Assessing the impact of quay-wall renovations on the nautical traffic in Amsterdam

A simulation study

J. van der Does de Willebois

Technische Universiteit Delft

TU Delft
Gemeente Amsterdam

DELFT UNIVERSITY OF TECHNOLOGY

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Assessing the impact of quay-wall renovations on the nautical traffic in Amsterdam

Author:
J. (Jeroen) VAN DER DOES DE WILLEBOIS

Supervisors:
Ir. H (Henk) VERHEIJ (CEG)
Prof. Dr. Ir. M. (Mark) VAN KONINGSVELD(CEG)
Prof. Dr. Ir. P. (Pieter) VAN GELDER (TPM)
P. (Pepijn) MEEUWSEN (Municipality of Amsterdam)

Ports and Waterways
Faculty of Civil Engineering and Geosciences (CEG)

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Executive summary

The canals of Amsterdam represent a draw for tourists and add to the value of real estate along the canals. More than 40% of Amsterdam tourists take a trip through the canals, accounting for more than 3 million canal travelers annually. Therefore, the tour boat sector is crucial for tourism in Amsterdam.

Many of the quay walls on Amsterdam's canals have either reached the end of their lifespan or need replacing because of damage caused by overloading and the overuse of heavy supply trucks. Currently, a length of 200 km out of the total length of 300 km of quay walls have reached the end of their 100-year service life, and some walls have even passed that limit. In 2017, five incidents of quay-wall failure occurred. In 2018, three such incidents occurred. Hence, these quay walls are in critical need of replacement. Many are located along busy canals, which means that closing these canals will almost certainly directly lead to the congestion of traffic flow on the water. This is highly undesirable for the tourist sector. At the moment, there is no research being conducted into how to manage quay-wall renovations without disturbing transport over water.

The main goal of this research project was to develop a first version of a tool with which the quay wall renovation planning can be tuned to the wishes for transport over water (e.g., passenger transport and pleasure craft). Thus, the main research question for this project was as follows:

"How can the impact on nautical traffic flow and congestion patterns of quay wall upgrade works in the canals of the City of Amsterdam be assessed?"

To answer this question, an analysis was first conducted of the main vessel types and their corresponding route-choice behavior on the network that makes up the Amsterdam canals traffic system. This analysis also included typical traffic flow and congestion patterns that the tool should be able to mimic based on the identified vessel types and network structure. The analysis found that the different vessel types that use the canals could be categorized according to their route-choice behavior. Specifically, three route categories could be distinguished: fixed routes (hop-on-hop-off boats and liner vessels), random routes with sightseeing points as waypoints (private boat tours), and completely random routes (pleasure craft). These categories were named "cruise vessels," "random cruise vessels," and "pleasure craft," respectively. The routes these vessels take on the network of Amsterdam canals determine the traffic flow and where congestion occurs. Vessels sail their routes on the canal network, and the properties of the network influence which routes they take. Therefore, the different vessel types with their corresponding route-choice behavior and the properties of the waterway network together determine the traffic flow and congestion patterns on the network.

Second, a model was constructed based on the information from the network analysis. An agent-based modeling framework was selected as a suitable framework, because it could give insight into not only *if* and *when* congestion occurs, but also *why* congestion occurs. The ABM framework is able to represent the distinct sailing speed and route selection of each vessel type, can reproduce the (routing) behavior of the three vessel types that interact, and had the additional option to incorporate the irrational behavior. Each vessel was modeled as an entity with its own logic (step-by-step instructions) and making its own decisions while moving on a graph. In order to reproduce observed traffic flow and congestion patterns, modeled vessel objects needed to move through this network, calculate their routes based on the network structure and properties, and queue at crossings. Therefore, this study applied network logic (graph theory) and queueing

theory. This project used the open-source NetworkX package in Python to construct a network (graph) based on the spatial coordinates of the Amsterdam canal network, with nodes at crossings and bridges and edges connecting the nodes. Each vessel object in the model used algorithms from the NetworkX package to calculate its route on the network. The model also used the SimPy package to simulate queueing and crossing congestion at crossings with discrete time steps. To summarize, the model simulated on a microscopic level, used discrete time steps, and applied the agent-based modeling framework.

Third, this tool was calibrated with data from Waternet and then applied to two network intervention scenarios: a canal closure and a one-way traffic regulation. This study applied the Mean Absolute Error (MAE) and the Normalized Mean Absolute Error (NMAE) to measure the goodness of fit between the measured data and the model results to calibrate the model. Results from the calibration showed that the model could reproduce the different traffic-demand scenarios. In the calibration, the model results fit the measured data within acceptable limits of approximately 65–85% in number of passages per hour per vessel type for the seven measurement locations. However, not all results fit the data within this range. The cruise vessel results for the Keizersgracht canal showed a significant overestimation for each scenario, meaning that more vessels sailed on this part of the canal in the simulation than those actually measured in reality. A second difficulty arose from the limited accuracy of the measurement data. Because of this limited accuracy, precise calibration of the random cruise vessels and the pleasure craft per location was not possible.

Nevertheless, this model showed promising first results. Based on results from the two intervention scenarios, the model can be used to analyze the consequences of an intervention at any location in the canal network. The implemented logic per vessel type combined with the network structure and properties can explain the results of a canal closure or a traffic regulation. The model gives insight into the rerouting behavior of the different vessel types, and thus more insight into the development of congestion patterns that would develop as a consequence of canal-upgrade works. Not only does the model show the consequences of canal quay-upgrade works on traffic flow and congestion patterns, but it also gives insight into *why* specific results occur. With this information, the impact of possible canal-upgrade works can be assessed and understood.

However, the model is not yet completed. This study implemented the necessary logic to reproduce traffic flow and congestion patterns, but additional logic (defined in section 3.2.2) should be implemented to obtain more reliable results.

One limitiation has to do with the data with which the model is calibrated. These data originate from 2013 and have a limited level of detail, as they distinguish cruise vessels but not the other vessel types. Consequently, the data are not very reliable for calibrating the model, meaning a number of assumptions had to be made.

Another limitation is that the model is still an approximation of reality, wherein a number of assumptions have been made. For example, the behavior of modeled vessels is based on interviews with captains from the different vessel types. There is no guarantee that the logic derived from these interviews represents the actual routing behavior of the captains. Therefore, the author recommends that the model be validated with data from an actual intervention before any conclusions are drawn. This study proposes two methods to validate the results of the model during an intervention. Preference is given to using RFID chip sensors, as this method gives the most accurate data on route-choice behavior. Given the time sensitivity of the upgrade works, however, the second method (counting of vessel types before and after an intervention) offers a quicker solution to acquiring the data needed to validate the model.

As this model is developed within a community setting at the TU Delft, this model, and other transport network analysis models, can be viewed and found at GitHub TU Delft - Transport Network Analysis[1]. A full overview of links to different parts of the python code can be found in Appendix A.

[1] `https://github.com/TUDelft-CITG/Transport-Network-Analysis`

Acknowledgements

This project is the last part of my masters in Hydraulic Engineering at the TU Delft. This research was conducted in collaboration with the Municipality of Amsterdam (Gemeente Amsterdam). They have provided me with excellent guidance and support throughout the entire project, and gave me much more insight into the fascinating engineering activities they undertake on a day-to-day basis.

As any thesis, it had its hurdles, its ups, and downs. With the support of friends, family, supervisors, and colleagues, challenges have been overcome which lead this thesis to its right end. Therefore, I would sincerely express my thanks to the people who supported me throughout the process.

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Jeroen van der Does de Willebois,
Amsterdam, March 2019

Contents

List of Figures

List of Tables

1
Introduction

1.1 Situation

The canals of Amsterdam are characteristic and iconic of the city center. Furthermore, they are a UNESCO World Heritage Site. The canals and the quay walls represent a draw for tourists and the value of real estate in the canals. Over time, the function and use of the quay walls has changed. The primary function of the quay walls is to separate land and the water. The quay walls keep the ground stable, and thus they are crucial for keeping the streets and other uses of public space intact. Originally, the quay walls played a key role in the loading and unloading of goods transported on water. This function has slowly changed, and in many places, the quay walls are now mainly used for parking. Because the inner-city of Amsterdam becomes busier every year, the pressure for the efficient use of public space is increasing; therefore, the use of the quays is also changing. Accordingly, some quay walls in the city center have been transformed into hop-on/hop-off (HoHo) locations for tourist boat trips. Other quay walls may start to be used again for their original loading and unloading function as entrepreneurs experiment with distributing goods by water. From a livability point of view, an increasing number of locations are being converted to provide enhanced access to the water. The expectation is that an increasing number of questions will arise regarding new uses of the quay walls to determine solutions for numerous functions in an increasingly busy city (Kooistra and Meulblok, 2018).

However, many of these quay walls have either reached the end of their lifespan or need replacing because of damage caused by the overloading and overuse of heavy supply trucks. To ensure safe usage of public space in the city center, the quay walls must be sufficiently safe. Therefore, they must not be allowed to become deformed. There is a high probability of quay-wall failure once they start to deform or sinkholes start to occur nearby. The Municipality of Amsterdam (MoA) estimated that approximately 200 km of in total 300 km of quay walls are in need of repair. Furthermore, it is estimated that it costs nearly EUR 25,000 to repair 1 m of quay wall in the center of Amsterdam. The total length of 200 km of quay wall that is in need of repair represents a replacement value of EUR 5 billion (200,000 m x EUR 25,000) (Gemeente Amsterdam, 2018b). This solution to this problem is two-fold: first, replace the quay walls so that they can last another 100 years. Second, a different function other than loading will be assigned to the quay walls to extend their service life. For example, relieve of loading by allocating the supply of goods to transport via the canals.

1.1.1 Quay-wall replacements

Currently, a large proportion of the quay walls have reached the end of their 100-year service life, and some have even already passed this limit. In 2017, five incidents of quay-wall failure occurred. In 2018, three incidents of quay-wall failure occurred (Kooistra, 2018). Examples of failures are presented in Figure 1.1.

(a) (b)

Figure 1.1: Entrepotdok (a) and Marnix street (b) quay-wall failure

A great need exists to renovate the quay walls that have a probability of failure. In 2017, 0.5 km of the MoA's 200 km of quay wall was renovated. Because there are many quay walls with a high probability of failure in the city center, the rate of 0.5 km per year is not sufficient. The MoA aims to renovate 2 km of quay wall each year (Gemeente Amsterdam, 2018c). When a quay wall is repaired or renewed, a part (or the whole) of the canal must be closed off, as can be seen in Figure 1.2.

(a) (b)

Figure 1.2: Placement of an emergency construction to prevent failure (Kooistra, 2018)

Many of the quay walls that have been identified as having a high probability of failure are located in busy canals, which means that closing these canals will almost certainly and directly lead to the congestion of the traffic flow on water. An additional problem is that not only quay walls must be replaced, but also bridges, locks, and water pipes. If a bridge is blocked and replaced, the entire canal becomes blocked.

1.1.2 Traffic in the canals

In the past few years, tourism in Amsterdam has greatly increased, which is expected to continue in the coming years. For example, in 2015, 17.3 million hotel nights were reserved in Amsterdam, a number that is expected to grow to 23.5 million in 2025 (Berents and Straver, 2015). This increase in tourists will equal an increase in customers seeking passenger transport on the canals, thereby increasing traffic (for more information, see Appendix D.

The canals of Amsterdam are attractive for the people of Amsterdam as well as for tourists visiting Amsterdam. The canals are now being used for tour boats, pleasure craft, and freight transport. There are already numerous ship movements in the canals. On a warm, sunny day in mid-July, as many as 200 ships pass by during peak hours (Gemeente Amsterdam, 2018a).

It is estimated that for an average busy location in the city-center on average 133.000 vessels pass by in a year time (Baarsma and Van der Voort, 2012). This traffic can be categorized into three segments:

- pleasure craft has the largest share, with 48.8 %; followed by
- passenger transport (47.3 %); and finally
- freight transport (3.9 %) (Baarsma and Van der Voort, 2012).

Pleasure craft traffic

The MoA has no volume policy on the number of permits for pleasure craft. This means that there are no restrictions on the amount of pleasure crafts on the canals. To be able to sail through the canals, a “vignette” must be bought, which must be renewed every year. Pleasure vessels are allowed to berth anywhere in the canals of Amsterdam if the vessel is shorter than 12 m. Based on this, an estimate can be made for the amount of pleasure craft in the canals of Amsterdam. The latest estimation is that Amsterdam has approximately 8.300 pleasure craft (Waternet, 2017), and 90 % of vignets are bought by people living in Amsterdam (Baarsma and Van der Voort, 2012).

Passenger transport traffic

A boat trip through the canals is one of the main attractions of Amsterdam, and more than 40% of tourists visiting the city take such a boat trip. Therefore, the tour boat sector is critical for tourism in Amsterdam with more than 3 million visitors yearly (Baarsma and Van der Voort, 2012). The passenger transport traffic can be sub-dived into 5 distinct categories:

1. closed and open ships longer than 14 meters (professionally steered large vessels);
2. closed cruise ships shorter than 14 meters (professionally steered closed vessels);
3. open ships shorter than 10 meters (professionally steered open vessels);
4. ships shorter than 5.5 meters which tourists can sail on their own ("Rent your own" vessels); and
5. pedal boats

The segment "professionally steered closed vessels" includes all closed vessels shorter than 14 meters. This segment includes closed vessels shorter than 10 meters. Any open vessel that is longer than 10 meters gets a permit for "professionally steered closed vessels".

Before 2016, the market for passenger transport was mostly dominated by shipping companies (69%) operating with vessels longer than 14 m. These vessels were used for classic sightseeing tours and line services with HoHo services. In 2016, the MoA implemented quicker release of permits for passenger vessels shorter than 14 m. Now, 200 permits for vessels shorter than 14 m are distributed, but in 2020, the market will be completely open and approximately 1000 permits are estimated to be distributed. For ships longer than 14 m, no extra permits were distributed (Waternet, 2017). Thus, an increase in tourism will mean an increase in traffic on the canals.

Freight vessel traffic

As a solution to relieve loading on the quays and extend their service life, a plan has been proposed by the MoA to move road traffic movements to transport on the canals. Part of the freight distribution could then take place via the canals, as well as via urban construction logistics. Because the canals are being used instead of the quays, the quays are less burdened by heavy trucks. This should also relieve pressure on the roads and streets of Amsterdam, which are now congested due to the small streets, private cars and high demand for goods in the city center. Currently, approximately 1 - 4% of the freight distribution for the city takes place via the canals.

1.2 Problem definition

The MoA expects to renew many quay walls during the next 10 to 20 years. Many of these quays are located in busy canals, and thus, closing these canals ensure immediate delay or congestion. Current research into traffic capacity on the canals does not take into account the renovation issues that the city will face in the next 20 years (Interview with "Programma Varen," 2018). Approximately 50 quay walls in the city center are in desperate need of repair, with new high-probability quay walls being identified every month. In addition, the amount of traffic on the canals in Amsterdam is expected to grow in coming years with the opening of the market for passenger transport and increasing tourism. In particular, the renovation of quay walls and bridges clashes with the desire to transport more goods over water.

1.3 Research objective and scope

1.3.1 Research objective

The main goal of this research is to develop a first version of a tool through which the quay wall renovations (planning) are tuned to the wishes for transport over water (e.g., passenger transport and pleasure craft). This tool should support the planning of renovation works of the 50 canal quay walls with an high probability of failure in relation to transport over water by providing insights into the consequences of each canal-wall renewal. At the moment, there is no research being conducted into how to manage quay-wall renovations without disturbing transport over water.

1.3.2 Research scope

The most high-probability quay-walls (around 50 quay-walls) in the historic center must be replaced in the next 10 years. Therefore, the geographic area of this research is limited to the historic center of Amsterdam, or "Stadsdeel Centrum." Thus, this study constructs a model to investigate the effects of quay-wall renovation in the city center.

1.3.3 Limitations of the study

Geographic demarcation

Outside of the scope off this study is the impact on land-based transport and nautical traffic outside the city center.

Bridges, locks and water pipes

This project only focusses on the consequences of renovations of canal-quay walls. Outside of the scope are the renewals of bridges, locks, and water pipes.

Traffic types

Not all traffic on the canals is taken into account. Freight transport only accounts for 1%–4% of the nautical traffic, and therefore is not included in this research.

Traffic demand scenarios

This study does not investigate all possible weather and day type scenarios that is making up the traffic demand for that particular day. Instead, four representative scenarios are constructed to represent all the possible traffic demand scenarios. The traffic demand during special events like Koningsdag or the Gaypride are not included in this research, because they represent unique situations.

Data

There is limited data available on the traffic demand on the canals of Amsterdam. The best available data is from June 2013 to January 2014, because the sensors were working at their most optimal state (they had just been installed), and furthermore, the least amount of canal-upgrade works were active during their period. This data is limited to three vessel categories based on length (0-4 meters, 4-14 meters, and $>$ 14 meters).

However, these categories do not justify the different type of vessels sailing on the canals of Amsterdam with their own route choice. It does distinguish the cruise vessels, because of all these vessels are longer than 14 meters, and no pleasure craft is longer than 14 meters. It does not distinguish the pleasure craft from the passenger transport for vessels shorter than 14 meters, as pleasure craft can be between 0-4 meters, but also between 4-14 meters.

Consequently, assumptions are made for the distribution of these vessel types for the different traffic demand scenarios. For the high demand traffic scenario, recent countings of Mobicon (Mobycon, 2018) are used as a guideline for the distribution. While these countings were on a Sunday beginning September, they do give insight into the distribution of vessel types for that particular traffic demand scenario. An overview of the distribution per vessel type per scenario is given in Table 2.7.

Crossings

Amsterdam has a lot of intersections and crossings with adjacent one-way bridges. In case of one-way bridges, waiting time of a one-way bridge is added to the waiting time to cross a crossing. There are a lot of different situations that can happen at a crossing with one-way bridges. Therefore, more research is needed before all situations are investigated at these crossings. This research is not part of the scope of this project. An assumption of first come first serve is used with a time penalty.

Most congestion occurs at crossings. Therefore, information on the capacity of each crossing is needed to reproduce reality. Unfortunately, only for the crossings at Prinsen- Leidsegracht, and Haarlemmersluis information on the capacity is available. These two crossings are used to estimate the capacity at other crossings.

1.4 Research question

The main research question for this project is:

"How can the impact on nautical traffic flow and congestion patterns of quay wall upgrade works in the canals of the City of Amsterdam be assessed?"

The following questions can be asked to further specify the research question:

1. *What are the main vessel types making up the traffic on the canals of Amsterdam in space and time and what are the traffic-flow and congestion patterns during a normal week/weekend day in summer/winter?*

2. *How can a model be setup that can simulate traffic on the canals of Amsterdam in order to analyze traffic-flow and congestion patterns for different traffic demand scenario's?*

   (a) *What modelling concepts are applicable?*

   (b) *What functional requirements does the model need to have in order to approximate the nautical traffic on the canals of Amsterdam?*

3. *Can the traffic on the Amsterdam canal network be reproduced for the previously identified traffic demand scenarios and vessel types?*

4. *Can consequences of quay upgrade works on congestion patterns and traffic flow (closed or limited access edges) be simulated for different traffic demand scenario's and how can such simulations be used to assess the effects of closing off or limited access to canals during quay wall upgrade works?*

1.5 Contribution to science and practice

The research goal of my graduation project is to define a model which can be used to identify and predict congestion patterns on the canals of Amsterdam as a consequence of canal upgrade works. A boat trip through the canals is one of the main attractions of Amsterdam, and more than 40% of tourists visiting the city take such a boat trip. Therefore, the tour boat sector is critical for tourism in Amsterdam with more than 3 million visitors yearly. New companies are also experimenting with transport over water as a means to reduce congestion on the narrow streets of Amsterdam. Thus, the less congestion on the canals, the better the city is accessible, livable and enjoyable.

At the moment, there is no insight in the mechanisms that cause congestion on the canals of Amsterdam. If canal-upgrade works take place on the canals, this problem could only get worse. Hence, insight is needed into the mechanisms that cause congestion and the consequences of canal-upgrade works.

To achieve my research goal I have investigated the existing traffic models and modeling frameworks. With this method, an agent-based model was constructed to reproduce the traffic sailing on the canals of Amsterdam, and to gain more insight into the behavior of each type of vessel. In this framework, each vessel type is modeled as an entity which sails on its own and makes its own decisions.

The contribution towards science is, therefore, the formulation of a first version of an agent-based model to simulate congestion for the nautical traffic with the use of graph and queuing theory. Most research into modeling of congestion in nautical traffic is either microscopic and follows the car lane-changing model, or is macroscopic. However, the nautical traffic follows other traffic rules and has different interactions than road traffic, especially on the canals of Amsterdam. The existing agent-based modelings for simulating nautical traffic either focus on safety, or on the delivery of freight (Xiao et al., 2013; Holmgren et al., 2013). Consequently, this research proposes a first model for modeling nautical traffic congestion using an agent-based approach.

I have used data from 2013-2014 from Waternet to calibrate the model. As a practical case, a canal closure and an implementation of one-way traffic have been simulated. Using simulations of this model, it is possible to gain insight into several details:

- Insight into the system as a whole.
- The formation of congestion due to canal-closure or implementation of one-way traffic.
- Insight why congestion occurs at several locations, and which vessel types are mainly responsible.

Hence, this model can support the planning of canal-upgrade works in such a way that congestion can be reduced and insight is given into the mechanisms that cause congestion.

As this model is developed within a community setting at the TU Delft, this model, and other transport network analysis models, can be viewed and found at GitHub TU Delft - Transport Network Analysis[1].

1.6 Reading guide

The remainder of this thesis is organized as follows: Chapter 2 derives an answer for the first sub-question: "*What are the main vessel types making up the traffic on the canals of Amsterdam in space and time and what are the traffic-flow and congestion patterns during a normal week/weekend day in summer/winter?*" First, the vessel types and the canal network of Amsterdam are discussed in section 2.1. The second part of this chapter Section 2.2) elaborates on the current traffic-flow and congestion patterns.

In the third chapter derives an answer for the following sub-question: "*How can a model be setup that can simulate traffic on the canals of Amsterdam in order to analyze traffic-flow and congestion patterns for different traffic demand scenario's?*"Section 3.2 discusses the first sub-subquestion "*i. What modelling concepts are applicable?*" Section 3.1 reviews the second sub-subquestion "*ii. What functional requirements does the model need to have in order to approximate the nautical traffic on the canals of Amsterdam?*", and explains how the model is built and which requirements it needs to fulfill which answers the main subquenstion partially.

The fourth chapter discusses the validation and calibration of the model with measurement data. This chapter answers the third subquestion: *Can the traffic on the Amsterdam canal network be reproduced for the previously identified traffic demand scenarios and vessel types?*.

Finally, chapter 5 discusses the consequences of interventions on the traffic flow and congestion patterns. This chapter sought to answer the final sub-question "*Can consequences of quay upgrade works on congestion patterns and traffic flow (closed or limited access edges) be simulated for different traffic demand scenario's and how can such simulations be used to assess the effects of closing off or limited access to canals during quay wall upgrade works?*". In Section 5.1, the results of two possible interventions (canal-closure, one-way traffic) of different traffic demand scenario's (scenario 1, 2, 3, and 4) are discussed. As there is no data to validate the results from Section 5.1, Section 5.2 draws a possible setup for measurements in order to validate the outcomes of Section 5.1.

Chapter 6 draws the conclusions of this research with which the main research question can be answered. This chapter also goes into detail into the validity of the model results and proposes recommendations for further research.

[1] https://github.com/TUDelft-CITG/Transport-Network-Analysis

2
Literature study

To answer subquestion one, this chapter analyses the main vessel types that make up traffic on the canals of Amsterdam and the traffic flow and congestion patterns due to the route choice of the different vessel types. First, Section 2.1 analyses key components that make up the nautical traffic behavior in Amsterdam, and Section 2.2 elaborates on the current traffic-flow and congestion patterns. With the information presented in these two sections, Section 2.3 answers the first subquestion.

2.1 Essential elements of the Amsterdam canals traffic system

The routes the vessels take on the network of Amsterdam determine the traffic flow and where congestion occurs. Vessels sail a route on the network and the properties of the waterway network (passage height per bridge, depth, one-way traffic) influence which route they take; thus influencing their route choice behavior. Therefore, the different vessel types and the properties of the waterway network together determine the traffic flow and congestion patterns on the network. Hence, to partially answer subquestion one, this section analyzes the waterway network of Amsterdam and the different vessels sailing on the network.

2.1.1 Characterizing the network

Canals

The fairway profiles of the canals of Amsterdam are based on the CEMT fairway profiles for inland waterways. Furthermore, because each canal in the city center has a different fairway profile, with different width, depth and shape, they each have a different capacity for the number of ships that can sail through the canals. These profiles have the following implications: large ships may not sail through small canals. For example, if the length of the ship is longer than 14 meters, it is not allowed to sail on the smaller canals because either it will not be able to make the turn, or taking the turn will cause too much time and therefore causing delay to other vessels. An overview of the fairway profiles is presented in Figure 2.1.

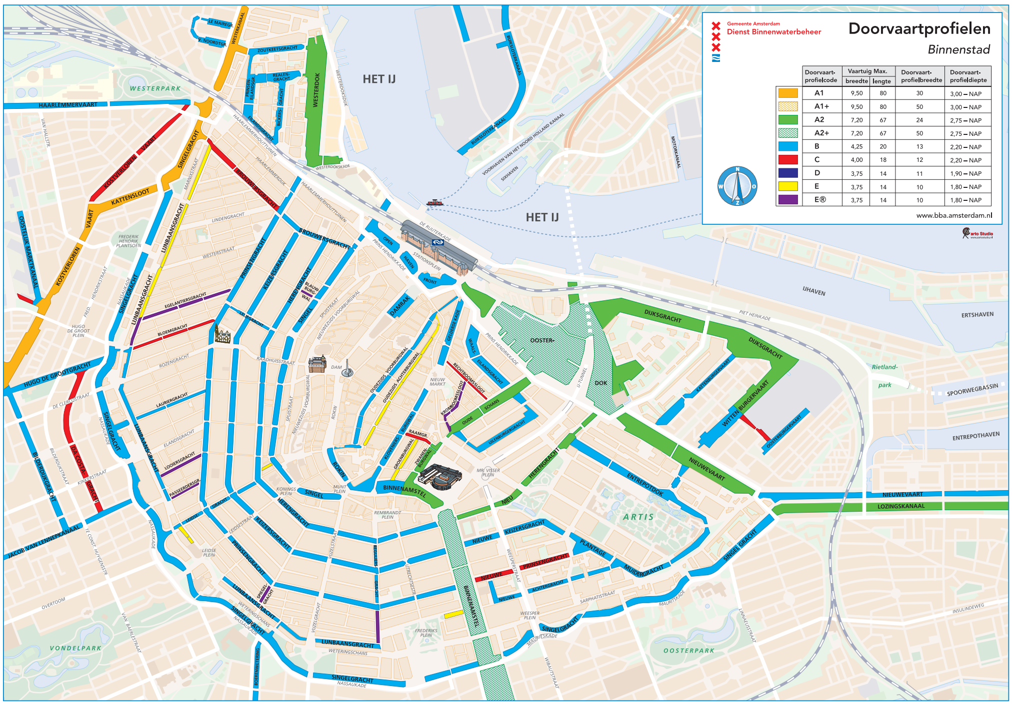


Figure 2.1: Fairway profiles in the inner-city of Amsterdam

Table 2.1: Legenda for Figure 2.1

Fairway profiles for the innercity of Amsterdam

Profiles	Color	Minimum passage width (m)	Maximum length vessels (m)	Maximum width vessels (m)	Fairway depth (m)
A1		30	80	9.5	3.00 - NAP
A1+		50	80	9.5	3.00 - NAP
A2		24	67	7.2	2.75 - NAP
A2+		50	67	7.2	2.75 - NAP
B		13	20	4.25	2.20 - NAP
C		12	18	4	2.20 - NAP
D		11	14	3.75	1.90 - NAP
E		10	14	3.75	1.80 - NAP
E*		10	14	3.75	1.80 - NAP

Hydraulic structures

There are a number of hydraulic structures such as (1) bridges; (2) locks; and (3) jetties in the inner-city of Amsterdam.

1. The bridges. There are 252 bridges located in the inner-city of Amsterdam (Datacharter, 2018). Because this research focuses on traffic that can sail under each bridge, no distinction is made between movable bridges and closed bridges. There is only one bridge where the passage height is too low for the cruise vessels. This bridge is located at the Keizersgracht near the Amstel. Figure 2.2 presents an overview of all the bridges in the inner-city. Each bridge is different, which means that for some bridges two-way traffic is possible, whereas for other bridges, vessels must wait their turn to pass. Almost all one-way bridges are situated at crossings. The bridges where only one-way traffic is possible play a significant role in the congestion on the canals of Amsterdam.

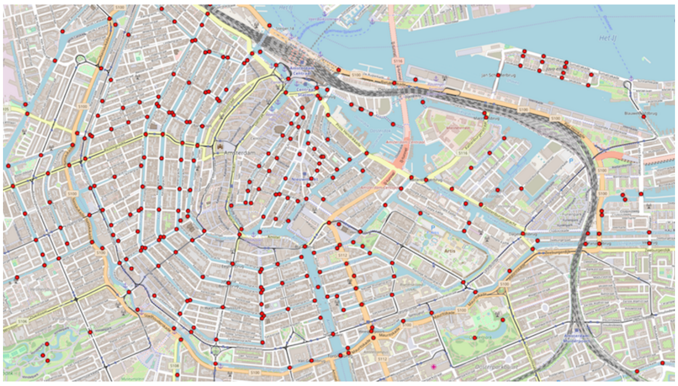


Figure 2.2: Overview of the bridges in the inner city of Amsterdam

2. The locks. There are several locks in the inner city of Amsterdam. Some locks are only used in the middle of the night as a water-management function, but this does not hinder the traffic. The locks in Amsterdam can cause hindrances to the nautical traffic because of the narrowing of the fairway, but this is not a direct result of the function of the locks itself. An overview of the locations of the locks is provided in Figure 2.3.

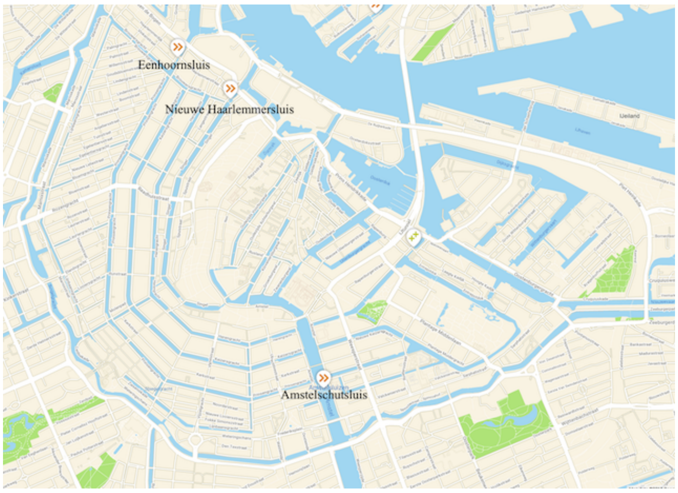


Figure 2.3: Overview of the locks in the inner city of Amsterdam

3. The jetties. In the past 10 years, the MoA created nearly 30 new jetties in the inner-city to serve as HoHo locations for cruise companies. In the coming years, the MoA aims to transform more than half of the (night) berths of the cruise companies in the inner-city center (Open Havenfrond, Damrak, and Rokin) into HoHo points (Berents and Straver, 2015). The jetties at the Open Havenfront, Damrak, and Rokin will partly be made available as HoHo points.

Current traffic regulations

On the first of January 2018, Waternet reduced the maximum speed from 7.5 to 6 km/h. This applies to all canals in the city center of Amsterdam. The only two exceptions are the two routes for freight transport: the Kostverlorenvaart and the Amstelvaart, the maximum speed on these two routes remain 7.5 km/h (Waternet, 2018).

Due to the number of traffic movements in some canals, Waternet started with a pilot in 2017 to implemented one-way traffic on the whole of Prinsengracht, including the known bottlenecks; the Korte Prinsengracht and the Eenhoornsluis. The purpose of this pilot is to ensure safe and efficient passage through the canals. The Singelgracht has a one-way traffic regulation as well, but only during high season (Gemeente Amsterdam, 2017a). The high season is from 1 April until 1 October. Figure 2.4 shows the one-way traffic regulations that are currently active.

In 2017, Waternet ran a pilot for a no entry traffic regulation at the Grimburgwal. Vessels arriving from Oudezijds Voorburgwal cannot sail into the narrow Grimburgwal, therefore preventing congestion. At the end of 2017, Waternet concluded that the pilot was a success and implemented the rule indefinitely (Waternet, 2018). Figure 2.4 shows a complete overview of the traffic regulations currently active. The figure is taken from Waternet and TNO (2018), where the yellow lines represent traffic sailing on the canals of Amsterdam the moment the figure was taken.

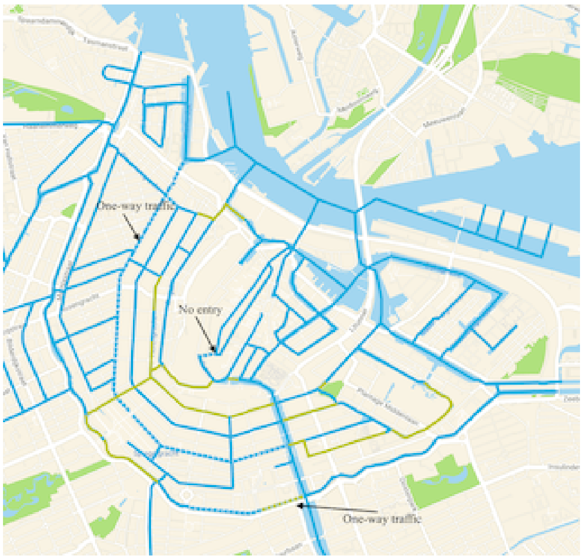


Figure 2.4: Overview of the traffic regulations active on the canals (Waternet and TNO, 2018)

2.1.2 Characterising representative vessel types

Many types of vessel sail in the canals of Amsterdam. Waternet categorizes each type of vessel according to the width, length, and purpose of each vessel (Benthem et al., 2017). In Figure 2.5, a quick overview is shown of the different categories of vessel types according to Waternet.

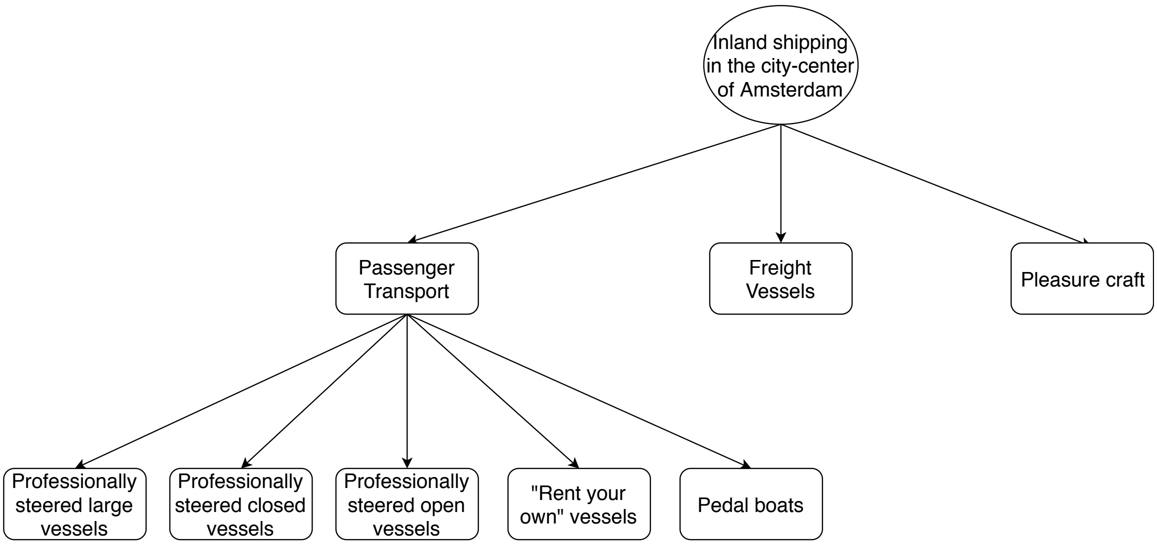


Figure 2.5: Vessel types on the canals of Amsterdam

Pleasure craft

Recreational sailing on the canals is a part of life in Amsterdam and it enhances the attractiveness of the city. Pleasure craft are allowed to berth and sail anywhere through the canals of Amsterdam if the vessel is shorter than 12 m. However, in a new policy documented in “Nota varen 2.1,” the MoA argues that most pleasure craft (80%) measure between 5–7 m (Gemeente Amsterdam, 2013). An example of this type of vessel is shown in Figure 2.6.

Figure 2.6: Pleasure craft on the canals of Amsterdam

Passenger transport

The cruise shipping sector is one of the most crucial sectors for tourism in Amsterdam and represents one of the largest attractions in the Netherlands in terms of number of visitors. The canals are a famous sight-seeing attraction for foreigners visiting Amsterdam. More than 40 % of the tourists visiting Amsterdam take a boat ride through the canals of Amsterdam (Gemeente Amsterdam, 2017b). The cruise industry draws more than 3 million visitors yearly, exhibiting a steady growth of up to 5 million visitors in 2015 and 2016. The passenger boat sector focuses mainly on the UNESCO World Heritage canals, which are located in the city center (Gemeente Amsterdam, 2017b). The passenger transport sector is divided into multiple segments, ranging from a standard tour on liner vessels to rent-your-own vessels. Table 2.2 lists the different categories of vessel with their particular maximum widths and lengths. As explained in Section 2.1.1, not every vessel is allowed to sail on every canal due to it size. In Figure 2.7, examples are shown of each type of vessel for each category.

Table 2.2: Categories of different type of vessels in passenger transport

	Dimensions	
Segment	**Length (m)**	**Width (m)**
I. Professional steered large vessels	$>14, \leq 20$	$>3.75, \leq 4.25$
II. Professional steered closed vessels	≤ 14	≤ 3.75
III. Professional steered open vessels	≤ 10	≤ 3.15
IV. "Rent your own" vessel	≤ 5.50	≤ 2.00
V. Pedal Boats	≤ 3.85	≤ 1.55

(a) I. Professionally steered large vessels

(b) II. Professionally steered closed vessels

(c) III. Professionally steered open vessels

(d) IV. "Rent your own" vessel

(e) V. Pedal Boats

Figure 2.7: Different types of vessels sailing in the canals of Amsterdam

Freight vessels

Freigth vessels only make up 1-4 % of all the vessel movements and thus is not part of this research.

Vessel types according to route choice behavior

To gain a greater insight into the traffic flow and congestion patterns on the canals of Amsterdam, analysis of route choice for each category (pleasure craft and passenger transport) is required. Each segment in the passenger transport category (Table 2.2) has its own type of route when sailing on the canals, and each company in each segment offers their own “unique” experience of Amsterdam seen from the canals. This translates to numerous different routes. This study performed a literature review and found no conclusive answers on the route choice behavior of passenger transport and pleasure craft. To gain more insight into the route choice behavior of each category, this study conducted interviews with captains of vessels in each category and segment, inquiring about their decisions about route choice during a normal day, during periods of congestion, and during a canal closure on their route. In this project, the route choice behavior of each captain of each type of vessel is the decision which route he or she takes as well as how the captain responds to congestion and canal closure. For instance, the HoHo liner service vessels (which are cruise vessels) must stop at each HoHo location. Whenever congestion occurs on a canal where there is also a HoHo point, the HoHo vessel will not deviate from its route. By contrast, the behavior of pleasure craft is more random. Their captains care less about which route to take as long as they do not experience too much congestion, or else they might deviate from their route.

The route choice of each segment of passenger transport can be subdivided into three categories: (1) sailing a fixed route via particular sightseeing points or HoHo points; (2) sailing a more random route through the canals to certain sightseeing points; and (3) sail a completely random route. The cruise companies (or professional steered large vessels in Table 2.2) have a fixed route and time window in which they must return. The professionally steered closed vessels and professionally steered open vessels choose their paths more randomly, because the experience involves a captain providing information and stories about Amsterdam over an hour. The captains of these charter vessels choose their route differently each time because they like sailing through the entire city instead of sailing the same route over and over again. Finally, the categories of rent-your-own vessels and pedal boats can be compared with pleasure craft because they sail through the canals more randomly than the charter vessels. The charter vessels have sightseeing points they sail toward, in contrast to pleasure craft, pedal boats, and rent-your-own boats, which sail a completely random path.

Therefore, the category "pleasure-craft" and each segment in the category "passenger transport" can be re-categorized according to their route choice behavior. These new different categories are summed up below.

1. **Fixed route category; named the "cruise" vessels.**
   Includes:
   - Professional steered large vessels: HoHo and cruise shipping vessels with a fixed route (Figure 2.7 (I)).
2. **Route towards sightseeing points category; named the "random cruise " vessels.**
   Includes:
   - Professional steered closed vessels (Figure 2.7 (II)).
   - Professional steered open vessels (Figure 2.7 (III)).
3. **Random route category; named the "pleasure craft" vessels;**
   Includes:
   - "Rent your own" vessel (Figure 2.7 (IV))
   - Pedal boats (Figure 2.7 (V))
   - Pleasure-craft (Figure 2.7 (VI))

In Figure C.1 in Appendix C, the results from the interviews on route choice behavior are shown during a normal day, during congestion, and during canal closure canal-closure.

