Impact of Increased Lock Capacity on Inland Waterway Freight Transport

TU Delft

Ministry of Infrastructure and the Environment

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Ministry of Infrastructure and the Environment

Preface

This thesis concludes my master degree in Transport, Infrastructure and Logistics at the Delft University of Technology. This research has been conducted in collaboration with the Dutch Ministry of Infrastructure and the Environment (Ministry of I&E), Directorate-General for Mobility and Transport, Maritime Affairs Directorate, the Seaport Division.

My thesis consists of a freight waterway transport network, where the current and future waterway network differ. They differ due to the construction of additional locks at IJmuiden and Beatrix. The impact of additional locks in the waterway network is examined.

It would have not been possible to complete this research without the support of my graduation committee, Bart Wiegmans, Rob Zuidwijk and Rudy Negenborn. I would like to thank Bart Wiegmans for his commitment, knowledge and methods to structure this report. What I have learned will be very helpful in future reports. Besides that, special thanks to my external supervisor Wouter Pietersma, who made it possible to explore policy-making, the experience gathered from the working group (ZTY) and for all other opportunities. Furthermore, I would like to thank Rutger Pol (Ministry of I&E), Paul Zeer (Ministry of I&E), Onno Miete (Rijkswaterstaat), Bas Turpijn (Rijkswaterstaat), and all other colleagues at the Ministry of I&E for their expertise and endless support!

Last but not least, I would like to thank my family and friends for their understanding, support and new insights during this rollercoaster ride. A special thanks to Maarten Rikken and Ronald Terlouw.

Kim Terlouw
The Hague, June 2015

Abstract

The Netherlands as the 'Gateway to Europe' is highly profitable for the Dutch Ministry of Infrastructure and the Environment (Ministry of I&E). To maintain this position, infrastructure investments are required to remove (potential) bottlenecks and to stimulate intermodal transport. This thesis focuses on two (potential) bottlenecks in the inland waterway network, namely the sea lock IJmuiden and inland waterway lock Beatrix. Sea lock IJmuiden connects the Port of Amsterdam with the North Sea and the new IJmuiden lock will replace the current northern lock. The Beatrix lock is an inland waterway lock and is one of the three main hinterland connections of the Port of Amsterdam. The need for additional locks at IJmuiden and Beatrix has been modelled in macro and micro simulation models, although the actual impact of both locks in the waterway network is unknown. Therefore, the research question is as follows:

What is the impact of constructing additional locks at IJmuiden and Princess Beatrix for freight transportation to and from the hinterland via inland waterways in the Netherlands?

The impact of additional locks is measured in ship arrivals and deadweight capacity of passing ships at both IJmuiden and Beatrix. To measure the impact, a studied waterway network was developed, which consists of nodes (terminals), links (waterways) and infrastructure components (locks). The studied waterway network includes (inter)national, regional and local details of nodes, links and components. As additional locks will be constructed, the current and future studied waterway network will differ. Differences in ship arrivals and deadweight capacity (i) without and (ii) with additional capacity are measured by making use of a simulation model.

To choose an appropriate model, existing macro-, meso and micro- waterway simulation models are evaluated to identify (potential) bottlenecks. The Dutch macro simulation model, BIVAS, determines (potential) bottlenecks by making use of ship register data over a year. The output data of BIVAS highlights a black spot at IJmuiden due to the fact that IJmuiden is managed by the Habour Master of the Port of Amsterdam and not by Rijkswaterstaat. As a result, ship register data is managed differently and difficult to include in the macro simulation model. This is why a black spot occurs and because of that, IJmuiden is not connected with its hinterland in any simulation model. Apart from that, critical nodes are made for the use of ship register data, as this data appears to be inaccurate. The inaccurate ship register data is used to identify (potential) bottlenecks and is therefore an indication for (future) infrastructure investments. The (potential) bottleneck is verified, by making use of micro simulation models. In addition, micro simulation models are used to determine (new) lock variables, (new) lock parameters and (new) lockage details. Apart from macro and micro simulation models, limited meso simulation models are available, which simulate multiple locks in one simulation model. Since the studied waterway network consists of multiple locks, this type of model becomes appropriate to illustrate the impact of additional locks in the studied waterway network.

Next to existing waterway simulation models, other research fields related to freight transport are also evaluated as limited waterway simulation models are available and lag behind. First, port simulation models simulate every terminal area separately next to a simulation model of all terminal areas. Therefore, the sum of all terminal areas becomes more important than evaluating them independently. As shippers travel through the waterway network focused only on themselves, the system as a whole is rejected. Second, road simulation models are able to simulate traffic management and policy changes and their effects on traffic flows. This is not possible for waterway simulation models, as only annual averages are taken into account. Furthermore, road simulation models via information systems are able to calculate the shortest routes even if traffic jams occur in the infrastructure. Third, rail simulation models are able to model fixed and variable freight trains throughout the rail infrastructure, which could be useful for waterway simulation models.

