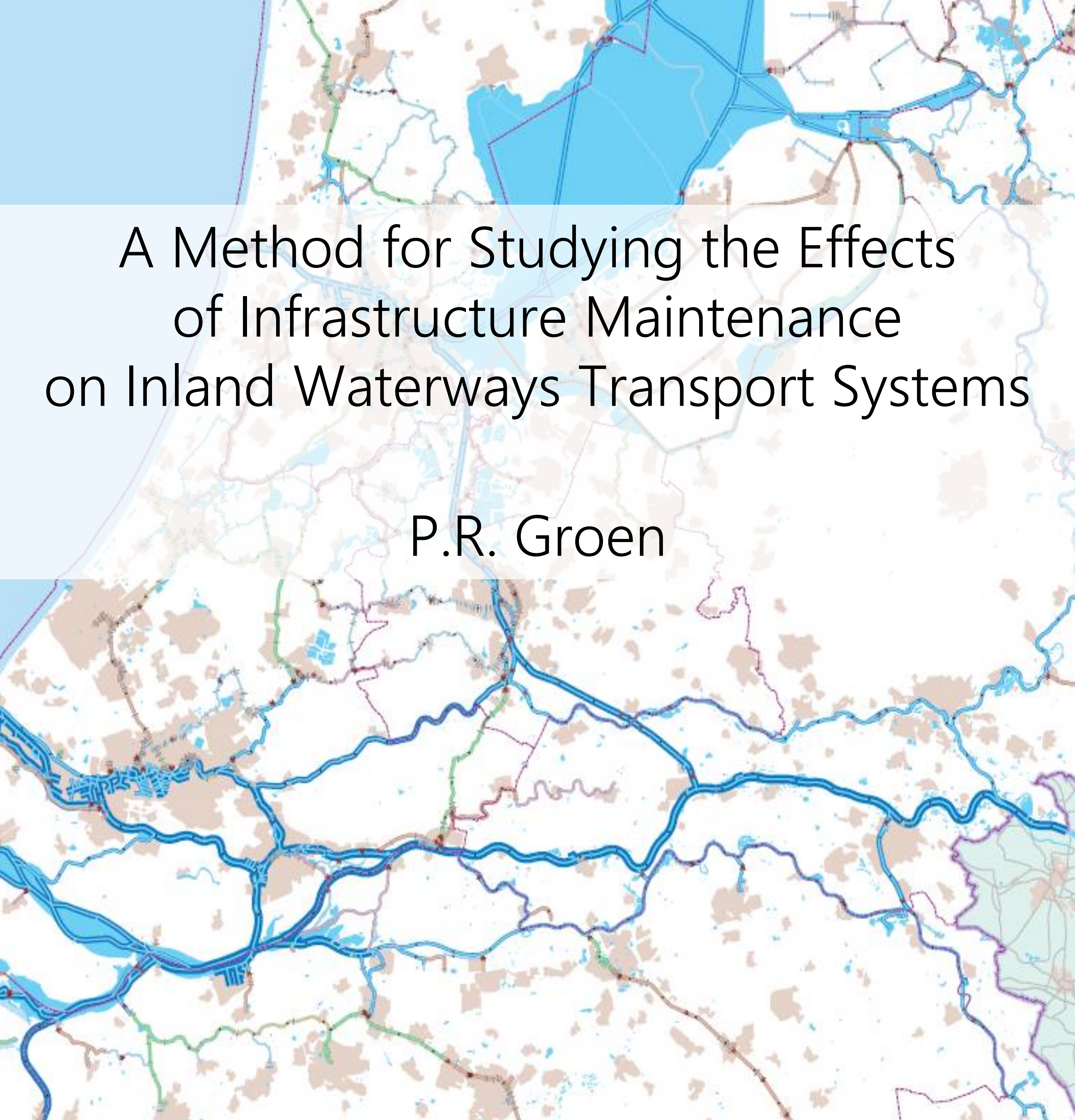

A Method for Studying the Effects of Infrastructure Maintenance on Inland Waterways Transport Systems

P.R. Groen

TU Delft

Witteveen + Bos

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A Method for Studying the Effects of Infrastructure Maintenance on Inland Waterways Transport Systems

by

P.R. Groen

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Thesis committee:	Prof. dr. ir. M. van Koningsveld	TU Delft
	Ir. P. Quist	TU Delft & Witteveen+Bos
	Ir. M. Duinkerken	TU Delft
	Ir. L. de Boom	Witteveen+Bos
	Ir. E. Bolt	Rijkswaterstaat
	Dr. ir. P. Taneja	TU Delft

Management Summary

The inland waterways are an important part of the freight transport system of the Netherlands. However, in the coming years a lot of maintenance and construction works are needed to keep the waterways network operational. In this research a method was developed that can be used to determine the impact of maintenance or construction works on the inland waterways system.

The developed method consists of several steps. First, a literature study was done to determine how performance of the system can be measured and what components are important to model. Second, an analysis of the current situation in the system is done using mainly AIS data. Finally, a simulation model was developed that can be used to imitate the inland waterways system to predict the impact of closing a waterway.

Performance of the Inland Shipping System

The effects of closing a waterway on the inland shipping system can be divided into two categories: performance of vessels and the performance of the network. These were both considered in this research as they provide different insights in the effects.

The performance of vessels can be best expressed in terms of total operational costs. This can be used to calculate the additional cost made per vessel and for the entire system that is studied. These costs or performance indicators can be further divided into three parts: distance, time and reliability costs. Distance costs are the cost made by sailing a certain distance and consists mainly of fuel costs. Time costs are costs that are the other costs required to operate a ship over time. The reliability costs are the costs of delays and unexpected waiting times.

The performance of a network is strongly related to the reliability costs of the vessels. The main bottlenecks of the inland waterways network are the locks. A change in the traffic volumes over waterways with locks on them can have a large effect on the average waiting time for these locks. The performance of locks is measured using two indicators for the waiting times: the average waiting time and the 90% confidence values for the waiting times. The effect of changing traffic volumes on the parameters is exponential and a small increase can therefore mean a large increase in waiting times.

Analysing the Vessel Movements

In this research a method was developed to analyse the system using a relatively new data source in inland shipping research. All freight vessels have an Automatic Identification System (AIS) that sends out a message at certain time intervals. This data is stored and can be used to track vessels moving over the inland waterways network. Because of privacy issues, this data source had not been used very often in the research on inland shipping before. Using this data source proved very useful as it can be used for many different aspects of the system. For analysing an inland waterways system using AIS, the focus was on three aspects: lock operating times, traffic assignment and the fleet composition.

From comparing the outcomes of the AIS analysis with another data source it was obtained that there are also some inaccuracies in the data. Several reasons for this can be found in the acquisition, storing and processing of the data. One perceived problem is that the AIS messages are not send/received, or contain wrong information. Another is that AIS data is messy and needs many modifications before it can be analysed. Overall, AIS seemed to underestimate the number of ships on a network.

Developed Simulation Model

The goal of the simulation model was to make a tool that can predict the expected change in performance in an inland shipping system. The simulation model was built using the open-source toolbox of OpenTNSim in which most of the required functionalities were present. The most important functions

of the simulation model were tested to see if there if they operated as intended. These functions are the basic movements, the generation of vessels between origins/destinations and the functioning of the lock. The complete model was checked on whether it functioned as planned by running the base scenario and comparing the results with the input traffic values. The R-squared model fit based on the in- and output matrices was calculated at 0.949, which is seen as a good model fit.

Simulating the Effects

The developed simulation model was tested on a case study with two situations: the base scenario that is based on the normal situation on the network and the scenario where a waterway at is closed off. This provided the change in performance measured in the performance indicators for vessels and the network, as were mentioned earlier.

The impact for vessels can be determined by calculating the change in operational costs for the three cost categories. In the case study, the average operational costs for vessels within the system boundaries grew by approximately 51%. This increase shows that the impact of closing a waterway can have a significant impact on the performance of inland ships.

In the case study a small shift in traffic over the network resulted in larger waiting times at the locks on a network. The case study was performed on a network section that has relatively low traffic volumes compared to other parts of the inland waterways network in the Netherlands. However, for some locks large increases in waiting times were observed. This means that it could be worthwhile to apply the method developed in this research when planning other construction and maintenance projects.

Conclusions

In the developed method, AIS data and a simulation tool were combined to try and recreate the real-world system as accurate as possible. It was found that this can be a useful combination as AIS can be used to eliminate certain assumptions that were otherwise needed as input for the simulation model. However, it was in this research not possible to eliminate all these required assumptions. There are some reasons for this, but most important is that AIS data is messy and needs modifications before it can be analysed. It was determined that using AIS comes with some accuracy issues as it seems to underestimate the number of ships on a network. The functions of the simulation model worked as intended and it can be adapted quite easily to other case studies. It can thus be concluded that the developed method can be applied when studying the effects of planned maintenance and construction works, but it is best used to estimate where the impacts are expected to be big rather than to calculate exact results.

Recommendations

It was found that the traffic volumes from AIS are an underestimation of the actual volumes. In the production, gathering and processing of the data there could be causes for this underestimation which should be further investigated.

Another application of AIS data in this research was the analysis of the lock passages by ships. In this research a normal distribution was used to imitate the observed behaviour of variation in lock operating times. Further research is required to see what distribution the best fit for the operating times of locks. Additionally, assumptions were made for the waiting, approach and exit times at locks. If a method is developed that can calculate these other delay components for locks from AIS it could be used to check accuracy of the simulation model developed in this and other research projects.

The effects of closing a waterway can reach beyond inland shipping. Should the costs for using a vessel increase too much, shippers might decide to switch to another transport mode. This is an undesirable effect as inland shipping is seen as a transport mode with relatively low negative external effects. Expanding the current method to include a last step in which a comparison is made between different transport modes would give a more complete idea of the impact of closing a waterway.

Preface

This research marks the final step in obtaining a Master of Science in Transport, Infrastructure & Logistics at the TU Delft. The project was done in cooperation with the engineering and consultancy firm Witteveen+Bos and they have provided me with excellent support.

I would like to take this opportunity to thank my graduation committee for their help and for guiding me through the process. First, I want to sincerely thank Peter Quist for his help in finding a subject for my research, introducing to all the right people at the Witteveen+Bos and his reassuring remarks. Next, I would like to express my thanks to Lex de Boom for his guidance through all the phases of the project, our meetings have always helped me find new approaches and energy to keep going. I would also like to thank Mark van Koningsveld for his hands-on approach and for helping me make the big decisions. I would also like to thank Mark Duinkerken for his sharp remarks during all the meetings. I would also like to thank Ernst Bolt for his help in analysing the inland shipping system in depth.

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1

Introduction

Inland waterways are an important part of the transport chains of certain ports. Especially for commodities with low cost to weight ratios barge transport is a viable option. For the Netherlands, the share of inland shipping in the transport of goods is especially high. Transport over inland waterways accounted for 38% of freight moved in Netherlands in 2017 (Eurostat, 2017). This is a relatively high percentage compared to other countries in the region. One of the reasons for this is the availability of an extensive waterways network.

Figure 1.1: Waterways in the Netherlands. Picture obtained from: CBS (2009)

Recently, the European Union accepted a proposal for a New Green Deal to tackle the impacts of its member states on climate change. Part of this proposal is the ambition to restructure the transport system in Europe (Commission, 2019). This includes a shift away from freight transport over roads towards rail and inland waterways. Both rail and inland waterways transport tend to have less negative environmental effects per unit type of cargo moved. Should the Green Deal policies of the European Union take effect, the Dutch waterways will see an even larger increase in traffic volumes.

The capacity of inland waterways is mainly defined by its bottlenecks. These are usually infrastructures such as locks and bridges or changes in the waterways like merging points. These are designed with a certain theoretical capacity in mind. If traffic volumes approach this theoretical capacity, chances of congestion increase exponentially. On the Rhine corridor, most infrastructure was built in the period after the second world war and is approaching the end of its lifetime. In response to this, the Dutch government plans to invest extra in maintenance and upgrading of crucial infrastructure.

Large scale maintenance or replacement of such structures can take several months or even years to complete. During these projects there are often periods during which traffic over the water segment is limited or not possible. Transport that would normally use this river or canal segment is then required to find an alternative route or modality. This can have negative effects in terms of congestion or operational costs for companies using this waterways segment. If these negative effects can be mapped, they can be considered when deciding on a strategy for planning the maintenance or construction works.

1.1. Problem description

Navigational locks, bridges and other infrastructures are a crucial part of river and water management. Because these constructions have a limited lifetime and because the characteristics of the surroundings can change, maintenance or construction projects are required from time to time. This can result in downtime or reduced throughput on the river or canal section. Therefore, companies and regions that depend on inland shipping can suffer from this reduced availability and capacity. This is expected to result in higher transport costs and possibly in an increased use of other modalities. Especially on hinterland connections with large volumes this can cause severe negative effects in terms of, for example, fuel costs and travel times.

There are currently concerns about the state of the infrastructure and the maintenance required in the coming years in the Netherlands. The Algemene Rekenkamer, an institute that checks the budgeting and expenditures of Dutch national government, concluded that the amount of deferred maintenance of the waterways, locks and bridges in the Netherlands has been increasing over the last couple of years. This amount was expected to increase to over 400 million euros by the end of 2019 (Rekenkamer, 2019). Which means that a lot maintenance is required in the next couple of years to keep the waterways functioning properly.

Usually, there is more than one way of performing maintenance or constructing infrastructure with respect to the availability of the concerned waterway. Therefore, a trade-off can often be made between the costs of quicker construction and the costs of down-time of the water section, which in turn can have negative effects for the transport network. These effects can be congestion and delay at the waterways section if the throughput capacity is reduced. If the section is completely closed, there will be additional costs for ships that have to take a detour if a detour is possible. In turn, this means increased traffic on other waterways with additional congestion as a result. These effects have a negative impact on the attractiveness of inland shipping. Although disturbance due to infrastructure maintenance or construction is a temporary state, during this period there could be severe hindrance with long term impacts on the usage of waterways transport.

As the Dutch government has stated the goal to stimulate the inland shipping sector, it is important to consider any negative effects concerning the costs of inland shipping. This includes the hindrance caused by maintenance or construction. To determine these costs the possible scenarios for the infrastructure project should be compared regarding the ship traffic on the relevant network. Because the inland shipping system can be complex and dynamic, this is not a straightforward procedure.

1.1.1. Research Gaps

This research is aimed at developing a working method for determining the effects of construction and maintenance projects while they are being carried out. Effect studies are a common practice when planning such a project (Rijkswaterstaat, 2018). However, these studies are usually only aimed at the impacts of the finished project. An effect study might not be necessary when a maintenance project is small, and the expected hindrance is low. But when the project duration is long, and the availability of a waterways is severely impacted an effect studies might be worthwhile. This research aims to make it easier to perform an effects study such that it can be included in the planning of construction and maintenance.

One example of research that has looked into the impact of construction works on the ship traffic is that of Deceuninck et al. (2018). In their research they studied the effect of imposing one-way traffic on a canal in the Port of Antwerp region. In their research they also used AIS for the collection of their inputs and used a simulation model to study the new situation. There are however some significant differences in the inputs required for this research as well as the requirements for the simulation model.

Analysis using AIS
One of the main parts of this research is the use of AIS for the analysis of the system. Yang et al. (2019) made an overview of the use of AIS in maritime and shipping research. They found that the use of AIS in research has quickly gained traction over the last couple of years for several different uses. Most of the earlier research was focused on the waterway safety problems and navigational optimisations. Since then, research has broadened and has been using AIS for more extensive applications and wider subjects. However, no research was found that used AIS for the analysis of inland ships on a complex network to determine the origins, destinations, and movements of traffic. Additionally, the use of AIS to analyse operational cycles of locks is a new application for this data source.

Deceuninck et al. (2018) also used AIS to analyse the traffic intensity on the studied canal and to determine the fleet composition. These analyses are also parts of this research but need to be expanded to fit the larger network with multiple edges and destinations.

Simulation tool
In this research the Python based simulation tool, OpenTNSim, developed at the TU Delft is used. This tool has been used in the simulation of inland shipping networks before with varying purposes. Vehmeijer (2019) used the model to study the emission of CO_2 on the two routes between the ports of Rotterdam and Antwerp. In her simulation model she also included some aspects that will used, and some expanded upon, most notably the including of locks on the network. van der Does de Willebois (2019) used OpenTNSim to study the effects of canal closures and one way traffic on the recreational and passenger traffic on the canals of Amsterdam. Some of the methods developed in his research are also used in this study.

This research further expands on the used simulation tool by adding a new option for the locks on the network. Additionally, the method developed in this research to add many specific origin and destination pairs to the model can be useful for later studies as well.

1.2. Research Objective

To make an informed decision on the right maintenance or construction strategy to be used on waterways infrastructure, it is important to know the impact it has on the transport network. The goal of this research is to develop a working method for determining the effects of reduced availability of a waterways section on inland shipping traffic. This consists of two main parts. The first is developing a method to analyse the network and traffic in an inland shipping system of interest. The second is to develop a method that uses the outcomes of the analysis to create a model of the system that can be used to predict the impacts of maintenance or construction.

1.2.1. Research Questions

From the research goal, a set of research questions is derived. The main question this research aims to answer concerns the increased transport costs and the modal split caused by the construction or maintenance of infrastructure. This is therefore formulated as:

What are the effects of temporary closing a waterways section on inland waterways transport?

From this main question and research goal, a set of sub-questions is also derived. These were aimed at guiding the research by splitting the research into smaller steps. The results found in answering each of these sub-research questions were used in the subsequent step of the process. This resulted in the list below, where with each sub-question a brief explanation is given about what its purpose is.

1. **What are important characteristics of inland waterways transport system with regard to traffic and network analysis?**

To provide some overall knowledge on the relevant aspects for the analysis of inland shipping networks, a literature study on the waterways and inland shipping transport is done. Additionally, it is examined on what parts of the field of transport modelling this research is focused.

2. **What are the indicators that can be used to measure the performance of an inland shipping system?**
   Before a simulation model can be constructed and applied to the case study, it must be known what effects are to be measured. This results in the key performance indicators that will be used to determine the generalised costs of ships in the system.

3. **How can important network and traffic characteristics be obtained from the data and information available?**
   To determine the effects of any change in an inland shipping system, the network characteristics should be determined. This means that network lay-out and surrounding area must be investigated. Additionally, an overview of the traffic and movements over the network should be obtained for which AIS data is used.

4. **How can the inland waterways system best be represented in a simulation environment?**
   The simulation model should adequately resemble the inland waterways to be of use. Therefore, it is important to make the correct decisions and assumptions when building the model.

5. **What is the impact of the closure of a waterways section on the performance of the inland waterways system?**
   Using the simulation model, the change in total performance of the vessels can be obtained by comparing the base scenario with the changed scenario. Additionally, a comparison between the performances of the locks on the network is made.

1.2.2. Research Scope

There is a great variety in maintenance and construction projects that influence the availability of waterways. Both in duration of a project and the impact on the possible throughput during the project there can be large differences. It is therefore not possible to include all variations within the scope of this research. To develop a working method that can easily be transferred to other situations a case study is used. The steps taken in this case study should be transferable to other situations and therefore the right network should be selected.

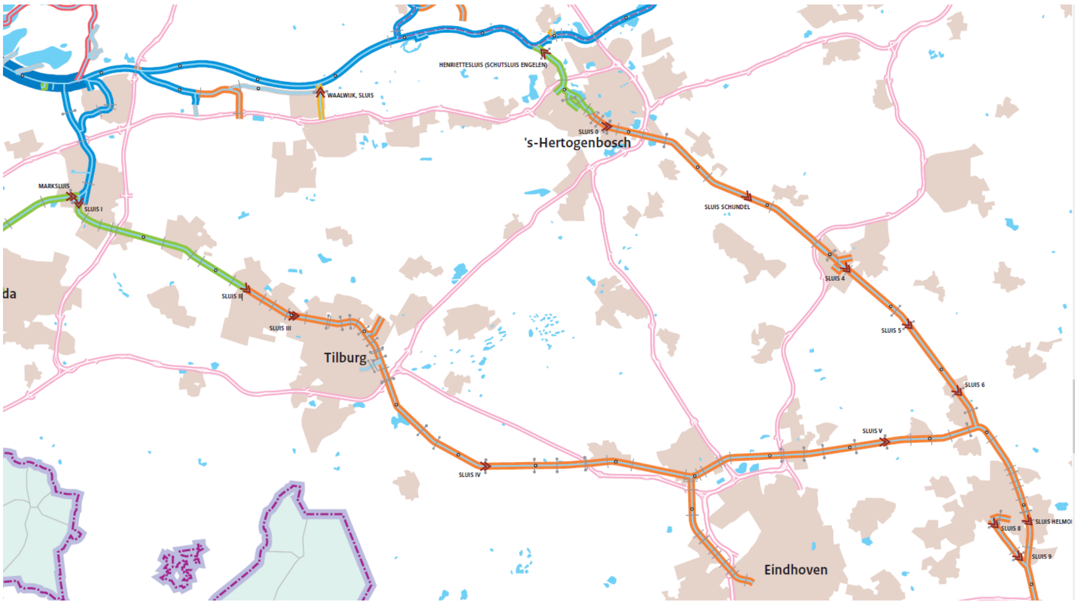

Figure 1.2: The part of the waterways network in the province of Noord-Brabant that is the subject of the case study. (Rijkswaterstaat, 2019)

The case study will focus on a part of the inland waterways network of The Netherlands represented in Figure 1.2. This is an interesting section to study for several reasons. The network contains several locks on multiple sections. Locks are bottlenecks and therefore important factors in the performance of vessels. Additionally, all important points on the network can be reached through more than one route. This makes detours possible in case of unavailability of a waterways section which also influence the performance of vessels. The focus will be on the scenario of replacing ”Sluis II”. This is a lock in the southwestern corner of the network that has been out of operation and will be replaced by a larger lock to allow large ships to reach more parts of the network. A schematic representation of the network is shown in Figure 1.3, where the position of ”Sluis II” and the other locks can be seen.

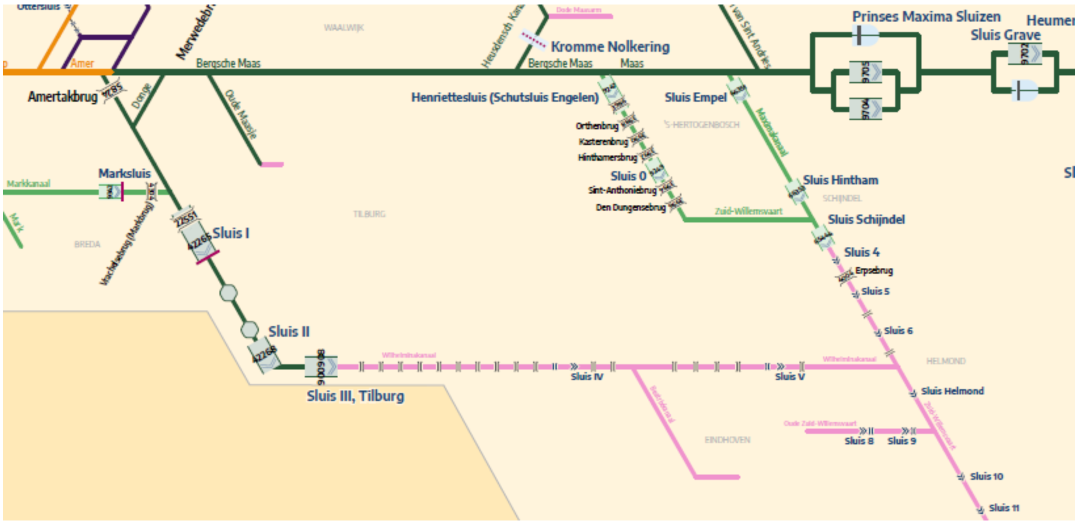

Figure 1.3: Schematic representation of the inland waterways network used in this research. (Rijkswaterstaat, 2019)

The construction of the lock could be done in several ways with varying impacts on the availability of the waterway. This means that several scenarios are possible for the prediction of impacts that can be modelled. In this research the scope is limited to a single situation of closing the waterway. Only the case of complete closure of the waterway is considered. So, solutions with one-way traffic, limited traffic or size restrictions are no further investigated. However, the steps in the developed method should be applicable to these situations without too much effort.

1.3. Research Approach and Methods

To gain an answer to the main research question a combination of research methods was used. These can also be deducted from the sub-research questions presented earlier and can be split into three main methods.

1.3.1. Literature Study

First, a literature study is done to provide some context to the research and determine what aspects should be considered in the later steps of the research. An overview of the relevant aspects of inland shipping is presented. Additionally, a brief explanation of the transport modelling concepts that are used will be given. The desk study should result in a set of cost factors or performance indicators by which the performance of the ships is measured.

1.3.2. Quantitative Data Analysis

Second, a more quantitative approach will be used to determine the current situation in system of the case study. The main data source for the analysis is AIS, which stands for Automatic Identification System. It is used for the analysis of various characteristics of the studied system, such as the operational times of the locks, the movements of the vessels and the traffic intensities on the network.

The analysis of the AIS data is mainly done in Python using the Dask package. This is a tool written to help with the processing of large data sets that might not fit into the working memory of the operating device. It consists of a task scheduler and a framework for storing data temporarily on disk. The exact working method with this tool is also explained step by step in Chapter 3. Using Dask eliminates the need for large computational capacities or the use of clusters and thus makes it easier to reproduce the method in other case studies.

Because AIS has not been used for creating vessel traffic overviews in inland shipping research before it is important to verify the results obtained in the analysis. Verification is done using another data source called IVS90, which has been used in previous studies.

1.3.3. Simulation Model for Predicted Impacts

Finally, a simulation model was developed to calculate the differences in performance between two scenarios. The simulation model uses an agent-based discrete event simulation approach. The model is coded in Python and is based on the OpenTNSim-package[1], developed at department of hydraulic engineering of the TU Delft. OpenTNSim is an open source set of tools that can be used for the analysis of transport networks and specifically in the context of water-based system. OpenTNSim is in essence a wrapper of the Python package Simpy, which is a general framework for process based discrete event simulations.

One of the functionalities of OpenTNSim is that it can recreate a network in a simulation environment relatively easily. This is especially useful for inland waterway studies where travelling between points is only possible over the network. To recreate such networks, OpenTNSim uses two other packages. The first is NetworkX, with which a network made of nodes and edges can be made. To all of these nodes and edges attributes can be given, which will be needed for the simulation. The network is generated from a shapefile made available by Rijkswaterstaat and transformed using a package called Osgeo[2].

The generation of the final results was done by simulating the traffic on the network for a period of time in two scenarios. One that represents the current situation and one in which an adjustment is made that corresponds with the case study. The simulation run for the current situation was also used to check whether the model outputs correspond with the expected values as obtained from the analysed data. Additionally, the most important parts of the simulation model were tested separately to verify whether they performed as expected.

1.4. Reader's Guide

This report is structured such that it follows the order of the research questions as provided in Section 1.2.1. In Chapter 2 the first two questions will be discussed. This resulted in an overview of the relevant aspects of the inland shipping sector, the performance indicators that will be used and a brief explanation on the theory of transport modelling and its relation to this research. Thereafter, in Chapter 3, the methods and results used for the analysis of the data are explained to answer the third research question. Chapter 4 expands on the choices made while designing and building the simulation model to answer the fourth research question. Additionally, the verification of the most important parts of the model is provided. The application of the simulation model provides the answer to the final sub-research question and the results are presented in Chapter 5. Thereafter, a discussion on the used methods and results is provided in Chapter 6. Finally, the conclusion of the research is provided and some recommendations for future research are given in Chapter 7.

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[1] OpenTNSim stands for: Open-source Transport Network Simulation

[2] Osgeo stands for: open-source geospatial foundation

2

Transport over Inland Waterways

The first step in developing a method for the analysis of inland waterways systems, is to study its characteristics and determine how the analysis can be approached best. It should be examined what parts of the system are relevant when determining the effects.

In this chapter an answer is provided to the first two research questions. To answer the question: *"What are the characteristics of inland waterways transport system with regard to traffic and network analysis?"*, first it is explained what steps are required for analysing transport systems in general. Then, the characteristics of the vessels relating to network analyses are discussed. Finally, it is explained what aspects of the inland waterways influence the capacity and throughput. With the information gained in these sections specific variables are defined that can be used to measure the performance. This provides an answer to the second research question: *"What are the indicators that can be used to measure the performance of an inland shipping system?"*.

2.1. Modelling of Freight Transport

The inland waterways is a transport system where vessels move goods between areas. In this transport system the vessels are the agents that travel over the network of linked waterways. In this section the general theory behind the modelling of transport systems and how it can be used to study the inland waterways is explained.

2.1.1. Four-Stage Transport Model

Numerous researches have been performed using a wide variety of models and simulation methods to gain insight in the dynamics of freight transport systems and to predict the effects of certain changes. An often used structure is the four stage structure as described by Tavasszy and de. Jong (2014). This is a general model that can be used to investigate the effects of all kind of changes to the system at every level and can be used for both freight and passenger modelling. In most cases, these changes are researched using scenarios with changed parameters. These scenarios can then be compared to the unchanged or base scenario.

An overview of the four stage model is presented in Figure 2.1. As can be seen in this figure, the four stages for are defined as: trip generation, trip distribution, mode choice and traffic assignment (van Nes, 2018). In the presented figure, an additional step is shown between the modal split and trips assignment: Time of Day. This addition to the classic four stage model was made to allow for differentiating between peak and off hours. This is an important distinction, as there can be large differences in traffic volumes over the day (Chen et al., 2013).

The first stage of the model, trip generation, concerns the production and attraction for each investigated area. The inputs for this level are usually based on regional, national, or other aggregated statistics. In the second stage, the production and attraction are translated to origin and destination combinations with associated transport volumes. In the third stage, the modal split for each origin/destination pair is

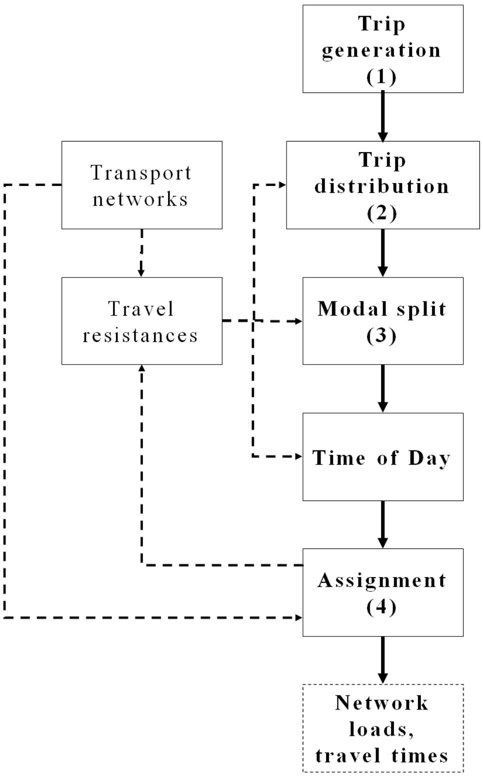


Figure 2.1: The classic four stage transport model with the addition of a time of day step. Adjusted from: van Nes (2018)

calculated. Lastly, in the fourth stage the routes by which the modality travel is determined. Complete transport models cover all the stages previously mentioned, where the output of an earlier stage is used as input for the subsequent stage. However, usually at least a few iterations back to an earlier step are required to obtain valid and reliable results (van Nes, 2018).

This research focuses mainly on the final stage of the model. The production, attraction and distribution of transport demand will be considered constant and will be based on the analysis of AIS data. This means that it is assumed that the results from the trip assignment does not influence the production etc. This assumption is made because the time frame of infrastructure construction and maintenance is short compared to time frames normally used (Furnish and Wignall, 2009) in the first two stages of transport modelling. This can span multiple years where the case study for example spans somewhere from 8 to 13 months. The modal split will not be modelled in this research but will be discussed after the results are obtained.

2.1.2. Modelling of Mode Choices

The decision to use a certain mode of transport for freight is dependent on many aspects. Cost per unit and time of movement are often the most important factors. Other aspects that influence the decision are for example flexibility, reliability, availability and sustainability (Tavasszy and de. Jong, 2014). The weight given to each aspect of transport can vary per good type and user. For example, for goods with a high value to weight ratio, time is an important factor.

Multiple factors can thus influence the decisions made by freighters for a certain mode of transport. All these factors can be translated to a form of costs, which can be combined in the total transport costs. With the total transport costs known for all available modes an estimation can be made of which will be the most attractive to use.

For goods that have a lower value per weight or volume ratio, transport over inland waterways is usually a good option. Additionally, inland barges can transport large quantities in terms of weight and volume for low costs compared to other transport options. Inland ships are a relatively slow mode of transport. However, they are able to transport large shipments in terms of volume and weight at relatively low rate (De Jong et al., 2011). Therefore, they are mostly suited to transport heavy goods or goods with a low value of time.

2.1.3. Time of Day

The added step to the four-stage model is aimed at providing a more realistic representation of the traffic demand. When the time of day distribution of traffic is not considered, there is a possibility that there will be large differences in the expected and actual network loads and congestion. This is especially important in the modelling of passenger transport, where peak hours experience far more traffic than the off-hours. With freight transport this effect is usually not as big, it is a significant factor nonetheless. Most freight movements happen during the day as most companies operate during office hours and there are extra costs associated with nigh time operations.

When the traffic loads on the network vary greatly during the day, it also influences the waiting times at bottlenecks like locks. Because this congestion behaviour has this strong influence on the performance of the locks, and thus also the ships, it is important to consider the time of day factor.