2.2 Typical traffic and congestion patterns

Now that the different vessel types have been acquired, insights are required into the day-to-day traffic flow and congestion patterns for constructing a model that can reproduce these patterns. To obtain an improved understanding of traffic flow and congestion patterns, this study performed data analysis on all count data from Waternet. Waternet provides data on 7 measurement points spread out over the city. Each point measures the number of vessels passing by each hour and the direction in which they are sailing. The best available data is from June 2013 to January 2014, because the sensors were working at their most optimal state (they had just been installed), and furthermore, the least amount of canal-upgrade works were active during their period. Therefore, this data represents the base scenario. As this data is already five years old, and there has been an increase in passenger transport from the past couple of years, this data does not completely display the current state of the network. Count data from subsequent years contained too much measurement errors and could therefore not be used for this project. However, recent measurements on three days in September 2018 show an overview of the numbers averaged over certain measurement days in the weekend, which can be used in this project (Mobycon, 2018). Section 2.2.1 discusses the type of scenarios, and Section 2.2.2 analyzes the traffic and congestion patterns based on the defined scenarios in Section 2.2.1 and the data from 2013–2014.

2.2.1 Traffic demand scenarios

Numerous different scenarios exist for traffic on the canals of Amsterdam. For example, more people will set sail on a warm sunny summer day than on a cold rainy winter day, because most people find it more attractive and enjoyable to sail on a sunny summer day. Because canal-upgrade works may take a whole year, insights are required into the traffic and congestion patterns of scenarios that take place during the year.

The main factors that influence the traffic demand on the canals of Amsterdam are as follows (Snelder and Calvert, 2013):

- Season type (summer, winter, spring, and fall),
- Weather type (sunny, normal, rainy),

- Day type (weekend, week, special event)

As many as 27 scenarios can be set up as a combination of these factors (Snelder and Calvert, 2013) (spring and fall have the same amount of traffic demand, and therefore they are counted together). Because 27 scenarios are too many to analyze in this research project, this study selected four scenarios to represent them.

Scenario 1: A traffic demand scenario must be setup to determine the influence of canal-upgrade works when traffic demand is highest. This would be a Sunday in July because most people do not work during the weekend or holiday, and thus have enough time to sail on the canals and the weather is optimal for doing so. Because Amsterdam is a popular destination for weekend city breaks, this means a peak for pleasure craft as well as other vessel types categories. The average temperature on such Sundays in 2013 was approximately 24 C (KNMI, 2018).

Scenario 2: A scenario must be setup to determine the difference between a weekday and a weekend day in July when temperatures are high and there is not much rain. During the week, most people have to work, and therefore have less or no time to sail. However, Amsterdam is still a highly attractive city for tourists, and thus there is still a high traffic demand on the canals during the summer.

Scenario 3 The third scenario is a weekend day during the winter when the weather is not particularly attractive for sailing. However, people still have free time to sail on the canals and tourists still visit Amsterdam for a weekend.

Scenario 4 The final scenario is a weekday during the winter when there are less tourists than during the weekend, the weather is not attractive for sailing (i.e., it is cold and rainy), and locals do not have free time to sail. Table 2.3 presents a brief overview of the traffic demand scenarios.

Table 2.3: Traffic demand scenarios

Scenarios	Summer (July)	Winter (December)
Weekend day	**Scenario 1**: High traffic demand	**Scenario 3**: Low traffic demand
Week day	**Scenario 2** : Medium traffic demand	**Scenario 4**: Very low traffic demand

2.2.2 Traffic demand

On average, 45,000 ships pass through the Prinsengracht (Prince's Canal) each year, and 50,000 ships pass through the Grimburgwal canal (Kruyswijk, 2017).

Traffic flow

In this section, the traffic pattern during the defined scenarios is analyzed from the count data from 2013–2014. As explained, data were taken from seven measurement points. The locations of these measurement points are shown in Figure 2.8. In Figures 2.9 and 2.10, two of the seven measurement points are shown, and the results from the other measurement points are shown in Appendix C. In these graphs, a clear distinction in traffic demand can be made between the different defined scenarios.

Figure 2.8: The measurement locations

Location	Number
Leidschegracht	1
Singel haarlemmersluis	2
Anne Frank	3
Sint antonie sluis	4
Singelgracht DNB-Heineken	5
Herengracht	6
Keizersgracht	7

Table 2.4: Legenda of Figure 2.8

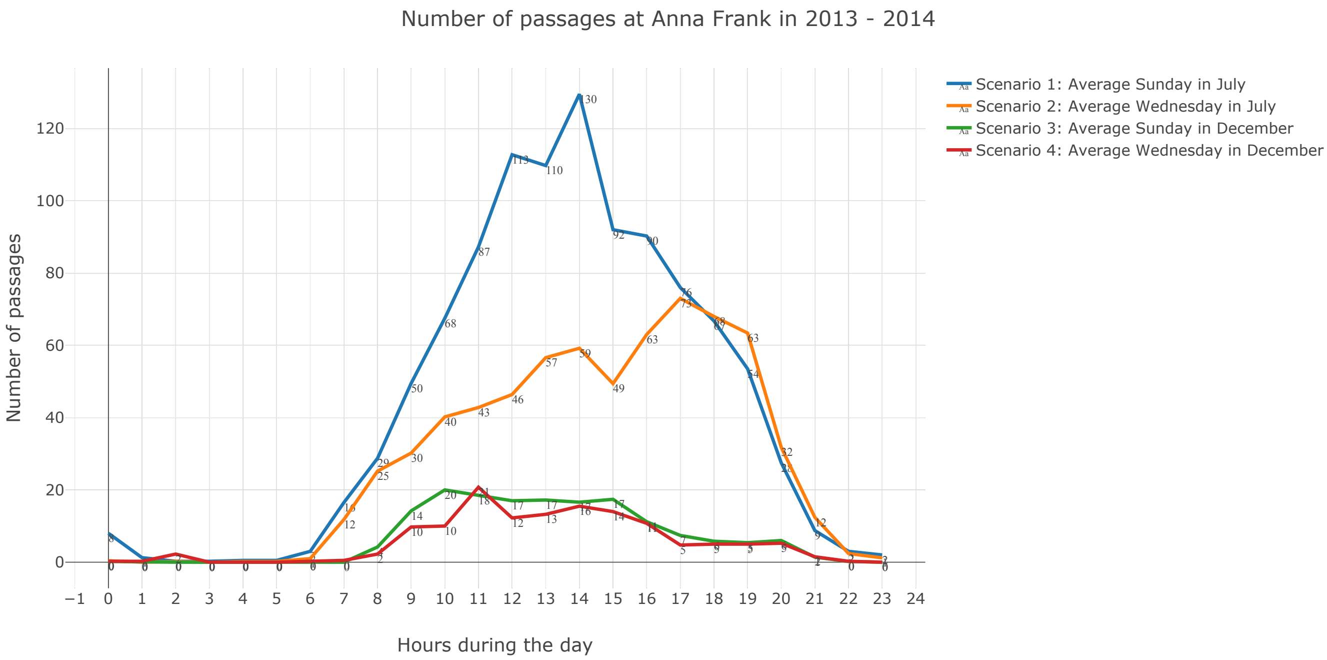


Figure 2.9: Traffic demand, averaged over each type of day, for different scenarios at Anne Frank

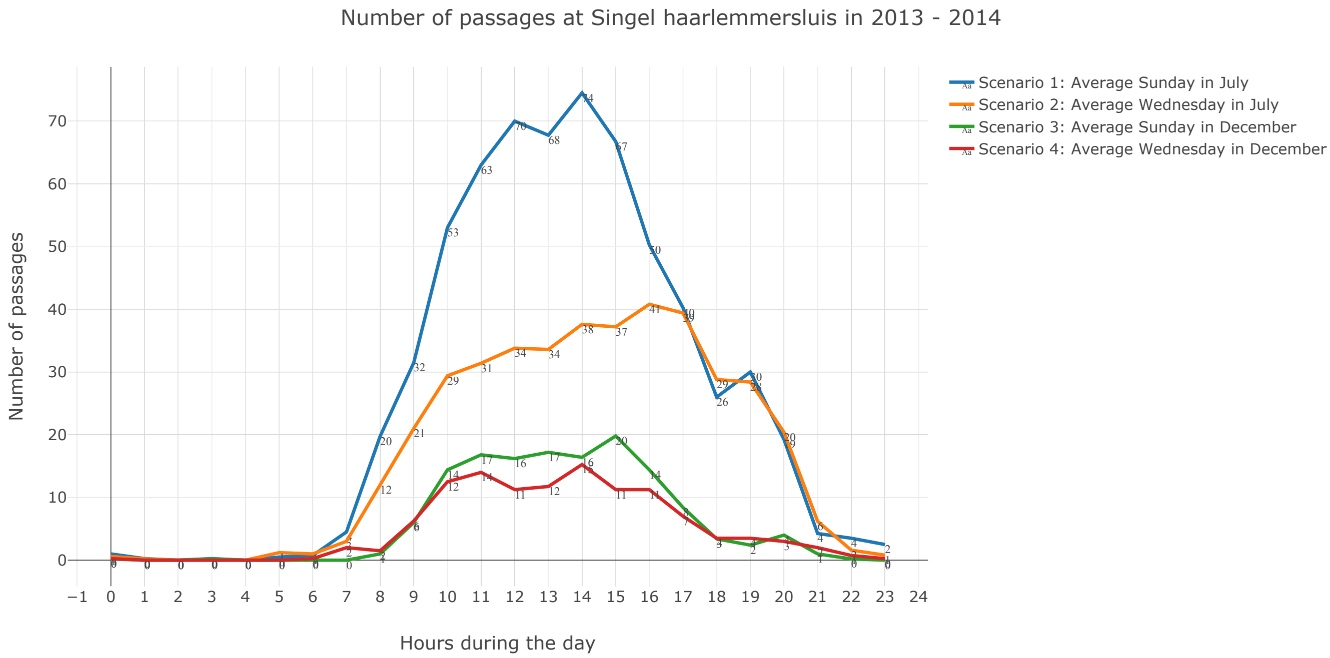


Figure 2.10: Traffic demand, averaged over each type of day, for different scenarios at at Singel Haarlemmersluis

To counter possible measurement errors, the data in the graph for each scenario are averaged over the number of days of that type in that particular month. As expected, a clear difference exists in traffic demand between scenarios 1 and 4. Furthermore, a significant difference exists in traffic demand between week and weekend days during summer. On a Sunday during summer, approximately 2 vessels per minute pass by during peak hours at Anne Frank.

Congestion

However, most congestion does not occur on the canals itself but at crossings between canals and at one-way passage bridges (Gemeente Amsterdam, 2018a). Due to the comprehensive network of (small) canals and the many bridges in the city-center, there are some points where congestion is experienced among the nautical traffic.

To understand why one-way passage causes congestion, a time-distance graph can be used. This graph illustrates the location of the stern of a vessel in time. The bridge passage is divided into four sections as the average navigation speed of a vessel is different within these areas. It can be stated that a bridge passage cannot occur at the initial navigation speed, V_I; hence, speed reduction is required. When a vessel nears a bridge, the vessel speed is reduced to navigate safely. The bridge passage itself occurs at a reduced but constant speed, V_R. The required speed reduction for a bridge passage depends on the physical dimensions of the vessel and the bridge passage itself. After passing the bridge, the vessel will accelerate until V_I is reached. Table 2.5 summarizes the navigation speed of recreational vessels passing the network of Figure 2.11.

Table 2.5: Passage of a bridge

Section	Situation	Navigation speed
I	Open water	Initial speed V_I
II	Nearing bridge	Deceleration + waiting
III	Bridge passage	Reduced speed V_R (constant)
IV	Open water	Acceleration until V_I

The time required for a vessel to pass a bridge is called the passage time. The passage time consists of the waiting time and the transit time of a vessel for a waterway section or hydraulic structure. The following situations can be expected to occur and are illustrated with a time-distance graph when a vessel approaches a bridge:

1. Situation 1: There is no bridge and the vessel navigates through the network
2. Situation 2: The bridge is free (no vessel passing) when the vessel arrives and it can pass straight away. If the passage width is wide enough, the vessel can pass without reducing speed. Then this situation is equal to situation 1;
3. Situation 3: If a vessel is passing from the opposite direction under the bridge when the vessel arrives, thus the vessel has to wait (and moor) until it can pass;
4. Situation 4: If the passage width is large enough, the vessel can pass straight away even when another vessel is passing. This situation is equal to situation 2.

The letters inside the graph indicate the following actions during the bridge passage:

A. Start speed reduction when approaching bridge complex

B. Vessel stationary near the bridge entrance to wait for bridge passage (start waiting time.)

C. Vessel increases speed to leave waiting area and pass the bridge

D. Bridge passage (start transit time)

E. Bridge passage finished, start speed acceleration towards waterway

F. Vessel continues the journey with initial speed

In Figure 2.11 the different situations are depicted.

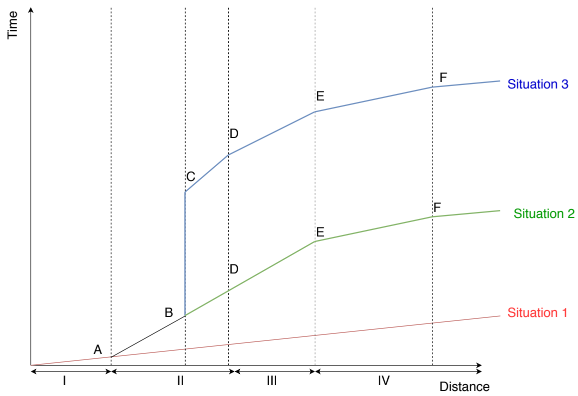


Figure 2.11: Bridge passage in the city center of Amsterdam

Because vessels have to decelerate or wait at one-way passage bridges, congestion can be caused whenever there are more vessels than the maximum capacity of a one-way passage bridge. Almost all of these bridges are located at a crossing.

Another serious point of congestion can be a crossing, which is any point where more than two fairways come together. This is because vessels may must wait before other vessels have crossed. Because the inner-city has a comprehensive system of canals, there are many crossings to be found. A similar time-distance graph can be drawn for a crossing.

In the case of Amsterdam, crossings often intertwine with bridge passages. This makes an interesting combination, as some bridges two-way passage is possible while at other bridges only one-way traffic is possible. In case of a two-way traffic bridge at a crossing, it can be considered as a "normal" crossing. In case of one-way bridges, waiting time of a one-way bridge is additional to the waiting time to cross a crossing. There are a lot of different situations that can happen at a crossing with one-way bridges. Therefore, more research is needed before an accurate time-distance graph can be drawn for different crossings in the case of Amsterdam. This is not part of the scope of this research. An assumption of first come first serve is used with a time penalty.

The capacity of a narrowing on the canals is approximately 60–90 passages per hour, whereas the capacity of a sharp corner at a juction at Haarlemmersluis is 36 per hour (Gemeente Amsterdam, 2018a). If said capacity is exceeded, it can be assumed that congestion occurs. To analyze the current congestion patterns for the four scenarios, data is required on the capacity of each crossing. Unfortunately, information on the capacity is only available for the crossings at Prinsen-Leidsegracht and Haarlemmersluis. The capacity at Prinsen-Leidsegracht is 120 passages an hour, whereas at Haarlemmersluis it is 36 (Gemeente Amsterdam, 2018a). Therefore, this study used these two crossings to estimate the capacity at other crossings.

In the case of Amsterdam canals traffic system, most congestion occurs at crossings (Gemeente Amsterdam, 2018a). For analyzing congestion patterns at crossings, data are required on the number of passages during each scenario to analyze whether congestion occurs during each scenario. Unfortunately, no measurement point is situated directly on a crossing, which makes it difficult to analyze congestion patterns using data from 2013–2014. However, recent measurements on three days in September 2018 show an overview of the numbers averaged over certain measurement days during the weekend, revealing that the capacity of most crossings is exceeded during the weekend on warm summer days (Gemeente Amsterdam, 2018a); this represents scenario 1. These results are shown in Table 2.6.

No data were available on the number of passages at each crossing that could be used to analyze congestion patterns for scenarios 2, 3, and 4. However, the assumption could be made after analyzing Figures 2.9 and 2.10 that little to no congestion occurs during the winter months (scenarios 3 and 4) at crossings because the difference is very large between the number of passages in winter and summer. Moreover, insufficient information is available to draw any conclusions about congestion patterns during scenario 2.

Table 2.6: Passages per hour at crossings (weekend) averaged from 31 August till 2 September (Gemeente Amsterdam, 2018a)

Crossing / Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Haarlemmersluis	31	48	56	76	88	99	108	102	90	69	67	47	28	5	1
Reguliersgracht - Herengracht	40	64	88	98	115	120	114	109	112	93	67	66	31	20	0
Prinsengracht - Leidsegracht	66	99	127	167	197	212	208	211	183	149	106	74	46	18	12
Kamper-/ Odebrug	-	73	101	118	148	198	173	150	126	93	65	56	42	6	3
Prinsegracht - Leliegracht	-	62	69	99	111	126	114	122	103	68	64	46	33	3	1

Distribution

Using the data from 2013–2014, it is not possible to derive the distribution of each type of vessel or the distribution from the newly formed categories as explained in Section 2.1.2. The data divide the distribution of vessel types according to the length of each vessel, which distinguishes three categories:

- Category 3: > 14 meters; cruise vessels
- Category 2: 4 - 14 meters; open and closed vessels
- Category 1: < 4 meters; pedal boats and small vessels

No direct relationship of the distribution can be determined on the three categories, as explained in Section 2.1.2. In the 4–14 m category, there are pleasure craft, which sail a random route, and professionally steered open/closed vessels, which sail only for an hour and a half and have a semi-random route. Therefore, data on the distribution are only usable for an order of magnitude. A direct relationship between the data category "longer than 14 meters" and the routing category from Section 2.1.2 "cruise vessel" can be established. Almost no pleasure craft is longer than 14 meters that sail on the canals of Amsterdam. Consequently, this data represents the number of vessel movements of the category "professionally steered large vessels", which can directly be translated to the routing category "cruise vessels".

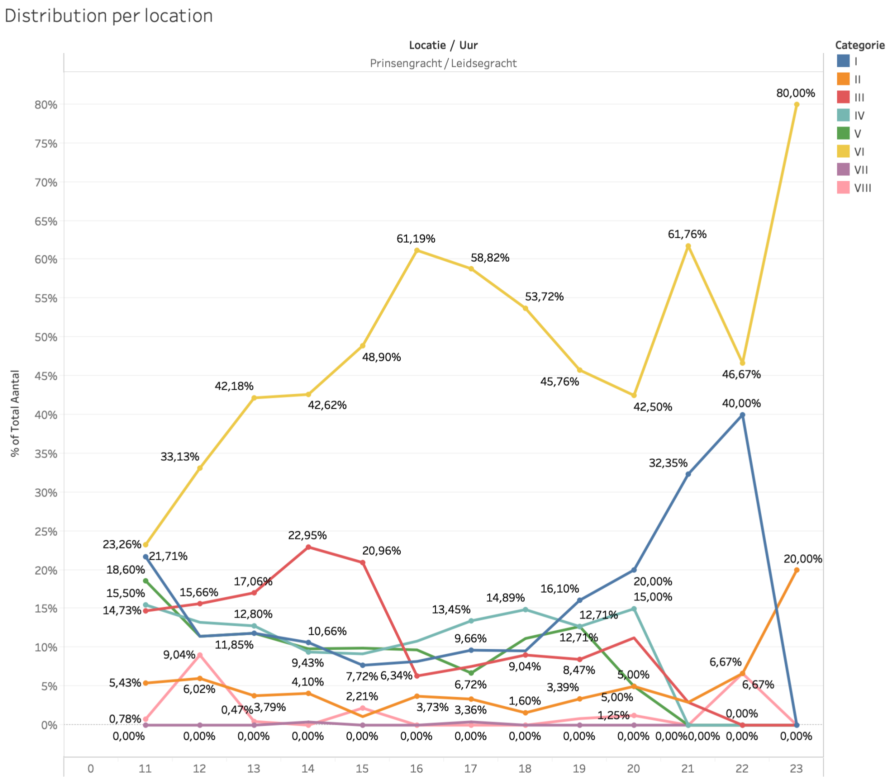
Data from a recent counting session during a weekend in September by Mobycon (Mobycon, 2018) shows every single category, from which the three categories explained in Section 2.1.2 can be derived. These data are usable for deriving the distribution of vessels as well as for deriving the distribution of vessels from the three categories as explained in Section 2.1.2 for scenario 1. An example is shown in Figure 2.12 for

Prinsegracht-Leidsegracht. These data are limited to a Friday, Saturday, and Sunday in August/early September, and thus, are not usable for deriving the distribution of vessels for scenarios 2, 3 and 4.

While these countings from Mobycon were on a Sunday beginning September, they do give insight into the distribution of vessel types for that particular traffic demand scenario. Based on these countings, an assumption of vessel distribution has been made. For the high traffic demand scenario, scenario 1, around 55% of the vessels are pleasure craft, around 15 -20% are cruise vessels, and approximately 25 - 30% of the vessels are random cruise vessels. For the medium traffic demand scenario, the assumption has been made that the number of pleasure craft is lower than during the weekend, but the amount of passenger transport stays more or less the same. The distribution is therefore as follows: around 35% of the vessels are pleasure craft, around 35% are random cruise vessels, and approximately 25 - 30% of the vessels are cruise vessels. For the low and very low traffic demand scenarios, the pleasure craft, the passenger transport "professionally steered open vessels", and the passenger transport "professionally steered closed vessels" is significantly reduced. This is shown in the data from Waternet as well. For scenario 3 and 4, there were so few pleasure craft and random cruise vessels on the canals that the distribution did not make much difference. An assumption has been made that 85% of the vessels are cruise vessels, 10 % are random cruise vessels, and 5 % are pleasure craft. Table 2.7 shows an overview.

Table 2.7: Average distribution of different types of vessels

Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Pleasure craft	55%	35%	5%	5%
Random cruise vessels	25% -30%	35%	10%	10%
Cruise vessels	15% - 20%	30%	85%	85%



The trend of % of Total Aantal for Uur Hour broken down by Locatie. Color shows details about Categorie. The data is filtered on Uur Year and Uur Hour. The Uur Year filter keeps 1899 and 1900. The Uur Hour filter keeps 14 of 14 members. The view is filtered on Locatie, which keeps Prinsengracht / Leidsegracht.

Figure 2.12: Distribution at the crossing at Leidsegracht - Prinsegracht

Table 2.8: Legenda for Figure 2.12

Segment	Category
Professionally steered large vessels	I
Professionally steered closed vessels	II
Professionally steered open vessels	III
"Rent your own" vessel	IV
Pedal Boats	V
Pleasure craft	VI
Freight	VII
Other	VIII

2.3 Conclusion

The analysis that has been made in this chapter served as a tool to identify the key elements to reproduce the traffic flow and congestion patterns on the canals of Amsterdam. Using the information presented in this chapter, the first sub-question can be answered, which was as follows:

What are the main vessel types making up the traffic on the canals of Amsterdam in space and time and what are the traffic-flow and congestion patterns during a normal week/weekend day in summer/winter?

The traffic on the canals of Amsterdam could be recategorized according to their route choice behavior. The route each vessel takes is based on the type of vessel and the properties of the canal network (passage height per bridge, width, one-way traffic etc). Moreover, three vessel categories could be distinguished, namely fixed routes, random routes with sightseeing points as way-points, and completely random routes. These categories are named "cruise vessels," "random cruise vessels," and "pleasure craft" respectively. A possible model should be able to reproduce these vessel types and their corresponding route choice behavior.

The day-to-day traffic flow resembles the following: the traffic flow during summer on a weekend day is significantly higher than during summer on a weekday, and a large difference exists between the summer and winter months. For example, as Figure 2.9 displays, the difference between summer and winter can be around 100 vessels per hour at Anne Frank.

Congestion occurs mainly at crossings, where the narrower or more central the position of a crossing, the more congestion is caused. Examples of these bottlenecks are Haarlemmersluis and the crossing at Prinsengracht-Leidsegracht. In scenario 1 (a weekend day in July), the capacity of crossings was exceeded, and congestion occurred. No information was available to analyze congestion patterns for scenario 2 (a weekday in July), and thus, no conclusion could be drawn for the congestion patterns during this scenario. Furthermore, no information was available to analyze congestion patterns for scenarios 3 and 4. However, the assumption was made that almost no congestion occurred during scenarios 3 and 4 because of the large difference in the number of passages between the summer and winter months (Figures 2.9 and 2.10).

Regarding the distribution of vessels, data on the number of passages were available and could be used to derive the distribution of the three categories explained in Section 2.1.2 for scenario 1, or at least provide an order of magnitude. These data were limited to a Friday, Saturday, and Sunday in September, and thus were not usable for deriving the distribution of vessels for scenarios 2, 3 and 4. Table 2.7 shows an overview of the assumptions made for the distribution of the vessel types for each scenario.

With the identified three vessel categories with corresponding route choice behavior, a possible model should be able to reproduce these traffic flows and congestion patterns.

3

Model setup

This chapter derives an answer to the second subquestion. First, Section 3.1 discusses the applicable modeling concepts and selects one based on information about the key components of the Amsterdam canals traffic system presented in Chapter 2. Subsequently, Section 3.2 explains the functional requirements the model needs to have to reproduce traffic flow and congestion patterns.

3.1 Modeling concepts

As Chapter 2 concluded, to reproduce the traffic on the canals of Amsterdam this project needs to model the three vessel types and their corresponding route-choice behavior, which is based on the canal network. Therefore, the model also needs to accurately represent the canal network properties, and needs to model the different vessel objects (representing the different vessel types) sailing on the network which calculate their route based on these network properties and queue at crossings. Given these requirements, this section examines different frameworks, existing transport models, and programming languages that could be applied to this problem and determines which combination is most suitable.

3.1.1 Existing nautical traffic models

First, this study reviews if any existing model can be applied for this problem. Thus, this section examines whether existing models are useful for modeling traffic on the canals of Amsterdam.

SIVAK II

SIVAK II (or simply SIVAK) is a simulation program used to provide insights in studies related to shipping traffic in waterways, locks, narrowings, bridges, and other construction sites. For example, a fairway (including the accompanying construction sites, if any) can be modeled using SIVAK II to identify whether certain construction sites impose a bottleneck for ships that pass. SIVAK II generates mainly quantitative data that are used to provide insights into the effect on shipping traffic when certain changes are made. Several changes are possible. In SIVAK II, ships are programmed with an origin and destination (OD) pair, and they can be programmed to find a new route based on Dijksta's shortest path theory for each new canal they sail into (Kats et al., 2010). However, given that the program requires each ship to have an OD pair, the random routes pleasure craft follow cannot be programmed easily. It is also relatively difficult to program irrational behavior into SIVAK II, yet such behavior is typical for canal traffic. Thus, SIVAK II is a less attractive option for this project

BIVAS

BIVAS is a traffic allocation model on a national scale and can be magnified to examine a single waterway in the network closely. BIVAS is an application for analyzing issues in an inland transportation network, such as the effect of blockages and management strategies for allocating traffic. It develops scenarios for the network based on the initial situation and is mainly used to evaluate construction sites and adjustments on the national waterways (ChartaSoftware, 2018). BIVAS is a static model that focuses on traffic intensity, in which behavior cannot be programmed. It calculates the fastest route based on the traffic situation before the model is run, and thus it does not model reality well because ships might take another route if a faster route is believed to be available because it does not account for changes to traffic once the ship is underway. Therefore, BIVAS is not a suitable option for modeling canal traffic.

SIMDAS

SIMDAS evaluates the safety and capacity of waterways by analyzing traffic flows using simulations of individual ship–ship and ship–environment interactions. Both the analysis and the simulation of traffic flows are part of the SIMDAS program, which focuses heavily on safety and vessel–vessel interactions. SIMDAS is a product of MARIN and is not available for public use, thus is not useful for this project.

TNO Traffic Model

In 2013, TNO constructed a traffic model to allow Waternet to monitor canal traffic more closely. This model uses measurements from 18 sensors in the inner-city of Amsterdam as input. The output of the model shows how much traffic flows through the canals in real-time and predicts the amount of traffic for the next 24 hours based on historical data (Snelder and Calvert, 2013; Waternet and TNO, 2018). The TNO traffic model, however, is unsuitable for modeling the effect of canal closures. When Waternet attempted to simulate the effects of a canal-closure, the model returned unrealistic results as it was unable to incorporate the irrational behavior of the traffic. The model is therefore only useful for real-time modeling and cannot be used for this project. Although the TNO traffic model cannot be used for this project, knowledge gained from building the TNO model, or input data from the model, may be useful.

3.1.2 Traffic model frameworks

As can be concluded from the previous section, the existing nautical traffic models do not offer a good solution for accurately modeling the traffic on the canals of Amsterdam. Hence, a new model needs to be constructed. This section investigates several methodologies or frameworks that could be used and evaluates their applicability.

Most of the traffic simulation models simulate dynamical systems. In these models, time is the essential independent variable. In the time aspect, a classification can be made into continuous simulation models and discrete simulation models.

Continuous simulation models represent real-world systems by describing how the parts of a system change state continuously over time in response to constant provocations. Discrete simulation models represent real-world systems by stating that their states change abruptly at points in time. There are generally two classes of discrete models (Lieberman and Rathi, 1997).

- discrete time
- discrete event

Discrete time models represent time as a series of time intervals with a known length, Δt. Within each such interval, the simulation model calculates the activities of system components, which may change the states of other system parts.

Discrete event systems are characterized by modeling entities that are idle much of the time until an event changes their state. For some systems, this approach is valid. For example, the street lights turn on at 9 pm until sunrise. The state of the street light changes as it is turned on at 9 pm, remains constant throughout the night until another event, turning the light off at sunrise, changes the state of the street light. By modeling this way, the computer only has to calculate every event instead of the state of the signal every time step, and thus substantial savings in computer time can be realized (Lieberman and Rathi, 1997).

For real-world situations and systems of whose size is limited and whose entities' state change infrequently, discrete event simulations are more suitable compared to discrete time simulation models and moreover, are considerably more economical in performance time. If, however, systems need to be modeled wherein entities experience a constant change in state, such as a traffic system, and where model purposes require precise descriptions, the discrete time model is expected to be a more suitable option (Lieberman and Rathi, 1997).

Simulation models may also be categorized to the level of detail.

Microscopic traffic models

Microscopic traffic models describe the details of traffic flow and the interactions taking place within that flow by reproducing single vehicle-driver units. Each unit adapts its response according to the other units and to the infrastructure around it. The microscopic classification of traffic is made via three fundamental variables: the position x (m), the speed v (m/s^{-1}) and the acceleration (m/s^{-2}) (Mammar et al., 2006). These models can be divided into three categories:thee car-following model, lane-changing models and gaps of the individual drivers ((Nor Azlan and Md Rohani, 2018)

- The car following model is based on the concept where the behavior of a vehicle is determined by the driving behavior of the vehicle in front of it. If the lead vehicle reduces speed, then the following vehicle to the lead vehicle reduces speed.
- The lane-changing model is a decision process to approximate the driver's behavior in performing a lane change within the given time., i.e., how the vehicle changes lane based on vehicles near it.
- Gap acceptance models are used to examine the size of the gap that will be accepted or refused by a car who intended to merge or cross the intersection.

Most microscopic models use a car-following model in combination with a lane-change model. Microscopic models cannot be used to investigate a large network because the amount of computational work required would be excessive (Casas et al., 2011). On the canals of Amsterdam, traffic is not restricted to lanes, and thus does not follow the rules of car-following and lane-change models. These concepts are applicable only on peak-traffic days, when many vessels sail on the canals. Overall, a microscopic traffic model based on these concepts may not be an attractive option.

Macroscopic traffic models

Macroscopic models are mostly applied to simulating traffic over highways covering large geographic areas. Where microscopic models track vehicles separately, macroscopic models use less detailed models and assume a sufficiently large number of vehicles on a road such that the traffic can be represented as a compressible fluid, with the main properties of flow, density and speed (Gentile, 2010). A macroscopic flow model for road links based on kinematic wave theory is joined with a node model for crossings, therefore reflecting congested networks including queue spillback (Gentile, 2010). Congestion arises when the number of cars traveling on link i-1 transitioning to the input node (start point) of link i (or the output node from link i-1) is larger than the maximum flow that can enter the link (Hueper et al., 2009). When there are too many cars (i.e., the density is too high) for the highway capacity, vehicles decelerate, causing queue spillback and a traffic jam. The shortfall of these models is in congested areas, as they are unable to model the required level of detail. These models operate on the assumption that there is always heavy traffic, and that highways have a maximum capacity (Immers et al., 2010). However, in the Amsterdam canals, most delays are experienced at crossings and narrowings rather than being the result of shockwaves in road traffic, meaning a macroscopic model is less attractive for this use.

Mesoscopic traffic models

Mesoscopic models provide a middle ground with their ability to model large networks with limited network coding, while giving a better representation of the traffic dynamics and individual travel behavior than their macroscopic equivalents (Vorraa and Brignone, 2008). However, they are still restricted in their capacity to reflect detailed traffic movements. On roads (edges), the behaviors of vehicles in the model are the same as in the macroscopic model explained in the previous section. As vehicles reach the end of a road, they encounter a crossing or intersection (node). At such a crossing (node), a microscopic model is implemented to simulate in detail the traffic interactions and how the vehicle continues to its next road. In such models, the more complicated areas in a traffic network (such as large roundabouts and complex intersections) benefit from the additional detail provided by the microscopic component (Burghout et al., 2006). An integrated option is that a vehicle may divert from a route when a faster route is found. Given the case of Amsterdam canals, where there is a maximum speed of 6 km/h (Waternet, 2018), when the capacity of the canals is exceeded and bottlenecks occur, the mesoscopic model is a possible option. However, during most of the year this is not the case.

Agent-based modeling

In agent-based modeling (ABM), decentralized individual "agents" make up a system, interacting with other agents within rather small areas according to each agent's localized knowledge (Kikuchi et al., 2002). Agents are computational entities that have properties, or state variables, and values (e.g., position, speed, age, and wealth). They also have rules of behavior. A gas molecule agent, for example, might have a rule to collide with another molecule, whereas a sheep agent might have a rule to eat grass if there is grass available nearby (Chaudhry, 2016). The goal of the ABM methodology is to model every entity at the same time, so that the results of these agent interactions can be observed (Chaudhry, 2016).

Traditional transport models study the performance of a complex transportation system, whereas the bottom-up ABM approach seeks to discover why travelers make certain decisions and how the transportation system performs when those decisions are made (Zheng, 2013). One of the important areas of study in transportation systems is the study of traveler behavior. Travelers' route choice behavior can be categorized into two types: before a trip (preplanned) and during a trip (enroute decisions).

Normally, microscopic, mesoscopic and macroscopic models assume that all travelers are homogeneous, have full knowledge of the network, and always take routes with the minimal cost (Zheng, 2013).

In reality, however, this is not the case. ABM acknowledges that travelers may have limited information about variables such as traffic conditions, incidents, and weather conditions. Hence, ABM captures the uncertainty of travelers' behavior, unlike discrete choice models that assume travelers are always rational with access to full information. ABM was specifically developed to address this complexity and to study individual decision making, wherein learning and interaction could be included. It allows the following aspects to be modeled (Zheng, 2013):

- It can update travelers' decisions and knowledge (learning) on a real-time basis.
- It can formulate and simulate the mechanism of travelers' complex decision-making process.
- It can predict travelers' responses to real-time, en-route information or similar unexpected provocations in the environment.
- It can potentially observe emergent behavior in response to a new environment structure.
- It can represent and obtain the individual traveler's rational and irrational behavior and preferences, which are hard to quantify or measure in conventional route-choice models.
- It can obtain interaction effects and collective behavior that originate from travelers' heterogeneity.

Agent-based modeling thus seems to be a very suitable framework to model the rational and irrational route choice behavior of vessels (in particular, the pleasure craft) sailing on the canals of Amsterdam. It could be used as a tool to understand not only *when* congestion occurs, but also to understand *why* congestion occurs. This study therefore selected the ABM framework for use in constructing a model. As ABM models every vessel as a single entity, it, therefore, models on a microscopic level.

3.1.3 Static versus dynamic

The main problems in transport planning modeling are encountered when static models are used. When these models are used in the short term-at the operational level of transport planning—the disadvantages are apparent immediately. Static models will not adjust route choices along the journey of a vehicle; the minimum travel time is calculated before departure. Dynamic models adjust the route according to the shortest travel time as determined enroute. Furthermore, route choices made by static models for multiple simultaneous travelers with the same OD pair are all the same. This will readily create congestion during peak times (Li, 2017; Chiu et al., 2011). Dynamic models work at a lower level, involving shorter durations and the runtime of the system. The interaction of system components such as congestion, rush hour, and network disruption can be considered in dynamic models. This makes the network performance estimated by a dynamic model closer to reality than that estimated by a static model (Li, 2017; Chiu et al., 2011).

The route followed by the traveler may change due to dynamic factors in a network. Existing static models, being incapable of analyzing effects such as queue spillback, oversaturation, and peak spreading, are, therefore, limited (Li, 2017; Chiu et al., 2011).

3.1.4 Programming languages & packages

Now that the choice for the model framework has been made, the next step is to define which language and packages can be used for this project. As seen in Chapter 2, a network needs to be constructed with properties that represent real-world spatial coordinates. Vessel objects should move on the network, calculate their route based on the network structure and properties, and queue at crossings so as to reproduce traffic flow and congestion patterns. To achieve these ends, this study applies network logic (graph theory) and queueing theory. Open-source packages are available for applying graph theory and queueing theory.

NetworkX [1] is an open-source package in Python that is widely used for solving graph theory problems. It contains algorithms for constructing a graph or network, assigning attributes and properties to edges (canals) and nodes (bridges and crossings), and calculating shortest paths based on network properties (Varoquaux et al., 2008). Because it is a widely used open-source package, and thus thoroughly tested, its algorithms can be trusted and used in this project.

SimPy [2] is an open-source package in Python to simulate discret-event and discrete time queueing theory problems. It can be used to model active components like customers, vehicles or agents. SimPy also provides various types of shared resources to model limited-capacity congestion points (like servers, checkout counters and tunnels). It can be used to apply queueing logic to vessel objects, enabling them to queue at crossings (Matloff, 2008). It is, like the NetworkX package, an often-used open-source package. Therefore, its algorithms can be trusted and used in this project.

Many different computing languages could have been used for this project; however, preference was given to languages with enough packages (algorithms) available, that were open-source, and were relatively easy to learn. However, given the availability of important packages such as SimPy and NetworkX, the usefulness of open-source object-oriented programming language to model vessels easily and the fact that the model is build within a community setting at the TU Delft which uses Python, this study selected Python to construct the model.

Many different computing languages could have been used for this project; however, preference was given to languages with available open-source, easy-to-learn packages (collection of algorithms). Given the availability of important packages such as SimPy and NetworkX; the usefulness of an open-source, object-oriented programming language in modeling vessels; and the fact that the model would built within a community setting at TU Delft that uses Python, this study selected Python as the model language.

3.1.5 Model concepts conclusion

Sub-subquestion 2(a) is as follows:*“What modeling concepts are applicable?”* The mesoscopic model framework and the ABM framework are applicable. These two concepts are different but are both suitable for this project.

As analyzed in Chapter 2, to reproduce actual traffic flow and congestion patterns, the model needs to reproduce the three vessel types with their corresponding route-choice behavior, which is based on the network properties. Therefore, ABM and the mesoscopic model are the most promising frameworks. Of these two, this project uses the ABM framework, because it can represent the distinct sailing speed and route selection of each vessel type, can reproduce the behavior of the three vessel types that interact, and offers the additional option of incorporating irrational behavior. For the simulation of time, this study uses discrete time steps. The use of discrete time steps is useful as agents move on the network. It does, however, require

[1] The package can be found at `https://networkx.github.io/documentation/stable/`

[2] The package can be found at `https://github.com/cristiklein/simpy`

more computational time as every step needs to be computed to update the state of the agent instead of updating it when an event occurs.

Many different computing languages could have been used for this project; however, preference was given to languages with enough packages (algorithms) available, that were open-source, and were relatively easy to learn. However, given the availability of important packages such as SimPy and NetworkX, the usefulness of open-source object-oriented programming language to model vessels easily and the fact that the model is build within a community setting at the TU Delft which uses Python, this study selected Python to construct the model.

Vessel objects in the model sail in discrete time steps and calculate their route based on the network structure and properties. Consequently, this project uses the NetworkX package to construct a network (graph) based on the spatial coordinates of the Amsterdam canal network, and each vessel object in the model uses the NetworkX package to calculate its route on the network. The model uses the SimPy package to reproduce queueing and crossing simulations at crossings.

The Waternet data are useful for validating the agent-based model constructed in Python and are used in this project together with the data from the interviews on route choice behavior of each type of vessel.

To model reality as well as possible, a decision must be made regarding whether the model is to be dynamic or static. The model in this project can be said to be partly dynamic and partly static. Whether to model a vessel's behavior as static or dynamic depends on the behavior of each vessel. Some vessels do not mind waiting in the queue, whereas other vessels will adjust their route whenever the canals are busy, thereby making their behavior dynamic. Figure C.1 presents the behavior of each category of vessel.

This study chose to make use of programming languages and frameworks instead of use existing models. SIVAK II would be the most applicable of the models listed in Section 3.1.1. Using SIVAK II, it is possible to model a network with objects and to program both dynamic routing and static routing for ships in the network. However, the model also requires that each ship has an OD pair; therefore, the random routes of pleasure craft cannot be programmed easily into SIVAK II, making it less attractive for use in this project.

3.2 Functional requirements

Chapter 2 showed the main elements needed to reproduce the traffic flow and congestion patterns, i.e. the different vessel types sailing on the network, calculating their own (new) route, and queue at crossings. Hence, using the ABM framework, a number of requirements exist that must be met to model the simulate nautical traffic in the most realistic manner. This section discusses the actual model design and gives an answer is to the second sub-subquestion 2 (b) (*ii. What functional requirements does the model need to have in order to approximate the nautical traffic on the canals of Amsterdam?)*.

3.2.1 Network

Before traffic on the canals can be modeled, the canals themselves must first be modeled. The model should be able to represent the network of canals realistically. Because captains of vessels calculate their route based on the structure of the network, the network can mathematically be represented as a graph. A graph $'G'$ is a set of vertices called nodes $'v'$, which are connected by edges $'e'$ (Wilson, 1996). $G = (v, e)$. Here, several properties are worthy of examination.

