridor. The loading rates implemented into the model are based on results of other studies. It should therefore also be checked if the total weight transported in the simulation coincides with the measured rates on this corridor. The simulation runs for a month and the results are therefore multiplied by 12 to be compared with the data from Table 2.7.The results are presented in Table 4.13.

Table 4.13: Number of vessels and transported weight in 2017

	Simulation results per month	Simulation results per year	Real data fleet 2017
Number of vessels	9207	108405	108500
Transported weight million [ton]	9.65	113.82	115.00

The number of vessels generated in the model coincides with the vessel passages measured at the Volkerak locks in 2017. The small difference of the simulation results with the number of vessels from the measuring data can be easily explained. 108500 vessels over 365 days gives an average of 297.26 vessels a day. The number of vessel generated in the simulation each day equals 297 vessels. This results in 108405 vessels per year. The difference of 95 vessels per year is therefore caused by the fact that a rounded number of vessels is generated in the model each day. It can therefore be concluded that the vessel generation is implemented correctly and can simulate the fleet size correctly.

The transported weight over the corridor is 113.82 million ton per year and therefore also simulated correctly when compared with the IVS-90 data from Rijkswaterstaat. It must be stated the determination of the exact loading rates per vessel class is difficult. The loading rates, used per vessel class, can be based on numbers obtained in several studies (Arcadis, 2016) (Buckmann, Harmsen, Korteweg, & Bozuwa, 2007)(Rijkswaterstaat, 2017a). These studies all use slightly different loading rates. This is often caused by different measuring techniques or measuring rates at different locations on the corridor. In this study the results from the IVS-90 data from the year 2017 are used. The average transported load per vessel is 1060 ton according to the IVS-90 data. The results of the simulation indicate an average of 1050 transported load per vessel. Indicating that loading rates are in the correct range and the model is able to simulate the real situation well.

Route choices

The second check relates to the sailing patterns of the fleet. In order to properly assess the emission levels of the fleet the route choices of the vessels in the model should coincide with the actual route choices of the vessels on the corridor. The route choices in the model are based on the height restrictions on the Scheldt-Rhine route and the destination of the vessels. If route choice is indeed based on these variables can be checked by comparing the distribution of vessels and transported weight over the corridor. The vessel and weight distributions of Figure 2.2 and Table 2.7 are compared to the results from the simulation model. The distributions over a year are compared in Tables 4.14 and 4.15. The results from the simulation model per month are presented in Figures 4.2 and 4.3.

Table 4.14: Fleet distribution over the corridor in one month in 2017

	Simulation per month	**Simulation per year**	**Percentage of total [%]**	**Real data fleet 2017**	**Percentage of total [%]**
Zuid - Beveland route	3383	39832	36.7	40000	36.8
Scheldt-Rhine route	5824	68573	63.3	68500	63.2

Table 4.15: Transported weight distribution on corridor in one month in 2017

	Simulation per month	**Simulation per year**	**Percentage of total [%]**	**Real data fleet 2017**	**Percentage of total [%]**
Zuid - Beveland route [million ton]	3.67	43	38	41	36
Scheldt-Rhine route [million ton]	5.98	70.40	62	74	64

Tables 4.14 and 4.15 both show the distributions of the transported weight and vessels on the corridor. It is very clear that the distribution of vessels over the corridor is almost similar to the IVS-90 data used as comparison. It can therefore be concluded that the route choice between the Zuid-Beveland route and the Scheldt-Rhine route can be estimated accurately by using destination and height restrictions as main decisive factors. The transported weight over the two routes is simulated quite accurate as well. This indicates that the loading rates per vessel class have been determined correctly and the vessel types taking the Zuid-Beveland route and Scheldt-Rhine route is distributed correctly as well. The fact that the total transported weight is smaller in the model can largely be explained by the fact that there are slightly less vessels in the simulation compared to the measured data.

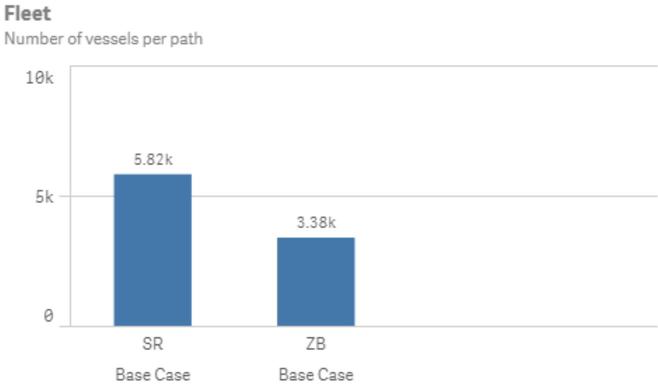

Figure 4.2: Fleet distribution in one month

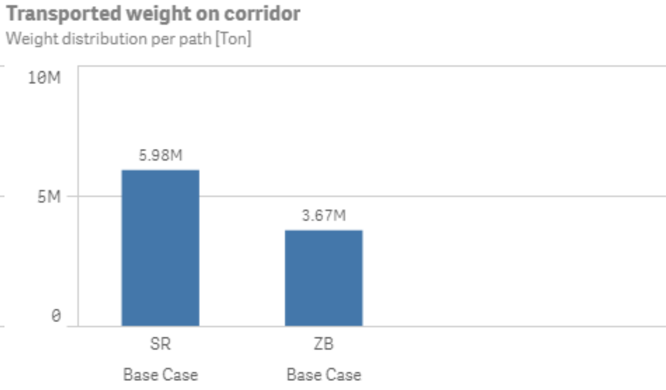

Figure 4.3: Weight distribution in one month

It can be concluded that basing route choice on the height restriction of the Scheldt-Rhine route and destination of vessels is an allowable simplification. The distribution of vessels over the corridor equals the IVS-90 data by 0.1%. The simulation model therefore gives an accurate display of the sailing patterns on the corridor.

Locks

In Section 4.1 the general functioning of the locks has been tested. To see if the simulation can simulate the actual patterns of the fleet around locks the simulation results around the locks should be calibrated. This is done by comparing the arrival rates at the locks in the simulation with the arrival rates obtained from IVS-90 data. After this the average waiting times at the locks are compared with the average waiting times experienced in 2017. As a final check the I/C ratio's at the locks are tested.

First the arrival rates at all the locks in the model are tested. The IVS-90 data presented in Figures 2.5 and 2.4 is combined with the results from the model. The results for the Kreekrak locks in both directions are presented in Figure 4.4.

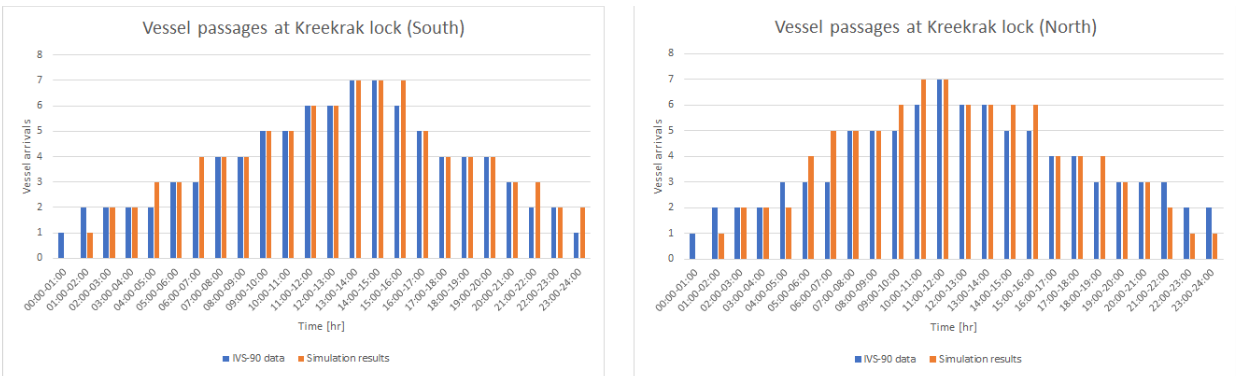

Figure 4.4: Arrival rates of vessels at Kreekrak locks, simulation and IVS-90 data

The results of the model fit the IVS-90 data well. There are some notes to make. For both the directions the model does not show any, or just one, vessel passages in the first two hours of the day while the IVS-90 data does show vessel passages. This can probably be explained by the fact that the simulation starts each day with vessels generated at the Volkerak locks and in Antwerp. After being generated the first vessels arriving at the Kreekrak lock will be there some hours after midnight, which can clearly be seen in the simulation results as well. The IVS-90 data also measures the vessels that overnight somewhere between the Volkerak and Antwerp and which therefore arrive at the Kreekraklock earlier. Another interesting observation can be found for the peak hours during the day. The south side of the Volkerak locks (north going vessels) has its peak hours starting earlier during the day. This makes sense as the Kreekrak locks are closer to Antwerp than to the Volkerak. Meaning that the peak from the Volkerak locks arrives at the Kreekrak locks later than the vessels sailing from Antwerp to the Kreekrak locks. Adding to this one can see that the Kreekrak locks are very busy almost the entire day. It can be concluded that the results from the model fit the IVS-90 data very well.

The second lock analysed is the Krammer lock on the Zuid-Beveland route. The result for this lock, in both directions, is presented in Figure 4.5.

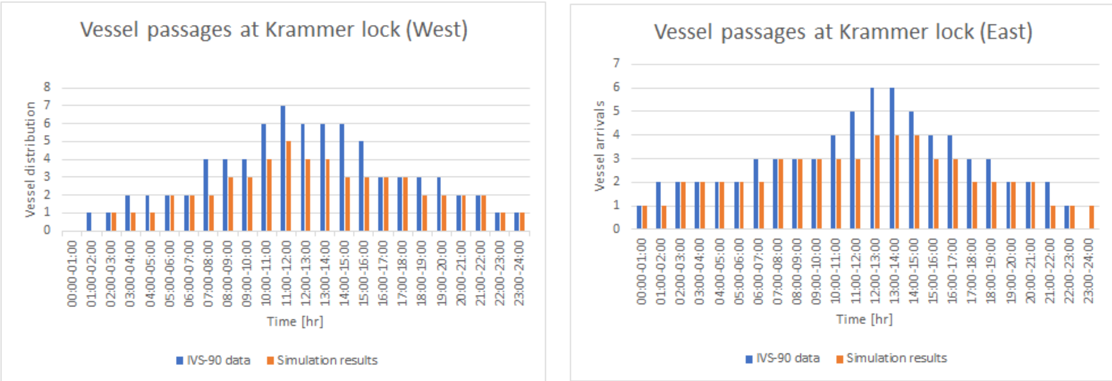

Figure 4.5: Arrival rates of vessels at Krammer locks, simulation and IVS-90 data

It is immediately clear that the simulation results show less vessels arriving at the Krammer locks in both directions. The total number of vessels arriving at the Krammer locks in the simulation is 109. This coincides with 36% of the fleet taking the Zuid-Beveland route and therefore this is the number of vessels that should pass the Krammer locks in the simulation. The difference with the measures IVS-90 data can be explained. The model is build upon the average amount of vessels sailing between Rotterdam and Antwerp per day. Based on the total amount of vessels measured by IVS-90 per year. The IVS-90 data used as a comparison in Figure 4.5 is based on a number of days in 2017. It seems that the number of days chosen as comparison days for the simulation are busier than the average day on the corridor. The total difference for both directions is 36 vessels, which is 1.5 vessel per hour and 0.75 vessel per direction per hour. It does not seem likely that these differences per hour will increase the waiting times very much. However, it can be seen from the Figures that the differences are largest during the peak hours which could have a larger effect on the waiting times. There are however also days with less traffic as somehow the average of 109 vessels per days should be met. This will again reduce the waiting times. This will most probably result in the same waiting times as the waiting times in the model, based on the average number of vessels per day over a year. It is important to note that the distribution of the vessels over the day, although in total less in numbers, is quite similar as the distribution of the IVS-90 data. This is important as the arrival rates of many vessels at the same time is causing capacity problems, especially at the Krammer locks. The last lock analysed is the Hansweert lock. The result is presented in Figure 4.6.

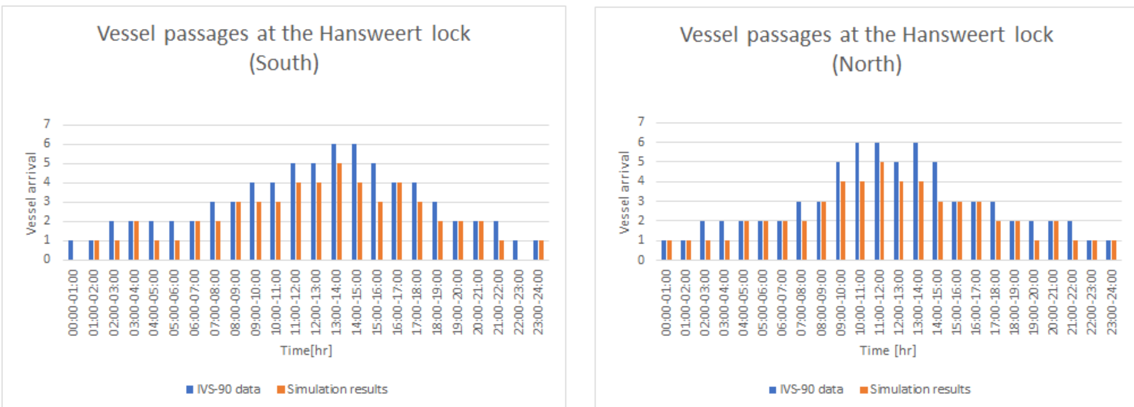

Figure 4.6: Arrival rates of vessels at Hansweert locks, simulation and IVS-90 data

The results for the Hansweert locks are similar to that of the Krammer locks. Which is convenient as this simulation assumes a closed system and the number of vessel passages at the Krammer locks should therefore be equal to that at the Hansweert locks. Figures 4.5 and 4.6 that this is indeed the case.

Figure 4.6 shows, that just like at the Krammer locks, the total number of vessel passages in the simulation equals 109. This is less than the IVS-90 data just like at the Krammer locks. As the same IVS-90 days are used for determining the arrival rates at the Krammer as the Hansweert locks this seems logical. The total difference in passages, between the simulation and the IVS-90 data, is 33 vessel passages. This is almost similar to the difference at the Krammer locks (36 more passages) which strengthens the assumption of a closed system on the corridor. Just as the Krammer locks results, the distribution over the day at Hansweert is similar to that of the IVS-90 data. Which strengthens the representation of the real situation by the model. It is concluded that the model can simulate arrival rates of vessels at locks for the Base case.

Now the arrival rates have been checked the average waiting times and I/C ratios should be tested. As has been explained in Chapter 2 the hindrance the fleet experiences from passing the lock can be measured by the level of the I/C ratio (ratio Intensity-Capacity). Ratio's higher than 0.5 are undesired as this results in average waiting times of 30 minutes and longer. The capacities determined in Chapter 2 are now combined with the intensities experienced in the model. Table 4.16 shows the capacities, intensities and associated average waiting times experienced by vessels in the simulation.

Table 4.16: I/C ratio's and average waiting times at the locks

Lock	**Capacity [vessels/ hour]**	**Capacity [capacity in ton/ hour]**	**Intensity in simulation [vessels/hour]**	**Intensity in simulation [capacity ton/hour]**	**I/C ratio**	**Waiting times experienced in simulation**
Kreekrak	18	29340	7.83	12763	0.43	21
Krammer	9	14670	4.5	7335	0.5	28
Hansweert	15	24450	4.5	7335	0.3	12

The intensities are calculated using the average arrival rates at locks per hour. This can be done by dividing the total number of vessels taking the Scheldt-Rhine route (in the simulation) by 24. The average loading capacity of 1630 ton per vessel is used to determine the intensity in ton per hour. The results presented in Table 4.16 show a clear picture. The Kreekrak lock has and I/C ratio of 0.43. Which should mean that the average waiting times at the Kreekrak lock are below the 30 minutes and therefore fulfill the SVIR requirement. This coincides with other studies done on the Volkerak lock (Rijkswaterstaat, 2017a). The Kreekrak lock has no official capacity problems in the current state but will most probably have problems in the future, as the transported cargo over the corridor is likely to further increase over the coming years in both economic growth scenarios (Rijkswaterstaat, 2017a). As every simulation is unique the simulation results of 10 simulation runs are combined. The waiting times at the Kreekrak lock fluctuate between 22 and 19 minutes, resulting in an overall average of 21 minutes. This average waiting time of 21 minutes is slightly higher than the stated 20 minutes in Table 2.4 (Rijkswaterstaat, 2017a). The average waiting time is however lower than the mentioned waiting times in a study focusing on the Scheldt area (Goffin et al., 2009). Indicating that there is no precise number on the average waiting times. The number of Rijkswaterstaat is assumed to be leading and as such the model result of 21 minutes presents the actual situation (20 minutes) quite accurately.

For the Zuid-beveland route the same is done. The waiting times on the Zuid-Beveland route are very accurate compared to the data presented in Table 2.2. The I/C ratio of 0.5 at the Krammer lock indicates that the waiting times at the Krammer lock should be around 30 minutes or higher. Which is the case for the simulation results. The I/C ratio at the Hansweert lock of 0.3 is low, indicating short waiting times. This is the case for the results in the simulations as well. It coincides well with the average waiting data in Table 2.2. The results from the simulations on average waiting times and total sailing times are presented as bar charts in Figure 4.7.

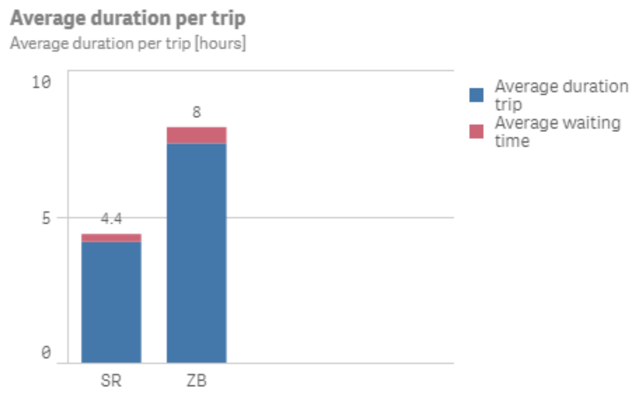

Figure 4.7: Average sailing time per route

Figure 4.7 shows that the average sailing time for the Scheldt-Rhine route equals 4.4 hour. The individual checks of the M8 and BII-I vessel classes showed average sailing times of about 4 hours (Table 4.7). On the Zuid-Beveland route the simulation shows an average sailing time of 8 hours, where the individual results from Table 4.8 showed sailing times of around 7.2 hours. The higher outcomes for the entire fleet can easily be explained by the fact that the M8 and BII-I vessel classes sail with average speeds that are high compared to most other vessel classes in the fleet. A combination of all vessel classes will therefore result in longer average sailing times, which is also confirmed by Figure 4.7

Emission levels

The last part of the model that needs to be checked are the total emission outcomes for the fleet. The model is developed as a tool for analysing the total emission patterns on the corridor. The most important calibration is therefore if the model is able to simulate the emission patterns and total levels correctly. First the outcomes of the total energy use on the corridor are compared to the total energy use in the province Zeeland produced by the inland shipping fleet and pleasure crafts in 2017(Rijkswaterstaat, 2017b). The results are presented in Table 4.17. The data of the climate monitor is also presented in Appendix C.

Table 4.17: Energy consumption and $C0_2$ emission

	Simulation results for a month [million kWh]	**Simulation results for a year [million kWh]**	**Data klimaatmonitor for a year [million kWh]**
Energy consumption sailing	19.18	230.16	-
Energy consumption stationary	0.71	8.3	-
Energy consumption total	19.89	234.22	994.44
	Simulation results for a month [million kg]	**Simulation results for a year [million kg]**	**Data klimaatmonitor for a year [million kg]**
CO2 emissions sailing	15.36	180.85	-
CO2 emission stationary	0.54	6.44	-
CO2 emissions total	15.91	187.33	259.93

The energy consumption on the corridor is almost about 1/4 of the energy consumption in Zeeland of pleasure crafts and commercial shipping together. Which makes sense as the Zuid-Beveland route and the Scheldt-Rhine canal are large transport axis in Zeeland and for the Netherlands. It is therefore very plausible that the fairways simulate almost halve of the entire energy consumption produced by vessels in Zeeland. The CO_2 emission contribution of the studied fairways to the total produced levels is even larger. This can be explained by the fact that the engines of inland vessels are dirty diesel engines producing more emissions with the same energy use than other vessels not having diesel engines. Many pleasure crafts for example. This results in high emission factors for vessels in the inland shipping fleet and thus a larger contribution to the total emissions produced in the province.

There is no reference material on the contribution of the stationary stage of vessel engines to the total energy consumption and emissions produced. A simple check can however be done to check whether the ratio shown in Table 4.17 coincides with a hand calculation on energy consumption in the stationary stage. The energy consumption of a vessel in the stationary engine stage is 15% of that produced during average sailing speeds. The waiting times and lock operating times are known so a rough estimation of the total energy consumption in stationary stage can be made. The average time where vessels are in stationary stage is about 136 minutes for both routes. This is 19% of the sum of the total sailing times. Knowing that the energy consumption in stationary stage is 15% of the normally consumed energy the total must lie around 1 million kWh. This is in the same range as the model result.

One last calibration check can be done with the emission production per sailed ton kilometer. The average emissions in gram per ton kilometer on the Scheldt-Rhine route is 25.2 g/tkm and on the Zuid-Beveland canal 25.4 g/tkm. Appendix C, Figure C.5 shows the average emissions in g/tkm for several vessel classes. The results from the model are between the emission productions of the individual vessels. Which is desired as the model comprises an entire fleet and not one individual vessels. The average emission per ton kilometer for both routes are quite similar. This makes sense as both routes have different factors increasing the height of the emission produced per ton kilometer. Based on the waiting times it could be reasoned that the emission factor in g/tkm on the Zuid-Beveland should be higher. However, the large 4-layer container vessels are forced to take this route which contributes to lower emission rates. This can be explained by the fact that the increase in energy use by larger vessels is smaller than the increase in transported weight. Which result in larger vessels, carrying more cargo, to have lower emission rates in gram per ton kilometer. On the Scheldt-Rhine route the average waiting times are lower than on the Zuid-beveland route indicating lower emission rates per ton kilometer. As the loading rates of vessels on both routes are almost equal it can be concluded that the factors influencing the emissions per ton kilometer even out, resulting in more or less equal emissions per ton/kilometer on both routes.

Now that this all is checked it can be concluded that the model can present the energy consumption levels and emission levels on the corridor correctly. The proper representation of the fleet distribution over the corridor has also been calibrated and checked. It is therefore now possible to determine the energy consumption and emission production patterns on the corridor. In Figures 4.8 and 4.9 the energy patterns and emission patterns for the Base case are presented.