2.1.4. Trip Assignment

With the expected number of trips over the network and their expected departure times known, movements over the transport network can be assigned. Trip assignment methods can be broadly divided into two types: static and dynamic. Static models produce network assignments that are aggregated estimates. These models are therefore mostly used to determine the effect of certain changes on traffic loads for larger networks and long periods of time. For such projects, the precise results for each network section are less important than obtaining an overall impression network loading. However, with this static approach it is difficult to study interaction effects and to obtain precise results for certain routes or network edges.
Therefore, dynamic traffic models often have an advantage when one wants to precisely study more complex systems. An often-used technique is simulation-based modelling. The advantages of simulation-based modelling are mainly in its ability to mimic the interaction between actors with relatively high precision. However, for this to effectively work the data requirements are also relatively high compared to other methods.

2.1.5. Inverse Trip Assignment Problem

When focusing only on the trip assignment, there still must be an origin/destination (OD) matrix for the studied modality. In this research, the historic traffic volumes of inland shipping are translated to an OD-matrix. This approach is called inverse trip assignment and are usually approached in one of three ways when studying traffic flows (Saw et al., 2014). These are the use of counting points, using surveys or using geographical information sources like cell phone response. However, most network traffic flow research is performed on passenger transport that uses a complex road network. Key differences with the inland shipping system are the number of trips, number of destinations and the availability of data. When analysing passenger transport, usually more aggregations and assumptions are needed as there is more data that is harder to collect. Although there are key differences the same kind of methods can still be used in analysing an inland waterways network.

When using counting points for the analysis of network flows, the flows over the edges of the network can be determined. This can give a very precise and reliable idea of the amount and form of traffic (Gawron, 1998). One downside of this method is that it is usually not possible to precisely determine the values in the origin/destination matrix. To obtain values for OD combinations usually a production and attraction model is used, as explained earlier in this section. Another problem with counting points is that having counting points on a network is often expensive in terms of placement and maintenance. Still, this method using counting points will be used in this research for the analysis of traffic flows.

The other method that can be used for determining the current trip assignment on an inland waterways network is through the use with geographical information. Being able to track every individual agent that moves over the network can give very precise results for traffic volumes between points or over certain edges. The main problem with this kind of method, is that the data is often hard to obtain. When it is available however, it can be a good source of information from which more than just the traffic volumes between points can be calculated.

Overall, it is important to know what the traffic on a network is before it can be modelled. This consists of two parts: the amount of traffic between origin/destination points and the routes taken between these points. This gives a complete overview of what traffic moves over the studied network and how.

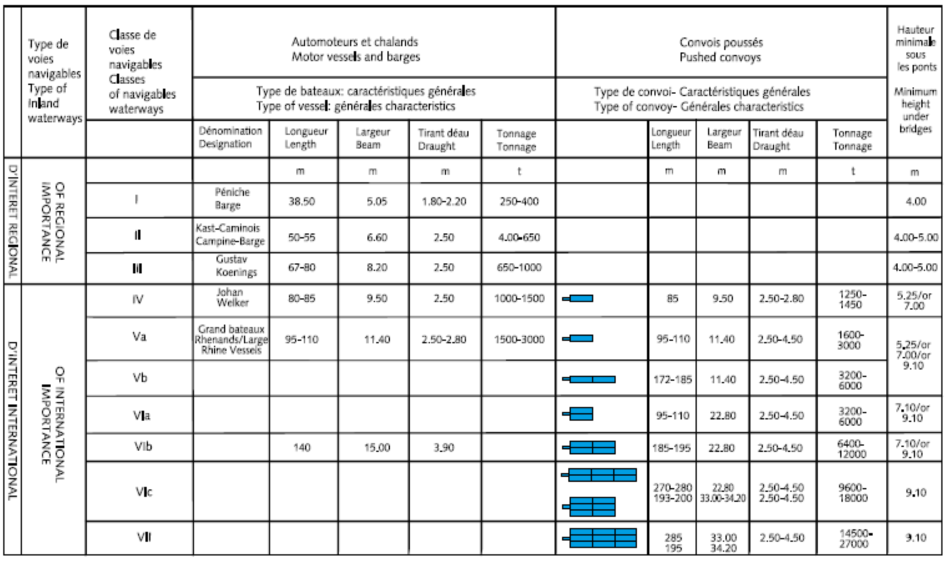
2.2. Inland Freight Vessels

Important part of every transport system are the agents that move between the locations with transport supply and demand. In the inland waterways system these are of course the vessels. Studying this transport system thus means studying the characteristics of the inland ships and the overall fleet. In this section it is explained how the performance of the vessels can be measured.

Using vessels to transport goods inland is relatively energy efficient and reliable. It is not very prone to delay or small-time inconsistencies compared to road or rail transport. Additionally, it is less prone to accidents or other highly disruptive events. This makes it easy to plan transportation and to connect it with a steady flow of goods (Wiegmans and Konings, 2015). Furthermore, inland shipping has a very cost-efficient profile for heavier and bulkier goods. This makes it an interesting option for several industries that must move large volumes and masses of goods (Hekkenberg, 2013).

2.2.1. Classification of the Inland Shipping Fleet

First, it is important to know that there is variety of ship types and sizes that operates on the inland waterways of the Netherlands. An official division of inland transport vessels into different size classes has been made by the European Conference of Ministers of Transport (Rijkswaterstaat, 2017). This division was made to increase the level of standardisation on the waterways in Europe. It can be summarised as in Figure 2.2. This division defines what ships can sail at what waterways and several other requirements for operations. This also works the other way around, as waterways are currently designed to accommodate a certain kind of ship class. This is also the cause for the upgrading of the lock in the case study, where allowable vessel size goes from II to IV. Larger vessels can move larger quantities of goods but are generally also more expensive to operate than smaller ships. This is important to keep in mind when studying an inland waterways system.



	Type de voies navigables Type of Inland waterways	Classe de voies navigables Classes of navigables waterways	Automoteurs et chalands Motor vessels and barges					Convois poussés Pushed convoys					Hauteur minimale sous les ponts Minimum height under bridges
			Type de bateaux: caractéristiques générales Type of vessel: générales characteristics					Type de convoi- Caractéristiques générales Type of convoy- Générales characteristics					
			Dénomination Designation	Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage		Longueur Length	Largeur Beam	Tirant déau Draught	Tonnage Tonnage	
				m	m	m	t		m	m	m	t	m
D'INTERET REGIONAL	OF REGIONAL IMPORTANCE	I	Péniche Barge	38.50	5.05	1.80-2.20	250-400						4.00
		II	Kast-Caminois Campine-Barge	50-55	6.60	2.50	4.00-650						4.00-5.00
		III	Gustav Koenings	67-80	8.20	2.50	650-1000						4.00-5.00
D'INTERET INTERNATIONAL	OF INTERNATIONAL IMPORTANCE	IV	Johan Welker	80-85	9.50	2.50	1000-1500		85	9.50	2.50-2.80	1250-1450	5.25/or 7.00
		Va	Grand bateaux Rhenands/Large Rhine Vessels	95-110	11.40	2.50-2.80	1500-3000		95-110	11.40	2.50-4.50	1600-3000	5.25/or 7.00/or 9.10
		Vb							172-185	11.40	2.50-4.50	3200-6000	
		VIa							95-110	22.80	2.50-4.50	3200-6000	7.10/or 9.10
		VIb		140	15.00	3.90			185-195	22.80	2.50-4.50	6400-12000	7.10/or 9.10
		VIc							270-280 193-200	22.80 33.00-34.20	2.50-4.50 2.50-4.50	9600-18000	9.10
		VII							285 195	33.00 34.20	2.50-4.50	14500-27000	9.10

Figure 2.2: Classification of ship and convoy sizes as defined by Conference of European Ministers of Transport. Image obtained from: Rijkswaterstaat (2017)

2.2.2. Costs for Inland Vessels

Inland ships have certain costs when transporting goods and travelling just as all transport modes (Rodrigue, 2020). This can be split into many different categories and sub-categories. Hekkenberg (2013) developed a model to calculate the total annual costs of operating an inland ship. The same working methods will be used in this research to determine a part of the costs of each trip made by inland ships on the network. A distinction is made between time and distance costs. Of these, sailing costs are the most straightforward and consist of the costs made by sailing a ship over a certain distance. This can be further divided into fuel and variable maintenance costs. Time costs are a bit more complex and based on several factors like personnel costs, capital costs and operational hours. The final cost component used in this research are the costs associated with the reliability of planning. In the following sections all costs categories will be explained in greater detail.

Fuel use

For all inland freight vessels, the largest part of the distance costs is the costs of fuel. These costs are a combination of the fuel consumption and the fuel price and account for around 20% of the total expenses made by inland ships (European Union and Tourism, 2009). The fuel consumption varies per ship and is dependent on the size of the ship, the age of the ship, the installed equipment etc. Additionally, there are several factors that are trip dependant. The fuel consumption of a ship is also influenced by the dimensions of the waterways, the load factor, wind, and water conditions. It is difficult to determine all these factors per ship and trip correctly. It might therefore be safer to use mean values per ships class.

The fuel consumption for each ship class is calculated through the average energy required by the engine to sail one km. The energy used by the engine is in turn a function of the total experienced resistance, travel speed and the conversion efficiency (Jan Hulskotte, 2012). The fuel use can thus be summarised as below. The *c* in this equation stands for the conversion coefficient which is a combination of the energy conversion efficiency of the motor and propeller of a ship. The average conversion efficiency of the propellor system is obtained from the research of Hekkenberg (2013) and is set at 0.55. The motor efficiency coefficient is obtained from the report of J.H.J. Hulskotte (2009) (Table D.11), and is set at 0.195 kg/kWh. The V stands for the speed of the vessel and the R for the total resistance. The speed of vessels per size class will be determined later in the AIS analysis. For the average resistance per vessel, the values as calculated in Vehmeijer (2019) her research are used. An interpolation of the total resistance for empty and loaded vessels done to simplify the inputs of the model. The resulting values can be found in Table 2.1. In addition to the fuel use by the main engine during sailing, ships also consume some fuel when they are not sailing. This is caused by auxiliary engines and main engines that run stationary. Although, this is only a small fraction of the fuel used while sailing, it is still added to the total use. It is assumed that around 15% of the energy use while sailing is used when waiting or in locks.

$$F_{consumption} = c * V * R \tag{2.1}$$

Table 2.1: Max length, load capacity and average resistance for the ship classes used in this research. Values adjusted from: Vehmeijer (2019) & Rijkswaterstaat (2017)

CEMT	Max length (m)	Max load (tonnes)	Resistance (kN)
I	39	400	13.0
II	55	650	23.1
III	85	1050	39.5
IV	105	2050	63.6
V	135	4000	88.0

The costs per unit of fuel has varied a lot over the recent years as it is directly linked to the price of crude oil. In the period between July of 2017 and July 2020, bunker prices of Low Sulphur Marine Gasoline Oil (LSMGO) in the Port of Rotterdam have fluctuated between 160 and 680 euros per ton (Ship and Bunker, 2020). It will therefore be difficult to accurately predict the fuel price during the case study, which is set in 2022 - 2024. At the time of writing, oil prices are at very low rates of approximately 180 euros per metric tonne for LSMGO. Prices are not expected stay this low and therefore the assumption is made that prices will somewhat recover (Russell-Webster, 2020). The fuel price in will thus be assumed recover to 300 euro per metric tonne.

Costs of time

The second cost category used in this research is the cost of time. As mentioned earlier, it can be rather complex to determine these costs accurately. However, an estimation is made using two cost components for different ship sizes using the method developed by R. Hekkenberg (Hekkenberg, 2013). First, the crew and capital cost per year for each ship size is determined. Then, these annual costs can be divided by the total number of operational hours per year. The number of operational hours can also vary depending on the sailing regime of a ship. Large line ships that travel long distances are often manned 24 hours per day, whereas ships that travel shorter distances often have less intensive schedules of five day work weeks and mostly daytime sailing. This gives a range in which the costs per operational hour can be given. This is summarised in Figure 2.3 for varying ship lengths and sailing regimes, where the difference between the regular and reduced curves indicate the range for personnel costs. As the case study in this research is on an area within the Netherlands that is within a daytime sailing of the major ports, it is assumed that there are mostly ships with less intensive sailing schedules on the network. This gives a range of approximately 0.030 - 0.045 euros per ton per hour depending on the ship size.

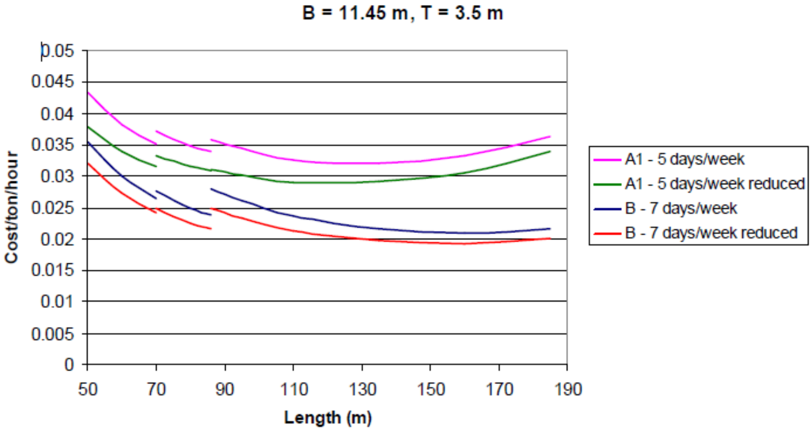


Figure 2.3: The costs in euros per ton per hour for various ship sizes and sailing regimes. Copied from: Hekkenberg (2013)

Reliability of planning

The final aspect of the performance of inland shipping that is considered in this research, is the reliability of planning. The plannability of ships is a bit more abstract than the previous two cost components. The concept is that when a shipment of freight experiences an unexpected delay, there is a customer waiting for its goods. This means a loss in productivity for said customer and shipping companies are therefore suited by avoiding delays. It is difficult to directly calculate the additional and indirect costs for one delayed hour. However, Jong et al. (2014) used a survey to determine the value of reliability from observing the stated choices. The survey was made by shippers in the freight sector and resulted in a valuation of every lost hour through delays per vehicle. Some of these results are presented in Table 2.2. In this table it can be seen that a cost of 300 - 360 euros is linked to every lost hour before locks. This is an average value assigned for all ships of all sizes without differentiating between ship sizes. The cost probably varies depending on the shipment size and the overall length of the trip. As Jong et al. (2014) did not differentiate between vessel sizes in their survey it is impossible to accurately say how this is distributed over vessel sizes. Therefore, the values will be used for all ships.

Performance Indicators for Inland Freight Vessels

The three cost categories mentioned above will be used to determine the increased costs for vessels in the case study. These are therefore also defined as three of the performance indicators used for the comparison of results.

Table 2.2: Value of reliability for different freight transport modes in euro per hour. Values obtained from: Jong et al. (2014)

	Road	**Rail**	**Inland Waterways**
Container	[2-40t truck]: 59	[Full train]: 880	[Ship waiting for quay]: 98
			[Ship waiting for lock]: 340
Non-Container	[2-15t truck]: 23	[Bulk]: 1200	[Ship waiting for quay]: 65
	[15-40t truck]: 44	[Other]: 1200	[Ship waiting for lock]: 300
All	[2-40t truck]: 38	[All]: 1100	[Ship waiting for quay]: 69
			[Ship waiting for lock]: 300

2.2.3. Economic Outlook Inland Shipping

The goal of this research is to determine the impact of decisions on the future system of inland shipping. This would mean that possible growth or shrinkage of the inland shipping sector would influence the outcomes of this research, which is based on data from 2018. Usually a macroeconomic forecast scenario as developed by Commission (2019) would be taken to make a correction for the expected growth. However, at the time of writing there has been a period of economic stagnation and even shrinkage. The exact impact of this on the inland shipping sector is yet to be determined. Without a good expectation scenario to use as a forecast, it is assumed that the demand for inland shipping remains constant for the coming years.

2.3. Capacity and Throughput of Inland Waterways

The second component in analysing the inland waterways transport system is the network itself. An inland waterways network can consist of many canals and rivers varying in size and shape. These can be very complex systems and are an entire research field in itself. However, for the analysis of transport over the network it is important to know what limits the capacity of a waterway.

Inland waterways are designed and maintained for a certain amount of vessel traffic. This capacity is dependent on several factors, but is mostly determined by obstructions like locks, bridges, and bends in the waterway. Especially locks can have a limiting effect on the maximum throughput (Chen et al., 2013). Locks have a maximum number of ships that can pass with each passage. One of the main focuses in this research is therefore on the delays caused by these hydraulic structures. In this section it is explained how a navigational lock operates and how the amount of traffic influences the waiting time for locks.

2.3.1. Navigational Lock Operations

Because navigational locks are a crucial part of the inland waterways transport system, it is important to know how they operate to represent them in a simulation environment. A navigational lock can be roughly split up into several different areas as presented in Figure 2.4. The approach areas are used by ships for slowing down, waiting, and manoeuvring before or after entering the lock. The lock chamber is where the ships are transferred to the correct water level. From the perspective of a single ship, passing a lock normally goes in the following steps:

1. Ship enters lock approach area
2. Ship waiting for turn in lock approach area
3. Ship enters the lock chamber
4. Lock door closes
5. Water is levelled
6. Lock door opens
7. Ship leaves the lock chamber
8. Ship exits through lock approach area

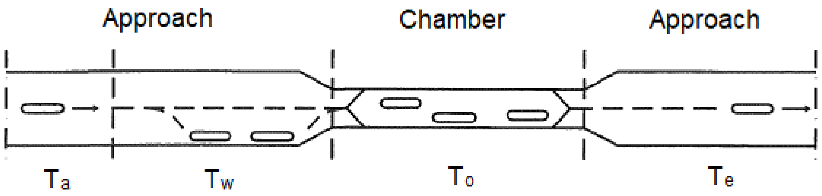


Figure 2.4: The different areas of a lock complex with their respective time factors for a passing ship. Copied and adjusted from: Groenveld et al. (2006)

From the perspective of the lock operator, the required operations to pass a single ship are mostly the same as steps 3-7 mentioned above. This changes when the water level in the lock does not matches the side an approaching ship. Should this not be the case, steps 4-6 are required to get the water in the lock chamber at the right level resulting in additional waiting time for the ship.

2.3.2. Lock Throughput

Locks are designed with a theoretical capacity of ships or tonnage per year. The capacity of a lock should match the traffic demand on the waterway to prevent large congestion from occurring. In Europe, locks are usually built to fit ships up to a certain class as defined by CEMT (1992). Building a larger lock is of course beneficial for the capacity. However, increased size also brings increased construction and operational costs, so balance should be found between these factors (Vrijburcht, 2000).

Theoretical Capacity

The theoretical throughput is based on the cycle time of the lock and the capacity of the lock chamber, as can be summarised in the formula below. Here *C* is the maximum number of ships that can pass the lock per unit of time. $T_{passage}$ is the total time needed for one chamber of ships to pass in one direction and N_{max} is maximum number of ships that fit in the chamber. The theoretical throughput calculated with this formula differs from the throughput achieved in reality (Groenveld et al., 2006), as will be explained below.

$$C = N_{max}/T_{passage} \tag{2.2}$$

The first component of the throughput of the lock is the cycle time. There are many factors that influence the duration of one cycle. Important factors are for example the size of the chamber, the water rise, the equipment, and the type of doors used. The passage time of a lock is not a constant. One of the reasons for this is that the difference in water level can vary throughout the year. There are many additional factors that influence the actual time it takes a ship to pass a lock, like the size of the ship, the capabilities of the captain, the weather conditions, number of ships passing at the same time and so on (Vrijburcht, 2000). This means that the passage time can vary significantly per passage and depend on the type and sizes of ships that pass.

The theoretical capacity of the lock chamber is normally not expressed in number of ships, but rather on the maximum tonnage that is able to pass each time. This is based the maximum number and the largest type of ship it was designed for. This maximum capacity is usually not reached as smaller ships can use the lock as well, or there is less than the maximum number of ships wanting to pass the lock. Additionally, there is again the situation where there is one ship approaching the lock, but from the wrong side. In this situation the lock must change its water level without any ship in it, before serving the approaching ship.

The theoretical throughput of a lock is thus based on the scenario where there is always a maximum sized ship present at the right side of the lock. Meaning that ships either must time their arrival perfectly or there is always a queue of ships waiting for the lock to be served in this scenario. In practice this would mean that there are large queues present, as ships do not arrive at the lock at a constant rate.

Queuing for Locks

The operation of a lock can be seen as a queuing theory problem in which the lock is the server and the ships are the agents that need to be served. A lock serves two directions of traffic, meaning that it also serves two lines of customers making it a bit more complicated than a simple one queue one server system and is two queuing systems that are linked. The systems thus deal with two arrival rates and sometimes needs two passages to serve one ship. Furthermore, this is the case for a single lock serving one ship per passage. When in practice all kinds of deviating situations, with multiple locks, ships and other factors are possible. It is therefore common practice to study the functioning of locks and their interactions with traffic through a computer simulation. Which makes it easier to determine the time spent by ships in the system and waiting in line.

$$T_{passage} = T_a + T_w + T_o + T_e \tag{2.3}$$

The time ships spent in the lock system can be roughly split into four parts, which is shown in Figure 2.4 and in the equation above. Here, T_a and T_e correspond to the time spent while slowing down, manoeuvring, and accelerating out of the lock areas. The operational time, T_o, is the time required by the lock to serve the ship. If a ship cannot be served directly there is also a waiting time, T_w. In this research, the focus will be on the waiting and operational times. The time ships must wait before being served depends on the number of passages they have to wait. This is of course linked to the number of ships that arrived before them that needs serving, or their position in the queue. The size of the queue before a lock is dependent on the time between the arrival of ships, the arrival rate, and the time required for one lock operation, the service time. As mentioned earlier, the arrival rate is in practice not a constant. Meaning that ships arrive at the lock according to a distribution. It was also determined in the previous section on the theoretical capacity of a lock that the service time is not a constant either. This has the effect that there is always a certain probability that a ship must wait before being served, even if the arrival rate is low and the service rate is high. When the traffic intensity or the arrival rate increases, the probability that a ship must wait increases as well. The average waiting time for the lock increases exponentially with increasing arrival rates. A good example of this effect can be seen in Figure 2.5, where the capacity and intensity for the Kreekraklock in the Netherlands is given.

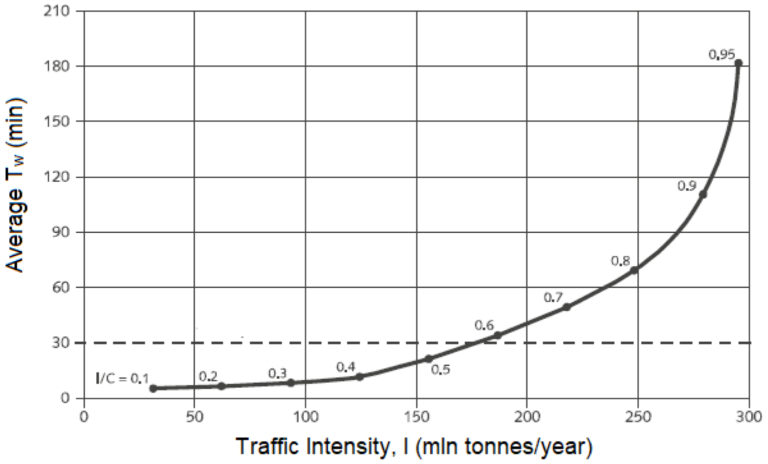


Figure 2.5: The average total waiting time as a function of the traffic intensity. Obtained and adjusted from: Rijkswaterstaat (2017)

In the figure above, the average waiting time as a function of the traffic intensity is given. The point values on the curve correspond with the intensity over capacity ratio and therefore approaches one. Having a ratio higher than one would theoretically result in infinite waiting times. In the curve the effect of increasing arrival rates on the average waiting time is indeed exponential. This means that a small increase in traffic intensity could mean a relatively large increase in waiting times. As mentioned in Section 2.2.2 unexpected waiting times can be very costly for shippers and should therefore be minimised where possible.

For many freighters, especially line services, the average waiting time at locks is not an accurate prediction. With an increasing average waiting time, the chance of having large outliers increases heavily as well. Therefore, the reliability of the passage time is often given for a 90% certainty value (Rijkswaterstaat, 2017). This 90% value has the tendency to increase more quickly with increased intensity. This value will therefore also be considered in the analysis of the locks on the network.

These effects on waiting times are relevant to the case of the network of lock II. Closing off a section of the network could mean that rerouting the traffic significantly increases waiting times at locks on the alternative route as this effect is exponential.

Performance Indicator for the Network
In addition to the three attributes by which the vessels on the network are measured, the performance of the locks on the network will be studied separately as well. It will be determined how the waiting time at every lock changes in the case study. The overall waiting time for the locks is also calculated in the reliability costs for ships, but it is interesting to determine which locks will be the bottlenecks.

2.4. Summary & Conclusion

This chapter was used to provide answers to the first two sub-research questions. This resulted in an overview of the characteristics of the inland shipping system that are required for the subsequent research steps. Additionally, the indicators by which the performance changes will be measured were defined. This section will briefly summarise these findings.

2.4.1. Overview of the Inland Shipping System

In this research, the waterways transport system is modelled. In the field of transport modelling this research is a trip assignment problem, which requires the expected distribution of transport as an input. Therefore, an OD-matrix is needed with the daily traffic volumes between areas of the network. Additionally, it will be important to determine the time of day during which the ships travel over the network as this can influence traffic congestion.

Inland shipping is an important mode of transport on which many companies rely for their operations. Inland ships are dependent on the network of available waterways and disruptions in this network can have a significant impact on the movements of inland vessels, which can strongly influence the costs made these ships. The freight vessels used for inland shipping can be divided into several size classes. The size of a vessel has a strong influence on the operational costs. These costs can be divided into the distance, time, and plannability costs.

One of the main determining factors for the performance of the vessels and the network is the amount of time that is needed to pass the locks on the network. Locks are the biggest bottlenecks as they have a limited capacity and a certain operating time often resulting in waiting times for ships. The time ships must wait is exponentially related to the traffic intensity at the lock. It will therefore be important to correctly reproduce them in the simulation model.

2.4.2. Performance Indicators

The second research question, was aimed at finding the performance indicators that can be used to measure the change in performance. This was split into the indicators for vessels and for the network.

- **Distance costs** - Are calculated through the fuel used by ships when travelling over the network

- **Time costs** - Are a combination of all the fixed yearly and variable time costs as calculated by Hekkenberg (2013).

- **Reliability costs** - The costs related to unexpected delays for inland ships, which are linked to the waiting time at locks

For the network, the performance indicators will be the waiting times at the locks. These are not calculated as extra costs for the network but will provide insights in where the bottlenecks are located. The waiting times will be split into two parameters:

- **Average Waiting Time** - The average waiting time for each lock will give an indication of what locks have the most impact on the vessel delays.
- **90% Confidence values for the waiting time** - In addition to the average waiting time, the 90% confidence value is used to indicate the impact on the plannability of freight transport using the waterways.

3

Data Analysis

Before the simulation model can be set-up and used to study, the state of the investigated system must be determined. This inverse trip assignment will provide an answer to the third research question. This question was formulated as: *"How can important network and traffic characteristics be obtained from the data and information available?"*. A combination of sources was used to obtain the most important characteristics. This can be divided into two categories: the vessel movements and the network characteristics. For the inland waterways, these two categories can be further divided as shown in Figure 3.1.

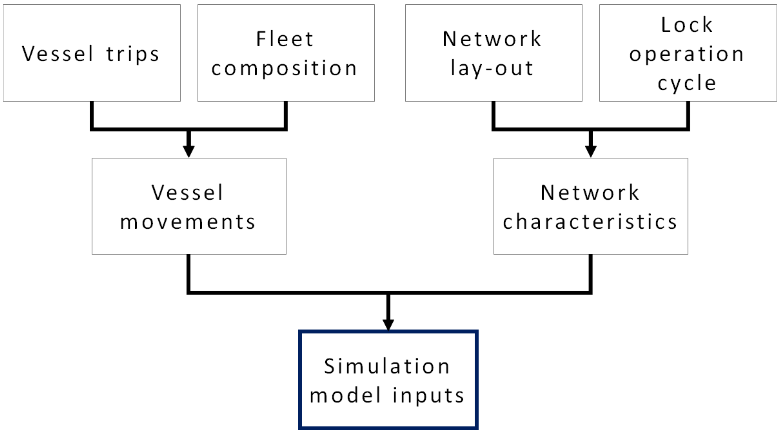


Figure 3.1: Input requirements for the simulation model that are obtained in the data analysis

In this chapter, first it is explained how the main data source can be obtained and prepared for further use. Then, to get an overview of the researched system, the network characteristics are discussed. Thereafter it is explained how the vessel movements can be determined using AIS data, otherwise called the inverse traffic assignment AUTOREF. For this both a method like the survey method as the counting point method are used. As AIS data source had not yet been used very often in research about inland shipping, the results of this analysis were checked using IVS90 data. This is discussed in the final section of this chapter.

3.1. AIS Data Preparation

Since 2008 all ships used for inland waterways transport with a CEMT class (Figure 2.2) of I or higher are obliged to have an Automatic Identification System (AIS) transponder. The AIS of each vessel sends a message to land based stations at certain time intervals. A sailing vessel sends a signal at a frequency of up to one per ten seconds. Each message contains information on the vessel and is stored by several parties, including Rijkswaterstaat. AIS is a geographic data source and can be used for the analysis of several aspects of the inland waterways system. Because every ship already has a transponder, the gathering of data is relatively easy and can be done for any network or area in Europe.

3.1.1. Data Gathering & Privacy Issues

An AIS transponder sends out a message every 20 seconds when the ship is sailing. Because of the high frequency of messages send by inland ships and the size of the area, the number of data entries per day for large and busier areas can be very large. This means that when a longer period is studied, the data set can become very large. This makes it generally more difficult to work with, as every calculation takes more time. On the other hand, studying a larger period means that small disturbances and anomalies are averaged out.

In addition to deciding what time period to study, it is important to define the geographic boundaries of the network. Here also a trade-off must be made. Selecting a larger area can provide more information on the destinations and routes taken by ships. However, this also means more AIS messages to analyse.

For the case study, it was decided to limit the time period of the data to three months. Additionally, the last available IVS90 data that was publicly available is from the year 2018. Therefore, the first three months of that year were chosen for the AIS analysis to be able to verify the data sources with each other. A set of JSON files was retrieved at the central information provision (CIV) department of Rijkswaterstaat. These files contain a total of approximately 70 million position messages that lie within the geographical area as shown in Figure 3.2 in the months of January, February and March of 2018.

Figure 3.2: Geographic boundaries used for selection of AIS data

Every position message contains the information as presented in Table 3.1, or a part of this. As can be seen from this example, the name of each ship is replaced by ”testschip-xxx”. This is done by Rijkswaterstaat for privacy reasons because many inland ship captains also live on their ships. Concerns over privacy of ship operators is also the main reason that AIS has not been used very often in research on inland ships. Although implementation of AIS for inland ships dates to 2008, lack of an agreement on data use has meant that only since a year or two it is made available on request by Rijkswaterstaat. Because of privacy, it was also agreed that the data is to be deleted once the research is completed.

Position Message Content

The primary purpose of AIS is to improve the safety on the water by making ships visible to each other (AIS, 2015). This purpose is reflected in the type of information contained in every position message, which can be divided into several categories. The first being the identification columns: ENI, MMSI, IMO, Callsign, Nationality and Name. These can normally be used by authorities or other ships to establish communication. All of these, except for the Nationality, are anonymised and given an artificial

Table 3.1: Possible columns in each AIS position message with their respective form and unit

Category	**Column**	**Unit/form**
ID	Name	testship-xxx
	ENI	Int
	MMSI	Int
	IMO	Int
	Callsign	P-xxxx
Location	Longitude	WGS84
	Latitude	WGS84
	COG	knots
	SOG	knots
	Timestamplast	Datetime64
Transponder position	Tostern	m
	Tobow	m
	Toport	m
	Tostarboard	m
Ship type	Vesseltyp	Int (0-100)
	Hazardouscargo	Int (0-5)

value.

The second category is the actual position message with Longitude, Latitude, COG, SOG and Timestamplast. The latter being the time the message was received with a precision of seconds. For most of the analyses in this research the time in combination with the longitude and latitude is used. The Course Over Ground (COG) could be a very helpful in determining the direction of ships, it is however rarely provided and set to either 0 or 360 in most cases. The same is true for Speed Over Ground (SOG) where in only a very small percentage (+/- 0.1%) of entries it is different from 0. COG & SOG are therefore not used in this research.

Another category is the ship dimensions with Length and Width of the ship, which are used to determine the CEMT class of ships. The fourth category of information in the messages concerns the position of the AIS transponder of the ship depicted by the distances Tostern, Tobow, Toport and Tostarboard. These values are mainly used in AIS mapping devices to allow for more precise placement on dynamic maps.

The final category contains the ship type and cargo. Vesseltype contains a double digit number that relates to the vessel type as defined by the Inland Transport Committee of the European Union (Committee, 2007) and is used to determine the cargo type of vessels on the network. Hazardouscargo is an addition to the vessel type and tells whether the ship sails with flammable, explosive or another type of dangerous goods according to the blue cones system (Wikipedia). This harzourdouscargo value will not be used, but it is a good example of what the original purpose of AIS was.

After the exploration of the data, it can be said that AIS data is often messy. The content of position messages can vary even for messages with the same identification numbers. It is therefore not always possible to make a distinction between vessel types, vessel dimensions and the cargo they move. Many of the entries miss one or more column values or have a value that is classified as ’unknown’ for their vessel type. The column values that appear to have the most value are the ones that are generated automatically like the geographical position and the time. Although it would be expected that the SOG and COG are also generated automatically, these are missing or set at zero for too many entries to be useful. The speed of vessels will therefore be calculated based on the geographical coordinates and the timestamps.