1. **Crossings and bridges as nodes**: A vertex v is an intersection point of a graph, also referred to as a node. It can be a location such as a city, a road intersection, or a transport terminal (e.g., a station, harbor, or airport) (Wilson, 1996). Because canals are connected at intersections (or crossings), each crossing should be modeled as a node. Because bridges in the canal network have dimensions and contain attributes such as passing height and one- or two-way passage, the bridges themselves should also be modeled as nodes.

2. **Canals as edges**: An edge e is a link between two nodes. A link denotes a connection between nodes. It can have a direction, which is generally represented as an arrow. If an arrow is not used, it means the link is bidirectional (Wilson, 1996). To model the canal network of Amsterdam realistically, the canals themselves can be modeled as edges because, just like edges, they connect intersections (crossings). As

a basis, edges are defined where there are canals, and nodes are defined where canals begin or end and where more than two canals come together. Edges can have attributes assigned such as distance, which can be used to add the geographical distance between bridges and crossings. To represent one-way traffic regulations, the canal network is represented as a bidirectional graph.

3.2.2 Vessels

To fully model vessels as realistically as possible, each vessel should be represented as a distinct entity meeting the requirements described below. These functional requirements are divided into two categories:

- *The essential functional requirements*
- *The additional functional requirements*

The essential functional requirements are the most critical for reproducing traffic flow and congestion patterns. To model canal traffic most realistically, textitthe additional functional requirements need to be implemented as well. For now, however, this project focuses on only the essential functional requirements.

The essential functional requirements:

1. **Move on the network**: Each vessel should be able to move (set a step) on the network. For example, if a vessel travels from node A to node B along edge 1, the vessel should be able to set steps based on its traveling speed and timestep in the direction of node B on edge 1. The vessel should know when it has arrived based on the distance between the nodes, because it continuously updates the distance left to travel before it reaches node B.
2. **Following route**: After the vessel calculates its route, it should follow that calculated route and stop when it reaches the end.
3. **Stay on the network (different timesteps)**: The vessel should always be on the network. This means that the vessel is always either on a node or traveling on an edge to a node. If the timestep is increased, and assuming that the speed of the vessel does not suddenly decrease, the step size (= speed x timestep) of the vessel should also increase. The vessel should be able to stay on the network for any given step size. This is best illustrated with the following example: If a vessel starts at node A, travels via edge 1 to node B, and then via edge 2 to node C, the vessel should travel via those edges to each node and should not deviate from those edges (deviation would represent traveling on land). If the step size happens to be larger than the distance between node A and node B, then at timestep 2 the vessel should be on edge 2 traveling to node C.
4. **Types of vessels**: Different vessel types (see Section 2.1.2) should be able to be modeled as different entities, each having different attributes, such as length, width, traveling speed, and route calculation behavior.
5. **Routing for the different vessels**: For each vessel, it is necessary to determine a route from origin to destination using the canal network. A vessel should, therefore, be able to calculate its own route before departing. This route calculated can vary based on the type of vessel, because each vessel type calculates its route in a different manner. In Section 2.1.2, three types of vessel were identified based on the route they take.
   (a) Cruise vessels
   Cruise vessels should calculate their predetermined route. The routes these vessels sail should mimic the routes these vessels take in reality.
   (b) Random cruise vessels
   A random cruise vessel should be able to calculate its own route based on the following conditions:
      - It calculates its route based on sightseeing points, the average sailing speed, the time it has, and the length of each canal of each canal.
      - A tour takes a maximum of 1.5 hours.
      - It does not or rarely travel(s) on the same canal twice.
      - It does not visit the same zone twice (unless it is the start point).
      - It selects its start point at random from among a set of possible locations.

- Whenever a sightseeing point is based within a closed-off canal, that location is removed from the sightseeing point list.

(c) Pleasure craft
A pleasure craft should be able to calculate its own route based on the following conditions:
- The sailing time can vary from 2 to 5 hours.
- It randomly calculates its route according to the average sailing speed, the time available, and the length of each canal.
- It is allowed to travel on the same canal twice.
- It is not allowed to turn around in the middle of a canal.

6. **Static rerouting and width restriction**: Whenever part of a route is not available, each vessel type has its own distinct set of rules for adjusting its route.

   (a) Cruise vessels
   As explained in Section 2.1.2, whenever part of its original fixed route is not available, a cruise vessel should be able to find the shortest detour route, so that it returns as soon as possible to its original route. This detour is shortest in distance and based on the canals it is allowed to sail. The cruise vessels are only allowed to sail on canals with fairway profile B (Figure 2.1) or higher.

   (b) Random cruise vessels
   Whenever a random cruise vessel calculates its own route, it should check if a sightseeing point is based within a closed-off canal. That location is removed from the sightseeing point list.

   (c) Pleasure craft
   WheneverA pleasure craft calculates its own route, it should check if a waypoint point is based within a closed-off canal. That location is removed from the waypoint point list.

7. **Queuing**: Vessels should be able to queue and wait whenever a one-way passage bridge or crossing is occupied.

The additional functional requirements:

1. **Queue spillback**: Because every vessel should be able to queue, its physical position in the queue should be the same as its position in the queue, which is based on the physical dimensions of each vessel that is in the queue before it. When a queue originates, the queue should spill back on the particular edge. When a queue gets very long, it could potentially influence other crossings.

2. **Approaching the queue** Whenever a vessel is within one step of the queue, its velocity should reduce linearly to zero. Hence, the time to arrive at the queue increases.

3. **Vessel-vessel interaction**: Not every vessel travels at the same speed, and thus vessels should be able to overtake other vessels. Because canals are not as wide as fairways, overtaking is not always possible when there is oncoming traffic. Therefore, the vessel should wait until the oncoming traffic has passed and then initialize overtaking.

4. **Sailing rules**: Vessels should be able to determine who has right of way when entering a crossing and, based on right-of-way sailing rules, cross when it is their turn.

5. **Dynamic routing**: A vessel should be able to adjust its route while en route. Reasons for adjustment include congestion occurring on a crossing that is part of the original route. To minimize delay times, a vessel could consider changing its route. This type of routing is called dynamic rerouting, or time-dependent (re)routing, as explained in Section 3.1.3. Another example of dynamic rerouting is when a random cruise vessel checks how much time it has left, and depending on how much delay time it has already experienced, it could choose to sail toward another sightseeing point or sail home because it may only sail 1.5 hours. It consequently calculates its route en route.

6. **Vessel-canal interaction**: Because not every vessel has the same physical dimensions, each vessel interacts differently with the physical properties of the canal network. For example, cruise vessels are almost too long to make a sharp corner. Thus, they take more time to maneuver on a crossing. Another example is found in overtaking on the canals. Cruise vessels may have to wait before overtaking another vessel because of the physical dimensions of each vessel, oncoming traffic, and the dimensions of the canal. However, a pleasure craft overtaking another pleasure craft in the same situation may not have to wait.

7. **Memory and learning**: Because captain of cruise vessels and random cruise vessels sail in the canals often, they know at which crossings congestion is usually experienced. Thus, they can choose to avoid certain crossings or canals that are notorious for congestion. This learning behavior plays a role in canal-closure. Whenever a canal has been closed off, traffic takes another route, which may cause congestion at certain points. When a captain experiences too much congestion, he or she will learn to avoid certain crossings or canals and readjust a route accordingly.

8. **Irrational behavior**: Sailing on the canals of Amsterdam can be quite chaotic. There are many inexperienced people who are unfamiliar with the crossings (e.g., one-way bridges in combination with a crossing). Examples of irrational behavior include irregular sailing speed, stopping, and taking too long to cross a crossing. Pleasure crafts in the model should be able to incorporate this type of sailing behavior. Moreover, actual pleasure crafts can immediately decide to adjust their route or return home. Thus, this type of dynamic rerouting and irrational behavior should be incorporated into the model.

3.2.3 Simulation

To model all the vessels that move on the network as realistically as possible, some functional parameters and requirements must be set to optimize the simulation and obtain the most realistic results.

1. **Vessels in simulation**: In the simulation, vessels should travel on their own calculated routes. Because this is an ABM framework, vessels travel by themselves and keep track of their own passage of time. The simulation environment does not decide whether a vessel should move; each vessel decides each timestep and whether to make a move. The simulation, therefore, just runs the time and space wherein the vessels can move.

2. **Timescale**: As explained in Section 2.1, nautical traffic demand in Amsterdam starts at approximately 00.00 and ends at 24.00. Thus, the timescale the model simulates should be a maximum of 24 hours.

3. **Discrete timestep**: To obtain the most detailed results, the timestep could be set as 1 second. This would mean that the step size of each vessel would be equal to its speed in meters per second. However, this would provide an overload of information and the simulation time would increase linearly because it would have to calculate each second. On the other hand, a step size that is too large would mean not only a decrease in simulation time but also the loss of valuable information. Thus, a proper timestep should be used.

4. **Vessel generator parameter**: The different traffic-demand scenarios defined in Section 2.2.1 can be reproduced using a defined vessel generator to generate the amount of traffic and distribution required for each traffic-demand scenario. To change the simulation output, different traffic demand scenarios can be used as inputs for the vessel generator.

5. **Canal-closure parameter**: The goal of this research is to build a tool to analyze the consequences of canal closures. Therefore, a parameter in the simulation should be the ability to alter the network by removing an edge or changing a two-way edge to one-way. To change the simulation output, different canal-closure scenarios can be used as inputs for the simulation.

6. **Crossings**: To simulate whose turn it is on a crossing, the crossing itself must also be simulated. Using a first-come first-served (FCFS) rule, the simulation must let vessels know when it is their turn to cross. The upper limit of the timestep depends on the minimum distance between two crossings, because a timestep that is too long could allow vessels to skip one crossing.

3.3 Model overview

This study built a model using *the essential functional requirements* identified in the previous section. This section, therefore, shows a complete overview of the model.

3.3.1 Network

As explained in Section 3.2, the canal network is mathematically represented as a graph $G = (v, e)$. Each canal is represented as an edge e, connecting two vertices v (nodes). Each bridge or crossing in the network is represented as a vertex v (node). The network is depicted as a graph in Figure 3.1 as generated with the

NetworkX package. To fully accommodate the current traffic regulations (one-way passage or no-entry), the network will be modeled as a directed graph. Whenever a canal can be used in both directions, it must be separated into two directed edges, one for each direction, containing nodes at the start and end of canals, at places where canals cross, and at bridges. Each edge can have associated costs and constraints, which are called the *attributes* of an edge, and which are used by a vessel to calculate its route. Because each vessel calculates its route based on the cost of each edge, the cost of an edge can be defined as the travel time it requires on each edge in each direction, which can be different for each vessel. The cost of each edge can be a product of the geographical length of the corresponding canal and the average travel speed on that edge, which is based on the amount of traffic and queuing along that edge.

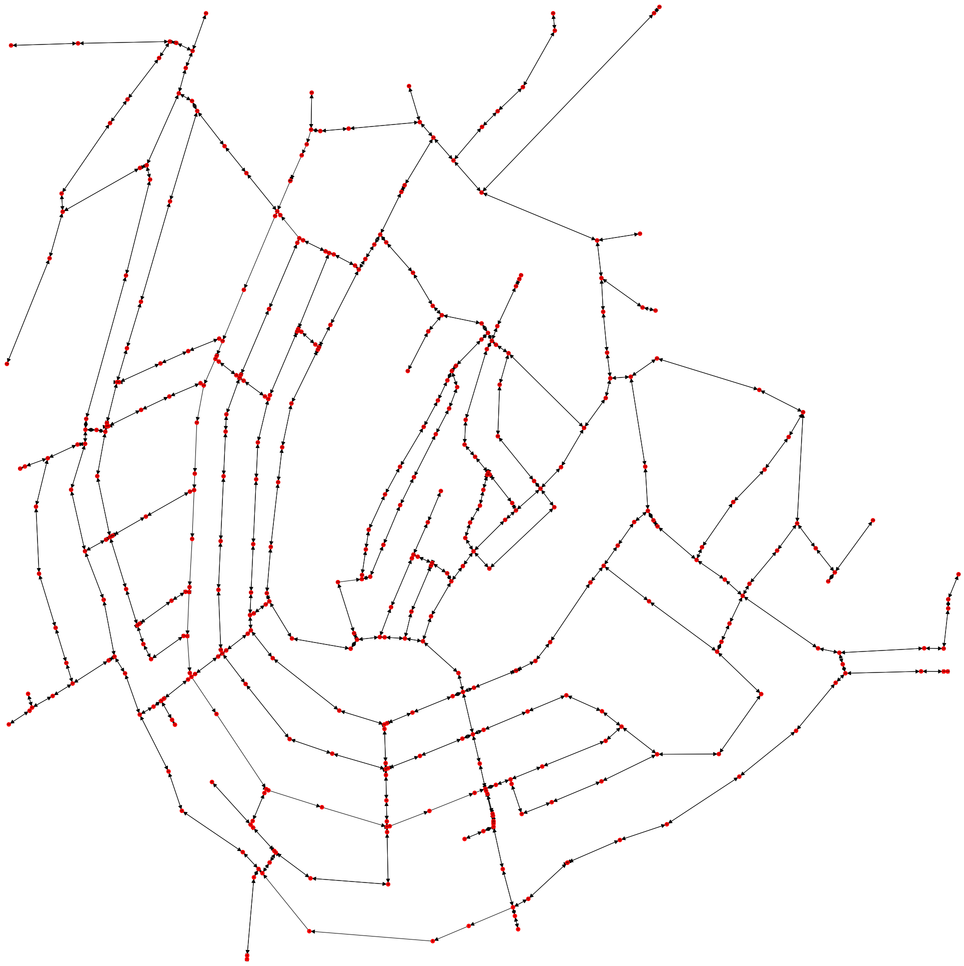


Figure 3.1: Graph of the canal network of Amsterdam, created with the NetworkX package in Python

3.3.2 Vessels

Each vessel is modeled as an object moving on a graph in time steps with different attributes (such as speed) and functions (such as routing and rerouting), and thus each vessel can think for itself and make its own choices based on the logic that has been programmed for it. For this project, the author implemented only *the essential functional requirements* described in Section 3.2.2. Chapter 6 makes recommendations for implementing t*the additional functional requirements*.

As analyzed in Section 2.1.2 and shown in Figure C.1, the vessels on the canals can be divided into three distinct categories based on route-choice behavior.

Routing algorithms

The functional requirement of route calculation is explained in terms of graph theory, because the graph with nodes and edges now represents the canal network. Formally, a graph is a pair of sets (V,E), where V is the set of vertices and E is the set of edges, formed by pairs of vertices. E is a multiset; in other words, its elements can occur more than once, so that every element has a multiplicity (Ruohonen, 2008). For a graph $G = (V(G), E(G))$:

- *Walk*: A Walk is defined as a sequence of alternating vertices(nodes) and edges such as $v_0, e_1, v_1, e_2, ..., e_k, v_k$ where each edge $e_i = (v_{i-1}, v_i)$, the Length of this walk is k. A walk is considered to be Closed if the starting vertex is the same as the ending vertex, that is $v_0 = v_k$. A walk is considered Open otherwise.
- *Trail*: A Trail is defined as a walk with no repeated edges (links).
- *Path*: A Path is defined as an open trail with no repeated vertices (nodes).
- *Circuits*: A Circuit is a closed trail. That is, a circuit has no repeated edges but may have repeated vertices.
- *Cycle*: A Cycle is defined as a closed trail where no other vertices are repeated apart from the start/end vertex (start and end node).

Consequently, whenever a vessel calculates a route on a graph, it is the same as calculating its Walk/Trail/-Circuit.

As explained in the previous section, there are different types of vessels, each calculating its own route. The general principle of each vessel is explained under the following headings, and a flowchart is used to derive a general sense of the algorithms behind the route and reroute calculations. The vessels calculate their route with help from path algorithms, such as Dijkstra's shortest path, taken from the NetworkX package.

Cruise vessels

Each cruise vessel has its own fixed set of routes. Figure 3.2 presents a flowchart of the algorithm that calculates its route. For HoHo liner vessels, the HoHo locations can be seen as waypoints. The algorithm takes the original path, uses the HoHo locations as waypoints, and calculates using Dijkstra's shortest path between these waypoints. If ever a canal is closed off, the cruise vessel will find its shortest path to the next waypoint but will try to stay as much as possible on the original route. A cruise vessel's route can be defined as a *circuit*, which is not the case for all routes of other vessels. Their speed is approximately the maximum sailing speed allowed.

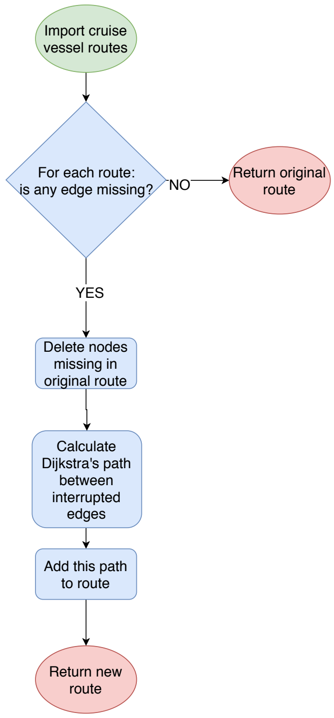


Figure 3.2: Flowchart of the algorithm for calculating a cruise vessel's route

Random cruise vessels

The goal of a random cruise vessel is to show as much of the city as possible to passengers within a limited amount of time. Trip times can vary among companies but on average are approximately 1.5 hours. The number of sightseeing points that can be visited depends on the route that is calculated. It can be quite a challenge to calculate the optimal route to visit as many sightseeing points as possible and be back in time at the start position. This problem can be represented as the traveling salesman problem (TSP). In simple terms, given a list of sightseeing points and the distances between each pair of sightseeing points (also represented by a distance matrix), what is the shortest possible route that visits each sightseeing point and returns to the original start point? The TSP can be described as an NP-hard[3] problem, meaning that it can take much computational time to solve the problem depending on how many combinations can be made, which exponentially increases with the number of sightseeing points to be visited. Furthermore, some functional requirements make the calculation of the most optimal route still more time consuming, such as vessels not being allowed to sail on the same edge twice or to turn around on an edge. These functional requirements make the distance matrix asymmetrical and more challenging to solve. The general outline to calculate the most optimal combination for a TSP problem is as follows:

Naive solution:

1. Consider the departure point as the starting and ending point.
2. Generate all (n-1)! permutations of sightseeing-points (n = number of sightseeing points).
3. Calculate the cost of every permutation and keep track of minimum cost permutation.
4. Return the permutation with minimum cost.

Time Complexity[4]: $\theta(n!)$

[3]Different complexity classes exists for optimization problems (Alsuwaiyel, 2015):

- P - A problem for which there exists a polynomial time algorithm
- NP – A problem for which there exists a polynomial time algorithm that is able to ascertain the feasibility
- NP-complete – A problem that is NP and at least as difficult as any acknowledged NP problem
- NP-hard - A problem that is not necessarily NP and at least as difficult as any NP problem

[4]The amount of time it demands to run an algorithm

Because many random cruise vessels sail on the canals of Amsterdam, calculating the optimal solution for each vessel given a random sample of sightseeing points and the functional requirements for route calculation (given in Section 3.2.2) requires too much calculation time.

Instead, a heuristic method is used to set up the algorithm for route calculation. The route may cover a maximum distance of 1.5 hours x 60 minutes x sailing speed (approximately between 5 and 6 km/h) = approximately 7500 - 9000 m depending on the average sailing speed. The algorithm works as follows. It picks a random sightseeing sample set from the sightseeing list and for each point in the sample checks what the shortest distances from and back to the starting point are using the Dijkstra's path algorithm with the cost of each edge as the weight function. It picks the point with the shortest distance, "sails" to that location, adds the number of meters sailed to the parameter meters sailed, marks the edges it has sailed on, removes the point from the random sample, and checks again for each remaining points what the shortest distance is from that particular sightseeing point to the other sightseeing points. Subsequently, it checks whether it is possible to sail to the nearest next location and back via a different route using Dijkstra's path algorithm with the cost of each edge as the weight function without exceeding the maximum meters to be sailed parameter. This routine continues until either no distance is left to sail, which means it only has time to sail back, or all sightseeing points have been visited. This heuristic method incorporates all functional requirements. Thus, a random cruise vessel's route can be defined as a *circuit*. Figure 3.3 presents a flowchart for this algorithm.

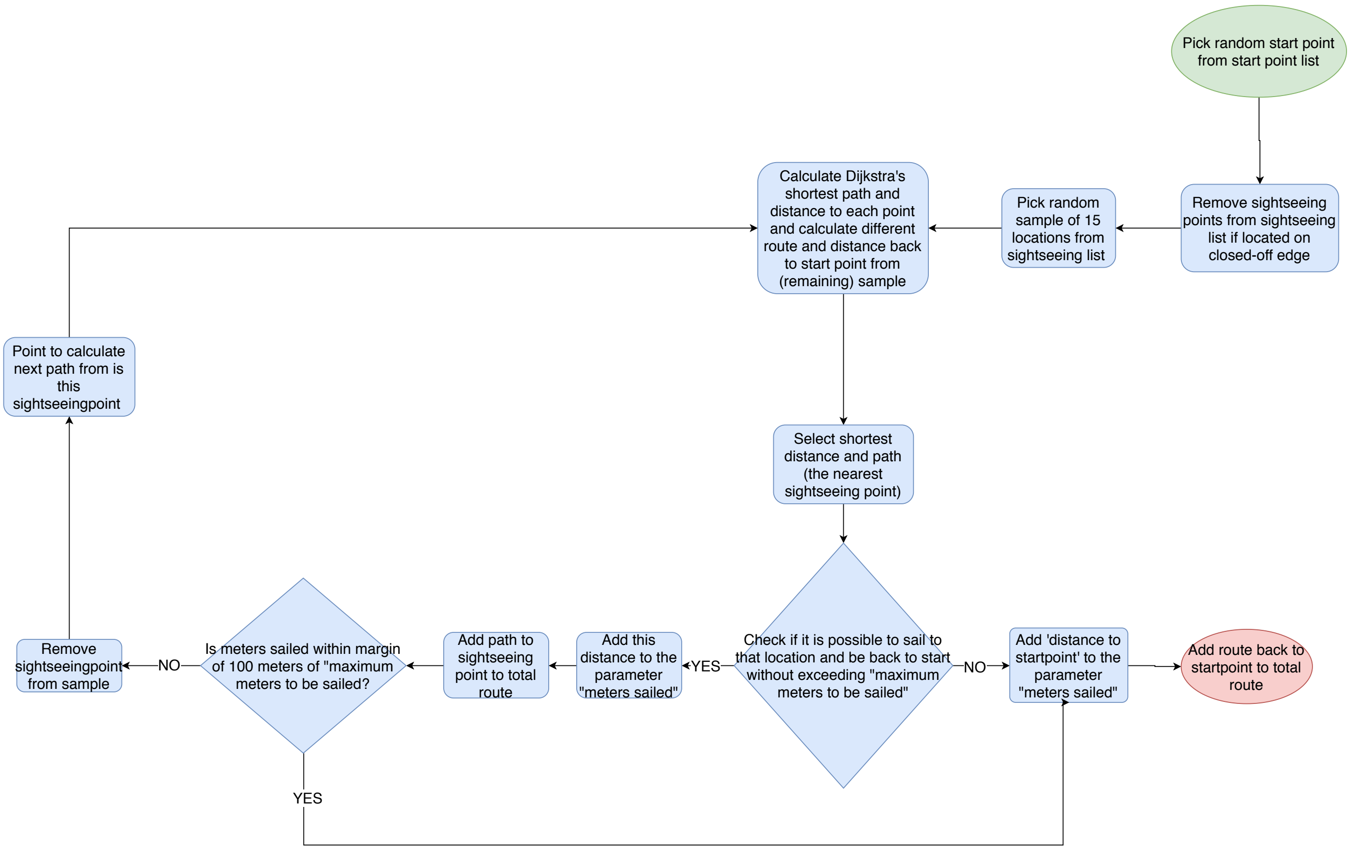


Figure 3.3: Flowchart of routing algorithm of "random cruise vessel"

Pleasure craft

Pleasure craft calculate their route based on the time they can sail and the average sailing speed. It is assumed that the travel speed of pleasure craft is somewhat lower than that of cruise and random cruise vessels. The trip may take a maximum of 5 hours x the sailing speed (approx. 5 - 6 km/h) = approximately 25,000 - 30,000 m (depending on the sailing speed), and a minimum of 2 hours x the sailing speed (approx. 5 - 6 km/h) = approximately 10,000 - 12,000 m (depending on the sailing speed). The algorithm for route calculation is somewhat similar to a "random walk." However, because of the maximum-length functional requirement, the random walk algorithm is not applicable for route calculation. The random walk algorithm was not designed for the purpose of creating a walk on a graph with maximum length that would then return to a start point.

Instead, a heuristic algorithm is set up, similar to that used for the random cruise vessel. However, instead of sightseeing points, random nodes in the graph are used and there are fewer functional requirements. Thus, a pleasure craft's route can be defined as a *Closed Walk*. Figure 3.4 illustrates this heuristic method.

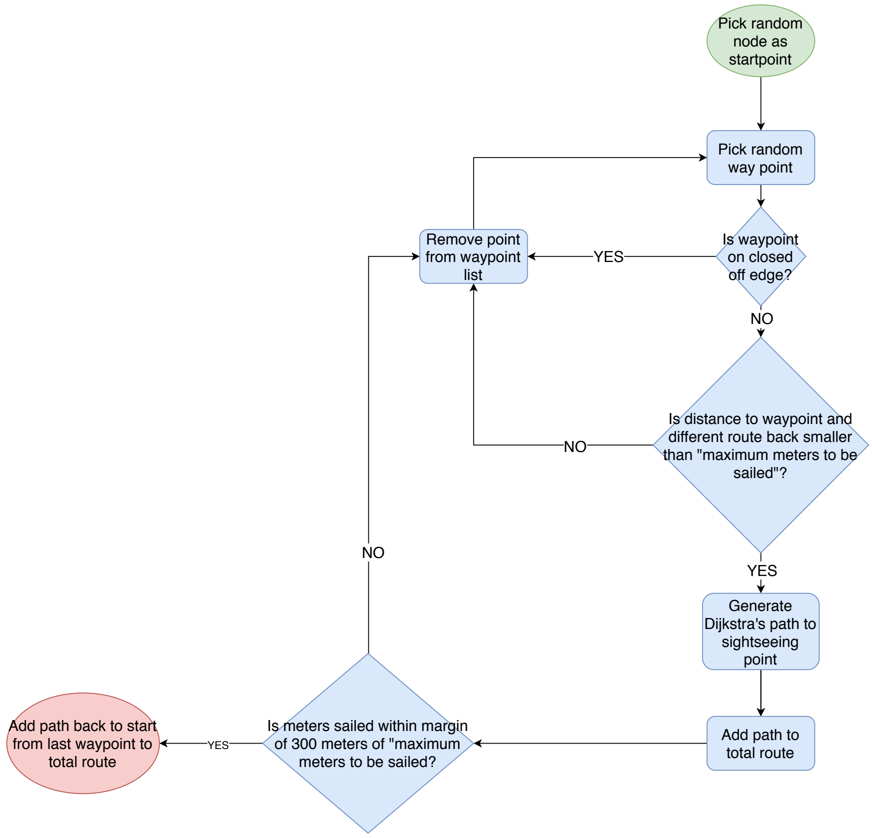


Figure 3.4: Flowchart of the algorithm used to calculate pleasure crafts' route

3.3.3 Simulation

Timestep and scale

The simulation must represent one full day, as was described in Section 3.2.2. The timestep chosen for the model is 10 seconds, meaning that for every timestep, 10 seconds of simulation time has passed. The timescale is 24 hours, starting at midnight. This information is passed to each vessel.

Pre-processing

Before conducting the actual simulation, some information must be acquired. The first item required in the simulation is the canal network being used, which is then transformed into a graph with nodes and edges, as explained in Section 3.2.2. The second item required is the specific traffic-demand scenario to be simulated. The third and last item required is the specific canal-closure scenario to be simulated, which identifies those edges to be removed from the graph.

Crossings

With the SimPy package, the crossings are simulated on an FCFS basis and are modeled as a server with a specific capacity. Whenever a vessel is positioned to cross a crossing within a given timestep, it makes a request at the specific server representing that crossing. The representative server then checks whether enough capacity exists at that moment. At some crossings, it is possible to serve four vessels simultaneously, whereas others may have room for only one or two vessels. If there is enough capacity, the vessel takes 20 seconds to cross the crossing. If the vessel has to wait because the capacity of the crossing is full, its speed is reduced to zero until it is that vessel's turn to cross. When it is, the vessel takes 40 seconds to cross the crossing because it has to start again and regain speed. Therefore, one position of the server capacity is occupied for 40 seconds if the vessel has to wait; otherwise, that position is occupied for 20 seconds.

Vessel generator parameter

The simulation must add vessels to the graph to represent any traffic-demand scenario. The vessel generator operates as follows. It checks which hour it is and then checks how many vessels should be generated on the graph to simulate the traffic demand for that hour. To reproduce the random arrival times of vessels, vessels are randomly distributed within each hour over the number of timesteps in that hour. Consequently, at some timesteps, more vessels may be generated than at other timesteps within the same hour. Each type of vessel has its own vessel generator to simulate the vessel type's arrival distribution.

3.3.4 Overview

Figure 3.5 and Figure 3.6 provides a complete overview of the flow of information between the vessels, the network, and the simulation, which has been described in previous sections.

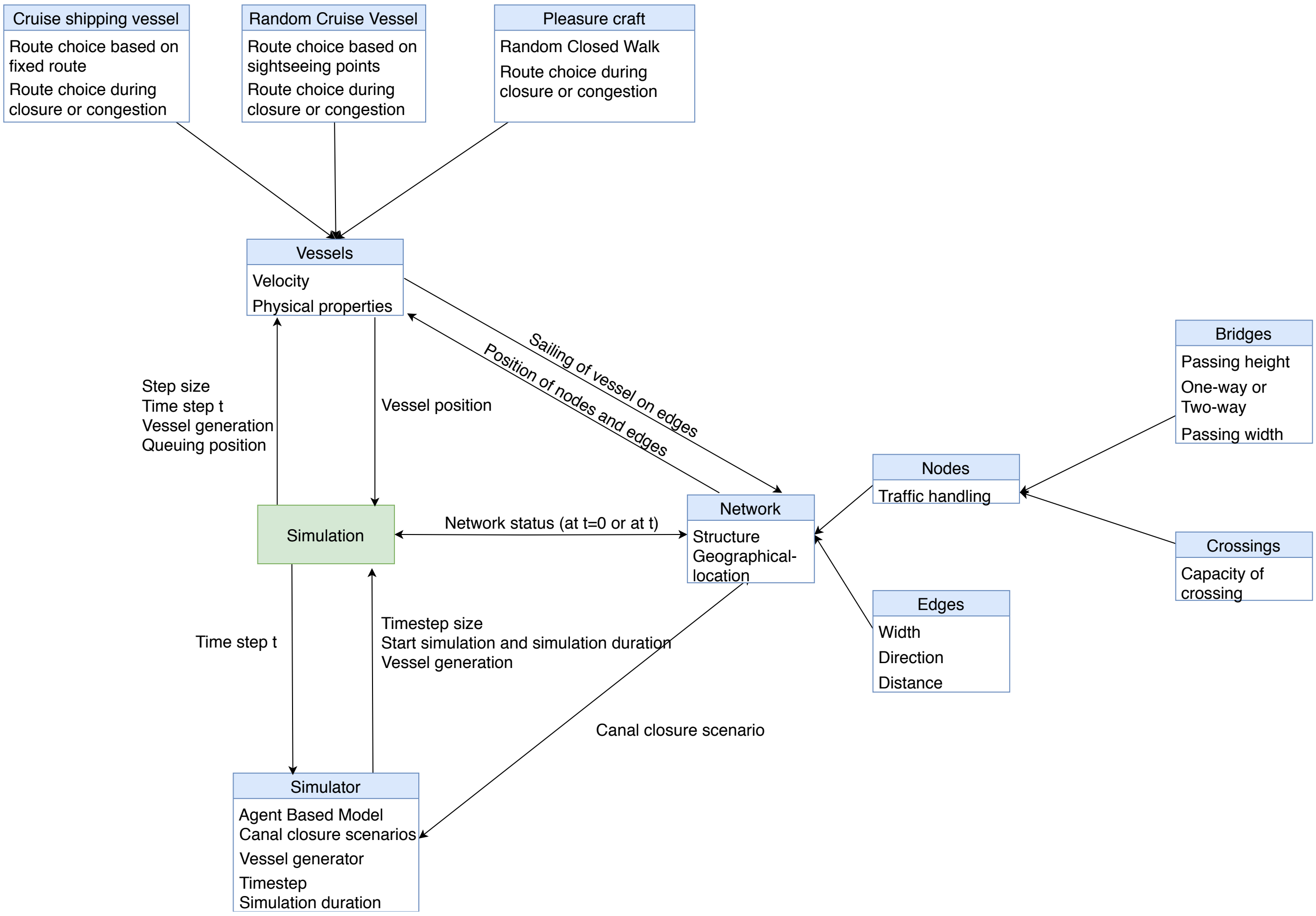


Figure 3.5: Object chart of the model

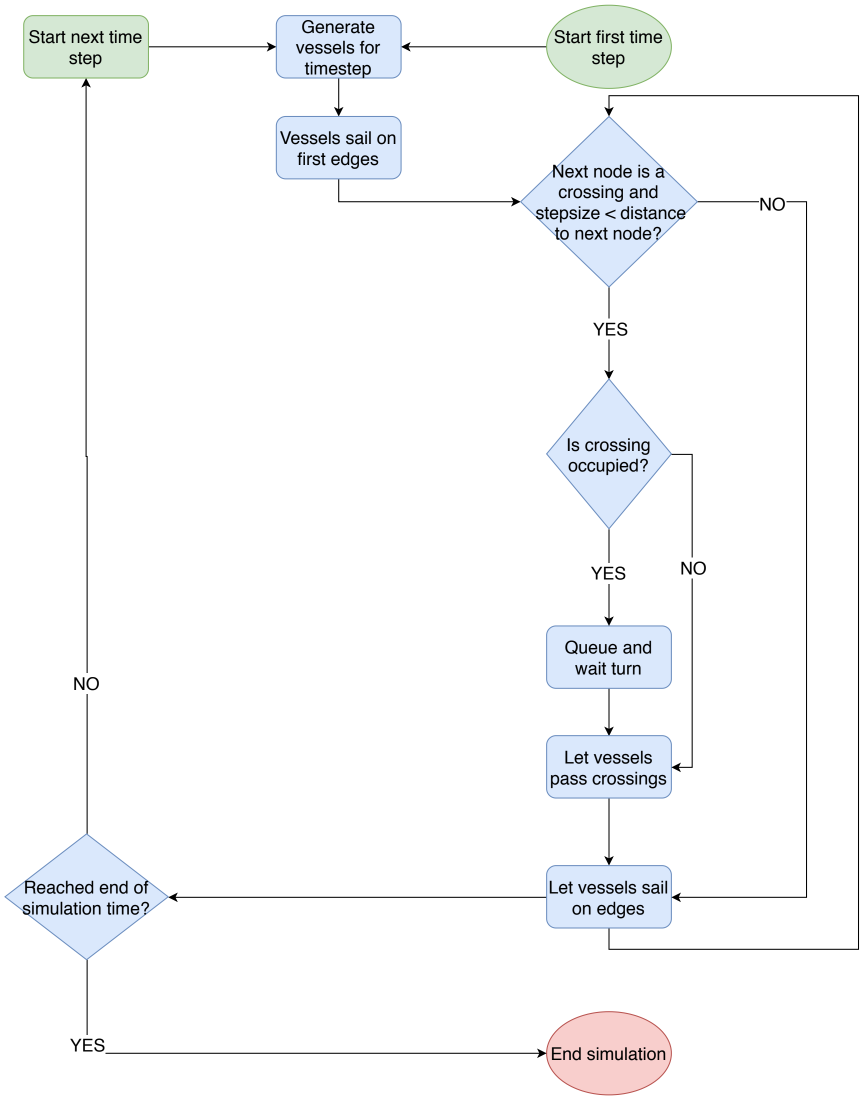


Figure 3.6: Flowchart of the whole simulation

3.4 Conclusion

This part of the thesis sought to answer the subquestion: *How can a model be set up that can simulate traffic on the canals of Amsterdam in order to analyze traffic flow and congestion patterns for different traffic demand scenarios?* Its sub questions were: *What modeling concepts are applicable?* and *What functional requirements does the model need to have to approximate the nautical traffic on the canals of Amsterdam?*

To answer the first sub-subquestion, the author selected the ABM framework to set up a model to assess the impact of canal-upgrade works on canal traffic. This framework could represent the distinct sailing speed and route-selection behavior of each vessel type, could reproduce the corresponding route-choice behavior of the three vessel types that interact, and offered an option for incorporating irrational behavior. Agent-based modeling was, therefore, a suitable framework to model the rational and irrational route-choice behavior of vessels (particularly the pleasure craft) sailing on the canals of Amsterdam. It could be used as a tool to understand not only *when* congestion occurs, but also to understand *why* congestion occurs. The level of detail is microscopic, and the time is modeled in discrete time steps. To summarize, the model simulates on a microscopic level, uses discrete time steps, and uses the agent-based modeling framework.

Many different computing languages could have been used for this project; however, preference was given to languages with enough packages (algorithms) available, that were open-source, and were relatively easy to learn. Given the availability of important packages, such as SimPy and NetworkX, the usefulness of open-source object-oriented programming language to model vessels easily and the fact that the model is build within a community setting at the TU Delft which uses Python, this study selected Python to construct the model. Each vessel was modeled as an entity with its own logic and making its own decisions while moving on a graph. To reproduce traffic flow and congestion patterns, vessel objects needed to move on this network, calculate their route based on the network structure and properties, and queue at crossings. Consequently, this project used the open-source NetworkX package to construct a network (graph) and to model vessel objects. The model uses the open-source SimPy package to reproduce queueing and crossing simulations in real time to reproduce congestion at crossings.

To answer the second sub-subquestion, in Section 3.2.2 a list of functional requirements was drawn up for each component of the model. *The essential functional requirements* are the most critical because those requirements are needed for the model to be able to reproduce traffic flow and congestion patterns. To model the traffic on the canals most realistically, *the additional functional requirements* need to be implemented as well. For the present, the author implemented *the essential functional requirements* as described in Section 3.2.2.

4
Calibration

This chapter answers the third subquestion. Section 4.1 tests the embedded functionality of the vessel agents, which are based on *the essential functional requirements*, and tests the structure of the network. These tests are set up to validate if the functionality needed for the traffic flow and congestion patterns is implemented and works the way it is supposed to; to test if the model has been built right internally. "In the validation of multi-agent simulation, internal validation corresponds to building the model right" (Truong et al., 2015, p. 2). If the model passes these tests, Section 4.2 calibrates the model with data from Waternet towards the different traffic demand scenarios to analyze how well it could reproduce reality. External validation is the test of the calibrated model with a different data set. Unfortunately, there is no different data set available for the external validation.

In this study, calibration is the fine-tuning of the output of the simulation model with the data from Waternet, which is numerical data independently derived from observations of the environment. Calibration is the fine-tuning of the output of the simulation model by changing the input of parameters (Truong et al., 2015).

4.1 Internal validation

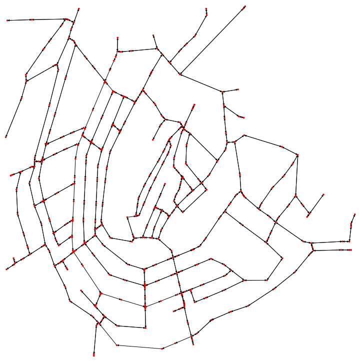
To validate the model internally, the different components of the model are tested. These are the network and the vessels sailing on the network. This section tests if the embedded functionality of each model component, as is described in Section 3.2, gives accurate results.

4.1.1 Network

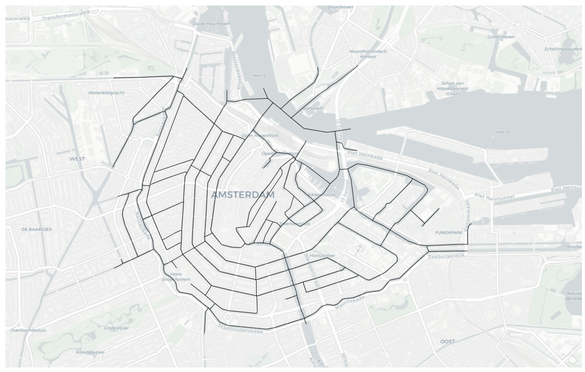
As described in Section 3.3.1, the network is modeled as a bi-directional graph. A visual representation is shown in Figure 3.1.

Test: Coordinates

To show that the coordinates of the network are the same as in reality, Figure 4.1 presents a graph overlay of a map of Amsterdam. The width and length of each canal are attributes of the representative edge of the canal. Moreover, nodes have attributes. At crossings, the nodes represent a server with a specific capacity, which is an attribute of that node.