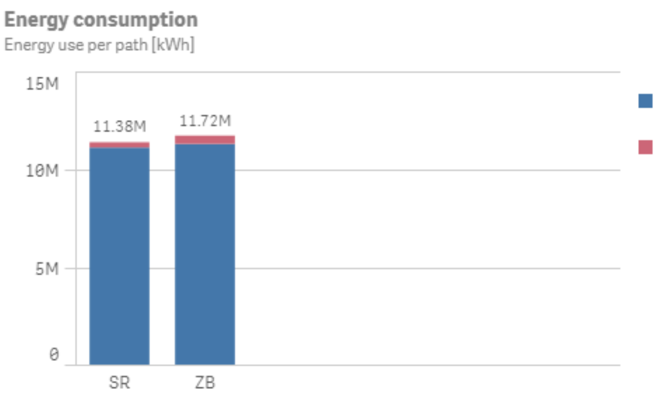

Figure 4.8: Energy consumption Base case per route

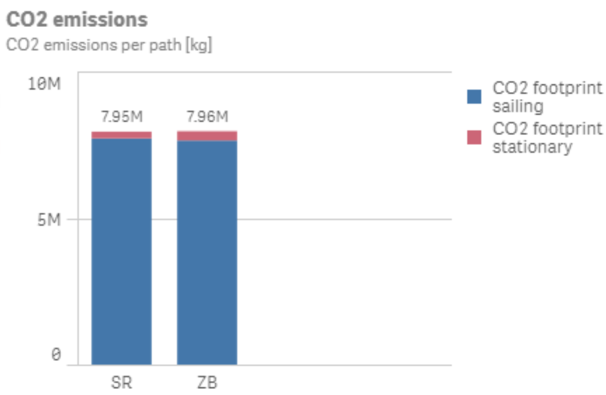

Figure 4.9: $C0_2$ emission Base case per route

Figure 4.8 shows that the energy consumption is higher on the Zuid-Beveland route although this route has less vessels sailing over it. Indicating that the larger sailing distance and longer waiting times have large influence on the total energy consumption. Figure 4.9 show that the emissions produced on both routes is almost equal. This is likely caused by the fact that the larger 4-layer container vessels take the Zuid-Beveland route and the smaller container vessels take the Scheldt-Rhine route. The emission factors of the often newer, large container vessels, are in general lower than the smaller ones. Resulting in a more even distribution of CO_2 emissions on the corridor.

4.2.2. Simulation Null-scenarios

The two Null-scenarios in this model are based on high and low economic forecasts in 2030, calculated by WLO. The expected composition of the fleet and the transported load for the two Null-scenarios have been discussed in detail in Section 2.2. In this Section of the calibration it is tested if the model can simulate the Null-scenarios in a proper way. This is done by first checking the fleet size and amount of weight transported in the simulation coincides with the forecasts for the corridor. After this the fleet distribution and transported weight distribution in analysed. The third and last analysis focuses on the waiting times in the simulation and the I/C ratio's. The results of the simulation are compared to other forecast studies and an analyses is made on the goodness of the fit of the model results and other studies.

Fleet composition

As has been calculated in Section 2.2 both the fleet size and transported cargo increases for the high and low Null-scenarios in 2030. In both cases the amount of transported cargo growths more than the fleet size. This indicates, assuming that the loading rates stay the same, that the average vessel size grows. The average transported cargo per vessel is therefore larger, in both Null-scenarios, than in the current situation. This will be analysed in more detail later in this Section. First the simulation model results for both Null-scenarios are compared to the expected fleet size and transported cargo size. Table 4.18 shows the results of the total fleet size and cargo size of the simulations combined with the economic forecasts from Tables 2.8 and 2.9.

Table 4.18: Number of vessels and transported weight for Null-scenarios 2030

	Fleet size 2030	**Simulation results fleet size 2030**	**Transported weight 2030 (mln.ton)**	**Simulation results transported weight (mln.ton)**
Null-scenario low	109700	109500	121	120.8
Null-scenario high	110500	110595	131	131.7

The simulation results match with the economic forecasts simulated. For the low economic scenario, simulated as the Null-scenario low, the expected fleet size is 109700 vessels per year. Equal to 300.50 vessel a day, which is not an integer number. In the model there are therefore 300 vessels implemented per day. This results in 109500 vessels a year which is a difference of 200 vessels a year. This is also the difference found in Table 4.18. The same is the case for the economic high scenario in 2030. A total of 110500 vessels each year coincides with 302.7 vessels a day. This is implemented in the model as 303 vessels each day and results in 110595 vessels each year.

In the low economic forecast the expected average transported load per vessel is 1093 ton (121 million/109700 vessels). In the high economic scenario this number is expected to 1186 ton per vessel. It can therefore be concluded that the average load carried per vessel increases compared to the current situation of 1060 ton. Assuming the loading rates stay the same, the average vessel size must increase over the next years. To simulate the increased vessel size the share of larger vessels in the simulation is increased. This resulted in an average transported load per vessel of 1103 ton for the low Null-scenario and 1190 ton in the high Null-scenario.

It should be taken into account that the model has slightly less vessels sailing over the corridor in the low Null-scenario and slightly more vessels sailing over the corridor in the high Null-scenario. This results in the total transported cargo to be a bit higher in the high Null-scenario and a bit lower in the low Null-scenario, when compared to the data taken as basis for the Null-scenarios.

Fleet and cargo distribution

According to the economic forecasts in Table 2.9 the number of vessels sailing over the Zuid-Beveland route is expected to increase more than the number on the Scheldt-Rhine route (Rijkswaterstaat, 2017a). The distribution of the fleet over the corridor should therefore be checked. The fleet distributions of both the low and high Null-scenario are presented in Figures 4.10 and 4.11.

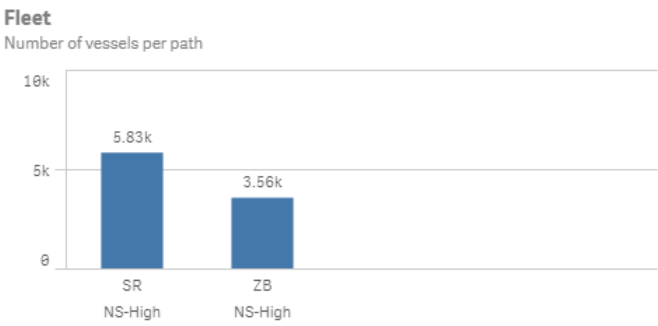

Figure 4.10: Fleet distribution Null-scenario high

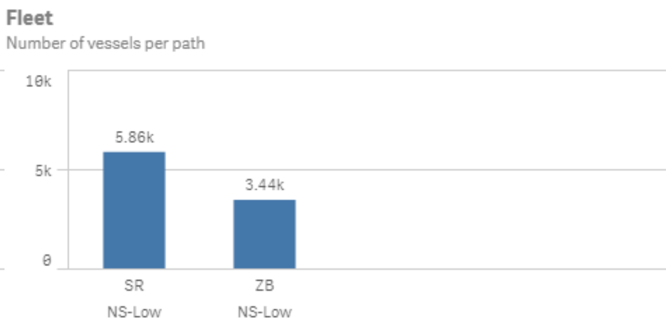

Figure 4.11: Fleet distribution Null-scenario low

The Null-scenario low sees an increase of vessel passages of 0.7% on the Scheldt-Rhine route compared to the Base case, shown in Figure 4.2. According to the economic fleet forecasts, Table 2.9, the growth should be 0.5% in 2030 (Rijkswaterstaat, 2017a). The growth on the Zuid-Beveland route is 1.7% in the simulation and according to Table 2.9 should be 1.5%. The high Null-scenario shows a growth of the fleet on the Zuid-Beveland route of 5% and a growth of only 0.20% on the Scheldt-Rhine route. Table 2.9 indicates that the expected growth on the Zuid-Beveland route is 3% and on the Scheldt-Rhine route equals 1%. The larger differences for the Null-scenario high can partially be explained by the fact that in the Base case the generated vessels is slightly lower than the actual number of vessels on the corridor. Where in the Null-scenario high, the generated vessels in the model is slightly higher than the expected number in 2030 for the high economic scenario. This results in a larger difference between the Base case and the Null-scenario high than in the current situation today and the expected situation in 2030.

Next to this the distributions of transported cargo over the corridor changes as well. The simulation results of both the high and low Null-scenario are presented in Figures 4.12 and 4.13.

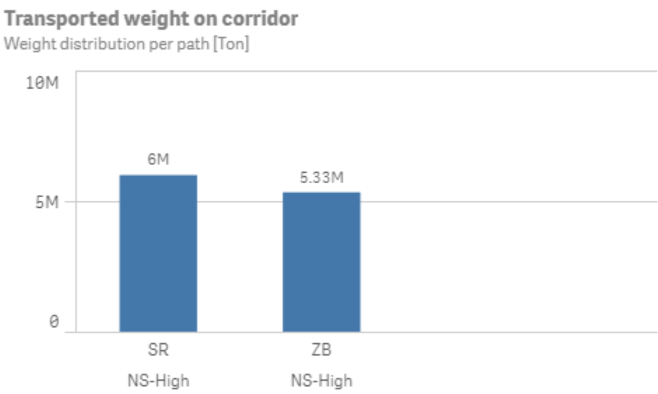

Figure 4.12: Transported cargo distribution Null-scenario high

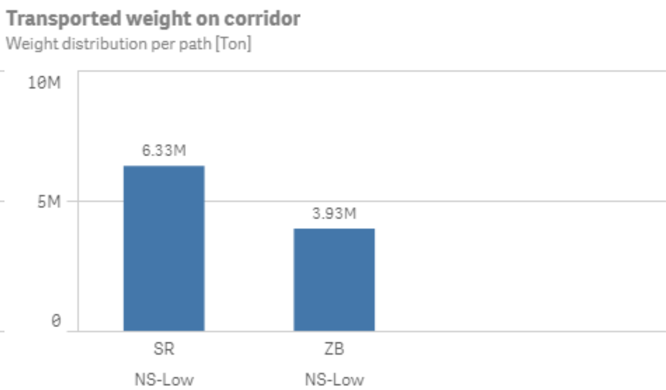

Figure 4.13: Transported cargo distribution Null-scenario low

The Null-scenario high shows a large increase in transported cargo over the Zuid-Beveland route. This can be explained by the fact that the increase of the fleet is much higher on the Zuid-Beveland route than on the Scheldt-Rhine route, especially for the high economic forecast. Additionally large, loaded vessels that are not able to take the Scheldt-Rhine route must take the Zuid-Beveland route. Resulting in more loaded and thus cargo transporting vessels to take the Zuid-Beveland route. For the Null-scenario the results are in the range of the Base case. Showing growth in fleet size and transported cargo but no significant changes in distributions.

Waiting times and I/C ratio's

Now the distributions, fleet and cargo size are checked the corresponding waiting times and I/C ratio's can be evaluated. The average carried cargo in the low Null-scenario equals 1103 ton per vessel. In the high Null-scenario the average carried cargo per vessel equals 1185 ton. In both cases the same average loading rates are assumed as in the Base case. The average loading capacity of vessels in the low economic scenario is therefore 1697 ton and in the high scenario 1823 ton. The average waiting times per lock and the calculated I/C ratio's are presented in Tables 4.19, 4.20 and 4.21.

Table 4.19: Waiting times per lock and total waiting times per route, Null-scenarios 2030

	Average waiting time Krammer lock [min]	**Average waiting time Hansweert lock [min]**	**Total waiting time Zuid-Beveland route [min]**	**Average waiting time Kreekrak lock [min]**	**Total waiting time Scheldt-Rhine route [min]**
Null-scenario low	35	14	49	25	25
Null-scenario high	42	16	59	30	30

Table 4.20: I/C ratio's Null-scenario low

Lock:	**Capacity [vessels/ hour]**	**Capacity [Ton/ hour]**	**Intensity in simulation [vessels/hour]**	**Intensity in simulation [capacity ton/hour]**	**I/C ratio**	**Waiting times experienced in simulation**
Kreekrak	16	27152	7.8	13575	0.48	25
Krammer	8	13576	4.7	8485	0.59	35
Hansweert	14	23758	4.7	7976	0.34	14

Table 4.21: I/C ratio's Null-scenario high

Lock:	**Capacity [vessels/ hour]**	**Capacity [Ton/ hour]**	**Intensity in simulation [vessels/hour]**	**Intensity in simulation [capacity ton/hour]**	**I/C ratio**	**Waiting times experienced in simulation**
Kreekrak	16	29168	8	14584	0.50	30
Krammer	8	14584	4.9	8933	0.61	42
Hansweert	14	25522	4.9	8933	0.35	16

From Table 4.20 it becomes clear that the Krammer locks becomes even more problematic than it is in the Base case. The waiting times are equal to 35 minutes and this is above the accepted maximum of 30 minutes waiting time. The other two locks stay below the I/C ratio of 0.5. In the low Null-scenario these two locks therefore still fulfill the waiting time requirements. This corresponds to the low economic fleet scenario for this corridor in 2030 (Rijkswaterstaat, 2017a). Table 4.21 states that in the high Null-scenario the I/C ratio's of the Kreekrak and Krammer locks become above or equal to 0.5. The Krammer locks therefore show a capacity issue in both the high and low economic forecasts. The Kreekrak locks only become problematic in the high economic scenario. This also corresponds to the high economic forecasts for this corridor in 2030 (Rijkswaterstaat, 2017a). It must be noted that the model simulates the Krammer locks in their current state. Meaning that the new salt/fresh water system is not yet implemented and the operational cycle of the lock therefore has the same duration as in the current state.

Results Null-Scenarios

Now that the components of the Null-scenarios that could be calibrated have been calibrated the emission outcomes of the Null-scenarios can by analysed. The outcomes for both Null-scenarios on energy consumption, emission levels and average waiting and sailing times are presented in the Figures below.

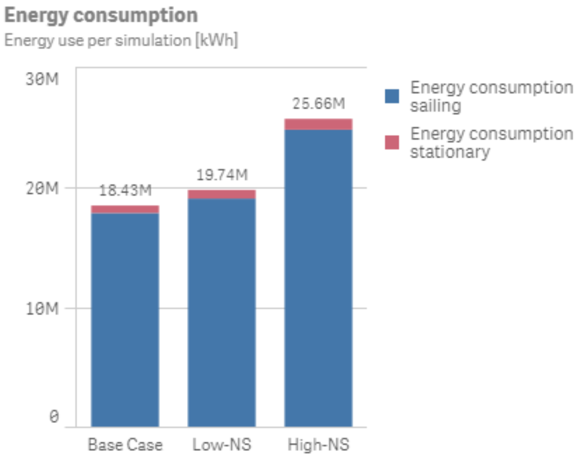

Figure 4.14: Energy consumption Base case and the two Null-scenarios

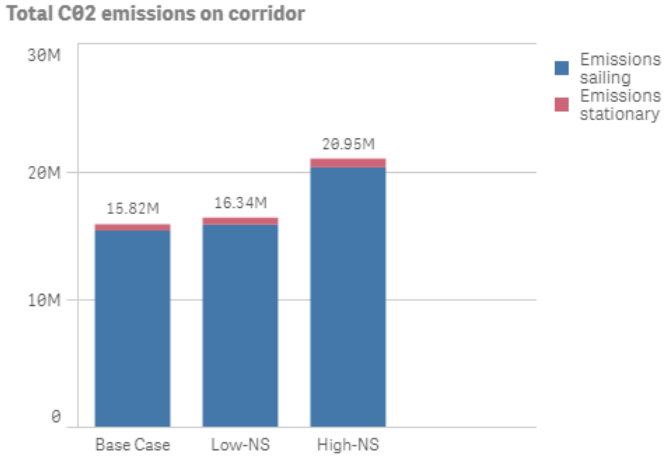

Figure 4.15: Emission levels Base case and the two Null-scenarios

Figures 4.14 and 4.15 present the energy use and emission levels for the Base case and the Null-scenarios. The outcomes confirm the analysed results from the previous Sections. In both economic fleet forecasts the fleet size and transported cargo size increases. In the low economic growth scenario this growth is limited which most probably result in slightly higher energy consumption levels and emission levels. This is confirmed by the low Null-scenario results presented in Figures 4.14 and 4.15. In the high economic growth scenario the fleet size and the amount of transported cargo show a much stronger increase until 2030. The associated energy use and emission levels should accordingly show a stronger increase. This is confirmed by the high Null-scenario for both the energy consumption and emission levels.

Next to the energy consumption and emission increases the waiting times are expected to increase as well. Figures 4.16 and 4.17 present the results of the two Null-scenarios.

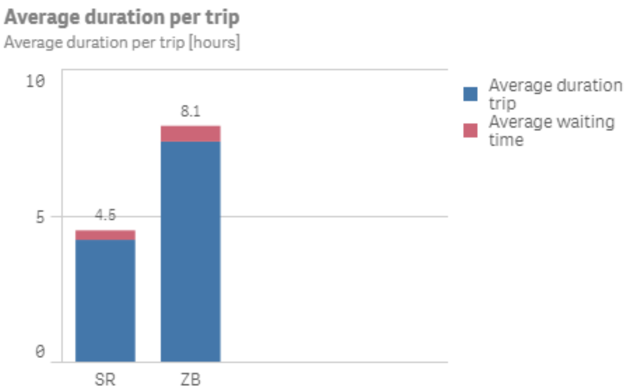

Figure 4.16: Average sailing and waiting times Null-scenario low

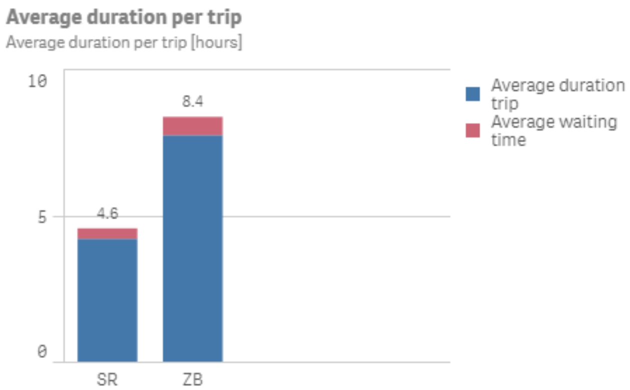

Figure 4.17: Average sailing and waiting times Null-scenario high

Figures 4.16 and 4.17 confirm the expected increase in waiting times and therefore also the increase in average total sailing times. This coincides with the economic fleet forecasts of longer waiting times on which the model is based (Rijkswaterstaat, 2017a).

4.3. Conclusion

This Chapter should answer the third sub question of this research. The third sub question states:

Can the levels of CO_2 emissions for the Base case and the Null-scenarios be simulated and what are the corresponding levels of CO_2 emissions?

To answer this question first the internal functioning of the simulation model needed to be validated. This has been done by validating the most important aspects relating to the corridor. Namely, the fleet, the locks and bridges and the emission calculations. First four checks have been carried out on the fleet assuring that individual vessels take the route they should based on their specific characteristics and the restrictions set on the network. Once the functioning of the fleet on the network has been tested, the functioning of the locks could be tested. This has been done by analysing the basic functioning of the locks an comparing it to how locks should function. The basic components for the emission calculations in the model have been compared to other studies focused on emission productions by the inland shipping fleet. After the functioning of these components had been verified the model as a whole could be analysed.

In Section 4.2 the model has been calibrated for the Base case and the Null-scenarios. This has been done to analyse how good the model could simulate the actual corridor and its functioning. This has first been done for the Base case. The Base case tries to simulate the current situation on the corridor and each component of this simulation can therefore be calibrated using data on the current functioning of the corridor. The the simulation outcomes on fleet distribution, transported cargo, arrival rates and waiting times at locks have been checked and verified. Once this was done it was possible to analyse the current energy consumption and emission levels on the corridor. Hereby answering the first part of this sub question. Namely, the ability of the model to simulate the current fleet, its components and the corresponding emission levels.

The last Section of the Chapter tried to calibrate the Null-scenarios implemented in the model. This has been done by comparing the results of the model with forecasts of Rijkswaterstaat on the fleet composition in 2030, for the high and low economic scenario (Rijkswaterstaat, 2017a). Making it possible to answer the last part of the third the question. It can be concluded that the individual model components work properly and that the current situation can be simulated correctly, to a certain extend, as the Base case in the model. The economic forecasts for 2030, simulated in the model as the Null-scenarios, show results that coincide with the expectations for this specific corridor in 2030. It is therefore concluded that also the energy consumption and emission patterns on the corridor can be simulated for the year 2030.

5 Application

Where Chapter 4 elaborated on the accuracy and the limitations of the model, this Chapter implements the measures and analyses the effects of the implementations. The fourth sub question of this research is therefore answered in this Chapter:

What are the effects of implementing measures on the CO_2 emission levels and what are the impacts of these implementations?

Section 5.1 presents the implementation of the three infrastructural modifications and analyses the impact of these measures. Section 5.2 presents the implementation of the fleet scenarios and their impact. All the design measures and fleet scenarios are implemented into the models Null-scenarios. This research tries to analyse the effects of future design measures and fleet scenarios. As the goal of Rijkswaterstaat is to have energy neutral operating transport networks by 2030, 2030 is chosen as basis year. Resulting in the two Null-scenarios forming the foundation for the designs measures and fleet impact scenarios.

5.1. Infrastructural modifications

This Section has its focus on the infrastructural modifications that can be implemented in the network. First the results of the increase of the bridges heights on the Scheldt-Rhine canal are analysed. Followed by the conversion of the Bathse sluice to an actual lock and the complete removal of the Kreekrak locks.

5.1.1. Increased bridge height on the Scheldt-Rhine canal

The design implementation to increase the bridge heights on the Scheldt-Rhine canal has been intensely studied for and with Rijkswaterstaat. The Scheldt-Rhine canal has five bridges not fulfilling the SVIR height requirements (Ministerie van Infrastructuur en Milieu, 2012). Besides the fact that main waterways, such as the Scheldt-Rhine canal, should be able to provide passage to 4-layer container vessels, the alternative route now taken is much longer and has two lock passages instead of one.

A cost-benefit study, on the increase of the bridge height on this corridor, resulted in a negative advise for almost all scenarios and economic forecasts (Arcadis, 2016). However, the alternative without the Moerdijk bridges in the analyses resulted in a positive outcome. A large part of the study done by Arcadis, for Rijkswaterstaat, focuses on the costs of the operation of bridge height increase. The Zuid-Beveland route is even mentioned as an argument for not increasing the bridge heights on the Scheldt-Rhine canal (Arcadis, 2016). From the perspective of the present study, taking a longer route is definitely not a recommended alternative. Additionally, the Moerdijk bridges are not part of the present study and it can therefore be interesting to compare the results obtained here with the cost-benefit analysis done by Arcadis.

This study has its complete focus on emission patterns and the influence of interventions on these patterns. Although reduction of CO_2 levels might not directly be easy to quantify in money it can contribute to a cleaner world in the future. Reasoned this way, the implementation of bridge height increase in the model could be a complement to the research already done. The outcomes of the bridge height increase on the Scheldt-Rhine route are analysed by first analysing the changes in sailing pattern and the changes in total sailing times. After which the effects of these changes on energy consumption and total emission levels are analysed.