3.1.2. Data Cleaning & Additions

After exploration of the contents and columns, the data can be prepared for the actual analysis. The goal of this step is to end up with a set of clean and workable files where each file represents one ship. A summary of the method used is given in Figure 3.3. All scripts used in this method are available on:

Github TU Delft - AIS utilities.

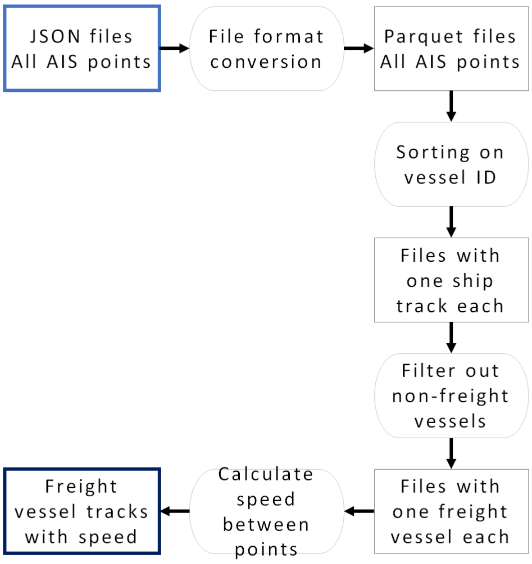


Figure 3.3: Summary of the method used in cleaning and preparing the AIS data for later use.

The data set was provided in three JSON files of approximately 10 GB each. In these files, each position message is a separate JSON object containing the column names with their respective values. Each object the top-level attribute has the value ”possitionmessage:”, which needs to be removed before the files can be further processed. To achieve this, the files were first split into smaller JSON-lines files (a file format with one JSON object per line) with 200 000 AIS entries each. Removing the top-level attribute of each JSON object was done using the text processing package ’re’ and Python. Finally, the clean JSON files were converted to Parquet using the Python library ’Pandas’. Parquet is a data storage type that makes processing of large sets more efficient and quicker by using a columnar format instead of a row format (Apache). This resulted in workable data files that could be used for further processing. Additionally, it is now possible to visualise the location of all points to get an overview and to see whether the data does indeed match the area of interest. The resulting plot is shown in Figure 3.4. It can be seen that the data does indeed match the area of interest because the shape matches the waterways as in Figure 1.2. It can even be seen where the smaller waterways are located that are not part of the freight transport network.

The next step in preparing the data is to group the AIS points that are related to each other. This means that the position messages of each individual ship are placed together and in chronological order. This resulted in 923 groups with unique identification numbers that should normally belong to a single ship. However, these numbers were assigned or altered in the process of anonymising the data. It is thus not known if there is this exact number of individual ships that has travelled the network in these months. After this sorting, all entry points where the vessel type was known to not be a cargo vessel were removed. Where the vessel type was unknown or empty, entries were kept in the data set. The vessel type as used in AIS and in this filtering was done using the table in Annex E of Committee (2007).

In addition to grouping and removing the irrelevant vessels, an extra value was added to each position message. A new column with an indication of the speed of the vessel was made by determining the distance between two entries and dividing it by the difference in time. The position of each entry is given in longitude and latitude according to the World Geodetic System 1984 (WGS 84). Therefore, it can be calculated what the adjusted length is between two points. As mentioned earlier, this method of determining the speed of the vessels is preferred over the use of the Speed Over Ground variable included in some position messages because it can be applied to all points and tracks.

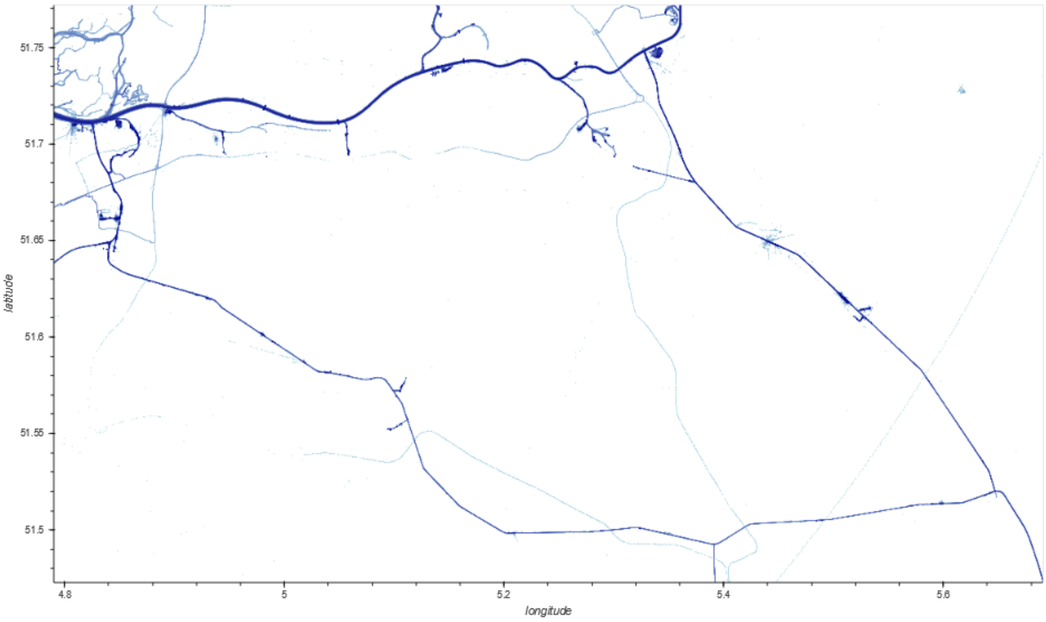


Figure 3.4: Visualisation of the geographic coordinates of all position messages in the AIS data

3.1.3. Processing & Computations

As mentioned, an AIS data set can become rather big. In this case study, the data set was too big to fit in the random-access memory (RAM) of the available hardware. Therefore, the operations were done using a Python based package called Dask (Dask). Dask can schedule and divide computational tasks over the available cores, where Python generally only uses one core. Additionally, it can store most excess data on disk enabling larger than RAM computations. Using this method could also be used for even larger data sets and should be able to provide the same results.

3.2. Network Characteristics

Studying an inland waterways system is a network analysis. Therefore, the attributes of the waterways network of interest must be obtained. The most important aspects of a waterways network are the lay-out, the edge constraints and the operation characteristics of the locks. For each of these inputs it will be explained how they can be obtained.

3.2.1. Network Lay-Out

First, the shape and size of the network edges must be defined. When a waterway is closed off due to construction or maintenance works, the vessels normally taking this route are forced to find another route. Therefore, the network that is studied in this case should consists of the original route of the traffic and all the relevant alternatives.

The case study concerns the network in Noord-Brabant as presented in Figure 1.2. These are the waterways relevant to the case study because the section that will be closed lies just west of Tilburg on the Wilhelminakanaal, which is the southern edge of the network. If ships are not able to pass this section, a detour is available over the northern and eastern edges of the presented network. These are the thus the waterways that are affected by the construction works.

To correctly mimic the actual waterways in a digital environment, an ESRI shapefile of the waterways sections with corresponding information should be obtained. A shapefile is an often-used file format in geographical information system software. To obtain the right lay-out, a publicly available file of all the waterways in the Netherlands (Government, 2019), published by the Dutch government can be used and adjusted. For the case study, this resulted in Figure 3.5. Next, the secondary waterways were removed, as these are unavailable for most freight vessels and will not be affected by a changing situation. Finally, the outer edges were cut some more to decrease the size of the network and as they do not add much to the analysis. These adjustments resulted in Figure 3.6.

Figure 3.5: Unadjusted network as cut-out of the Dutch waterways shapefile

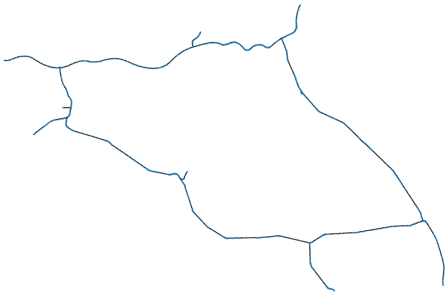


Figure 3.6: Network lay-out for the case study after adjustment and selection of relevant waterways

All the operation on the shapefile were done using the open source software of QGis[1]. QGis is an open-source Python based Geographical Information System Project which has several tools to create and adjust these types and networks.

3.2.2. Locations of Origins/Destinations

Another important network aspect that is used in the simulation, is the location of the most important origin/destination points for inland ships. This will be used as a starting point for the AIS analysis to determine into what geographical regions the network needs to be divided. There are several inland barge terminals on the network, some industrial areas with water-based activities and four possible entry points by which the network can be accessed. These were used as the starting point for dividing into sub-regions. The goal of this division is to end up with as few regions as possible, without merging two important vessel destinations with a significant distance between them into one. Ultimately, this procedure resulted in twelve origin/destination areas, which are shown in Figure 3.7. A summary of the most important characteristics is also shown in Table 3.2.

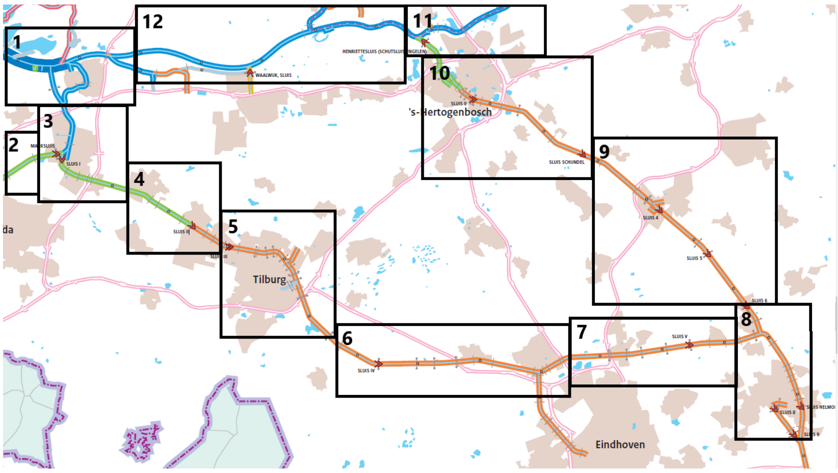


Figure 3.7: Aggregated origin/destination locations on the network. Image adapted from: Rijkswaterstaat (2020)

These are the regions used as origins and destinations in the OD-matrices that will be made from the AIS analysis later in this chapter. The difficulty with determining the most important regions and

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[1] QGis is available at: https://www.qgis.org/en/site/index.html

Table 3.2: Origin/destination areas with their relevant attributes

Area nr.	Main attributes	Waterway classes (CEMT)
1	- Direction to Port of Rotterdam	V/VI
2	- Direction to Port of Antwerp	IV
3	- Oosterhout inland port area - Lock I counting point	V
4	- Barge terminal Tilburg - Lock II	IV
5	- Tilburg industrial port area	II
6	- Exit to Eindhoven port area	II
7	- Industrial area Lieshout	II
8	- Direction to Limburg/Belgium	II
9	- Barge terminal Veghel	II
10	- Port area Den Bosch	II/IV
11	- Direction to Germany	V
12	- Direction to river Waal	V

locations on the network is to balance amount of detail with the computational capacity and work required. An OD-matrix has a size of the number of origins/destinations squared. A larger OD-matrix is not necessarily a problem for the analysis of the data, but it is when using a simulation model. On the other hand, when the number of origins/destinations is too small, the precision of the results will suffer. Thus, the twelve areas defined in Table 3.2 are expected to provide the right level of detail while trying to minimise the number of areas.

3.2.3. Edge Constraints

The waterways are represented in the network as edges. As each waterway has a certain size and lay-out, this should be translated to the modelled network as well. The waterways in Europe are divided in classes (Section 2.3), as such the edges in the network are given restrictions according to this classification.

Additionally, waterways have a certain capacity restriction. The capacity is dependent on many factors, especially for busier sections. However, for simplicity it is assumed that the vessel capacity of an edge is only dependent on the speed of the vessels and the length of the section.

3.2.4. Locks on the Network

One of the most important parts of the network are the locks, which are the expected bottlenecks at which congestion is expected. It is therefore important to correctly define where these locks are located exactly and how they operate. These factors will have to be translated to inputs for the simulation model. In this section it is explained what sources of information were used and what decisions were made concerning the locks in the case study.

Locations of the Locks

Before any further analysis can be performed, it must be known where the locks are located and what their size is. The case study network contains several locks that are currently operational. These can be seen in Figure 1.3, where the locks are added to the network with the exception of ”Sluis V” as this lock is not currently in use. To translate the actual situation on the network to the digital environment, the locks must be added to the network file obtained in the previous section (Section 3.2.1). All lock that are operational were added at their respective locations on the network by adjusting the name and attributes at the corresponding edge in the network file. This was done using the QGis software, just as previously.

Additionally, for each lock the size is required. The size of the locks is obtained from Vaarweginformatie.nl, which is an online dashboard provided by Rijkswaterstaat to share information on all the (Rijkswaterstaat, 2020). Sizes of the locks on the network are included in Table 3.3.

3.2.5. Time lost at locks

When passing an obstruction, like a navigational lock, ships are delayed by a certain amount of time. For a lock, the total time of the delay is split into the operational time, the waiting time, and the approaching/exiting time. A division between these times was made, because they can be linked to different areas of the lock (Figure 2.4). The approach/exit, waiting and operational time are all determined in a different way, as will be explained in the following sections.

Approach, exit and waiting times

The approaching and exiting times are defined as the extra time needed for manoeuvring in and out of the lock. Ships need to slow down when approaching and accelerate when exiting. This causes a delay relative to sailing on an unobstructed waterway. Attempts were made to determine the approach and exit delays from the AIS data. However, accurate analysis of vessel movements in the approaching areas proved to be difficult.

The time spend by ships in the lock approach area is a combination of the approaching time and the waiting time. Trying to single out the approaching time did not provide any usable results. Additionally, from the data appeared that ships are often allowed to use the waiting areas of locks as short-term mooring areas. The times spent in the approaching areas by these ships were often much higher than could be expected from the traffic intensity, which further complicated producing reliable results. It was therefore decided that assumption on the delays must be made. Delays are expected to be different for various ship types and classes, where larger ships are usually less manoeuvrable. In Table 3.3 the assumed approach and exit delays are presented. They are based on the largest CEMT-class of ships they can hold.

Waiting time

The time ships spend waiting for their turn before they can enter the lock is the waiting time. This is one of the performance indicators as defined in Chapter 2 for both the locks and the vessels on the network. Vessels normally wait for their turn temporarily moored in the approaching area of the lock. The same problem arises when trying to define the waiting time as with the approach and exit times. It was therefore decided to calculate the waiting times at the locks through the simulation model.

Operational time

The operational time of each lock is obtained from the AIS data. The operational time is defined as the time spend by ships in the lock chamber and is one part of the before mentioned total time it takes ships to pass a lock. The time spend in the lock chamber can be linked to several steps in the lock cycle as defined in Section 2.3.1. Every moment from entering the lock to exiting are captured within the geographical area of the lock chamber. Therefore, the total time spend here covers most of the cycle, including the opening of the lock doors before exiting and the closing of the doors once the ship is in the chamber.

To obtain the average time in the lock chamber, the AIS data was used. The prepared data, as obtained in Section 3.1, was filtered on the geographical area of the lock chamber of the studied lock. Because ships could have passed the lock more than once in the time span of the data set, a distinction must be made between the trips. Each trip should pass the lock only once. The trips were defined based on the vessel id number and the time of passing. To distinguish between different trips made by the same vessel, a cut-off time was used. Based on the timestamp of each AIS-point the time difference between all the points could be determined. If the time difference between two points is greater than the defined cut-off time, it means that those points belong to different trips.

Choosing different cut-off times appeared to slightly influence the mean and variance of the calculated operational times of the locks. Therefore, the mean and standard deviation of cut-off times ranging from 2-8 hours were calculated for several locks. The results of this analysis are provided in Table B.1 and summary is also presented in Figure B.1. From this figure it can be derived that the operational time appears to increase a little when longer cut-off times are used but seem to converge to a certain value. This appears to be similar for all locks that were analysed, and the standard deviation follows this same behaviour. Therefore, it was decided that the results that correspond with a cut-off time of 7 hours is used. This resulted in an operation time for every time a lock was passed during a trip. For each lock then a distribution could be made to determine the spread of the operation times. To show what such distributions look without overcrowding the plot, the obtained probability function of two locks is given in Figure 3.8 as an example. Here it can be seen that the curves have slightly different forms, but both have clear higher probabilities in their centre. Although it might not be a perfect fit, the curves roughly follow the shape of a normal distribution. This is the case for all the locks on the network. Therefore, the operation times of the locks will be treated as having a normal distribution.

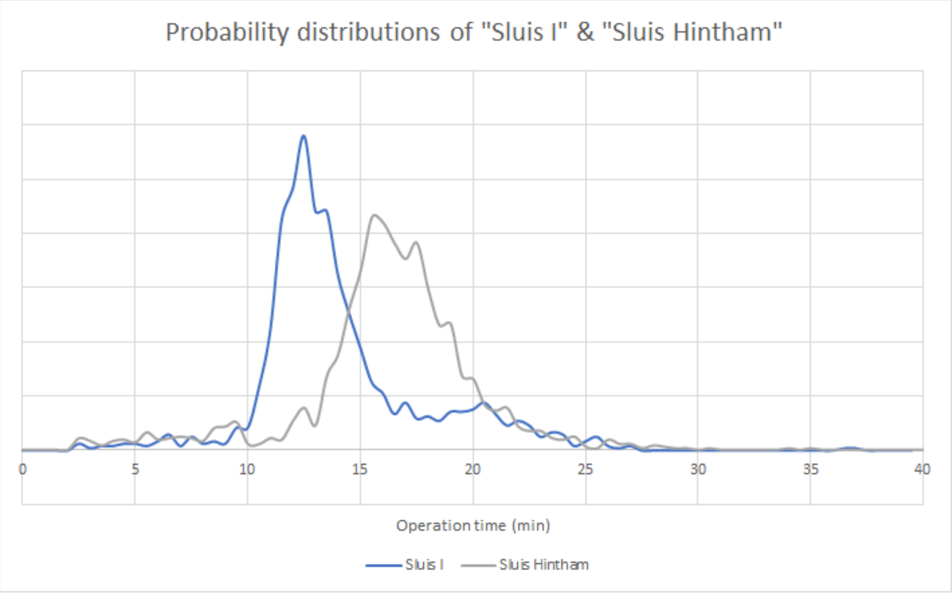

Figure 3.8: Probability distribution for lock I and lock Hintham as obtained from the AIS analysis.

To give an indication of the spread and distributions of the other locks, Figure 3.9 was made. Here all the locks are presented with their mean and spread. As the operation times will be treated as normally distributed, it is possible to determine the standard deviations. This, together with the means, results in the values as provided in the ’operational time’ column in Table 3.3. These are the values that will be used later in the simulation model.

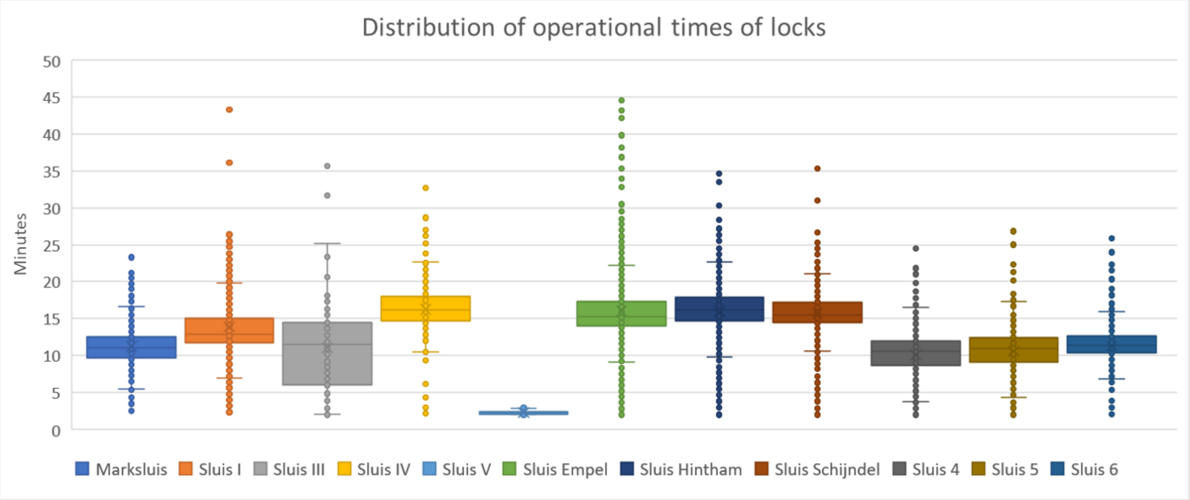

Figure 3.9: Mean and distribution of lock operational times

In the table and figures the values for ’Sluis V’ are included. This lock has been out of use since 2010, which can also be derived from the supposed operational time being rather low, compared to the other locks. It was included in the analysis to verify the used method and the information on vaarweginformatie.nl (Rijkswaterstaat, 2020).

Table 3.3: Operational times of the locks on the network as obtained from AIS with a 7h cut-off time.

Lock	**Dimensions**			**Operational time**		**Additional delay**
	Length (m)	**Width (m)**	**CEMT**	**Mean (min)**	**St.Dev. (min)**	**Approach/Exit (min)**
Marksluis	120	14	V	11.35	3.02	4
Sluis I	120	14	V	13.91	3.93	4
Sluis III	115	11	IV	11.08	6.31	4
Sluis IV	65	17	II	16.23	3.87	3
Sluis Empel	115	13	IV	16.18	4.58	4
Sluis Hintham	115	13	IV	16.02	3.85	4
Sluis Schijndel	110	13	IV	15.73	3.28	4
Sluis 4	110	13	IV	10.10	3.33	4
Sluis 5	110	13	IV	10.75	3.56	4
Sluis 6	110	13	IV	11.28	3.09	4
Sluis V	*65*	*12*	*II*	2.31	0.32	-

Observations from the lock analysis

There several things that can be taken from the analysis of the locks on the network. Here the most important ones will be summarised and discussed.

- **Difficulty defining the approach, exit and waiting times**
  In the analysis of the locks, it was possible to obtain the operation times with a mean and variance. It proved difficult to determine the other parts of the total time that ships are delayed. Especially, the approach and exit times are difficult to obtain as the analysis of AIS is most straightforward when it is possible to split in clear cut geographic areas. However, the approach areas of locks are also used by ships waiting to be served and sometimes even to rest/spend the night.
- **Variance in the lock operating time**
  In most lock studies, the operation time of locks is assumed to be constant. From the AIS analysis it can be said that this is probably not a good assumption. The shape of the distribution differs slightly per lock, but all roughly resemble a normal distribution. The variance is different per lock, but the spread is significant enough to keep in mind when simulating the lock operations.

3.3. Vessel Traffic & Characteristics from AIS

The movement of inland vessels on the network can be split up in two parts. The first part is defined as the vessel traffic. This consists of the number of vessels that travel between all the origin and destination locations defined earlier, and the time of departure for those vessels. The second part concerns the characteristics of these vessels, which is summarised in the size of the vessels.

To determine the daily traffic over the network, the number of trips between the origin and destination locations will determined to create an origin and destination matrix (OD-matrix). As there are quite a few uncertainties in this method, the traffic on the network will also be determined using virtual counting points placed on the network. With the results from both methods, a comparison is made between them to check if the obtained OD-matrix is accurate.

In addition to being a verification method for the OD-matrix estimation, the counting points will also be used to determine the time of day at which ships travel the network and what the composition of the fleet is.

3.3.1. Origins & Destinations Estimation

One the main uses of the AIS data is to generate an overview of travel between the areas as defined in Figure 3.7. To do so, the tracks obtained for the vessels in the data preparation need to be further split up into trips. The general method used for splitting one vessel track into one-way trips is to determine the origin and destination is presented in Figure 3.10 and will be explained further in this section. At the end of the section, the observations that can be made from results are discussed.

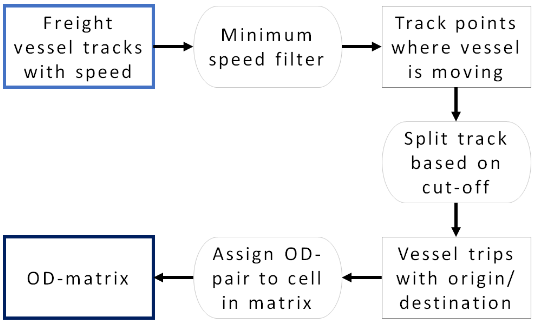

Figure 3.10: Summary of the steps used to obtain the OD-matrices

Method for obtaining OD-matrices

As ships are being tracked through their entire time on the network, it is in most cases not very straightforward to determine where the actual origin and destination of a trip lie. Easiest would be if it could directly be determined where a ship has stopped to load, unload or rest. However, ship often must stop or slow down stop for a certain amount of time, at for example locks. This means that within a single trip there can be many instances where the ship is moving at a very slow pace. This must be considered when determining the end points of trips. Thus, simply splitting a track into multiple trips whenever the speed falls to zero is not possible. However, if the speed of a ship is zero for a longer time, it could be concluded that it is either moored or anchored.

However, another problem arises when using the calculated speed in determining trip end points. This comes from the accuracy of the AIS systems. When ships are moored, their change is position is supposed to be near zero. As with all positioning systems there is a certain error in every message send and received. For moored ships this means that they often appear to move around a small area. The speed, as was applied in a previous step, is therefore also slightly above zero for such points. After further exploration, it was observed that the position messages for moored ships had speeds of up to 0.28 m/s or 0.54 knots. These are very low values compared to the cruising speeds of inland ships. It was therefore decided to only use points where the approximated speed was above 0.4 m/s. This ensures an extra margin of error without removing points that could be useful. A test run was also performed where the limit was 0.3 as will be discussed later.

Next, a decision must be made on where the line lies between ships stopping temporarily during the trip and stopping at a destination. This is called the cut-off time and should be higher than the waiting time at locks or other temporary stops and lower than the time used for unloading/loading a ship. A balance must be found between setting the cut-time to low and unnecessary splitting a trip and setting it too high resulting in counting two trips as one. A cut-off time of one hour could mean that if a ship has to wait to pass a lock with larger traffic volumes, it would appear that the lock is one of the destinations. On the other hand, a cut-time of six hours could mean that a container vessel could be moored, unloaded and off again without registering as two separate trips. It was therefore decided to test several cut-off times to observe the changes and differences.

With the cut-off time known, the files containing unique identification numbers were split into tracks, each with an unique track number. Subsequently, for each track the first and the last position message were retrieved resulting in two lists with origins and destinations respectively. With these known, the track can be assigned to an OD-pair and added to the matrix. This process was repeated for various minimum speeds and cut-off times to see how they related to the traffic volumes. This resulted in the matrices as provided in Appendix A. In Table 3.4 some summarising values are given for the combinations that were used.

In the first matrix, Table B.2, the entire AIS data set was used without filtering out the non-freight vessels to test whether this gave different results. When comparing this matrix to the second one, it can be seen that it does indeed change the traffic volume by large amount. This second matrix, Table B.3, is also the result of a test run but to determine the impact of the minimum vessel speed on the obtained traffic. When comparing this matrix with the subsequent one where the minimum speed is higher, the total traffic does indeed decrease a bit when using a higher minimum speed.

With these variables checked, the next step is to determine the impact of the cut-off time on the traffic volumes. This is done using three different cut-off times of two, four and six hours. As can be seen in Table 3.4, the cut-off time significantly impacts the amount of trips that is observed. This poses a problem, as this makes it difficult to determine an optimum value. This is the main reason that the traffic volumes will also be checked using virtual counting points as will be explained in Section 3.3.3.

Table 3.4: Comparison between OD-matrices with varying cut-off times, minimum speeds and vessel selection

Cut-off time (h)	Vesseltype selection	Minimum speed (m/s)	Total observed trips	Main diagonal share	Unaccounted trips share
2	No	0.3	17091	56.98%	4.66%
2	Yes	0.3	14203	53.49%	3.85%
2	Yes	0.4	13778	45.75%	3.00%
4	Yes	0.4	10475	40.49%	1.80%
6	Yes	0.4	9098	39.70%	1.80%

Observations from OD-matrices
From the resulting tables, several observations can be made. These most important ones are:

- **Differences in total number of trips between OD-matrices**
  The number of total trips observed at different cut-off times varies greatly. This makes it difficult to determine what numbers are useful as input for the simulation model. Therefore, additional information is needed before the most fitting OD-matrix can be chosen.

- **Difference in total number of trips and trips in OD-matrices**
  The sum of all trips in each matrix differs slightly from the length of the list with unique track numbers. This value does seem to go down with increasing cut-off times and higher minimum speeds. One possible explanation could be that there are ships with AIS trackers exiting the main waterways of the network and end their trip outside the defined geographical areas. This adds an uncertainty to the observed values and could indicate that the chosen method for determining OD-matrix is sub-optimal.

- **Round traffic or inner-regional traffic**
  The numbers on the main diagonal of the matrices show the number of trips that start and finish in the same areas. These trips account for approximately 60% with low filter settings going to approximately 40% for higher cut-off times and minimum speeds. This could large number of round trips could be caused by several reasons. For example, one reason could be that several ships make small trips between resupply quays, fuelling stations, sleeping areas etc. The relative decrease of trips on the main diagonals could indicate that a higher cut-off time results in a more accurate division of trips over the OD-matrices.

- **Traffic over the Amer-Bergsche Maas route**
  A large share of the traffic is between the areas 1, 11 and 12. These represent the northern part of the network and are by themselves not relevant for this research as there are no locks on this section. Additionally, this is a CEMT-V class river that has a relatively large capacity compared to the traffic load it has. The OD traffic counts between these areas are not further considered in this research.

- **Passing traffic**
  One of the main concerns associated with closing the watersection at Lock II (area 4), was that traffic that does not have its destination in Noord-Brabant, but is just passing the network, would

experience delays. However, in all the OD-matrices the traffic from areas 1, 11 and 12 to area 8 and vice-versa seems to average around four ships per day. This indicates that most of the traffic on the southern and eastern edges of the network is destination traffic.

Combining these observations indicates that the OD-matrix cannot be readily translated to the simulation model, as too many uncertainties still exist. Therefore, another method is used to assist in choosing an OD-matrix that is suited for use in the simulation model.

3.3.2. Vessel Traffic from Counting Points

To get a better grasp on the results in the OD-matrices, another approach is used to check the traffic on the network. By using virtual counting points on the network, the traffic volumes on network edges can be determined without relying on just the start and end points of trips. The goal of this method is to obtain the amount of traffic that moves in either direction on the waterway. In addition to checking the OD-matrices with this method, the counting points will also be used to analyse the size composition of the fleet and the time of day at which ships travel. The steps required to create a virtual counting point are explained below. A summary of the steps is again provided, in Figure 3.11

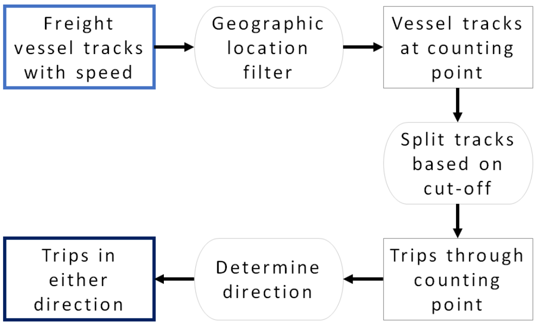

Figure 3.11: Method to create virtual counting points on the network that can be used for analysis of passing traffic.

To completely cover the network between the relevant zones as in Figure 3.7, the edges as in Figure 3.12 need to be covered. The counting points are divided over the edges that are relevant to the case study. Meaning that the northern part of the waterway is not included in the analysis. Of the counting points presented in Figure 3.12, especially the one within area 4 is important. This edge corresponds with Lock I on the Wilhelminakanaal, where an actual counting point for the IVS90 system was in 2018. This will later be used for verification of the obtained results.

To create a virtual counting point a small geographical box is drawn over a waterway. The side of the box that runs parallel to the waterway should be long enough such that a ship passing through the box sends at least two position messages. After defining the corners of the box, the AIS data as prepared in chapter 3.2.2 was filtered on these coordinates. By putting these counting points on sections of the waterway where no mooring, anchoring, or turning is allowed, the need for minimum speeds is eliminated.

Then a similar method as with the OD-matrix estimation was used to obtain unique track numbers. Here the cut-off time was set to two hours. Additionally, the direction of the ship was added to the trip which will is useful when comparing to the results of the OD matrix. After this step, the vessels passing the counting point can be analysed. For the traffic volumes this resulted in the values presented in Figure 3.13. The actual numbers are also added in Table B.7.

Vessel Sizes

In addition to the traffic volumes and their direction, it can also be obtained what the dimensions of the ships passing a counting point are. For this the same CEMT-classes as in Figure 2.2 are used. When grouping by the length of ships, the distribution as in Figure 3.14 is obtained. The exact numerical results are also presented in Table B.8.