(a) Network test: NetworkX graph for simulation



(b) Network test: NetworkX graph on map to test the geographical layout

Figure 4.1: Results of test for the network graph

4.1.2 Vessels

In Chapter 3, some functional requirements were set up that agent vessels must possess to approximate the behavior of vessels in reality. A number of tests were set up to validate whether the vessels meet these requirements, from which possible results may be explained. This section tests the embedded functionality of the vessel agents, which are based on *the essential functional requirements*. The following test have been set up:

- Test 1: Move on the graph
- Test 2: Follow a route
- Test 3: Stay on the graph
- Test 4: Type of vessels
- Test 5: Routing for different vessels
- Test 6: Static rerouting and width restriction
- Test 7: Queuing

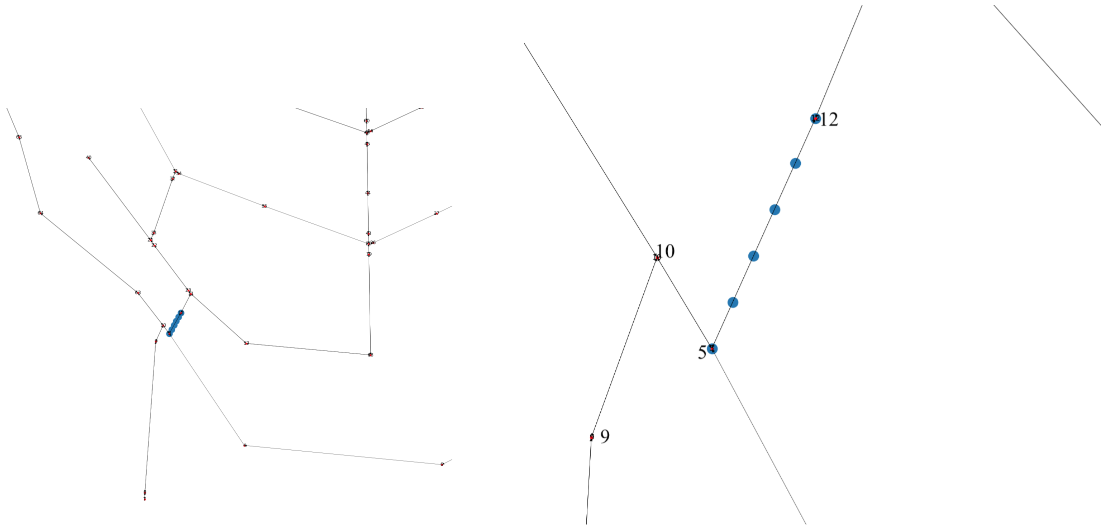
The results of test 1, 2 and 3 are fully explained in this section. The other tests with results can be found in Appendix B.1. The *additional functional requirements* have not been implemented and, therefore, not tested.

Test 1: Move on the graph

This test was performed to validate whether vessels set steps to the next node in their route list and adjust their course whenever they pass a node and move on to the next. This test validates if the vessel is capable of moving in steps from one node to the next node along the edge. This is tested to let a vessel with a speed of 1 m/s and a timestep of 10 seconds travel over an edge of the graph between two nodes. Because no exact distances exist between the two nodes, the vessel cannot take precise steps. Hence, the last step is not the complete step size. The vessel passes the test when it arrives with the exact number of steps as analytically calculated. The vessel passed this test and the results are shown in Table 4.1 and in Figure 4.2.

Table 4.1: Results test 1

Vessel	Results
Timestep	10 s
Route	[5,12]
Distance edge	49,633293143156 m
speed vessel	1 m / s
Stepsize vessel in m per timestep	10 m
Results without last step	4
Last step	0,96332929 m
Results with last step:	5 steps
Results analytically	4,96332929 steps



(a) Test 1: edge traveled on

(b) Test 1: edge traveled on zoomed in

Figure 4.2: Test 1

Test 2: Follow a route

A route in the model is a list of nodes that must be visited. For example, if a graph contains five nodes (A, B, C, D, and E) that are connected in sequence (A > B, B > C, C > D, and D > E), a possible route could be [A,B,C]. This vessel must visit the first three nodes. This test validates whether the vessel is capable of following a route and stopping when it reaches its end. A vessel passes this test when the start and end node are the same as stated in the route and it arrives with the exact number of steps as analytically calculated. The vessel passed this test and the results are shown in Table 4.2 and in Figure 4.3.

Table 4.2: Results test 2

Vessel	Results
Timestep	1 s
Route	[10, 5, 12]
Distance edge(s)	72,567765200 m
speed vessel	1 m / s
Stepsize vessel in m per timestep	1 m
Results without last step	72
Last step	0,567752011 m
Results with last step	73 steps
Results analytically	72,567765200 steps

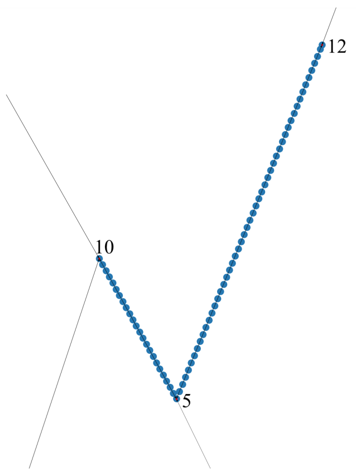


Figure 4.3: Test 2

Test 3: Stay on the graph

Because the canal network is not one straight line but a network of connected bridges and crossings, the vessels should be able to make turns and stay on the edges. Vessels also need to stay on the edges if the timestep is made larger. If the timestep increases, the step size of the vessels increases too. If the step size is larger than the remaining distance to the next node plus the distance to the node after that, and the that node is located at an angle to the previous node, the vessel should adjust its angle and move from that node on the next edge . This is tested to let a vessel with a speed of 1 m/s and a timestep of 1 second travel from node A to node C via node B, over the two edges with known distances. Vessels pass this test when they have not deviated from the graph due to possible overshoot and arrive within the exact number of steps as analytically calculated. The vessel passed this test as it stayed on the graph for different time steps, and the results are shown in Table 4.3, Table 4.4 and in Figure 4.4 and Figure 4.4.

Table 4.3: Results test 3: timestep = 1 s

Vessel	Results
Timestep	1 s
Route	[131, 130, 129, 128]
Distance edge(s)	302,9801208651 m
speed vessel	1 m / s
Stepsize vessel in m per timestep	1 m
Results without last step	302
Last step	0,9801208657 m
Results with last step	303 steps
Results analytically	302,9801208651

Table 4.4: Results test 3: timestep = 100 s

Vessel	Results
Timestep	100 s
Route	[131, 130, 129, 128]
Distance edge(s)	302,9801208651 m
Speed vessel	1 m / s
Stepsize vessel in m per timestep	100 m
Results without last step	3
Last step	2,9801208657 m
Results with last step	4 steps
Results analytically	3,029801208651

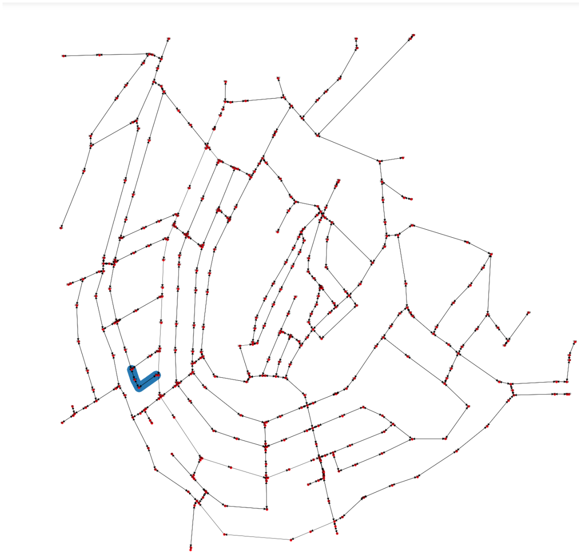
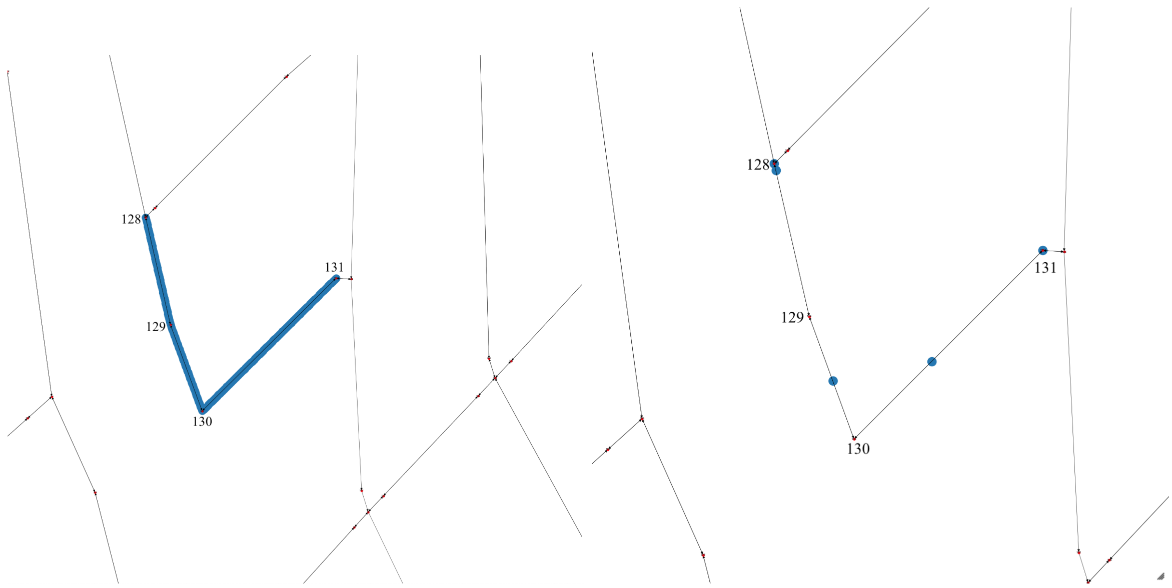


Figure 4.4: Test 3: overview



(a) Test 3: timestep = 1 s

(b) Test 3: timestep = 100 s

Figure 4.5: Test 3: different timesteps

4.1.3 Internal validation conclusion

The model passed 7 of the 7 tests. These test validated the model internally and proved that the model components give accurate results. Thus, the model components work the way they supposed to, and, therefore, the model should be able to mimic the nautical traffic.

4.2 Calibration of the model

In the previous section, the capabilities and limits of the model were determined through analysis. Next, the model was calibrated towards the different scenarios to analyze how well it could reproduce reality. Section 4.2.1 explains how the model results are compared with the measurement results. Section 4.2.2 discusses the calibration of the model towards the four traffic scenarios analyzed in Chapter 2 for the various vessel types as well as provides possible reasons for the errors between the model results and measurements.

4.2.1 Goodness of Fit

Many statistical methods are available to compare measurement data with model results in order to calibrate the model. One of the most used statistical methods is a “goodness of fit,” which indicates how well the model results fit the measurement data (Truong et al., 2015). There are different statistical methods to determine a “goodness of fit".

In general, statistical methods such as root mean square error (RMSE) are popular methods for validating simulation outputs with empirical data and checking fitness conditions (Truong et al., 2015). Most statistical goodness of fit tests, such as the Chi-squared test, actually measure the badness of fit. The test rejects a model if its alpha level is below 0.05. Such tests can reveal whether a model has a bad fit but they cannot show that a model has a good fit (Schunn and Wallach, 2005). The RMSE measures the actual goodness of fit and it is not prone to cancelation errors (positive and negative errors that cancel each other out):

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \tag{4.1}$$

Where $\hat{y}_i$ is the prediction value, y_i the measured value, and n is the number of data points. The RMSE shows the results on an absolute scale, thereby making it difficult to compare the model results of different locations. To solve this problem, the coefficient of variation(CV(RMSE))could be applied. The CV(RMSE) is the RMSE divided by the mean of the measured values $\bar{y}$. The CV(RMSE) provides a quantification of the typical size of the error relative to the mean of the observations. This metric also provides an indication of the model's ability to predict the overall shape that is reflected in the data (Ruiz and Bandera, 2017). The advantage of using the CV is that it can compare across different variables because they are now measured on the same relative scale (ratio). Consequently, the CV results for each location can be compared with each other, thereby providing a general score of how well the model is calibrated to each scenario. The CV(RMSE) returns a score between 0 and 1, with 0 implying a perfect fit and 1 implying that there is no fit.

$$CV(RMSE) = \frac{\sqrt{\frac{\Sigma_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}}}{\bar{y}} \tag{4.2}$$

However, the (CV) RMSE has a downside. The consequence of squaring the deviations is that more emphasis is placed on points that do not fit well than on points that do fit well (i.e., a prediction that is two units off the data produces a penalty four times as large as a point that is one unit off the data) (Schunn and Wallach, 2005). This means that RMSE penalizes large errors more than more than it does small errors. For example, the RMSE places larger errors if being 10 off is more than twice as worse than being 5 off. If being off 10 is just twice as worse as being 5 off, the Mean Absolute Error (MAE) is more usable.

MAE is an another statistic method that is often used to measure model performance. In simple words, it is the average over the test sample of the absolute differences between prediction and actual observation where all individual differences have equal weight. "An advantage of this measure is that it provides a value that is very easy to understand. For example, a model fit with a MAE of 1.5 seconds means that the model's predictions were off from the data on average by 1.5 seconds" (Schunn and Wallach, 2005, p. 25). As the MAE does not punish errors as severely as the the RMSE, there is a risk of overfitting the model (Schunn and Wallach, 2005). In formula:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i| \tag{4.3}$$

Where, identical to the RMSE, $\hat{y}_i$ is the prediction value, y_i the measured value, and n is the number of data points. To compare the model results of each location, the MAE is normalized with the mean of the measured values $\bar{y}$. This value is called the Normalized Mean Absolute Error (NMAE). The NMAE also returns a score between 0 and 1, with 0 implying a perfect fit and 1 implying that there is no fit.

$$NMAE = \frac{\frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i|}{\bar{y}} \tag{4.4}$$

There is some discussion in the scientific community if it is better to use MAE or the RMSE (Chai and Draxler, 2014; Cort and Kenji, 2005; Willmott et al., 2009). This study uses the MAE and the NMAE metrics to compare the results of the model with the measurement data to analyze how well the model results fit the measurement data, as the MAE and the NMAE are easy to understand and to interpret.

4.2.2 Scenario calibration with the vessel generator parameter

The calibration can be done with the vessel generation parameter(s) in combination with the vessel speed parameter. First, this section calibrated the vessel generation parameter for each vessel type towards the different traffic demand scenarios. After this, the effect of the calibration of the vessel speed parameter was analyzed. Each vessel has its own speed. currently, the maximum speed on the canals is 6 km/h. However, as the data is from 2013, the maximum speed back then was 7.5 km/h. Therefore, to calibrate towards the data from 2013-2014, vessels may sail with a maximum speed of 7.5 km/h.

The NMAE makes it possible to measure the accuracy of the model for each location and to compare the results of each location with each other. Artificial measurement points were created at the same locations in the network to compare the model results with the measured results. Each scenario shows the best fit and the worst fit of the results of the seven locations. Table 2.7 shows the distribution per vessel type used for the different scenarios as input for the model. An overview of the results for each scenario for each location are found in Appendix B. The MAE gives the average error in an absolute value. For example, in Table 4.6, the model results at Leidschegracht are on average 5.677 vessel off the measured values. A goodness of fit value around and above 70%, or a error margin smaller than 30%, but under 90%, is considered an acceptable fit. Table 4.5 shows the legenda for the graphs in this section.

Table 4.5: Legenda for the graphs in Section 4.2.2

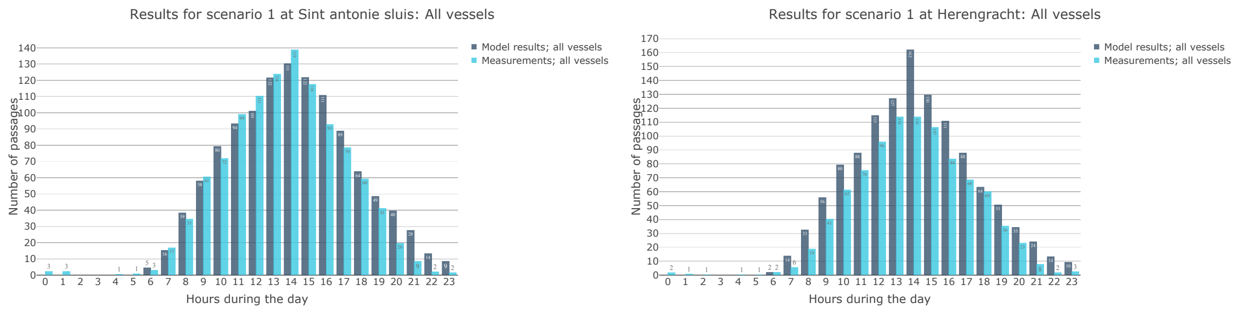
Results	Color
Model results	(blue)
Measurement results	(cyan)

Scenario 1: High traffic demand; results

Scenario 1 is a weekend day in summer, when the traffic demand is high. The MAE and the NMAE results are in displayed Table 4.6. The best fit is the location at the St Antonie Sluis, which shows an NMAE error of 13.83 percent (Figure 4.6). This error margin means that the model has a good fit with the measured values because it has an accuracy of 86,17%. However, the location Herengracht has an NMAE error margin of 31.14%, or on average according to the MAE, its prediction is approximately 12 vessels passages off the measured values. The results of Herengracht are shown in Figure 4.6. The overall fit ranges between the error margin of 16,93% and 36,42%, which indicates goodness of fit between 68% and 85%.

Table 4.6: Scenario 1: MAE and NMAE for the measurement location; all vessels

Location	**MAE**	**NMAE**
Leidschegracht	5.677	15.32%
Singel Haarlemmersluis	3.833	14.61%
Anne Frank	6.844	15.87%
Sint Antonie Sluis	6.25	13.83%
Singelgracht DNB-Heineken	2.438	13.85%
Herengracht	11.91	31.14%
Keizersgracht	5.875	22.66%



(a) St Antonie Sluis; best fit **(b)** Herengracht; worst fit

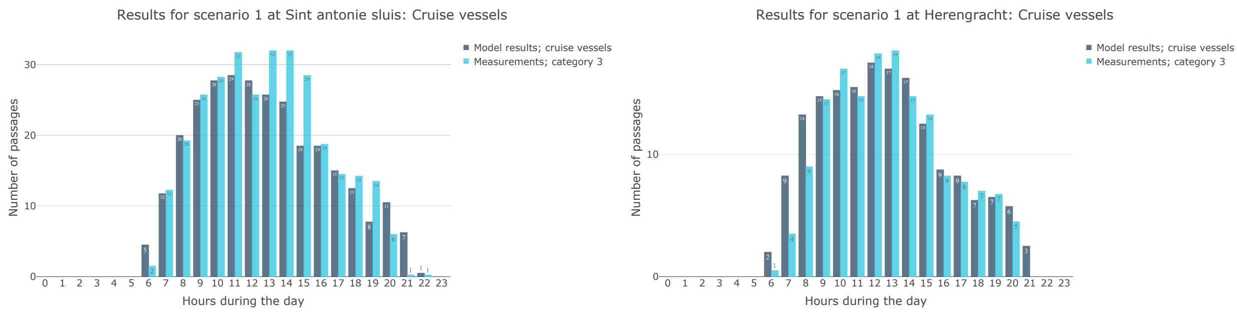
Figure 4.6: Scenario 1: All vessels: Results for St Antonie Sluis and Herengracht

Scenario 1: Cruise vessels

The NMAE does not provide information about whether the model results for these locations over- or underestimate. For example, the model underestimates (too few passages) for the location of Keizersgracht (Figure 4.8 (b)) but overestimates (too many passages) at Herengracht. The results for the other locations can be found in Appendix B. The results per vessel type are plotted to explain the differences between the model results.

Table 4.7: Scenario 1: MAE and NMAE for the cruise vessels of the measurement locations

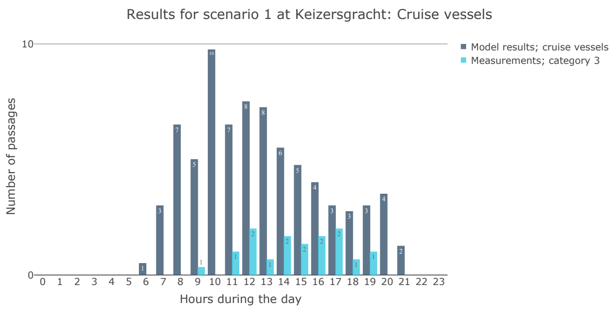
Location	MAE	NMAE
Leidschegracht	1.135	24.82%
Singel haarlemmersluis	1.719	18.92%
Anne Frank	1.896	27.58%
Sint Antonie Sluis	2.219	17.49%
Singelgracht DNB-Heineken	1.146	47.63%
Herengracht	0.9792	14.85%
Keizersgracht	2.559	498.0%



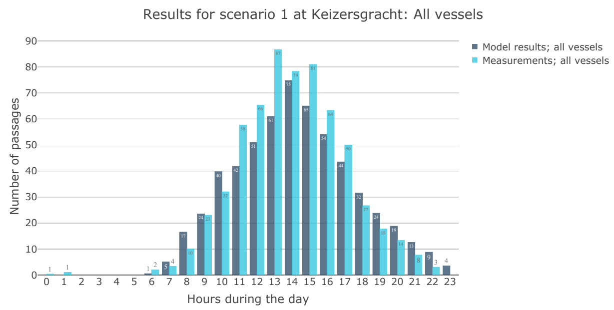
(a) St Antonie Sluis; cruise vessels **(b)** Herengracht; cruise vessels

Figure 4.7: Scenario 1: cruise vessels: Results for Herengracht andSt Antonie Sluis

Table 4.7 presents the fit of the data between the model results for the cruise vessels and the measured data between the cruise vessels. The worst fit is at Keizersgracht where the model significantly overestimates compared with the measured data. Overall, the model fits the measured data for the cruise vessels quite well, with the exceptions of Singelgracht DNB-Heineken and Keizersgracht. The substantial error for the cruise vessels at Keizersgracht is because not many vessel movements occur there. Hence, four or five movements above the measured data signify a significant difference between the two, and thus a substantial error. As Table 4.6 shows, the overall error is still quite good for the location Keizersgracht, which means that the error is compensated by the results from the pleasure craft and random cruise vessels in the model. The results for Keizersgracht are displayed in Figure 4.8. The location at Herengracht does perform well for the cruise vessels, in contrast to the results for all the vessels, with an NMAE error margin of 14.85%. This low error margin means that the error for this location originates from either the random cruise vessels or the pleasure craft.



(a) Keizersgracht; cruise vessels



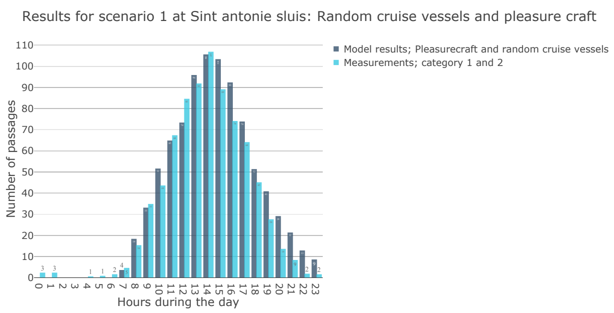
(b) Keizersgracht; all vessels

Figure 4.8: Scenario 1: Results for location Keizersgracht

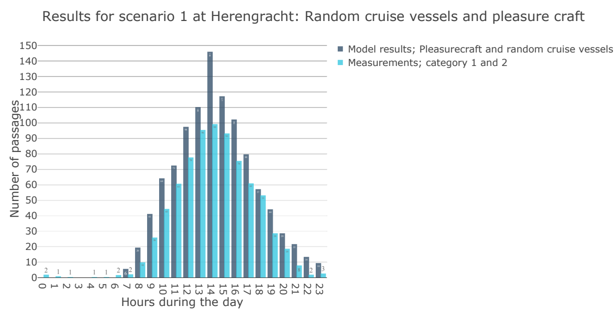
Scenario 1: Random cruise vessels and pleasure craft
As explained in Section 2.2.2, Waternet data cannot distinguish between random cruise vessels and pleasure craft because the data are subdivided based on a length criterion and not on the type of vessel. Therefore, it is difficult to analyze whether the error between the model and measured data originates from the random cruise vessels or the pleasure craft. The results are presented in Table 4.8.

Table 4.8: Scenario 1: MAE and NMAE for the pleasure craft and random cruise vessels of the measurement locations

Location	MAE	NMAE
Leidschegracht	5.5	16.93%
Singel Haarlemmersluis	3.219	18.77%
Anne Frank	6.594	18.19%
Sint Antonie Sluis	6.177	19.01%
Singelgracht DNB-Heineken	2.042	13.44%
Herengracht	11.53	36.42%
Keizersgracht	6.330	24.90%



(a) St Antonie Sluis; Random cruise vessels and pleasure craft



(b) Herengracht; random cruise vessels and pleasure craft

Figure 4.9: Scenario 1: pleasure craft and random cruise vessels: Results for St Antonie Sluis and Herengracht

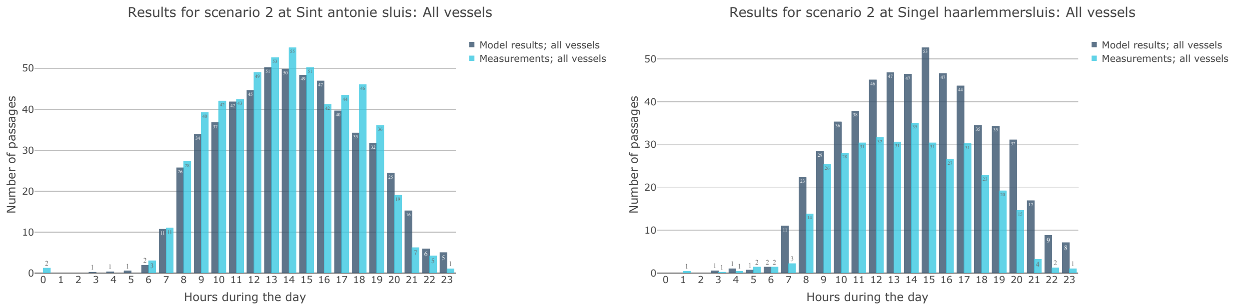
The results of the pleasure craft and the random cruise vessels do seem to match quite well with the overall measured data for categories 1 and 2 (explained in Section 2.2.2), as seen in Table 4.8. The fit ranges between the error margin of 16.93% and 36.42%, which indicates a goodness of fit between 64% and 83%. However, these results may be a false positive because they could be a consequence of compensation. This same error is observed at Keizersgracht. The results for the random cruise vessels may be compensated by the results for the pleasure craft and vice versa. No data are available to check a possible error. The error from Herengracht is caused by the overestimation of the random cruise vessels and pleasure craft, as seen in Figure 4.9. The results for the only the random cruise vessels or the pleasure craft can be found in Appendix B.

Scenario 2: Medium traffic demand; results

This scenario has a medium traffic demand. The assumption is made that because it is on a weekday in summer, fewer pleasure craft sail on the canals of Amsterdam than on weekends. Table 2.7 has been used as input for this scenario. The results from scenario 2 show the best fit to be at St Antonie Sluis with an error margin of 13.32%, and the worst fit to be at Haarlemmersluis with an error margin of 58.43%. The fit of the overall results are still quite good because most locations show a fit between 70% and 86%, with the exception of Singel Haarlemmersluis.

Table 4.9: Scenario 2: MAE and NMAE for the measurement locations

Location	MAE	NMAE
Leidschegracht	4.188	22.76%
Singel Haarlemmersluis	8.521	58.43%
Anne Frank	4.225	20.12%
Sint Antonie Sluis	3.162	13.32%
Singelgracht DNB-Heineken	2.088	29.94%
Herengracht	2.846	16.44%
Keizersgracht	1.368	19.98%



(a) St Antonie Sluis; best fit

(b) Singel Haarlemmersluis; worst fit

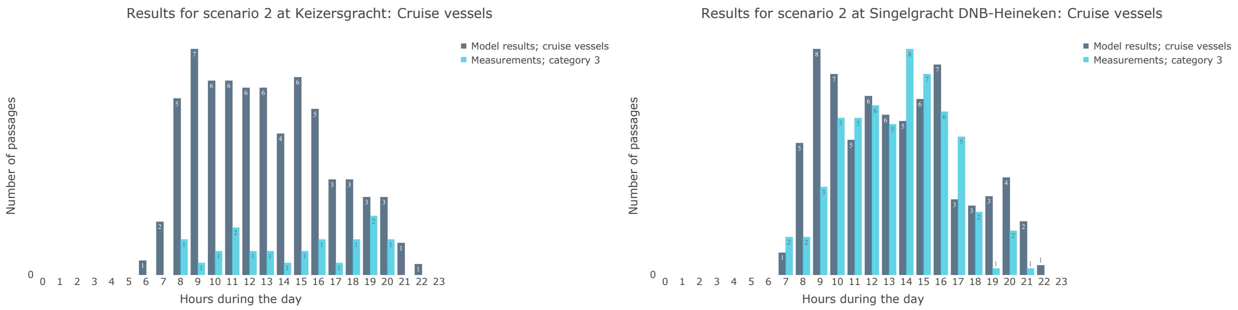
Figure 4.10: Scenario 2: all vessels; Results for St Antonie Sluis and Singel Haarlemmersluis

Scenario 2: Cruise vessels
The results per vessel type are plotted to explain the error between the model en the measurement results. Table 4.10 shows an overview of the fit per location for the cruise vessels.

Table 4.10: MAE and NMAE for cruise vessels at the measurement locations

Location	MAE	NMAE
Leidschegracht	0.6292	14.72%
Singel Haarlemmersluis	2.375	26.66%
Anne Frank	1.375	19.57%
Sint Antonie sluis	2.054	16.28%
Singelgracht DNB-Heineken	0.9667	44.28%
Herengracht	1.183	19.16%
Keizersgracht	2.064	464.4%

The results for the cruise vessels are well within limits (a fit between 74% and 85%), with the exception of two locations. The results for cruise vessels in scenario 2 show that Keizersgracht has a substantial error, which is displayed in Figure 4.11. This error is the same error observed in scenario 1. Again, the substantial error is because few cruise vessel movements were observed at Keizersgracht. Thus, a difference of two or three passages results in a significant error. The overall error for Keizersgracht is still within limits; therefore, the error of the cruise vessels is compensated by the random cruise vessels and the pleasure craft. In addition, the location Singelgracht DNB-Heineken shows a significant error.



(a) Cruise vessel passages at Keizersgracht

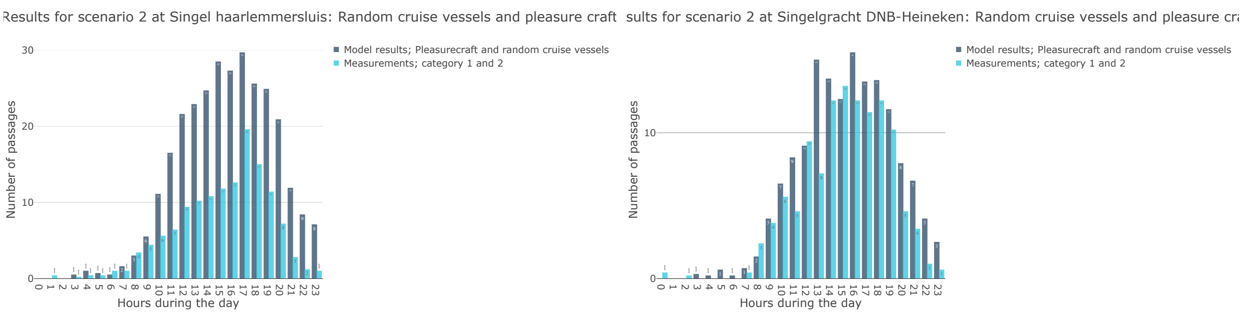
(b) Cruise vessel passages at Singelgracht DNB Heineken

Figure 4.11: Scenario 2: cruise vessels; Results at worst fit locations

Scenario 2: Random cruise vessels and the pleasure craft
Table 4.11 presents the error for the pleasure craft and random cruise vessels. The model results reveal an error of 117.7% at Haarlemmersluis and 33.31% for Singelgracht DNB-Heineken. These two locations are displayed in Figure 4.12. The results for the only the random cruise vessels or the pleasure craft can be found in Appendix B.

Table 4.11: MAE and NMAE for the random cruise vessels and the pleasure craft at the measurement locations

Location	MAE	NMAE
Leidschegracht	3.842	27.20%
Singel Haarlemmersluis	6.679	117.7%
Anne Frank	3.392	24.27%
Sint Antonie Sluis	2.192	19.70%
Singelgracht DNB-Heineken	1.596	33.31%
Herengracht	2.354	21.14%
Keizersgracht	1.762	27.52%



(a) Random cruise vessels and pleasure craft passages at Singel Haarlemmersluis

(b) Random cruise vessels and pleasure craft passages at Singelgracht DNB Heineken

Figure 4.12: Scenario 2: random cruise vessels and pleasure craft; Results for Singel Haarlemmersluis and Singelgracht DNB Heineken

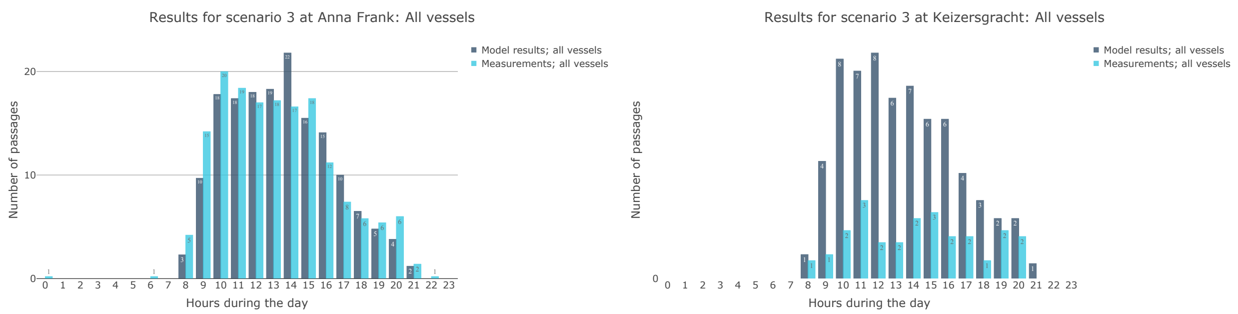
The model overestimates at these locations; however, it is unclear if the error originates from the pleasure craft or the random cruise vessels because no information is available on what the number of passages per vessel type should be for this location. Section 4.2.4 discusses possible reasons for the error.

Scenario 3: Low traffic demand; results

In this scenario, there is a low traffic demand. The traffic consists mainly of passenger transport because not many people will deem the weather pleasant enough to sail, even though it is at the weekend. The overall fit for this scenario is shown in Table 4.12. The location Singelgracht DNB-Heineken did not have measurement data for this scenario. Therefore, the MAE and the NMAE are not displayed in the Table for this location. The best and worst fits are displayed in Figure 4.13.

Table 4.12: Scenario 3: MAE and NMAE for the measurement locations

Location	MAE	NMAE
Leidschegracht	1.004	19.00%
Singel Haarlemmersluis	1.162	19.64%
Anne Frank	1.192	17.57%
Sint Antonie Sluis	1.521	18.13%
Singelgracht DNB-Heineken	-	-
Herengracht	1.254	32.43%
Keizersgracht	1.725	222.6%



(a) Anne Frank; best fit

(b) Keizersgracht; worst fit

Figure 4.13: Scenario 3: all vessels; Results for Anne Frank and Keizersgracht

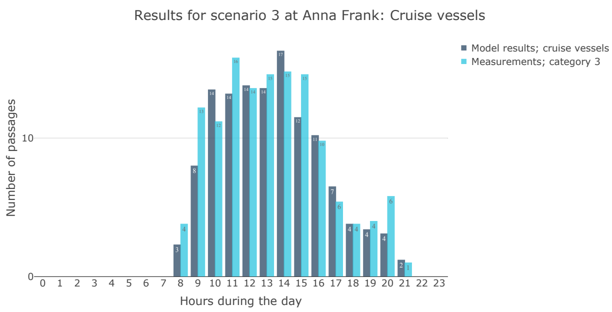
The overall fit displays a good fit with a range from 67% to 82%. The location Keizersgracht presents the most significant error of 222.6%. Anna Frank has the best fit with an error margin of 17.57%. Table 4.13 lists the results for cruise vessels.

Table 4.13: MAE and NMAE for the cruise vessels at the measurement locations

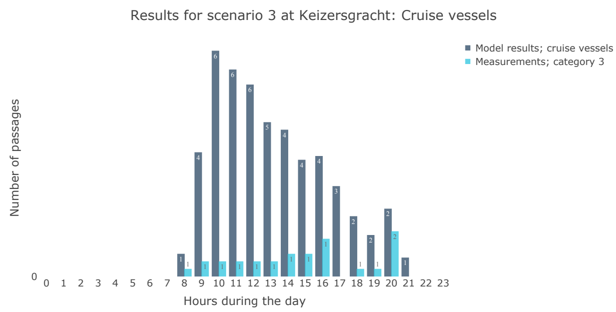
Location	MAE	NMAE
Leidschegracht	0.7875	21.43%
Singel Haarlemmersluis	1.079	22.76%
Anna Frank	0.8917	16.41%
Sint Antonie Sluis	1.350	20.0%
Singelgracht DNB-Heineken	-	-
Herengracht	0.8667	31.14%
Keizersgracht	1.508	603.2%

Scenario 3: Cruise vessels
The most substantial error is identical to scenarios 1 and 2 at Keizersgracht. The other measurement locations show a good fit between the model results and the measurement data, with a goodness of fit ranging

between 69% and 83%. Possible reasons to explain the error are discussed in Section 4.2.4. Figure 4.14 displays the worst and best fits for cruise vessels.



(a) Cruise vessel passages at Anna Frank



(b) Cruise vessel passages at Keizersgracht

Figure 4.14: Scenario 3: cruise vessels; Results for Anne Frank and Keizersgracht

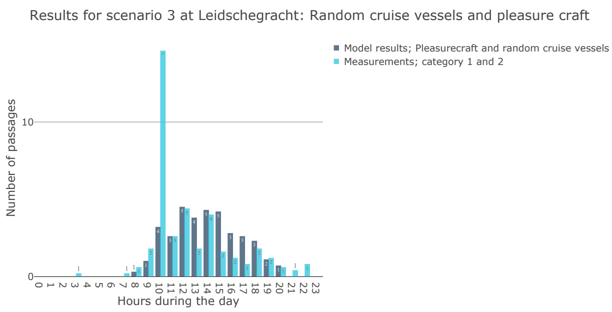
Scenario 3: Random cruise vessels and the pleasure craft

The results for pleasure craft and random cruise vessels are more substantial than in the previous scenarios. Table 4.14 shows the error for the pleasure craft and the random cruise vessels.

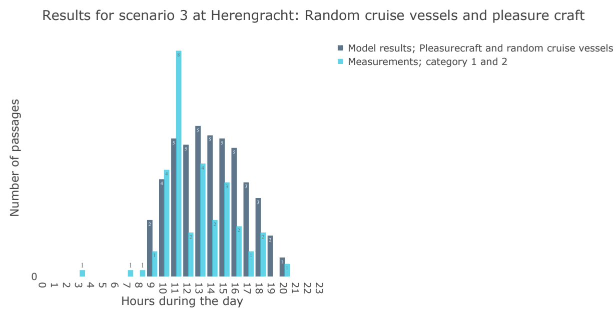
Table 4.14: MAE and NMAE for the random cruise vessels and the pleasure craft at the measurement locations

Location	MAE	NMAE
Leidschegracht	0.9667	60.11%
Singel haarlemmersluis	0.4417	37.59%
Anna Frank	0.8667	64.20%
Sint Antonie Sluis	0.6375	38.83%
Singelgracht DNB-Heineken	-	-
Herengracht	0.8375	77.31%
Keizersgracht	0.3667	69.85%

The graphs of the results show outliers in measurement data of Leidsegracht, Herengracht, and Anne Frank. Figure 4.15 shows the results of two of the seven locations. The outlier at Leidsegracht is substantial, making the error significant for that location. Overall, very few passages occur at each location; thus, if the results are slightly higher or lower than the measurements, the error can snowball. As expected, the cruise vessels make up most of the traffic during this scenario. The results for the only the random cruise vessels or the pleasure craft can be found in Appendix B.



(a) Random cruise vessels and pleasure craft passages at Leidschegracht



(b) Random cruise vessels and pleasure craft passages at Herengracht

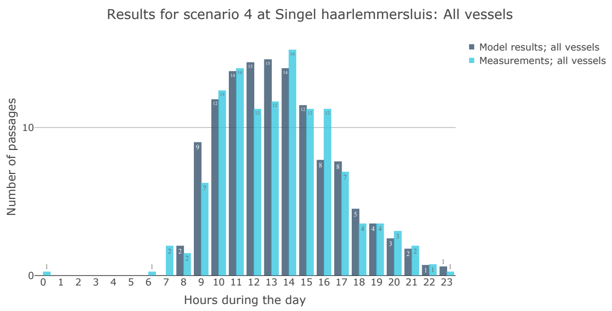
Figure 4.15: Scenario 3: random cruise vessels and pleasure craft; Results for Leidschegracht and Herengracht

Scenario 4: Very low traffic demand; results

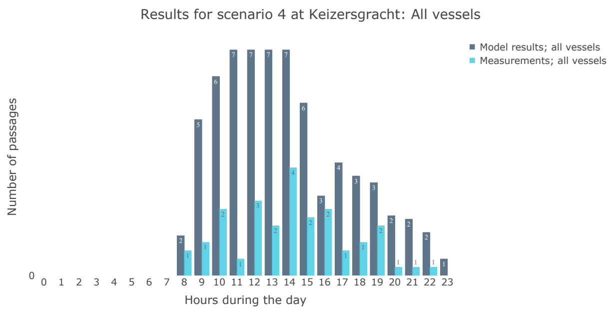
This scenario is a weekday in winter, when the traffic demand is very low. Identical to scenario 3, the traffic consists mainly of passenger transport. The overall goodness of fit results for this scenario are shown in Table 4.15. The location Singelgracht DNB-Heineken also did not have data for this scenario. Therefore, the MAE and the NMAE are not displayed in the table. Figure 4.16 shows the results of the best and worst fit locations.