Sailing patterns and duration

The bridge height increase takes away the height restriction on the Scheldt-Rhine route. This allows large 4-layer container vessels, heading for Antwerp, to take the Scheldt-Rhine route again. It is therefore expected that the sailing patterns of large container vessels, with destination Antwerp, will change. In the low Null-scenario the share of 4-layer container vessels in the entire fleet is smaller than the share of these vessels in the high Null-scenario. It is therefore expected that the effects are largest for the High Null-scenario. In Figures 5.1 and 5.2 the results for the two Null-scenarios are presented.

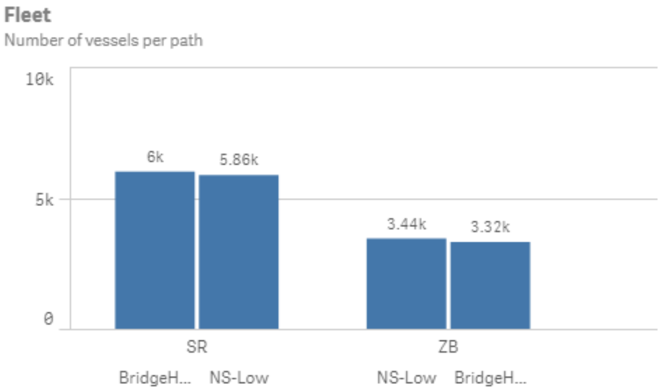

Figure 5.1: Fleet distribution for low Null-scenario and implemented higher bridges

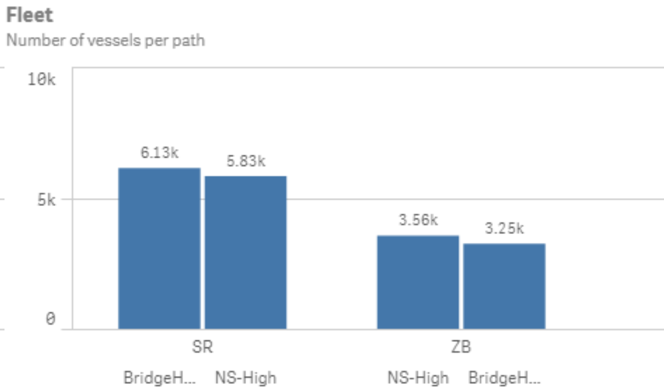

Figure 5.2: Fleet distribution for high Null-scenario and implemented higher bridges

Figures 5.1 and 5.2 indeed show that the effect of the bridge height increase effects the high-Null scenario the most. In the high-Null scenario, three hundred vessels a month now take the Scheldt-Rhine route instead of the Zuid-Beveland route. The total number of vessels on the Scheldt-Rhine route increases with 5%. In total 65.5% of the fleet now takes the Scheldt-Rhine route. For the low Null-scenario the changes are much smaller, just 2% of the fleet normally taking the Zuid-Beveland route now changes its course to the shorter Scheldt-Rhine canal.

The effects of these changes in sailing patterns on the average sailing times on the route are presented in Appendix E, Section E.1. Changes in the low Null-scenario are very small but the high Null-scenario shows clear changes in waiting times. Increasing the bridge height results in a decrease in waiting times on the Zuid-Beveland route and an increase in waiting times on the Scheldt-Rhine route. The changes in waiting times are presented in Table 5.1.

Table 5.1: Waiting times after implementation higher bridges

Lock:	**Waiting time Null-scenario low**	**Waiting time Null-scenario low with increased bridge height**	**Waiting time Null-scenario high**	**Waiting time Null-scenario high with increased bridge height**
Kreekrak	25	26	30	34
Krammer	35	33	42	38
Hansweert	14	14	16	14

Increasing the bridge height on the Scheldt-Rhine canal results in more vessels taking the Scheldt-Rhine route which increases the number of vessels arriving at the Kreekrak locks every day. For the high Null-scenario this results in 10 extra vessels arriving at the Kreekrak locks every day. The consequence of this can immediately be felt in the form of waiting times before the Kreekrak locks. In the high Null-scenario the waiting times increase from 30 minutes to an average of 34 minutes. Which results in the Kreekrak locks not meeting the SVIR requirement of 30 minutes maximum waiting time. On the other hand the implementation does result in the decrease of waiting times on the Zuid-Beveland route. However, in both Null-scenarios the Krammer locks stay problematic and does still not meet the SVIR requirements (Ministerie van Infrastructuur en Milieu, 2012). Which changes are predominant on the outcomes of energy consumption and emission levels is discussed in the next Section.

Energy consumption and emission levels

Increasing the bridge height on the Scheldt-Rhine route changes the sailing patterns of vessels in the fleet. In the low Null-scenario the changes in sailing patterns appear smaller than the changes in the high Null-scenario. The changed sailing patterns influence the average sailing times of vessels on both routes. The effects of these changes can be translated to changes in energy consumption and emission levels. The achieved changes, based on the increase of bridge height, are presented in the Figures below.

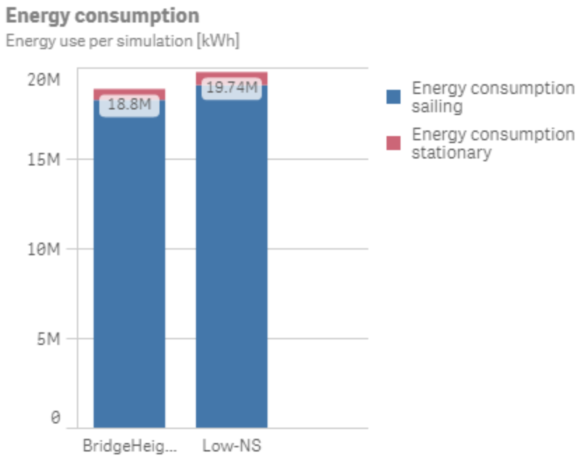

Figure 5.3: Energy consumption in the low Null-scenario and with higher bridges

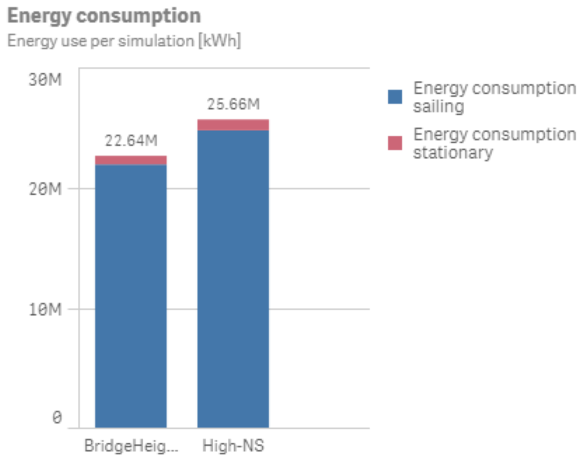

Figure 5.4: Energy consumption in the high Null-scenario and with higher bridges

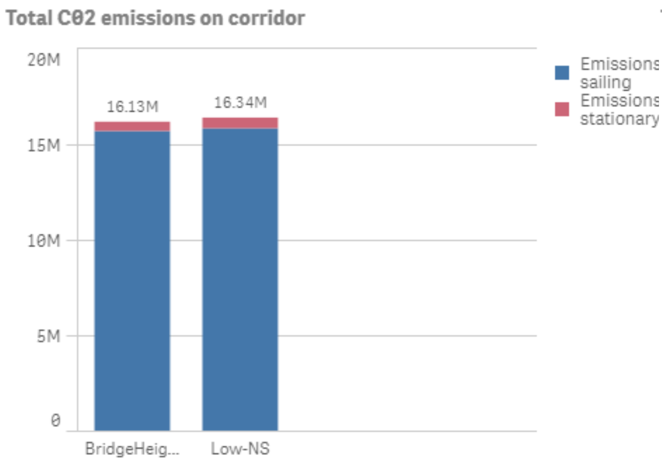

Figure 5.5: Emission levels in the low Null-scenario and with higher bridges

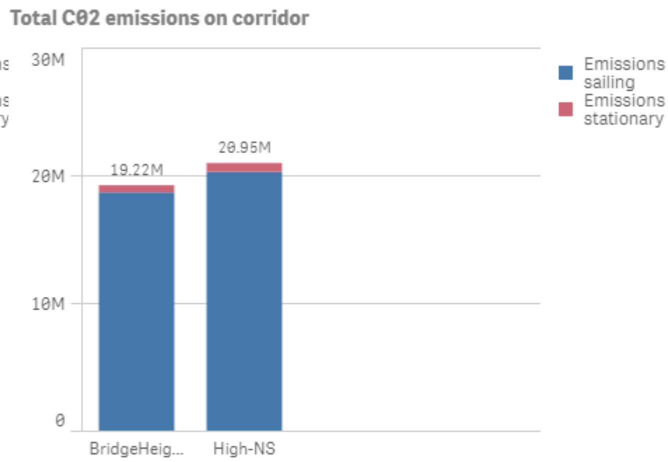

Figure 5.6: Emission levels in the high Null-scenario and with higher bridges

The Figures above show a clear pattern. The bridge height increase results in a reduction of the total energy consumption and emission levels on the corridor. The changed sailing patterns, of the large container vessels, to the shorter Scheldt-Rhine route and the reduction in waiting times on the Zuid-Beveland route have a stronger influence on the energy consumption than the increased waiting times at the Kreekak locks. Which can be explained by the fact that during waiting the energy use is 15% of the energy use during sailing. Because of this, vessels taking a shorter route influence the energy consumption more than vessels waiting in stationary conditions. The reduction of the emission level in the low Null-scenario equals 210,000 kg, which is equivalent to 1.3% of the total emission levels. In the high Null-scenario the emission levels reduce with 8.25% which is a significantly larger change than in the low economic scenario.

It can be concluded that increasing the bridge heights on the Scheldt-Rhine route changes the sailing patterns of the large container vessels, and with this changes in waiting times at the locks occur. The overall changes in the low Null-scenario are small and result in an decrease of the emission levels of 1.3%. In the high Null-scenario the sailing patterns of 5% of the fleet change. This results in an increase of waiting times at the Kreekrak locks and a decrease in waiting times at the locks on the Zuid-Beveland route. The emission levels are reduced with 8.25%, which is a significant reduction. However, the question remains if this reduction is large enough, as due to this implementation, the the capacity problems at the Kreekrak locks increase and the waiting times become higher than 30 minutes.

5.1.2. Conversion Bathse sluice into a lock

This Section focuses on the conversion of the Bathse sluice into a full lock. As has been mentioned in Section 3.3.1 the Bathse canal is located next to southern part of the Scheldt-Rhine canal. Just before the Kreekrak locks the Scheldt-Rhine canal has a bifurcation point. This is where the Bathse canal starts. In Chapter 4 it became clear that the Kreekrak locks will experience higher waiting times in 2030, both for the high and low Null-scenario. Additionally, with the fleet size and vessels size increasing over the coming years, the number of vessels forced to take the longer Zuid-Beveland route will only increase. The conversion of the Bathse lock could be a solution.

The results of the Null-scenarios showed that the Krammer locks will have serious capacity problems in 2030, for both Null-scenarios. The Kreekrak locks are also expected to become problematic. Waiting times, in both Null-scenarios, are expected to become around the 30 minutes and therefore become to high. The expected increase in vessel size will force even more vessels to take the Zuid-Beveland route although they have destination Antwerp.

The above mentioned trends increase the energy consumption and emission levels on the corridor. The Bathse lock could provide a solution for most of these issues. To analyse the implementation of the Bathse locks this Section is divided into sub Sections. First the distribution of vessels over the corridor is analysed and compared to the original Null-scenarios. In the subsequent Section the effects of the changing sailing patterns on the average sailing times are analysed. The last Section analyses the energy consumption and emission pattern changes and the effects of these changes on the total emission levels.

Fleet distribution corridor

Where in the Null-scenario there where two route choices there are now three. The implementation of the Bathse lock results in multiple sailing pattern changes. The fleet distribution over the paths is presented in Figures 5.7 and 5.8 for implementation in both Null-scenarios.

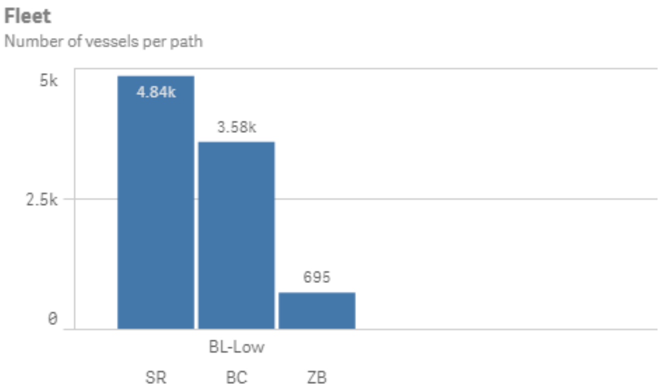

Figure 5.7: Fleet distribution after implementation Bathse lock in Null-scenario low

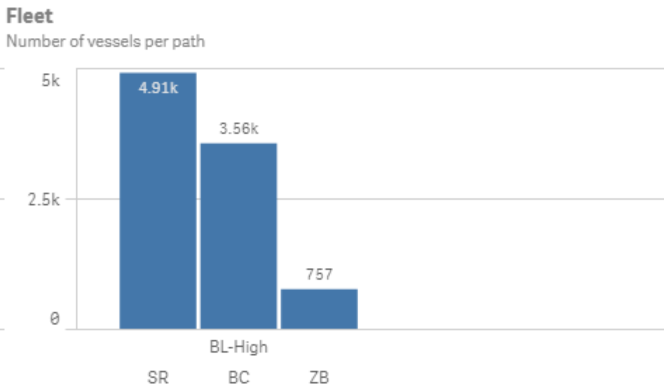

Figure 5.8: Fleet distribution after implementation Bathse lock in Null-scenario high

The distribution shows that instead of about 37% of the fleet taking the Zuid-Beveland route now about 10% takes the Zuid-Beveland route. The height restriction is still in place so the large container vessels still need to take the longer Zuid-Beveland route. However, the majority of the Zuid-Beveland fleet now takes the Bathse canal route as there is only one lock passage and the route is shorter. Next to this, the vessels that need to be at the west-side of the Antwerp port can now take the Bathse canal route. By taking the Bathse canal these vessels only pass one lock instead of two. One instead of two because before vessels (with destination west-side of the Antwerp port) had to pass the Kreekrak locks and Berendrecht locks. These changes effect the average sailing times and emission levels. In the next Section the changes in sailing times are analysed.

Average sailing times

As the sailing patterns change on the corridor, the average duration per trip changes as well. The results of the total sailing times are presented in Figures 5.9 and 5.10.

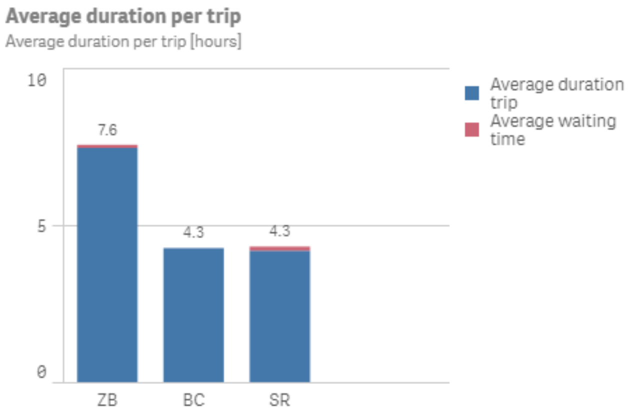

Figure 5.9: Average sailing and waiting times after implementation Bathse lock in low Null-scenario

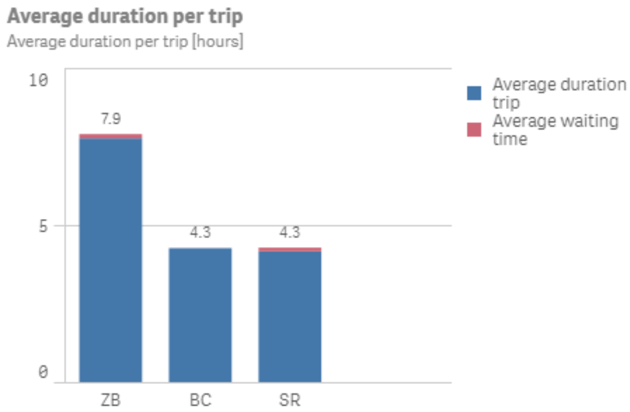

Figure 5.10: Average sailing and waiting times after implementation Bathse lock in high Null-scenario

From Figures 5.9 and 5.10 it becomes clear that indeed the average sailing times decrease. Especially on the Zuid-Beveland route the differences are large. A large part of the fleet now takes the Scheldt-Rhine or Bathse canal route. This reduces the average sailing times on the Zuid-Beveland route with approximately half an hour. This is mainly caused by the large reduction in waiting times before locks on this route.

In the high Null-scenario the total waiting times on the Zuid-Beveland route reduce from 59 minutes to 30 minutes, a reduction of 49%. In the low Null-scenario the total waiting times on the Zuid-Beveland route reduce from 49 to 27 minutes, a reduction of 45%. Additionally, both Null-scenarios see a reduction of average waiting time at the Kreekrak locks of respectively, 25 and 30 minutes to 18 minutes.

The large reductions in waiting times at the locks are very promising in terms of capacity issues expected in 2030. If this measure also reduces the emission levels of the fleet is discussed in the next Section. Table 5.2 shows the waiting time reduction per lock for the low and high Null-scenarios.

Table 5.2: Waiting time changes after implementation Bathse lock

Scenario:	**Krammer locks [min]**	**Krammer locks with Bathse lock implementation [min]**	**Hansweert locks [min]**	**Hansweert locks with Bathse lock implementation [min]**	**Kreekrak locks [min]**	**Kreekrak locks with Bathse lock implementation [min]**
Null-scenario low	35	18	14	7	25	18
Null-scenario high	42	22	16	8	30	18

Emission levels

This Subsection covers the changes in energy consumption and emission levels caused by the changing fleet behaviour. To get an indication of where most changes occur the low Null-scenario is first analysed per path. Figure 5.11 presents the energy consumption per path, with and without the implementation of the Bathse lock. The abbreviation BC stands for the Bathse canal route and BL-low is an abbreviation for Bathse lock in the low Null-scenario.

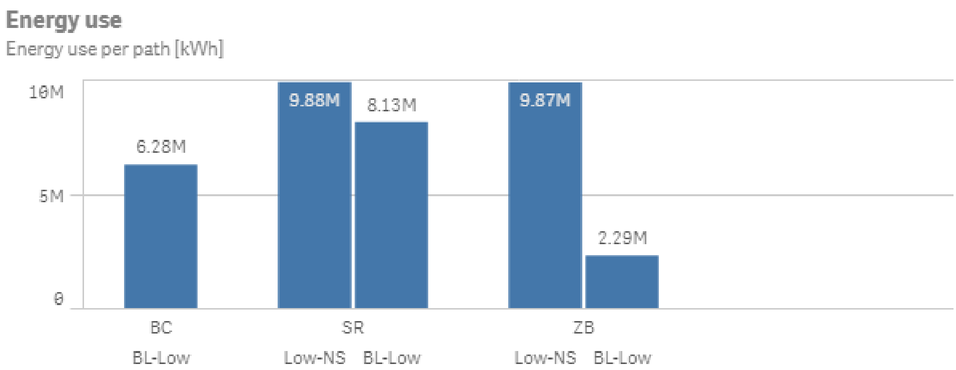

Figure 5.11: Energy consumption per path for Bathse lock scenario and Null-scenario low

From Figure 5.11 it becomes clear that in the low Null-scenario no vessels take the Bathse canal route. Which should be the case as the Bathse route did not existed in the low Null-scenario. There are multiple observations that can be made from Figure 5.11. First the Scheldt-Rhine canal is analysed.

Figure 5.11 clearly shows that the energy consumption decreases on the Scheldt-Rhine canal. This is caused by two factors namely, the reduction in waiting times before the Kreekrak locks and the partial change in sailing behaviour of the fleet. The reduction in energy consumption on this part of the corridor is almost 18%.

The Zuid-Beveland route sees the largest reduction in energy use. Where the energy use used to be 9.87 million kWh a month, it reduces to 2.29 million kWh a month with the implemented of the Bathse lock. This is equal to a reduction of 77% on this part of the corridor. The large reduction is caused by the fact that the majority of the fleet now chooses the shorter Bathse canal route and not the Zuid-Beveland route.

It should be noted that part of these reductions is compensated by the fleet now taking the Bathse canal route. Where the reduction on the Scheldt-Rhine route and the Zuid-Beveland route is very large a considerable part is now produced on the Bathse canal route. The final results on the energy consumption and emission levels are presented in the four Figures below.

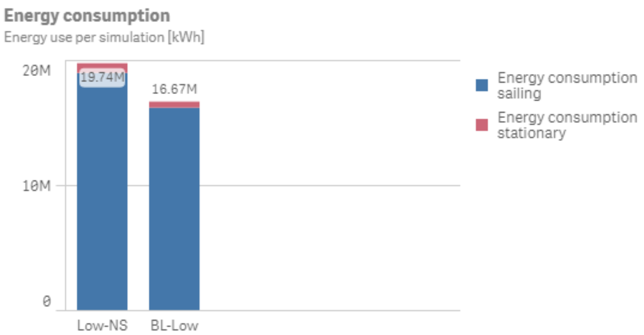

Figure 5.12: Energy consumption in the low Null-scenario with implementation Bathse lock

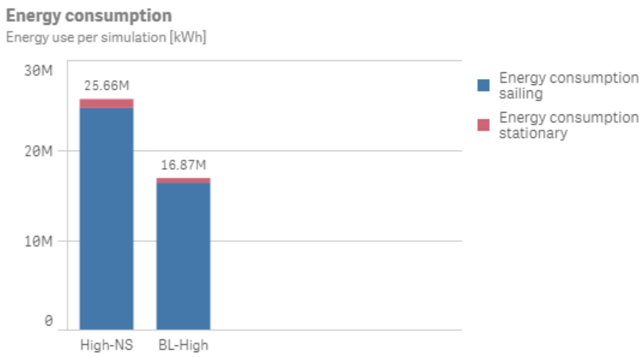

Figure 5.13: Energy consumption in the high Null-scenario with implementation Bathse lock

Figures 5.12 and 5.13 clearly show a reduction in energy consumption of the fleet. The implementation of the Bathse lock in the low Null-scenario reduces the energy consumption by 15.5%. In the high Null-scenario this reduction is higher and results in a total reduction of 35%. The reduction in total emission levels for both Null-scenarios are presented in Figures 5.14 and 5.15.