Next to this, as existing waterway simulation models run short and lag behind, a new simulation model has been developed to determine the impact of increased lock capacity in the studied waterway network. Discrete event simulation in Simio Simulation is used to examine the impact. The new simulation model includes three impact variables for the future added locks: Nmax (average number of ships per lockage); weights of links (rerouting of ships as ships are able to load deeper); and decreased enter/departure time of ships (larger dimensions of locks). All impact variables are determined out of the analysis of existing simulation models. In addition, as with both current and future cases, a fourth additional impact variable is evaluated, namely an alternative ship departure pattern at nodes. This is due to the fact that ship data registration appears to be inaccurate.

The new simulation model illustrates significant differences in ship arrival patterns for the current case (without additional locks) and the future case (with additional locks). It appears to be difficult to prospect future ship arrival patterns and peak arrivals, as separate impact variables result in completely different ship arrival patterns and peak arrivals. In addition, none of the impact variables are dominant when observing the impact of a combination of them all.

Despite the unpredictable future ship arrival patterns, three scenarios have been developed for current and future ship arrival patterns. The first scenario assumes valid ship data registration for both current and future cases. The second scenario assumes valid ship data registration for the current case and an alternative ship data registration for the future case and the third scenario assumes alternative ship data registration for both cases. The output of the scenarios appear to be positive in terms of equally distributed ship arrival patterns and peak arrivals, while scenario 2 and 3 appear to be neither positive or negative. Thus, every ship arrival pattern for each hour can be measured to be positive or negative in terms of equally distributed ship arrival patterns and peak arrivals. It is important to acknowledge that peaks remain in ship arrival patterns, despite of the fact that additional locks will be constructed in the studied waterway network.

The impact of additional capacity in the studied waterway is thus difficult to prospect. Future ship arrival patterns at IJmuiden might be managed by traffic management and therefore will decrease future peak arrivals. For Beatrix this is not the case, since ship arrival patterns and peak arrivals will remain or even increase in the future. Thus, even with additional capacity, the Beatrix lock might remain a (potential) bottleneck. The effect of constructing additional locks at Beatrix could be increased by managing ship arrival patterns. Even with traffic management, the construction of Beatrix might be postponed if fleet sizes do not increase. Therefore, the impact of constructing additional locks at IJmuiden and Beatrix is larger for IJmuiden as they schedule ship arrivals with traffic management. By doing so, the system is optimized as a whole, which means that shippers do not have the opportunity to optimise their own route through the waterway network.

Future research is required to evaluate the implementation of traffic management at Beatrix. Implementing traffic management will have sufficient benefits, but also disadvantages. Especially for shippers (dis)advantages might occur, as they have to travel through the waterway network also at off-peak hours. The reason why many shippers travel through the network at peak hours is explained by fuel savings, due to upstream/downstream benefits. The exact disadvantages, in terms of costs, for shippers travelling through the waterway network at off-peak hours, however, are unknown. Moreover, traffic management could lead to benefits for fixed shuttle services, but for variable (on-demand) services, this might be more complicated. Besides that, the many surrounding terminals at the Beatrix lock make arrival time difficult to prospect. Despite the unknown consequences of implementing traffic management, the Schuttevaer (Dutch organization of inland waterway operators) acknowledges the potential of traffic management and is willing to cooperate.

Future research is also required to increase the reliability of ship data registration. Many dynamic information systems are available for inland waterway transport. Apart from the availability, none of these information systems is used as input data for any simulation model. Moreover, by improving input data, the simulation models can be improved in terms of accurateness and future freight flows. It is recommended that Rijkswaterstaat and the Ministry of I&E cooperate to improve the data input and further development of existing waterway simulation models.

Increased lock capacity in inland waterway freight transport is only positive for the short-term ship arrival patterns and peak arrivals. In the long-term, structural traffic management changes are also required to improve inland waterway freight transport. Waterway freight transport has substantial potential to stimulate intermodal transport and to strengthen the Netherlands' position as the 'Gateway to Europe'. If the sector, Rijkswaterstaat and the Ministry of I&E can work closely together, the potential can be realized. Otherwise, inland waterway freight transport and its infrastructure investments will be placed at risk.