Table 4.15: Scenario 4: MAE and NMAE for the measurement locations

Location	MAE	NMAE
Leidschegracht	1.204	28.47%
Singel Haarlemmersluis	0.8458	17.28%
Anne Frank	1.523	27.33%
Sint Antonie Sluis	1.521	22.12%
Singelgracht DNB-Heineken	-	-
Herengracht	1.623	51.08%
Keizersgracht	1.758	222.1%



(a) Singel haarlemmersluis; best fit



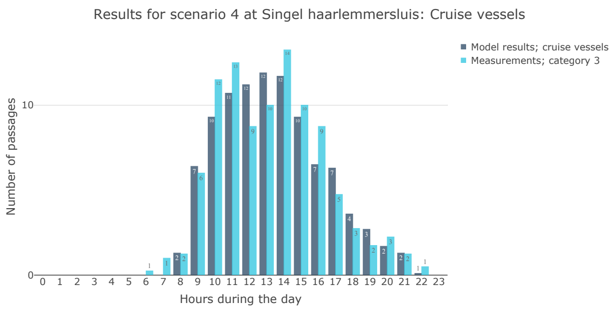
(b) Keizersgracht; worst fit

Figure 4.16: Scenario 4: all vessels; Results for Singel Haarlemmersluis and Keizersgracht

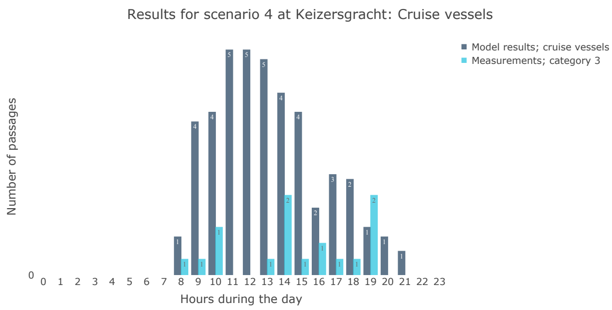
Overall, the model results display a good fit with the measured results. The goodness of fit ranges between 67% and 82%. The two exceptions are Herengracht and Keizersgracht with errors of 51% and 222.1%, respectively. As in the previous scenarios, the results per vessel type are analyzed. Table 4.16 presents the results for the cruise vessels.

Table 4.16: MAE and NMAE for the cruise vessels at the measurement locations

Location	MAE	NMAE
Leidschegracht	0.6521	20.80%
Singel Haarlemmersluis	0.7875	19.59%
Anne Frank	0.8688	21.12%
Sint Antonie Sluis	1.304	23.53%
Singelgracht DNB-Heineken	-	-
Herengracht	0.5396	20.64%
Keizersgracht	1.276	437.5%



(a) Singel Haarlemmersluis; best fit for cruise vessels



(b) Keizersgracht; worst fit for cruise vessels

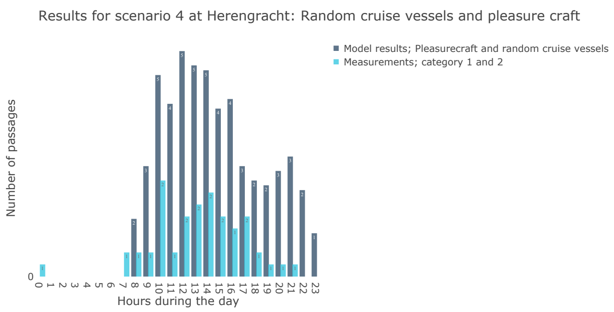
Figure 4.17: Scenario 4: cruise vessels; Results for Singel Haarlemmersluis and Keizersgracht

Scenario 4: Cruise vessels

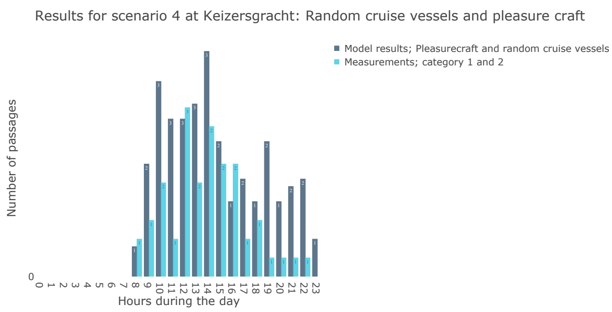
Similar to scenarios 1, 2, and 3, the error is substantial at Keizersgracht for the cruise vessels. The other measurement locations show a good fit ranging between 69% and 83%. Possible reasons for the error are discussed in Section 4.2.4. In Figure 4.17, the best and worst fits are displayed for the cruise vessels. These results are almost equal to the results for all vessels, which signifies that the traffic on the canals during this scenario mainly consist of cruise vessels. The errors for the pleasure craft and random cruise vessels are more substantial than in the previous scenarios. Table 4.17 shows the error of the pleasure craft and random cruise vessels. Figure 4.18 shows the result of the locations with the worst fit.

Table 4.17: MAE and NMAE for the random cruise vessels and the pleasure craft at the measurement locations

Location	MAE	NMAE
Leidschegracht	0.8146	74.48%
Singel Haarlemmersluis	0.5958	68.09%
Anne Frank	1.325	90.86%
Sint Antonie Sluis	0.8167	61.25%
Singelgracht DNB-Heineken	-	-
Herengracht	1.396	248.2%
Keizersgracht	0.5271	92.00%



(a) Random cruise vessels and pleasure craft passages at Herengracht



(b) Random cruise vessels and pleasure craft passages at Keizersgracht

Figure 4.18: Scenario 4: random cruise vessels and pleasure craft; results for Herengracht and Keizersgracht

Scenario 4: Random cruise vessels and the pleasure craft

Very few passages occur at each location for pleasure craft and random cruise vessels. Thus, the error snowballs with small differences. Despite the more significant errors shown in Table 4.17 for the random cruise vessels and pleasure craft, the overall fit is within limits. Hence, the cruise vessels make up most of the traffic during this scenario. The results for the only the random cruise vessels or the pleasure craft can be found in Appendix B.

4.2.3 Calibration of the vessel speed parameter

To test the influence of the vessel speed parameter three scenarios have been set up. It can be assumed that the vessels on the canals of Amsterdam do not sail with a speed less than 4.5 km/h and with a maximum of 7.5 km/h (calibrating with the data set from 2013). The high traffic demand scenario is used to test the influence of the vessel speed parameter.

- Null-scenario: Calibrated model for the high traffic demand scenario from Section 4.2.2
- Scenario A: Vessels may sail with a speed of 4.5 km/h.
- Scenario B: Vessels may sail with a speed of 6 km/h or less
- Scenario C: Vessels may sail with a speed of 7.5 km/h or less.

The results of each scenario are compared with the calibrated scenario. In the calibrated scenario, the vessel speed input was the following:

- Cruise vessels: Uniform speed between 6 - 7.5 km/h
- Random cruise vessels: Uniform speed distribution between 5 - 6 km/h
- Pleasure craft: Uniform speed distribution between 5 - 6 km/h

Scenario A, B, and C influence the sailing speed of the cruise vessels, as they will always sail the maximum speed allowed or possible. Scenario A, B and scenario C influence the results of the random cruise vessels and the pleasure craft, as they have been calibrated with a fluctuating value between 5 and 6 km/h. Table 4.18 shows an overview of the values used for each speed scenario.

Table 4.18: Overview of values for the vessel speed parameter per scenario

Type	Calibrated null Scenario	Scenario A	Scenario B	Scenario C
Cruise vessels	6 - 7.5 km/h	4.5 km/h	6 km/h	7.5 km/h
Random cruise vessels	5 - 6 km/h	4.5 km/h	6 km/h	6 km/h
Pleasure craft	5 - 6 km/h	4.5 km/h	5 km/h	5 km/h

Scenario A: 4.5 km/h

This section shows the results for the calibration wit vessels speed with a maximum of 4.5km/h.

Table 4.19: Maximum of 4.5 km/h: Results for all vessels compared to calibrated results

Location	**Scenario A** MAE	**Scenario A** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	8.969	24.21 %	5.677	15.32%
Singel haarlemmersluis	3.296	12.57 %	3.833	14.61%
Anna Frank	9.604	22.27 %	6.844	15.87%
Sint antonie sluis	7.121	15.76 %	6.25	13.83%
Singelgracht DNB-Heineken	4.221	23.98 %	2.438	13.85%
Herengracht	4.312	21.27 %	25.91	31.14%
Keizersgracht	8.275	31.91 %	5.875	22.66%

Table 4.20: Maximum of 4.5 km/h: Results for the cruise vessels compared to calibrated results

Location	**Scenario A** MAE	**Scenario A** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	1.090	23.84 %	1.135	24.82%
Singel haarlemmersluis	1.979	21.79 %	1.719	18.92%
Anna Frank	2.433	35.39 %	1.896	27.58%
Sint Antonie Sluis	2.125	16.75 %	2.219	17.49%
Singelgracht DNB-Heineken	0.9813	40.78 %	1.146	47.63%
Herengracht	1.398	21.20 %	0.9792	14.85%
Keizersgracht	2.461	478.9 %	2.559	498.0%

Table 4.21: Maximum of 4.5 km/h: Results for the random cruise vessels and pleasure craft compared to calibrated results

Location	**Scenario A** MAE	**Scenario A** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	8.412	25.90 %	5.5	16.93%
Singel haarlemmersluis	2.871	16.74 %	3.219	18.77%
Anna Frank	8.725	24.07 %	6.594	18.19%
Sint Antonie Sluis	5.625	17.31 %	6.177	19.01%
Singelgracht DNB-Heineken	4.302	28.31 %	2.042	13.44%
Herengracht	3.669	25.59 %	11.53	36.42%
Keizersgracht	9.869	38.83 %	6.330	24.90%

When the speed had been reduced (Scenario A), the model performed worse. The results show that, due to lowering of the speed, the model is not constantly underestimating the results but results vary from location to location. However, the error at Herengracht does show a significant reduction. This reduction is mainly due to the random cruise vessels and the pleasure craft.

Scenario B: maximum of 6 km/h

This section shows the results for the calibration wit vessels speed with a maximum of 6 km/h.

Table 4.22: Maximum of 6 km/h: Results for all vessels compared to calibrated results

Location	**Scenario B** MAE	**Scenario B** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	5.298	14.30 %	5.677	15.32%
Singel haarlemmersluis	3.821	14.57 %	3.833	14.61%
Anna Frank	7.5	17.39 %	6.844	15.87%
Sint Antonie Sluis	5.879	13.01 %	6.25	13.83%
Singelgracht DNB-Heineken	2.829	16.07 %	2.438	13.85%
Herengracht	7.375	26.28 %	11.91	31.14%
Keizersgracht	7.231	27.89 %	5.875	22.66%

Table 4.23: Maximum of 6 km/h: Results for the cruise vessels compared to calibrated results

Location	**Scenario B** MAE	**Scenario B** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	1.152	25.19 %	1.135	24.82%
Singel haarlemmersluis	2.050	22.57 %	1.719	18.92%
Anna Frank	1.963	28.55 %	1.896	27.58%
Sint Antonie Sluis	2.288	18.03 %	2.219	17.49%
Singelgracht DNB-Heineken	1.065	44.26 %	1.146	47.63%
Herengracht	1.231	18.67 %	0.9792	14.85%
Keizersgracht	2.636	513.0 %	2.559	498.0%

Table 4.24: Maximum of 6 km/h: Results for the random cruise vessels and the pleasure craft compared to calibrated results

Location	**Scenario B** MAE	**Scenario B** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	5.329	16.41 %	5.5	16.93%
Singel haarlemmersluis	3.208	18.71 %	3.219	18.77%
Anna Frank	7.483	20.64 %	6.594	18.19%
Sint Antonie Sluis	5.058	15.56 %	6.177	19.01%
Singelgracht DNB-Heineken	2.552	16.79 %	2.042	13.44%
Herengracht	6.615	26.90 %	11.53	36.42%
Keizersgracht	8.183	32.20 %	6.330	24.90%

Concluding from this scenario, the model more or less performs the same as the calibrated scenario. The cruise vessels perform more or less the same. However, the random cruise vessels and the pleasure craft perform better for the location Herengracht.

Scenario C: 7.5 km/h

This section shows the results for the calibration wit vessels speed with a maximum of 7.5 km/h.

Table 4.25: Maximum of 7.5 km/h: Results for all vessels compared to calibrated results

Location	**Scenario C** MAE	**Scenario C** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	5.056	13.65 %	5.677	15.32%
Singel haarlemmersluis	3.887	14.82 %	3.833	14.61%
Anna Frank	7.871	18.25 %	6.844	15.87%
Sint Antonie Sluis	6.158	13.63 %	6.25	13.83%
Singelgracht DNB-Heineken	2.829	16.07 %	2.438	13.85%
Herengracht	6.829	27.85 %	11.91	31.14%
Keizersgracht	7.008	27.03 %	5.875	22.66%

Table 4.26: Maximum of 7.5 km/h: Results for the cruise vessels compared to calibrated results

Location	**Scenario C** MAE	**Scenario C** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	0.8354	18.27	1.135	24.82%
Singel haarlemmersluis	2.550	28.07 %	1.719	18.92%
Anna Frank	2.017	29.34 %	1.896	27.58%
Sint Antonie Sluis	2.492	19.64 %	2.219	17.49%
Singelgracht DNB-Heineken	1.294	53.78 %	1.146	47.63%
Herengracht	1.219	18.49 %	0.9792	14.85%
Keizersgracht	2.611	508.1 %	2.559	498.0%

Table 4.27: Maximum of 7.5 km/h: Results for the random cruise vessels and the pleasure craft compared to calibrated results

Location	**Scenario C** MAE	**Scenario C** NMAE	**Null scenario** MAE	**Null scenario** NMAE
Leidschegracht	5.125	15.78 %	5.5	16.93%
Singel haarlemmersluis	3.513	20.49 %	3.219	18.77%
Anna Frank	7.367	20.32 %	6.594	18.19%
Sint Antonie Sluis	6.350	19.54 %	6.177	19.01%
Singelgracht DNB-Heineken	2.702	17.78 %	2.042	13.44%
Herengracht	6.231	29.68 %	11.53	36.42%
Keizersgracht	8.286	32.60 %	6.330	24.90%

The results for Scenario C show that at some locations, the fit is slightly better and at other slightly worse. The increase in speed does not lead to a significant difference for all the locations, thus the speed increase for cruise vessels did not make a difference.

Conclusion

Concluding, the vessel speed parameter does make a difference for the goodness of fit of the model with the measurement data. However, different settings of the vessel speed parameter per vessel type do not show better results for the goodness of fit compared with the calibrated scenario. Hence, this study uses the values for the speed parameter for the null scenario as Table Table 4.18 shows.

4.2.4 Explained error

In general, the error might be more substantial than the NMAE and the MAE insinuate. The MAE divides the data with all the data points. This provides a slightly shifted view because it also includes the points where there is no traffic, and thus the model does not need to perform well. For these data points, the model has, therefore, a perfect fit. Hence, this statistical method may produce a lower error margin and thus superior results.

The central question of this subsection is as follow how much of the error can be explained by the behavior of the different types of vessels? The traffic flow on the canals of Amsterdam consists of different types of vessels (Figure 2.7), each with their own route choice behavior. The different vessel types discussed in Section 2.1 are generalized into three categories in the model. Consequently, an error will always exist because these three vessel types are an approximation of reality.

From the three categories, model results from the cruise vessels and measurement data of category 3 can be directly compared, because type three directly represents cruise vessels. Therefore, the errors in the model results can directly be explained by cruise vessels' behavior.

However, the other two categories cannot directly be compared with the different vessel types. The range of lengths of pleasure craft can be from 0 to 4 m (small vessels) up to 10 m, thereby fitting into both categories of the measured data from Waternet (category 1 and 2). No direct comparison can be made between model data and the measurements between these type of vessels.

Scenario 1

The model results showed a good fit at Keizersgracht. However, when the results were inspected per vessel type, a different conclusion was revealed. The error at Keizersgracht was significant for the cruise vessels. Too few pleasure craft and random cruise vessels as well as too many cruise vessels sail through this canal. A possible explanation for the difference between the model and the measurements for cruise vessel passages is that the routing of the cruise vessel companies may have changed. When possible results of an intervention are examined, the error for the cruise vessels at Keizersgracht must be taken into account.

The overestimation at Herengracht in scenario 1 is a consequence of too many pleasure craft and random cruise vessels sailing on the Herengracht. The cruise vessels show a good fit with the measured results. Thus, the routing algorithms of either the pleasure craft or the random cruise vessels require adjusting. Possible explanations for the difference in the random cruise vessels could be that the routing algorithm of either might not be working optimally, and therefore they select the Herengracht instead of other canals.

Scenario 2

The error for the cruise vessels is substantial for the location of Keizersgracht. The same error can be found in scenario 1. Usually, the routing of cruise vessels is not adjusted during the weekend. The number of pleasure craft and random cruise vessels compensate for the error of cruise vessels on the Keizersgracht. The model overestimates the number of passages for the cruise vessels, random cruise vessels, and pleasure craft at Singel Haarlemmersluis. Possible reasons for the cruise vessels is that their routing is adjusted or that some routes are preferable to others during the week. Regarding the other vessels, no information exists on what the distribution per vessel type should be for these locations. Consequently, it is difficult to state whether the routing of the pleasure craft, random cruise vessels, or both need to be altered.

Scenario 3

The model overestimates at the location Keizersgracht for the cruise vessels. This was expected because the same error was revealed in the previous two scenarios. Very few vessel movements occur for the random cruise vessels and pleasure craft. Consequently, small differences between the model and measurement data result in significant errors. These errors have not manifested in the overall fit of the results; therefore, most of the traffic demand is from cruise vessels.

Scenario 4

Identical to scenarios 1, 2, and 3, the Keizersgracht presents a significant error because of overestimation. This error was explained in the previous scenarios. Similar to scenario 3, the cruise vessels make up most of the traffic demand for this scenario. Scenario 4 shows few movements for random cruise vessels and pleasure craft. Thus, the error snowballs with small differences. The overall fit of the data is still quite good despite the error of the Keizersgracht.

4.3 Conclusion

This part of the thesis sought to answer the subquestion: *Can the traffic on the Amsterdam canal network be reproduced for the previously identified vessel types?*

To answer this question, the model was tested on the different model components and thus validated internally if the functionality needed for the traffic flow and congestion patterns is implemented and works the way it is supposed to; to test if the model has been built right internally. After the internal validation, the model has been calibrated with the data from Waternet to test until what extent the model was able to reproduce reality.

To validate the model internally, the different components of the model have been tested. These are the network and the three vessel types sailing on the network. The model passed 7 of the 7 tests. These test internally validated the model and proved that the model components (the simulation, the three different vessel types and the network) give accurate results. It met *the essential functional requirements* for reproducing congestion and traffic flow (such as moving and staying on a graph). The model was able to create different types of vessels, and these vessels could move on the graphs using different timesteps, could calculate their own route according to their vessel type, could statically reroute themselves based on canal disruptions in the network, and could queue at crossings. The *additional functional requirements* have not been implemented and, therefore, not tested. The results of the test are shown in Appendix B.

The next step was to calibrate the model with the data from Waternet to test until what extent the model was able to reproduce reality. With this method, the model was calibrated to the different traffic demand scenarios. Results show that the model, which is calibrated based on data from Waternet, can reproduce the different traffic demand scenarios. This study used two parameters for each vessel type to calibrate the model: the vessel generator and the vessel speed parameter. The vessel generator combined with the following settings for vessel speed parameter for each vessel showed the best fit:

- cruise vessels: uniform speed between 6 -7.5 km/h,
- random cruise vessels: uniform speed between 5-6 km/h,
- pleasure craft: uniform speed between 5-6 km/h.

In general, the model results fit the measured data within acceptable limits of around 65–85% in number of passages per hour per vessel type for the seven measurement locations. However, not all the results fit the data within this range. The cruise vessel results for the Keizersgracht canal show a significant overestimation for each scenario, meaning that more vessels sailed on this part of the canal in the model than actually measured in reality. A second difficulty arises from the limited accuracy of the measurement data. Because of this limited accuracy, precise calibration of the random cruise vessels and the pleasure craft per location was not possible.

5
Application

Now that the limits and accuracy of the model are known, this project applied the model to possible intervention scenarios. To answer the last subquestion, this project simulated two possible intervention scenarios to examine the capabilities of the model. Section 5.1 describes the two possible interventions and explains the results. However, no information is available to validate the intervention model results. Consequently, Section 5.2 proposes two methods to take measurements that could validate the model results.

5.1 Interventions

As the introduction of this thesis describes, during canal-upgrade works a canal is blocked or is significantly reduced capacity for nautical traffic. In the case of reduced capacity, implementing a one-way traffic restriction can help reduce congestion on a partially blocked canal. An example of such a partially blocked canal can be seen in Figure 1.2 in Chapter 1. This study distinguishes two types of interventions where canal-upgrade works are in progress: complete canal closure or regulating traffic by implementing a one-way traffic restriction on a canal.

Most congestion occurs at crossings (Gemeente Amsterdam, 2018a). Therefore, the crossings are used to analyze the congestion patterns resulting from an intervention. Figure 6.1 shows the locations of these crossings. Unfortunately, information on capacity is available only for the crossings at Prinsen-Leidsegracht (Figure 6.1 ; 2) and Haarlemmersluis (Figure 6.1 ; 1) (Gemeente Amsterdam, 2018a). The crossings at Prinsen-Leidsegracht (2) and Haarlemmersluis (1) are two different types of crossings. Haarlemmersluis is a crossing where three canals meet, with a narrow passage in one of the canals. Prinsengracht-Leidsegracht is a crossing where four canals meet, with three adjacent bridges. These are the two narrowest crossings among the 11 listed, thus their capacities have been used as a lower limit when estimating congestion at the other crossings. Based on the capacities of these two crossings, an overview of the estimated capacity per crossing has been made for the other crossings. Table 5.1 lists the estimated capacity for each crossing. If said capacity is exceeded, congestion occurs. The crossings in Table 5.1 are the other narrow crossings in the Amsterdam city center and are located on busy canals; therefore, congestion is most likely to occur at these locations. The other crossings have been simulated with an estimated capacity of 350 passages per hour.

Figure 5.1: Crossings

Number	Crossing	Estimated capacity
1	Haarlemmersluis	36
2	Prinsengracht and Leidsegracht	120
3	Keizersgracht and Leidsegracht	140
4	St Antonie Sluis	200
5	Reguliersgracht and Keizersgracht	130
6	Prinsengracht and Leliegracht	140
7	Keizersgracht and Leliegracht	140
8	Herengracht and Leliegracht	140
9	Keizersgracht and Brouwersgracht	100
10	Herengracht and Brouwersgracht	100
11	Prinsengracht and Brouwersgracht	70
12	Leliegracht (canal)	-

Table 5.1: Legenda of Figure 6.1

The relative and absolute change in passages per location after an intervention are calculated with equations 5.1 and 5.2, with x_o as the value for that particular hour from the calibrated null scenario, and x_n the new value after the intervention. With these equations, changes in expected passages for each crossing can be compared to each other. To best reflect these changes, n_{hours} is taken from the moment the first passage is measured.

$$Absolute\ change = \frac{\sum_{i=1}^{n_{hours}} x_n - x_o}{n_{hours}} \tag{5.1}$$

$$Relative\ change = \frac{\sum_{i=1}^{n_{hours}} (\frac{x_n - x_o}{x_o} * 100)}{n_{hours}} \tag{5.2}$$

5.1.1 Canal-closure

The model can be used as a tool to analyze the consequences of intervention scenarios. As a practical case, this project simulated a canal closure for part of the Prinsengracht. Figure 5.2 shows the location of the simulated closure. Because canal-upgrade works can continue for as long as one year, the model simulated a canal closure for each traffic demand scenario. Table 5.2 shows the legenda for the graphs in this section.

Table 5.2: Legenda for the graphs in Section 5.1.1

Results	Color
Calibrated model results	
Intervention results	

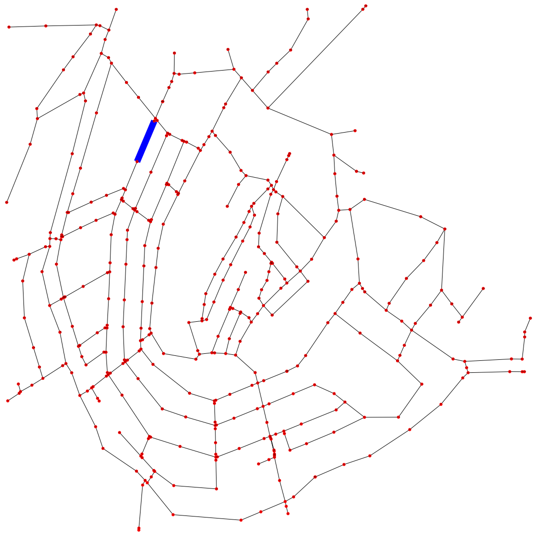


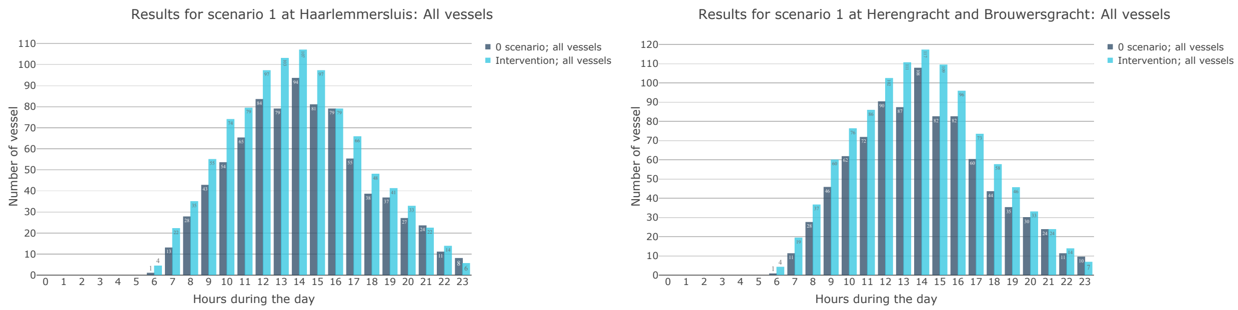
Figure 5.2: The edge marked blue shows the location of the closed off canal

Scenario 1: High traffic demand

Scenario 1 models a high-traffic situation on a weekend day in July. Table 5.3 shows the simulated change in traffic for each location for scenario 1. The change in number of passages can be analyzed by comparing the number of passages per vessel type to the original number. As can be observed from Table 5.3, the crossings at Haarlemmersluis and at Prinsengracht and Brouwersgracht show significant traffic changes. The drop of 80% at Prinsengracht and Brouwersgracht can be explained by the fact that the canal adjacent to this crossing is closed off. Figure 5.3 graphs the number of passages by time of day for the two crossings with the greatest increases in traffic. Indept explanation of the results can be found in Section 5.1.1; "Results explained".

Table 5.3: Results canal-closure; Scenario 1: all vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	10.4	19%	94	14	107	14
Prinsengracht and Leidsegracht	3.92	3.97%	241	14	255	14
Keizersgracht and Leidsegracht	1.69	1.79%	271	14	272	14
St Antonie Sluis crossing	0.986	-0.174%	234	14	241	15
Reguliersgracht and Keizersgracht	-1.01	-0.964%	150	14	141	14
Prinsengracht and Leliegracht	3.41	3.54%	142	14	145	14
Keizersgracht and Leliegracht	9.07	6.84%	216	14	216	14
Herengracht and Leliegracht	6.39	6.49%	182	14	174	14
Keizersgracht and Brouwersgracht	-0.0393	-0.864%	112	14	109	14
Herengracht and Brouwersgracht	12.1	20.6%	108	14	117	14
Prinsengracht and Brouwersgracht	-51.4	-80.0%	109	14	23	15
Leliegracht (canal)	14.1	19%	140	14	153	14



(a) Haarlemmersluis **(b)** Herengracht and Brouwersgracht

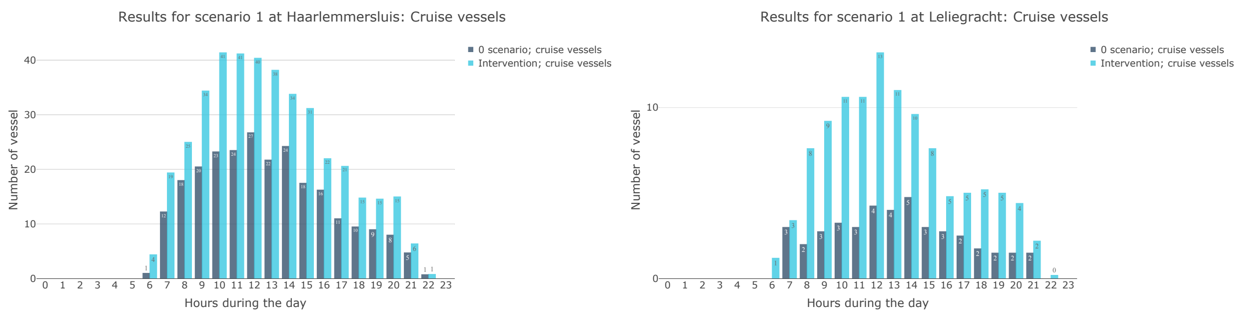
Figure 5.3: Results for scenario 1; All vessels: Prinsengracht and Leidsegracht; Herengracht and Brouwersgracht

Scenario 1: Cruise vessels

Table 5.4 shows the change of the cruise vessel passages per location. Indept explanation of the results can be found in Section 5.1.1; "Results explained".

Table 5.4: Results canal-closure; Scenario 1; cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	9.93	59.6%	27	12	41	10
Prinsengracht and Leidsegracht	-0.185	1.38%	24	10	22	12
Keizersgracht and Leidsegracht	0.181	4.22%	15	10	13	11
St Antonie Sluis crossing	0.182	-2.29%	31	11	34	11
Reguliersgracht and Keizersgracht	0.246	6.45%	19	11	21	9
Prinsengracht and Leliegracht	0.35	7.22%	11	9	14	12
Keizersgracht and Leliegracht	3.87	51.2%	12	12	19	12
Herengracht and Leliegracht	0.0115	2.19%	18	13	17	9
Keizersgracht and Brouwersgracht	9.07	184%	10	12	24	11
Herengracht and Brouwersgracht	8.57	61.6%	23	12	36	10
Prinsengracht and Brouwersgracht	-10.9	-100%	18	9	0	0
Leliegracht (canal)	4.76	168%	5	14	13	12



(a) Haarlemmersluis **(b)** Leliegracht

Figure 5.4: Results for scenario 1; cruise vessels; Haarlemmersluis and Leliegracht

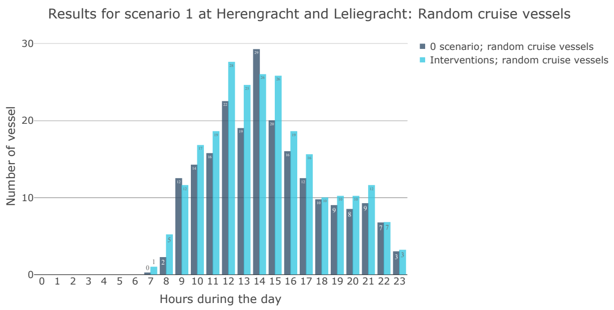
Under scenario 1, the crossings at Keizersgracht and Brouwersgracht, Keizersgracht and Leliegracht, Herengracht and Brouwersgracht, and Haarlemmersluis, along with the canal at Leliegracht, show substantial traffic increases after the canal closure. Cruise vessels cope with the canal closure by redirecting their routes through the crossings at Haarlemmersluis and at Keizersgracht and Leliegracht, and via the canal at Leliegracht. Figure 5.4 graphs the number of passages by time of day for the locations Haarlemmersluis and Leliegracht.

Scenario 1: Random cruise vessels

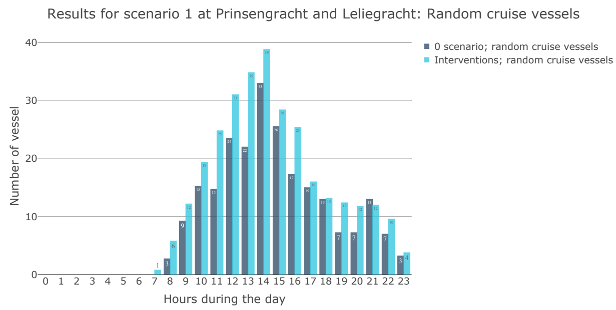
Table 5.5 shows the changes in the number of random cruise vessel passages for each crossing. Interestingly, the Keizersgracht and Brouwersgracht crossing shows an overall decrease in passages by random cruise vessels, while it shows an increase in passages by cruise vessels. The results also show an increase in passages at Prinsengracht and Leliegracht crossing and Leliegracht canal. Figure 5.5 graphs the number of passages by time of day for these locations.

Table 5.5: Results canal-closure; Scenario 1; random cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	-0.729	-4.36%	33	14	32	14
Prinsengracht and Leidsegracht	1.81	12%	44	14	46	14
Keizersgracht and Leidsegracht	0.857	7.21%	52	14	52	14
St Antonie Sluis crossing	0.668	0.921%	44	14	47	13
Reguliersgracht and Keizersgracht	-0.0107	5.89%	39	14	34	14
Prinsengracht and Leliegracht	4.79	33.2%	33	14	39	14
Keizersgracht and Leliegracht	2.73	12.5%	44	14	45	14
Herengracht and Leliegracht	2.07	14.4%	29	14	28	12
Keizersgracht and Brouwersgracht	-5.93	-28.6%	36	14	24	14
Herengracht and Brouwersgracht	-2.61	-14.1%	33	14	25	14
Prinsengracht and Brouwersgracht	-11	-97.1%	22	14	1	9
Leliegracht (canal)	6.55	41.9%	31	14	40	14



(a) Herengracht and Leliegracht



(b) Leliegracht

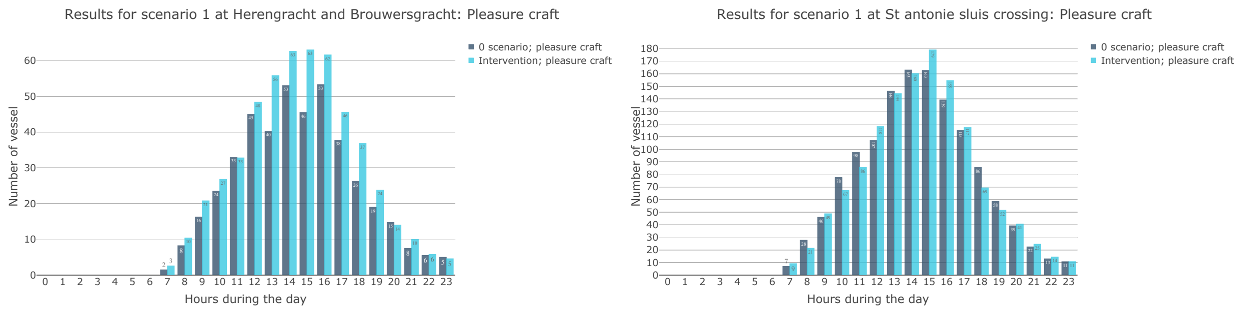
Figure 5.5: Results for scenario 1; random cruise vessels; Herengracht and Leliegracht; Leliegracht

Scenario 1: Pleasure craft

The results for pleasure craft passages for scenario 1 are shown in Table 5.6. The only location that shows a large change in the number of passages is the crossing at Herengracht and Brouwersgracht. The peak of pleasure craft passages is slightly higher at St Antonie sluis and at Prinsengracht and Leidsegracht. Figure 5.6 graphs the number of passages by time of day for these two locations.

Table 5.6: Results canal-closure; Scenario 1; pleasure craft

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	1.32	10.3%	41	16	41	14
Prinsengracht and Leidsegracht	2.21	2.73%	187	15	194	14
Keizersgracht and Leidsegracht	0.629	0.667%	211	14	213	14
St Antonie Sluis crossing	0.132	0.238%	163	14	179	15
Reguliersgracht and Keizersgracht	-1.24	-4.56%	94	15	93	15
Prinsengracht and Leliegracht	-1.71	-5.49%	102	15	97	14
Keizersgracht and Leliegracht	2.41	0.636%	161	14	157	14
Herengracht and Leliegracht	4.31	4.95%	135	14	133	14
Keizersgracht and Brouwersgracht	-3.14	-9.93%	70	15	66	14
Herengracht and Brouwersgracht	6.23	19.9%	53	16	63	15
Prinsengracht and Brouwersgracht	-30.2	-71%	80	15	23	15
Leliegracht (canal)	3.13	4.11%	104	14	108	15



(a) Herengracht and Brouwersgracht **(b)** St Antonie Sluis crossing

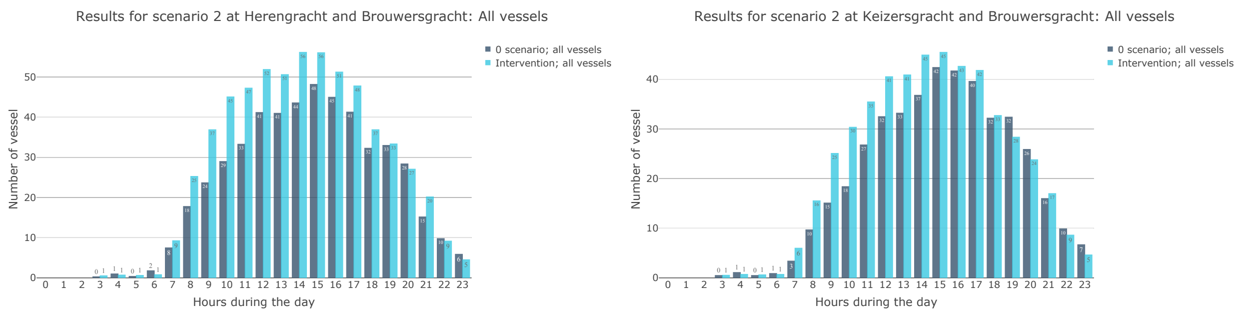
Figure 5.6: Results for scenario 1; pleasure craft; Herengracht and Brouwersgracht; St Antonie Sluis crossing

Scenario 2: Medium traffic demand

Table 5.7 shows an overview of the changes at each location for the medium traffic demand scenario, which is a weekday in July. The crossings at Haarlemmersluis, at Herengracht and Brouwersgracht, and at Prinsengracht and Brouwersgracht show significant changes. The drop of 80% at Prinsengracht and Brouwersgracht can be explained by the fact that the canal adjacent to it is closed off. Figure 5.7 graphs the number of passages by time of day for the crossings at Herengracht and Brouwersgracht and Keizersgracht and Brouwersgracht. Section 5.1.1; "results explained" discusses possible explanations of the results.

Table 5.7: Results canal-closure; Scenario 2; all vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	8.71	22.3%	55	15	67	15
Prinsengracht and Leidsegracht	0.686	0.886%	80	16	83	15
Keizersgracht and Leidsegracht	0.481	0.624%	78	16	79	16
St Antonie Sluis crossing	1.31	3.04%	73	15	77	13
Reguliersgracht and Keizersgracht	-0.583	0.212%	53	16	53	15
Prinsengracht and Leliegracht	0.314	0.671%	50	15	50	16
Keizersgracht and Leliegracht	3.07	8.29%	62	15	65	16
Herengracht and Leliegracht	1.14	4.2%	50	16	51	16
Keizersgracht and Brouwersgracht	3.9	15.9%	42	15	45	15
Herengracht and Brouwersgracht	7.5	22.4%	48	15	56	14
Prinsengracht and Brouwersgracht	-22.2	-80.7%	38	15	8	17
Leliegracht (canal)	4.03	12.6%	46	15	53	16



(a) Herengracht and Brouwersgracht **(b)** Keizersgracht and Brouwersgracht

Figure 5.7: Results for scenario 2; Herengracht and Brouwersgracht; Keizersgracht and Brouwersgracht

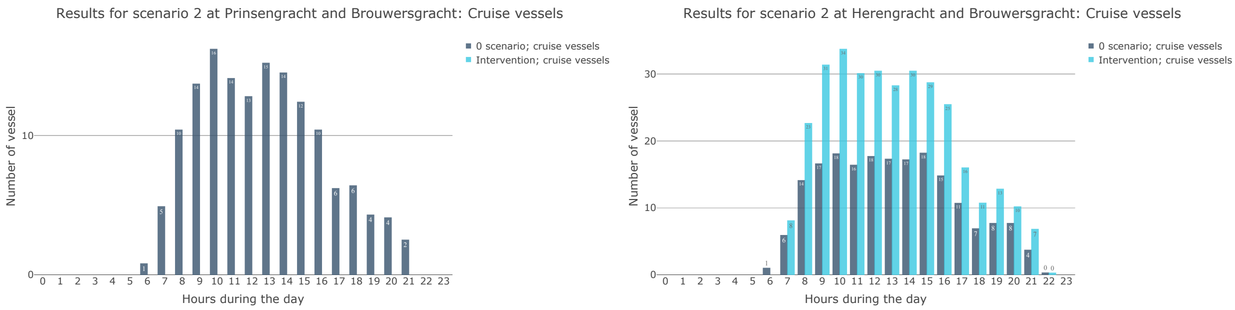
Scenario 2: Cruise vessels

Table 5.8 shows the change in the number of cruise vessel passages at each location. The cruise vessels show a 100% drop in passages at the Prinsengracht and Brouwersgracht crossing and a significant increase at

Haarlemmersluis, at Keizersgracht and Leliegracht, at Keizersgracht and Brouwersgracht, and at Herengracht and Brouwersgracht crossings, and at the Leliegracht canal. Figure 5.8 graphs the number of passages by time of day for the crossings at Herengracht and Brouwersgracht and at Keizersgracht and Brouwersgracht

Table 5.8: Results canal-closure; Scenario 2; cruise vessles

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	8.64	46.2%	25	10	39	10
Prinsengracht and Leidsegracht	-0.0646	-1.44%	18	10	17	10
Keizersgracht and Leidsegracht	-0.0661	-2.31%	10	12	11	10
St Antonie Sluis crossing	-0.285	-2.28%	30	9	30	10
Reguliersgracht and Keizersgracht	-0.223	-1.49%	18	13	20	10
Prinsengracht and Leliegracht	0.318	9.00%	12	13	11	14
Keizersgracht and Leliegracht	4.15	59.8%	11	10	17	10
Herengracht and Leliegracht	0.257	1.06%	16	10	18	10
Keizersgracht and Brouwersgracht	8.5	162%	7	15	20	10
Herengracht and Brouwersgracht	8.64	62.8%	18	15	34	10
Prinsengracht and Brouwersgracht	-10.2	-100%	16	10	0	0
Leliegracht (canal)	3.98	162%	6	10	10	14



(a) Prinsengracht and Brouwersgracht

(b) Herengracht and Brouwersgracht

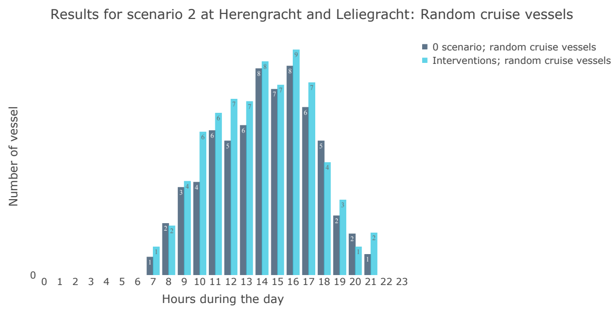
Figure 5.8: Results for the cruise vessels at Prinsengracht and Brouwersgracht; Keizersgracht and Brouwersgracht

Scenario 2: Random cruise vessels

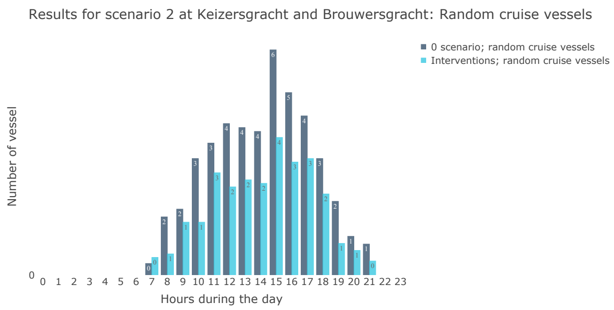
The results for the random cruise vessels are depicted in Table 5.9. The crossing at Haarlemmersluis shows a significant increase. While the relative increase is large, the maximum number of passages still remains 2. Figure 5.9 graphs the number of passages by time of day for the crossings at Herengracht and Brouwersgracht and at Keizersgracht and Brouwersgracht. Interestingly, the crossing at Keizersgracht and Brouwersgracht shows a decrease of 37.7%, while passages of cruise vessels increased at this location.