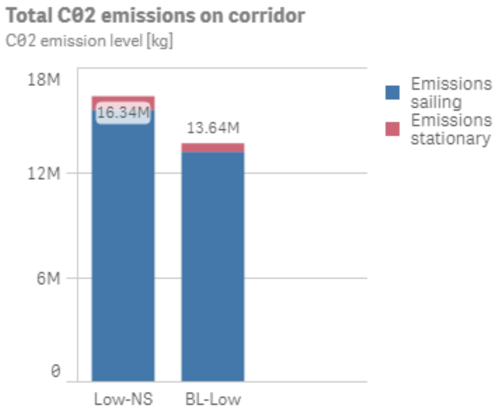

Figure 5.14: Emission levels in the low Null-scenario with implementation Bathse lock

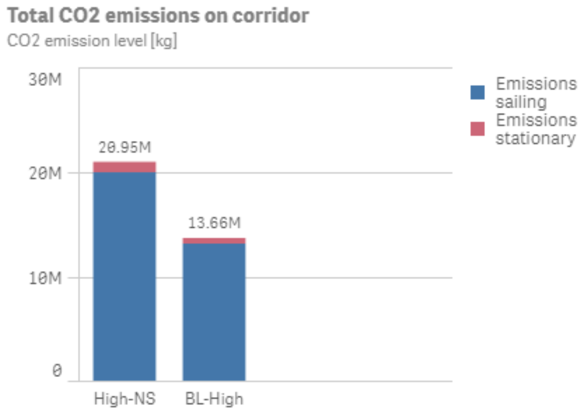

Figure 5.15: Emission levels in the high Null-scenario with implementation Bathse lock

The emission levels decrease with substantial amounts as can be seen from Figures 5.14 and 5.15. In the low Null-scenario the reduction in total emission level equals 16.5%. This is even a bit larger than the total energy consumption reduction. This is most probably caused by the fact that sailing patterns have changed. Apparently, the vessel distribution with the Bathse lock implementation changes in such a way that the cleaner vessels (lower emission factors) take the longer Zuid-Beveland route and the more polluting vessels the shorter route. This causes the difference between emission levels to be larger than the difference in energy consumption levels. This reasoning makes sense as the large 4-layer container vessels are often rather new and therefore have cleaner engines with consequently, lower emission factors.

The reduction in the high Null-scenario is even larger. The emission level is reduced with 35%. In both Null-scenarios the reduction in emission levels is very high and this design measure is therefore very interesting. Not only do the emission levels decrease with large numbers, the capacity problems at the Krammer locks and Kreekrak locks are also solved without expansion of the locks needed. The waiting times on the Zuid-Beveland route reduced with respectively, 45% and 49%. On the Scheldt-Rhine the Kreekrak locks see a waiting time reduction of respectively, 28% and 40%.

It should however be noted that in the Bathse lock is assumed to have a large capacity and is therefore able to handle the vessels arriving at the lock very fast. Overall it can be stated that, with focus on emission reduction, this design measure could be very useful.

It can be concluded that the implementation of the Bathse lock influences the sailing patterns of the fleet. The changed sailing patters towards the Bathse canal route largely reduce the waiting times on the Zuid-Beveland route and Scheldt-Rhine route in both Null-scenarios. These changes reduce the emission levels on the corridor significantly. In the low Null-scenario a totel emission reduction of 16.5% can be seen and in the high Null-scenario this reduction equals 35%.

5.1.3. Removal Kreekrak locks

The removal of the Kreekrak locks is probably the most extreme measure presented in this research. The effects of the Kreekrak locks on the emission levels is not known and with the expected increase of fleet and cargo size it is interesting to see what effect the complete removal of the Kreekrak locks would have. The possible other effects associated with the removal of the lock, such as salinization of the Zoomlake are out of the scope of this research and therefore not studied.

Other than in the first design measure, bridge height increase, the sailing patterns are not expected to change for this implementation. It is highly unlikely that, even with the Kreekrak locks removed, vessels with destinations other than Antwerp will take the Scheldt-Rhine route. They will still have to sail through the port of Antwerp, take the Berendrecht locks and continue their journey. Vessels, with a destination other than Antwerp, choosing this option over the Zuid-Beveland route is highly unlikely. The sailing patterns should therefore stay the same for this measure. All the changes felt by this measure should be felt on the Scheldt-Rhine route and the Zuid-Beveland route should in principle have the same characteristics.

Appendix E, Section E.2 shows the fleet distribution of the Kreekrak removal measure together with the Null-scenarios. The fleet distribution stays the same for both the Null-scenarios. As a consequence the waiting times and total average sailing times stay the same for the Zuid-Beveland route. The focus for this measure is therefore on the changes on the Scheldt-Rhine route. The changes in waiting times at the locks are presented in Table 5.3.

Table 5.3: Waiting times after implementation Kreekrak locks removal

Lock:	**Waiting time Null-scenario low**	**Waiting time Null-scenario low with removal Kreekrak locks**	**Waiting time Null-scenario high**	**Waiting time Null-scenario high with removal Kreekrak locks**
Kreekrak	25	0	30	0
Krammer	35	35	42	42
Hansweert	14	14	16	16

As anticipated, the waiting times at the Kreekrak locks become zero in both Null-scenarios. On the Zuid-Beveland route the waiting times stay the same as nothing changes on the Zuid-Beveland route. This results in the total sailing times presented in Figures 5.18 and 5.19. As comparison, Figures 5.16 and 5.17 show the average sailing times of the Null-scenarios without removal of the Kreekrak locks.

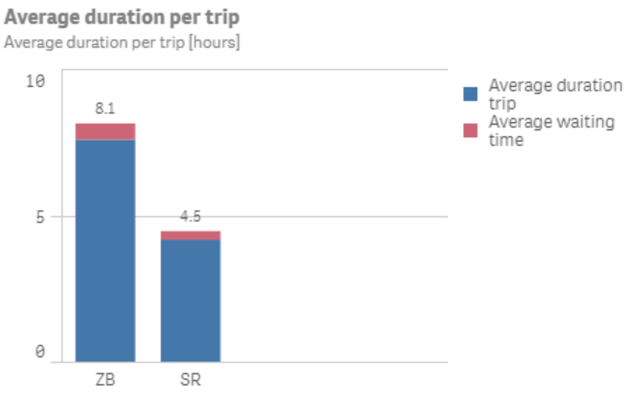

Figure 5.16: Average sailing times in low Null-scenario

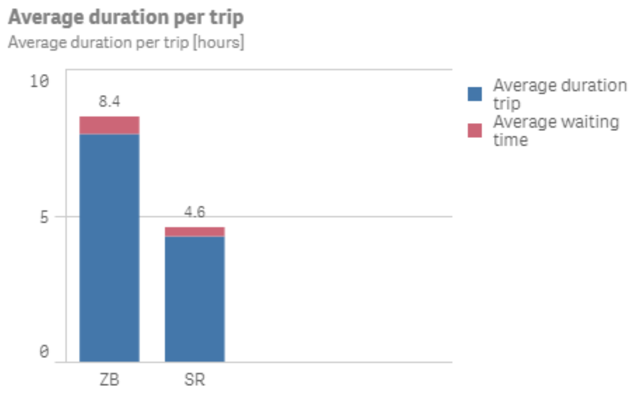

Figure 5.17: Average sailing times in high Null-scenario

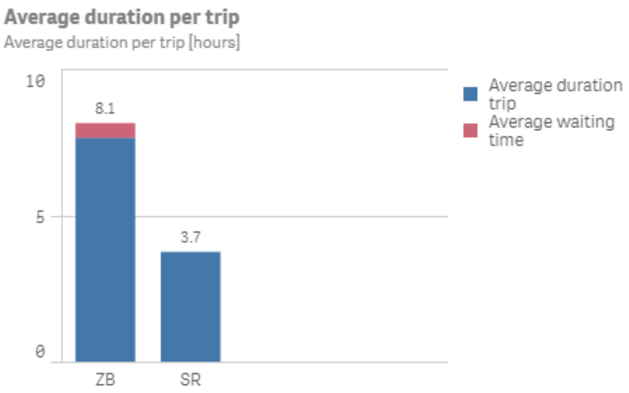

Figure 5.18: Average sailing times after removal of the Kreekrak locks in low Null-scenario

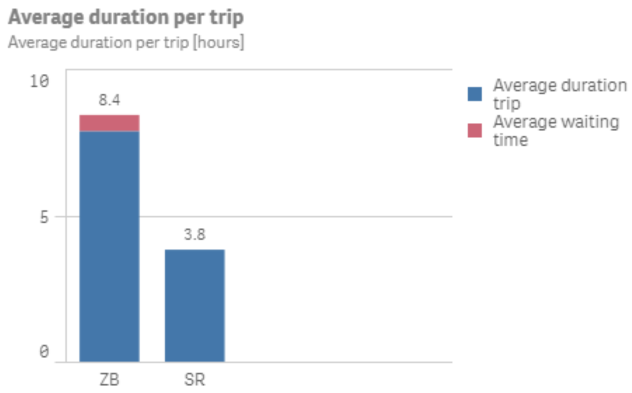

Figure 5.19: Average sailing times after removal of the Kreekrak locks in high Null-scenario

From Figures 5.18 and 5.19 it becomes clear that indeed the sailing times decrease on the Scheldt-Rhine route in both Null-scenarios. There are no waiting times any more and the average duration per trip decreases with about 48 minutes. However, the energy use around locks is only 15% of the energy use during sailing. The effects of removal of the Kreekrak locks may be felt in sailing times but the effect may be limited for the energy consumption and emission levels. The effects of the Kreekrak locks removal on the energy consumption and emission levels is presented in the Figures below. The Kreekrak locks removal is indicated as KL high or low. Indicating that it is implemented in the high or low Null-scenario.

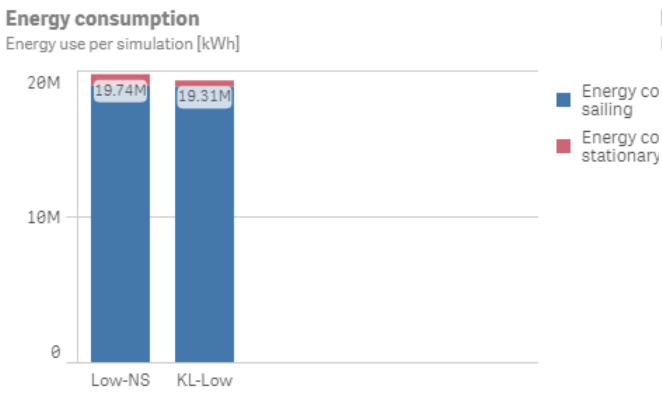

Figure 5.20: Energy consumption in the low Null-scenario with removed Kreekrak locks

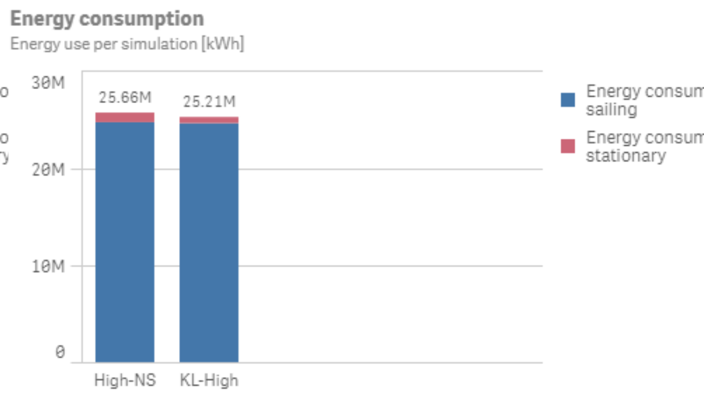

Figure 5.21: Energy consumption in the high Null-scenario with removed Kreekrak locks

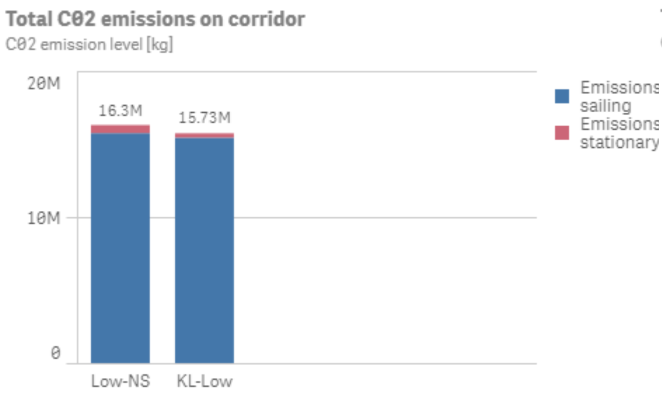

Figure 5.22: Emission levels in the low Null-scenario with removed Kreekrak locks

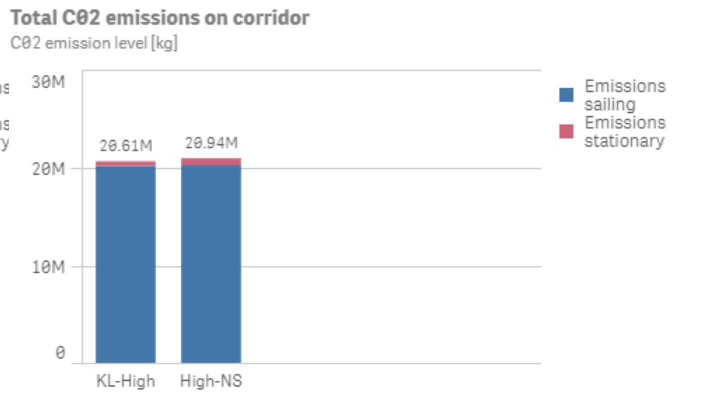

Figure 5.23: Emission levels in the high Null-scenario with removed Kreekrak locks

From Figures 5.20 and 5.21 it becomes clear that there is a reduction in energy use in both the Null-scenarios. This results in the lowering of the emission levels shown in Figure 5.22 and 5.23. In the low Null-scenario the emission levels decrease with a total of 3.5%. In the high Null-scenario the emission levels decrease with 1.6%.

Next to the emission reduction in kg it is interesting to see what the removal of the Kreekrak locks does to the reduction in gram per ton kilometer. On the Zuid-Beveland route there should be no changes visible and on the Scheldt-Rhine route a reduction of the emissions in gram/ton kilometer is expected. The results of the emissions in gram per ton kilometer, for the removal of the Kreekrak locks, are presented in Table 5.4.

Table 5.4: Emission levels per route with removed Kreekrak locks [g/tkm]

Route:	**Emissions Null-scenario low [g/tkm]**	**Emissions Null-scenario low Kreekrak locks removal [g/tkm]**	**Emissions Null-scenario high [g/tkm]**	**Emissions Null-scenario high Kreekrak locks removal [g/tkm]**
Zuid-Beveland	24.1	24.1	25.1	25.1
Scheldt-Rhine	23.7	23.4	24.9	24.8

From Table 5.4 it becomes clear that indeed the emission levels, in gram per ton kilometer, stay the same on the Zuid-Beveland route and reduce on the Scheldt-Rhine canal. The reductions are however small, for both the Null-scenarios.

It can be concluded that with the removal of the Kreekrak locks the average sailing times on the Scheldt-Rhine corridor reduce significantly (48 minutes). This results in the lowering of the emission levels of 3.5% in the low Null-scenario and 1.6% in the high Null-scenario. Although the average sailing times are reduced with at least 48 minutes this is not really felt in the emission levels. The reduction in both cases is not very striking. However, by removing the Kreekrak locks the capacity problem in the high Null-scenario is completely taken away. As the expansion of the Kreekrak locks is most probably necessary in the future, further research in the complete removal can be interesting as it positively effects the capacity problems and emission levels on the corridor.

5.2. Fleet scenarios

This Section analyses the implementation of the three fleet scenarios. The three fleet scenarios are implemented in both Null-scenarios for 2030.

5.2.1. High cube containers

As is explained in Section 3.3.2 high cube containers appear more often within the container fleet. The effects of a container fleet completely consisting of high cube containers is therefore included as a scenario in this study. A container fleet with only high cube containers results in the following height changes. 3-layer container vessels will have a height of 7.97 meter instead of 7 meter. 4-layer container vessels will become 10.42 meter high instead of 9.1 meter. The effect of the high cube containers will mostly be felt on the Zuid-Beveland route. On the Scheldt-Rhine route the height restriction is already 8.7 meter. Meaning that 4-layer container vessels are not able to pass this route today and this will stay the same in the case of high cube containers. The 3-layer container vessels become 7.97 meter, in the case of the high cube container scenario, and will still be able to take the Scheldt-Rhine route just as they do today. The implementation of this scenario will therefore only affect the Zuid-Beveland route. On the Zuid-Beveland route two movable bridges are present. The 4-layer container vessels now all have to wait for the movable bridges to be opened. Just like the removal of the Kreekrak locks sailing patterns will not change. The change in emissions levels and sailing times on the Zuid-Beveland route are analysed below.

As a first indicator of change the average sailing times are checked. The results implemented in both the Null-scenarios are presented in Figures 5.24 and 5.25.

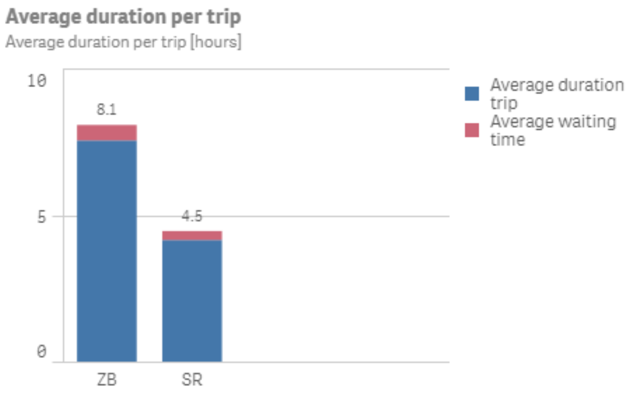

Figure 5.24: Average sailing time for High cube container scenario in low Null-scenario

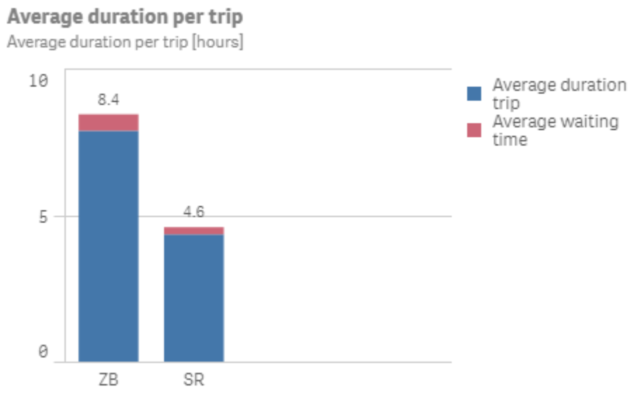

Figure 5.25: Average sailing time for High cube container scenario in high Null-scenario

From Figures 5.24 and 5.25 it becomes clear that there is no effect on the average sailing times on the Zuid-Beveland route. This can be explained by the fact that the number of vessels that need to wait is a small number of the fleet sailing over the Zuid-Beveland route. The majority of the fleet taking the Zuid-Beveland route are general and bulk cargo vessels. These vessels can easily pass the movable bridges that are encountered. Additionally, the vessels that do have to wait before the movable bridges do not have to wait long. In general the operating time of a bridge is about 10 minutes. The fact that the number of container vessels on the route is relatively small combined with short bridge operating times it makes sense that the average sailing times over a month stay more or less equal.

As the average sailing times stay the same there is no big difference expected in energy consumption and emission levels. This is indeed the case. Figures 5.26 and 5.27 show the emission levels of both Null-scenarios with the high cube container scenario implemented. Appendix E, Section E.3 presents the energy consumption levels for both cases. In the Figures, the abbreviation HC stands for high cube container scenario. The low and high stand for the implementation in the high or low Null-scenario.

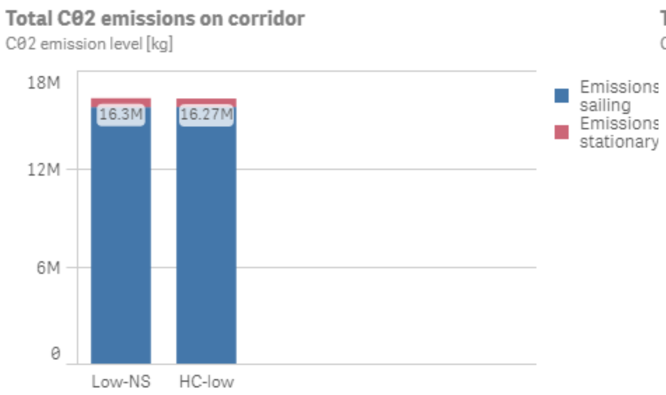

Figure 5.26: Emission level for high cube container scenario in Null-scenario low

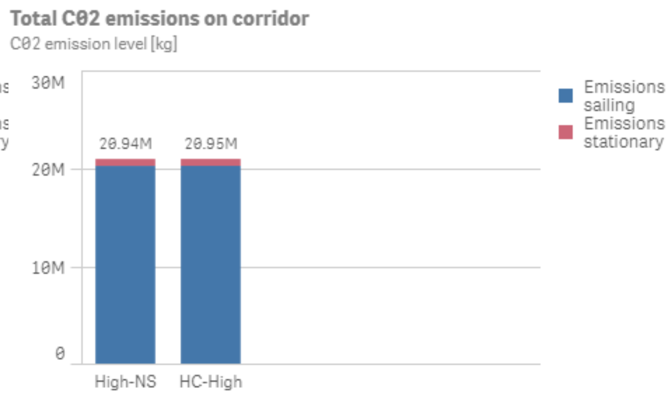

Figure 5.27: Emission level for high cube container scenario in Null-scenario high

Figures 5.26 and 5.27 indeed confirm that the implementation of a high cube container fleet does not effect the emission levels on the corridor. The very small difference between two charts in Figure 5.27 is a rounding error as from appendix E, Section E.3 it is clear that the energy consumption in the high Null-scenario is totally equal to that of the high Null-scenario with high cube containers. The difference seen in Figure 5.26 is a bit larger but still very small. The total difference is 0.18% from the low Null-scenario. Again, this could be caused by measurement errors or vessels generations in the model that are slightly different.It can be concluded that the introduction of a complete high cube container fleet does not affect the emission levels on this corridor.

5.2.2. Standard vessels and departure slots

This Section discusses the results of the standard vessels and departure slots scenario. In this scenario it is analysed if a complete other approach for the inland shipping fleet would significantly reduce the emission levels on the corridor. This scenario assumes three vessel types within the entire fleet. The vessels used in this approach are the M8, C4 and BII-4 vessel types. These vessels are chosen as they are three completely different vessels with the ability to carry a wide range of cargo. Next to this the dimensions of these vessel types fit the current lock dimensions on the corridor very well. Which makes the locking process more efficient. Next to only having, three vessels classes in the system, time slots are introduced. This assures an even distribution of vessels over the entire day and prevents peak levels during the day. Another adaption has been made concerning the loading rates of vessels. in this scenario the vessels are assumed to be loaded to their fullest extend. To keep the situation realistic halve of the fleet sails fully loaded and the other half sails completely empty. The results of this scenario are analysed in the Section below.