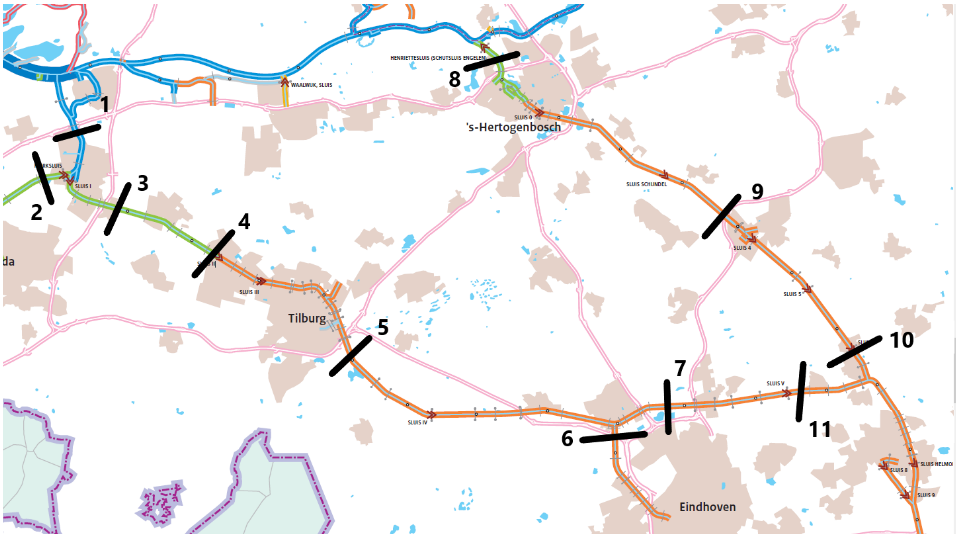

Figure 3.12: Location of virtual counting points on the network. Image adapted from: Rijkswaterstaat (2020)

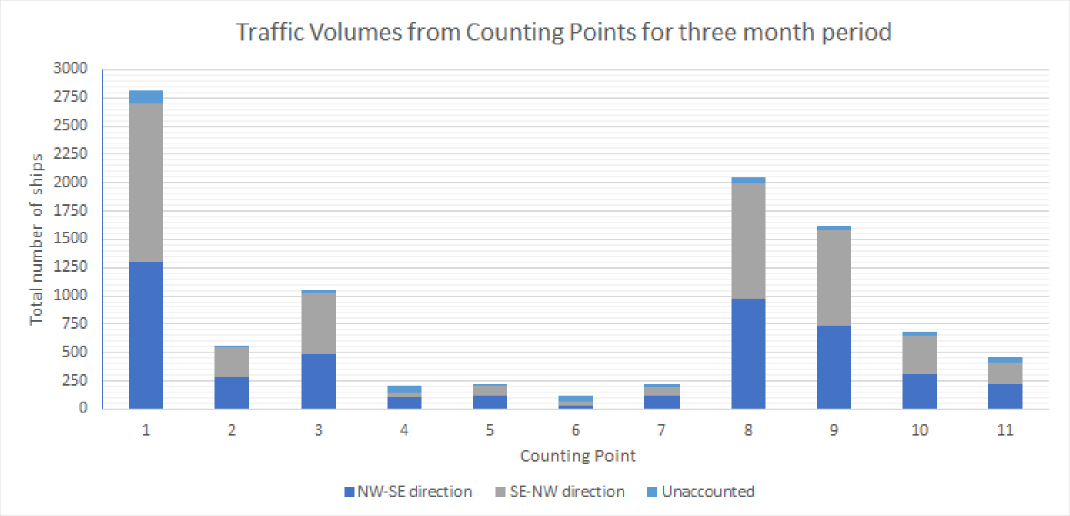

Figure 3.13: Traffic volumes in two directions, obtained from AIS analysis. Summation freight vessels over a three month period.

Time of Day

Just as with the distribution of vessel sizes for each counting point, it can also be determined in what time periods ships pass the counting points. This is important information as it tells at which times the waterways, and therefore the locks, experience the highest traffic intensities. Having an uneven distribution over the day increases the waiting times at locks and will therefore be used in the simulation. The distribution of each counting point is presented in Figure 3.15. Here is can be seen that the time of day distributions for all counting points follow a similar curve. Therefore, the mean distribution of vessels over time, weighted by the total traffic of each counting point, is given in Figure 3.16.

Observations from the Virtual Counting Points

The values obtained from the virtual counting points are on themselves not enough to determine the actual flow of traffic. However, there are several points that can be taken from the results.

- **Traffic intensities on different routes**
  There appears to be a large difference in the traffic volumes over different parts of the network. The traffic volumes on the eastern route, the Zuid-Willemsvaart, are relatively high compared

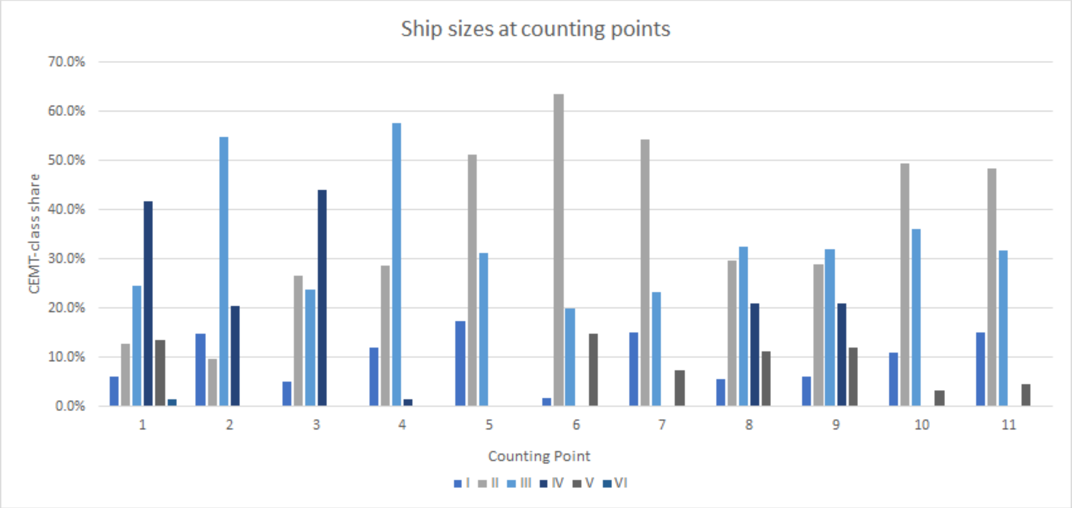

Figure 3.14: Distribution of ships per CEMT-class for each counting point. Aggregation of freight vessels over a three-month period.

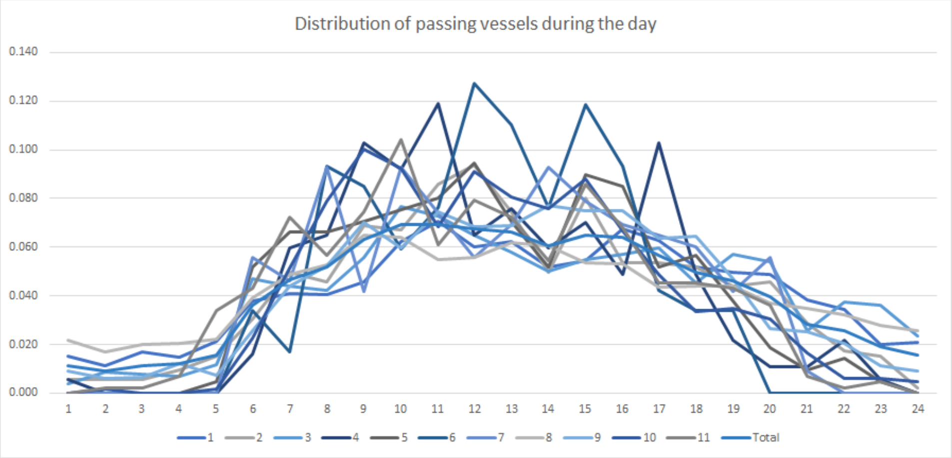

Figure 3.15: Distribution of ships passing all the counting points during the day. Passing times grouped by the hour.

to the southern route. Meaning that the eastern part of the network has more companies that use inland shipping and that the eastern route is the fastest way to get to destinations further upstream. Also, there appears to be a high number of ships that have their destination in the west of the network. Which would make sense, as there are two inland terminals in these areas.

- **Ship sizes and CEMT-classes of waterways**
When looking at the values in Figure 3.14, it could be obtained for each counting point what the dominant ship size is. There is however a slight mismatch for some counting points. For example, counting point 6 and 7 are positioned on a waterway with CEMT-II label, there are ships with class CEMT-V registered anyways. This could point to an inaccuracy in AIS entries. Ship size can change for ships and push barges depending on their configuration and must therefore be entered in the AIS system manually.

- **More traffic during the day**
It appears that the crews on inland vessels usually like to sleep at night and that most of the ships travel during the day. The effect time has on the traffic intensity at counting points appears to be larger for the smaller waterways. Although this probably mainly caused by the opening times of the locks on these smaller waterways ('Sluis IV' is closed from 00:00 - 06:00). It is not possible to directly translate the time of passing at the counting points to departure times of vessels from their origin point on the network. It does however provide an indication as to when vessels generally

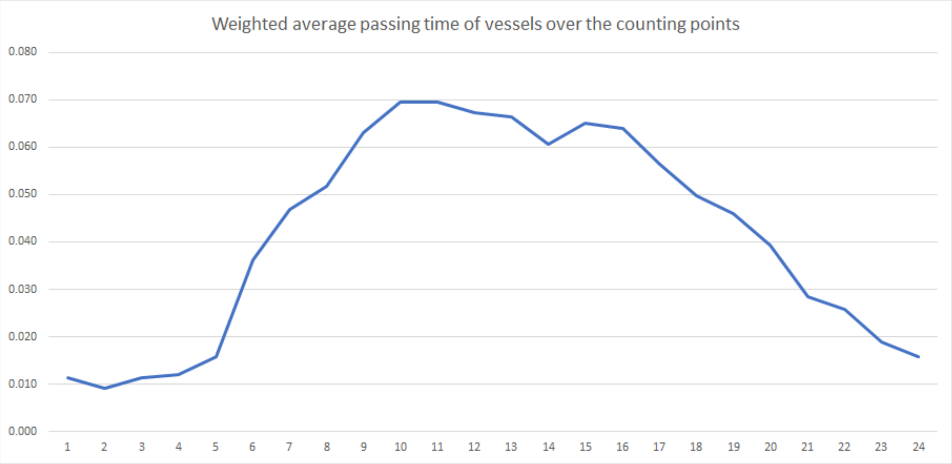

Figure 3.16: Averaged distribution of ships passing the counting points during the day. Passing times grouped by the hour.

travel. The distribution as shown in Figure 3.16 will therefore be used in the simulation model.

3.3.3. Comparing Counting Points & OD-Matrices

To make a comparison between the two methods explained above, the OD-matrices translated to an expected network assignment. From this network assignment, the expected loads on the counting points can be obtained. Which can then be compared to the values from the virtual counting points. For this comparison, only the last three OD-matrices are used.

Shortest Paths

As there is a loop present in the network, for most OD-pairs more than one route is possible. This poses a problem as this makes it impossible to say with complete accuracy which route is taken. However, it is possible to make some assumptions on the route choice. In general, it can be assumed that ship take the route that takes the least time to reach their destination. This is usually the shortest route as well, however not every waterway can travelled with the same speed. Ships usually travel at higher speeds on waterways with high CEMT-classes resulting in lower travel times. To determine the speed of vessel on the network, for several parts of the network the average speed over an edge was determined. This was done by using the approximated speed as applied in Section 3.3.1. It should be noted that this is very rough estimation of the average speed of vessels, as the speed over ground is dependent on many factors can vary over time.

Using the distances between regions and the approximated speed on the waterways it was determined what the weighted distances were. Then the shortest path is for each OD-pair was determined using Dijkstra's shortest path algorithm. This was done using the script as provided by Mellon.

Estimated Traffic on Counting Points

Using the travel routes between OD-pairs, the expected traffic volume on each counting point can be determined. In this assignment, counting point 6 is assigned zero traffic as it is registering no passing ships and only ships travelling within the area. The results of this assignment can be found in Table B.10 and in Figure 3.17.

Table 3.5: Estimated traffic volumes at counting points from OD-matrices, divided by the actual traffic volumes obtained from the virtual counting points.

	Counting Point											**Fit**	
Cut-off time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Average**	**σ**
2	0.771	0.800	0.837	1.254	0.946	0.000	1.279	0.685	0.822	0.880	0.887	0.916	0.1877
4	0.593	0.592	0.667	0.975	0.793	0.000	1.198	0.570	0.695	0.872	0.774	0.773	0.1886
6	0.474	0.504	0.419	0.876	0.752	0.000	1.122	0.528	0.646	0.854	0.704	0.688	0.2084

When dividing these results to the results obtained from the virtual counting points, the fractions

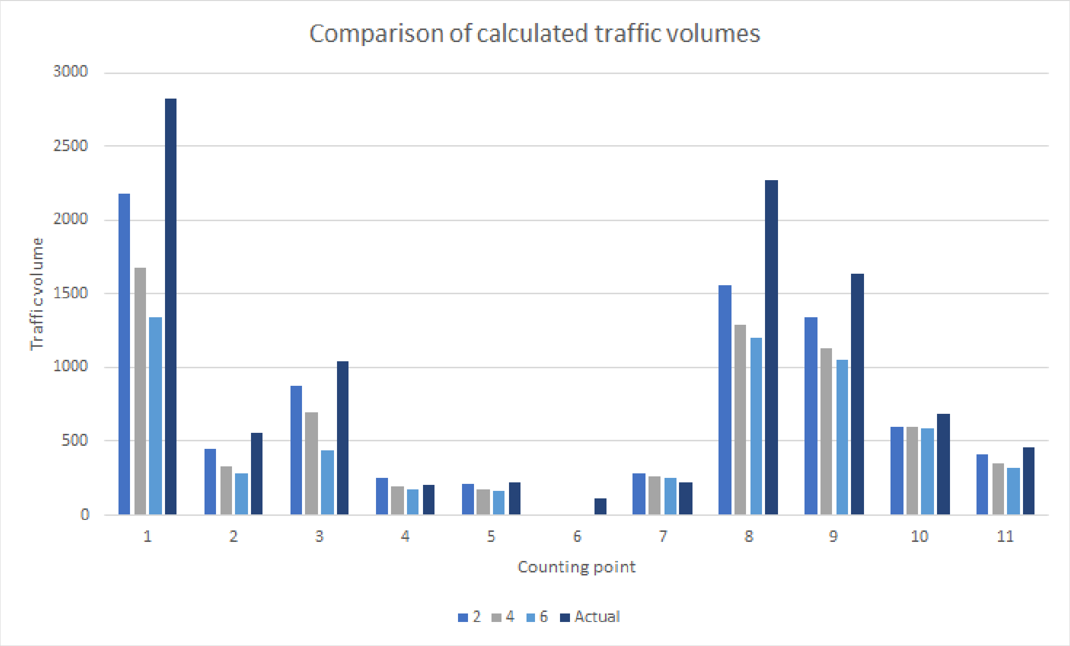

Figure 3.17: Expected traffic volumes over the counting points as calculated from the OD-matrices using a shortest path assignment. Summation of freight vessels over a three-month period.

as in Table 3.5 are obtained. Here it can be seen how close the estimations match the earlier results. Here it can be seen that there are still significant differences between the results of the two methods. In the columns on the right, the average fit of each inverse trip assignment from the OD-matrices is compared with the virtual counting points.

Observations from the Comparison
From the comparison between the two methods several observations can be made. The main findings are as follows:

- **Underestimation of traffic from OD-matrices**
  The total volume of vessel traffic is lower when obtained from the OD-matrices compared to the virtual counting points.
- **Traffic volume estimation varies per route/area**
  There appears to be some correlation between the network area a counting point is located and the estimation of traffic volumes. For the western part (counting points 1, 2 and 3) and eastern part (counting points 8 - 11) it is estimated significantly lower than expected. Whereas, for the southern part (4, 5 and 7) estimated values are higher than expected.
- **Low amounts of traffic on southern route**
  For determining the effects of closing the waterway section for the construction of a lock, the main input is the traffic passing this point in a business as usual situation. For the case study, these numbers appear to be rather low. This would directly mean that the overall impact of closing for construction on inland shipping is rather low.

3.4. Verification of AIS Analysis

As AIS has only been accessible for research since 2017, it has not been used in research into inland shipping extensively. Therefore, it is hard to determine the accuracy of the data. A comparison with IVS90 data is made to determine the reliability of AIS. IVS90 stands for information and following system 1990 and was used till 2019 to keep track of vessel movements on the inland waterways of the Netherlands. Information for this data set is gathered at certain locks, ports, and traffic posts. From the IVS90 data, both the trips each vessel makes, and the size of the vessel can be obtained. One of the problems with the data in IVS90, is that there are concerns that it is not very precise and that there are several wrong inputs when registering a ship as much of the information was processed manually. This means that information is often copied from previous entries or information is registered differently.

There was a IVS90 counting point available on the network during the period of which AIS data was acquired. This is on the same edge and location as counting point 3 in Figure 3.12 at the lock ”Sluis I”. The number of passages in either direction was obtained for the first three months of 2018, the same period as the AIS data. Taking the average number of passages for both AIS and IVS90 results in the numbers presented in Table 3.6. Here it can be seen that there is an average difference of approximately 15% in the number of counted passages between the two data sources. This could be caused by several reasons in both methods. However, a large overestimation of the number of passages seems unlikely. Therefore, it is expected that the analysis of AIS data results in an underestimation of the actual traffic.

In both IVS90 and AIS only freight vessels are considered, and it could be that there is a wrong classification for the vesseltype in some entries. There can be several other explanations for the different outcomes. It is possible that an AIS message is missed by the land-based receiver and is thus not registered in the data set. Additionally, ships are able turn their transponders off which also means that passages could be missed. Finally, there could be problems with storing the data.

Next to possible problems with the AIS data gathering and storage, it could also be that the method used to determine the traffic from counting points results in an underestimation of the number of passages. Therefore, a check was done where the cut-off time was set to one hour, instead of two. However, this did not change the results significantly. It increased the number of average monthly passages by just four. It can therefore be said that the cut-off time is not a major cause of the difference in outcomes between the two methods.

Table 3.6: Monthly traffic volumes at counting point 3/lock I, for both IVS90 and AIS data sources.

	SE	**NW**	**Unaccounted**	**Total**
AIS	163	180	6	349
IVS90	189	214	0	403

With this comparison to IVS90, one counting point has been checked. Although it is expected that the found deviation is similar for other counting points, it is not possible to know for sure. The input for the simulation model is an OD-matrix and from the comparison of the OD-matrix and counting point methods in Section 3.3.3, it was determined that the OD-matrix with the largest traffic volumes was the best fit. Based on the comparison in this section, this OD-matrix would appear to be even more of an underestimation of traffic volumes. This can of course influence the accuracy of the developed model.

3.5. Summary & Conclusion

This chapter provided an answer to the third research question, *”How can important network and traffic characteristics be obtained from the data and information available?”*, by presenting the results of the data analysis. In this section the main findings are discussed.

3.5.1. Use of AIS as Data Source

All freight vessels have an Automatic Identification System (AIS) that sends out a message at certain time intervals. This data is stored can be used to track vessels moving over the inland waterways network. Because of privacy issues, this data source had not been used very often in the research on inland shipping before. AIS can be used to determine various characteristics of the transport system, but it needs some modifications before it can be used. Additionally, the size of the data set can become very large when large areas or time periods are studied.

3.5.2. Overview of the Network

Closing a waterway can impact the traffic volumes on other waterways when ships are able to take a detour. Therefore, a complete network of impacted waterways should be analysed when studying the impact of some construction and maintenance projects. This network should be divided into different areas that represent aggregated origin and destination points between which most freight vessels are expected to travel. In defining the areas, a trade-off is made between many areas for higher accuracy and less areas for faster computing times in both the data analysis and later in the simulation.

The locks on the network can all have different operating times. This operating time was obtained by measuring how long ships spent in the lock chamber using the AIS data. From this analysis it was obtained that the operating time is not fixed but appears to be distributed by function that resembles a normal distribution. From AIS, it was not possible to accurately obtain the waiting time or approach exit times at locks.

3.5.3. Traffic on the Network

The trips made by vessels over the network can be summarised in an Origin/Destination-matrix. This OD-matrix can also be obtained from AIS by determining the start and end points of each trip. This method is not very accurate, but it gives a good indication of number of daily trips between all regions. From the OD-matrix, it is not possible to determine which routes are taken by the vessels. Therefore, an additional method must be used. By placing virtual counting points on the network, the traffic volumes on edges of the network can be determined. Combining these two methods results in the number of trips between points and the likely route taken.

In addition to the number of daily trips, it can also be obtained from AIS during which hours of the day ships travel on the network. This can be summarised in an hourly distribution with higher expected traffic volumes during the day. The final aspect that was obtained from AIS was the composition of the fleet, with the percentage of ships in each size class.

3.5.4. Inaccuracy of Methods

Using AIS for creating an OD-matrix is a relatively new approach. It is therefore not readily known what the accuracy of this data is. It was found that calculating OD-matrices using the origin and destination points of vessel trips is likely to underestimate the traffic volumes on the network.

4

Simulation Set-Up

In the previous chapter it was explained how the current or past state of an inland waterways transport network can be analysed. The next step is to create a simulation model that represents the situation of the studied system. Correctly recreating the system in a simulation model makes it possible to apply changes and calculate the effects. In this research the goal is to create a method that could be applied to various situation and networks. This is also considered while designing and building the simulation model.

This chapter first discusses the modelling concepts that were used as a basis. Thereafter, the requirements are defined. Then, the set-up of the simulation model is explained in more technical details. Finally, the model will be tested for reliability and validity to check whether it performs as expected.

4.1. Modelling Concepts

The simulation tools used and built upon in this research are a product of the department of Hydraulic Engineering of the TU Delft called Open Source Transport Network Simulation (OpenTNSim). This is a combination of functionalities and tools that have also been used for some previous research into network analysis problems of inland shipping. Notable previous master thesis works that used this model are a research into transport between the ports of Antwerp and Rotterdam (Vehmeijer, 2019) and a research into the movements of recreational vessel in the canals of Amsterdam (van der Does de Willebois, 2019). The steps taken in this research for setting up the simulation model are partly inspired by these previous works. Several examples for how to configure the model are provided with the OpenTNSim package, which is available at: github.com/TUDelft-CITG/OpenTNSim.

OpenTNSim is a Python based toolbox that uses the Simpy simulation package as a base. Simpy is simulation framework that can be used for process-based discrete event simulations (Revision). Discrete event simulation is a method where the operating of a system is modelled from event to event. Events can either be defined as fixed time steps or as instances that a change occurs. This second method means that the model determines when change is going to occur in the simulation and skips ahead to the next event. This has a benefit compared to fixed time increment simulation because not every time slice has to be calculated, often resulting in less required calculations. (Matloff, 2008)

Another important aspect of the OpenTNSim package is that it is an agent-based model (ABM). An agent-based model uses individual entities, the agents, to recreate more complex systems in which each entity acts in its own interest or by a certain set of simple rules. This complies well with the inland shipping system, where each ship acts in its own interests but must follow certain rules when interacting with others. This method of applying simple rules to agents in a system to get a better of a more complex system also means that verification of every part of the model is very important as small changes can often lead to large differences in results. (Giancarlo Fortino, 2005)

4.1.1. Other simulation tools

To perform effect studies for waterway infrastructure projects several other simulation and calculation tools have been used in the past. However, these are often not as accessible because payments are often required, or the software is not publicly available. Additionally, these are usually not specifically aimed at nautical traffic studies. As mentioned, the method and model developed in this research should be easily transferable to other situations as well. Therefore, accessibility and availability were important aspects while selecting the right tool.

One other simulation tool that is used by Rijkswaterstaat to study vessel traffic at waterways and obstructions is SIVAK II. This is a simulation tool that has been used since 1991. In SIVAK most of the functionalities required for this research are present, such as the functioning of locks, the generation of certain fleet compositions, the route planning for vessels etc. Although SIVAK would have been a very good alternative for this study, there are some downsides to using it compared to OpenTNSim. One of main reasons is that SIVAK II has been replaced by a newer simulation package that is not publicly available. (Rijkswaterstaat, 1998)

4.1.2. Model Objectives

The simulation model that is developed in this research is aimed at analysing the performance of the inland waterways system. To achieve this, it must be able to mimic the real-world system in a virtual environment. In this virtual environment changes are then made to measure differences in performance. The performance of the system can be measured in many attributes, but for this research the goal is to determine the generalised costs for all inland ships on the network. The generalised costs are calculated from a combination of the fuel use, travel time and plannability. The simulation tool should thus be aimed at calculating these values. Based on these observations, the objectives of the model are defined as:

1. **Represent real world system**
   The case study for this research concerns a section of the Dutch inland waterways network. Therefore, the network, with all its obstacles and resistances, needs to be accurately depicted in the virtual environment. Additionally, the movements of vessels should be imitated. This means that information gathered in the previous chapter should be translatable to the model.

2. **Calculate performance of inland ships**
   The performance of inland ships is ultimately calculated in the generalised costs. The model must be able to calculate the factors that impact the generalised costs for each inland freight vessel on the network. These factors were defined earlier in Chapter 2 as: fuel costs, costs per unit of time and the costs of unreliability. The goal of the research is to determine the change in performance. The focus of the model should therefore be on the vessels and traffic flow affected by the closing of the waterway at 'Sluis II'.

3. **Apply changes in the virtual system**
   To determine the impact of closing a waterway, the simulation model should be able to make changes in the accessibility of the waterway sections. It is not necessary that can be done during simulation, rather in the set-up of a scenario.

4.1.3. Model Requirements

From the objectives, it can be determined what requirements the model needs to meet. These can then be used to make the actual design of the simulation. Most of the requirements relate to the first objective and are formulated to ensure the results are generated in the right way. The following requirement are set for the model:

1. **Network representation**
   The network with its dimensions forms the basis on which the simulated vessels will travel. Therefore, a correct graph should be used in which the nodes and edges represent the waterways. With this a balance should be found between precision and simplicity. Increasing the number of nodes and edges possibly increases the accuracy of the simulation but also increases the number of steps calculated in the simulation. As a discrete event simulation environment is used and each

vessel reaching a node is seen as an event, the number of nodes and edges directly relates to the number of steps calculated.

2. **Agent movements**
   The agents in the simulation represent the vessels and should travel in a similar way. This means that they should be able to move between points on the network with an appropriate speed. Additionally, they should be able to interact with the obstructions and each other while moving over the network. This means that they wait when an edge is full or when a lock is busy transferring other vessels.

3. **Vessel generation**
   The number of trips made in the simulation between origin/destination pairs should resemble the matrix as obtained in Chapter 3. In addition to simulating the right number of trips between each pair, it should also be possible to set the time of day at which ships depart from their origin points to correctly mimic the variation traffic volumes throughout the day. Finally, it should be possible to generate different kind of vessel sizes to comply with the distribution of vessels.

4. **Route choice**
   The simulation model should be able to determine a fastest route between two points for a ship. This way not only the right amount of ships is simulated, but also the correct route a ship takes. To comply with the method used in Chapter 3 Dijkstra's shortest path algorithm is preferred. For this simulation, only the width, depth and length are considered. These are the most important factors for determining possible routes and whether a ship fits in a lock chamber. The height of ships is thus not considered. When no route is possible for a ship, the model should return an error.

5. **Lock operation**
   Important aspect of the research is the impact of locks on the travel times and delays of ships. Therefore, the model should be able to simulate the lock operation cycle. This means that the time spent by ships in the lock chamber and the delays caused by approaching and waiting are all considered. The model should be able to set the time spent in the lock chamber and slowing down/accelerating as fixed values. The waiting time should follow from the time spent by ships in a virtual waiting line.

6. **Logging of time and distance travelled**
   To obtain the desired output, the model should be able to keep track of the movements of each ship. This can be further split up in two components. The first is the time each ship spends on the network. This consists of both the travel time and the waiting times for the locks. This can later be translated to some of the operational costs for ships. Secondly, the distance travelled, and the total energy spent during a trip should be tracked. This consists of energy used by the main engines and energy used by the auxiliary engines that are used when waiting. The used energy can directly be converted to the amount fuel used, which in turn is an important part of the costs.

7. **Closing of waterway section**
   From the final model objective, it is obtained that it should be possible to change parts of the network to simulate different scenarios. It should be sufficient to be able to apply these changes before running a scenario and not during a simulation run.

8. **Duration of a simulation**
   It should be possible to keep the simulation running for set periods of time. To mitigate start and end effects, it is desired that the simulation time is at least one month.

4.1.4. Model Outline

With the requirements and objectives in mind, the outline of the model is defined. In essence, the simulation model is a tool to predict the expected traffic assignment on the network in varying situations. This assignment is based on the inputs gathered on the real waterways and traffic system and transforms them to the desired output values. A summary of the intended structure of the simulation model is presented in Figure 4.1. The first two model objectives can be traced in this outline by the inputs and results, respectively.

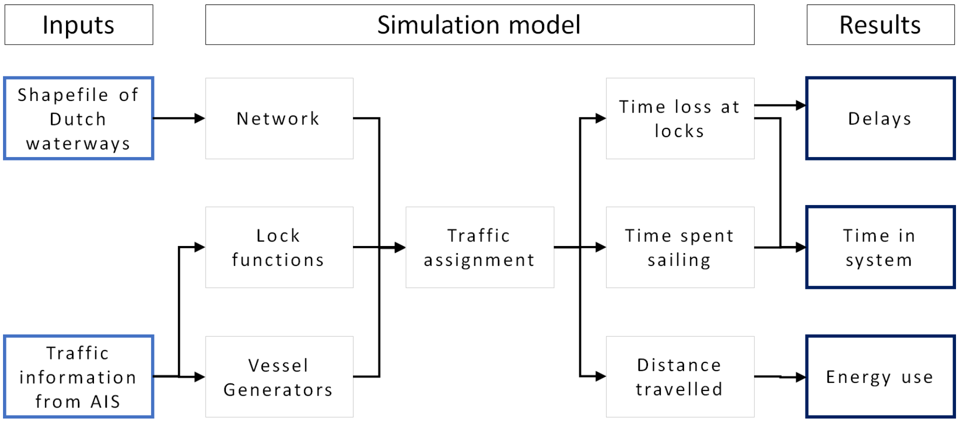

Figure 4.1: Summary of the simulation model structure

Specifying Model Inputs

The next step in developing the simulation model is to specify the inputs that are needed.In Chapter 3 most of the inputs for the model were derived from analysing the network and the AIS data. In Figure C.1 a description of the required inputs is given, and the steps needed to translate them to the intended outputs. For each input it will now be explained how was obtained and will be used.

- **Network**
  At the base of the simulation is a network file that contains information on the location, name and length of the edges and nodes. In Section 3.2 it is explained how the network was obtained and adjusted for use in the simulation. The final resulting shapefile is loaded into the environment when initialising the simulation environment.

- **OD-matrix**
  For the generation of vessels an arrival rate needs to be specified. This arrival rate is specified for each unique OD-pair and is based on the matrix in Table B.4. However, some changes must be made before it can be used in the simulation model. As mentioned in the second model objective, the focus is on the traffic flows that are affected by the closure of the waterway between the regions 4 & 5 (Figure 3.7. Traffic between areas that have no locks on route are therefore left out of the simulation. This represents much of the traffic moving over the northern edges of the network. Additionally, the matrix from AIS has a lot of traffic that appears to move within an area. This is also left out as it would not result in movements of any ship. As the simulation model works with a daily arrival rate as an input, the arrivals are divided by sum of days in the analysed months. After these adjustments the OD-matrix becomes as in Table D.12.

- **Distribution of ships during the day**
  For the generation of vessels an arrival rate needs to be specified to calculate a predicted inter arrival time. The average arrival rate is obtained from the OD-matrix and is given for a 90-day period. This needs to be reduced to an hourly arrival rate, where it is possible to distinguish between times of day. More ships travel during daytime hours, as derived from the analysis in Section 3.3.2, and the generation of vessels should be adjusted accordingly. For the distribution of vessels generated the values as presented in Figure 3.16 are used for each day.

- **Vessel size distribution**
  The vessel size has influence on several aspects of the cost function. The fleet composition should thus be like the actual situation. The distribution of vessel classes is therefore derived from the counting point method of the AIS analysis. It is preferred that for each OD-pair a fleet composition is used that would result in the same graph as in Figure 3.14. Assigning a different fleet composition function to every OD-pair is not a straightforward method that would require

many assumptions. Additionally, the simulation environment is not really suited to deal with many fleet composition input functions. It was therefore decided that one single function was used based on the traffic on the counting points 3-11, as these are on the relevant network edges. This distribution is then rounded to numbers with a precision of 5%. The final vessel distribution is presented in Table D.9.

- **Vessel speed**
  The speed of vessels has an influence on the time spend in the system and on the energy consumption. These are two of the performance indicators used to determine the effects of changes in the system. It is important that the calculated results for these factors are similar to reality. Ideally, the simulated speed is like the actual speed of vessels in the system. In the real system the speed of ships is not constant and depends on numerous variables. However, having variable speeds for vessels makes the simulation model more complicated. It was therefore decided to set the speed to an average constant value. These averages were obtained from the report of Vehmeijer (2019) and are shown in Table D.10.

- **Lock operational times**
  Each lock has an operational time that varies according to a normally distributed function with a mean and standard deviation as in Table 3.3. These values are used in the simulation to mimic the variability that exist in the lock operation process. A general normally distributed process with these means and standard deviations could results in a negative value. As this is not possible, a minimum operational time of zero is used for the simulation.

4.2. Internal Verification of Parts

A simulation is a representation of a real-world situation. It should therefore be determined with which accuracy this representation is made. Therefore, all the parts will be tested before application. In previous works ((Vehmeijer, 2019), (van der Does de Willebois, 2019)) the OpenTNSim model underwent some testing of parts and verification so it is expected that there should be no problems with the basic functionalities. However, there have been some changes and updates. So, for completeness and to ensure that everything was implemented in the set-up of this model as well, the crucial parts will still be checked. Therefore, the basic movements of vessels over a small network will be tested first. Thereafter, the route finder will be checked on a slightly more complicated network. Thereafter, the function that generates the vessels between an origin and destination pair is checked on whether it translates all the input variables correctly. Finally, the performance of the locks is checked.