Table 5.9: Results canal-closure; Scenario 2; random cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	0.236	31.4%	2	15	2	16
Prinsengracht and Leidsegracht	0.494	19.7%	11	15	12	16
Keizersgracht and Leidsegracht	0.285	6.37%	13	14	14	14
St Antonie Sluis crossing	1.11	9.46%	15	16	16	13
Reguliersgracht and Keizersgracht	0.188	8.08%	12	17	11	14
Prinsengracht and Leliegracht	0.439	12%	8	16	8	16
Keizersgracht and Leliegracht	0.379	12.8%	11	14	11	16
Herengracht and Leliegracht	0.578	17.8%	8	16	9	16
Keizersgracht and Brouwersgracht	-1.15	-37.7%	6	15	4	15
Herengracht and Brouwersgracht	-0.242	-2.89%	5	15	3	15
Prinsengracht and Brouwersgracht	-2.89	-95.4%	5	15	0	12
Leliegracht (canal)	0.654	26.2%	7	14	8	16



(a) Herengracht and Leliegracht



(b) Keizersgracht and Brouwersgracht

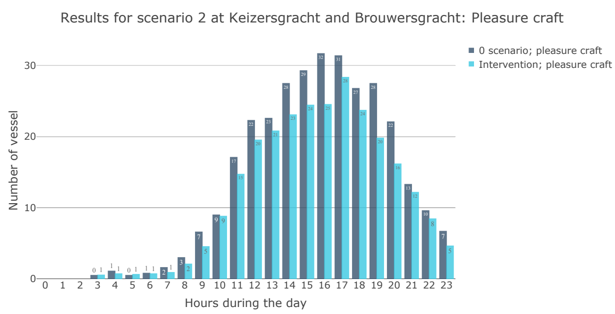
Figure 5.9: Results for the pleasurecraft at Herengracht and Leliegracht; Keizersgracht and Brouwersgracht

Scenario 2: Pleasure craft

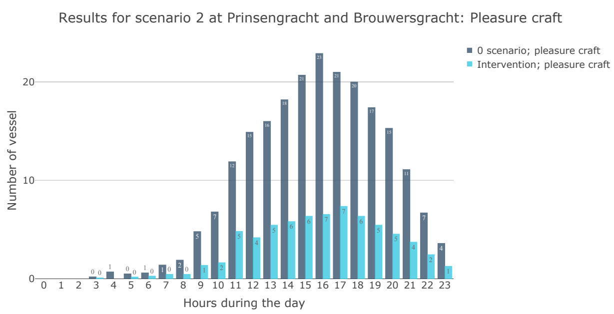
The results for pleasure craft passages are shown in Table 5.10. The number of passages shows an overall decrease of 15%. Possible explanations are given in Section 5.1.1. Figure 5.10 graphs the number of passages by time of day for the crossings at Keizersgracht and Brouwersgracht and at Prinsengracht and Brouwersgracht. These two locations show the most considerable change.

Table 5.10: Results canal-closure; Scenario 2; pleasure craft

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	-0.0814	0.4%	31	17	34	17
Prinsengracht and Leidsegracht	0.294	0.957%	58	17	57	15
Keizersgracht and Leidsegracht	0.277	0.669%	60	16	58	16
St Antonie Sluis crossing	0.564	2.52%	36	17	34	17
Reguliersgracht and Keizersgracht	-0.554	-1.85%	30	16	27	15
Prinsengracht and Leliegracht	-0.421	-2.29%	35	15	33	15
Keizersgracht and Leliegracht	-1.44	-4.6%	44	15	43	16
Herengracht and Leliegracht	0.354	2.61%	30	16	30	16
Keizersgracht and Brouwersgracht	-3.4	-15.6%	32	16	28	17
Herengracht and Brouwersgracht	-1.0	-5.34%	28	17	29	17
Prinsengracht and Brouwersgracht	-10.1	-68.2%	23	16	7	17
Leliegracht (canal)	-0.334	-2.65%	36	15	36	16



(a) Keizersgracht and Brouwersgracht



(b) Prinsengracht and Brouwersgracht

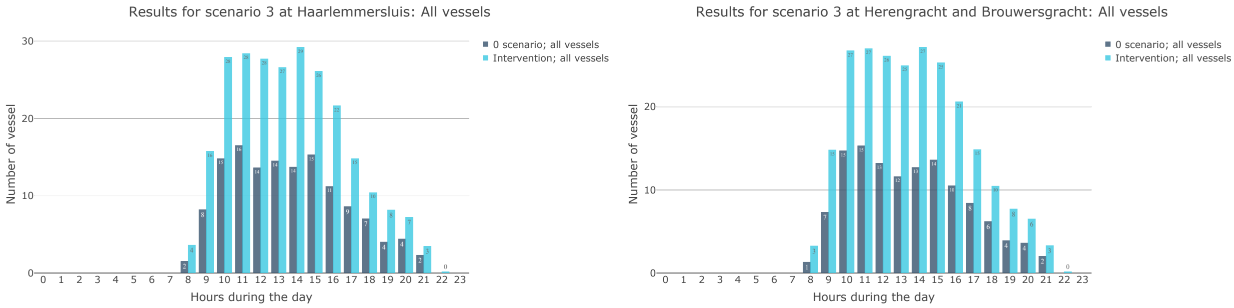
Figure 5.10: Results for Scenario 2 for pleasure craft at Keizersgracht and Brouwersgracht; Prinsengracht and Brouwersgracht

Scenario 3: Low traffic demand

Not many people sail on the canals on a weekend day in December. Therefore, an intervention will have less impact on the nautical traffic. As analyzed in Section 4.2.2, most of the traffic sailing on the canals during winter consists of cruise vessels. The routing for cruise vessels in winter is slightly different than during the summer. Thus it is interesting to analyze the results. Table 5.11 shows the results for this scenario. As Table 5.11 displays, the cruise vessels reroute via the crossings at Haarlemmersluis, at Keizersgracht and Leliegracht, and at Herengracht and Brouwersgracht. Figure 5.11 graphs the number of passages by time of day for Haarlemmersluis and the crossing at Herengracht and Brouwersgracht. Indept explanation of the results can be found in Section 5.1.1; "Results explained".

Table 5.11: Results canal-closure; Scenario 3; all vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	8.69	81.5%	16	11	29	14
Prinsengracht and Leidsegracht	0.286	9%	30	14	26	11
Keizersgracht and Leidsegracht	0.282	3.01%	22	13	22	11
St Antonie Sluis crossing	0.246	0.285%	29	13	30	14
Reguliersgracht and Keizersgracht	0.0192	6.01%	18	11	16	15
Prinsengracht and Leliegracht	0.846	15.6%	18	14	16	12
Keizersgracht and Leliegracht	4.22	49.6%	14	12	20	11
Herengracht and Leliegracht	0.25	-6.88%	14	11	13	10
Keizersgracht and Brouwersgracht	7.77	139%	9	10	21	11
Herengracht and Brouwersgracht	8.62	89.2%	15	11	27	14
Prinsengracht and Brouwersgracht	-11.1	-96.2%	21	14	1	15
Leliegracht (canal)	4.85	104%	8	14	16	12



(a) Haarlemmersluis

(b) Herengracht and Brouwersgracht

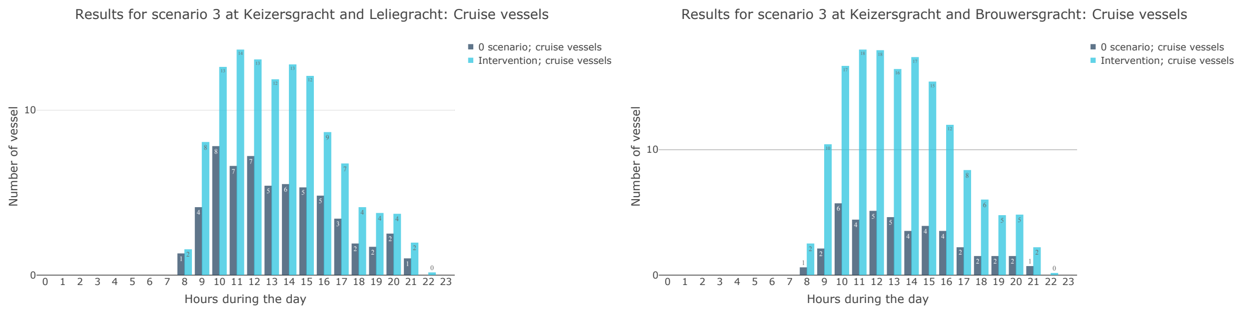
Figure 5.11: Results for scenario 3; all vessels at Haarlemmersluis; Herengracht and Brouwersgracht

Scenario 3: Cruise vessels

The results for the passages of cruise vessels are displayed in Table 5.12. Because the traffic on the canals mainly consists of cruise vessels in scenario 3, the results for cruise vessel passages are proportional to the results for all vessels as displayed in Table 5.11. Figure 5.12 graphs the results of Keizersgracht and Leliegracht and at Keizersgracht and Brouwersgracht.

Table 5.12: Results canal-closure; Scenario 3; cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	8.54	96.2%	14	11	26	14
Prinsengracht and Leidsegracht	0.00714	8.07%	22	14	18	10
Keizersgracht and Leidsegracht	0.0786	2.95%	13	11	13	11
St Antonie Sluis crossing	0.0462	0.146%	21	13	21	13
Reguliersgracht and Keizersgracht	-0.0231	6.52%	13	14	11	11
Prinsengracht and Leliegracht	0.985	28.6%	12	14	11	12
Keizersgracht and Leliegracht	4.28	98.5%	8	10	14	11
Herengracht and Leliegracht	0.107	-7.64%	9	11	9	10
Keizersgracht and Brouwersgracht	8.46	275%	6	10	18	11
Herengracht and Brouwersgracht	8.62	114%	12	10	24	14
Prinsengracht and Brouwersgracht	-9.08	-100%	16	14	0	0
Leliegracht (canal)	4.72	268%	3	11	11	12



(a) Keizersgracht and Leliegracht

(b) Keizersgracht and Brouwersgracht

Figure 5.12: Results for scenario 3; cruise vessels at Keizersgracht and Brouwersgracht; Keizersgracht and Leliegracht

Scenario 3: Random cruise vessels

Table 5.13 shows the results for passages of random cruise vessels. Not many of these vessels sail on the canals in scenario 3. Hence, a difference of 1 passage will cause a more considerable relative change. The peak number of passages has not changed significantly. However, these results may suggest a more substantial change than what is actually the case. The maximum number of passages for most crossings is approximately 5. Thus an increase of 1 passage is a significant increase.

Table 5.13: Results canal-closure; Scenario 3; random cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	0.127	60.8%	1	14	1	15
Prinsengracht and Leidsegracht	0.0708	1.51%	5	13	5	14
Keizersgracht and Leidsegracht	0.121	1.68%	5	13	5	14
St Antonie Sluis crossing	0.242	6.36%	6	13	7	13
Reguliersgracht and Keizersgracht	0.00417	6.84%	5	15	4	16
Prinsengracht and Leliegracht	0.0833	15.5%	4	14	3	12
Keizersgracht and Leliegracht	0.0917	10.5%	4	14	4	15
Herengracht and Leliegracht	0.15	13.8%	4	14	3	15
Keizersgracht and Brouwersgracht	-0.567	-25.3%	3	14	1	15
Herengracht and Brouwersgracht	-0.142	-3.92%	1	10	1	15
Prinsengracht and Brouwersgracht	-1.23	-90.0%	2	14	0	11
Leliegracht (canal)	0.175	22.6%	3	14	3	10

Scenario 3: Pleasure craft

The number of pleasure craft that sail on the canals in scenario 3 is also not substantial. Overall, the intervention does not seem to have much impact on the number of pleasure craft passages. The results are shown in Table 5.14. The peak number of passages also does not change much after the canal closure.

Table 5.14: Results canal-closure; Scenario 3; pleasure craft

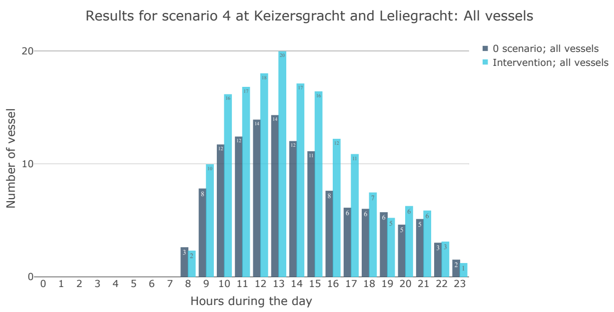
Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	0.075	22.2%	3	11	3	16
Prinsengracht and Leidsegracht	0.25	15.5%	5	15	4	15
Keizersgracht and Leidsegracht	0.117	15.3%	6	15	5	13
St Antonie Sluis crossing	-0.025	13.2%	4	16	3	16
Reguliersgracht and Keizersgracht	0.0417	10.6%	2	13	2	13
Prinsengracht and Leliegracht	-0.238	7.42%	3	16	3	14
Keizersgracht and Leliegracht	-0.171	-5.86%	4	13	4	16
Herengracht and Leliegracht	0.0167	4.84%	3	13	3	14
Keizersgracht and Brouwersgracht	-0.175	1.83%	3	12	3	16
Herengracht and Brouwersgracht	0.158	30.3%	2	11	2	16
Prinsengracht and Brouwersgracht	-0.829	-59.9%	2	12	1	15
Leliegracht (canal)	-0.0292	15%	3	16	3	14

Scenario 4: Very low traffic demand

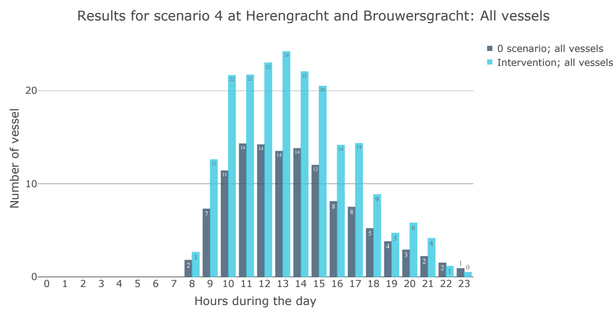
Section 4.2.2 shows that in the low traffic demand scenario, the traffic consists almost solely of cruise vessels. Consequently, the results for cruise vessel passages are effectively all of the results for scenario 4. Table 5.15 displays the results for this scenario. Figure 5.13 graphs the number of passages by time of day for the crossings at Keizersgracht and Leliegracht and at Herengracht and Brouwersgracht. Indept explanation of the results can be found in Section 5.1.1; "Results explained".

Table 5.15: Results canal-closure; Scenario 4; all vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	6.26	69.9%	16	12	26	13
Prinsengracht and Leidsegracht	-0.196	3.92%	26	13	26	13
Keizersgracht and Leidsegracht	-0.389	0.0429%	21	12	21	13
St Antonie Sluis crossing	0.304	4.24%	26	13	26	12
Reguliersgracht and Keizersgracht	-0.293	-1.36%	18	10	17	11
Prinsengracht and Leliegracht	0.50	5.06%	13	13	14	13
Keizersgracht and Leliegracht	3.15	33.4%	14	13	20	13
Herengracht and Leliegracht	0.264	5.94%	13	13	14	13
Keizersgracht and Brouwersgracht	5.26	86.4%	10	11	18	13
Herengracht and Brouwersgracht	5.79	65.1%	14	11	24	13
Prinsengracht and Brouwersgracht	-8.57	-91.4%	15	11	1	13
Leliegracht (canal)	3.47	60.9%	8	12	14	13



(a) Keizersgracht and Leliegracht



(b) Herengracht and Brouwersgracht

Figure 5.13: Results for scenario 4; all vessels for crossings at Keizersgracht and Leliegracht ; Herengracht and Brouwersgracht

Scenario 4: Cruise vessels

The results for cruise vessel passages in scenario 4 are almost the same as those for scenario 3. The crossings at Haarlemmersluis, at Keizersgracht and Brouwersgracht, at Herengracht and Brouwersgracht, and at Keizersgracht and Leliegracht display a significant increase in the number of passages.

Table 5.16: Results canal-closure; Scenario 4; cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	6.29	87.1%	12	13	22	13
Prinsengracht and Leidsegracht	-0.608	-3.58%	17	13	16	13
Keizersgracht and Leidsegracht	-0.388	-3.33%	11	11	11	13
St Antonie Sluis crossing	-0.221	2.62%	19	13	17	12
Reguliersgracht and Keizersgracht	0.0615	7.08%	13	10	12	11
Prinsengracht and Leliegracht	0.346	12%	7	10	8	13
Keizersgracht and Leliegracht	3.32	88.5%	7	13	12	13
Herengracht and Leliegracht	0.20	7.37%	8	13	8	11
Keizersgracht and Brouwersgracht	6.09	267%	5	11	15	12
Herengracht and Brouwersgracht	6.09	99.3%	10	14	20	13
Prinsengracht and Brouwersgracht	-7.15	-100%	11	13	0	0
Leliegracht (canal)	3.25	205%	3	12	8	15

Scenario 4: Random cruise vessels and pleasure craft

Table 5.17 and Table 5.18 present the results for passages of random cruise vessels and pleasure craft, respectively. For both, the number of passages, except at the Prinsengracht and Brouwersgracht crossing, did not change significantly. The relative increase at some locations may be high, but the actual number of passages changed with 1 or 2. Because there are so few random cruise vessels and pleasure craft sailing on the canals in this scenario, hardly any conclusions can be drawn from these results.

Table 5.17: Results canal-closure; Scenario 4; random cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	-0.142	4.58%	3	11	3	11
Prinsengracht and Leidsegracht	0.204	13.2%	4	12	4	13
Keizersgracht and Leidsegracht	0.188	12.3%	4	9	4	11
St Antonie Sluis crossing	0.219	21.7%	4	11	4	10
Reguliersgracht and Keizersgracht	-0.0962	21.5%	3	9	3	10
Prinsengracht and Leliegracht	0.242	80.0%	3	11	3	11
Keizersgracht and Leliegracht	0.0769	49.1%	4	10	4	11
Herengracht and Leliegracht	-0.0308	19.8%	3	10	2	9
Keizersgracht and Brouwersgracht	-0.562	-15.2%	4	11	2	11
Herengracht and Brouwersgracht	-0.285	10.9%	3	11	2	11
Prinsengracht and Brouwersgracht	-0.877	-93.8%	2	11	0	9
Leliegracht (canal)	0.365	78.5%	3	11	3	11

Table 5.18: Results canal-closure; Scenario 4; pleasure craft

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	0.121	43.3%	2	12	2	13
Prinsengracht and Leidsegracht	0.139	3.61%	6	14	6	12
Keizersgracht and Leidsegracht	-0.236	-3.86%	8	14	6	13
St Antonie Sluis crossing	0.321	13.2%	5	13	5	13
Reguliersgracht and Keizersgracht	-0.268	-9.93%	4	12	3	14
Prinsengracht and Leliegracht	-0.0536	-0.436%	4	13	3	13
Keizersgracht and Leliegracht	-0.0214	1.12%	5	14	5	13
Herengracht and Leliegracht	0.10	3.62%	4	12	5	13
Keizersgracht and Brouwersgracht	-0.30	-6.18%	2	13	2	13
Herengracht and Brouwersgracht	-0.0214	3.39%	2	15	2	13
Prinsengracht and Brouwersgracht	-1.19	-68.6%	3	13	1	13
Leliegracht (canal)	0.10	5.46%	4	14	4	13

Results explained

In scenario 1, the overall increase in passages at Haarlemmersluis is a consequence of the cruise vessels' rerouting. Because the canals adjacent to the closed-off canal have a one-way traffic restriction in place, cruise vessels reroute and take the Haarlemmersluis (coming from 't IJ), then via Herengracht and Brouwersgracht, Keizersgracht and Brouwersgracht, Keizersgracht and Leliegracht, and finally the Leliegracht canal to get back to the Prinsengracht. This reroute is a substitute for the regular Eenhoornsluis route when sailing from t IJ.

The increases at Prinsengracht and Leliegracht, at Keizersgracht and Leliegracht, and at Herengracht and Leliegracht are due to the rerouting algorithm used by cruise vessels and random cruise vessels, as these crossings are along the shortest path to the Prinsengracht. The crossing at Keizersgracht and Brouwersgracht shows no decrease. Nevertheless, cruise vessel passages show an increase at this location. However, the number of passages for random cruise vessels and pleasure craft drop. Thus the cruise vessels compensate for the random cruise vessels and the pleasure craft.

The routes of the random cruise vessels are based on sightseeing points. The overall increase in the number of passages for these vessels at Keizersgracht and Leliegracht and at Prinsengracht and Leliegracht show that the vessels sail around the closure. The routing algorithm for these vessels removes any sightseeing point that is located on a closed-off edge and then uses Dijkstra's algorithm to reach the next point. Because a one-way traffic restriction is active on the Prinsengracht and the upper part is closed, the vessels sail via the Keizersgracht and use the Leliegracht canal to reach any sightseeing points on the Prinsengracht.

Pleasure craft vessels sail more randomly on the canals. The impact of a canal closure should not have much influence on the number of passages. The results show that the number of passages at the crossing at Prinsengracht and Brouwersgracht drops significantly, while the number of passage at Herengracht and Brouwersgracht increases. The routing algorithm removes any waypoint that is on the closed-off canal. Thus, fewer vessels take the Brouwersgracht, because they navigate less often to the upper part of the Prinsengracht. This explains the decrease at the crossing at Keizersgracht and Brouwersgracht.

The scenario 1 observations also hold for scenario 2, because the same routing algorithms are applied. The only difference is the number of passages and the distribution of vessels at each location. Fewer pleasure craft sail on weekdays, and they start sailing later in the day. The distribution per vessel type is therefore different, but the reroute choices per vessel type stay the same.

Even fewer pleasure craft and random tour vessels sail during scenarios 3 and 4. The same rerouting behavior that was observed in scenarios 1 and 2 can be deduced from results of scenarios 3 and 4. The routing and frequency of the cruise vessels are slightly different during winter, which explains the difference in the number of passages at each location.

Conclusion canal closure

The capacity is exceeded at almost every crossing in scenario 1. Already at the calibrated null scenario, the capacity has been exceeded. Thus, congestion is expected to occur even in the null scenario at these crossings. The canal closure makes congestion worse at Haarlemmersluis and at Herengracht and Brouwersgracht. The Haarlemmersluis crossing has a capacity of 36 vessels per hour. A canal closure adds an average of 13 additional vessels at the peak, for a total of 117 passages during peak hours. On average, the number of vessels that pass this crossing increases by 10.4 vessels per hour under a canal closure. This increase is fully one-third of the crossing capacity. The increase in the number of passages at Haarlemmersluis can be explained by the rerouting of cruise vessels. The capacity at Brouwersgracht is also exceeded and thus congestion may occur there. However, the crossing capacity is an estimate based on the capacity at Prinsengracht. In reality, the capacity of this crossing may differ from the estimate. A third consequence of canal closure is the increased usage of the Leliegracht canal. In scenarios 2, 3 and 4, capacity is not reached or exceeded.

From Section 4.2, it became clear that the cruise vessels did not fit the measurement data for the location Keizersgracht. As the canal-closure was not on the Keizersgracht, the error did not play a big role in the results from the canal-closure, because the cruise vessels which sailed on the Keizersgracht did not need to reroute. It does, however, plays a part when the absolute number of passages per crossing is examined. The model over-estimated for the number of passages for the cruise vessel at the Keizersgracht. The maximum difference between the measured data and the model results were 8 passages per hour. This means that the absolute results at some locations could differ with 8 passages per hour as a consequence of this error.

The order of magnitude of around 260 vessels per hour at Prinsengracht and Leidsegracht and at Keizersgracht and Leidsegracht seems large. However, recent counts from Mobycon shows that on a Sunday in early September, 270 vessels passed the crossing at Prinsengracht and Leidsegracht (Mobycon, 2018). Therefore, the model does not seem to overpredict at locations that have not been calibrated.

5.1.2 One-way traffic

The location of the one-way traffic restriction intervention is shown in Figure 5.14. Section 5.1.1 described the canal-closure outcomes in detail for all four scenarios, showing that the reroute behavior observed in scenario 1 could also be observed in scenarios 2, 3, and 4. Therefore, this one-way traffic intervention section does not go into detail on results of scenarios 2, 3 and 4. Scenario 1 is the most interesting, as congestion patterns occur in this scenario. Table 5.19 shows the results of this intervention under scenario 1 for all vessels. Table 5.20 displays scenario 1 results for cruise vessels, Table 5.21 for random cruise vessels, and Table 5.22 for pleasure craft.

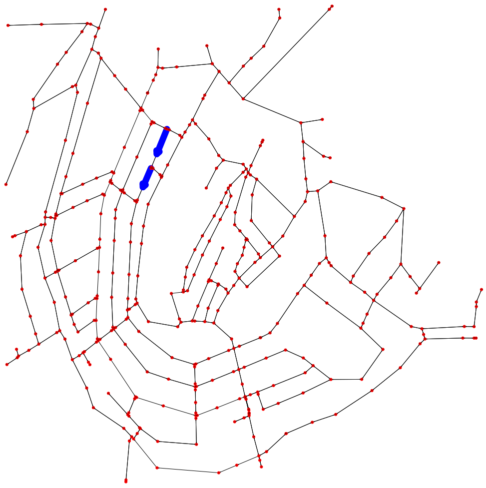


Figure 5.14: The edges marked blue shows the location of the one way traffic implementation, the direction of the arrows show the direction of the traffic

Table 5.19: Results one-way traffic; Scenario 1; all vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	8.29	13.9%	94	14	104	14
Prinsengracht and Leidsegracht	2.74	3.74%	241	14	248	14
Keizersgracht and Leidsegracht	1.11	1.83%	271	14	265	14
St Antonie Sluis crossing	0.232	-1.67%	234	14	234	14
Reguliersgracht and Keizersgracht	0.829	2.84%	150	14	146	14
Prinsengracht and Leliegracht	0.979	0.272%	142	14	147	14
Keizersgracht and Leliegracht	12.8	11.3%	216	14	232	14
Herengracht and Leliegracht	5.0	5.84%	182	14	185	14
Keizersgracht and Brouwersgracht	8.43	13.3%	112	14	131	14
Herengracht and Brouwersgracht	-6.61	-12.5%	108	14	94	14
Prinsengracht and Brouwersgracht	-0.757	2.21%	109	14	107	14
Leliegracht (canal)	-0.236	-0.239%	140	14	136	14

Table 5.20: Results one-way traffic; Scenario 1; cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	1.31	8%	27	12	28	10
Prinsengracht and Leidsegracht	0.169	-0.0154%	24	10	21	12
Keizersgracht and Leidsegracht	0.712	10.1%	15	10	14	12
St Antonie Sluis crossing	0.475	-5.84%	31	11	35	13
Reguliersgracht and Keizersgracht	0.215	5.15%	19	11	21	12
Prinsengracht and Leliegracht	-0.619	-4.46%	11	9	10	12
Keizersgracht and Leliegracht	8	98.6%	12	12	26	11
Herengracht and Leliegracht	-0.050	-0.0538%	18	13	19	10
Keizersgracht and Brouwersgracht	8.64	173%	10	12	23	13
Herengracht and Brouwersgracht	-0.554	-5.81%	23	12	22	11
Prinsengracht and Brouwersgracht	-0.696	-3.69%	18	9	15	13
Leliegracht(canal)	-0.223	-6.85%	5	14	4	10

Table 5.21: Results one-way traffic; Scenario 1; random cruise vessels

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	2.71	14.6%	33	14	38	14
Prinsengracht and Leidsegracht	1.36	11%	44	14	42	13
Keizersgracht and Leidsegracht	0.539	7.57%	52	14	47	14
St Antonie Sluis crossing	0.543	-0.486%	44	14	44	15
Reguliersgracht and Keizersgracht	1.07	12.9%	39	14	35	14
Prinsengracht and Leliegracht	-0.0714	-0.517%	33	14	36	14
Keizersgracht and Leliegracht	1.67	7.14%	44	14	50	14
Herengracht and Leliegracht	1.83	13.1%	29	14	32	14
Keizersgracht and Brouwersgracht	0.354	2.83%	36	14	39	14
Herengracht and Brouwersgracht	-1.31	-7.57%	33	14	27	14
Prinsengracht and Brouwersgracht	0.271	9.21%	22	14	23	14
Leliegracht (canal)	0.50	2.84%	31	14	33	14

Table 5.22: Results one-way traffic; Scenario 1;pleasure craft

Crossings	Absolute average change	Relative average change	**0 Scenario:** Max passages per hour	**0 Scenario:** Max passages at hour of day	**Intervention:** Max passages per hour	**Intervention:** Max passages at hour of day
Haarlemmersluis	4.21	18.8%	41	16	47	15
Prinsengracht and Leidsegracht	1.19	2.36%	187	15	190	14
Keizersgracht and Leidsegracht	-0.136	-0.221%	211	14	208	15
St Antonie Sluis crossing	-0.779	-1.45%	163	14	166	14
Reguliersgracht and Keizersgracht	-0.439	0.0857%	94	15	98	15
Prinsengracht and Leliegracht	1.61	2.33%	102	15	102	14
Keizersgracht and Leliegracht	3.27	3.96%	161	14	161	14
Herengracht and Leliegracht	3.22	4.09%	135	14	138	14
Keizersgracht and Brouwersgracht	-0.386	-0.529%	70	15	73	14
Herengracht and Brouwersgracht	-4.76	-18.4%	53	16	47	14
Prinsengracht and Brouwersgracht	-0.404	3.03%	80	15	72	14
Leliegracht	-0.529	-0.336%	104	14	100	14

One-way traffic: results explained

Interestingly, the crossings at Keizersgracht and Brouwersgracht, at Keizersgracht and Leliegrach, and at Herengracht and Brouwersgracht show an increase in passages, while the crossing at Keizersgracht and Brouwersgracht displays a decrease. Table 5.20 provides an answer to this observation. It shows that the cruise vessels' rerouting is responsible for most of the increase and decrease at these locations. An increase is also observed at Haarlemmersluis. This increase is primarily the result of additional passages by random cruise vessels and pleasure craft. Because of the element of randomness in their routing, more pleasure and random cruise vessels chose to take the Haarlemmersluis.

One-way traffic: conclusion

After implementation of a canal closure, the Keizersgracht and Brouwersgracht crossing could go from being near capacity to exceeding capacity, as the number of peak hour passages in the model results shifts from 112 to 131 passages. Overall, not many changes can be observed after implementing one-way traffic restriction at this particular location, in contrast with the results of the canal closure. This could be a result of the location of the one-way restriction, but could also be a result of the canal's still being accessible.

5.2 Validation of rerouting results

The model is calibrated and validated using data from a standard scenario—that is, one without intervention. The results in Chapter 5 are from the different vessel behaviors interacting with each other when a part of the network is not sailable, which interrupts the vessels' normal routines.

However, the rerouting logic that the vessels in the model apply during an intervention was developed based on interviews with captains who represent the three different vessel categories. There is no data available on the number of passages per vessel type for specific locations, nor AIS or RFID data gathered during an intervention with which to validate the results of a modeled intervention; thus the model results for a canal closure cannot yet be validated. This section, therefore, proposes two methods to acquire the data needed to validate the model results.

5.2.1 Method 1

Vessels would be tracked to analyze which rerouting decisions vessel captains make whenever part of their standard route is not sailable. Recently, Waternet installed RFID sensors in the city center of Amsterdam. As of 2019, every vessel that sails on the canals of Amsterdam needs to have an RFID chip. With the RFID sensors, all vessels could be tracked. The resulting data could be analyzed to recognize patterns for each type of vessel to determine the types of rerouting decisions they make. These patterns could be used to validate the rerouting logic of the vessels in the model. This data could also be used to track the number of passages and the distribution of vessels at critical points such as crossings, and it could be compared to modeled results of vessel distribution before and during an intervention.

Set up

The model results are a product of the interacting behaviors of multiple vessels. If the behaviors of real vessels were measured, the behaviors of model vessels can be compared to them. There is only a need to measure these behaviors at a time when lots of data points can be captured, which would best be done during weekends in July. With such data, patterns in normal routing behavior and their behavior during congestion could be examined. The RFID sensors would need to be placed at crossings near an intervention and at other critical points so that congestion could also be measured.

Measurements

Before intervention-driven behavior could be measured, a null scenario would have to be measured. A full weekend (Friday, Saturday and Sunday) in July should provide a sufficiently large data sample to represent the null scenario, or 0 scenario, which would include the behavior of vessels during peak hours (i.e., during congestion). This 0-scenario data could then be used to calibrate the model before the intervention. To collect intervention data, a full canal closure or one-way traffic restriction could be put in place on a weekday. The following weekend, when there would be enough traffic on the canals, measurements could be taken.

Results

After intervention measurements were taken, they could be compared to the null-scenario data to subtract rerouting decision patterns. These rerouting decisions could then be compared to the logic implemented for each type of vessel in the model and to the distribution patterns for each type of vessel during the intervention. Discrepancies between model results and measurement results could be explained in this way.

5.2.2 Method 2

The second option to acquire the data needed to validate the model would to count vessels before and after canal intervention. These counts would also identify vessel type, as Mobycon did last July (Mobycon, 2018). The gathered data would then be compared to model results. If the model produced the same distribution of vessels at specific locations with the same number of crossing passages, both before and after the intervention, the model could be considered validated.

Set up

Before the intervention could take place, a null scenario would have to be measured. As described for Method 1 above, a full weekend (Friday, Saturday and Sunday) in July should provide sufficient data to represent the null scenario including congestion behavior of vessels. A full canal closure or one-way traffic restriction could then be put in place on a weekday, with measurements taken the following weekend.

Measurements

Measurements would be taken at crossings near the intervention and at other critical crossings in the center of Amsterdam. Recent research by Mobycon (Mobycon, 2018) located these critical crossings. Over the course of a full 24 hours, the following items would be measured at 15-minute intervals:

- Number of vessels
- Passages per vessel type
- The direction vessel type is headed to
- The direction vessel type arrived from

These measurements should be done for the null scenario as well as for the intervention scenario during the whole weekend.

Results

The model would need to be calibrated with the 0-scenario data before the intervention. If 0-scenario and model-derived passage count per vessel type per measurement location figures match, the model could be considered validated. If model results for a vessel type do not match 0-scenario data, the routing algorithm for that vessel type would be considered to not adequately represent reality. This method could validate the model, and potential discrepancies between the model results and reality could be explained. Such a method would not, however, provide information suggesting how an error should be corrected. It does not contain information of the rerouting decisions.

5.2.3 Preference of methods

Method 1 above would provide the higher quality data. Not only would it tell whether model results match, but it would also offer information on actual behavior for each vessel type. Such information could improve the model and thus give more accurate results during a canal closure. Nevertheless, this method is more time consuming, as not all RFID sensors are at the right locations, and some have yet to be installed. Method 2 would give results more quickly, as it would be easier to set up. Yet, the data it provides would not be as precise as the RFID data from Method 1, because while it would tell which part of the model does not adequately represent reality, it would not show how to improve the model to make it better represent reality.

5.3 Conclusion

Using the information presented in this chapter, the last sub-question can be answered, which was as follows:

Can consequences of quay upgrade works on congestion patterns and traffic flow (closed or limited access edges) be simulated for different (weather) scenario's and how can such simulations be used to assess the effects of closing off or limited access to canals during quay wall upgrade works?

Now that the limits and accuracy of the model are known, this project applied the model to possible intervention scenarios. To answer the last subquestion, this project simulated two possible intervention scenarios, a canal-closure and an implementation of one-way traffic, as a practical case to assess the predictive ability of the model. The exact location and results of the canal-closure can be found in Section 5.1.1; The exact location and results of the one-way traffic regulation can be found in Section 5.1.2.

Concluding from these two intervention scenarios, the model can be used to analyze the consequences of an intervention at any location in the canal network. The implemented logic per vessel type combined with the network structure and properties, as discussed in Section 4.1, can explain the results of a canal closure or a traffic regulation. The model gives insight into the rerouting behavior of the different vessel types, and thus more insight into the development of congestion patterns as a consequence of canal upgrade works. With this information, the impact of possible canal upgrade works can be assessed and understood.

From Section 4.2.2, it became clear that the cruise vessels did not fit the measurement data for the location Keizersgracht. This error plays a part when the absolute number of passages per crossing is examined. The model over-estimated for the number of passages for the cruise vessel at the Keizersgracht. The maximum difference between the measured data and the model results were 8 passages per hour. This means that the absolute results at some locations could differ with 8 passages per hour as a consequence of this error.

However, the model is still an approximation of reality, wherein a number of assumptions have been made. There is still a lot more research to be done in order for the model to represent reality more closely. The results from the model are a result from interviews with captains from the different vessel types. These results from the interviews do not mean that this logic represents the actual routing behavior of the captains. Before any conclusion from the model results can be drawn, the model needs to be validated with data from an actual intervention. Therefore, this study proposes two methods to validate the results of the model during an intervention. In this study, preference is given to the RFID chip sensors as it gives the most accurate data on route choice behavior. Though, given the time sensitivity of the upgrade works, method 2 offers a more quickly solution to acquire the data needed to validate the model.

6
Conclusion(s) & Discussion

This chapter, Section 6.1 discusses the sub questions from where the main question can be answered. The valdity of the results are discussed in Section 6.2, and recommendations for further research are made in Section 6.3.

6.1 Conclusion(s)

In this section, an answer to the main question is derived by first answering the subquestions. Each chapter in this thesis addressed a subquestion. This section discusses the conclusions from each chapter to answer each subquestion, after which the main question can be answered.

6.1.1 Amsterdam canals traffic system and congestion patterns

The analysis that has been made in the literature study, Chapter 2, served as a tool to identify the key components to reproduce the traffic flow and congestion patterns on the canals of Amsterdam. Using the information presented in this chapter, this section answers the first sub-question, which was as follows:

What are the main vessel types making up the traffic on the canals of Amsterdam in space and time and what are the traffic-flow and congestion patterns during a normal week/weekend day in summer/winter?

Different vessel types use the canals ofAmsterdam. Moreover, the traffic on the canals of Amsterdam could be recategorized according to their route choice behavior. The route each vessel takes is based on the type of vessel and the properties of the canal network (passage height per bridge, width, one-way traffic etc). Moreover, three vessel categories could be distinguished, namely fixed routes, random routes with sightseeing points as way-points, and completely random routes. These categories are named "cruise vessels," "random cruise vessels," and "pleasure craft" respectively. These vessel types, together with the canal network of Amsterdam, can be used in the model to reproduce the vessel types on the canals of Amsterdam and their corresponding route choice behavior.

The day-to-day traffic flow resembles the following: the traffic flow during summer on a weekend day is significantly higher than during summer on a weekday, and a large difference exists between the summer and winter months. For example, as Figure 2.9 displays, the difference between summer and winter can be around 100 vessels per hour at Anne Frank.

Congestion occurs mainly at crossings, where the narrower or more central the position of a crossing, the more congestion is caused. Examples of these bottlenecks are Haarlemmersluis and the crossing at Prinsengracht-Leidsegracht. In scenario 1 (a weekend day in July), the capacity of crossings was exceeded, and congestion occurred. No information was available to analyze congestion patterns for scenario 2 (a weekday in July), and thus, no conclusion could be drawn for the congestion patterns during this scenario. Furthermore, no information was available to analyze congestion patterns for scenarios 3 and 4. However, the assumption was made that almost no congestion occurred during scenarios 3 and 4 because of the

large difference in the number of passages between the summer and winter months (Figures 2.9 and 2.10).
Regarding the distribution of vessels, data on the number of passages were available and could be used to derive the distribution of the three categories explained in Section 2.1.2 for scenario 1, or at least provide an order of magnitude. These data were limited to a Friday, Saturday, and Sunday in September, and thus were not usable for deriving the distribution of vessels for scenarios 2, 3 and 4. Table 2.7 shows an overview of the assumptions made for the distribution of the vessel types for each scenario.