Sailing and waiting times

This scenario is implemented to show to what extend changes can be reached within the inland shipping fleet. One of those changes is trying to reduce the sailing times on the corridor by introducing time slots every hour. In this way vessels are distributed over the day evenly and capacity issues at locks should mainly be solved. Till what extend the implemented scenario reaches this goal can be done by analysing the waiting and total sailing times. In Figures 5.28 and 5.29 the total waiting and sailing times for both Null-scenarios are presented.

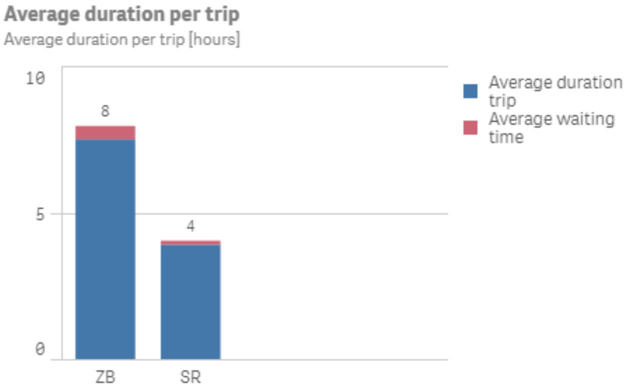

Figure 5.28: Average sailing time for standard vessel scenario in low Null-scenario

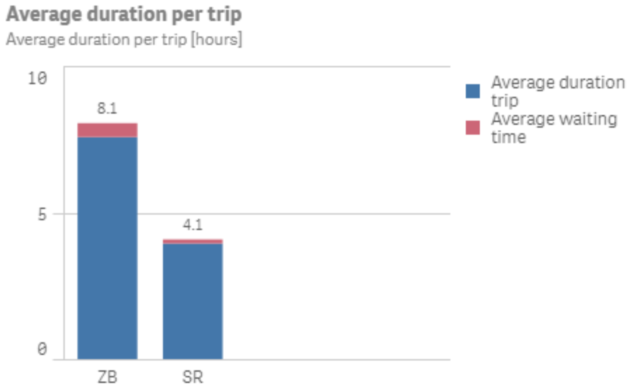

Figure 5.29: Average sailing time for standard vessel scenario in high Null-scenario

From Figure 5.28 it can be seen that indeed the sailing times are reduced for the low Null-scenario. The average sailing time on the Zuid-Beveland route is on average 7.5 hours. The total waiting time before the two locks is 27 minutes. Where in the low Null scenario the average waiting times used to be equal to 49 minutes on the Zuid-Beveland route. This means that the introduction of sailing time slots can reduce the average waiting times on the Zuid-Beveland canal with almost 45%. Vessels on the the Scheldt-Rhine canal experience average sailing times of 3.91 hours and average waiting times of 7.9 minutes. The waiting times, in the low Null-scenario, used to be 25 minutes on the Scheldt-Rhine route and are therefore reduced with 68%.

Figure 5.29 shows the results for the high Null-scenario. The implementation of standard vessels and time slots shows the same trend as in the low Null scenario. Average waiting times on the Zuid-Beveland route reduce with 50% to 28.4 minutes. On the Scheldt-Rhine route the average waiting times reduce with 72% to 8.3 minutes. The waiting times for the high and low Null-scenario are very close to each other. This makes sense as the vessels are implemented evenly over the day with 4 or 3 vessels each hour. Differences between the number of vessels in the high and low Null-scenario should therefore not be very large as the distribution of vessels is very wide and one vessel more or less an hour should not create large differences.

Energy consumption and emission levels

As has been seen for the previous scenarios and measures the reduction in waiting times does not effect the total emission levels on the corridor extremely. It contributes to the reduction of the emission levels but in the end the sailing patterns seem to have the largest influence. In this scenario the sailing patterns do not necessarily change but the size of the fleet is immensely reduced . Where in the low Null-scenario 109700 vessels where needed to transport the 121 million ton cargo, now only 33059 vessels per year are needed. In the high Null-scenario, where 131 million ton cargo needs transportation, not 110500 vessels are needed but only 35791 vessels. This is all caused by increasing the efficiency rates of the vessels on the corridor. Additionally, the vessels that are used in this scenario are the larger vessels within the fleet. The average loading rates of vessels on the corridor is now 7320 ton. The reduction of vessel passages with these numbers can have large effects on energy consumption and emission levels on the corridor. The results for both Null-scenarios are presented in the Figures below.

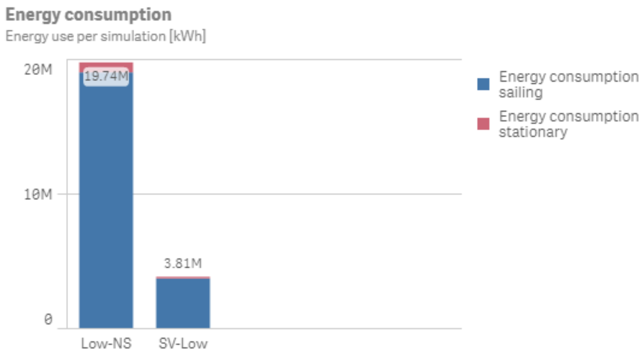

Figure 5.30: Energy consumption for standard vessels scenario in Null-scenario low

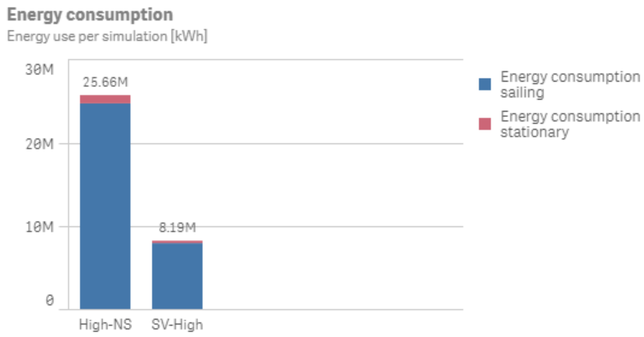

Figure 5.31: Energy consumption for standard vessels scenario in Null-scenario high

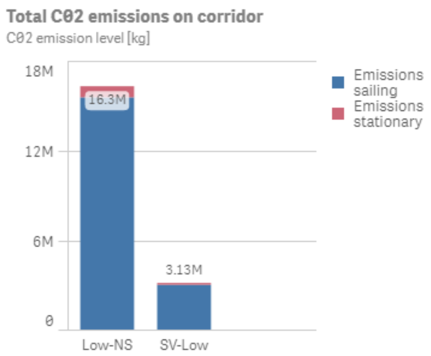

Figure 5.32: Emission level for standard vessels scenario in Null-scenario low

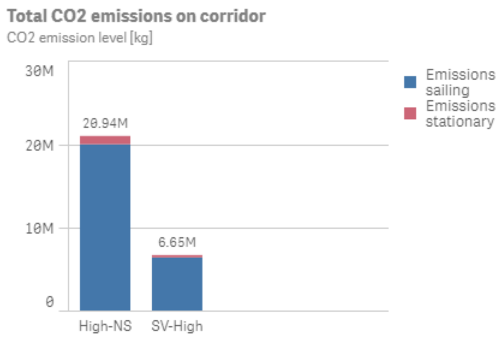

Figure 5.33: Emission level for standard vessels scenario in Null-scenario high

The results from the Figures above are very clear. An extremely large reduction in energy consumption and therefore emission levels can be achieved when the loading rates of vessels are optimised. In this scenario the fleet is even assumed to sail halve empty and halve loaded. This means that even more reduction could be achieved if a system could be developed where vessels always carry cargo. In the low Null-scenario the emission levels have been reduced with 80.8% to only 3.13 million kg a month. In the high Null-scenario the emission levels have decreased with 68% to 6.66 million kg per month. These numbers are very large and show the potential for the inland shipping fleet for reducing its emission levels. Next to the emission reduction in kg it is also interesting to see the reduction in gram per ton kilometer. As the efficiency levels of the loading rates are much higher in this scenario than any other scenario or measure implemented, it can be very interesting to see what the potential in the reduction in gram per ton kilometer can be on this corridor. In Table 5.5 the results in gram per ton kilometer are presented.

Table 5.5: Emission levels per route after implementation of standard vessels and time slots[g/tkm]

Route:	Emissions Null-scenario low [g/tkm]	Emissions Null-scenario low Kreekrak locks removal [g/tkm]	Emissions Null-scenario high [g/tkm]	Emissions Null-scenario high Kreekrak locks removal [g/tkm]
Zuid-Beveland	24.1	15.2	25.1	8.4
Scheldt-Rhine	23.7	14.8	24.9	8

The emission reduction in gram per ton kilometer is just like the emission levels in kg much lower than in the Null-scenarios without standard vessels and time slots. The results from Table 5.5 show the potential of the inland shipping fleet. Transport over rivers and canals is already a relative clean form of transport but there is even more potential. This scenario shows how a change of fleet composition combined with time slot sailing and efficient loading rates can reduce the emission levels with very large numbers. Additionally, taking away the capacity issues at locks as well. With the world becoming a 24/7 economy more and more and the pressure of governments increasing on industries to reduce their emission levels, this scenario seems very interesting.

5.2.3. Sea level rise

The last fleet impact scenario is sea level rise. This scenario only effects the Zuid-Beveland route as this part of the route is connected to sea and experiences the tide. The Scheldt-Rhine canal does not experience sea level rise as it is completely closed of from the sea by locks. However, even with a sea level rise of 1 meter by 2030, no changes will occur in emission levels even on the Zuid-Beveland route. Even with the unrealistic high number of 1 meter sea level rise by 2030, the 3-layer container vessels will still be lower than the clearance height of 9.1 meter on the Zuid-Beveland route. Resulting in the same situation as the high cube container scenario, where only 4-layer container vessels need to stop for the bridges. This already showed to have such a small effect on the total emission levels that no, or almost no, changes where noticeable in the model. To still make this scenario relevant, it is not simulated separately but in combination with the high cube container scenario. The combination of these two scenarios would result in the 3-layer container vessels also having to wait before the movable bridges on the Zuid-Beveland route. The results of the combination of these two scenarios are presented in the Figures 5.34 till 5.37.

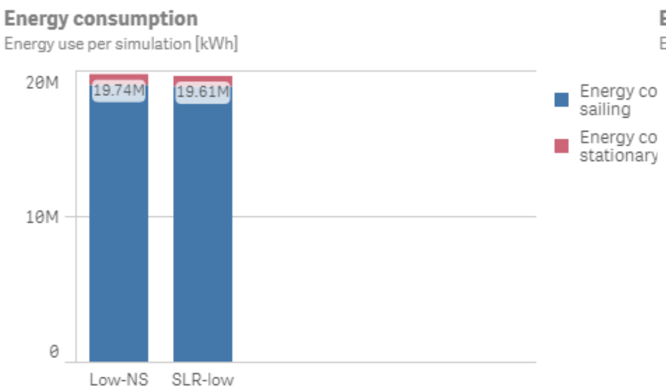

Figure 5.34: Energy consumption for sea level rise and high cube containers in Null-scenario low

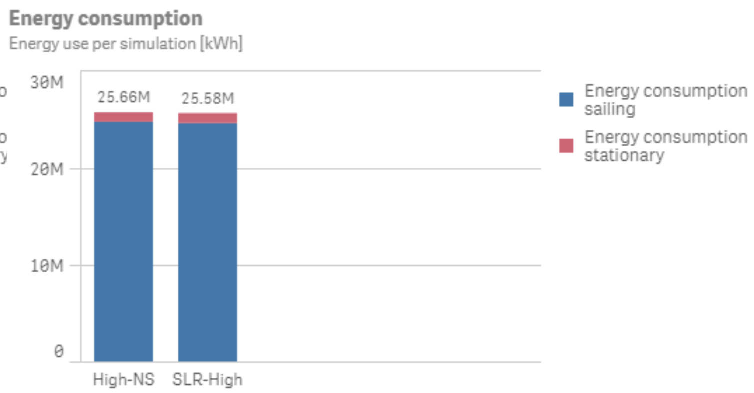

Figure 5.35: Energy consumption for sea level rise and high cube containers in Null-scenario high

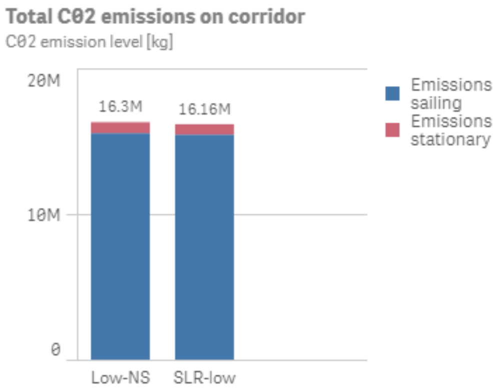

Figure 5.36: Emission level for sea level rise and high cube containers in Null-scenario low

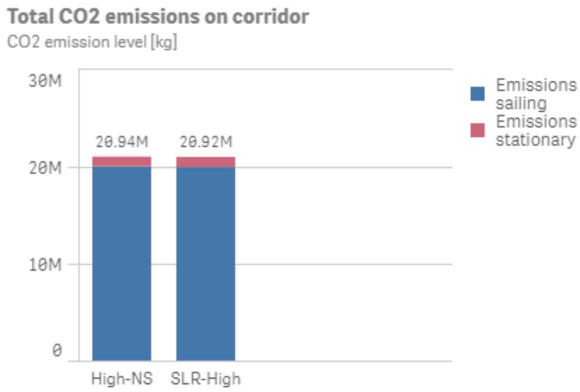

Figure 5.37: Emission level for sea level rise and high cube containers in Null-scenario high

From both the energy consumption and emission Figures it is clear that no changes occur also in the combination case of sea level rise and high cube containers. The levels of emission and energy consumption are even a bit lower in the high Null-scenario with the bridge height restriction than in the normal high Null-scenario. This can be caused by a small difference in vessels that are generated at different points in time and can not be related to the implementation of the scenario. The model does not seem accurate enough to monitor such small changes as occur in this scenario. The effect of this scenario is just to small and a to small part of the fleet is impacted by this scenario. It must be noted that on the Zuid-Beveland route the total container transport is way lower than on the Scheldt-Rhine canal making the effects of a scenario like the one studied here even harder.

5.3. Conclusion

This Chapter should answer the fourth sub question of this research:

What are the effects of implementing civil engineering design measures and fleet impact scenarios on the CO_2 emission levels and what are the impacts of these implementations?

To answer this sub question all measure implementations have been implemented and analysed. The main outcomes of all 6 measure implementations are presented below. First, the infrastructural modifications have been implemented in the model followed by the fleet scenarios.

The increase of the bridge heights on the Scheldt-Rhine route resulted in a change in sailing patterns of the large 4-layer container vessels with destination Antwerp. The 4-layer container vessels, with destination Antwerp, that were forced to take the Zuid-Beveland route could now take the Scheldt-Rhine route again. Changes in waiting times and emission levels were very small in the low Null-scenario. It can therefore be concluded that, for the low economic forecast, increasing the bridge heights on the Scheldt-Rhine canal does not significantly effect the emission level in 2030.

In contradiction to the low Null-scenario, the high Null-scenario did show promising results. The changes in sailing patterns resulted in a reduction of waiting times before the locks on the Zuid-Beveland route. The waiting times at the Krammer locks reduced from 42 minutes to 38 minutes and the waiting times at the Hansweert locks reduced from 16 to 14 minutes. The reduction of the waiting times at the Krammer locks is however not enough to take away the capacity problem at the Krammer locks. Additionally, the increased fleet size on the Scheldt-Rhine route resulted in the waiting times, at the Kreekrak locks, to increase to 34 minutes. Which increases the capacity problem at the Kreekrak locks. Taking all these changes into account still resulted in an overall reduction of the emission level of 8.25%.

Second, the implementation of the Bathse lock has been studied. The implementation of the Bathse lock resulted in sailing pattern changes and waiting time reductions at all locks. Almost all vessels with destinations other then Antwerp and the west-side of the port of Antwerp changed their sailing pattern. Vessels with destinations Gent/Terneuzen and Vlissingen now take the Bathse canal route as it is shorter and faster than the Zuid-Beveland route. Faster because the Bathse route has only one lock where the Zuid-Beveland has two.

Additionally, vessels with destination, the outer (west-side) port of Antwerp now take the Bathse canal route. Also for these vessels, the route is shorter and faster as it only contains one lock instead of two. The results in the high and low Null-scenario are presented in Tables 5.6 and 5.7

Third, the complete removal of Kreekrak locks was also implemented in the model. This implementation did not change the sailing patterns of the fleet, it only reduced the waiting times before the Kreekrak locks to zero. So except for the change in waiting times at the Kreekrak locks everything stayed the same. The change in emission production is therefore only caused by the decrease in waiting time at the Kreekrak locks. The results of the complete removal of the Kreekrak locks are presented in Tables 5.6 and 5.7. The relative small reductions in emission level, for both the high and low Null-scenario, shows that a reduction in waiting time does not influence the emission level as much as changes in sailing patterns do.

After the implementation of the infrastructural modifications the fleet scenarios have been implemented in the model. For both the sea level rise and the high cube container scenario not much changed. Both scenarios effect the fleet by the increase of the average vessel height or a reduction in air draught of the bridges. The effect of both scenarios is the same, namely 4-layer container vessels now have to wait before the movable bridges on the Zuid-Beveland route to open before they can pass. Nothing changes on the Scheldt-Rhine route as this route already had a height restriction for the 4-layer container vessels. Both the scenarios, even when they are combined, do not results in significant changes in emission levels of the fleet. The results are presented in Tables 5.6 and 5.7. This is most probably caused by the fact that the part of the fleet now having to wait in front of the bridges is very small. Additionally, waiting times before bridges are generally short (10 min) which reduces the effect on emission levels even more.

Finally, the scenario of standard vessels and time slot sailing has been implemented in the model. This scenario gave very promising results in both Null-scenarios. The efficient loading rates combined with three large standard vessels and time slot sailing reduced both the waiting times in front of locks as the emission levels of the fleet. The capacity problems expected at both the Krammer and Kreekrak locks are taken away and the emission levels are reduced with very large numbers. The results are presented in Tables 5.6 and 5.7.

Table 5.6: Emission level reductions for implemented measures

Situation:	**Bridge height increase** [%]	**Bathse lock** [%]	**Kreekrak locks removal** [%]	**High cube containers** [%]	**Standard vessels and time slots** [%]	**Sea level rise** [%]
Null-Scenario low	1.3	16.5	3.5	0.18	80.8	0.66
Null-Scenario high	8.25	35	1.6	0	68	0.31

Table 5.7: Waiting time changes for implemented measures

Infrastructural modification:	**Kreekrak locks** [%]	**Krammer locks** [%]	**Hansweert locks** [%]	**Fleet scenario:**	**Kreekrak locks** [%]	**Krammer locks** [%]	**Hansweert locks** [%]
Bridge height increase (low Null-scenario)	+ 4.0	- 5.7	0	**High-cube containers (low Null-scenario)**	0	0	0
Bridge height increase (high Null-scenario)	+ 13.3	- 9.5	-12.5	**High-cube containers (high Null-scenario)**	0	0	0
Bathse lock (low Null-scenario)	- 28.0	- 48.5	- 50.0	**Standard vessels + time slot sailing (low Null-scenario)**	- 68.0	- 45.7	- 42.9
Bathse lock (high Null-scenario)	- 40.0	- 47.6	- 50.0	**Standard vessels + time slot sailing (high Null-scenario)**	- 72	- 51	- 50
Removal Kreekrak locks (low Null-scenario)	- 100	0	0	**Sea level rise (low Null-scenario)**	0	0	0
Removal Kreekrak locks (high Null-scenario)	- 100	0	0	**Sea level rise (high Null-scenario)**	0	0	0

6

Conclusions, discussion and recommendations

In this Chapter the conclusions, discussion and recommendations of the research are presented. In Section 6.1 the research question is answered. In Section 6.2 the validity of the results is discussed. The Chapter closes with the Section presenting recommendations for further research.

6.1. Conclusion

This Section is divided in Subsections each answering one sub question of this research. The last Subsection gives a final conclusion on the research and thereby answers the research question.

6.1.1. Fleet and corridor characteristics

The analysis performed in Chapter 2, has been conducted to outline the factors influencing the emission production of the inland shipping fleet on the Rotterdam-Antwerp corridor. By using the information obtained in this Chapter the first sub question of this research could be answered:

What information on fleet, corridor and emission data is needed to be able to determine the current CO_2 emission levels on the Rotterdam-Antwerp corridor?

The CO_2 emission levels on the corridor can be determined by calculating the emission productions of every vessel in the fleet separately. Emission production levels for individual vessels depend on multiple variables. Important variables are emission factors and energy consumption (required engine power times sailing time). Required engine power depends on the total resistance encountered by the vessel. The encountered resistance depends on the characteristics of the fairway and the typical characteristics of the vessel class to which the vessel belongs. As such all the important data on the fleet and the fairways has been collected and the total resistance and emission factors have been determined per vessel class.

Another important aspect that influences the total emission production is the sailing distance. Data on the sailing patterns of the fleet have been collected. Following this data, the assumption of basing route choice only on destination and the height restriction of the Scheldt-Rhine canal seemed a proper simplification. With this information the energy consumption per vessel could be determined. The translation from energy consumption to CO_2 emissions has been made by multiplying the energy consumption with the fuel dependent emission factors. This resulted in the CO_2 emissions per vessel.

Additionally, data has been collected on the economic forecasts for 2030. Which made it possible not only to derive the CO_2 emission levels for vessels in the Base case (situation 2017) but also for vessels in the Null-scenarios (expected situations in 2030).

Concluding, the information needed to determine the emission levels on the corridor depends on the size of the fleet and their sailing patterns and characteristics. Objects on the fairways such as locks and bridges influence the sailing patterns and duration and consequently the emission levels. Once all the objects on the fairway are mapped and the distribution of the vessels over the corridor is known the resistance and emission factor calculations can be used to determine the emission levels of individual vessels.

6.1.2. Model concepts

Chapter 3 answered the second sub question by outlining the model approach and concepts used to built the model.

How can a model be developed that simulates the sailing patterns on the Rotterdam-Antwerp corridor in the current state, possible future states and have the ability to determine the accompanied emission levels?

To answer this sub question, first the possible model concepts have been discussed. The simulation model should be able to simulate the sailing patterns on the fairways between Rotterdam and Antwerp and show the related emission production of the fleet. It is therefore important that the model is able to accurately simulate the different emission stages of vessels without the simulation time becoming too long. Therefore, a discrete event simulation model has been chosen. Discrete event simulation models update when a change in state occurs and can simulate the fleet without simulation times becoming to0 long.