4.2.1. Basic movements

At the base of the simulation are the ships/agents moving over the edges of the network. For simplicity and a good overview a small section on the eastern edge of the network was cut out (Figure 4.2) to test these basic movements. A cut out of the original network was used because of the extra node and edge attributes stored in the file, some of which are used in the simulation set-up. This specific section was chosen as it has some variation in edge length and the middle edge corresponds with the lock 'Sluis Empel', which is needed in later verification steps.

The first test is used to check if vessels move over the network as intended, the movements are logged correctly and to test if the energy use is calculated correctly. For this test, two vessels with different speed, size and energy consumption are simulated between the two end points of the test network. The results of the test can be found in Table D.1. From the log file it can be seen that the vessel indeed moves from point to point at the intended speed. The energy use is not calculated directly but is obtained afterwards and resulted in a total use for the shown vessel. This complies with the expected value and it can thus be said that this part of the simulation model works as intended.

4.2.2. Vessel generation

The generation of vessels consists of a few components. To test whether the inputs are translated to the simulation correctly the vessel generation will be tested in several scenarios, where the focus lies on the functioning of a single vessel generator. The inputs for the vessel generator can be divided into three parts: the number of daily trips, the distribution of vessel sizes and the distribution of trips over

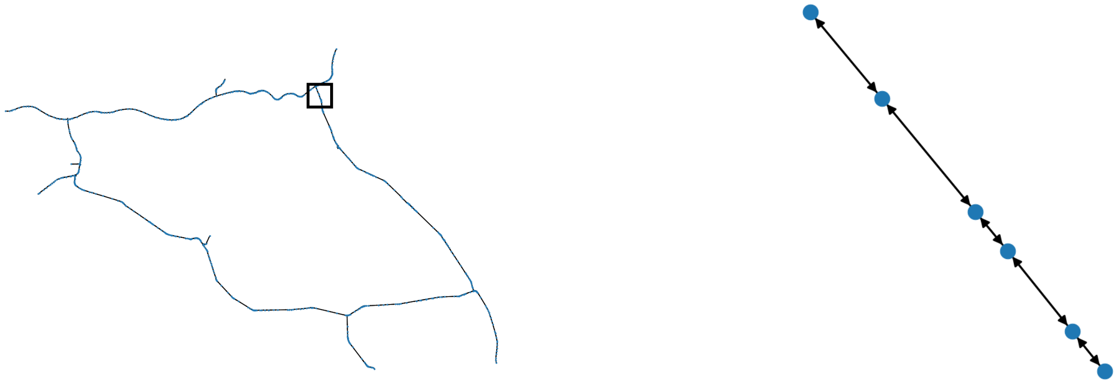

Figure 4.2: Lay-out of the test network and its corresponding location in the original network

the hours of a day. To test if these inputs are translated correctly, they are varied within a constant environment. The network as in Figure 4.2 is also used for this, moving ships from north to south for a period of 100 days.

Varying arrival rates

The first series of scenarios is run to test the influence of the daily arrival rate on the generation of vessels. For this a varying arrival rate from 0.5 to 50 ships per day was used following a Poisson arrival process. No further distinction is made between hours of the day for the input, meaning that there should be no difference between night and day. A summary of these first test scenarios and their results is given in Table D.2. In this table the vessel generator initially performs better at higher arrival rates. This poses a problem, as the daily arrival rates in the case study are in the range of 0.2 to 2.5 ships per day. Running the simulation model multiple times with for these lower arrival rates over 100 days does not results in significantly different results.

Therefore, two other tests are designed to see if the same problems exist if the number of simulated days is increased. In the first one, the arrival rate is constant at 0.5 daily ships and the number of simulated days is varied. In the second test multiple scenarios are tested where the mean arrival rate is varied from 0.05 to 5 with increasing step sizes. In this test, the number of expected ships is kept constant at 5000. The results of these tests are provided in Table D.3 and Table D.4.

From the three tests it can be stated that the generation of vessels is relatively higher when the number of expected vessels is lower. This is important to keep in mind when applying the simulation model to the case study, as the daily arrival rates are in the range of 0 to 2.5 ships per OD-pair. Because each OD-pair will be assigned a separate vessel generator, the number of simulated days/months will need to be high enough to mitigate the problem presented in this section.

Varying fleet compositions

To test whether the correct distribution of vessels is generated, a similar approach as for the arrival rates is used. A total of 1000 ships for each scenario will be simulated with varying fleet compositions. Both the exact input distributions and the exact results are given in Appendix D. These results are also summarised in Figure 4.3 and Figure 4.4. In these figures there is a small variation between the input and output compositions. These variations are considered to be within acceptable margin, and it can therefore be concluded that this part of the vessel generator operates correctly.

Varying time of day distribution

The final series of test for the vessel generator is to check whether the time of day distribution is applied correctly. In this verification step three scenarios with different time of day distributions are used. In each scenario two mean inter arrival times are used of 0.1 and 1 day. Scenario 1 is the same as in

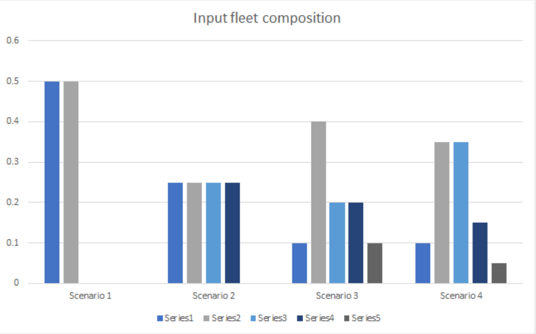

Figure 4.3: Various fleet composition scenarios to be tested in the simulation environment

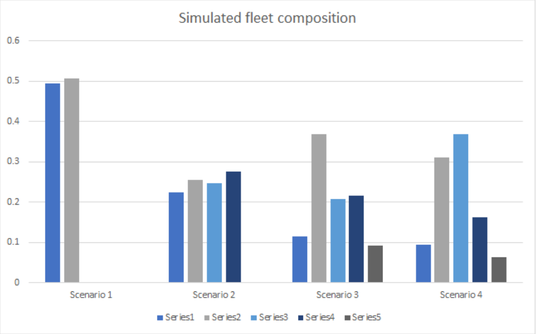

Figure 4.4: Simulated fleet compositions from the scenarios

previous test with the generator, as here the arrival rate is constant over the day. In the second scenario, the time of day distribution is uniform where the arrival rate is 1/48 for the first half of the day and 1/16 for the second half. This distribution was added to test how the generator handles the abrupt change in arrival rate between hours. Finally, the distribution as obtained from the AIS analysis, Figure 3.16, is tested. The results of the tested scenarios are presented in Figure 4.5, Figure 4.6 and Figure 4.7. From these distributions the vessel generation does indeed follow the input values.

4.2.3. Lock functionalities

The locks on the network are a big influence in the performance of inland ships. They are also one of the more complex functions in the simulation model and it is thus important to verify if they work as intended. This is done in three steps with increasing complexity. First it is checked how simulated ships pass the lock and how it influences their trip. Then, it is tested whether the lock functions with ships coming from both sides. Finally, the impact of the operation time function on the lock cycle is tested. Using a distributed function for the operational times is a new functionality in the OpenTNSim, which means it has not been tested before.

In OpenTNSim, a lock can be assigned to the edges between two nodes. The lock function will interact with vessels arriving at either of its nodes and will create events for the vessels corresponding with lock passage process. When creating a lock function between two nodes, at both nodes a waiting area will be created at which vessels will wait their turn before serving. When a ship is served by the lock it operates in three steps. First, a fixed amount of time is taken for the manoeuvring into the lock after which the ship is in the lock chamber. Then, the operational time is determined according to the predetermined normal distribution. This time is taken to convert the chamber and opening/closing the lock doors. Finally, another fixed number of minutes is taken for the clearing the lock entrance and manoeuvring out of the area.

Basic lock operations

The first lock verification step is similar to the test of the basic movement. The same network (Figure 4.2 is used, only a lock is added on the edge in the centre. This corresponds with the lock 'Sluis Empel' and therefore the corresponding mean operation time is used: 16 minutes. Simulating one ship to travel from north to south results in output as presented in Table 4.1. Here it can be seen that the lock converts the chamber as planned and an additional 4 minutes are taken on each side. As mentioned, these 4 minutes represent the time that a ship needs for slowing down, accelerating, and manoeuvring when not in the lock chamber.

Lock operations with two way traffic

To verify if the simulated lock keeps track of the water level and if ships enter the waiting line correctly, another test is run with multiple vessels coming from both directions. In the results of the first lock verification step the water level seems to adjust as planned. This test will show whether this holds for one or more full cycles. In the test vessels are generated at fixed intervals of 30 minutes to see how the waiting line progresses.

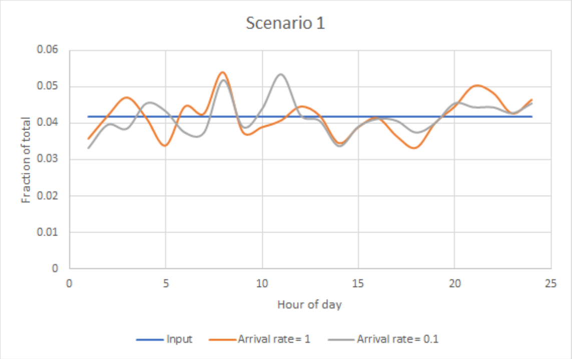

Figure 4.5: Time of day distribution for scenario 1

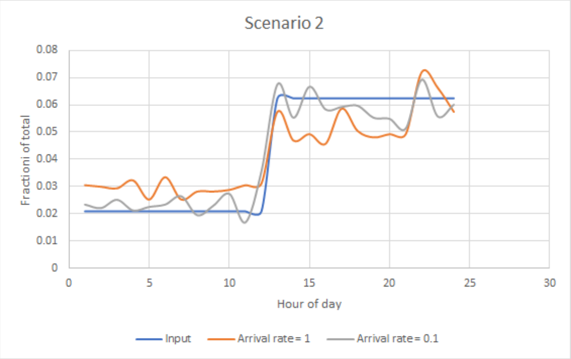

Figure 4.6: Time of day distribution for scenario 2

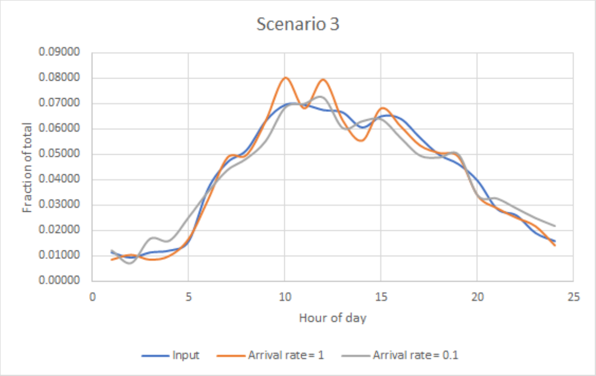

Figure 4.7: Time of day distribution for scenario 3

Table 4.1: Operational log of the lock when simulating one passing ship.

Step	Message	Timestamp	Level	Time difference (min)
1	Lock doors closing start	2020-01-01 13:04:05.5	Node 2	-
2	Lock doors closing stop	2020-01-01 13:08:05.5	Node 2	4
3	Lock chamber converting start	2020-01-01 13:08:05.5	Node 2	0
4	Lock chamber converting stop	2020-01-01 13:24:05.5	Node 1	16
5	Lock doors opening start	2020-01-01 13:24:05.5	Node 1	0
6	Lock doors opening stop	2020-01-01 13:28:05.5	Node 1	4

After running the test simulation, the resulting logs of the lock and the ships were obtained. A part of the log of the lock and one of the vessels logs are added in Section D.3. From the log of the lock, Table D.7, it can be seen that the water level and operational cycle follow the same routine for both direction and work as intended. In Table D.8 the log of the selected ship is given. Here it can be seen that the ship enters a waiting area twice for 12 and 48 minutes each. This means that the ship entered the waiting line after another ship and after that other ship moved into the lock chamber, could shift to the first place in the waiting line. Then another full cycle of 2x24 minutes was needed before the selected ship could enter the lock chamber. This shows that lock function works as intended.

Varying operational times for the lock cycle

The final step in the verification of lock functionality, is checking if the varying distribution time gives the expected results. This is done using three different scenarios where the number of generated vessels is constant, but the mean operating time and the variance are different. The following combinations will be tested:

1. Mean operating time: 16.18 min, standard deviation: 4.58
2. Mean operating time: 32.36 min, standard deviation: 4.58
3. Mean operating time: 16.18 min, standard deviation: 9.16

Each simulation was done using a total of 1000 generated ships moving from north to south, which means that the lock should operate a total of 2000 cycles. Running the simulation with these three scenarios resulted in distribution of operation times as shown in Figure 4.8. The three functions have a shape that resembles a normal distribution, except for scenario 3. In the curve of scenario 3 there is a spike at values around zero, which is a result of the fact that the operation time cannot be lower than 0. The variance in this simulated scenario is much larger than will be used for any of the locks in this research. Therefore, this problem will not extend to later simulations. The mean and standard deviation can also be calculated from the simulations and become as shown in Table 4.2. As can be seen the differences between the input distribution and the obtained one are very similar. These results indicate that the variable lock operation time works as intended.

Table 4.2: Original and simulated lock operation times

	Original		**Simulated**		**Difference**	
Scenario	Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
1	16.18	4.58	16.23	4.50	0.31%	-1.69%
2	32.36	4.58	32.43	4.56	0.20%	-0.54%
3	16.18	9.16	16.04	8.95	-0.88%	-2.33%

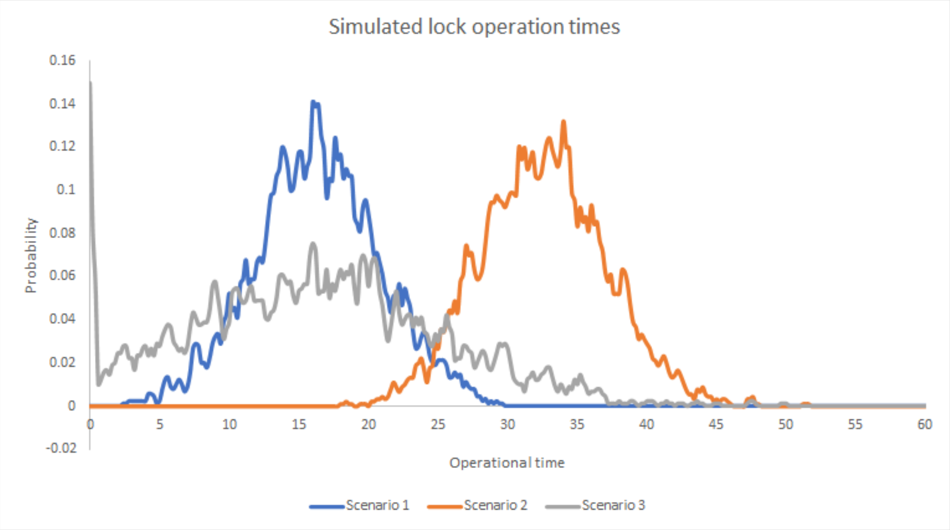

Figure 4.8: Distribution of lock operation times for three different combinations of means and variances.

4.3. Validation using Base Case

The final validation will be done by simulation of the null scenario in the use case. This is the situation as it currently is without obstruction of a waterways section. Applying all the input parameters as defined in Section 4.1.4. The results of this base scenario are then compared with the results from the AIS analysis.

4.3.1. Output OD-matrix

One of the main tests of the model is to see whether the correct amount of ships is simulated on the network between the OD-pairs. Using the OD-matrix in Table D.12, a total of 81 origin/destination pairs will be generated. This is a significant scale up from using one vessel generator as tested in one of the verification steps. After running the simulation model for a full year, for each of the simulated vessels the origin and destination are obtained. To generate the output OD-matrix all vessels are assigned to the output matrix cell. This resulted in the OD-matrix as in Table D.13. As it is difficult to directly see the change compared to the input matrix, a comparison matrix made by dividing the expected values by the simulated ones in Table D.14. From these tables it can be seen that the simulation model generated 7.2% too many vessels. This is not unexpected, as many of the OD-pairs have relatively low arrival rates and in Section 4.2.2 similar behaviour was obtained. Considering only the cells that have values higher than 0, the root mean square error (RMSE), mean absolute error (MAE) and R-squared values were calculated to test the model fit. These are presented in Table 4.3 and are based on the daily arrival rates. These values represent the deviation between the observed and expected values in a different way. The RMSE gives the root of the sum all squared errors and thus punishes large deviations more than smaller ones. The MAE calculates the mean of the absolute differences of the values. It can thus be said that the model has an average absolute deviation of almost 0.1 ship per vessel generator per day. This is seen as an acceptable margin of error and the model will be used with these settings. Finally, the R-squared value of the model fit is calculated. The R-squared is calculated by taking the square of the correlation coefficient of the expected and observed values and returns a value between 0 and 1. An R-squared value of 1 means a perfect correlation and model fit and 0 a total mismatch between the model and the data. What R-squared value is accepted as a good fit depends heavily on the situation. However, an R-squared value of 0.949 is accepted as a good model fit in this research.

Table 4.3: Goodness of fit test results for OD-matrix of the base scenario.

Test	**Value**
RMSE	0.1522
MAE	0.0974
R-Squared	0.949

4.4. Summary & Conclusion

The goal of this chapter was to expand on the methods and tools used in developing the simulation model. This provided an answer to the fourth sub-research question: *”How can the inland waterways system best be represented in a simulation environment?”*. This was done through first identifying the goals, requirements and required inputs. With these aspects known the model was constructed and tested. This section will summarise the findings of this step.

4.4.1. Goals & Requirements

The aim of the simulation model is to calculate the expected change in performance in the inland shipping system. The model should resemble the real-world situation with acceptable accuracy, for which several functionalities are required.

4.4.2. Verification of Functions

The most important functions of the simulation model were tested to see if there if they operated as intended. These functions are the basic movements, the generation of vessels between origins/destinations and the functioning of the lock.

Vessel are generated between origin and destination pairs according to a certain arrival rate. This functioned as expected for high arrival rates, but troubles arise when using low arrival rates. This is mostly a start-up problem and can be mitigated by increasing the number of simulated days. Otherwise, the vessel generator function worked as intended and can be used to generate various fleet compositions at varying rates throughout the day.

The final component that was tested separately were the locks. The vessels passing the lock followed the expected steps both for one- and two-way traffic. Finally, the varying operating time for locks was tested. This was a new function in the OpenTNSim environment and worked as intended.

4.4.3. Validation

Finally, the complete model was checked on whether it functioned as planned by running the base scenario and comparing the results with the input values. The most important aspect to be checked was the scalability of the vessel generation for the entire OD-matrix. The R-squared model fit based on the in- and output matrices was calculated at 0.949, which is seen as a good model fit. Therefore, it can be concluded that the model functions as intended and can be used for the comparison of the two scenarios.

5

Model Application

In the previous chapter a simulation model was designed and tested. The model will now be applied in a case study to show what impact construction and maintenance can have on the performance of an inland waterways system. The simulation model is applied to two situations: a base scenario where no changes are applied and the use case where a waterway section is closed off. Comparing the outcomes of these scenarios will provide an answer to the fifth research question: *"What is the impact of the closure of a waterways section on the performance of the inland waterways system?"*.

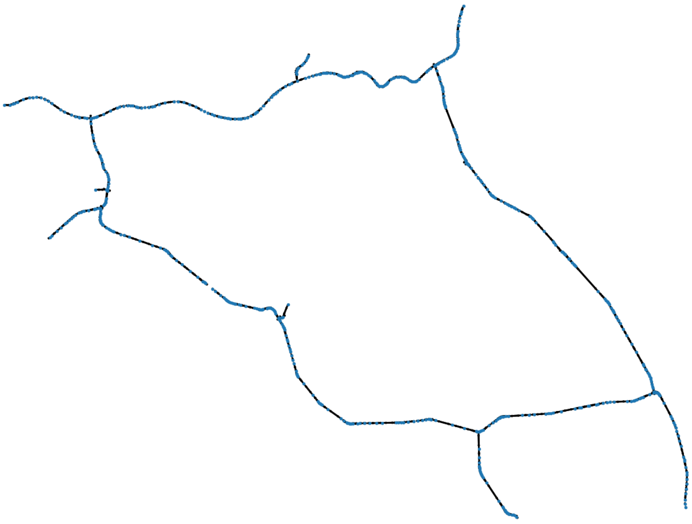

Figure 5.1: The network as used in the simulated use case.

To determine the impact of the change made in the network, the scenarios will be compared on several aspects. The most important one is the generalised cost of transport for the vessels on the network. This corresponds with the first three performance indicators as stated in Section 2.4. Additionally, the traffic intensities at the locks will be compared to see how the changes in traffic influenced the waiting times.

5.1. Scenario Description & General Comparison

For the case study, the only change in input is the network layout. Closing the waterway section at the location of "Sluis II" corresponds with the planned construction works. The other input variables will remain the same as with the base scenario. As mentioned, the simulation will be run for a time span of one year to obtain more reliable results and are then converted back to monthly averages. The new lock that will be constructed at the location has a planned construction time ranging from 7 to 14 months depending on the exact location of the lock. The results obtained from the comparison between the case and the base scenario are then used to calculate the additional costs of transport for the inland shipping system.

To obtain the desired network of the case study, the shapefile as in Figure 3.6 is adjusted with the edge at the lock construction location removed. This results in the network shown in Figure 5.1, where if looked at closely a missing edge can be spotted on the south-western part of the network. This missing edge means that are no movements possible between two adjacent nodes and vessels have find another route.

The virtual runtime of the simulation model will be set at one year to mitigate some of the problems found in the previous chapter with the generation of vessels. The results will then be converted to monthly numbers.

5.1.1. Goal of Scenario Comparison

The goal of the case study is to determine how the inland shipping sector could be affected by construction and maintenance works. To achieve this, a comparison between two scenarios is made to calculate the change in performance. The first scenario, the base case, should resemble the real situation in the system as close as possible. This is based on the results of the data analysis in Chapter 3. The second scenario is used to determine how the system is expected to react to the change in the network. The change in performance will be determined in two categories: the generalised costs for vessels and the waiting times at locks.

If the results of the calculations show that there is indeed a large impact on the vessels and the network in the case study, it is expected that this will hold for other scenarios as well. This would mean that it could be very useful to apply this method to an inland waterways system before planning maintenance and construction works.

5.1.2. Comparison of General Output

Before, the impacts on the performance indicators are studied the general output of the scenarios are compared. As the same inputs have been used for both cases, the general output results should be similar. However, there are several functions with random number generators so there should be some differences in the outcomes. For completeness, a comparison between the fleet composition, OD-matrices and the time of day distribution is made. Large differences in these outputs could also potentially mean large differences in the costs hurting the accuracy of the results.

First, the length of every vessel in the simulation environment gathered. Counting the number of times each length occurs results in the compositions as in Figure 5.2 with the exact percentages in Table E.1. From these results the fleet composition in both scenarios is very close to the input values. There is a slight negative difference in the number of CEMT-IV class ships simulated and expected for both cases and positive for the other ship classes. This might result in a slight underestimation of the overall costs but is not seen as a major problem.

From the arrival times of the simulated vessels, the time of day distribution is made for both scenarios. This resulted in the curves shown in Figure 5.3. The generated curves appear to generally follow the input. However, there are significant deviations from the expected curves meaning that there could be a significant impact on the simulation results. To determine the goodness of fit with the input results the root mean square error, mean absolute error and R-squared values are calculated for the two scenarios. These result in the values as presented in Table 5.1.

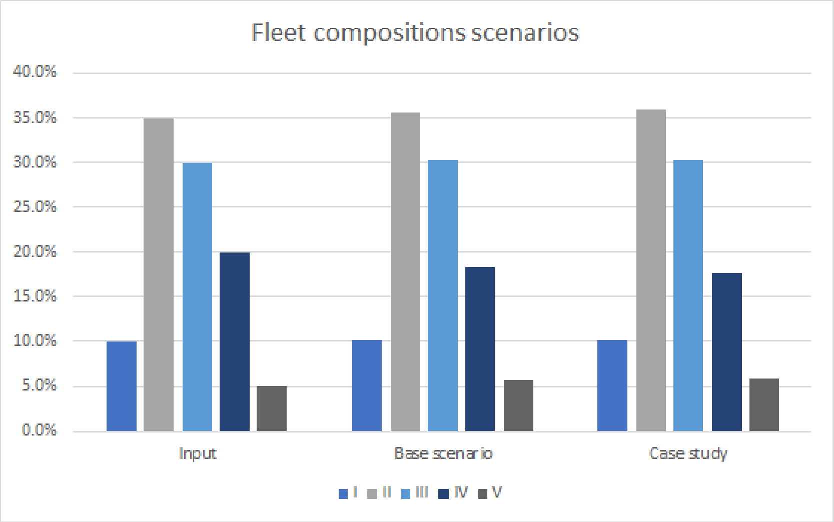

Figure 5.2: Simulated vessel sizes in the scenarios compared to the input values.

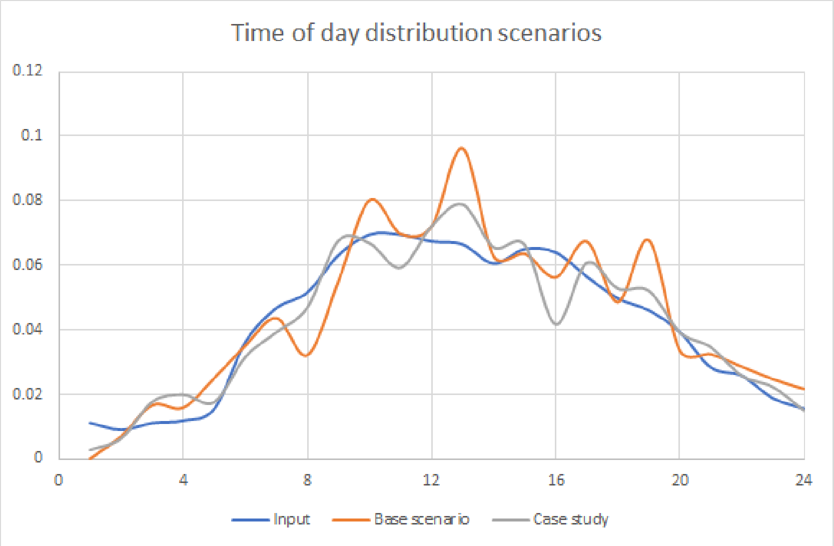

Figure 5.3: Simulated time of day in the scenarios compared to the input values

5.2. Vessel Performance Change

To give an indication of the impacts of closing a waterway on the vessels, the costs are estimated. The generalised cost of transport for the vessels on the network is based on the distance, time and reliability costs as described in Section 2.2.2. In this section the results of both scenarios for these values will be compared. Together these result in the estimated total monthly cost increase for the vessels within the system, which could be used to make an informed trade-off when deciding what the best construction or maintenance strategy is. All three cost components are also discussed separately to determine if they are indeed influential on the overall costs made by ships and if they change between scenarios.

5.2.1. Fuel Consumption

The first of the cost components consist of the fuel consumption. From the distances travelled and the speeds of vessels during the simulation the energy use in kWh is calculated. This can subsequently be converted to the specific fuel in kg as explained in Section 2.2.2. Applying this method results in the numbers as provided in Table E.2. To compare the outcomes of the two scenarios this can also be presented as in Figure 5.4 and Figure 5.5. From these results it can be seen that there is an increase in the overall fuel consumption of 18%.

Table 5.1: Model fit indicators for the simulated number of vessels over the times of day. Values based on ships per day.

	RMSE	MAE	R-squared
Base scenario	0.36	0.26	0.835
Case study	0.25	0.19	0.896

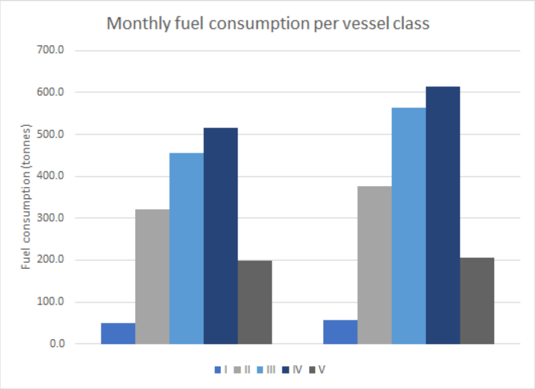

Figure 5.4: Monthly fuel consumption in the base scenario and use case per vessel class.

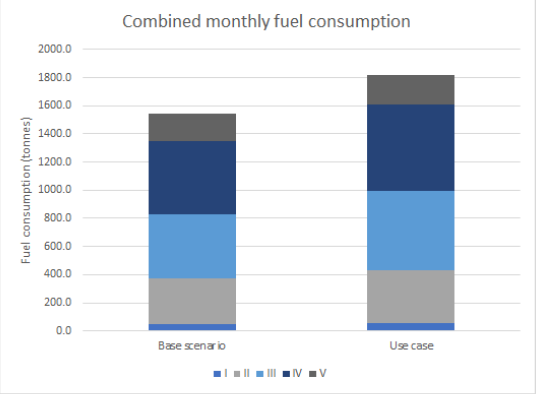

Figure 5.5: Monthly fuel consumption in the base scenario and use case stacked for comparison.

This fuel consumption is mainly calculated from the distance travelled by ships and the energy required by the engine to propel the ship with that size. For each vessel size class one value was assumed. Additionally, the fuel use varies slightly with the age of the engines used. This could not be obtained from the AIS data and therefore one value was assumed here as well. Finally, the fuel consumption is also determined by the speed at which vessels travel and how much cargo they carry. These values were also assumed to be constant for each vessel type. The combination of all these assumptions means that the fuel use approximates the actual fuel use by ships on the network.

Overall, an estimated increase of 18% in total fuel consumption for ships in the system is a significant increase. When applying this model to other inland waterways systems this number could change as it is mainly dependent on the distance sailed by ships. This increase of fuel consumption in the case study does mean that must be considered when analysing other systems.

5.2.2. Time in the System

The total time spent by ships in the system can be readily obtained from the simulation model results. This resulted in values as in Table 5.2. Here it can be seen that the average time in the system increased by an average of approximately 40%. This is a significant increase. Compared to the fuel consumption, the time spend in the system has increased even more.

Table 5.2: Time spent in the system per vessel trip and totals per month.

	Average per ship (h)		**Total per month (h)**		
CEMT	**Base scenario**	**Case study**	**Base scenario**	**Case study**	**Change**
I	4.64	6.37	486.9	645.6	137.4%
II	4.38	6.06	1612.2	2212.7	138.4%
III	4.07	5.95	1273.6	1848.6	146.2%
IV	4.03	5.66	852.9	1195.1	140.3%
V	4.43	6.13	260.5	319.7	138.4%
Total	4.25	5.98	4486.0	6221.7	140.8%

The time spent by vessels in the system is a combination of three factors: the distance travelled, the sailing speed and the time spent at locks. The distance travelled as calculated is expected to be fairly accurate as the network closely resembles reality. As mentioned above when discussing the fuel use, the speed of vessels was assumed to be constant for every vessel class. Therefore, the time in the system might be slightly different. The time spent at locks is based on the operating time and the waiting time. Of these, the operating time is expected to be fairly accurate, because this was based on results from the AIS analysis. The waiting time is however less certain, because it was not possible to verify these values with AIS. Overall, the accuracy of the time spent in the system is mainly dependant on whether the calculated waiting time is valid.

5.2.3. Waiting Time

The final performance indicator for inland vessels is the waiting time for locks. Only the time spend waiting and not the time within the lock chamber itself are considered for this variable. The time in locks is seen as part of the travel time which can be scheduled, even though there is a variation in the operation times. Gathering these times for both the scenarios results in Table E.3 and Figure 5.6.

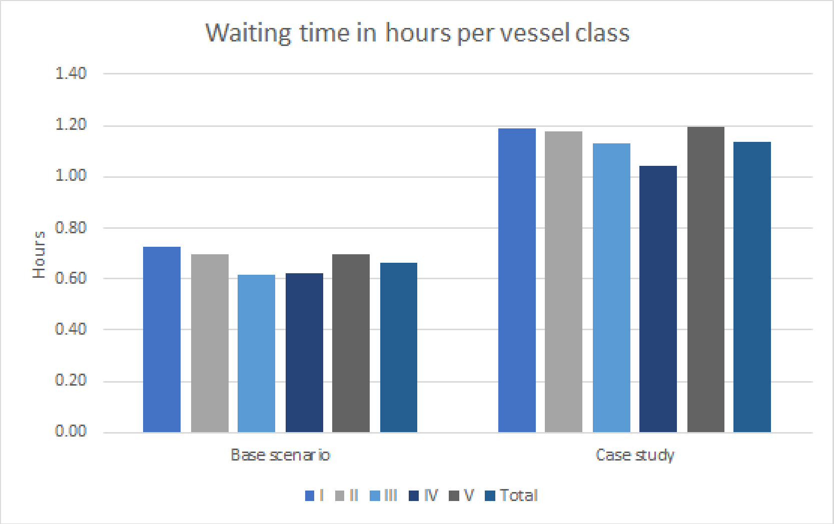

Figure 5.6: Waiting time trip for each vessel class in the two scenarios.

From these results it can be seen that the waiting time has almost doubled in the use case scenario. The average waiting times for vessel on the network increases to approximately 75 minutes, compared to approximately 40 minutes previously. This increase in average waiting time is probably caused by two factors. The amount of traffic at certain locks could have increased by such an amount that the waiting time starts to increase exponentially. Which is expected to have happened at the eastern part of the network. Because there are several operational locks on these waterways the effect is of course larger than for just one lock. Another cause could be that the ships normally travelling over the waterway with the closed of section now simply must pass more locks. On their alternative route, the detour, these ships will have to pass up to six locks as opposed to a maximum of three on the original route. Even at low traffic volumes, there will always be some waiting time at locks. Therefore, there will always be an increase in the average waiting time for all ships when more locks must be passed. Overall, it is expected that both these factors contribute to the increase in total waiting time.