With the identified three vessel categories with corresponding route choice behavior, a possible model should be able to reproduce these traffic flows and congestion patterns.

6.1.2 Model setup

This part of the thesis sought to answer the subquestion: *How can a model be set up that can simulate traffic on the canals of Amsterdam in order to analyze traffic flow and congestion patterns for different traffic demand scenarios?* Its sub questions were: *What modeling concepts are applicable?* and *What functional requirements does the model need to have to approximate the nautical traffic on the canals of Amsterdam?*

To answer the first sub-subquestion, the author selected the ABM framework to set up a model to assess the impact of canal-upgrade works on canal traffic. This framework is able to represent the distinct sailing speed and route selection of each vessel type, can reproduce the corresponding (route choice) behavior of the three vessel types that interact, and has the additional option to incorporate the irrational behavior. Agent-based modeling is, therefore, a very suitable framework to model the rational and irrational (route choice) behavior of the vessels (in particular the pleasure craft) sailing on the canals of Amsterdam. It could be used as a tool to understand not only *when* congestion occurs, but also to understand *why* congestion occurs. The level of detail is microscopic, and the time is modeled in discrete time steps. To summarize, the model simulates on a microscopic level, uses discrete time steps, and uses the agent-based modeling framework.

Many different computing languages could have been used for this project; however, preference was given to languages with enough packages (algorithms) available, that were open-source, and were relatively easy to learn. Given the availability of important packages, such as SimPy and NetworkX, the usefulness of open-source object-oriented programming language to model vessels easily and the fact that the model is build within a community setting at the TU Delft which uses Python, this study selected Python to construct the model. Each vessel was modeled as an entity with its own logic and making its own decisions moving on a graph. Vessel objects in the model sail and calculate their route based on the network structure and properties. Consequently, this project used the open-source NetworkX package to construct a network (graph) based on the spatial coordinates of the Amsterdam canal network, and each vessel object in the model uses the NetworkX package to calculate its route on the network. The model uses the open-source SimPy package to reproduce queueing and crossing simulations at crossings in real time to reproduce congestion at crossings.

To answer the second sub-subquestion, in Section 3.2.2, a list of functional requirements, *the essential functional requirements* and *the additional functional requirements*, was set up for each component of the model. *The essential functional requirements* are the most critical because those requirements are needed for the model to be able to reproduce traffic flow and congestion patterns. To model the traffic on the canals most realistically, *the additional functional requirements* need to be implemented as well. For now, the author implemented *the essential functional requirements* as described in Section 3.2.2

6.1.3 Calibration

In this chapter, Chapter 4, this study tested the different model components to validate if the model had been built right internally. If the implemented functionality (based on the *the essential functional requirements*) works the way it supposed to, the model has the logic to reproduce traffic flow and congestion patterns. After the internal validation, the model has been calibrated with the data from Waternet to test until what extent the model was able to reproduce reality. With this method, this chapter derived an answer for the third subquestion: *Can the traffic on the Amsterdam canal network be reproduced for the previously identified traffic demand scenarios and vessel types?*

To validate the model internally, the different components of the model have been tested. These are the network and the three vessel types sailing on the network. The model passed 7 of the 7 tests. These test internally validated the model and proved that the model components (the simulation, the three different vessel types and the network) give accurate results. It met *the essential functional requirements* for reproducing congestion and traffic flow (such as moving and staying on a graph). The model was able to create different types of vessels, and these vessels could move on the graphs using different timesteps, could calculate their own route according to their vessel type, could statically reroute themselves based on canal disruptions in the network, and could queue at crossings. The *additional functional requirements* have not been implemented and, therefore, not tested. The results of the test are shown in Appendix B.

The next step was to calibrate the model with the data from Waternet to test until what extent the model was able to reproduce reality. This study applied the Mean Absolute Error (MAE) and the Normalized Mean Absolute Error (NMAE) to measure the goodness of fit between the measured data and the model results to calibrate the model. With this method, the model was calibrated to the different traffic demand scenarios. Results show that the model can reproduce the different traffic demand scenarios. This study used two parameters for each vessel type to calibrate the model: the vessel generator and the vessel speed parameter. The vessel generator combined with the following settings for vessel speed parameter for each vessel showed the best fit:

- cruise vessels: uniform speed between 6 -7.5 km/h,
- random cruise vessels: uniform speed between 5-6 km/h,
- pleasure craft: uniform speed between 5-6 km/h.

In general, the model results fit the measured data within acceptable limits of around 65–85% in number of passages per hour per vessel type for the seven measurement locations. However, not all the results fit the data within this range. The cruise vessel results for the Keizersgracht canal show a significant overestimation for each scenario, meaning that more vessels sailed on this part of the canal in the model than actually measured in reality. A second difficulty arises from the limited accuracy of the measurement data. Because of this limited accuracy, precise calibration of the random cruise vessels and the pleasure craft per location was not possible.

6.1.4 Application

With the information presented in Chapters 2, 3, and 4, Chapter 5 sought to answer the final sub question: *Can consequences of quay upgrade works on congestion patterns and traffic flow (closed or limited access edges) be simulated for different traffic demand scenario's and how can such simulations be used to assess the effects of closing off or limited access to canals during quay wall upgrade works?*

Now that the limits and accuracy of the model are known, this project applied the model to possible intervention scenarios. To answer the last subquestion, this project simulated two possible intervention scenarios, a canal-closure and an implementation of one-way traffic, as a practical case to generate predictions for an possible intervention.

Concluding from these two intervention scenarios, the model can be used to analyze the consequences of an intervention at any location in the canal network. The implemented logic per vessel type combined with the network structure and properties, as discussed in Section 4.1, can explain the results of a canal closure or a traffic regulation. The model gives insight into the rerouting behavior of the different vessel types, and thus more insight into the development of congestion patterns as a consequence of canal upgrade works. Therefore, model simulations can be used to assess and understand the impact of possible canal upgrade works on the nautical traffic.

6.1.5 Final conclusion

Each of the subquestions answered a part of the research question. Combining the information from the previous chapters, the main research question can be answered:

"*How can the impact on nautical traffic flow and congestion patterns of quay wall upgrade works in the canals of the City of Amsterdam be assessed?”*

Many different methods could be applied to assess the impact on waterborne traffic flow and congestion patterns of canal quay upgrade works in the canals of the City of Amsterdam. This study chose to construct an agent-based model in Python with the open-source packages NetworkX and SimPy to simulate the different vessel types with corresponding (route choice) behavior making up the nautical traffic in Amsterdam. The model has been calibrated with data from Waternet from 2013. The author used this model to assess the consequences of canal-quay upgrade work scenarios by simulating them in the model.

The model shows promising first results. Not only does the model show the consequences of canal-quay upgrade works on the traffic flow and congestion patterns, but it also gives insight into *why* specific results occur.

However, the model is not yet completed. This study implemented the necessary logic to reproduce traffic flow and congestion patterns, but additional logic (as explained in Section 3.2.2) should be implemented to obtain more reliable results. Section 6.3 discusses these recommendations in further detail.

A second remark is the data with which the model is calibrated. These data originate from 2013 and have a limited level of detail as it can only distinguish cruise vessels but not the other vessel types. Consequently, the data is not very reliable for calibrating the model and a number of assumptions have been made. Section 6.3 discusses this in further detail.

As this model is developed within a community setting at the TU Delft, this model, and other transport network analysis models, can be viewed and found at GitHub TU Delft - Transport Network Analysis[1].

6.2 Validity of results

It is essential to examine the reliability and validity of the results obtained from the simulations. Therefore, the reliability of certain aspects of the model are reviewed here.

6.2.1 Start situation

The start situation of the vessels in the model may be very different in reality than the approximation in the model. The model is validated and calibrated on count data, but this data does not reflect the start position of the vessels. The starting situation of the modeled vessels may be different in reality than that is approximated by the model.

Cruise vessels

The start situation of the cruise vessels is approximated based on the latest routes that are publicly available. Therefore, this approximation would be the closest to reality.

Random cruise vessels

The random cruise vessels in the model start at a random node based on the locations of the largest cruise shipping companies. In reality, however, these vessels may berth at other places outside the city center and sail toward the city center at the start of each day. Therefore, the actual starting locations of the random cruise vessels may differ from what is approximated in the model.

Pleasure craft

The pleasure craft in the model start at a random node and calculate a random route from there, thus they may start at crossings or bridges. This may not be the case in reality, however, as most pleasure craft berth at given places on a canal or in a harbor outside the city center. Hence, the actual starting locations of the pleasure craft also may differ from what is approximated in the model.

[1] `https://github.com/TUDelft-CITG/Transport-Network-Analysis`

6.2.2 Modeled vessels

Types and behavior

The three vessel types in the model are an approximation of the six (excluding freigth vessels) vessel types identified by Waternet (Figure 2.5). The model routing behavior is also an approximation of the routing behavior per vessel type. In reality, however, each vessel type has its own routing behavior. For example, captains of random cruise vessels may have preferred routes or may want to sail in certain areas or avoid other areas because of congestion. Similarly, people who rent pleasure craft may prefer to sail in certain parts of the canal system. The model results, therefore, may not adequately reflect the actual behavior of the different vessel types.

From Section 4.2, it became clear that the cruise vessels did not fit the measurement data for the location Keizersgracht. This error plays a role if the absolute number of passages per crossing is examined. The model over-estimated for the number of passages for the cruise vessel at the Keizersgracht. The maximum difference between the measured data and the model results were 8 passages per hour. This means that the absolute results at some locations could differ with 8 passages per hour as a consequence of this error.

As Section 4.1.2 concluded, not all functional requirements are implemented in the model's vessel logic. The sailing behavior of these model vessels, therefore, may differ from the behavior of their real counterparts. One area in which these differences may be apparent is in the encountering and overtaking of other ships on the small canals. In the model, each vessel can overtake any other vessel at any point in time. In reality, this is not always the case. The small canals of Amsterdam do not allow more than one vessel at a time to overtaking a given vessel.

Time-dependent dynamic rerouting also affects the reliability of the results. This logic has not been implemented in the model but does play a role in reality. Cruise vessels and random cruise vessels need to be back in time to pick up the next round of tourists. If they experience too much delay due to congestion while en route, they may choose to cut a trip short and sail back to their starting point. This logic could change the routes they take and thus reduce the reliability of the model results.

Human behavior

Another contributor to congestion at some crossings is human behavior. There are many examples of tourists who do not know how to sail pedal boats or rented vessels getting stuck at narrow crossings or bridges, thus causing congestion. The model does not take human behavior into account.

6.2.3 Crossings

Modeled capacity

The modeled capacities for specific crossings are displayed in Table 5.1. However, these are estimations based on the known capacity at the Prinsengracht and Leidsegracht crossing and at Haarlemmersluis. For the other crossings in the model, the capacity is set to an average of 350 vessels per hour, as these crossings are not as narrow as the two known crossings. In reality, every crossing has its own unique physical dimensions and, therefore, a unique capacity. The capacity per hour also depends on vessel type. For example, cruise vessels take much longer to turn at small crossings than do small pleasure craft, thus the capacity per crossing is much lower for cruise vessels. Yet the model treats these vessels equally. The crossing capacity estimations used in the model may not accurately reflect reality, leading to the model's displaying congestion when there would be no congestion or vice versa.

First-come, first served

Crossings in the model serve vessels on a first-come, first-served basis. In reality, however, sailing rules are also applied. For example, large cruise vessels have the right of way on crossings, and other vessels need to wait. These rules are not implemented in the model.

6.2.4 Data and validation

The model is calibrated using data from 2013–2014. However, due to recent policy changes, more passenger transport vessels and fewer pleasure craft now sail on the canals of Amsterdam. This change could increase any discrepancy between model results and reality.

A second issue regarding the measurement data is its accuracy. The data from 2013–2014 specifies three categories of vessels based on length (4 meters, 4-14 meters, and > 14 meters). However, the random cruise vessels and pleasure craft have similar length ranges, thus no distinction could be made between the two. Only cruise vessels could be distinguished in this data, requiring that an assumption be made about vessel distribution. For the high demand traffic scenario (scenario 1), recent countings of Mobycon (Mobycon, 2018) are used as a guideline for the distribution. While these countings were on a Sunday beginning September, they do give insight into the distribution of vessel types for that particular traffic demand scenario. Based on these countings, an assumption of vessel distribution has been made. Scenario 1 assumes that approximately 55% of the vessels are pleasure craft, 15–20% are cruise vessels, and 25–30% are random cruise vessels. For scenario 2, the assumption has been made that fewer pleasure craft sail in the canals on a weekday. The assumed distribution, therefore, is as follows: approximately 35% of vessels are pleasure craft, approximately 35% are cruise vessels, and the remaining 25–30% are random cruise vessels. For scenarios 3 and 4, there were so few pleasure craft and random cruise vessels on the canals that the distribution did not make much difference. An assumption was made of 85% cruise vessels, 10% random cruise vessels, and 5% pleasure craft.

A third issue is that the model has only been trained and calibrated with one dataset; the data from Waternet. The results are, therefore, prone to errors. This model has yet to be validated with another dataset, as validating with the same dataset as the model has been trained with results in overfitting and a bias (Ng, 2018).

The fourth issue is regarding the use of the MAE and the NMAE during the calibration. In general, the error might be more substantial than the NMAE and the MAE insinuate. The MAE divides the data with all the data points. This provides a slightly shifted view because it also includes the points where there is no traffic, and thus the model does not need to perform well. For these data points, the model has, therefore, a perfect fit. Hence, this statistical method may produce a lower error margin and thus superior results.

In addition, this single metric presents only one projection of the model errors and, therefore, just highlights a particular aspect of the error characteristics. "A combination of metrics, including but certainly not limited to RMSEs and MAEs, are often required to assess model performance" (Chai and Draxler, 2014, p. 1250).

The last issue is concerning the renovation works that were active when the measurements took place in from June 2013 until January 2014. Table 6.1 shows an overview. Archives of the Municipality do not tell what the impact of renovation works was on the traffic flow, e.g., a narrowing or blocking of a canal. As a consequence, influence of these renovation works have not been included in the model. While these maintenance and renovation works are not near a measurement point, but they do influence the routes the vessels take. Some canals may be busier because of the rerouting of some vessels.

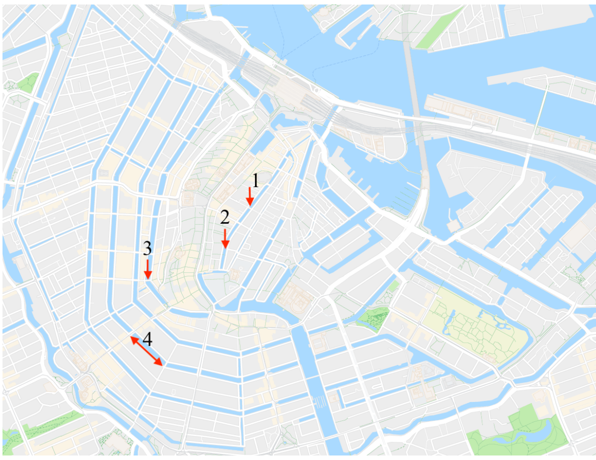


Figure 6.1: Maintenance works in 2013

Number	Name	Type
1	Lommertbrug	Bridge maintenance
2	Makelaarsbruggetje	Bridge maintenance
3	Raambrug	Bridge maintenance
4	Prinsengracht	Quay-wall maintenance

Table 6.1: Legenda of Figure 6.1

6.3 Further research

Some elements can be added to further improve the model. During this project not enough information was available to implement these elements.

6.3.1 Vessel types and route choice behavior

Vessel types

As discussed in the previous section, Section 6.2, the six (excluding freigth vessels) vessel types identified by Waternet are represented by only three vessel types in this model. In order to reproduce reality more closely, more research needs to be done into the seven vessel types and their routing behavior so as to incorporate them into the model accurately. If the seven different vessel types are incorporated, the model should produce more accurate results. For example, pedal boats may not typically sail throughout the entire canal network but stay on certain canals.

Vessel logic

As discussed in the section on internal validation, the vessels in the model passed 7 of the 7 tests applied. However, *The additional functional requirements* are not implemented. To further enhance the model and gain more accurate results, *The additional functional requirements* described in Section 3.2 need to be implemented as well. Briefly described, these are:

1. Queue spill-back
2. Approaching the queue
3. Vessel-vessel interaction
4. Sailing rules
5. Dynamic routing
6. Vessel-canal interaction
7. Memory and learning
8. Irrational behavior

Agent activation

A final remark is the way the model activates the vessels (agents). Time in most agent-based models moves in steps. At each step of the model, one or more of the agents are activated and take their own step and interacting with one another or the environment. The scheduler is a special model element which controls the order in which agents are activated. As the model added each vessel one by one to the simulation, these vessels are consequently activated one by one in the same order every time step. Therefore, some vessels may end up higher in a queue just because they were added at the beginning of the simulation and thus activated earlier every time step. To better replicate reality, the model should shuffle their order every timestep.

6.3.2 Crossings

In order to accurately predict and reproduce congestion, the actual capacity of each crossing needs to be measured. This study only estimated the capacity for each crossing in order to analyze whether or not congestion would occur. The model did not account for the type of vessel passing a crossing. In reality, however, cruise vessels take much more time to maneuver through a crossing than small pleasure craft do. Thus, more research needs to be done to quantify how many vessels of each type each crossing can handle.

This study assumed a first-come, first-served model to calculate time penalties at crossings. In reality, however, sailing rules are applied, and there is much unpredictable behavior on these crossings. Due to the narrow physical properties of some crossing and adjacent one-way bridges, many inexperienced captains do not know how to proceed through the crossing. This results chaotic situations on busy days. More research is needed to allow for more accurate modeling of the handling of traffic at these crossings.

6.3.3 Data and validation

The data from 2013–2014 showed the null situation, having been gathered when some canal-upgrade works were active. The model results would also benefit from more up-to-date data. The data used was gathered in 2013–2014. Due to recent policy changes, the distribution of vessel types and the number of passages at each crossing may have since changed. Thus, new measurements need to be taken to get the most up-to-date results from the model.

Validation of model

The model is calibrated with data that showed only a rough distinction between different vessel types, as explained in Chapter 2. No distinction could be made between random cruise vessels and pleasure craft. Therefore, more accurate data is needed in order to validate the model results for these types of vessels. This study made an assumption for the distribution of each vessel type for each scenario.

Validation of intervention results

The model is still an approximation of reality, wherein a number of assumptions have been made. For example, the behavior of the vessels is based on interviews with captains from the different vessel types. These results from the interviews do not mean that this logic represents the actual routing behavior of the captains. Therefore, the author recommends that the model is validated with data from an actual intervention before any conclusion is drawn. This study proposes two methods to validate the results of the model during an intervention. Preference is given to use the RFID chip sensors as it gives the most accurate data on route choice behavior. Though, given the time sensitivity of the upgrade works, method 2 (counting of vessel types before and after an intervention) offers a more quicker solution to acquire the data needed to validate the model.

6.3.4 Traffic demand scenarios

Scenarios throughout the year

This thesis constructed four different traffic demand scenarios to represent all the different traffic demand scenarios on the canals of Amsterdam. However, in reality, every scenario has its own traffic demand. Hence, more research needs to be done into different traffic demand scenarios, and consequently, these traffic demand scenarios could then be used for the model.

Unique situations

The traffic on the canals of Amsterdam can be chaotic during the weekend in the summer. However, there are unique situations where traffic demand is exceptionally high. During Koningsdag and Gaypride, for example, it is custom for the locals of Amsterdam to celebrate these days by sailing on the canals of Amsterdam. As a consequence, many people sail on the canals which creates something that approximates chaos. A possible continuation of this research could include these unique situations. The agent-based modeling is, therefore, a suitable framework as it is possible to incorporate irrational behavior.

Forecasting

The next 10-20 years the MoA will renovate many quay-walls in the city center of Amsterdam. Due to recent policy changes (explained in Appendix D), the distribution of vessel types and the number of passages at each crossing may have changed since 2013 and may change in the future as well. Hence, to assess the impact of a quay-wall renovation in, for example, 2025, a traffic demand prognosis needs to be made for the next 20 years.

6.3.5 Long term consequences

As canal-quay upgrade works may take a whole year, that means that a canal could be closed off for an entire year. Because this thesis modeled the consequences for a day, it gave insight into the short term consequences of interventions for the different traffic demand scenarios.

However, after some time, captains who sail on the network regularly learn where it will be crowded during the day and could choose to avoid certain canals or crossings the next trip. Hence, the long term consequences might differ from the short term impact nautical traffic.

As was explained in Section 3.1, the agent-based model framework offers a solution to incorporate learning and uncertainty of route choice behavior. It is therefore interesting to investigate the long term consequences of network interventions. But first, it is necessary to model the nautical traffic more realistically using *The additional functional requirements*(Section 3.2.2) before modeling long term consequences.

The current model simulates every vessel individually with a timestep of 10 seconds. Therefore, it will take a lot of computational time to simulate a long time period and to much detail will be taken into account. A mesoscopic agent-based model will be more applicable for long term analysis (Jeerangsuwan and Kandil, 2014; Tchappi Haman et al., 2017).

The effect of the provision of information

What if captains have more knowledge of where it is busy throughout the day, i.e., a Google maps type of network update on congestion? Would a new equilibrium establish sooner and less congestion will arise as a consequence of canal-quay upgrade works?

With the agent-based model, such situations can be simulated. To approximate reality as closely as possible, agents can be modeled as entities with limited knowledge of their environment. To bridge this equilibrium seeking phase, agents can be given a network update on congestion. With this method, the effect of the provision of information can be modeled and investigated.

6.3.6 Optimization of the planning of canal-upgrade works

A possible continuation of this research would be to apply it to optimize canal-upgrade works in such a way that they cause the least amount of congestion and that the greatest number of canal-upgrade works could be undertaken. Therefore, economic factors could be included as well. But first, the model should be working well enough before taking economic factors into consideration.

6.3.7 Additional related topics for further research

Bridges, locks and water pipes

This study focused on the consequences of canal-quay upgrade works. However, not only quay walls but also bridges, locks, and water pipes are in need of replacement. A possible continuation of this research, after the improvement and validation of this model, could be to investigate the impact of bridges, locks, and water pipes upgrade works on the nautical traffic.

Water transport related C02 emmisions

With the current climate change problems in the world, every country is faced with the challenge to reduce their C02 emissions. Therefore, a potential next step of this research could be to investigate the waterborne related C02 emissions on the canals of Amsterdam and to investigate the possible impact of electric sailing.

Waterborne city distribution

Freight transport is a significant cause of congestion on the roads along the canals of Amsterdam. DHV Research (2007) showed that 80% of the loading and unloading activities take place on the road due to lack of space. An average stop to load and unload can take some time, and during that time, the passing of other traffic is impossible. Therefore, other traffic seems severely affected by freight distribution. In addition, shopkeepers are affected by unpredictable trip times (i.e., congestion) and residents experience hinder from emissions and noise (Duin et al., 2017). Therefore, the thought has arisen to reuse the canals as a 'new' freight distribution system for the city of Amsterdam. A possible continuation of this research, and on the research of Duin et al. (2017), is to investigate into waterborne city distribution in Amsterdam.

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A: Python Code Archive

This appendix provides links to the Python code developed within this study. The outline refers to the figures and tables in the sections created with the corresponding code. This code can be found by following the QR codes below.

A.1 Code from Chapter 4

A.1.1 Internal validation (Section 4.1)

Code for tests 1 - 7 (Section 4.1)

Figure A.1: QR code with link to code

A.1.2 Scenario calibration (Section 4.2.2)

Model configuration for high traffic demand scenario (scenario 1, Section 4.2.2)

Figure A.2: QR code with link to code

Model configuration for medium traffic demand scenario (scenario 2, Section 4.2.2)

Figure A.3: QR code with link to code

Model configuration for low traffic demand scenario (scenario 3, Section 4.2.2)

Figure A.4: QR code with link to code

Model configuration for very low traffic demand scenario (scenario 4, Section 4.2.2)

Figure A.5: QR code with link to code

A.2 Code from Chapter 5

A.2.1 Canal-closure (Section 5.1.1)

Canal-closure: Model configuration for high traffic demand scenario (scenario 1, Section 5.1.1)

Figure A.6: QR code with link to code

Canal-closure: Model configuration for medium traffic demand scenario (scenario 2, Section 5.1.1)

Figure A.7: QR code with link to code

Canal-closure: Model configuration for low traffic demand scenario (scenario 3, , Section 5.1.1)

Figure A.8: QR code with link to code

Canal-closure: Model configuration for very low traffic demand scenario (scenario 4, Section 5.1.1)

Figure A.9: QR code with link to code

A.2.2 One-way traffic Section 5.1.2

One-way traffic: Model configuration for high traffic demand scenario (scenario 1, Section 5.1.2)

Figure A.10: QR code with link to code

One-way traffic: Model configuration for medium traffic demand scenario (scenario 2)

Figure A.11: QR code with link to code

One-way traffic: Model configuration for low traffic demand scenario (scenario 3)

Figure A.12: QR code with link to code

One-way traffic: Model configuration for very low traffic demand scenario (scenario 4)

Figure A.13: QR code with link to code

B: Internal validation

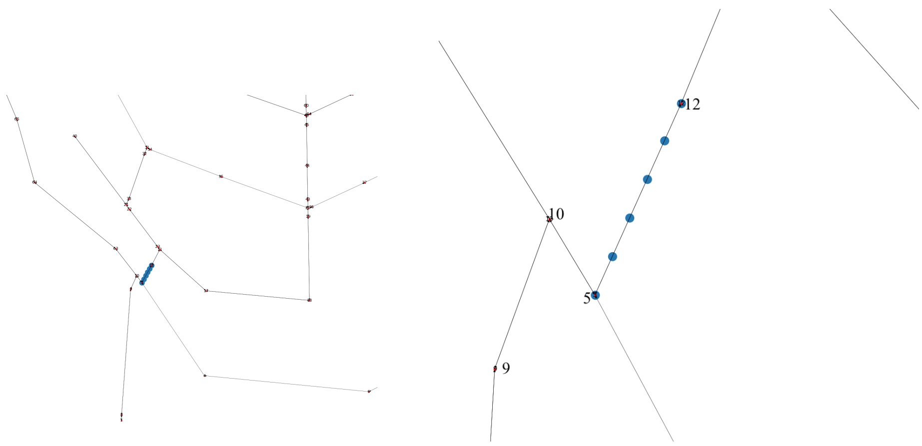
B.1 Tests for the essential functional requirements

Test 1: Move on the graph

This test was performed to validate whether vessels set steps to the next node in their route list and adjust their course whenever they pass a node and move on to the next. This test validates if the vessel is capable of moving in steps from one node to the next node along the edge. This is tested to let a vessel with a velocity of 1 m/s and a timestep of 10 seconds travel over an edge of the graph between two nodes. Because no exact distances exist between the two nodes, the vessel cannot take precise steps. Hence, the last step is not the complete step size. The vessel passes the test when it arrives with the exact number of steps as analytically calculated. The vessel passed this test and the results are shown Figure Figure B.1.

Table B.1: Results test 1

Vessel	Results
Timestep	10 s
Route	[5,12]
Distance edge	49,633293143156 m
Velocity vessel	1 m / s
Stepsize vessel in m per timestep	10 m
Results without last step	4
Last step	0,96332929 m
Results with last step:	5 steps
Results analytically	4,96332929 steps



(a) Test 1: edge traveled on

(b) Test 1: edge traveled on zoomed in

Figure B.1: Test 1

```
In [74]: ves_1 = ves_list[0]
         print("vessel time stepsize in s: ", ves_1.step_size)
         print ("route:", ves_1.path)
         print("distance edge in meters: ", w_G.edges[5, 12]['dis'] )
         print("Velocity in m/s:", ves_1.velocity)
         print("stepsize vessel in m per timestep :", ves.move)
         print("analytically, it should take: distance edge / stepsize = number of steps: ", w_G.edges[5, 12]['dis'] / ves.move)
         print("number of steps taken: ", len(ves_1.step_list))

         vessel time stepsize in s:  10
         route: [5, 12]
         distance edge in meters:  49.63329293143156
         Velocity in m/s: 1
         stepsize vessel in m per timestep : 10
         analytically, it should take: distance edge / stepsize = number of steps:  4.963329293143156
         number of steps taken:  5
```

Figure B.2: Test 1

Test 2: Follow a route

A route in the model is a list of nodes that must be visited. For example, if a graph contains five nodes (A, B, C, D, and E) that are connected in sequence (A > B, B > C, C > D, and D > E), a possible route could be [A,B,C]. This vessel must visit the first three nodes. This test validates whether the vessel is capable of following a route and stopping when it reaches its end. A vessel passes this test when the start and end node are the same as stated in the route and it arrives with the exact number of steps as analytically calculated. The vessel passed this test and the results are shown in Figure B.3.

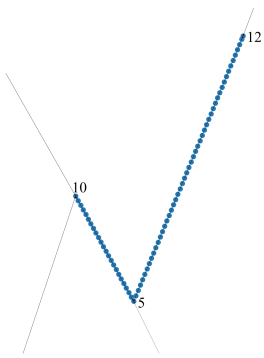


Figure B.3: Test 1

Table B.2: Results test 2

Vessel	Results
Timestep	1 s
Route	[10, 5, 12]
Distance edge(s)	72,567765200 m
Velocity vessel	1 m / s
Stepsize vessel in m per timestep	1 m
Results without last step	72
Last step	0,567752011 m
Results with last step	73 steps
Results analytically	72,567765200 steps

```
In [32]: distance_total = 0
         ves_1 = ves_list[0]

         for i in range(len(path_test)-1):
             distance_total += w_G.edges[path_test[i], path_test[i+1]]['dis']

         print("Analytically, it should take: distance edge / stepsize = number of steps: ",\
             distance_total  / ves_1.move )
         print("Or in round off steps:", math.ceil(distance_total  / ves_1.move))

         print("vessel time stepsize in s: ", ves_1.step_size)
         print("Route:", ves_1.path)
         print("Distance edge in meters: ", distance_total )
         print("Velocity in m/s:", ves_1.velocity)
         print("stepsize vessel in m per timestep :", ves_1.move)


         print("Number of steps taken by vessel: ", len(ves_1.step_list))
         print("Distance last step was:", ves_1.last_step_log[0])
         print("Total distance of vessel sailed:",  ves_1.move* (len(ves_1.step_list)-1) + ves_1.last_step_log[0] )

         Analytically, it should take: distance edge / stepsize = number of steps:  72.56776520054612
         Or in round off steps: 73
         vessel time stepsize in s:  1
         Route: [10, 5, 12]
         Distance edge in meters:  72.56776520054612
         Velocity in m/s: 1
         stepsize vessel in m per timestep : 1
         Number of steps taken by vessel:  73
         Distance last step was: 0.5677652011129568
         Total distance of vessel sailed: 72.56776520111296
```

Figure B.4: Test 1

Test 3: Stay on the graph

Because the canal network is not one straight line but a network of connected bridges and crossings, the vessels should be able to make turns and stay on the edges. Vessels also need to stay on the edges if the timestep is made larger. If the timestep increases, the step size of the vessels increases too. If the step size is larger than the remaining distance to the next node plus the distance to the node after that, and the that node is located at an angle to the previous node, the vessel should adjust its angle and move from that node on the next edge . This is tested to let a vessel with a velocity of 1 m/s and a timestep of 1 second travel from node A to node C via node B, over the two edges with known distances. Vessels pass this test when they have not deviated from the graph due to possible overshoot and arrive within the exact number of steps as analytically calculated. The vessel passed this test and the results are shown in Figure B.4.

Table B.3: Results test 3: timestep = 1 s

Vessel	Results
Timestep	1 s
Route	[131, 130, 129, 128]
Distance edge(s)	302,9801208651 m
Velocity vessel	1 m / s
Stepsize vessel in m per timestep	1 m
Results without last step	302
Last step	0,9801208657 m
Results with last step	303 steps
Results analytically	302,9801208651

Table B.4: Results test 3: timestep = 100 s

Vessel	Results
Timestep	100 s
Route	[131, 130, 129, 128]
Distance edge(s)	302,9801208651 m
Velocity vessel	1 m / s
Stepsize vessel in m per timestep	100 m
Results without last step	3
Last step	2,9801208657 m
Results with last step	4 steps
Results analytically	3,029801208651

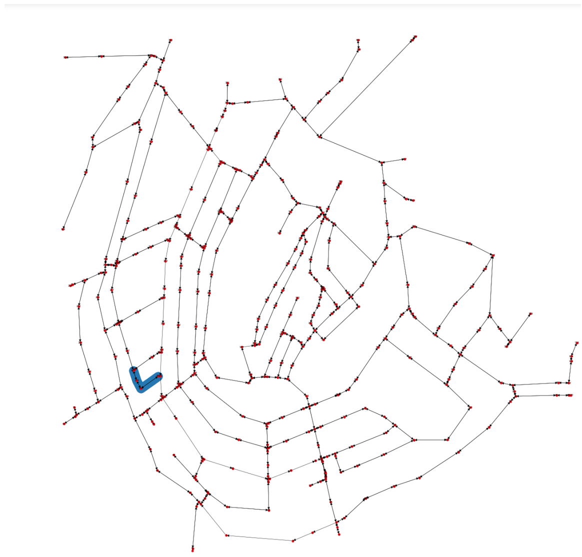
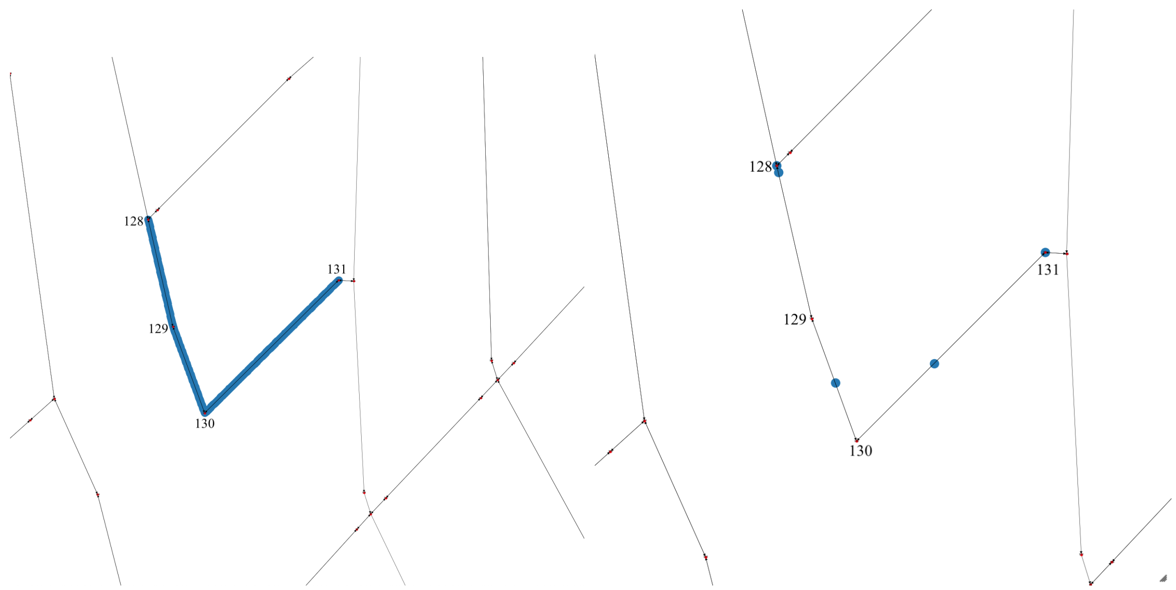


Figure B.5: Test 3: edge traveled on: Overview



(a) Test 3: timestep = 1 s

(b) Test 3: timestep = 100 s

Figure B.6: Test 3: different timesteps

```
In [17]: distance_total = 0
ves_1 = ves_list[0]

for i in range(len(path_test)-1):
    distance_total += w_G.edges[path_test[i], path_test[i+1]]['dis']

print("Analytically, it should take: distance edge / stepsize = number of steps: ",\
    distance_total  / ves_1.move )
print("Or in round off steps:", math.ceil(distance_total  / ves_1.move))

print("vessel time stepsize in s: ", ves_1.step_size)
print("Route:", ves_1.path)
print("Distance edge in meters: ", distance_total )
print("Velocity in m/s:", ves_1.velocity)
print("stepsize vessel in m per timestep :", ves_1.move)


print("Number of steps taken by vessel: ", len(ves_1.step_list))
print("Distance last step was:", ves_1.last_step_log[0])
print("Total distance of vessel sailed:",  ves_1.move* (len(ves_1.step_list)-1) + ves_1.last_step_log[0] )
# ves_1.cross_time_list

Analytically, it should take: distance edge / stepsize = number of steps:  302.9801208651205
Or in round off steps: 303
vessel time stepsize in s:  1
Route: [131, 130, 129, 128]
Distance edge in meters:  302.9801208651205
Velocity in m/s: 1
stepsize vessel in m per timestep : 1
Number of steps taken by vessel:  303
Distance last step was: 0.9801208657879571
Total distance of vessel sailed: 302.98012086578797
```

(a) Test 3: timestep = 1 s

```
In [29]: distance_total = 0
ves_1 = ves_list[0]

for i in range(len(path_test)-1):
    distance_total += w_G.edges[path_test[i], path_test[i+1]]['dis']

print("Analytically, it should take: distance edge / stepsize = number of steps: ",\
    distance_total  / ves_1.move )
print("Or in round off steps:", math.ceil(distance_total  / ves_1.move))

print("vessel timestep size in s: ", ves_1.step_size)
print("Route:", ves_1.path)
print("Distance edge(s) in meters: ", distance_total )
print("Velocity in m/s:", ves_1.velocity)
print("Stepsize vessel in m per timestep :", ves_1.move)


print("Number of steps taken by vessel: ", len(ves_1.step_list))
print("Distance last step was:", ves_1.last_step_log[0])
print("Total distance of vessel sailed without last step:", ves_1.move* (len(ves_1.step_list)-1) )
print("Total distance of vessel sailed with last step:",  ves_1.move* (len(ves_1.step_list)-1) + ves_1.last_step_log[0]
# ves_1.cross_time_list

Analytically, it should take: distance edge / stepsize = number of steps:  3.029801208651205
Or in round off steps: 4
vessel timestep size in s:  100
Route: [131, 130, 129, 128]
Distance edge(s) in meters:  302.9801208651205
Velocity in m/s: 1
Stepsize vessel in m per timestep : 100
Number of steps taken by vessel:  4
Distance last step was: 2.9801208651441136
Total distance of vessel sailed without last step: 300
Total distance of vessel sailed with last step: 302.9801208651441
```

(b) Test 3: timestep = 100 s

Figure B.7: Test 3: Different timesteps

Test 4: Type of vessels

Each type of vessel has a different velocity, and thus should arrive at a different time to the other types. The test lets the three different types of vessels start on the same graph with the same route [A, B, C]. The cruise vessel moves at 2 m/s, the pleasure craft moves at 4 m/s, and the random cruise vessel moves at 6 m/s; therefore, the cruise vessel should arrive first, then the random cruise vessel, and finally the pleasure craft.

Vessels pass this test when the order of arrival is correct and arrive within the number of steps calculated to reach the end. The results are shown in Figure B.8.

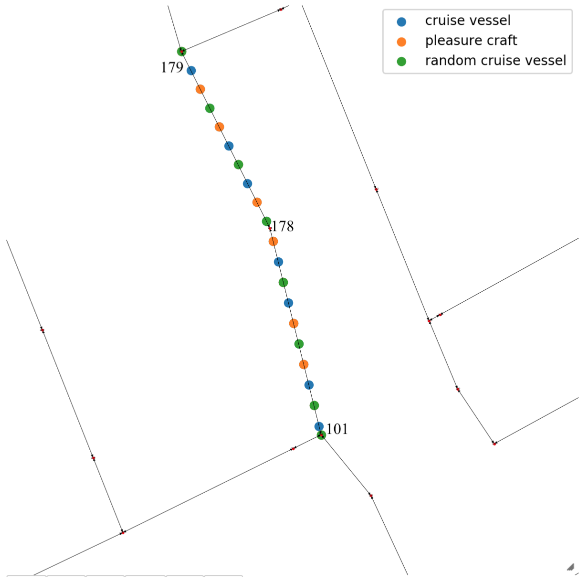


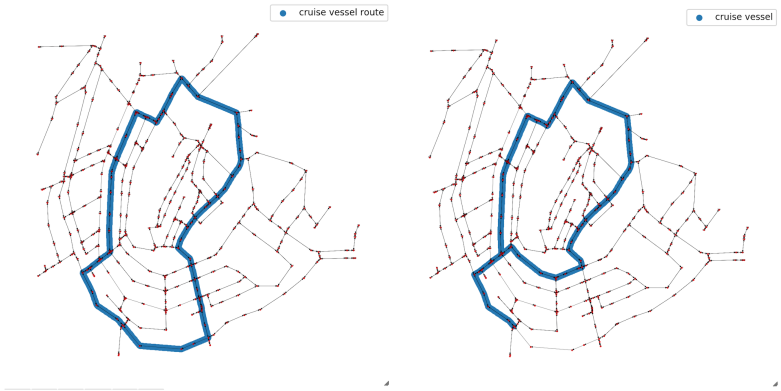
Figure B.8: Test 4:visualisation

```
vessel timestep size in s:  10
Route: [179, 178, 101]
Distance edge(s) in meters:  388.41633392421437

CRUISEVESSEL
velocity of cruise =  2 m/s
Stepsize vessel for type %s vessel in m per timestep : 20
Analytically, it should take for type cruise vessel: distance edge / stepsize = number of steps:  19.420816696210718
Or in round off steps: 20
Number of steps taken by vessel %s:  20
Distance last step was: 8.416333924370944
Total distance of vessel sailed without last step: 380 ,which is  0.4208166962185472 step
Total distance of vessel sailed with last step: 388.4163339243709

PLEASURECRAFT
velocity of pleasure =  4 m/s
Stepsize vessel in m per timestep : 40
Analytically, it should take for type pleasure vessel: distance edge / stepsize = number of steps:  9.710408348105359
Or in round off steps: 10
Number of steps taken by vessel:  10
Distance last step was: 28.41633392422481 ,which is  0.7104083481056203 step
Total distance of vessel sailed without last step: 360
Total distance of vessel sailed with last step: 388.41633392422483

RANDOM CRUISE VESSEL
velocity of random_cruise =  6 m/s
Stepsize vessel in m per timestep : 60
Analytically, it should take for type random_cruise vessel: distance edge / stepsize = number of steps:  6.4736055654
03573
Or in round off steps: 7
Number of steps taken by vessel:  7
Distance last step was: 28.416333924281176 ,which is  0.4736055654046863 step
Total distance of vessel sailed without last step: 360
Total distance of vessel sailed with last step: 388.41633392428116
```

Figure B.9: Test 4: results

Test 5: Routing for different vessels

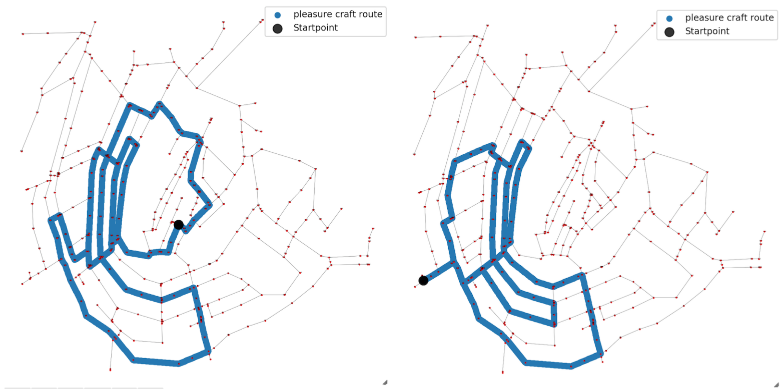
As explained in Section 2.1.2, each type of vessel has its own particular route. Each vessel should be able to calculate its own route when generated. This test validates the calculated route for each type of vessel that it should be calculating and whether it meets all requirements. The test shows the different calculated routes for the various vessels. Vessels pass this test when the calculated routes meet the requirements of each type. The results are shown in the Figures B.10, B.11, and B.12.