Second, the model requirements have been discussed. One of the requirements was that the model should be able to simulate the sailing patterns of the vessels. This has been done by basing route choice on the static components destination and the height restriction of the Scheldt-Rhine route. The dynamic behaviour of vessels around locks has been simulated by the implementation of a lock selection component. This allows vessels to switch to the shortest queue upon arrival. Additionally, the model should be able to simulate the functioning of individual components on the corridor such as locks and bridges.

Generated vessels should be able to calculate their route, be able to move over the chosen waterway and queue in front of locks and bridges in order the reproduce the traffic flows, congestion patterns and the emission levels. These requirements have been met by applying graph theory and queuing theory. The open-source NetworkX package from Python has been used to build the network (graph) based on the shapefiles (geographical coordinates) of the waterways between the Volkerak locks and the port of Antwerp. Generated vessels use the algorithms of the NetworkX package to calculate their route. The open-source package SimPy has been used to simulate queue formation in front of locks and movable bridges.

6.1.3. Calibration

Chapter 4 was all about the validation and calibration of the model. By validating and calibrating the model the third sub question of the research was answered:

Can the levels of CO_2 emissions for the Base case and the Null-scenarios be simulated and what are the corresponding levels of CO_2 emissions?

To answer this sub question first the internal components of the model where validated. First the behaviour of the vessels sailing over the paths was validated. This showed that the simplification of route choice based only on height restrictions and destinations was an allowable simplification. Additionally, vessels registered the encounters with obstacles such as locks and bridges. A check showed that vessels reacted on queues in front of locks and changed lane if the queue at the other lane was shorter. Indicating that the lock selection component functions as it should function. Once the vessel behaviour was validated the lock functioning was checked. All the locks on the corridor fulfilled the basic requirements.

The last internal validation focused on the outcomes of the resistance calculations. As they form the basis for the emission calculations they are very important. The resistance outcomes where compared with another study done on resistance calculations for inland vessels. The values coincided well except for the resistance levels of empty vessels. The resistance results of empty vessels in this research are lower than the ones in the comparison research (Bolt, 2003). The reasons are most probably the differences in vessel speed, fairway dimensions and draught of the vessels.

Section 4.2 focused on the calibration of the entire model and thereby analysing how good the model can simulate the sailing patterns on the corridor. This has first been done for the Base case (situation 2017). It became clear that the model is able to simulate the sailing patterns of the fleet in detail. Where in reality 36.8% of the fleet takes the Zuid-Beveland route in the model 36.7% takes the Zuid-Beveland route.

The arrival rates of vessels at locks could also be simulated quite well. The arrival rates in the model (at locks) have been compared to the arrival rates obtained from IVS-90 data, Figures 4.4, 4.5 and 4.6. The arrival rates at the Kreekrak locks where almost entirely the same as the arrival rates obtained from the the IVS-90 data.

Other than the Kreekrak locks the arrival rates at the Zuid-Beveland route showed differences. The arrival rate pattern was the same but the number of vessels arriving at the Zuid-Beveland locks in reality was larger than the total number of vessels arriving at the Zuid-Beveland locks in the model. This is most probably caused by the natural fluctuation of the fleet over different days. The days used as comparison clearly showed busier days on the Zuid-Beveland route. The model simulates the average number of vessels a day, based on data of one entire year and consequently does not incorporate variations in vessel numbers over the days. Furthermore the waiting times and average sailing times, in the Base case simulation, coincided with data of Rijkswaterstaat for the current situation on the corridor (Rijkswaterstaat, 2017a). Indicating that the model simulates the fleet distribution and average arrival rates in a proper way.

As a last calibration the Null-scenarios where checked. These Null-scenarios should simulate the expected situation on the corridor in 2030 according to current economic forecasts of Rijkswaterstaat (Rijkswaterstaat, 2017a). This has been done by comparing the fleet growth and distribution of the fleet over the corridor in 2030. The fleet showed correct growths for the low Null-scenario. For the high Null-scenario the fleet growth was a bit to large.

Finally, the expected waiting times where checked. The I/C ratios and waiting times coincided with other research done on this corridor for 2030. Overall the Null-scenarios presented the expected fleet format well.

By validating the internal components and calibrating the final outcomes of the Base case and the Null-scenario the third sub question of this research has been answered. The model can simulate the current situation and the forecasts for 2030. Apart from some small differences the model coincides very well with the reality.

6.1.4. Application

In Chapter 5 all the design measures and fleet scenarios have been implemented. This was done to answer the fourth and final sub question of this research:

What are the effects of implementing measures on the CO_2 emission levels and what are the impacts of these implementations?

This sub question has been answered by implementing all measures in the model. It became clear that the effect of different scenarios and design measures differ very much.

The fleet scenarios sea level rise and high cube containers had no effect on the emission levels of the fleet. The effects on height changes where not large enough to significantly influence the emission levels on the Zuid-Beveland route. The fleet scenario of standard vessels and time slot sailing had however a very large impact on the emission levels. The time slot sailing took away the high intensity hours at locks during the afternoon and thereby decreased the waiting time a lot. The increased loading rates resulted in less vessels needed to transport the same amount of cargo. This drastically reduced the emission levels on the corridor.

All infrastructural modifications resulted in reductions in emission levels of the fleet. The implementation of the Bathse lock showed by far the largest differences. If the Bathse lock is implemented into the high Null-scenario the emission levels can be reduced up till 35%. The impacts of the design measure Bathse lock and the fleet scenario standard vessels and time slot sailing are by far the largest and most interesting measures in reducing emission levels and waiting times. The final results for all measures are presented in Tables 6.1 and 6.2.

6.1.5. Conclusion

All the sub questions of this research are answered to be able to answer the research question of this study:

What measures will contribute to the reduction of the CO_2 emissions, by the inland shipping fleet, on the Rotterdam-Antwerp corridor, in specific the Zuid-Beveland and Scheldt Rhine route?

Most measures implemented in this research can contribute to the reduction of the total CO_2 emission levels. The level of these contributions however varies widely. The removal of the Kreekrak locks on the Scheldt-Rhine route would reduce the emission levels with 3.5% in the best scenario possible. Taking into account all the complications related to the removal of this lock, the reduction level is most probably to small and therefore the removal of the lock does not seem a realistic option in pursuing reduction of emission levels by the inland shipping fleet.

The increase of the bridge heights on the Scheldt-Rhine canal can reduce the emission levels on the corridor with 8.25%. This reduction is a result of the high Null-scenario. In the Arcadis study there was one scenario where the cost-benefit analyses resulted in a positive outcome (Arcadis, 2016). Namely, the scenario where the Moerdijk bridges are not included in the calculations and where this scenario is implemented in the high economic forecast. As the Moerdijk bridges are not included in the present research the results of the present research, for the increase of the bridge heights on the Scheldt-Rhine canal, are in line with the results of the study done by Arcadis (Arcadis, 2016).

The last infrastructural modification gives the most promising results. The implementation of the Bathse lock reduced the emission level with 16.5% in the low scenario and with 35% in the high Null-scenario. Not only does it reduce the emission levels it also reduces the waiting times at the Kreekrak and Krammer locks taking away the capacity problems at these locks expected in 2030.

Two of the three implemented fleet scenarios did not show significant changes. The sea level rise and high cube container scenario showed to have little to no effect on the emission levels on the corridor. The decreased air draught and increased vessel height only effected a small part of the fleet. The part of the fleet that was effected experienced small changes in emission productions. This resulted in no changes on the overall emission levels.

The standard vessel and time slot sailing scenario did however show a massive reduction of the emission levels on the corridor. In the best scenario the emission levels can be reduced with 80%. This scenario shows the large potential the inland shipping fleet has on reducing its emission levels. Where it is already seen as a relatively clean way of transportation, a scenario like this could make the inland shipping fleet even more competitive compared to other transport modes.

As a final conclusion it can be stated that both the implementation of the Bathse lock and standard vessels with time slot sailing are very interesting if one wants to reduce the emission levels on the corridor. Additionally, both these implementations reduce the intensities on the Scheldt-Rhine route and Zuid-Beveland route. This results in lower waiting times at the locks. Especially, the Krammer and Kreekrak locks benefit significantly for both measures. The results of all implemented measures are presented in Tables 6.1 and 6.2.

Table 6.1: Emission level reductions for implemented measures

Situation:	**Bridge height increase** [%]	**Bathse lock** [%]	**Kreekrak locks removal** [%]	**High cube containers** [%]	**Standard vessels and time slots** [%]	**Sea level rise** [%]
Null-Scenario low	1.3	16.5	3.5	0.18	80.8	0.66
Null-Scenario high	8.25	35	1.6	0	68	0.31

Table 6.2: Waiting time changes for implemented measures

Infrastructural modification:	Kreekrak locks [%]	Krammer locks [%]	Hansweert locks [%]	Fleet scenario:	Kreekrak locks [%]	Krammer locks [%]	Hansweert locks [%]
Bridge height increase (low Null-scenario)	+ 4.0	- 5.7	0	**High-cube containers (low Null-scenario)**	0	0	0
Bridge height increase (high Null-scenario)	+ 13.3	- 9.5	-12.5	**High-cube containers (high Null-scenario)**	0	0	0
Bathse lock (low Null-scenario)	- 28.0	- 48.5	- 50.0	**Standard vessels + time slot sailing (low Null-scenario)**	- 68.0	- 45.7	- 42.9
Bathse lock (high Null-scenario)	- 40.0	- 47.6	- 50.0	**Standard vessels + time slot sailing (high Null-scenario)**	- 72	- 51	- 50
Removal Kreekrak locks (low Null-scenario)	- 100	0	0	**Sea level rise (low Null-scenario)**	0	0	0
Removal Kreekrak locks (high Null-scenario)	- 100	0	0	**Sea level rise (high Null-scenario)**	0	0	0

6.2. Discussion

This Section highlights the shortcomings of this research by first discussing some model inputs. After this the assumptions made for the implementation of the design measures and scenarios are discussed. This all is done to check the validity of the research results.

6.2.1. Model inputs

There are some features of the model inputs that need to be discussed as they could be of influence on the outcomes. First the resistance outcomes implemented into the model are discussed.

Resistance calculations

Chapter 4 showed that the resistance outcomes for empty vessels where lower than the outcomes from other researches that used the same formulas to determine the resistance. This could have been caused by differences in vessel speed, fairway dimensions and used vessel draughts. This is however an uncertainty that should be taken into account. Additionally, water velocities are assumed to be absent in the model which is correct if the fairway studied is a canal. The largest part of this corridor consists of canals making this assumption largely valid. However, the Zuid-beveland route passes the Wester and Oosterschelde. This part of the route does experience flow velocities and this is not incorporated into the model. These flow velocities can be both beneficial or negative for the final resistance outcome. As the resistance outcomes were lower in this research than in the comparison research the flow velocities might also be one of the causes (Bolt, 2003). The resistance being one of the most important components for the energy consumption calculations, and subsequently for the emission calculations, the lower resistance for the empty vessels might cause the emission and energy consumption levels to be lower than expected. The Base case showed energy consumption outcomes that were realistic but a bit on the low side. This could be explained by the slightly lower resistance results. If this is true, all the results will have slightly larger emission levels than the results from the model. This will however not influence the conclusions presented. If the resistance levels are indeed to0 low, this is the case for every case discussed and therefore will not result in different emission ratios between the Null-scenarios and the implemented measures and scenarios.

Tidal influences

Another point of discussion is the exclusion of the tide. Where the tide does not play a role on the Scheldt-Rhine canal it does on parts of the Zuid-Beveland route. Tides are not known to cause frequent and long disturbances on this route. There are however moments in the year high water can hinder vessels. Additionally, low water might cause tidal windows once in a while for large vessels. Additionally, the tide can also influence the resistances vessels experience during sailing. In this research the experienced resistance is assumed to be constant during average sailing speeds while this might not exactly be the case with tides and thus flow velocities present. The effects of neglecting the tide are not expected to be very large on the resistance. The flow velocities generated by the tide can in one case be beneficial and in the other case negative for the resistance. Assuming the average between the two, as is done in this research, seems valid. As it is known that high and low tide do not cause problems, such as delays, on the Zuid-Beveland route often the tide is not expected to influence average sailing and waiting times.

Fleet size

Another point of discussion is the size of the fleet generated each day. The number of vessels in the model every day is based on the total amount of vessels measured during the year. The number of vessels each day is therefore based on an average taken from one year of measurements. This means that peak days are not simulated in the model. The IVS-data used in Figures 4.5 and 4.6 showed that the total number of vessels on the Zuid-Beveland route in the model was lower than the measured number of vessels passing the Krammer and Hansweert locks. The total difference over the entire day was 36 vessels. This means that each hour 1.5 more vessels arrive at the locks than in the simulation model. This could increase the total average waiting times. However, there are also days less vessels arrive at the locks than in the simulation, resulting in lower waiting times than simulated. As the total average waiting times and I/C ratio's coincide with the studies and measurements done by Rijkswaterstaat the assumption of the same number of vessels on the corridor each day is expected to be valid (Rijkswaterstaat, 2017a).

Krammer locks

The operating times of the Krammer locks are based on the current average operating times of 30 minutes. However, there are plans of implementing a new system for the separation of fresh and salt water at the lock. This new system is expected to reduce the average operating time significantly. This reduction in operating time might reduce the waiting times with 13 minutes. Testing is currently performed and the exact results and effects are not yet known. Opinions are divided on the effects of this new separating system. It is therefore not implemented into the model. However, if the waiting times would indeed be reduced with 13 minutes, this would change the Null-scenario outcomes at the Krammer locks significantly. The waiting times will in the low Null-scenario decrease from 35 minutes to 22 minutes. In the high Null-scenario the waiting times will reduce from 42 to 29 minutes. In both cases the waiting times become lower than the maximum waiting times of 30 minutes. The large decrease in waiting times will most probably have effect on the emission levels produced in the Null-scenarios. However, again if the waiting times can indeed be reduced with 13 minutes, this will be the case for all implementations done in this research. The conclusions, on emission level reduction, are therefore not expected to change.

Network

The research has modelled the fairways between Rotterdam and Antwerp. The two possible routes to and from Antwerp are therefore modelled, namely the Zuid-Beveland and Scheldt-Rhine route. However, on the west side of the Hansweert locks the vessels can also sail towards Terneuzen, Gent or Vlissingen. This part of the corridor has not been modelled. The distance between the the south end of the Hansweert locks to Antwerp is the same as the distance from the Hansweert locks to Terneuzen (difference less than 100m). Vessels with destination Terneuzen therefore produce the same amount of emissions in the model as when they would sail towards Terneuzen. However, vessels with destination Vlissingen or Gent sail further in the real situation. This results in the model results to have slightly lower emission levels on the Zuid-Beveland route than in the real situation.

6.2.2. Measure inputs

Next to the general model inputs for the Base case and Null-scenarios assumptions have been made for the implementations of measures in the model.

Sea level rise
In the scenario sea level rise the effects on the clearance height have been implemented into the model. It has not been studied how the sea level rise would effect the lock operating times of the Hansweert and Krammer locks. An increase in sea level rise could be beneficial for the operating times of the locks. This could effect the waiting times and thus the average sailing times and emission levels. Next to this the resistance experienced by vessels on the Zuid-Beveland route could change because of the sea level rise. This study does not go into detail on the effects of sea level rise on the resistance parameter and the duration of the lock operations. If these effects are positive on both the locking times and the resistance experienced this could mean that the energy consumption levels reduce and thus the total emission levels. However, the level of sea level rise is very much an uncertainty and the effects of the rise on the resistance and lock operating times is therefore difficult to determine. It should therefore be stated that the actual changes in emission levels, caused by sea level rise, can differ from the results in this study when taking into account changes in lock operating times and resistance experienced.

Bathse lock
For the scenario Bathse lock different assumptions have been made. First of all the Bathse lock is modelled in such a way that it can handle the intensities encountered on the corridor in 2030. The capacity of the Bathse lock has therefore been set very high in order to prevent long waiting times. This assumption makes sense as it is not expected that Rijkswaterstaat would realise a new lock that is not able to handle the capacities in the coming 30 to 50 years. It should be noted that of course funding's play a role in the realisation of new objects such as a lock. The Bathse lock might be realised but even if it is realised it does not mean that it will have the capacities implied in this research.

For the Bathse lock design measure, sailing patterns changed on the corridor. From the perspective that skippers want their cargo to be at their destination as fast as possible with the lowest associated costs these patterns have assumed to alter.It has been assumed that the created Bathse lock route is preferred above the other two routes for the following vessels. Vessels with destination or origin the outer port of Antwerp. It is assumed that vessels that do not have a destination in the port of Antwerp but on the western side of Antwerp prefer to choose the Bathse lock route. Vessels with destination Vlissingen, Terneuzen and Gent are also assumed to prefer the Bathse lock route. The Bathse lock route is shorter and will allow vessels to pass only one lock after the Volkerak locks and not two. Besides this the waiting times on the Krammer locks are very high and with enough capacity at the Bathse lock skippers will most probably prefer this route.

6.3. Recommendations

To finalise this research in this Section recommendations for future studies are given. There are multiple Sections in this study where future studies could produce more complete insights.

6.3.1. Network

This study focused on the fairways between the Volkerak locks and Antwerp: the Zuid-Beveland route and the Scheldt-Rhine route. It would be very useful to incorporate all the parts of the network in the province of Zeeland all the way from Rotterdam to Belgium. Including the locks at Terneuzen and the ports of Vlissingen, Terneuzen and Gent would give a more complete picture of the activities on the corridor. Including pleasure crafts and seagoing vessels would complete the sailing patterns of the entire corridor.

6.3.2. Emission calculations

There is little known about the exact energy consumption of vessels in lock areas. Most researches use the 15% rule for energy consumption around locks, so does this research. However, it would be very interesting to see the exact energy consumption levels for different vessel manoeuvres in the lock areas. An in depth study on factors influencing the energy consumption levels in and around locks would create much larger levels of detail on energy consumption and thus emission levels.

6.3.3. Route choice skippers

This research mainly based route choice on destination and restrictions on the corridor, which gave proper results for this specific case. However, there might be other fairways where a specific destination does not immediately provide the most obvious route choice. A future study focusing on choice behaviour would be very interesting and a good contribution to the developed model. This would give the choices made by skippers a more fundamental basis and make the model more generic. This would make it easier to implement the model in other cases.

6.3.4. Implementation of other emissions

CO_2 emissions are not the only emissions produced by the inland shipping fleet. The inclusion of nitrogen oxides and hydrocarbons would create a model that is able to determine all the important emissions produced by the inland shipping fleet. As not only CO_2 emissions are becoming a more pressing issue also the above mentioned emissions should be reduced. A model showing the effects of the scenarios and design measures on all these emission levels would be very interesting.

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A

Appendix

A.1. Lock capacity data

Table A.1: Capacity data locks (Goffin et al., 2009)(Rijkswaterstaat, 2017a)

Locks:	**N_max**	**Sailing in lock [min]**	**Sailing out lock [min]**	**Loop time [min]**	**Share loaded vessels**	**Operation time [min]**	**Lock chambers**
Kreekrak	4	7	6	8	65	10	2
Krammer	3	5	4	6	65	30	2
Hansweert	3	5	4	6	65	15	2

A.2. Emission factor data

Table A.2: Emission factors based on manufacturing years engines (Hulskotte,2009)

Construction year	**Specific fuel use [g/kWh]**
1900 - 1974	235
1975 - 1979	230
1980 - 1984	225
1985 - 1989	220
1990 - 1994	210
1995 - 2002	210
2003 - 2007	200
2008 - 2012	200
2012 - 2017	195
2018 - 2022	185

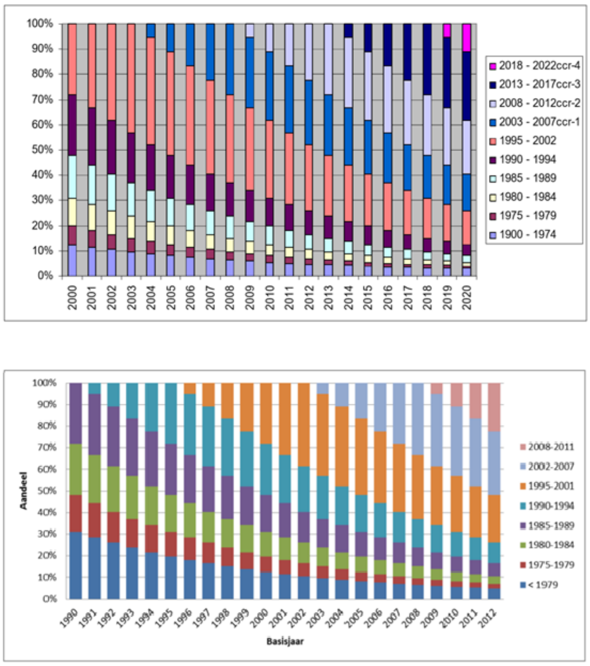

Figure A.1: Distribution manufacturing years engines per vessel class (Hulskotte & Bolt, 2012)(Verbeek & van Gompel, 2017)

B

Results resistance and emission factors

B.1. Total resistance per vessel class

Table B.1: Scheldt-Rhine route

Type	Rf [N]	Rp [N]	Rz [N]	Rtotal [N]		Type (empty)	Rf [N]	Rp [N]	Rz [N]	Rtotal [N]
BI	31.083	32.326	262	63.671		**BI**	21.710	5.443	6	27.159
BII-1	39.994	45.257	499	85.750		**BII-1**	30.351	7.431	10	37.792
BII-2B	62.631	76.000	2.006	140.637		**BII-2B**	62.130	14.862	37	77.029
BII-2L	77.706	51.722	382	129.810		**BII-2L**	48.537	7.431	6	55.974
BII-4	100.689	760.069	1.155	861.913		**BII-4**	100.069	14.862	22	114.953
BII-6B	119.606	79.167	1.929	200.702		**BII-6B**	154.292	22.293	48	176.633
BII-6L	136.854	76.000	811	213.665		**BII-6L**	136.862	14.862	15	151.739
BO1	11.840	15.335	106	27.281		**BO1**	7.491	2.979	3	10.473
BO2	16.740	19.464	134	36.338		**BO2**	11.402	3.781	4	15.187
BO3	20.377	22.118	152	42.647		**BO3**	14.375	4.297	5	18.677
BO4	22.794	24.182	171	47.147		**BO4**	16.444	4.698	5	21.147
C1b	9.382	18.517	305	28.204		**C1b**	9.060	6.301	26	15.387
C1l	11.064	9.258	35	20.357		**C1l**	10.162	5.041	8	15.211
C2b	41.667	50.914	1.262	93.843		**C2b**	47.587	22.758	128	70.473
C2l	65.466	45.257	281	111.004		**C2l**	53.852	14.862	22	68.736
C3b	41.667	50.914	1.262	93.843		**C3b**	47.587	22.758	128	70.473
C3l	65.466	45.257	281	111.004		**C3l**	53.852	14.862	22	68.736
C4	65.466	45.257	281	111.004		**C4**	53.852	14.862	22	68.736
M0	5.097	8.250	65	13.412		**M0**	4.479	2.578	4	7.061
M1	6.301	10.521	97	16.919		**M1**	5.564	3.617	7	9.188
M10	57.576	65.693	832	124.101		**M10**	49.859	22.275	67	72.201
M11	71.742	69.100	751	141.593		**M11**	62.487	23.430	60	85.977
M12	84.040	82.727	1.096	167.863		**M12**	74.153	28.050	87	102.290
M2	11.840	16.783	147	28.770		**M2**	11.057	6.453	14	17.524
M3	19.367	24.375	193	43.935		**M3**	14.514	8.213	19	22.746
M4	21.483	28.828	271	50.582		**M4**	18.189	10.560	28	28.777
M5	25.042	28.828	226	54.096		**M5**	21.211	10.560	23	31.794
M6	32.143	38.304	355	70.802		**M6**	28.958	15.675	43	44.676
M7	36.898	37.109	287	74.294		**M7**	36.628	16.558	37	53.223
M8	50.393	55.474	586	106.453		**M8**	42.668	18.810	48	61.526
M9	60.212	55.474	475	116.161		**M9**	51.004	18.810	39	69.853