5.2.4. Combining the Costs Factors

The total change in performance for the inland shipping system is measured in the change in total costs for vessels. In Section 2.2.2, the costs related to each cost factor are explained. In short, the values used become as in Table 5.3. With these unit costs and the summarised results of the three previous sections (Table E.4 & Table E.5), the results of the scenarios can be calculated. The final result of this section can be seen in Figure 5.7. Additionally, the calculated values are provided in Table 5.4. The total monthly costs of the system have increased by almost 51%, or by approximately 250.000 euros. Which accounts for around 285 euro per ship travelling through the system. This is a significant change in the performance of inland shipping.

Table 5.3: Direct unit costs per cost factor used for calculation of the change in performance.

Cost factor	Unit	Associated cost per unit
Fuel consumption	tonnes	300
Time in system	tonnes * hours	0.032 - 0.040
Waiting time	hours	300

The calculated total system costs are of course heavily dependent on the values in Table 5.3. Of these values mainly the fuel costs could vary greatly because it is dependent on the oil price (Section 2.2.2). It is expected that time costs are fairly accurate as they are based on an extensive calculation model developed by Hekkenberg (2013). The reliability costs, or costs for unexpected waiting time, are based on a single survey performed by Jong et al. (2014). The fact that a single value was obtained for all inland vessels in all situations, means that a large variability is possible. Overall, the calculated system costs could be very different depending on the choices made for these values.

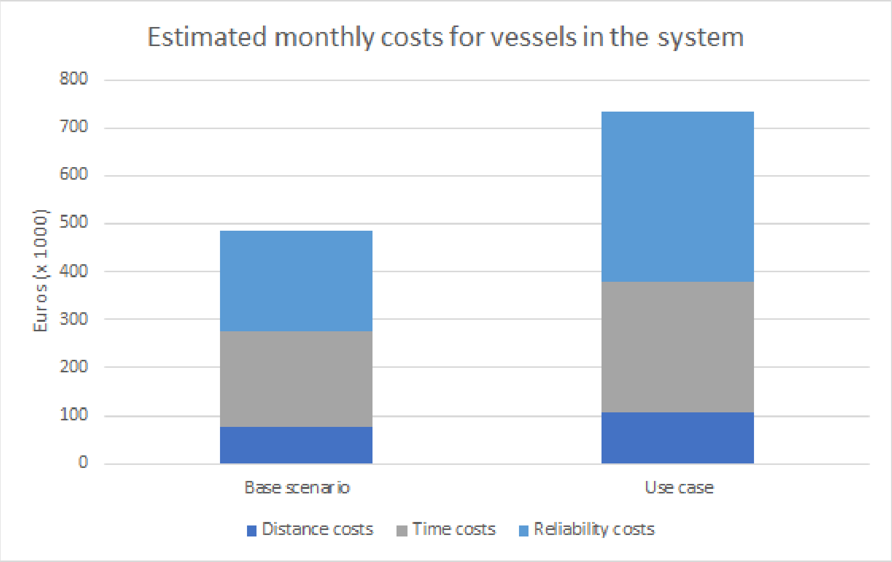

Figure 5.7: Change in estimated operational costs for in the two scenarios of the case study.

The results that were calculated only concern the part of trips that are within the boundaries of the network. For many trips this is only a part of the total journey as they have destinations well beyond these borders. It is therefore not possible to determine the relative impact of the waterway closure on the total costs made by ships. Stating the impact of the closure on the relative performance of inland vessels compared to other transport modes is therefore difficult as well. However, the total monthly costs for the system can be used in the planning of the construction works of the new lock. The quantification of the impact of closing the waterway could be used in the trade-off between construction and external costs.

Table 5.4: Total monthly costs for inland ships in the system in the two scenarios. Rounded to hundreds, for exact numbers: Table E.6

	Distance costs	Time costs	Reliability costs	Totals
Base scenario	77200	198100	210200	**485500**
Use case	106900	271300	354800	**733000**
Change	29700	73200	144600	**247500**

5.3. Waiting Times at Locks

In the previous section the outcomes of the model were used to estimate the impact of changes in the network on the vessels. It is also possible to use these outcomes to focus more on parts of the network. Being able to do so makes it possible to use the simulation model and developed method applicable for more than just estimating the cost increase of ships. Analysing the outcomes of the model with a focus on the locks will give a good overview on where bottlenecks will develop during construction works. This can be important information as it could be used to mitigate the effects of closed off section by applying countermeasures.

In the case study, the time ships spent waiting at locks has increased compared to the base scenario. The waiting times at locks was were also defined as the performance indicators for the network in Chapter 2. In this section the results of the analysis regarding these variables are discussed. The exact numerical results of this can be found in Appendix E, Table E.7 and Table E.8.

5.3.1. Traffic Volumes at Locks

To determine the change in performance of the locks, it should first be determined what the change in traffic volume is. From the simulation model output it can be determined how many times the lock changed the water level. Because there is exactly one ship in the chamber for every operation this results in the number of ships that have passed the lock. In Figure 5.8 the traffic volumes for both scenarios of the case study are shown.

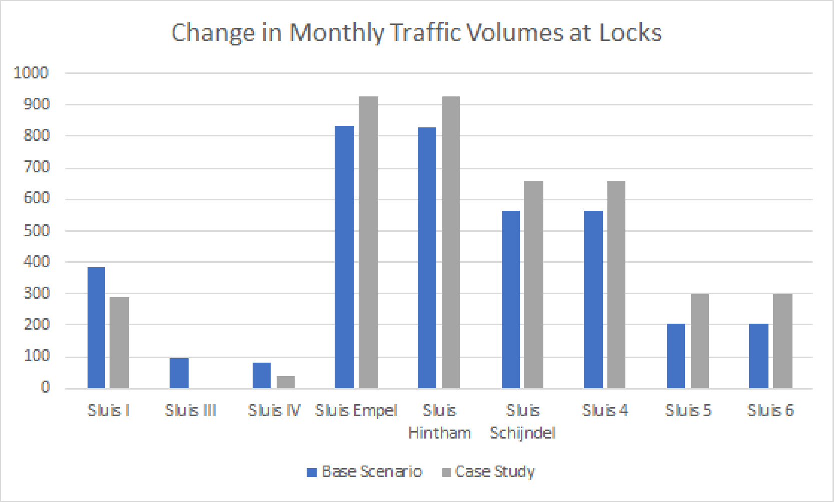

Figure 5.8: The change in traffic volumes between the base scenario and case study for the active locks on the network.

There is a slight shift in the movement of vessels. The locks on the route with the closed of waterways section ("Sluis I", "Sluis III" and "Sluis IV") all experience a similar drop in total traffic volume. The locks on the other route all experience a similar increase in traffic. This complies with expectations, as some traffic is diverted and needs to take a detour. The changes observed in the traffic volumes comply with expectations. Additionally, in the simulation output of the case study, "Sluis III" has no passing traffic. "Sluis III" is located between the closed of waterways section and the origin/destination point that was assigned to that region. This means that there is no route between any origin and destination combination that moves over that edge. Although a decrease to zero might not be expected in reality, it will probably approach this number as there is no real destinations for freight vessels on the waterways section between "Sluis III" and the construction site.

5.3.2. Average Waiting Times for Locks

Knowing the change in traffic volumes at the bottlenecks of the network on itself does not directly mean that the congestion can be predicted. For this reason, the simulation model includes the locks with varying operating times. Knowing the expected waiting time for locks can be valuable information as it makes it easier to effectively apply countermeasures should they become too large.

In the previous section, on the performance change of vessels, an increase of approximately 70% in total waiting time for the vessels in the system was observed. When comparing this to the change in traffic patterns presented above, it can be expected that the locks on the eastern route of the network have experienced an exponential growth in waiting times. To verify this, for each lock the total amount of time spend by vessels in the queue was gathered. Dividing this by the number of passages gives the average waiting time at each lock in the two scenarios as shown in Figure 5.9.

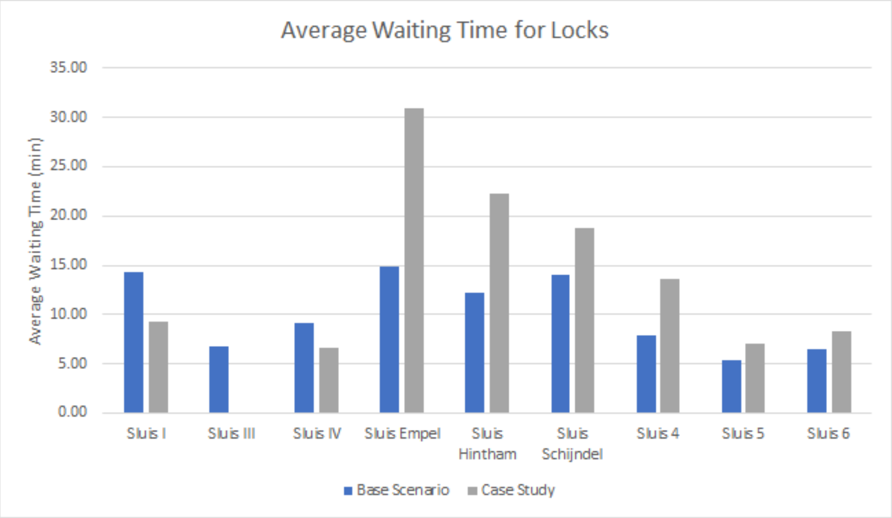

Figure 5.9: The average waiting times for vessels at locks on the network in the base scenario and case study.

In the base scenario, all the average waiting times are within the range of 5-15 minutes even for the locks with a relatively large number of monthly passages. In the average waiting times from the case study, it can be seen which locks have seen an increase in activity. Comparing the traffic volume changes in Figure 5.8 with the change in average waiting time in Figure 5.9, it can be seen that the relation between these variables is not linear. Especially at ”Sluis Empel” and ”Sluis Hintham” the increase in traffic has resulted in a large increase in waiting times. At the other locks on that same route, the effect of traffic increase appears to be limited.

5.3.3. The 90% Certainty Value for Waiting Time

The second performance indicator for the locks was the 90% confidence value for the waiting times. This additional parameter can be used to give better insight in how the plannability of vessels is impacted by changes on the network.

The 90% values can be calculated from the list of waiting times for each lock and result in the values as shown in Figure 5.10. The values for each lock in either scenario is shown, with the base scenario on the left with the lighter colours and the case study on the right. The stacked columns represent the 90% confidence values. The lower part of each column represents the average waiting times.
In Section 2.3.1 it was determined that the 90% value is expected to react more to changes in traffic intensity than the average waiting time. This is mostly confirmed by the results from the simulation model. However, there is some variation in effect between the locks. For the locks that have low average waiting times in the base scenario, the change is relatively small in the case study as well. Even for ”Sluis 5” & ”Sluis 6” the 90% waiting time has increased by 10-20%, while the traffic volume has increased by approximately 30%. Especially ”Sluis Empel” appears to be close to its practical capacity as 10% of all passing ships must wait over 85 minutes. It would be expected that the same behaviour would arise at ”Sluis Hintham”, as they have the same amount of traffic volumes and similar operation times. However, here the increase is significantly smaller. This means that there are more factors that

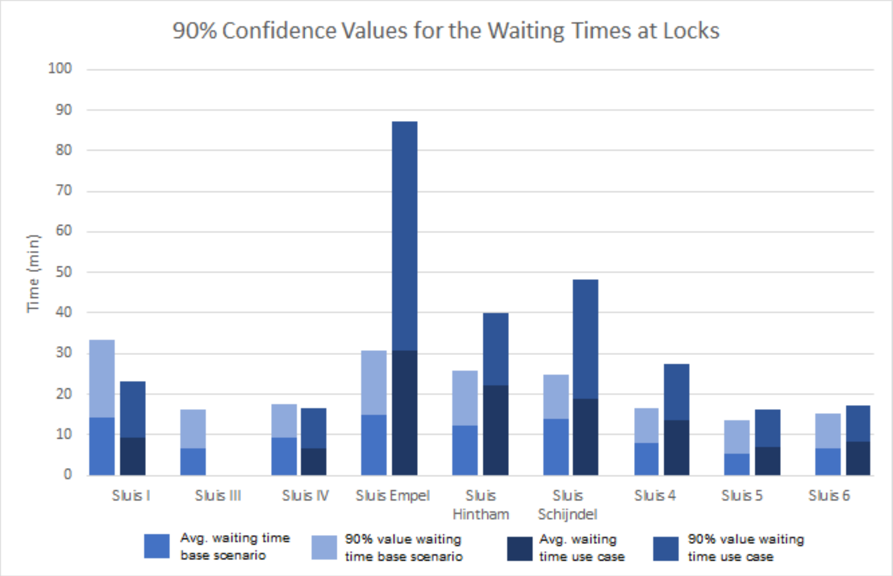

Figure 5.10: The 90% confidence values for the waiting times of vessels at locks on the network in the base scenario and case study.

influence the waiting times.

One factor that should be considered while looking at the difference between the locks is that there is a difference between operational times of locks and how they are distributed. The simulated operational times with their variance are included in Table E.7 and Table E.8. The values for all locks are similar in both cases and are close to the input values that were obtained from the AIS analysis. The operational time directly influences the time ships must wait when in the queue. Additionally, a larger variance should also increase the chance of extreme waiting times which in turn is important in calculating the 90% values.

Another aspect that might influence the waiting times is the sequence of the locks. All the locks that were studied are on one of two waterways. This means that a ship passing over the waterway must pass every lock in the same order. If traffic volumes are high enough, this could result in a certain rhythm of ships travelling between the locks. This in turn could result in lower waiting times for locks in between other locks on the same waterway. This would explain to some extend the difference between ”Sluis Empel”-”Sluis Hintham” and ”Sluis Schijndel”-”Sluis 4”, which are in most senses like each other. It is difficult to determine from this research how this effect would translate to reality. The rhythm effect is expected to be higher in a simulation environment, because in a simulation there is less variation in a lot variables and parameters.

Overall, the results from the simulation indicate that there is a significant effect on the performance of the locks on the network in the case study. This is caused by a shift in traffic that is quite small in absolute values. Based on these results, it would be advisable to apply the method developed in this research on situations where maintenance is planned as well.

5.4. Summary & Conclusion

To answer the final research question: *”What is the impact of the closure of a waterways section on the performance of the inland waterways system?”*, the simulation model was applied in a case study. In this case study, two scenarios were compared: the base scenario that is based on the actual situation on the network and the scenario where a waterway is closed off. This provided the change in performance measured in the performance indicators for vessels and the network. This performance change in the case study, indicate where the impact of the waterway closure can be most severe. In this section the main findings are discussed in two parts: the impact on the vessels and the impact on waiting times at the locks.

5.4.1. Change in Vessel Performance

The impact for vessels was determined by calculating the change in operational costs. This was split into three costs factors based on the performance indicators: distance costs, time costs and reliability costs. These costs calculations were used to determine what aspects of operating a vessel were impacted most. For the case study, the following results were found:

- **Distance costs** - The distance costs are based on the fuel use. In the case study the fuel consumption within the boundaries of the network increased by approximately 18% compared to the original situation. This increase is mainly the result of ships having to take a detour within the system.
- **Time costs** - The time costs are based on the total time spent in the system multiplied by the cost per time unit. The time spent in the system consists of two parts. The time spent sailing and the time spent at locks. In the case study, this increased by approximately 40% compared to the base scenario.
- **Reliability costs** - The reliability costs are based on the time spent waiting for locks as this is the time that cannot be calculated when planning a trip. On average, the time spent waiting for locks increased by 35 minutes or 70% per vessel. This increase is an interesting result, as the traffic volumes in the case study are not very high compared to many other parts of the inland waterways network in the Netherlands.

The total costs increase in the case study was estimated at about 250 000 euros per month for the vessels. This value was based on three cost variables mentioned above and gives an indication of how big the impact is on the vessel companies in the system. It should be noted that the value is strongly influenced by several assumptions made for each cost variable. It is therefore not advised to directly use this value, but rather use it as indication of the order of magnitude. Of the cost variables, the waiting time was the biggest influence on the change in performance.

5.4.2. Waiting Times at Locks

The output of the simulation model can also be used to analyse the impacts of closing a waterway on the congestion at the bottlenecks of the network. Knowing what parts are affected most, will make it easier to apply countermeasures effectively.

The impact of the closed waterway on the waiting times at locks was calculated in two parts: the average waiting time and the 90% certainty value. The change in traffic volumes at the locks resulted in an overall increase of waiting time, but the impact varies significantly between locks.

- **Average waiting time** - The average waiting time at locks increased for all locks on the detour route and decreased for the locks on the waterway with the closed of section. Especially the locks with high traffic volumes had relatively large increase in average waiting time.
- **90% certainty waiting time** - To give a better indication of the plannability, the 90% confidence values are used. The changes in traffic volumes appeared to be of greater influence on this variable for the busier locks. For the locks with a lower number of passages the impact of changes in traffic volume on the 90% value were relatively smaller than on the average waiting time.

Overall, the results from the case study indicate that a small shift in traffic over the network can results in much larger waiting times. The case study was performed on a network section that has relatively low traffic volumes compared to other parts of the inland waterways. This means that it could be worthwhile to apply the method developed in this research when planning other construction and maintenance projects.

6

Discussion of Methods & Results

In the previous chapters, the steps taken in answering the sub-questions were explained. In answering these questions all the parts relating to main research questions were gathered. In this chapter the methods and assumptions used in the research steps are discussed to give an overview on their advantages and limitations. One of the goals of this research was to develop a method that could be used in determining the impact of the closing of waterways section. It is therefore important to provide some perspective on the chosen methods and how they could influence the outcomes.

This chapter is structured to follow the previous chapters in this report. First, the methods and outcomes of the AIS analysis are discussed. Then, the limitations and characteristics of the simulation model are treated. Thereafter, the validity of the results of the scenario comparison and their applicability are explained. Finally, a summary of the findings of this chapter is given.

6.1. Analysis of AIS Data

Getting an accurate overview of the actual traffic situation was instrumental for the simulation input. Using AIS as data source to analyse the network and traffic was a relatively new method that had not been used like this before. AIS can be used for many different aspects of this analysis which makes it an interesting tool. There are however some limitations that were found, and the accuracy often appeared to be lacking.

One of the general downsides of AIS data is that every vessel track consists of many points resulting in a large data set. This meant that data of only three months was used for the analysis. This means that there could be seasonal or temporary effects influences the outcomes of the analysis. To try and mitigate these effects, the first three months of 2018 were chosen. During this period no abnormalities could be found for the studied network or the inland shipping sector in general.

6.1.1. Examining the Lock Areas

The locks on the network were considered crucial components with a large impact. Analysis of the actual functioning was therefore also important. AIS provided an interesting tool in this case. With AIS it could be determined that the operating times can be different for locks that are similar in size. Additionally, it was found that there is quite a variation in the operating times of locks. This means that there is an increased probability of waiting times compared to locks with fixed times. The variation in operating times that was obtained from AIS was higher than expected for several locks (Figure 3.9). Most of the locks on the studied network have a stable water level difference between their two sides. This means that outliers on the lower side are unlikely as there is a minimum amount time required to level the water in the lock chamber. However, each lock that was studied has these outliers for the operating time. Outliers on higher side of the operating time can be more easily explained. There are several scenarios possible where a ship spends more than the usual time within the lock chamber, like a broken engine or problems with the lock equipment.

From the AIS lock analysis it was obtained that the distribution of operating times resembled a normal distribution. It was decided to use this distribution as it was also easy to implement in the simulation model. However, this distribution has a tail on either side of the mean. For the locks in the simulation this would means that a negative value for the operating time is possible as well. Because this is not realistic, a minimum value of zero was set which has a small impact on the simulated distribution. There are of course other distributions that do not have this characteristics and that could be a better fit for this problem.

The use of AIS proved to have limitations in analysing the lock operations in general. Efforts were made to determine how ships move and spend their time in the lock approach areas. This was done through assigning sailing statuses to parts of a vessel track moving through the lock area. This gave improbable results for the waiting times when expanding the method to more than one ship. One of the expected reasons is that lock approach areas are used for temporary or overnight stays as well. Because the waiting times are calculated in the simulation model as well, it was decided to leave this part out of the analysis. Having the waiting times from AIS would have been a good tool to validate the simulation model later in the research.

6.1.2. Translating Vessel Movements to an OD-matrix

Another new application of AIS was to determine the specific daily/monthly traffic between areas along the network. Creating an OD-matrix with twelve different allows for precise simulation of traffic. However, the OD-matrices obtained from the analysis showed some limitations of the method. Depending on the cut-off time used, there is a large variation in the number of observed trips between OD-pairs. Additionally, a lot of traffic that seems to stay within one area. This varied per obtained matrix but ranged up to 45% of total trips.

Because it was not possible to say which matrix was the best fit, a check was done using another method that is expected to be more accurate. By creating virtual counting points, it was possible to compare how much traffic passed. This could be compared to the expected traffic from the OD-matrices. Based on this comparison it was obtained that the matrix with the highest traffic volumes was still an underestimation.

Another verification step using a different data source was done to test the accuracy of the method using counting points. From this comparison it was obtained that the counting points method probably underestimates the number of trips observed as well. Overall, this could mean that the OD-matrix used is an underestimation of actual traffic volumes. This is important to consider when looking at the results obtained later in the research.

6.1.3. Possibilities of AIS

With AIS all parts of the inland waterways network are covered because ships send messages whether they are moored or sailing. It is therefore possible to analyse all kinds of aspects of the inland shipping system. In this research the focus has been on the locks, the origins/destinations of trips, the fleet composition, and the time of day ships travel. There are several other applications that could be interesting, like analysis of vessel speeds on various waterway sections or more extensive route analyses.

6.2. Limitations of the Simulation Model

When developing a simulation model there are several choices that must be made that could influence the outcomes and results. There is often a trade-off between model complexity or similarity to reality and ease of use or applicability.

6.2.1. Low Traffic Volumes between OD-pairs

While testing the vessel generator function, it was found that it had difficulty with low arrival rates. This proved a problem as there were several origin/destination pairs in the case study that have a low arrival rate. By running the simulation for a longer time this problem could be mitigated, but there remained an overestimation of traffic volumes at low rates. Overall, the model fit was determined to be accurate enough to determine the main effects in the research. But this means that the simulation model is less usable for situations with low traffic volumes.

6.2.2. Single fleet composition & time of day distribution

While setting up the simulation model it was decided to use a single fleet composition and a single time of day distribution. This was done to decrease the complexity of the model, but it also means that some unrealistic trips are simulated.

Not all waterways of the network have the same allowed ship size. By using one fleet composition it was not possible to have size restrictions on the waterways. This should result in an underestimation of the average vessel size for some trips and an overestimation for others. It is expected that these level each other out to some extent. It does however add another uncertainty in the results.

The variation in time of day distributions for different parts of the network was considered small enough to justify using just one distribution in the simulation model. Additionally, in the verification of the time of day functionality it was found that time of day distribution of the model varies slightly for each run. Meaning that using different distributions did not add a lot to the accuracy of the model.

6.2.3. Scalability of the Model

The system that was reproduced in the simulation model is considered a network with relatively low traffic volumes. Nonetheless, the computation times increased significantly with increased run times. Adding more complexity or variables is expected to have a further negatively influence on this. Applying the model to other parts of the inland waterways network with higher traffic volumes or more origin/destination areas is also expected to increase this further. This means that there could be some problems with the scalability of the developed model.

6.3. Results from the Simulation

From comparing the two scenarios, the changes in values the performance indicators were calculated. For both the vessels and the locks on the network the results are based on some assumptions that should be considered before using them.
First, it should be noted that the traffic volumes used as input for the simulation model are those of 2018. The demand for inland shipping can vary throughout the years, as it is influenced by external factors like droughts or economic downturns because of pandemics.

6.3.1. Calculating the Costs

In calculating the change in total costs made by vessels in the system, fixed values were used that resulting in a single value for each cost factor. These were obtained from literature and could be different over time and per situation. The total costs per scenario could therefore variate significantly as well. However, it does provide an insight in the order of magnitude of the impact on the costs made by vessels and companies.

The cost of marine fuel that was used, is based on recent prices. As the oil price fluctuates significantly, it could be that this changes in either direction in the coming months or years. The costs for time and reliability are expected to be more constant but could change over time as well.

6.3.2. Lock Results

With a shift of vessels movements over the network the waiting times at the locks changed as well. In general, the behaviour of the waiting time parameters at the locks could be explained by the exponential effect represented in the curve in Figure 2.5. There are however differences between the locks that appear to have other causes. One of these causes could be a certain rhythm effect for locks in between other locks. Another could be the variation in the operating times.

In the simulation model, it was assumed that only one ship fits in the lock chamber at once. In reality, there are situations possible where two or more smaller vessels can pass at the same time. For locks with low traffic volumes this effect might be quite small. However, for locks with a high number of passages and waiting times, this could have significant effect.

The waiting times that were a result of simulating the base scenario could not be verified, because it was not possible to obtain the waiting times from locks. This would have given a lot of insight in the reliability of the results. Especially since the waiting time proved to be the largest cost factor for vessels.

6.4. Applicability of Methods & Results

The results obtained in the steps of this research could have an application in the planning and decision-making process of construction works. Additionally, the overall method, or parts of it, developed in this research might be applicable in similar situations or research projects.

6.4.1. Functionalities of simulation model

The simulation model was developed using the open-source toolbox of OpenTNSim. Previous graduation projects have also used and developed various functions of this package. This research expanded the lock function of the toolbox by adding an option to vary the operating time of the lock. Additionally, a method was developed to translate an OD-matrix to a set of vessel generator functions that might prove usable for other research projects as well.

6.4.2. Trade-off for construction planning

The cost increase for inland vessels during construction work at "Sluis II" were estimated at approximately 250 000 euros per month. The construction works are expected to result in the waterway being closed for a period of eight to fourteen months depending on exactly how and where it is planned. The obtained number could be used as consideration when making this decision. Then, it should of course be kept in mind that this number is an estimation and could be different in reality.

6.4.3. Identification of bottlenecks

In addition to providing a cost estimation, it was obtained what locks are expected to be impacted the most by the new situation. This gives an indication of where measures could be applied to help mitigate the problems caused by the rerouted traffic.

6.4.4. Impact on Modal Split

The change in performance for vessels in the system was calculated in terms of costs. It could be possible that when the costs for inland vessels increase, the competitive position of inland waterways transport decreases. This could have secondary effects on the use of inland vessels if the situation lasts for a prolonged time. If the costs increase is high enough, the mode of transport chosen by companies in the region could shift more towards road transport. This is an undesired effect for the Dutch government as the negative external effects of road transport are higher.

It is difficult to calculate the total change in competitive position for inland shipping in the performed case study, because only this part of the waterways network was studied. This means that often a large part of the trip made vessels is made outside the system borders. Therefore, a comparison between modes would require a much larger scope and accurate statistics on the transport demand.

Effect studies like this research are usually aimed at the long-term effects of measures. The impact of maintenance and construction works are temporary, which means that it is difficult to determine what the long-term consequences are. It could be that there is a temporary shift towards road traffic during construction of "Sluis II" and that the situation returns to normal when the project is finished.

6.5. Summary

In this chapter the advantages and limitations of the methods and results of this research were discussed. This provided insights in the accuracy and applicability of those methods and results. These can be summarised as follows:

- **AIS analysis** - It can said that using AIS for an inland waterways network studies showed promising results and provided insights into several aspects of the system. There are however concerns regarding the accuracy of the data and the traffic volumes obtained. The AIS analysis formed the basis for the inputs for the rest of the research and inaccuracies could therefore have an impact on later results.

- **Limitations of simulation model** - In the simulation model some of the inputs were simplified to reduce the model complexity. Although it is expected to have little impact on the results, it does add some uncertainty.
- **Simulation results** - The costs that were calculated for the inland vessels are dependent on three variables for which the values were obtained from literature. These are a great influence on the total calculated costs.
- **Applicability of results** - The results obtained in this research mainly provide an indication on the additional costs for the system and possible development of bottlenecks on the network.

7

Conclusions & Recommendations

In this final chapter, the conclusions of this research are given. Thereafter, recommendations for future research are given.

7.1. Conclusion

Inland shipping is an important mode of transport on which many companies rely for their logistic operations. Inland ships are dependent on the network of available waterways and disruptions in this network can have a significant impact on the movements of inland vessels. This can in turn strongly influence the costs made these ships. In the coming years a lot of maintenance and construction projects are required to keep the Dutch waterways functioning properly. This research aimed to develop a method that can help determine the impacts of such projects on the performance of the inland shipping system. The main research question was therefore formulated as:

What are the effects of temporary closing a waterways section on inland waterways transport?

By answering this question for a case study, a working method was developed that consists of several steps. In each step it was important that it could be easily used on other cases as well. Analysing an inland waterways system required three steps. First, a literature study was used to determine how performance of the system can be measured and what components are important to model. Second, an analysis of the current situation in the system is done using a combination of data sources. Finally, a simulation model was developed that can be used to imitate the inland waterways system to predict the impact of closing a waterway.

The case study that was used concerned an inland waterways network in the south of the Netherlands, where one section of the network will be closed off due to construction works. On the network, there is a detour possible for ships normally travelling over the closed off section. However, on this detour there are several locks that could develop into bottlenecks with high ship waiting times.

7.1.1. Modelling the Inland Shipping System

To determine the impact of closing a waterway section, it must first be determined how this can be measured. This can be divided into two categories: performance of vessels and the performance of the network. These were both considered in this research as they provide different insights in the effects.

The performance of vessels can be best expressed in terms of total operational costs. This can be used to calculate the additional cost made per vessel and for the entire system that is studied. These costs or performance indicators can be further divided into three parts:

- **Distance costs** - These are the costs made travelling a certain distance and are determined mostly by fuel expenses.
- **Time costs** - These are a combination of all the fixed yearly and variable time costs like personnel, maintenance and financial costs.

- **Reliability costs** - These are the costs related to the plannability of transport. When ships experience an unexpected delay, it has a negative effect on the transport performance and can be expressed in terms of costs.

The performance of the network is strongly related to the reliability costs of the vessels. It was obtained that the main bottlenecks of the inland waterways network are the locks. A change in the traffic volumes over waterways with locks can have a large effect on the average waiting time for these locks. To gain a better insight in the development of these waiting times in different scenarios, the performance of the locks is studied as well. The performance of locks is measured using two indicators for the waiting times:

- **Average Waiting Time** - The average waiting time for each lock will give an indication of which locks have the most impact on the vessel delays.

- **90% Confidence values for the waiting time** - In addition to the average waiting time, the 90% confidence value is used to indicate the impact on the plannability of freight transport using the waterways. The 90% confidence value gives a better indication of the distribution of the waiting times than the average waiting time.

The effect of changing traffic volumes on the parameters is exponential and a small increase can therefore mean a large increase in waiting times.

7.1.2. Analysing the Vessel Movements

To determine the situation on the network the traffic volumes over the waterways and the characteristics of that traffic should be determined. In this research a method was developed to analyse the system using a relatively new data source in inland shipping research. All freight vessels have an Automatic Identification System (AIS) that sends out a message at certain time intervals. This data is stored and can be used to track vessels moving over the inland waterways network. Because of privacy issues, this data source had not been used very often in the research on inland shipping before. Using this data source proved very useful as it can be used for many different aspects of the system. However, from comparing the outcomes of the analysis it was obtained that there are also some inaccuracies in the data. For analysing an inland waterways system using AIS, the focus was on three aspects: lock operating times, traffic assignment and the fleet composition.

The operating times of the locks on the network were found by determining the time spend by vessels in the lock chamber. It was concluded that the operating times of the locks have a significant spread that appears to resemble a normal distribution. An example of two of these distributions is presented in Figure 7.1. Because of this observation, the locks in the simulation model were also assigned a variable operating time.

The second aspect that should be obtained from AIS was the original traffic assignment. This can be summarised in an Origin/Destination-matrix with average daily trips between areas on the network. This method of creating an overview of traffic between areas can easily be used in the analysis of other network sections as well. From verification with other methods and data sources it was obtained that these traffic volumes were probably an underestimation of actual traffic volumes. However, using this method does provide a more complete overview of traffic movements than methods that use other data sources.

In addition to the volumes, some other characteristics of the traffic can be obtained using AIS as well. The time of day at which vessels travel can also obtained. The time of day is an important factor for the expected congestion on the network. The other characteristic is the composition of the fleet travelling the network was determined. The size of ship influences the cost performance indicators and therefore a distinction is made between five CEMT-classes. The share of each vessel class can be estimated by obtaining the length of vessels travelling over the network.

Overall, several stepwise methods for analysing different component of the inland waterways system were developed that can be used in other case studies as well.