(a) Example 1 route cruise vessel

(b) Example 2 route cruise vessel

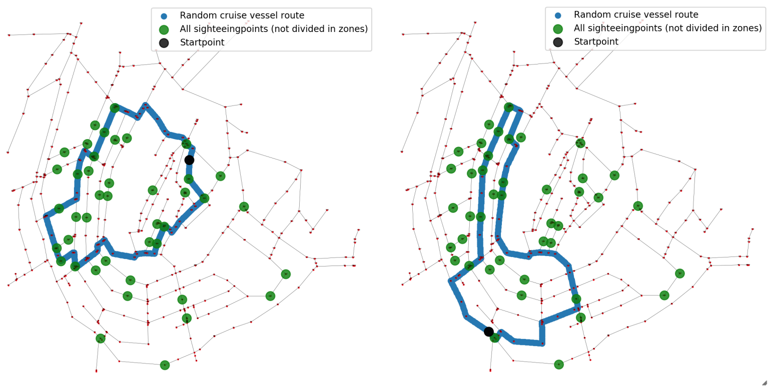
Figure B.10: Test 5: Routes cruisevessel



(a) Example 1 pleasure-craft

(b) Example 1 pleasure-craft

Figure B.11: Test 5: Routes pleasurecraft



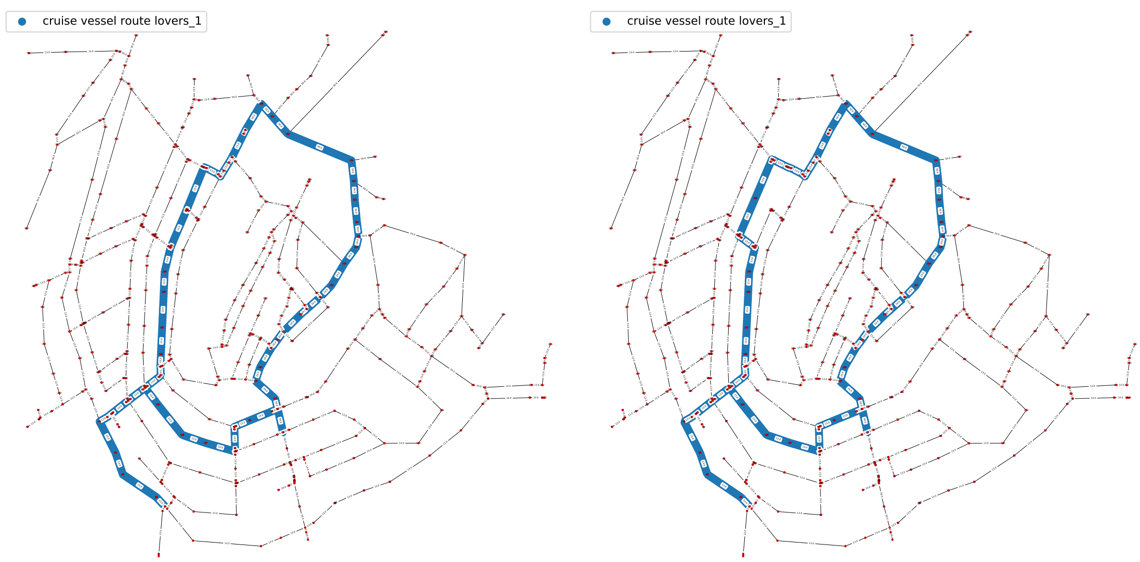
(a) Example 1 random cruise vessel

(b) Example 1 route random cruise vessel

Figure B.12: Test 5: Routes random cruise vessel

Test 6: Static rerouting and width restriction

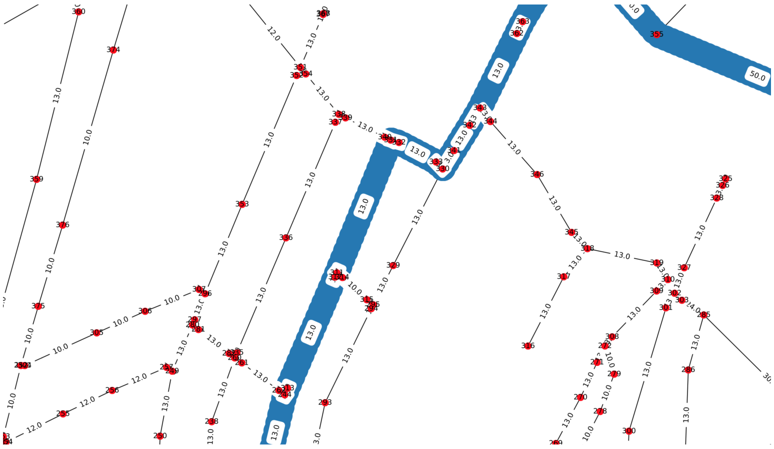
This test validates whether the vessels reroute their routes whenever an edge is closed according to Table C.1. To model canal-closure, the specific edge is removed from the graph. The test removes an edge on the graph and shows that no vessel travels on the removed edge. In addition, cruise vessels have width restrictions, meaning that they cannot sail on canals with a width smaller than 13 m. The cruise vessel will pass the test when it recalculates its route based on this restriction and when the shortest path back to its route matches the analytically calculated shortest path. All the vessels passed this test and the results are shown in Figure B.14.



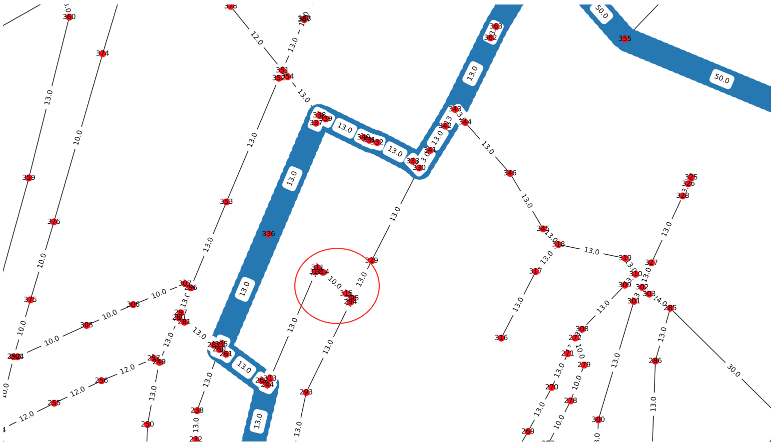
(a) Normal situation

(b) Rerouting with width restriction

Figure B.13: Test 5: Route cruise vessel during intervention



(a) Normal situation



(b) Rerouting with width restriction zoomed in

Figure B.14: Test 6: intervention with width restriction

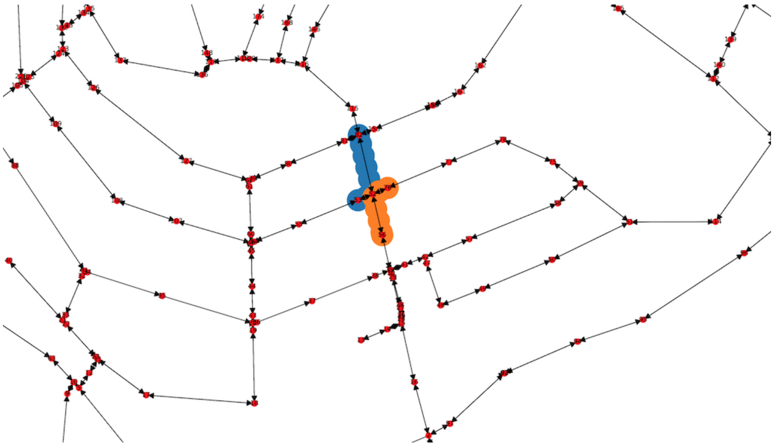
(a) Example 1 random cruise vessel route during intervention

(b) Example 2 pleasurecraft route during intervention

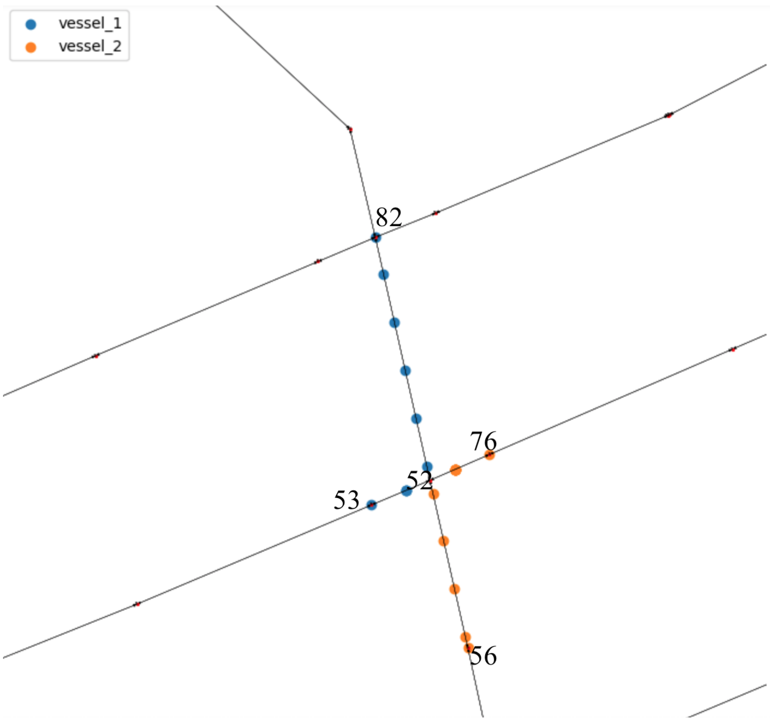
Figure B.15: Test 6: intervention for other vessels

Test 7: Queuing

Each vessel has to wait if a crossing or one-way bridge is occupied. This test validates whether vessels queue at crossings as well as queuing at one-way bridges, because the same logic can be applied. If vessels pass this test, they also pass the test for one-way bridges. Two vessels start near a crossing. If no queue occurs, the total travel time equals the distance of each edge divided by the step size of each vessel. If queuing does occur and the vessel has to wait and cross, the travel time will be larger. When the crossing is not occupied, a vessel only takes 20 seconds to cross because it still has velocity. However, when a vessel has to wait because the crossing is occupied, it takes 60 seconds to cross because its initial velocity is zero. Vessels pass when the total travel time minus waiting time minus crossing time equals the analytically calculated travel time. One vessel waited at the same time step when another vessel was crossing. The results are shown in Figure Figure B.16.



(a) Visual results vessels during queuing



(b) Visual results vessels during queuing

Figure B.16: Test 6: intervention for other vessels

```
In [59]: distance_total_ves_1 = 0
ves_1 = ves_list[0]

for i in range(len(route_1)-1):
    distance_total_ves_1 += w_G.edges[route_1[i], route_1[i+1]]['dis']
print("Vessel_1 timestep size in s: ", ves_1.step_size)
print("Route:", ves_1.path)
print("Distance edge(s) in meters: ", distance_total_ves_1 )
print("Velocity in m/s:", ves_1.velocity)
print("Stepsize vessel in m per timestep :", ves_1.move)
print("")
print("Analytically, it should take: distance edge / stepsize = number of steps: ",\
    distance_total_ves_1  / ves_1.move )
print("Or in round off steps:", math.ceil(distance_total_ves_1  / ves_1.move))
print("")
print ("Arrived at crossing at timestep:", ves_1.time_step_crossing[0])
if ves_1.time_step_waiting:
    print("Started waiting at timestep:", ves_1.time_step_waiting[0])
if ves_1.time_step_end_waiting:
    print("Ended waiting at timestep:", ves_1.time_step_end_waiting [0])

print("Number of steps taken by vessel_1: ", len(ves_1.step_list))
print("Total wait time in timesteps:", ves_1.total_wait_time)
print("Total crossing time in timesteps:", ves_1.cross_time)
print("Distance last step was:", ves_1.last_step_log[0])
print("Total distance of vessel sailed without last step:",\
      ves_1.move* (len(ves_1.step_list)-1 - ves_1.total_wait_time - ves_1.cross_time),\
      ", which is ",ves_1.last_step_log[0] / ves_1.move , "step")
print("Total distance of vessel sailed with last step:", \
      ves_1.move* (len(ves_1.step_list)- 1 - ves_1.total_wait_time - ves_1.cross_time)
      + ves_1.last_step_log[0] )

Vessel_1 timestep size in s:  10
Route: [53, 52, 82]
Distance edge(s) in meters:  203.06105984074387
Velocity in m/s: 3
Stepsize vessel in m per timestep : 30

Analytically, it should take: distance edge / stepsize = number of steps:  6.768701994691463
Or in round off steps: 7

Arrived at crossing at timestep: 1
Number of steps taken by vessel_1:  9
Total wait time in timesteps: 0
Total crossing time in timesteps: 2
Distance last step was: 23.06105984070409
Total distance of vessel sailed without last step: 180 , which is  0.7687019946901363 step
Total distance of vessel sailed with last step: 203.0610598407041
```

(a) Results vessel one during queuing

```
In [61]: distance_total_ves_2 = 0
ves_2 = ves_list[1]
for i in range(len(route_1)-1):
    distance_total_ves_2 += w_G.edges[route_2[i], route_2[i+1]]['dis']
print("Vessel_2 timestep size in s: ", ves_2.step_size)
print("Route:", ves_2.path)
print("Distance edge(s) in meters: ", distance_total_ves_2 )
print("Velocity in m/s:", ves_2.velocity)
print("Stepsize vessel in m per timestep :", ves_2.move)

print("")
print("Analytically, it should take: distance edge / stepsize = number of steps: ",\
    distance_total_ves_2  / ves_2.move )
print("Or in round off steps:", math.ceil(distance_total_ves_2  / ves_2.move))

print ("Arrived at crossing at timestep:", ves_2.time_step_crossing[0])
print("Started waiting at timestep:", ves_2.time_step_waiting[0])
print("Ended waiting at timestep:", ves_2.time_step_end_waiting [0])

print("Number of steps taken by vessel_2: ", len(ves_2.step_list))
print("Total wait time in timesteps:", ves_2.total_wait_time)
print("Total crossing time in timesteps:", ves_2.cross_time)
print("Distance last step was:", ves_2.last_step_log[0])
print("Total distance of vessel sailed without last step:",\
      ves_2.move* (len(ves_2.step_list)-1 - ves_2.total_wait_time - ves_2.cross_time),\
      ", which is ",ves_2.last_step_log[0] / ves_2.move , "step")
print("Total distance of vessel sailed with last step:", \
      ves_2.move* (len(ves_2.step_list)- 1 - ves_2.total_wait_time - ves_2.cross_time)
      + ves_2.last_step_log[0] )

Vessel_2 timestep size in s:  10
Route: [76, 52, 56]
Distance edge(s) in meters:  157.04867216150546
Velocity in m/s: 3
Stepsize vessel in m per timestep : 30

Analytically, it should take: distance edge / stepsize = number of steps:  5.234955738716849
Or in round off steps: 6
Arrived at crossing at timestep: 1
Started waiting at timestep: 1
Ended waiting at timestep: 3
Number of steps taken by vessel_2:  14
Total wait time in timesteps: 2
Total crossing time in timesteps: 6
Distance last step was: 7.048672161521031
Total distance of vessel sailed without last step: 150 , which is  0.23495573873677 step
Total distance of vessel sailed with last step: 157.04867216152104
```

(b) Results vessel two during queuing

Figure B.17: Test 7: Results

B.2 Possible tests when additional logic has been implemented

Test 8: Vessel-vessel queue

As every vessel should be able to queue, they should also physically position in a queue based on their position in the queue and on physical dimensions of each vessel that is in the queue before it. The vessels pass the test when their position in the queue represents their location on the edge.For example, if every vessel has a length of four meters and a safety margin of one meter between the vessels an a vessel has three vessels waiting before it on the same edge, its location should be sixteen meters plus three meters of margin is nineteen meters from the crossing on the edge. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 9: Queue spillback

Following test 8, this test validates whether a vessel's position changes when its position in the queue changes. If its position in the queue changes, its physical location should move up in the queue. Vessels pass this test if when each timestep in the queue moves up, its physical location moves up too. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 10: Approaching in the queue

Whenever a vessel is within one step of the queue, its velocity should reduce linearly to zero. Hence, the time to arrive at the queue increases. Vessels pass this test when their arrival time at the queue includes the reduction of velocity. The test analytically calculates the time it should take, as the last step to queue should take twice as long because of the linear reduction of velocity. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 11: Vessel-vessel interaction (overtaking and encountering)

All vessels should interact with each other on the canals. This test verifies whether overtaking is possible when there is no oncoming traffic but not possible if there is oncoming traffic.This logic was not implemented on the vessels, and therefore this requirement was not tested. Two situations exist: the first is with no oncoming traffic and the second is with oncoming traffic. The first vessel travels at timestep $t = 0$ with a velocity of 1 m/s. The second starts at timestep $t = 3$ with a velocity of 2 m/s. This means that at timestep $t = 8$ they will be at the same position. If there is no oncoming traffic, vessels one and two arrive with the same number of steps as analytically calculated (step size divided by the length of the edge). In situation two, vessel three departs at $t = 0$, also with a certain velocity, and arrives at the exact same location as vessels one and two at the same time. Vessels pass this test when they wait until there is no oncoming traffic and then overtake. This test calculates how many steps each vessel should analytically take before arriving (step size divided by the length of the edge). If the vessel has reduced its velocity to the same as that of the vessel sailing before it, these numbers should not coincide. Vessel logs should state where it reduced its velocity to the vessel sailing before it and increased velocity when it overtook the vessel, and thus the exact number of timesteps it took before arriving at the end of the edge. This overtaking procedure can also be analytically calculated and should match the vessel logs because the position of each vessel and what their velocity is upon overtaking are known. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 12: Sailing rules

As explained in section Section 3.2.2, sailing rules must be applied. This test verifies whether the vessels properly apply these rules during the simulation. Vessels pass this test when they apply the rules to a crossing, such as the right of way to vessels coming from the right, giving the right of way to cruise vessels, and largest vessels go first before smaller vessels. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 13: Dynamic (re)routing

This tests whether vessels can adjust their route when en route. For example, cruise vessels may avoid certain crossings if they hear about congestion on the VHF. Another example are the random cruise vessels. Random cruise vessels may calculate which attractions they can visit with the amount of time they have left. Due to congestion, they could lose sailing time and thus not be able to sail to certain sightseeing points because they have to be back in time. This logic was not implemented on the vessels, and therefore this requirement was not tested. This test is set up as follows: a random cruise vessel will sail its predetermined calculated route, along which the test creates artificial congestion, and the vessel will experience delay time. If the vessel adjusts its route and is back at its starting point in time, the vessel passes the test. The second test is for the cruise vessel. The test creates artificial congestion along the vessel's route, and the vessel must decide whether the delay time is within acceptable limits and that rerouting would cause more delay, or whether rerouting would cause less delay and it should reroutes. Vessels pass when they choose to reroute when congestion causes more of a delay than rerouting would. This logic was not implemented on the vessels, and therefore this requirement was not tested.

Test 14: Memory

When vessels have sailed the same edges repeatedly, this test verifies whether vessels recognize delay times during certain (peak) hours and reroute to avoid certain points, thereby reducing delay time. This logic can certainly be part of the logic of each vessel; however, the simulation scale must be longer than 1 day, and preferably 1 month. Vessels pass this test when they successfully identify at which points congestion will probably occur during certain hours of the day, and thus learn to reroute. This logic was not implemented in the vessels, and therefore this requirement was not been tested.

Test 15: Irrational behavior

This test verifies whether the irrational sailing behavior of pleasure craft is included. This behavior includes certain percentage chance of stopping in the middle of the edge for a time step, taking more time at crossings, and a certain percentage chance of not letting other vessels overtake because of not sailing in a straight line. This logic was not implemented in the vessels, and therefore this requirement was not tested.

C: Vessels and route behavior

C.1 Results from interviews with captains

		Behaviour during:		
Categories	**Vessels**	**Day to day**	**Congestion**	**Canal closure**
Fixed route	Professional steered large vessels: HoHo	Sailing to each HoHo point in 75 min	Stays on route	Shortest path in distance to get back on main route
	Professional steered large vessels: Fixed route	Sailing fixed route towards sightseeing points in max 90 min	Only during heavy congestion (delay more than 15 min) it avoids part and chooses other route	Shortest path in distance to get back on main route or takes an alternative route
Random route with waypoints	Professional steered open vessels	Sailing random route towards sighseeing points Never sailing twice on the same	Only during heavy congestion (delay more than 15 min) it avoids some canals or crossings	Takes other route towards sightseeing point
	Professional steered closed vessels	Sailing random route towards sightseeing points Never sailing twice on the same	Only during heavy congestion (delay more than 15 min) it avoids some canals or crossings	Takes other route towards sightseeing point
Random route	'Rent your own" vessel	Sailing random route	Does not know congestion is on part of the route, so keeps on sailing pre-determined route	Takes random other route
	Pleasure-craft	Sailing random route towards certain canals	Does not know congestion is on part of the route, so keeps on sailing pre-determined route	Takes random other route
	Pedal boats	Sails random route	Does not really care much for congestion	Takes random other route

Figure C.1: Behaviour of different category of vessels

D: Amsterdam fleet and permit system

Amsterdam has a long history in which canals play a major aspect the formation of the city as it is now. Before the 19th century, the canals were mainly important for the water management and to transport goods in and out of the city. The transport of goods were of great economic and financial importance. The ships of the VOC berthed at the IJ, from where goods were transported with smaller vessels to warehouses in the inner-city of Amsterdam. The towage routes were important routes for the domestic transport. However, the construction of the central station in 1889 marked a turning point. Goods were now mainly being transported via roads and railroads, and the canals were no longer necessary. Nowadays the canals are being used by recreation vessels, touring boats, houseboats and a new initiative is proposed to use the canals for distribution of goods for the HoReCa (Berents and Straver, 2015).

D.1 Pleasure craft

Recreational sailing on the canals is part of Amsterdam and it enhances the attractiveness of the city. To be able to sail trough the canals, a 'vignet' has to be bought, which has to be renewed every year. Pleasure vessels are allowed to berth and sail anywhere in the canals of Amsterdam, if the vessel is smaller than 12 meters. However, in a new policy documented in "Nota varen 2.1", the MoA argues that pleasure-craft larger than 10 meters should berth in yacht harbors as most pleasure craft (80%) is between 5-7 meters (Gemeente Amsterdam, 2013). Since the implementation of a new licensing system for these 'vignets' in 2012, the number of people in possession of an pleasure craft decreased from around 11.200 in 2012 to 7276 in 2017 (Waternet, 2018), (Waternet, 2017). In table D.1, an overview of the bought licenses for pleasure craft is shown.

Table D.1: Overview of bought BHG licensen throughout the years (Waternet, 2018)

Type	2013	2014	2015	2016	2017
Regular	7994	7651	6788	6455	5868
Membership*	668	511	514	494	100
Environmental **	1281	1486	1439	1344	1308
Environment (% of total)	12.9%	15.4%	16.5%	16.2%	18.0%
Total	9943	9648	8741	8293	7276

* vessels from outside Amsterdam, who are not allowed to berth in the city centre
** Special tarrifs for environmental friendly vessels

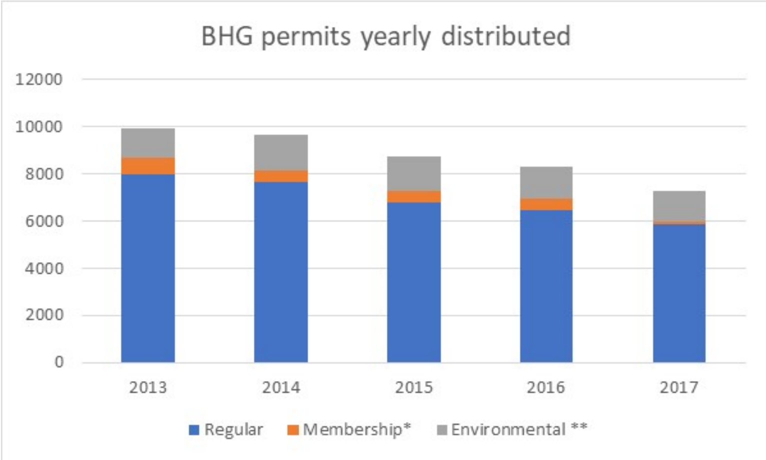


Figure D.1: Overview of bought licenses.

This is a fair representation of the actual amount of pleasure-craft in the city centre, as there is just a small amount of people who do own a pleasure-craft, but refused to pay for a vignet. Therefore, sailing in the canals illegally. The number of vessels without a vignette (192 vessels) decreased in 2017 compared to 2016 (197 vessels). The payment rate (number of sold vignettes minus no vignette / sold vignettes) is 97%. In 2016 this was 98% (Waternet, 2018). This means that 3% of the vessels is not registered using the BHG system. There is also the possibility to buy a day-vignet for day-visitors. But these vessels aren't allowed to berth for the night in the centre, so the statistics depicted in table D.1 represents the actual amount of pleasure-craft fleet in the city centre.

D.2 Passenger transport

The tour boat sector is one of the most important sectors for tourism in Amsterdam, and represents one of the largest attractions in the Netherlands in terms of number of visitors. The canals are a famous sight-seeing attraction for the foreigners visiting Amsterdam. More than 40 % of the tourists visiting Amsterdam takes a boat ride trough the canals of Amsterdam (Baarsma and Van der Voort, 2012). The shipping cruise industry draws more than 3 million visitors yearly, with a steady growth up to 5 million visitors in 2015 and 2016. The tour boat sector focuses mainly on the UNESCO world heritage canals, which are located in the city centre (Gemeente Amsterdam, 2017b). In table D.2, the growth rate of number of visitors is depicted, which is visualized in figure D.2. The year 2015 showed a remarkable growth, but this was due to the event SAIL.

Table D.2: Number of people who takes a boat-ride through the canals (Rekenkamer Metropool Amsterdam, 2017)

Year	Number of visitors (x1000)	Growth	Growth in percentage
2009	2811	-	-
2010	3072	261	9.3%
2011	3195	123	4.0%
2012	3250	55	1.7%
2013	3489	239	7.4%
2014	3780	291	8.3%
2015	4869	1089	28.8%
2016	5191	322	6.6%

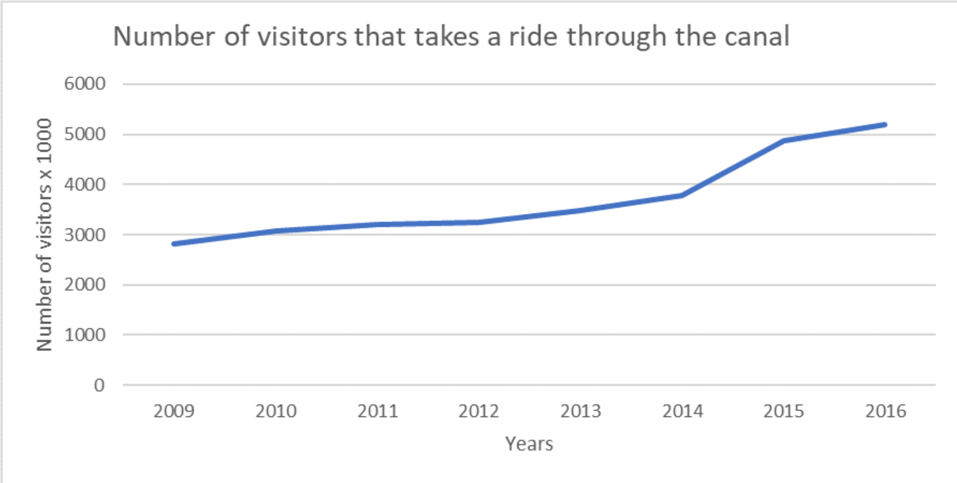
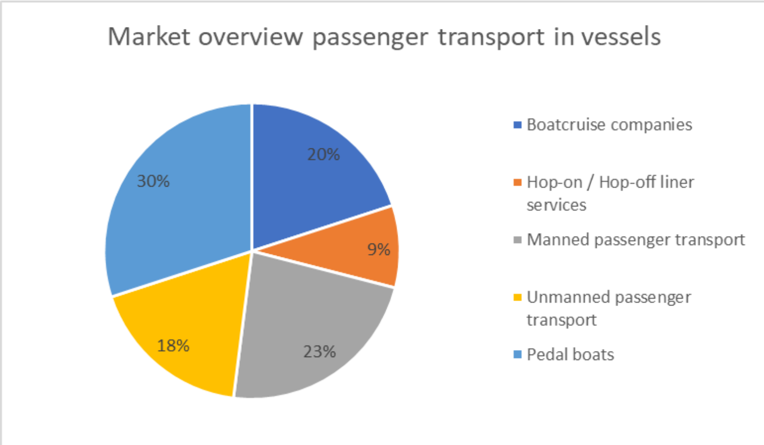


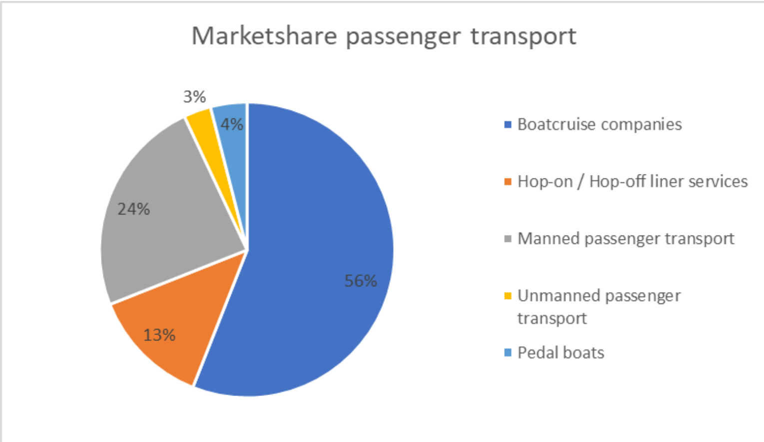
Figure D.2: Overview growth in visitors taking a boat-ride trough the canals of Amsterdam (Rekenkamer Metropool Amsterdam, 2017)

D.2.1 Market for passenger transport

In 2012, there was only a distinction in manned and unmanned vessels. The length of the unmanned vessels could be 5.50 meters at maximum, and these vessels were only allowed to carry a maximum of 6 persons. Manned vessels could have a maximum length of 20 meters, and up to 100 people could be transported for sigh seeing. The market for passenger transport looked like the following according towards the research of SEO (Baarsma and Van der Voort, 2012), from whose advise the new policy in 2013 is based on. A fifth of the licenses issued are used to provide classic bout tour trips in the city centre. In addition, almost 10 per cent of the licenses are for liner services: these are mostly round trips with a hop-on hop-off system that sails past various tourist attractions in the city. Almost a quarter of the licenses issued are for manned passenger transport (open and closed) over the water. Most of these permits relate to the rental of sloops and saloon boats with various packages (such as dinner cruises, staff outings, meeting boating etc.),but also lifeboats and water taxis fall under this category. Finally, there are permits for unmanned rental boats and pedal boats issued. The market looked like the graphs in figure D.3.



(a) Market overview passenger transport in vessels



(b) Market share passenger transport in per category

Figure D.3: Market overview passenger transport in 2012 (Baarsma and Van der Voort, 2012)

D.2.2 New licensing system

For the touring boat sector, different permits are given for different zones. The canals of Amsterdam can be subdivided into two zones geographically. The inner city is located fully in zone 1.

- Zone 1: Amsterdam including the center zone (all of the inland waterways of Amsterdam, but not the port waterways. Other rules apply to the port waterways)
- Zone 2: Amsterdam excluding the center zone. The outer limit is the municipal boarder.

Old legislation in 2008 only made distinction between "professionally steered" and "non-professionally steered" vessels. In 2013, new legislation made the distinction into different categories for zone 1. As this thesis focuses on the inner-city, the focus is on zone 1 and the allowance for permits. These are shown in table D.3.

The new legislation also stated a new policy on volume for the different categories. This meant that more permits for vessels smaller than 14 meters were given out after 2020 and completely open the market after 2030. For vessels larger than 14 meters, permits for an indefinite period were withdrawn and transformed into permits for a definitive amount of time, and each 10 years a new redistribution round will be held for the few permits that are available for this segment (Rekenkamer Metropool Amsterdam, 2017). A schematic overview is given in figure **??**.

D.2.3 Unforeseen developments

In 2016 the European court of justice mandated in a court rule that this policy of a closed market was against the European law for open markets. The MoA need to implement the release of new licenses for passenger

Table D.3: New categories for licenses in passenger transport

Segment	Dimensions Length (m)	Width (m)
Professional steered large vessels	>14, ≤ 20	>3.75, ≤ 4.25
Professional steered closed vessels	≤ 14	≤ 3.75
Professional steered open vessels	≤ 10	≤ 3.15
"Rent your own" vessel	≤ 5.50	≤ 2.00
Pedal Boats	≤ 3.85	≤ 1.55

vessels smaller than 14 meters more quickly. Therefore the MoA had decided to implement the new policy with effect from 1 February 2017 (Waternet, 2017). In table D.4, an overview is given for the amount of permits given out in 2017, with the remarkable growth in pedal boats and "unmanned" ships. Now 356 permits for vessels smaller than 14 meters are given out, as can be seen in table D.4, but Waternet expects that around 1000 permits will be given out.

Table D.4: Permits 2017 (Waternet, 2018)

Segment	Total number of permits in 2016	Total number of permits in 2017	Total number of actual sailing vessels in 2017	Not used permits in 2017*
Professional steered large vessels	147**	148**	144	4
Professional steered closed vessels	60	85	61	24
Professional steered open vessels	75	103	80	23
"Rent your own" vessel	16	19	132***	5
Pedal Boats	3	1	100****	0
Total	301	356	517	56

*Permits must be used within a year of receiving
**There are 11 historic vessels of the 148 vessels whom can keep their permit for indefinite amount of time.
*** 14 permits account for 132 vessels
**** in 2013, one permit has been granted for 100 pedal boats

Also, the policy to revoke and change the permits for indefinite period to an definite amount of time for the vessels larger than 14 meters could not be implemented. The Raad van State ruled in June 2017 that the length criterion on which the new legislation was based on, did not hold ground in court. The argument that larger ships were the cause of delay for nautical traffic did not hold ground, because of the reason that if a vessel larger than 14 meters used a bow truster, no delay was experienced in turning on the canals (Rekenkamer Metropool Amsterdam, 2017). Therefore, the old policy as described in section **??** for the vessels larger than 14 meters is now active. The MoA is developing a new policy regarding the permits for boats longer than 14 meters(Rekenkamer Metropool Amsterdam, 2017).

D.3 Freight vessels

The North Sea Canal, the IJ and the Amsterdam Rhine Canal are a main route for sea and inland shipping, an important pillar of the Dutch economy. The Kostverlorenvaart, the Amstel and the North Holland Canal are also important sailing routes for inland shipping, although these are used far less intensively than the North Sea Canal, the IJ and the Amsterdam-Rhine Canal. Two main transport routes run trough the inner-city of Amsterdam. In 2013, about 2.5 million tons of goods is transported over the canals. This mainly concerns transit for goods. Next to the domestic transport via the Kostverlorenvaart and the Amstel, freight transport by water, which also involves distribution in the city, for example of building materials, business waste flows and beverage deliveries to catering establishments, is seen by the municipality as a potentially attractive alternative to transport via road (Baarsma and Van der Voort, 2012).

D.3.1 Construction logistics

In interviews held with logistic companies (Blomschuiten B.V. and Blueline) who already delivered construction goods via water for few construction projects in Amsterdam, they said it was difficult to say how much trips they were making each day or week to deliver goods to the construction site. Each construction project is different (different location, size, materials etc), and therefore they could not make an estimate how much trips by boat a project needed. No literature is available on the transport of construction logistics via water and how much ship-movements it will cause. However, a new initiative called Amsterdam Vaart could give more insight. Amsterdam Vaart is a joint project between the municipality of Amsterdam, Harbour of Amsterdam, TNO and Waternet. Together with a lot of suppliers, they want to move the transport of construction goods towards the canals. TNO will be gathering data to test the viability of the project. They will have two pilot cases. The first is called "Overhoek". This construction site is very easily accessible via the water, as it is located across central station. GSA will deliver the goods via water. The second use case is "project zuid-as". Hopelfully, this data is in the near future available.

D.3.2 Distribution of goods for the HoReCa

With regard to city-logistics via the water, just a few articles can be found which are related to waterborne urban freight transport. There are a few other concepts of waterborne urban distribution in other cities. Janjevic Ndiaye (2014) mention a couple of waterborne urban freight transport initiatives in European cities like (Duin et al., 2017):

- The Beer Boat (Utrecht) for deliveries to local shops, hotels and restaurants;
- Vert Chez Vous (Paris) for parcel deliveries;
- DHL floating distribution centre (Amsterdam) parcel deliveries;
- Franprix (Paris) Supermarket deliveries;
- POINT-P (Paris) transportation of palletized constructionmaterial;
- Paper recycling (Paris) by barge, Paris.

Literature search found other recent contributions with respect to city logistics for HoReCa concept based on canals and vessels in Amsterdam. Duin et al., 2014, did a simulation study on the canals of Amsterdam focusing on on-time delivery of HoReCa using touring boat traffic, pleasure craft traffic and freight vessels and one "hub" from where the goods where distributed. The developed model of the vessel concept was based on the discrete event modelling, since the transport and loading operations can be represented as a chronological sequence of (some- times parallel) events. The vessels are using common shared infrastructure such as canals and loading zones. They did not model the entire canal system, but a part of the historic center where 40 % of the HoReCa resides. The research question of this paper was: *To what extent is it possible to distribute goods at city- level to shops and restaurants via the canals without causing inconvenience for the other users of the canals and meanwhile satisfying meeting the logistics requirements of the shopkeepers?*

Case-specifically, they concluded that operating with four ships reduces the waiting time with 92 % and the (order-) lead time drops with 53% "(Duin et al., 2014). With the new concept, the other type of traffic did indeed found some nuisance by implementing the new system. But the amount of delay (up to 5 minutes) was negligible compared to the gain in efficiency.
As they did not fully model the entire canal system, and not taking into account recent decisions made in the city council of Amsterdam, Duin et al., 2017 decided to do another study into the feasibility of this concept. In this new concept includes for the establishment of four new transshipment hubs, located on the outskirts of the city, from where electric vessels can sail goods to the inner-city. These locations, which are small city harbours, are situated near large motorways, allowing for a good connection to the existing freight traffic road network (Berents and Straver, 2015). The research question of this paper was:
'What fleet size is required for large-scale urban distribution through the canals of Amsterdam, making use of (up to four) new transhipment hubs, without compromising quality of delivery?'

The locations were proposed in the draft program WaterVision by the municipality Amsterdam: Marktkanalen, the Riekerhaven, the Duivendrechtsevaart and the Nieuwe Vaart (Berents and Straver, 2015). This time, they used the entire inner city as the domain for their discrete-event model.

The system model has no limitations with respect to the storage capacity at the hub locations. Transshipment and storage are located at the same location. The inner-city is divided in three zones. Each zone can be delivered by two hub locations. At the wide canals a speed of 7.5 (km/h) is allowed, while at the smaller canals a speed of 6.0 (km/h) is considered (Duin et al., 2017). The delivery by vessels starts after 8.00 am if the vessels are sufficient loaded. In general this deliverance process lasts until 6.00 pm, but delivery until 0.00 pm is also possible. This is in line with the supply patterns provided by DHV (2007) "(Duin et al., 2017). The unload points are derived from a list made by the municipality of Amsterdam called "steigerplan" and google maps.

The study provided that two hub locations combined with two vessels are sufficient in the low demand scenario.The other scenarios showed some contradictory findings. It should be mentioned here that occupation rates of 0.92 are extremely high. This implies tight scheduling and no incidents should occur. Backup facilities should be foreseen for these occasions. The waiting times are growing when one hub location is closed. Also working times after 9:00 pm and even after 0:00 pm occur more often (Duin et al., 2017).

E: Model results

Due to the sheer size of the results (324 graphs), the results of each location could not been included in this Appendix. The extra appendix is submitted as a different file.