Table B.2: Zuid-Beveland route

Type	**Rf** [N]	**Rp** [N]	**Rz** [N]	**Rtotal** [N]		**Type (empty)**	**Rf** [N]	**Rp** [N]	**Rz** [N]	**Rtotal** [N]
BI	31.083	32.326	128	63.537		**BI**	21.710	5.443	3	27.156
BII-1	42.889	45.257	242	88.388		**BII-1**	30.351	7.431	5	37.787
BII-2B	73.519	76.000	927	150.446		**BII-2B**	62.130	14.862	19	77.011
BII-2L	94.978	51.722	184	146.884		**BII-2L**	48.537	7.431	3	55.971
BII-4	118.415	76.000	534	194.949		**BII-4**	100.069	14.862	11	114.942
BII-6B	119.606	79.167	856	199.629		**BII-6B**	154.292	22.293	24	176.609
BII-6L	161.082	76.000	375	237.457		**BII-6L**	136.131	14.862	7	151.000
BO1	11.840	15.335	49	27.224		**BO1**	7.491	2.979	2	10.472
BO2	16.740	19.464	66	36.270		**BO2**	11.402	3.781	2	15.185
BO3	20.377	22.118	70	42.565		**BO3**	14.375	4.297	2	18.674
BO4	22.794	24.182	79	47.055		**BO4**	16.444	4.698	3	21.145
C1b	9.382	18.517	150	28.049		**C1b**	9.060	6.301	13	15.374
C1l	11.064	9.258	18	20.340		**C1l**	10.162	5.041	4	15.207
C2b	41.667	50.914	590	93.171		**C2b**	47.587	22.758	63	70.408
C2l	70.277	45.257	136	115.670		**C2l**	53.852	14.862	11	68.725
C3b	41.667	50.914	590	93.171		**C3b**	47.587	22.758	63	70.408
C3l	70.277	45.257	136	115.670		**C3l**	53.852	14.862	11	68.725
C4	70.277	45.257	136	115.670		**C4**	53.852	14.862	11	68.725
M0	5.097	8.250	32	13.379		**M0**	4.479	2.578	2	7.059
M1	6.301	10.521	48	16.870		**M1**	5.564	3.617	4	9.185
M10	60.190	65.693	400	126.283		**M10**	49.859	22.275	19	72.153
M11	74.410	69.100	361	143.871		**M11**	62.487	23.430	30	85.947
M12	84.238	82.725	522	167.485		**M12**	74.153	28.050	43	102.246
M2	11.840	16.783	73	28.696		**M2**	11.057	6.453	7	17.517
M3	19.367	24.375	95	43.837		**M3**	14.514	8.213	9	22.736
M4	21.483	28.828	14	50.325		**M4**	18.189	10.560	14	28.763
M5	25.042	28.828	111	53.981		**M5**	21.211	10.560	12	31.783
M6	32.143	38.304	174	70.621		**M6**	28.958	15.675	21	44.654
M7	36.898	37.109	140	74.147		**M7**	36.628	16.558	34	53.220
M8	50.393	55.474	283	106.150		**M8**	42.668	18.810	44	61.522
M9	64.582	55.474	230	120.286		**M9**	51.004	18.810	19	69.833

B.2. Emission factors per vessel class

Type	**emissionfactor** [kg/kwh]		**Type**	**emission factor** [kg/kwh]
BI	0,710		**C3l**	0,680
BII-1	0,710		**C4**	0,680
BII-2B	0,710		**M0**	0,714
BII-2L	0,710		**M1**	0,731
BII-4	0,710		**M10**	0,650
BII-6B	0,710		**M11**	0,640
BII-6L	0,710		**M12**	0,640
BO1	0,710		**M2**	0,700
BO2	0,710		**M3**	0,700
BO3	0,710		**M4**	0,699
BO4	0,710		**M5**	0,698
C1b	0,710		**M6**	0,716
C1l	0,710		**M7**	0,704
C2b	0,710		**M8**	0,680
C2l	0,710		**M9**	0,650
C3b	0,710		**-**	-

C

Emission data the Netherlands

C.1. Energy consumption

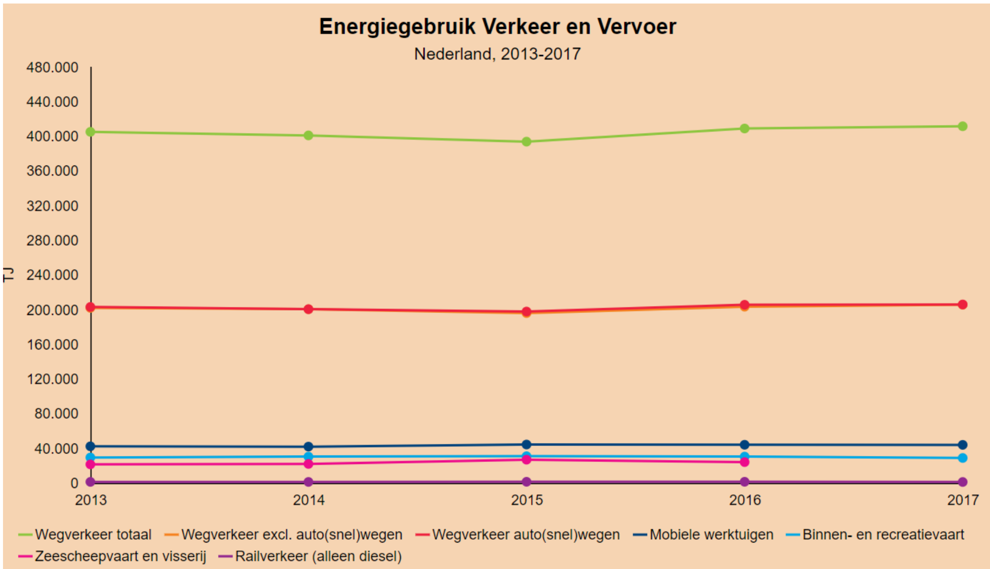

Figure C.1: Energy consumption by the traffic sector in the Netherlands

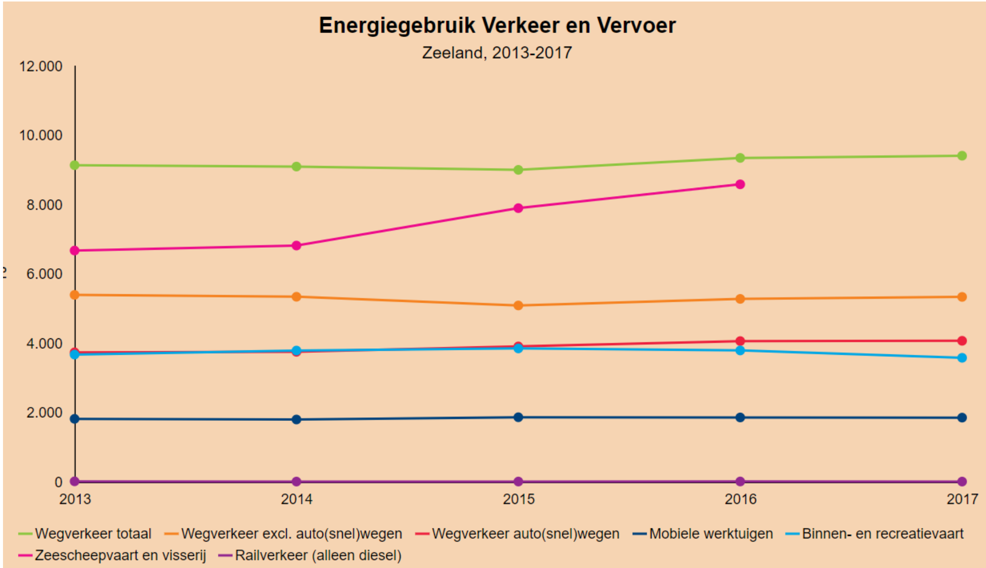

Figure C.2: Energy consumption by the traffic sector in Zeeland

C.2. CO_2 emissions

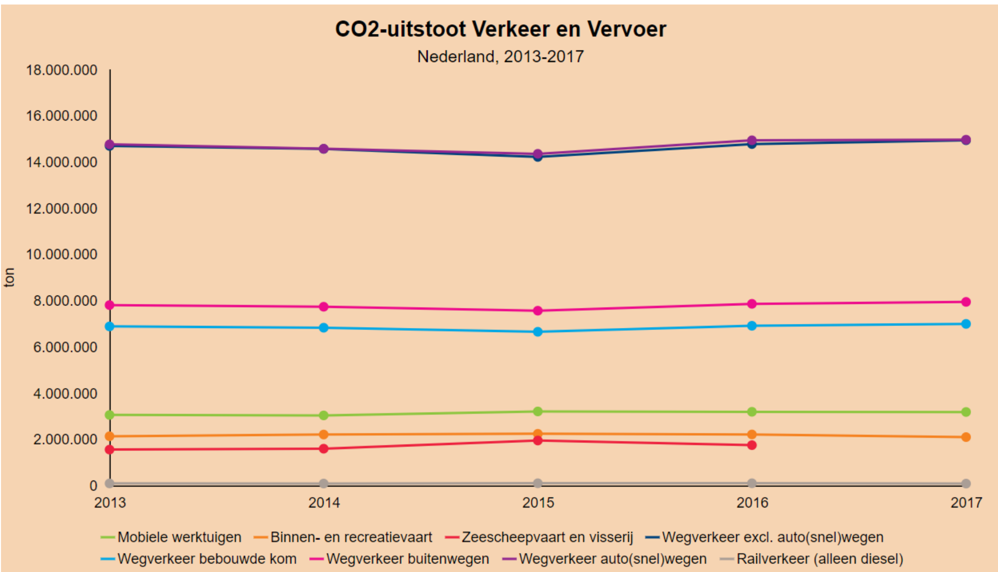

Figure C.3: CO_2 emissions by the traffic sector in the Netherlands

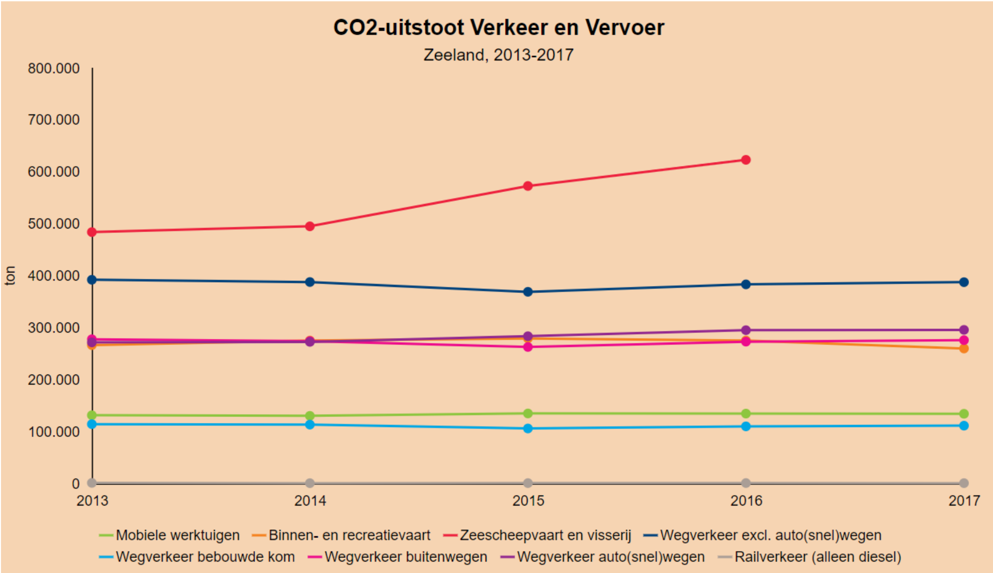

Figure C.4: CO_2 emissions by the traffic sector in Zeeland

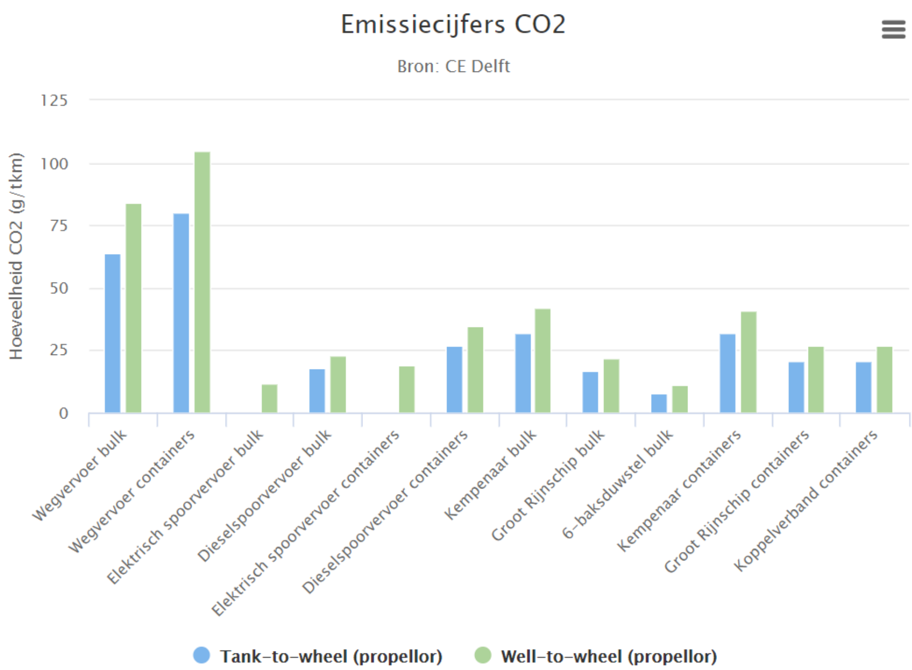

Figure C.5: CO_2 emissions in g/tkm

D

Static route choices

D.1. M8 vessel

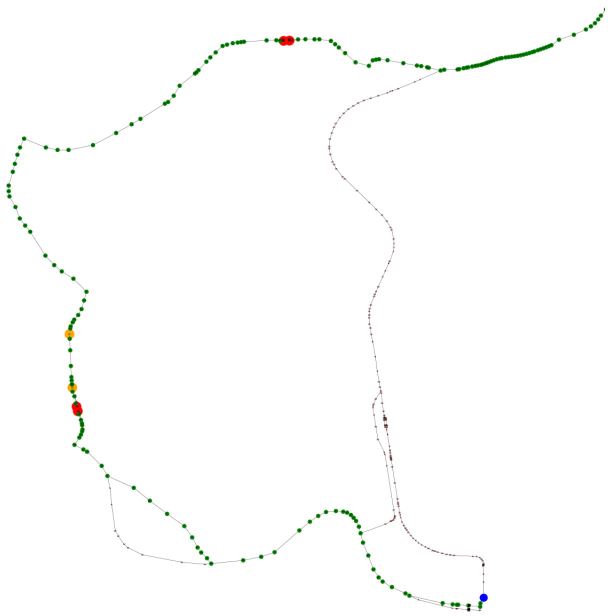

Figure D.1: Loaded M8 vessel with destination Antwerp

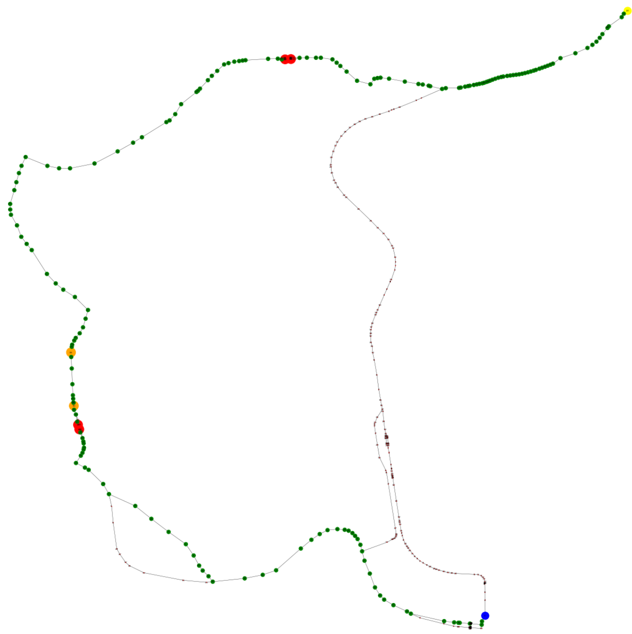

Figure D.2: Loaded M8 vessel with destination other than Antwerp

Path	Zuid-Beveland
Destination	Antwerp
Height	9.1m
Loaded	1.0

Path	Zuid-Beveland
Destination	Other
Height	9.1m
Loaded	1.0

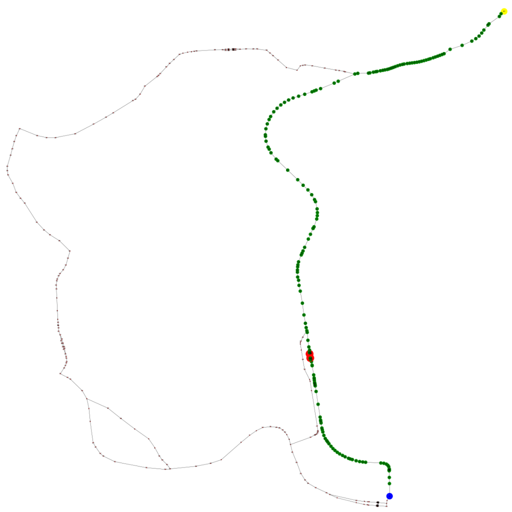

Figure D.3: Empty M8 vessel with destination Antwerp

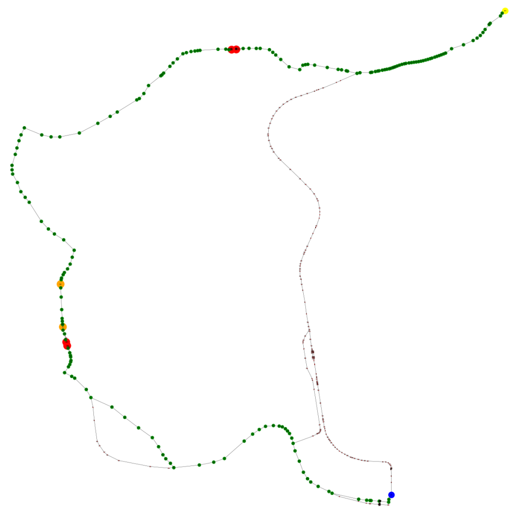

Figure D.4: Empty M8 vessel with destination other than Antwerp

Path	Scheldt-Rhine
Destination	Antwerp
Loaded	0.0

Path	Zuid-Beveland
Destination	Other
Loaded	0.0

D.2. BI-1 vessel

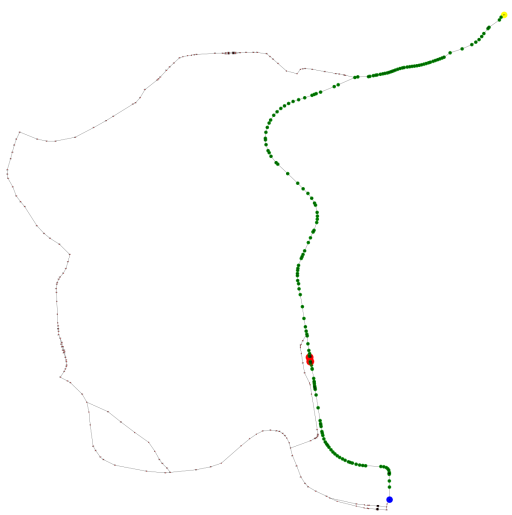

Figure D.5: Loaded BII-1 vessel with destination Antwerp

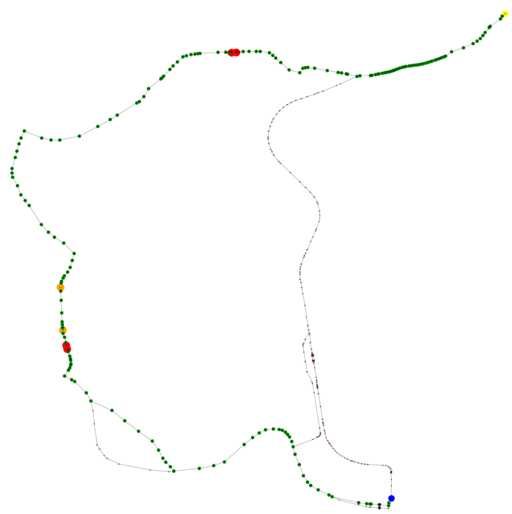

Figure D.6: Loaded BII-1 vessel with destination other than Antwerp

Path	Scheldt-Rhine
Destination	Antwerp
Height	7.0m
Loaded	1.0

Path	Zuid-Beveland
Destination	Other
Height	7.0m
Loaded	1.0

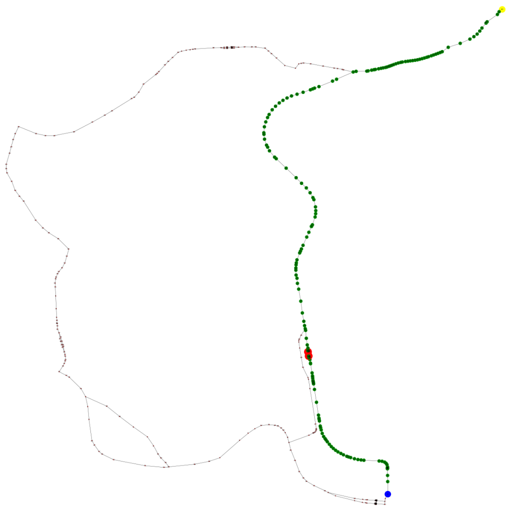

Figure D.7: Empty BII-1 vessel with destination Antwerp

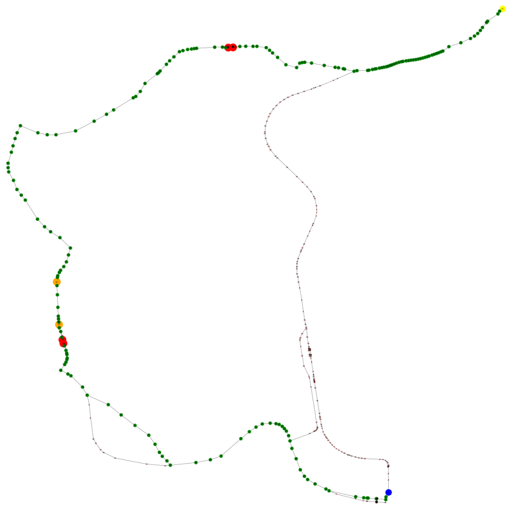

Figure D.8: Empty BII-1 vessel with destination other than Antwerp

Path	Scheldt-Rhine
Destination	Antwerp
Loaded	0.0

Path	Zuid-Beveland
Destination	Other
Loaded	0.0

D.3. Sailing times

Table D.1: Sailing times Scheldt-Rhine route (Bureau Voorlichtingen Binnenvaart, 2019)