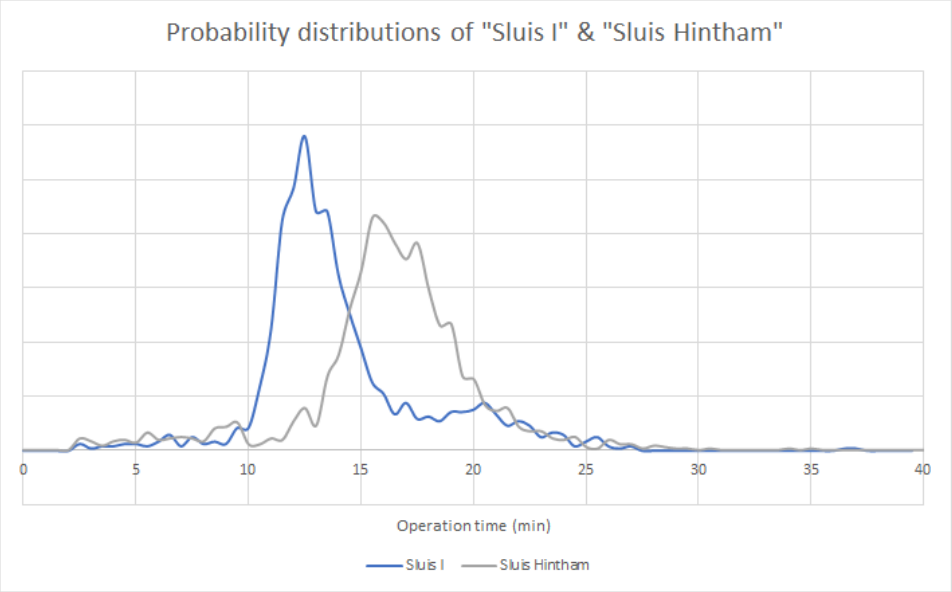

Figure 7.1: Probability distribution for lock I and lock Hintham as obtained from the AIS analysis.

7.1.3. Developed Simulation Model

The goal of the simulation model was to make a tool that can predict the expected change in performance in an inland shipping system. The model should resemble the real-world situation with acceptable accuracy, for which several functionalities were required. The simulation model was built using the open-source toolbox of OpenTNSim in which most of the required functionalities were present. The most important functions of the simulation model were tested to see if there if they operated as intended. These functions are the basic movements, the generation of vessels between origins/destinations and the functioning of the lock.

Vessel are generated between origin and destination pairs according to a certain arrival rate. This functioned as expected for high arrival rates, but troubles arise when using low arrival rates. This is mostly a start-up problem and can be mitigated by increasing the number of simulated days. Otherwise, the vessel generator function worked as intended and can be used to generate various fleet compositions at varying rates throughout the day.

The final component that was tested separately were the locks. The vessels passing the lock followed the expected steps both for one- and two-way traffic. Finally, the varying operating time for locks was tested. This was a new function in the OpenTNSim environment and worked as intended. The developed function for the locks can easily be used in other network studies that use OpenTNSim.

Finally, the complete model was checked on whether it functioned as planned by running the base scenario and comparing the results with the input values. The most important aspect to be checked was the scalability of the vessel generation for the entire OD-matrix. The R-squared model fit based on the in- and output matrices was calculated at 0.949, which is seen as a good model fit. Therefore, it can be concluded that this part of the model functions as intended and can be used for the comparison of scenarios.

7.1.4. Simulating the Effects

The developed simulation model was tested in two situations: the base scenario that is based on the actual situation on the network and the scenario where a waterway at is closed off. This provided the change in performance measured in the performance indicators for vessels and the network, as were mentioned earlier.

The impact for vessels was determined by calculating the change in operational costs. The results

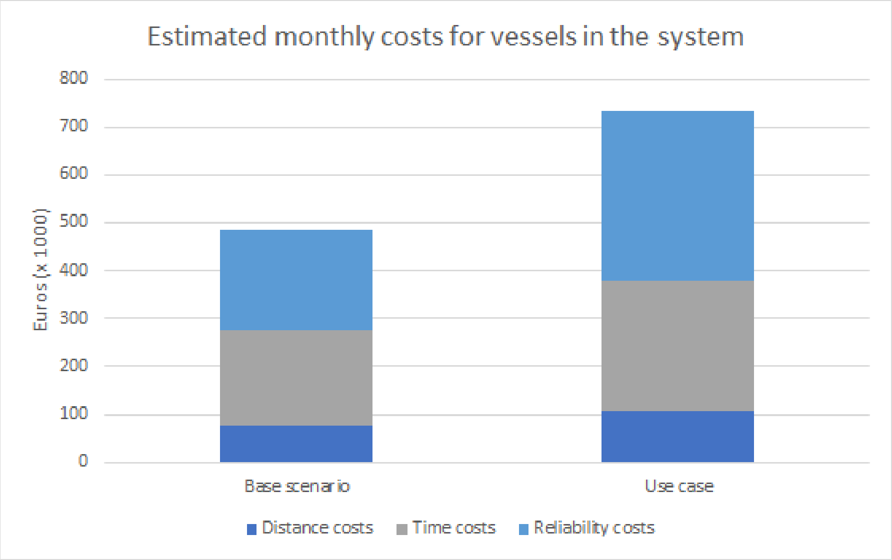

Figure 7.2: Change in estimated operational costs for in the two scenarios of the case study.

of this calculation are presented in Figure 7.2. In the case study the fuel consumption increased by approximately 18% compared to the original situation. The time costs are based on the total time spent in the system multiplied by the cost per time unit. The time spent in the system consists of two parts. The time spent sailing and the time spent at locks. In the case study, this increased by approximately 40% compared to the base scenario. The reliability costs are based on the time spent waiting for locks as this is the time that cannot be calculated when planning a trip. On average, the time spent waiting for locks increased by 35 minutes or 70% per vessel. In total, the additional costs for vessels in the system were estimated to increase by approximately 51%, or 250.000 euros per month. This value should not be directly used in any decision making concerning the construction project as it is based on several assumptions. It does however provide an indication on the scale of the impact on the vessels in the system. When planning construction or maintenance works, it could be useful to consider this impact.

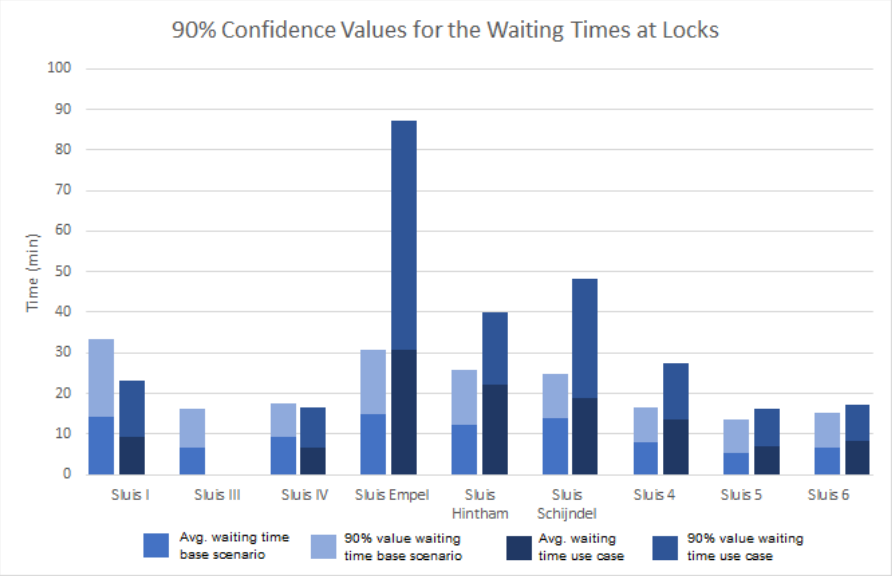

Figure 7.3: The mean and 90% confidence values for the waiting times of vessels at locks on the network in the base scenario and case study.

The impact of the closed waterway on the congestion at certain bottlenecks can be divided in two parts: the average waiting time and the 90% certainty value. The change in traffic volumes at the locks resulted in an overall increase of waiting time, but their impact varies significantly between locks. The results of the performance of the locks are shown in Figure 7.3. The average waiting time at locks increased for all locks on the detour route and decreased for the locks on the waterway with the closed of section. Especially the locks with high traffic volumes had relatively large increase in average waiting time.

To give a better indication of the plannability, the 90% confidence values can be used. The changes in traffic volumes appeared to be of greater influence on this variable for the busier locks. For the locks with a lower number of passages the impact of changes in traffic volume on the 90% value were relatively smaller than on the average waiting time.

Overall, the results from the case study indicate that a small shift in traffic over the network can results in much larger waiting times. The case study was performed on a network section that has relatively low traffic volumes compared to other parts of the inland waterways. This means that it could be worthwhile to apply the method developed in this research when planning other construction and maintenance projects.

7.1.5. Accuracy of the Simulation Model

This research was aimed at developing a method that can be used to predict the impact of construction or maintenance works on the inland shipping system. This method consists of several steps in which decisions were made that can influence the accuracy of the outcomes. Ideally, the calculated change in performance for each variable could be checked using the results of the data analysis. It was possible to check whether the model was able to simulate the correct number of ships between origin/destination pairs. The performance changes found in this research give a good indication of where the impact of closing a waterway can be expected the most. This is especially on the waiting times at certain locks. Overall, the outcomes of the simulation model seem realistic. Although it is difficult to check how accurate the calculated change in each performance indicator is, they are within an expected range.

7.1.6. Final Conclusion

In the developed method, AIS data and a simulation tool were combined to try and recreate the real-world system as accurate as possible. It was found that this can be a useful combination as AIS can be used to eliminate certain assumptions that were otherwise needed as input for the simulation model. However, it was in this research not possible to eliminate all these required assumptions. There are some reasons for this, but most important is that AIS data is messy and needs modifications before it can be analysed. It was determined that using AIS comes with accuracy issues as it seems to underestimate the number of ships on a network. The functions of the simulation model worked as intended and it can be adapted quite easily to other case studies. It can thus be concluded that the developed method can be applied when studying the effects of planned maintenance and construction works, but it is best used to estimate where the impacts are expected to be high rather than to calculate exact results.

7.2. Recommendations for Future Research

The recommendations for future research can be split into three parts. The first part are possibilities for further research using AIS for the analysis of the inland shipping system. The second part concerns the further expansion of the simulation tools and possible applications. Lastly, ideas for comparison with other transport modes are explained.

7.2.1. AIS for Inland Shipping Research

In this research it was found that AIS can have several applications in studying the inland shipping system. Before further research can accurately be conducted, it should be further explored what the limitations and inaccuracies of this data source are. It was found that the traffic volumes from AIS are probably an underestimation of the actual situation on the network. In the production, gathering and processing of the data there could be causes for this underestimation. Further comparison with other data sources like IVS90, or the new IVSNext, will result in a better overall understanding of the limitations of AIS.

There are also more specific applications of AIS that could be further investigated. One of the main steps in this research has been creating an origin/destination matrix to represent the vessel trips between areas on a network. The OD-matrices seemed to underestimate the traffic volumes between areas on the network. The method used in this research assigns a lot of traffic to the main diagonal of the matrices, which means that it seems to stay within one area. This is unlikely and the method could therefore be improved further. Being able to develop accurate OD-matrices could prove very useful for a variety of research topics.

Another application of AIS data in this research was the analysis of the lock passages by ships. It could be very interesting to further investigate the variations of the lock operating times and their possible causes. In this research a normal distribution was used to imitate the observed behaviour of variation in lock operating times. This distribution was chosen because it was applicable in the simulation model. However, a normal distribution has no specified minimum whereas a lock cannot have a negative operating time. It would therefore be interesting to see what the distribution is with the actual best fit to the found results from the AIS analysis. Additionally, attempts were made in this research to analyse the entire lock area without success. This meant that their assumptions were made for the waiting, approach and exit times at locks. If a method is developed that can calculate these other delay components for locks from AIS it could be used to check accuracy of the simulation model developed in this and other research projects. Currently it is not known how accurate the simulation model exactly is with respect to the obtained waiting times.

One final recommended use of AIS that was identified but not examined is the speed of vessels on the waterways. The speed of vessels is dependent on many variables and it could be interesting to see what influences the speed of vessels on certain waterways. This could also be an interesting addition to the developed simulation model.

7.2.2. Further Expansion of Simulation Tools

The simulation model developed in this research made use of functions and tools developed in earlier projects. This toolbox could be further expanded to increase the possible accuracy and applicability.

In this research the locks were a crucial part of the system. The lock module as currently implemented in the toolbox could be further expanded to include more complicated planning of serving sequences. Additionally, the lock function could be expanded by developing an optimisation tool that is able to determine if two ships fit in a lock chamber at the same time. These additions could make the lock function even more reliable.

7.2.3. Determining the Change in Modal Split

The effects of closing a waterway can reach beyond inland shipping. Should the costs for using a vessel increase too much, shippers might decide to switch to another transport mode. This is an undesirable effect as inland shipping is seen as a transport mode with relatively low negative external effects. Determining the impact on the modal split was ultimately left out of the scope of this research because of a lack of available data and time restrictions. Expanding the current method to include a last step in which a comparison is made between different transport modes could be a very interesting topic for further research.

A

Article Version of Report

A Method for Studying the Effects of Infrastructure Maintenance on Inland Waterways Transport Systems

Pieter Groen
Thesis Paper
Msc. Transport, Infrastructure & Logistics
Faculty of Civil Engineering & Geosciences Technical University Delft
p.r.groen@student.tudelft.nl

Abstract

The inland waterways are an important part of the freight transport system of the Netherlands. In the coming years, a lot of maintenance and construction works are needed to keep the network operational. This can temporarily impact the availability of the waterways section which can have negative effects on the performance of inland vessels and the waiting time for locks at alternative routes. In this research a method was developed that can be used to study these effects. In the method AIS data is used to analyse several aspects the inland waterways transport system. Additionally, a simulation model was developed in which the results of the AIS analysis are used to create an accurate representation of the system. The method was applied to case study to determine the applicability. It was concluded that the developed method can be applied when studying the effects of planned maintenance and construction works, but it is best used to estimate where the impacts are expected to be high rather than to calculate exact results.

Key words

Inland waterways; AIS; Traffic analysis; Agent-based simulation

I. Introduction

Inland waterways are an important part of the transport chains of certain ports. Transport over inland waterways accounted for 38% of freight moved in Netherlands in 2017 [1]. Recently, the European Union accepted a proposal for a New Green Deal to tackle the impacts of its member states on climate change. Part of this proposal is the ambition to restructure the transport system in Europe [2]. This includes a shift away from freight transport over roads towards rail and inland waterways. Both rail and inland waterways transport tend to have less negative environmental effects per unit type of cargo moved. Should the Green Deal policies of the European Union take effect, the Dutch waterways will see an even larger increase in traffic volumes.

The capacity of inland waterways is mainly defined by its bottlenecks. These are usually infrastructures such as locks and bridges or changes in the waterways like merging points. Most infrastructure was built in the period after the second world war and is approaching the end of its lifetime. In response to this, the Dutch government plans to invest extra in maintenance and upgrading of crucial infrastructure. Large scale maintenance or replacement of such structures can take several months or even years to complete. Usually, there is more than one way of performing maintenance or constructing infrastructure with respect to the availability of the concerned waterway. Therefore, a trade-off can often be made between the costs of quicker construction and the costs of down-time of the water section. These effects can be congestion and delay at the waterways section if the throughput capacity is reduced. If the section is completely closed, there will be additional costs for ships that have to take a detour if a detour is possible. In turn, this means increased traffic on other waterways with additional congestion as a result. These effects have a negative impact on the attractiveness of inland shipping. Although disturbance due to infrastructure maintenance or construction is a temporary state, during this period there could be severe hindrance with long term impacts on the usage of waterways transport.

Effect studies are a common practice when planning such a project [3]. However, these studies are usually only aimed at the impacts of the finished project. An effect study might not be necessary when a maintenance project is small, and the expected hindrance is low. But when the project duration is long, and the availability of a waterways is severely impacted an effect studies might be worthwhile. In this research a method was developed that can be used to determine the impact of maintenance or construction works on the inland waterways system. The used method consists of three steps. First, a literature study is done to determine how performance of the system can be measured and what components of the studied system are important to model. Second, an analysis of the current situation in the system is done using mainly AIS data. Finally, a simulation model is developed that can be used to imitate the inland waterways system to predict the impact of closing a waterway. To test the method, it is applied to a case study of a network section in the Netherlands. An overview of this network is given in Figure 1.

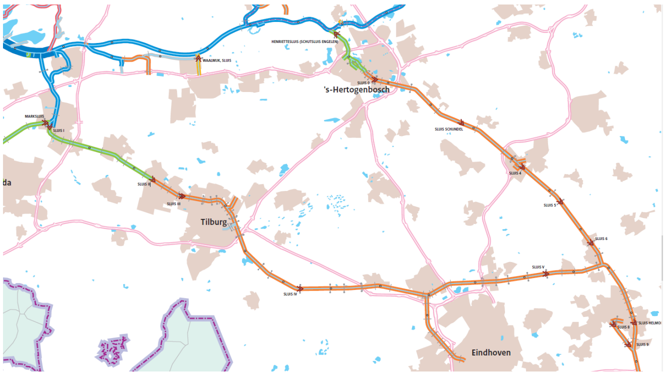

Figure 1: The waterways network in the province of Noord-Brabant that is the subject of the case study. Adjusted from: [4]

II. Literature Review

The first step in developing a method for the analysis of inland waterways systems, was to study its characteristics and determine how the analysis can be approached best. It was examined what parts of the system are relevant when determining the effects. First it was determined what steps are required for analysing transport systems in general. Then, the characteristics of the vessels relating to network analyses are discussed. Finally, it is explained what aspects of the inland waterways influence the capacity and throughput. With the information gained in these sections specific variables are defined that can be used to measure the performance.

A. Modelling of Transport

The inland waterways is a transport system where vessels move goods between areas. In this transport system the vessels are the agents that travel over the network of linked waterways. For the modelling of transport system, an often-used structure is the four stage structure as described by Tavasszy et. al. (2014) [5]. The four stages for are defined as: trip generation, trip distribution, mode choice and traffic assignment. This research focuses only on the final stage of the of the model. The input for this stage is an origin/destination (OD-)matrix for each studied modality [6]. In this research, the historic traffic volumes of inland shipping are translated to an OD-matrix. This approach is called inverse trip assignment [7].

B. Analysing Inland Waterways System

Important part of every transport system are the agents that move between the locations with transport supply and demand. In the inland waterways system these are the vessels. Inland shipping is an important mode of transport on which many companies rely for their operations. Inland ships are dependent on the network of available waterways and disruptions in this network can have a significant impact on the movements of inland vessels, which can strongly influence the costs made these ships [8]. The freight vessels used for inland shipping can be divided into several size classes. The size of a vessel has a strong influence on the operational costs.

The second component in analysing the inland waterways transport system is the network itself. An inland waterways network can consist of many canals and rivers varying in size and shape. For the analysis of transport over the network it is important to know what limits the capacity of a waterway. This capacity is dependent on several factors, but is mostly determined by obstructions like locks, bridges, and bends in the waterway. Especially locks can have a limiting effect on the maximum throughput [9]. Locks have a maximum number of ships that can pass with each passage and the time ships must wait is exponentially related to the traffic intensity at the lock [10]. One of the main focuses in this research is therefore on the delays caused by these hydraulic structures.

C. Measuring the Performance

The effects of closing a waterway on the inland shipping system are divided into two categories: performance of vessels and the performance of the network. These are both considered as they provide different insights in the effects.

The performance of vessels can be best expressed in terms of total operational costs [8]. This can be used to calculate the additional cost made per vessel and for the entire system that is studied. These costs, or performance indicators, can be further divided into three parts: distance, time, and reliability costs. Distance costs are the cost made by sailing a certain distance and consists mainly of fuel costs and will be calculated using the method of J. Hulskotte & R. Verbeek (2009) [11]. Time costs are costs that are the other costs required to operate a ship over time and are calculated using the method of R. Hekkenberg (2013) [12]. The reliability costs are the costs of delays and unexpected waiting times and are calculated using the values as determined by De Jong et al. (2014) [13].

The performance of a network is strongly related to the reliability costs of the vessels. The main bottlenecks of the inland waterways network are the locks [9]. A change in the traffic volumes over waterways with locks on them can have a large effect on the average waiting time for these locks. The performance of locks is measured using two indicators for the waiting times: the average waiting time and the 90% confidence values for the waiting times [4]. The effect of changing traffic volumes on the parameters is exponential and a small increase can therefore mean a large increase in waiting times [14]. Knowing where the impact of changing traffic flows is highest could make it easier to invent and apply possible countermeasures.

III. Analysis of Vessel Traffic with AIS

In this research a method was developed to analyse the system using a relatively new data source in inland shipping research [15]. All freight vessels have an Automatic Identification System (AIS) that sends out a message at certain time intervals. This data is stored and can be used to track vessels moving over the inland waterways network. Because of privacy issues, this data source had not been used very often in the research on inland shipping before. Deceunick et al. (2018) [16] also used AIS to analyse the traffic intensity on a canal and to determine the fleet composition. These analyses are also parts of this research but need to be expanded to fit the larger network with multiple edges and destinations.

Using this data source proved very useful as it can be used for many different aspects of the system. For analysing an inland waterways system using AIS, the focus was on three aspects: lock operating times, traffic assignment and the fleet composition.

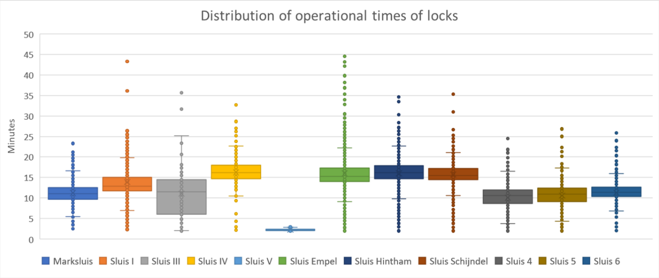

Figure 2: Box and whisker plot of the operating times of locks in the case study

A. *Lock Operating Times*

In the literature review it was determined that navigational locks can be the main bottlenecks of inland waterways. It is therefore important to know how long it takes ships to pass these obstructions. The average time it takes for a ship to pass a lock is mainly determined by the traffic volume and the operating time. Using AIS to calculate the time spend in the lock chamber, the operating times for the locks could be determined. For the locks on the studied network it was obtained that the operating time is variable rather than a constant. This is can be seen in Figure 2 where for each lock the observed operating times are summarised.

B. *Traffic Assignment*

To get an overview of the traffic situation on the waterways network, it must be determined how many trips are made on average between areas on the network. The trips made by vessels over the network can be summarised in an Origin/Destination-matrix. This OD-matrix can also be obtained from AIS by determining the start and end points of each trip.

Because AIS tracks ships throughout their time in the system each observed vessel track can consist of multiple trips. To split the AIS data of each vessel into multiple trips, a new trip is started if the vessel had not moved significantly for a certain amount of time (the cut-off time). Then the origin and destination of the trips could be gathered in the OD-matrix. The time between trips was varied to compare the resulting OD-matrices. Here it was found that this cut-off time had a large impact on the observed traffic volumes.

To determine which matrix is the best representation of the actual traffic situation on the network, an additional method was used. First, shortest path between for each OD-pair was calculated. With the expected routes between the pairs, the traffic in the OD-matrices could be assigned to the network. This resulted in estimated traffic flows on all the edges of the network. Next, virtual AIS counting points were placed on the network. By analysing the number of vessels passing these points, the actual traffic flows on the edges were obtained. The results of both methods could then be compared to determine which OD-matrix resulted in the best fit. For the case study this is shown in Figure 3. Here the calculated flows of three OD-matrices with different cut-off times (2-, 4- & 6 hours) are compared to the flows observed using the counting points (actual). All calculated flows seem to underestimate the number of trips between areas on the network, but the lower cut-off time is the best fit. Therefore, this matrix was used as an input for the simulation model.

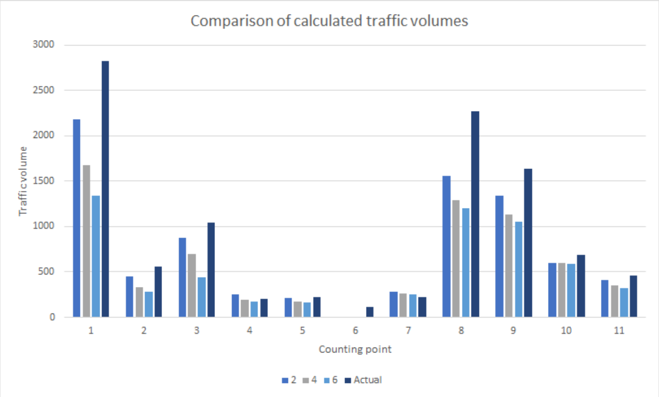

Figure 3: A comparison between the traffic flows over edges on the network to determine the best fitted OD-matrix

In addition to the average number of trips, it was also determined at what time of day most vessels travelled the network. This is an important parameter because it has an influence on the waiting times at locks. Using AIS, a distribution of the trip starting times was made. This resulted in the graph shown below in Figure 4.

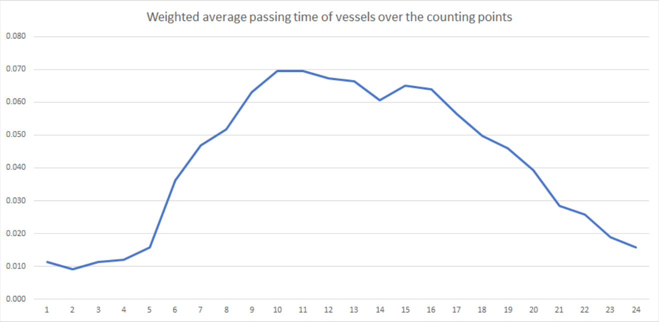

Figure 4: The distribution of vessel movements over the hours of the day.

C. *Fleet Composition*

The size of a vessel influences the distance and time costs of a vessel. Therefore, it was determined what what the sizes of the vessels on the network were. Using the AIS data, the vessels were grouped in size classes [17]. This resulted in a distribution that can be used as input for the simulation model. For the case study the distribution became as shown in Figure 5.

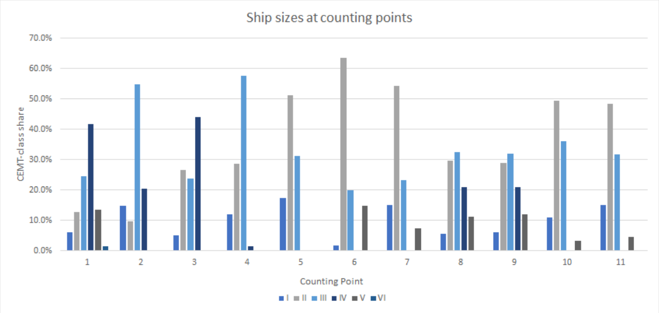

Figure 5: The distribution of the sizes of vessels on the network.

D. *Accuracy of AIS*

From comparing the outcomes of the AIS analysis with another data source it was obtained that there are also some inaccuracies in the data. Several reasons for this can be found in the acquisition, storing and processing of the data. One perceived problem is that the AIS messages are not send/received, or contain wrong information. Another is that AIS data is messy and needs many modifications before it can be analysed. Overall, AIS seemed to underestimate the number of ships on a network.

IV. Developed Simulation Model

In this research the Python based simulation tool, OpenTNSim[1], developed at the TU Delft is used [18]. This tool has been used in the simulation of inland shipping networks before with varying purposes. L. Vehmeijer (2019) [19] and J. van der Does (2019) [20] used OpenTNSim to study different parts of the inland waterways network. This research further expanded on the used simulation tool by adding a new option for the locks on the network. Additionally, the method developed in this research to add many specific origin and destination pairs to the model can be useful for later studies as well.

The goal of the simulation model was to make a tool that can predict the expected change in performance in an inland shipping system. In OpentTNSim most of the required functionalities were present. The most important functions of the simulation model were tested to see if there if they operated as intended. These functions are the basic movements, the generation of vessels between origins/destinations and the functioning of the lock. The complete model was checked on whether it functioned as planned by running the base scenario and comparing the results with the input traffic values. The R-squared model fit based on the in- and output matrices was calculated at 0.949, which is seen as a good model fit.

V. Results

The developed simulation model was tested on a case study with two situations: the base scenario that is based on the normal situation on the network and the scenario where a waterway at is closed off. Closing the waterway meant that some vessels needed to take a detour, changing the flow of traffic. This provided some insights in the possibilities of the developed method and the applicability of the results. The outcomes of the two scenarios were compared on two aspects: the impact on the vessels and the impact on the waiting times at the locks.

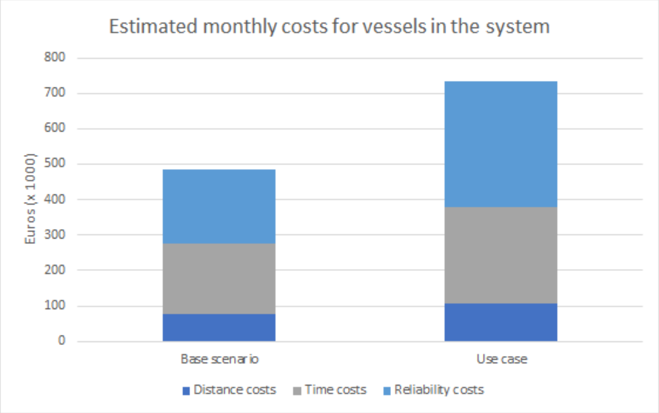

Figure 6: A comparison of the performance of vessels in the case study.

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[1] OpenTNSim stands for: Open-source Transport Network Simulation and can be found at: `https://opentnsim.readthedocs.io/en/latest/`

A. *Performance Change of the Vessels*

The impact for vessels was determined by calculating the change in operational costs for the three cost categories. In the case study, the average operational costs for vessels within the system boundaries grew by approximately 51% as is shown in Figure 6. This increase shows that the impact of closing a waterway can have a significant impact on the performance of inland ships.

B. *Performance Change of the Locks*

Additionally, the change in waiting times at the locks on the network was studied separately. This provides better insight where the shift in traffic flow has the most impact. This is measured in the values mentioned in Section 2C: average waiting time and the 90% confidence values for the waiting time. In the case study the traffic volumes at the locks shifted slightly, as can be seen in Figure 7.

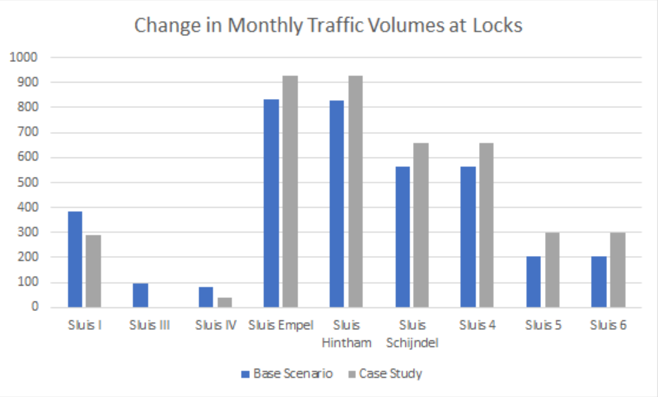

Figure 7: Change in simulated traffic volumes at the locks between the two scenarios

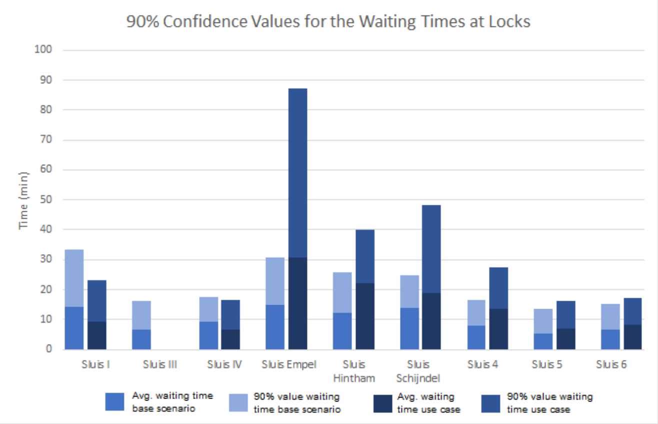

Figure 8: Change in simulated average- and 90% value waiting times at the locks between the two scenarios

The shift in traffic affected the two waiting time parameters as shown in Figure 8. Here it can be seen that the shift in traffic flows can have a large impact on the simulated waiting times. This change is observed mainly at the locks with higher overall traffic volumes and higher variations in lock operational times.

VI. Discussion

One of the goals of this research was to develop a method that could be used in determining the impact of the closing of waterways section. It is therefore important to provide some perspective on the chosen methods and how they could influence the outcomes.

A. *AIS Analysis*

One of the general downsides of AIS data is that every vessel track consists of many points resulting in a large data set. This meant that data of only three months was used for the analysis. This means that there could be seasonal or temporary effects influences the outcomes of the analysis. To try and mitigate these effects, the first three months of 2018 were chosen. During this period no abnormalities could be found for the studied network or the inland shipping sector in general.

The locks on the network were considered crucial components. With AIS it could be determined that the operating times vary can be different for locks that are similar in size. The variation of the operating times roughly follows a normal distribution. Because of time restrictions no further research was done to find a better fitting distribution. This means that it was possible in the simulation to have negative operating times, which is not possible.

Another new application of AIS was to determine the specific daily/monthly traffic between areas of the network. However, the OD-matrices obtained from the analysis showed some limitations of the method. Depending on the cut-off time used, there is a large variation in the number of observed trips between OD-pairs. Additionally, a lot of traffic that seems to stay within one area. This varied per obtained matrix but ranged up to 45% of total trips. Additionally, it was obtained that the methods used for the AIS analysis probably underestimate the number of trips observed.

B. *Limitations of the Simulation Model*

In developing the simulation model several choices were made that could influence the outcomes and results. There is often a trade-off between model complexity or similarity to reality and ease of use or applicability.

While testing the vessel generator function, it was found that it had difficulty with low arrival rates. By running the simulation for a longer time this problem could be mitigated, but there remained an overestimation of traffic volumes at low rates. Overall, the model fit was determined to be accurate enough to determine the main effects in the research. But this means that the simulation model is less usable for situations with low traffic volumes.