Scheldt-Rhine route	**Speed [m/s]**	**Distance [km]**	**Total passage time [min] (Rijkswaterstaat, 2017)**	**Total sailing time hand calculation [hr]**	**Total sailing time Blue Road Map [hr]**
M8-loaded	3.77	50.5	36	3.72 + 0.60 = 4.32	4.30
M8-empty	5.33	50.5	36	2.63 + 0.60 = 3.32	3.30
BII_1-loaded	3.55	50.5	36	3.95 + 0.60 = 4.55	4.50
BII_1-empty	4.78	50.5	36	2.93 + 0.60 = 3.53	3.45

Table D.2: Sailing times Zuid-Beveland route (Bureau Voorlichtingen Binnenvaart, 2019)

Zuid-Beveland route	**Speed [m/s]**	**Distance [km]**	**Total passage time [min] (Rijkswaterstaat, 2017)**	**Total sailing time hand calculation [hr]**	**Total sailing time Blue Road Map [hr]**
M8-loaded	3.77	80.0	83	7.28 + 1.38 = 8.66	8.10
M8-empty	5.33	80.0	83	4.16 + 1.38 = 5.54	5.15
BII_1-loaded	3.55	80.0	83	6.26 + 1.38 = 7.64	7.6
BII_1-empty	4.78	80.0	83	4.65 + 1.38 = 6.03	5.98

Table D.3: Simulation results M8 vessels loaded and empty combined

Path	**Simulation**	**Sailing time M8 vessels [hr]**
Scheldt-Rhine	Baseline measurement	3,900040373
Zuid-Beveland	Baseline measurement	7,326602178

Table D.4: Simulation results BII-1 vessels loaded and empty combined

Path	Simulation	Sailing time BII_1 vessel [hr]
Scheldt-Rhine	Baseline measurement	3,901039347
Zuid-Beveland	Baseline measurement	7,089146491

D.4. Lock recognition by vessels on Zuid-Beveland route

This section presents the results of vessels encountering locks on the Zuid-Beveland route. The nodes 178-179 and 317-365 and the edges between them represent the Krammer locks. The nodes 220-221 and 208-209 and the edges between them represent the Hansweert locks. The results for both locks are presented in the Tables below.

Table D.5: Lock recognition Krammer locks

Generated Vessel:	Arrival nodes	Lock chamber	Time after start simulation [s]	Message	Time after start simulation [s]	Message	Queue
Vessel: 41	364-365	1	23939	Sailing from node 364 to node 365 stop	23939	Sailing into lock start	No
Vessel: 68	364-365	1	32434	Sailing from node 364 to node 365 stop	32434	waiting to pass lock start	Yes
Vessel: 49	403-317	1	39374	Sailing from node 403 to node 317 stop	39374	sailing into lock start	No
Vessel: 88	403-317	1	52586	Sailing from node 403 to node 317 stop	52586	waiting to pass lock start	Yes
Vessel: 42	139-179	2	24901	Sailing from node 139 to node 179 stop	24901	Sailing into lock start	No
Vessel: 152	139-179	2	49089	Sailing from node 139 to node 179 stop	49089	waiting to pass lock start	Yes
Vessel: 145	379-178	2	60817	Sailing from node 379 to node 178 stop	60817	Sailing into lock start	No
Vessel: 136	379-178	2	60552	Sailing from node 379 to node 178 stop	60552	waiting to pass lock start	Yes

Table D.6: Lock recognition Hansweert locks

Generated Vessel:	Arrival nodes	Lock chamber	Time after start simulation [s]	Message	Time after start simulation [s]	Message	Queue
Vessel: 41	272-209	1	32755	Sailing from node 272 to node 209 stop	32755	Sailing into lock start	No
Vessel: 68	272-209	1	43303	Sailing from node 272 to node 209 stop	43303	waiting to pass lock start	Yes
Vessel: 49	210-208	1	29960	Sailing from node 210 to node 208 stop	29960	sailing into lock start	No
Vessel: 145	210-208	1	49780	Sailing from node 210 to node 208 stop	49780	waiting to pass lock start	Yes
Vessel: 42	222-221	2	34871	Sailing from node 222 to node 221 stop	24901	Sailing into lock start	No
Vessel: 224	222-221	2	66585	Sailing from node 222 to node 221 stop	66585	waiting to pass lock start	Yes
Vessel: 136	279-220	2	50155	Sailing from node 279 to node 220 stop	50155	Sailing into lock start	No
Vessel: 150	279-220	2	52251	Sailing from node 279 to node 220 stop	52251	waiting to pass lock start	Yes

D.5. Logs directly from the model

```
In [78]: vessel_log = pd.DataFrame.from_dict(vessels[113].log)
         #
         print(vessel_log.to_string())
         print(len(vessels))

119      Sailing from node 71 to node 72 start  42143.037493   0          POINT (4.2314428 51.4466323)
120       Sailing from node 71 to node 72 stop  42145.016123   0          POINT (4.2314332 51.4466868)
121                waiting to pass lock start   42145.016123   0          POINT (4.2314332 51.4466868)
122                 waiting to pass lock stop   43645.295994   0          POINT (4.2314332 51.4466868)
```

```
In [79]: vessel_log = pd.DataFrame.from_dict(vessels[0].log)
         #
         print(vessel_log.to_string())
         print(len(vessels))

120      Sailing from node 71 to node 72 stop   3426.125591    0          POINT (4.2314332 51.4466868)
121                  Sailing into lock start    3426.125591    0          POINT (4.2314332 51.4466868)
122                   Sailing into lock stop    3726.125591    0   POINT (4.231142699999999 51.4481184)
```

```
In [80]: vessel_log = pd.DataFrame.from_dict(vessels[60].log)
         #
         print(vessel_log.to_string())
         print(len(vessels))

236     Sailing from node 132 to node 73 stop  35233.628294   0             POINT (4.2308522 51.44955)
237                  Sailing into lock start   35233.628294   0             POINT (4.2308522 51.44955)
238                   Sailing into lock stop   35533.628294   0   POINT (4.231142699999999 51.4481184)
```

```
In [81]: vessel_log = pd.DataFrame.from_dict(vessels[120].log)
         #
         print(vessel_log.to_string())
         print(len(vessels))

236     Sailing from node 132 to node 73 stop  51396.705152   0             POINT (4.2308522 51.44955)
237               waiting to pass lock start   51396.705152   0             POINT (4.2308522 51.44955)
238                waiting to pass lock stop   52124.537687   0             POINT (4.2308522 51.44955)
```

```
In [221]: vessel_log = pd.DataFrame.from_dict(vessels[243].log)
          #
          print(vessel_log.to_string())
          print(len(vessels))

233  Sailing from node 154 to node 155 start  74427.489159   0  POINT (4.2295964 51.4495493)
234   Sailing from node 154 to node 155 stop  74429.947103   0  POINT (4.2296124 51.4494714)
235                  Sailing into lock start  74429.947103   0  POINT (4.2296124 51.4494714)
236                   Sailing into lock stop  74729.947103   0  POINT (4.2299153 51.4480348)
```

```
In [222]: vessel_log = pd.DataFrame.from_dict(vessels[85].log)
          #
          print(vessel_log.to_string())
          print(len(vessels))

233  Sailing from node 154 to node 155 start  41364.208405   0  POINT (4.2295964 51.4495493)
234   Sailing from node 154 to node 155 stop  41366.521267   0  POINT (4.2296124 51.4494714)
235               waiting to pass lock start  41366.521267   0  POINT (4.2296124 51.4494714)
236                waiting to pass lock stop  43091.976750   0  POINT (4.2296124 51.4494714)
```

```
In [223]: vessel_log = pd.DataFrame.from_dict(vessels[156].log)
          #
          print(vessel_log.to_string())
          print(len(vessels))

233  Sailing from node 154 to node 155 start  55233.429691   0  POINT (4.2295964 51.4495493)
234   Sailing from node 154 to node 155 stop  55235.692833   0  POINT (4.2296124 51.4494714)
235               waiting to pass lock start  55235.692833   0  POINT (4.2296124 51.4494714)
236                waiting to pass lock stop  56396.231559   0  POINT (4.2296124 51.4494714)
```

```
In [224]: vessel_log = pd.DataFrame.from_dict(vessels[112].log)
          #
          print(vessel_log.to_string())
          print(len(vessels))

119  Sailing from node 216 to node 156 start  41236.031601   0  POINT (4.2302279 51.4465533)
120   Sailing from node 216 to node 156 stop  41237.406225   0  POINT (4.2302182 51.4465982)
121               waiting to pass lock start  41237.406225   0  POINT (4.2302182 51.4465982)
122                waiting to pass lock stop  43378.749360   0  POINT (4.2302182 51.4465982)
```

Figure D.9: Logs waiting before locks individual vessels

```
# EnviromentReport notebook for plot calculations
env.enviromental_report.plot_energy_usage()
env.enviromental_report.plot_path_usage()
env.enviromental_report.plot_co2_emission()
env.enviromental_report.plot_co2_emission_km_load()
env.enviromental_report.plot_transported_weight_corridor()
```

```
Queues:  Krammerlock 0 1 588.6517415210956
Queues:  Kreekraklock 3 2 588.6819130082697
Queues:  Kreekraklock 3 3 588.7316856638448
Queues:  Kreekraklock 3 4 588.7776034809807
Queues:  Kreekraklock 3 4 588.7856770026647
Queues:  Hansweertlock 0 0 588.7900479995277
Queues:  Krammerlock 0 0 588.8578314873112
Queues:  Kreekraklock 4 3 588.9261055338145
Queues:  Kreekraklock 4 3 588.9290286920863
Queues:  Hansweertlock 0 0 588.9312376193715
Queues:  Hansweertlock 0 0 588.9639048358763
Queues:  Kreekraklock 4 4 588.9907899921125
Queues:  Kreekraklock 4 4 589.0086250812152
Queues:  Hansweertlock 0 0 589.0857847706396
Queues:  Hansweertlock 0 1 589.1736725047238
Queues:  Hansweertlock 0 1 589.1889735020333
Queues:  Krammerlock 0 0 589.3100744801784
Queues:  Kreekraklock 2 3 589.4533935284924
Queues:  Kreekraklock 2 3 589.4537046600589
```

```
In [10]: env.enviromental_report.get_transported_weight_corridor()
```

Figure D.10: Logs from simulation on queue formation at Kreekrak lock

```
In [41]: # this way I can see activity at lock
         for edge in FG.edges(data=True):
             if (edge[2]["Object"] == "Lock"):
                 lock_log = pd.DataFrame.from_dict(edge[2]["attribute"].log)
                 print(edge[2]["attribute"].lock_name,edge[2]["attribute"].nodes, lock_log)
```

```
4     Ship in lock  2.619293e+04    Vessel 19  POINT (4.2299153 51.4480348)
5    Ship out lock  2.751293e+04    Vessel 19  POINT (4.2299153 51.4480348)
6     Ship in lock  2.752870e+04    Vessel 57  POINT (4.2299153 51.4480348)
7    Ship out lock  2.884870e+04    Vessel 57  POINT (4.2299153 51.4480348)
```

```
In [41]: # this way I can see activity at lock
         for edge in FG.edges(data=True):
             if (edge[2]["Object"] == "Lock"):
                 lock_log = pd.DataFrame.from_dict(edge[2]["attribute"].log)
                 print(edge[2]["attribute"].lock_name,edge[2]["attribute"].nodes, lock_log)
```

```
18    Ship in lock  1.486167e+04     Vessel 6
19   Ship out lock  1.618167e+04     Vessel 6
20    Ship in lock  1.662195e+04    Vessel 26
21    Ship in lock  1.787002e+04    Vessel 29
22   Ship out lock  1.794195e+04    Vessel 26
```

Figure D.11: Logs Kreekrak lock

D.6. Dynamic route choice locks

The queue formation at the Hansweert lock and Krammer lock during a random moment in the simulation is presented in Tables D.7 and D.8.

Table D.7: Queue formation at the Hansweert locks

Time since start simulation [hr]	**Queue lock chamber 1**	**Queue lock chamber 2**
204.57605574276542	0	0
204.67547844546272	0	1
204.76347986928337	0	0
204.985817581111	1	0
205.1072233620342	0	2
205.16533715611808	0	0

Table D.8: Queue formation at the Krammer locks

Time since start simulation [hr]	**Queue lock chamber 1**	**Queue lock chamber 2**
158.758136789783	0	1
158.8455173058631	1	0
158.96202536041088	1	1
204.985817581111	1	0
159.13023240671401	0	2
159.3693983753214	1	0

D.7. Locks

Table D.9: Lock message at Krammer locks

Generated vessel:	**Arrival nodes**	**Lock chamber**	**Sailing direction**	**Time since start simulation [s]**	**Message lock**
Vessel: 123	364-365	1	North	53520	Ship in lock
Vessel: 123	364-365	1	North	55406	Ship out lock
Vessel: 96	403-317	1	South	55920	Ship in lock
Vessel: 96	403-317	1	South	57806	Ship out lock
Vessel: 3	139-179	2	North	15858	Ship in lock
Vessel: 3	139-179	2	North	18258	Ship out lock
Vessel: 26	379-178	2	South	18673	Ship in lock
Vessel: 26	379-178	2	South	21073	Ship out lock

Table D.10: Lock message at Hansweert locks

Generated vessel:	**Arrival nodes**	**Lock chamber**	**Sailing direction**	**Time since start simulation [s]**	**Message lock**
Vessel: 3	210-208	1	North	7769	Ship in lock
Vessel: 3	210-208	1	North	9269	Ship out lock
Vessel: 7	272-209	1	South	9449	Ship in lock
Vessel: 7	272-209	1	South	1140	Ship out lock
Vessel: 21	279-220	2	North	20410	Ship in lock
Vessel: 21	279-220	2	North	21910	Ship out lock
Vessel: 31	222-221	2	South	23089	Ship in lock
Vessel: 31	222-221	2	South	24589	Ship out lock

D.8. Emission calculations

Table D.11: Average speed comparisons

Vessel class:	**Average speed loaded [m/s]**	**Average speed [m/s] Schatting energieverbruik binnenvaartschepen (Bolt,2003)**	**Average speed empty [m/s]**	**Average speed [m/s] Schatting energieverbruik binnenvaartschepen (Bolt,2003)**
M1	3.08	3.17	4.47	4.50
M2	3.36	3.79	4.64	4.80
M3	3.86	3.87	4.64	4.69
M4	4.00	4.08	4.88	4.78
M5	3.92	4.38	5.03	5.29
M6	3.92	4.34	5.19	5.28
M7	3.77	3.75	5.36	5.00
M8	3.77	4.59	5.33	5.14

E

Simulation results

E.1. Results increased bridge height on the Scheldt-Rhine canal

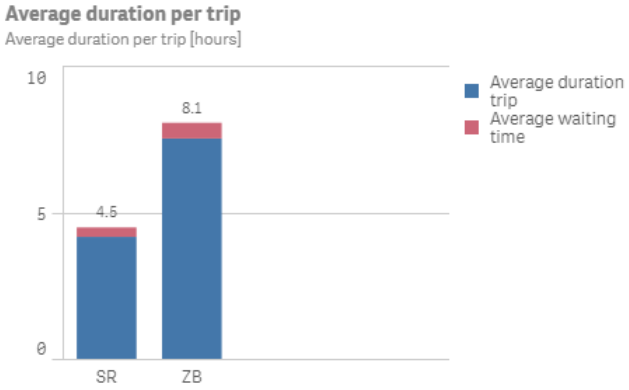

Figure E.1: Average sailing and waiting times for the low Null-scenario

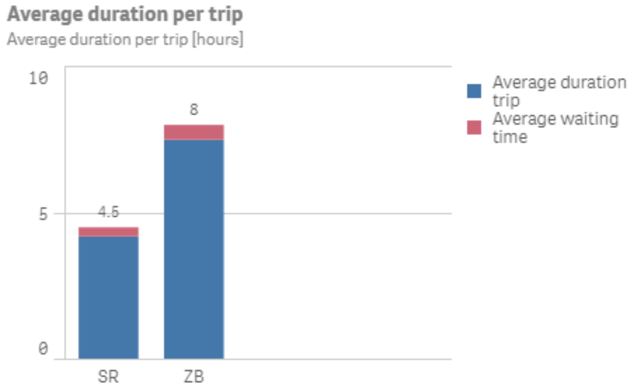

Figure E.2: Average sailing and waiting times for the bridge height increase implemented in the low Null-scenario

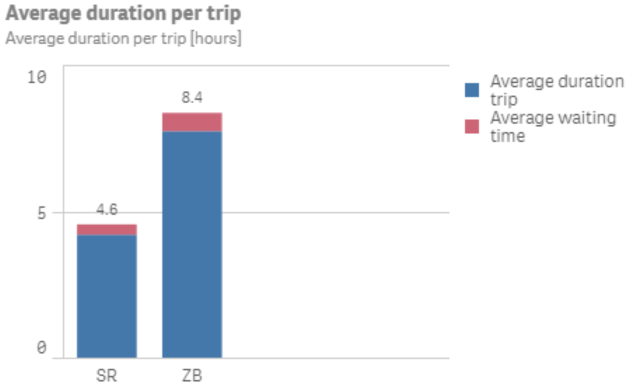

Figure E.3: Average sailing and waiting times for the high Null-scenario

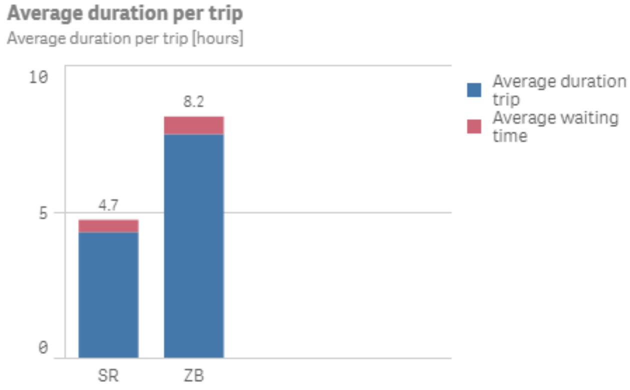

Figure E.4: Average sailing and waiting times for the bridge height increase implemented in the high Null-scenario

E.2. Results removal Kreekrak lock

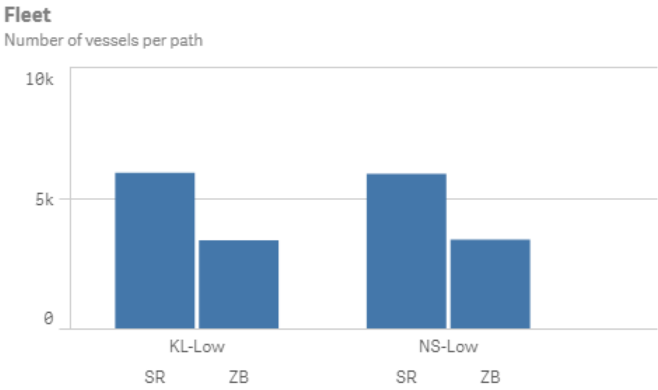

Figure E.5: Fleet distribution for Kreekrak lock removal in low Null-scenario

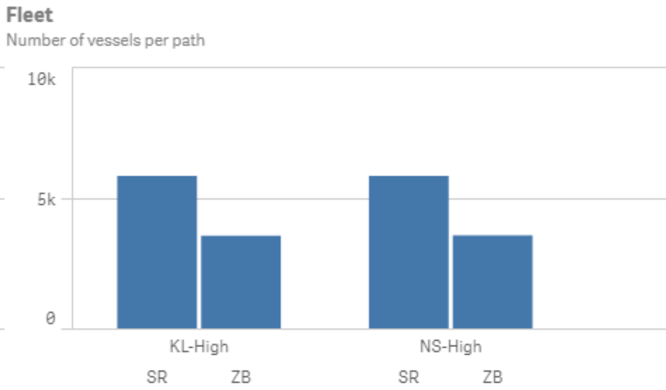

Figure E.6: Fleet distribution for Kreekrak lock removal in high Null-scenario

E.3. Results high cube containers

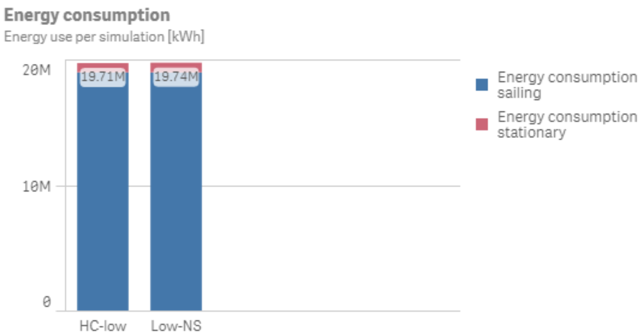

Figure E.7: Energy consumption for high cube container scenario in Null-scenario low

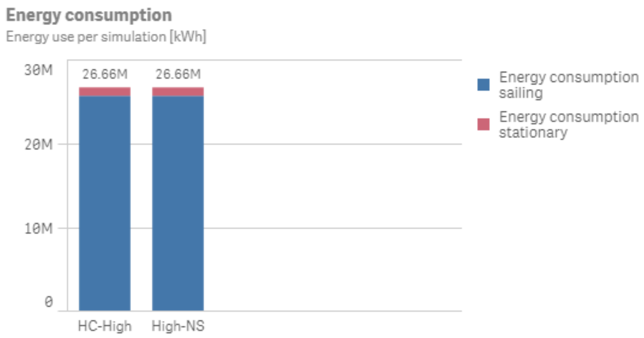

Figure E.8: Energy consumption for high cube container scenario in Null-scenario high