While setting up the simulation model it was decided to use a single fleet composition and a single time of day distribution. This was done to decrease the complexity of the model, but it also means that some unrealistic trips are simulated. Not all waterways of the network have the same allowed ship size. By using one fleet composition it was not possible to have size restrictions on the waterways. This should result in an underestimation of the average vessel size for some trips and an overestimation for others. It is expected that these level each other out to some extent. It does however add another uncertainty in the results.

The system that was reproduced in the simulation model is considered a network with relatively low traffic volumes. Nonetheless, the computation times increased significantly with increased run times. Adding more complexity or variables is expected to have a further negatively influence on this. Applying the model to other parts of the inland waterways network with higher traffic volumes or more origin/destination areas is also expected to increase this further. This means that there could be some problems with the scalability of the developed model.

VII. Conclusion

In the developed method, AIS data and a simulation tool were combined to try and recreate the real-world system as accurate as possible. It was found that this can be a useful combination as AIS can be used to eliminate certain assumptions that were otherwise needed as input for the simulation model. However, it was in this research not possible to eliminate all these required assumptions. There are some reasons for this, but most important is that AIS data is messy and needs modifications before it can be analysed. It was determined that using AIS comes with some accuracy issues as it seems to underestimate the number of ships on a network. The functions of the simulation model worked as intended and it can be adapted quite easily to other case studies. It can thus be concluded that the developed method can be applied when studying the effects of planned maintenance and construction works, but it is best used to estimate where the impacts are expected to be big rather than to calculate exact results.

VIII. Recommendations

In this research it was found that AIS can have several applications in studying the inland shipping system. Before further research can accurately be conducted, it should be further explored what the limitations and inaccuracies of this data source are. It was found that the traffic volumes from AIS are probably an underestimation of the actual situation on the network. In the production, gathering and processing of the data there could be causes for this underestimation.

There are also more specific applications of AIS that could be further investigated. One of the main steps in this research has been creating an origin/destination matrix to represent the vessel trips between areas on a network. The OD-matrices seemed to underestimate the traffic volumes between areas on the network. Being able to develop accurate OD-matrices could prove very useful for a variety of research topics. Another application of AIS data in this research was the analysis of the lock passages by ships. It could be very interesting to further investigate the variations of the lock operating times and their possible causes. In this research a normal distribution was used to imitate the observed behaviour of variation in lock operating times. It would be interesting to see what distribution the best fit is to the found results from the AIS analysis. Additionally, attempts were made in this research to analyse the entire lock area without success. This meant that their assumptions were made for the waiting, approach and exit times at locks. If a method is developed that can calculate these other delay components for locks from AIS it could be used to check accuracy of the simulation model developed in this and other research projects.

The effects of closing a waterway can reach beyond inland shipping. Should the costs for using a vessel increase too much, shippers might decide to switch to another transport mode. This is an undesirable effect as inland shipping is seen as a transport mode with relatively low negative external effects. Determining the impact on the modal split was ultimately left out of the scope of this research because of a lack of available data and time restrictions. Expanding the current method to include a last step in which a comparison is made between different transport modes is could be a very interesting topic for further research.

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B

AIS Analysis

This appendix contains the main results of the AIS analysis.

B.1. Lock Analysis from AIS

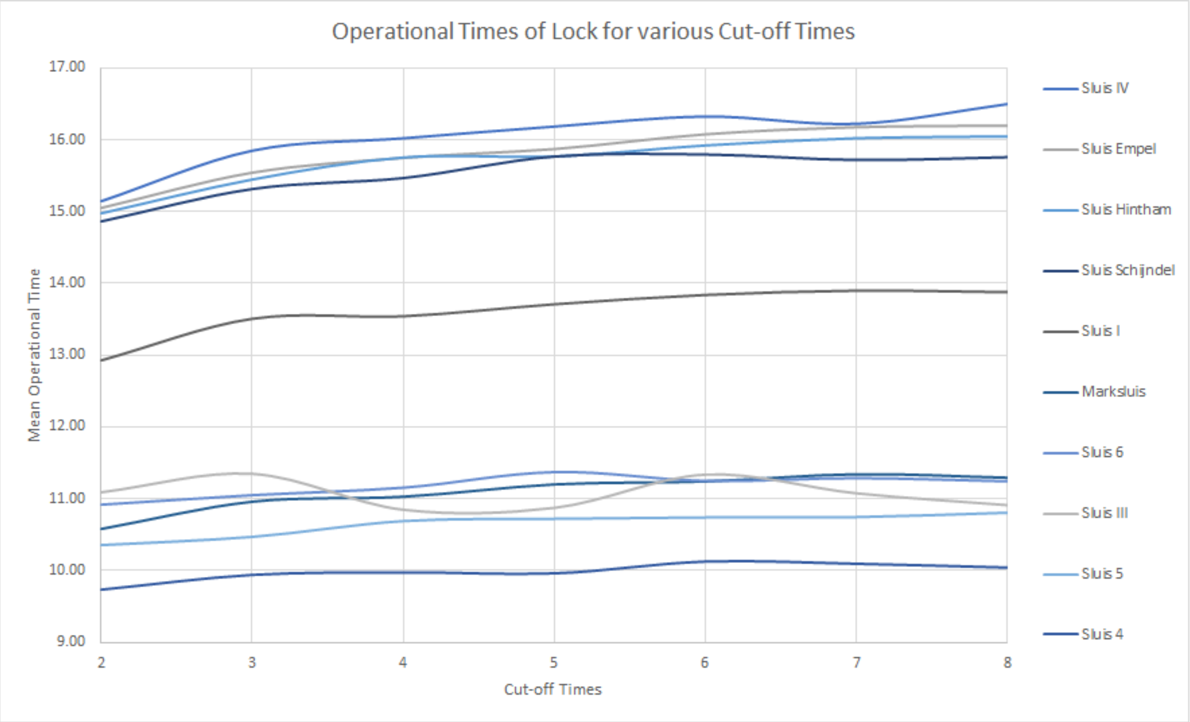

Figure B.1: Mean operation times of locks on the network for various cut-off times

Table B.1: Mean operational time and variance of all the locks on the network for varying cut-off times

	Cut-off time													
Lock	2		3		4		5		6		7		8	
	Mean	St.dev	Mean	St.dev	Mean	St.dev	Mean	St.dev	Mean	St.dev	Mean	St.dev	Mean	St.dev
Marksluis	10.59	3.38	10.97	3.44	11.04	3.16	11.21	3.23	11.25	3.13	11.35	3.02	11.30	3.01
Sluis I	12.93	4.37	13.51	4.11	13.55	3.93	13.72	4.05	13.85	3.85	13.91	3.93	13.89	3.80
Sluis III	11.09	6.04	11.34	6.56	10.85	6.02	10.88	5.97	11.33	5.95	11.08	6.31	10.91	6.00
Sluis IV	15.15	4.60	15.85	4.33	16.03	4.00	16.19	3.72	16.33	3.88	16.23	3.87	16.50	3.66
Sluis Empel	15.06	5.20	15.55	4.85	15.75	4.81	15.88	4.62	16.08	4.55	16.18	4.58	16.20	4.54
Sluis Hintham	14.97	4.62	15.44	4.31	15.75	4.06	15.76	4.13	15.92	3.93	16.02	3.85	16.04	3.81
Sluis Schijndel	14.87	4.09	15.32	3.76	15.47	3.56	15.77	3.30	15.80	3.23	15.73	3.28	15.77	3.28
Sluis 4	9.73	3.43	9.94	3.37	9.98	3.31	9.96	3.43	10.13	3.27	10.10	3.33	10.04	3.27
Sluis 5	10.35	3.83	10.47	3.78	10.69	3.69	10.73	3.83	10.74	3.69	10.75	3.56	10.81	3.64
Sluis 6	*10.92*	*3.27*	*11.05*	*3.16*	*11.16*	*3.11*	11.37	3.19	11.25	3.06	11.28	3.09	11.24	3.02
Sluis V	2.31	0.32	2.31	0.32	2.31	0.32	2.31	0.32	2.31	0.32	2.31	0.32	2.31	0.32

B.2. OD-Matrices from AIS

Table B.2: OD-Matrix between regions with a 2h cut-off time, minimum speed of 0.3 m/s and no vessel type filter

		Destination											
Nunique IDs:	**17091**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Origin	**1**	3801	296	403	152	51	7	22	12	176	65	838	474	6297
	2	262	1	36	0	0	1	2	0	0	0	13	11	326
	3	369	21	782	29	11	2	6	4	0	2	122	62	1410
	4	145	0	16	115	4	0	2	1	0	0	4	5	292
	5	50	1	7	1	265	16	5	9	1	2	21	7	385
	6	14	1	4	4	15	1	8	7	2	2	3	2	63
	7	11	3	4	3	4	4	85	12	12	14	7	2	161
	8	30	0	2	7	7	5	40	48	42	25	49	36	291
	9	215	0	9	0	0	0	10	14	1258	45	164	59	1774
	10	55	1	1	1	0	0	6	5	68	388	54	39	618
	11	328	37	71	2	14	0	8	11	176	82	1246	126	2101
	12	638	84	50	14	20	0	1	7	61	16	391	1294	2576
	Sum	5918	445	1385	328	391	36	195	130	1796	641	2912	2117	16294

Table B.3: OD-Matrix between regions with a 2h cut-off time, minimum speed of 0.3 m/s and with just freight vessels

		Destination											
Nunique IDs:	**14203**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Origin	**1**	3501	254	389	141	43	4	18	9	164	64	790	420	5797
	2	258	0	25	0	0	1	2	0	1	0	15	12	314
	3	334	23	611	28	7	2	5	4	0	1	106	62	1183
	4	150	0	14	119	4	0	1	1	0	0	4	4	297
	5	20	1	6	1	159	11	5	6	0	0	19	6	234
	6	11	1	4	4	13	10	7	10	1	1	3	1	66
	7	8	3	4	3	2	5	77	10	12	12	6	2	144
	8	28	0	2	7	7	5	40	53	21	25	44	32	264
	9	147	0	8	0	0	0	7	12	1028	42	148	46	1438
	10	53	1	2	1	0	0	5	7	62	318	53	32	534
	11	328	36	71	2	10	0	7	11	160	71	716	115	1527
	12	574	74	50	13	16	0	2	4	33	13	366	713	1858
	Sum	5412	393	1186	319	261	38	176	127	1482	547	2270	1445	13656

Table B.4: OD-Matrix between regions with a 2h cut-off time, minimum speed of 0.4 m/s and with just freight vessels

		Destination												
Nunique IDs:	**13778**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Origin	**1**	2222	265	399	148	45	16	20	74	190	73	790	436	4678
	2	274	0	40	0	1	1	2	1	1	0	15	11	346
	3	350	24	679	30	9	11	6	5	0	2	119	68	1303
	4	167	0	15	132	6	0	2	10	0	0	4	6	342
	5	23	1	9	2	146	20	5	37	0	0	20	6	269
	6	15	2	6	5	14	27	13	44	5	3	6	1	141
	7	11	2	3	3	3	14	107	61	15	14	6	3	242
	8	26	0	3	7	12	40	50	91	27	37	51	35	379
	9	183	0	5	0	0	6	13	79	1115	54	169	47	1671
	10	61	1	1	1	0	4	7	52	75	337	77	35	651
	11	329	35	37	3	10	5	8	61	190	88	543	118	1427
	12	596	73	59	13	20	0	2	21	33	15	368	716	1916
	Sum	4257	403	1256	344	266	144	235	536	1651	623	2168	1482	13365

Table B.5: OD-Matrix between regions with a 4h cut-off time, minimum speed of 0.4 m/s and with just freight vessels

		Destination												
Nunique IDs:	**10475**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Origin	**1**	2076	180	301	123	37	19	16	90	143	60	776	401	4222
	2	210	1	31	0	0	0	2	3	1	0	12	10	270
	3	259	22	339	25	5	8	4	7	1	2	92	58	822
	4	142	0	8	37	2	0	1	9	0	0	5	2	206
	5	13	1	6	1	85	12	4	33	0	0	13	7	175
	6	18	1	7	2	8	6	11	41	4	3	6	3	110
	7	9	2	3	2	1	12	37	48	8	12	6	3	143
	8	40	0	3	7	13	39	39	73	17	34	47	36	348
	9	121	0	4	0	0	7	5	61	442	38	125	44	847
	10	43	1	1	0	0	4	5	53	39	130	58	31	365
	11	313	28	26	1	8	4	6	71	140	66	471	91	1225
	12	551	63	46	10	14	0	2	28	29	12	330	468	1553
	Sum	3795	299	775	208	173	111	132	517	824	357	1941	1154	10286

Table B.6: OD-Matrix between regions with a 6h cut-off time, minimum speed of 0.4 m/s and with just freight vessels

		Destination												
Nunique IDs:	**9098**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sum**
Origin	**1**	1944	164	279	108	32	19	15	101	121	52	756	357	3948
	2	23	1	4	0	0	0	2	3	1	0	12	10	56
	3	231	20	291	10	5	6	4	8	1	3	75	52	706
	4	130	0	2	23	2	0	1	8	0	0	2	2	170
	5	10	0	4	1	65	12	4	30	0	0	14	6	146
	6	19	2	6	2	7	5	9	36	4	4	6	3	103
	7	10	2	3	2	1	10	18	40	4	9	8	4	111
	8	43	0	3	6	11	34	32	79	15	24	49	36	332
	9	102	1	2	0	0	7	3	52	277	27	111	42	624
	10	38	1	1	0	1	4	4	43	33	96	45	30	296
	11	298	29	22	1	9	5	7	73	125	61	391	78	1099
	12	499	57	40	7	10	0	2	30	21	12	308	357	1343
	Sum	3347	277	657	160	143	102	101	503	602	288	1777	977	8934

B.3. Traffic volumes at virtual counting points

Table B.7: Total traffic volumes at counting points split into directions, three month period

Counting Point	**NW-SE direction**	**SE-NW direction**	**Unaccounted**	**Total**
1	1305	1394	117	2823
2	276	270	13	559
3	488	541	18	1047
4	105	44	52	201
5	118	87	17	222
6	27	45	46	118
7	112	79	31	222
8	973	1020	60	2271
9	736	846	42	1632
10	308	337	40	685
11	216	193	51	460

Table B.8: Traffic volumes at counting per CEMT class, three month period

		Counting point										
CEMT class	**Max length**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
I	**40**	138	66	43	24	38	2	33	110	84	70	67
II	**56**	288	44	224	57	112	73	119	575	404	313	216
III	**80**	559	246	200	115	68	23	51	628	447	229	142
IV	**87**	948	92	371	3	0	0	0	404	294	0	1
V	**185**	311	0	2	0	0	17	16	219	167	20	20
VI	**200**	32	0	0	0	0	0	0	0	0	0	0
Total		2276	448	840	199	218	115	219	1936	1396	632	446

Table B.9: Traffic volumes at counting per CEMT class, share of total

		Counting point										
Max length	**CEMT class**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
40	**I**	6.1%	14.7%	5.1%	12.1%	17.4%	1.7%	15.1%	5.7%	6.0%	11.1%	15%
56	**II**	12.7%	9.8%	26.7%	28.6%	51.4%	63.5%	54.3%	29.7%	28.9%	49.5%	48%
80	**III**	24.6%	54.9%	23.8%	57.8%	31.2%	20.0%	23.3%	32.4%	32.0%	36.2%	32%
87	**IV**	41.7%	20.5%	44.2%	1.5%	0.0%	0.0%	0.0%	20.9%	21.1%	0.0%	0%
185	**V**	13.7%	0.0%	0.2%	0.0%	0.0%	14.8%	7.3%	11.3%	12.0%	3.2%	4%
200	**VI**	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%
Total		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

B.4. Comparing virtual counting points and OD-matrices

Table B.10: Estimated traffic on counting points based on OD-matrices with cut-off times of 2, 4 and 6 hours.

Counting Point

Cut-off time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**SUM**
2	2176	447	876	252	210		284	1555	1341	603	408	8152
4	1673	331	698	196	176		266	1294	1134	597	356	6721
6	1337	282	439	176	167		249	1199	1054	585	324	5812
Actual	**2823**	**559**	**1047**	**201**	**222**	**118**	**222**	**2271**	**1632**	**685**	**460**	**10240**

C

Simulation Model Outline

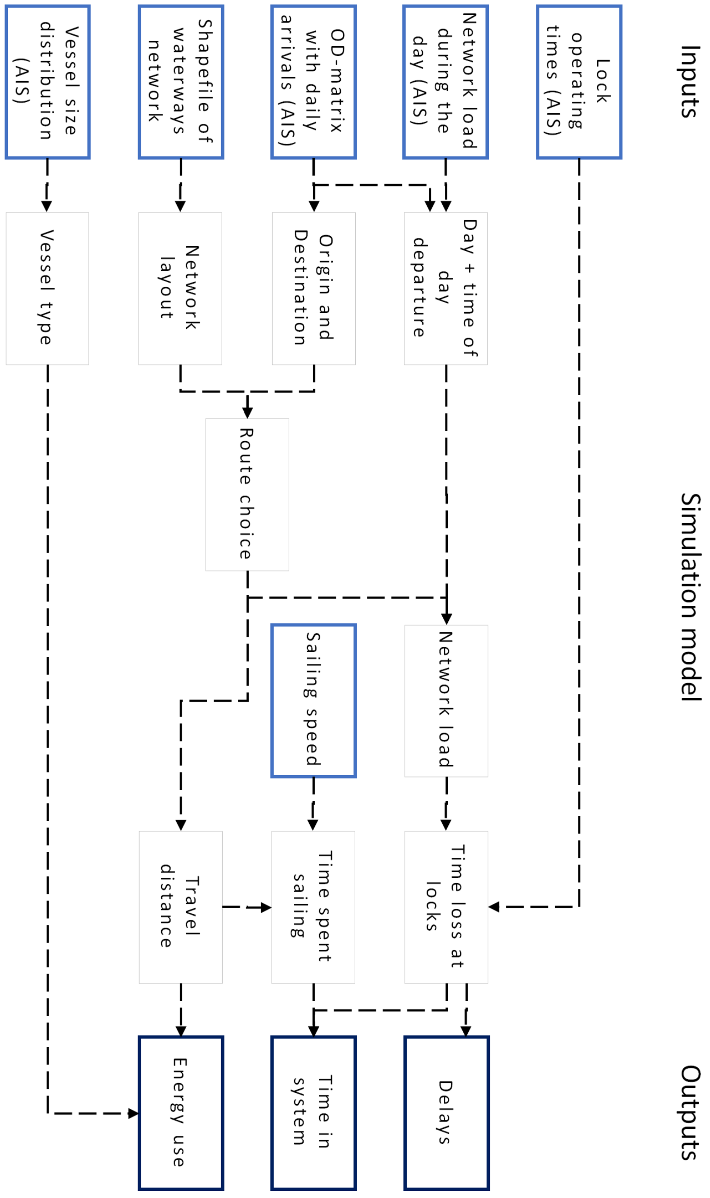

Figure C.1: Detailed outline of the simulation model.

D

Verification & Validation Results

D.1. Basic Movements

Table D.1: Operational log of one ship sailing between points

Step	Message	Timestamp	Geometry - x	Geometry - y	Distance travelled (m)	Speed (m/s)
0	Sailing	02:30:00.000000	5.337	51.734	181	4.0
1	Sailing	02:30:45.240740	5.336	51.736	181	4.0
2	Sailing	02:32:16.764548	5.333	51.740	726	4.0
3	Sailing	02:33:25.697310	5.330	51.744	516	4.0

D.2. Vessel generator verification results

Table D.2: Vessel generator verification scenarios and results for varying arrival rates, without variation over the time of day. Simulation over a 100 day period.

Scenario	Daily arrival rate	Expected vessels	Simulated vessels	Difference
1	0.1	10	21	110%
2	0.5	50	70	40%
3	1	100	126	26%
4	5	500	528	5.6%
5	10	1000	1031	3.1%
6	50	5000	5013	0.3%

Table D.3: Verification of vessel generator mechanics varying the total number of expected ships, while keeping the arrival rate constant at 0.5 ships per day.

Scenario	Daily arrival rate	Expected vessels	Simulated vessels	Difference
1	0.5	100	136	36.00%
2	0.5	500	544	8.80%
3	0.5	1000	1040	4.00%
4	0.5	5000	5025	0.50%

Table D.4: Verification of vessel generator mechanics varying the daily arrival rate while keeping the total number of expected ships constant.

Scenario	Daily arrival rate	Expected vessels	Simulated vessels	Difference
1	0.05	5000	5026	0.52%
2	0.1	5000	5024	0.48%
3	0.2	5000	5025	0.50%
4	0.5	5000	5025	0.50%
5	1	5000	5025	0.50%
6	2	5000	5019	0.38%
7	5	5000	5019	0.38%

Table D.5: Simulated vessel counts per size class in the vessel generator verification

	Vessel counts per class				
Scenario	I	II	III	IV	V
1	494	506	0	0	0
2	224	255	246	275	0
3	114	369	208	216	93
4	94	310	369	163	64

Table D.6: Input and output fleet compositions in the vessel generator verification

	Input shares (CEMT-class)					Output shares (CEMT-class)				
Scenario	I	II	III	IV	V	I	II	III	IV	V
1	50.00%	50.00%	-	-	-	49.4%	50.6%	-	-	-
2	25.00%	25.00%	25.00%	25.00%	-	22.4%	25.5%	24.6%	27.5%	-
3	10.00%	40.00%	20.00%	20.00%	10.00%	11.4%	36.9%	20.8%	21.6%	9.3%
4	10.00%	35.00%	35.00%	15.00%	5.00%	9.4%	31.0%	36.9%	16.3%	6.4%

D.3. Lock operation cycle verification results

Table D.7: Part of the lock operational log for the second lock verification step

Step	Message	Timestamp	Value	Time difference (min)
0	Lock doors closing start	2020-01-01 01:32:16.7	Node 2	-
1	Lock doors closing stop	2020-01-01 01:36:16.7	Node 2	4
2	Lock chamber converting start	2020-01-01 01:36:16.7	Node 2	0
3	Lock chamber converting stop	2020-01-01 01:52:16.7	Node 1	16
4	Lock doors opening start	2020-01-01 01:52:16.7	Node 1	0
5	Lock doors opening stop	2020-01-01 01:56:16.7	Node 1	4
6	Lock doors closing start	2020-01-01 01:56:16.7	Node 1	0
7	Lock doors closing stop	2020-01-01 02:00:16.7	Node 1	4
8	Lock chamber converting start	2020-01-01 02:00:16.7	Node 1	0
9	Lock chamber converting stop	2020-01-01 02:16:16.7	Node 2	16
10	Lock doors opening start	2020-01-01 02:16:16.7	Node 2	0
11	Lock doors opening stop	2020-01-01 02:20:16.7	Node 2	4

Table D.8: Operational log of one selected ship in the second lock verification step

Step	Message	Timestamp	Time loss (min)	Geometry - x	Geometry - y	Distance travelled (m)	Speed (m/s)
0	Sailing	02:30:00.000000	0	5.337	51.734	0	0.0
1	Sailing	02:30:45.240740	0	5.336	51.736	181	4.0
2	Waiting in waiting area start	02:32:16.764548	0	5.337	51.734	181	2.0
3	Waiting in waiting area stop	02:44:16.764548	12	5.337	51.734	0	0.0
4	Waiting in line-up area start	02:44:16.764548	0	5.337	51.734	0	0.0
5	Waiting in line-up area stop	03:32:16.764548	48	5.337	51.734	0	0.0
6	Passing lock start	03:32:16.764548	0	5.337	51.734	0	0.0
7	Passing lock stop	03:56:16.764548	24	5.333	51.740	726	0.5
8	Sailing	03:56:16.764548	0	5.333	51.740	0	0.0
9	Sailing	03:58:25.697310	0	5.330	51.744	516	4.0

D.4. Base Scenario Inputs

Table D.9: Vessel distribution used as input for the simulation model as adjusted from the AIS analysis.

Max length	CEMT class	Observed	Model Input
40	I	9.0%	10.0%
56	II	34.9%	35.0%
80	III	31.7%	30.0%
87	IV	18.1%	20.0%
185	V	6.3%	5.0%
200	VI	0.0%	0.0%
Total		100.0%	100.0%

Table D.10: Average speed of vessels in each size class used in the simulation. Adapted from: Vehmeijer (2019)

Vessel class	Speed (m/s)
CEMT-I	3.7
CEMT-II	4.0
CEMT-III	4.2
CEMT-IV	4.4
CEMT-Va	4.0

Table D.11: Fuel use per kWh for various engine built years. Copied from: J.H.J. 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

Table D.12: Final OD-matrix to be used in the simulations. Adjusted from Table B.4.

O\D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
1	-	-	-	1.67	0.50	0.20	0.23	0.83	2.13	0.83	-	-	6.40
2	-	-	-	-	-	-	-	-	-	-	0.17	0.13	0.30
3	-	-	-	0.33	0.10	0.13	0.07	0.07	-	-	1.33	0.77	2.80
4	1.87	-	0.17	-	0.07	-	-	0.13	-	-	0.07	0.07	2.37
5	0.27	-	0.10	-	-	0.23	0.07	0.43	-	-	0.23	0.07	1.40
6	0.17	-	0.07	0.07	0.17	-	0.17	0.50	0.07	-	0.07	-	1.27
7	0.13	-	-	-	-	0.17	-	0.70	0.17	0.17	0.07	-	1.40
8	0.30	-	-	0.10	0.13	0.47	0.57	-	0.30	0.43	0.57	0.40	3.27
9	-	-	0.07	-	-	0.07	0.17	0.90	-	0.60	1.90	0.53	4.23
10	0.70	-	-	-	-	0.07	0.10	0.60	0.83	-	0.87	0.40	3.57
11	-	0.40	0.43	-	0.13	0.07	0.10	0.70	2.13	1	-	-	4.97
12	-	0.83	0.67	0.17	0.23	-	-	0.23	0.37	0.17	-	-	2.67
Total	3.43	1.23	1.50	2.33	1.33	1.40	1.47	5.10	6.00	3.20	5.27	2.37	**34.63**

D.5. Base Scenario Results

Table D.13: Simulated daily ships between OD-pairs in the base scenario

O\D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
1	0.00	0.00	0.00	1.69	0.58	0.19	0.20	0.85	2.35	0.85	0.00	0.00	6.70
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.19	0.39
3	0.00	0.00	0.00	0.34	0.12	0.15	0.07	0.07	0.00	0.00	1.47	1.10	3.32
4	1.67	0.00	0.10	0.00	0.10	0.41	0.00	0.15	0.00	0.00	0.00	0.07	2.51
5	0.41	0.00	0.12	0.00	0.00	0.20	0.05	0.41	0.00	0.00	0.34	0.08	1.61
6	0.18	0.00	0.05	0.07	0.20	0.00	0.22	0.42	0.07	0.59	0.08	0.00	1.88
7	0.15	0.00	0.41	0.00	0.23	0.20	0.00	0.42	0.17	0.15	0.07	0.00	1.80
8	0.40	0.00	0.41	0.14	0.19	0.41	0.41	0.00	0.36	0.52	0.61	0.41	3.85
9	0.00	0.00	0.08	0.00	0.00	0.10	0.20	0.61	0.00	0.68	2.03	0.39	4.10
10	0.85	0.00	0.00	0.00	0.00	0.05	0.17	0.71	1.08	0.00	0.61	0.28	3.75
11	0.00	0.42	0.42	0.00	0.14	0.10	0.15	0.42	1.86	1.10	0.00	0.00	4.61
12	0.00	0.86	0.42	0.24	0.28	0.00	0.00	0.24	0.40	0.19	0.00	0.00	2.62
Total	3.66	1.28	2.01	2.47	1.82	1.82	1.48	4.29	6.29	4.08	5.42	2.52	37.14

Table D.14: Difference between input matrix and simulated ships in percentages for the base case.

O\D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
1	-	-	-	102%	115%	93%	87%	102%	110%	102%	-	-	105%
2	-	-	-	-	-	-	-	-	-	-	122%	140%	130%
3	-	-	-	102%	119%	114%	102%	102%	-	-	110%	144%	119%
4	90%	-	61%	-	152%	-	-	114%	-	-	0%	102%	106%
5	154%	-	119%	-	-	87%	76%	94%	-	-	145%	127%	115%
6	107%	-	75%	102%	122%	-	132%	84%	102%	-	127%	-	149%
7	114%	-	-	-	-	122%	-	60%	102%	91%	102%	-	129%
8	133%	-	-	135%	140%	88%	72%	-	120%	121%	108%	102%	118%
9	-	-	127%	-	-	152%	122%	68%	-	113%	107%	73%	97%
10	121%	-	-	-	-	76%	169%	119%	130%	-	70%	69%	105%
11	-	105%	97%	-	102%	152%	152%	60%	87%	110%	-	-	93%
12	-	104%	63%	142%	119%	-	-	102%	109%	112%	-	-	98%
Total	107%	104%	134%	106%	137%	130%	101%	84%	105%	128%	103%	106%	107.2%

E

Scenario Comparison Results

E.1. General Output Comparison

Table E.1: Fleet composition comparison between the two scenarios and the input values

CEMT	Input	Base scenario	Case study
I	10.0%	10.1%	10.2%
II	35.0%	35.5%	35.9%
III	30.0%	30.3%	30.3%
IV	20.0%	18.3%	17.7%
V	5.0%	5.7%	5.8%

E.2. Fuel Consumption

Table E.2: Total monthly fuel consumption in the base scenario and the use case.

CEMT	Fuel use base scenario (tonnes)	Fuel use use case (tonnes)	Change
I	50.7	57.1	113%
II	321.9	375.5	117%
III	456.9	563.7	123%
IV	516.2	614.8	119%
V	198.0	206.6	104%
Total	1543.7	1817.7	118%

E.3. Waiting Times

Table E.3: Time spent waiting for locks per trip and monthly totals for the entire system for both scenarios

	Per trip (h)		**Total per month (h)**		
CEMT	**Base scenario**	**Case study**	**Base scenario**	**Case study**	**Change**
I	0.72	1.32	76.1	120.3	163.8%
II	0.70	1.31	257.8	429.8	168.1%
III	0.62	1.25	193.5	350.6	182.5%
IV	0.62	1.16	131.9	219.6	166.8%
V	0.70	1.33	41.2	62.3	170.3%
Total	0.66	1.26	700.5	1182.6	171.4%

E.4. Combining Cost Factors

Table E.4: .9Summary of the results for the base scenario on monthly basis.

CEMT	Max length (m)	Max load (tonnes)	Number of ships	Fuel use (tonnes)	Time spent in system (h)	Time spent waiting (h)
I	38.5	400	105.0	8.4	486.9	76.1
II	55	650	368.2	53.6	1612.2	257.8
III	85	1050	312.7	76.1	1273.6	193.5
IV	105	2050	211.5	86.0	852.9	131.9
V	135	4000	58.8	33.0	260.5	41.2
Total			1056.2	257.3	4486.0	700.5

Table E.5: Summary of the results for the use case on monthly basis.

CEMT	Max length (m)	Max load (tonnes)	Number of vessels	Fuel use (tonnes)	Time spent in system (h)	Time spent waiting (h)
I	38.5	400	101.3	11.2	645.6	120.3
II	55	650	365.2	73.6	2212.7	429.8
III	85	1050	310.5	110.5	1848.6	350.6
IV	105	2050	211.2	120.6	1195.1	219.6
V	135	4000	52.2	40.5	319.7	62.3
Total			1040.3	356.4	6221.7	1182.6

Table E.6: Exact results for the total monthly cost calculations per scenario. Totals per month.

	Base scenario				Use case			
CEMT	**Distance costs**	**Time costs**	**Reliability costs**	**Totals**	**Distance costs**	**Time costs**	**Reliability costs**	**Totals**
I	2535	6232	22836	31603	3361	8264	36091	47717
II	16093	35630	77347	129070	22087	48900	128946	199933
III	22844	48141	58045	129029	33158	69875	105183	208216
IV	25812	66444	39562	131818	36167	93098	65883	195149
V	9900	41673	12370	63943	12153	51154	18675	81983
Total	**77184**	**198119**	**210160**	**485463**	**106925**	**271292**	**354779**	**732997**

E.5. Lock Analysis

Table E.7: Summary of lock analysis results for simulation of the base scenario.

Lock	Traffic Count	Mean operation time (min)	St.dev (min)	Total waiting time (h)	Average waiting time per ship (h)	90% Value
Sluis I	385	13.76	4.05	92.16	14.36	33.28
Sluis III	96	11.23	6.04	10.89	6.81	16.07
Sluis IV	81	16.25	3.97	12.35	9.15	17.48
Sluis Empel	832	16.09	4.51	205.66	14.83	30.75
Sluis Hintham	830	15.97	3.90	169.73	12.27	25.67
Sluis Schijndel	566	15.63	3.25	131.67	13.96	24.71
Sluis 4	565	10.11	3.39	74.81	7.94	16.46
Sluis 5	206	10.74	3.48	18.61	5.42	13.60
Sluis 6	207	11.21	2.97	22.43	6.50	15.36

Table E.8: Summary of lock analysis results for simulation of the case study.

Lock	Traffic Count	Mean operation time (min)	St.dev (min)	Total waiting time (h)	Average waiting time per ship (h)	90% Value
Sluis I	291	13.71	3.82	44.85	9.25	23.16
Sluis III	-	-	-	-	-	-
Sluis IV	41	16.03	3.82	4.55	6.65	16.43
Sluis Empel	929	16.31	4.69	477.96	30.87	87.24
Sluis Hintham	927	16.08	3.88	344.75	22.31	39.86
Sluis Schijndel	660	15.61	3.38	207.28	18.84	48.24
Sluis 4	659	10.15	3.35	148.77	13.55	27.54
Sluis 5	297	10.76	3.63	34.98	7.07	16.17
Sluis 6	298	11.24	3.02	41.39	8.33	17.12

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