Content

List of Abbreviations

- Min. I&E: Ministry of Infrastructure and the Environment
- Min. of V&W: Ministry of Traffic and Waterways (nowadays Min. I&E)
- IWW: Inland Waterways
- IWT: Inland Waterway Transport
- EU: European Union
- Beatrix lock: lock complex existing of 2 'twin locks' named Princes Beatrix locks at Nieuwegein
- IJmuiden lock: lock complex existing of 5 locks named IJmuiden locks at IJmuiden
- OD: Origin and Destination
- CEMT: Conference Europeene des Ministres de Transport (ship classification)
- GPS: Global Positioning System
- AIS: Automatic Identification System
- WVL: Water, Traffic and Environment which is a department within Rijkswaterstaat (in Dutch: Water, Verkeer en Leefomgeving)
- DVS: Navigation of shipping traffic which is a department within Rijkswaterstaat (in Dutch: Dienst, Verkeer Scheepvaart)
- VWM: Traffic and Water Management which is a department within Rijkswaterstaat (in Dutch: Verkeer- en Watermanagament)
- BIVAS: Inland waterway analysis simulation model (in Dutch: Binnenvaart Analyse Systeem)
- SIVAK: Simulationmodel for waterways and civil works (in Dutch: Simulatiepakket voor de Verkeersafwikkeling bij Kunstwerken)
- IVS 90: Information and tracking system (in Dutch: Informatie- en Volgsysteem voor de scheepvaart)
- IVS 90+1: Information and tracking system with for each time unit one additional ship passages
- CPB: government body for economic planning (in Dutch: Centraal Plan Bureau)
- SSS – Short Sea Shipping
- COROP: Identification for regions in the Netherlands (in Dutch: Coordinatie Commissie Regionaal OnderzoeksProgramma)
- BICS: Inland waterway information and communication system of Rijkswaterstaat (in Dutch: Binnenvaart Informatie en Communicatie Systeem)
- I/C: Intensity/Capacity ratio to identify occupation rates of infrastructure components
- FIFO: First-In First-Out
- LIFO: Last-In First-Out
- Nmax: average amount of ships able to pass an infrastructure component in one lockage
- KPI: Key Performance Indicators
- IDVV: Impuls Dynamic Waterway Trafficmangement (in Dutch: Impuls Dynamisch Verkeermanagement Vaarwegen)

1 Introduction

Intermodal freight transport is essential to our economy and society. Freight must travel from an origin to a destination anywhere in the world using many modes. It is not possible to transport freight only by road as congestion and pollution would be too high. Hence intermodal transport aims to increase economies of scale and limits environmental impact by using multiple modalities. Intermodal transport is defined by the European Commission as *"the transportation of freight in an intermodal container or vehicle, using multiple modes of transportation (rail, water and road) without any handling of the freight itself when changing modes."* To ensure liveability and accessibility in regions, several policies at the European, national and regional level, stimulate intermodal transport.

The European Commission defined long-term objectives to increase intermodal transport in 2040 (Directorate-General for Mobility and Transport, 2011). To stimulate intermodal transport and to ensure freight flows between different European member states, the European Commission defined 9 main freight corridors in the European Union. The corridor analyses were done to determine pre-identified projects defined as (potential) bottlenecks or missing links, now or in the future. Most importantly, this is to improve the infrastructure at those bottlenecks, to cause an increase in modal split or a decrease in travel time. Pre-identified projects are determined for road, rail and water and may vary between an infrastructure component, link or node in the network. The European Commission give guidance to member states and stimulates initiatives by funding.

In the Netherlands, the importance of stimulating intermodal transport has already existed since 1993 (Ministry of Infrastructure and the Environment, 2010). The Ministry of Infrastructure and the Environment (Ministry I&E) have implemented several initiatives to establish a better connection for all modalities to and from the hinterland of the Dutch ports. This hinterland connection is essential to improve intermodal transport and to maintain the position as the 'Gateway to Europe' (Ministry of I&E, 2014). As the Port of Rotterdam is ranked as the largest port of Europe and the Port of Amsterdam is ranked as Europe's fourth port in terms of throughput (Port of Amsterdam, 2014b), this position is extremely profitable for the Netherlands and therefore very important for the Dutch government.

To improve intermodal transport and to maintain the position of the Netherlands as 'Gateway to Europe', infrastructural investments are required to remove (potential) bottlenecks as they are identified in those corridor analyses. The Ministry of I&E has a specific budget available to stimulate projects/initiatives to improve the infrastructural network and to avoid congestion of all modalities. Improvements in the infrastructure network could be local or regional investments in nodes, links or components. This is in particular for waterways or rail tracks that are intensively used for transport to neighbouring countries and beyond. Dutch ports are also used for transit of goods. Therefore these infrastructural projects have international interest and belong to the European infrastructure network (Appendix A).

This thesis focuses on two pre-identified projects defined in freight corridor analyses of the European Commission. Both pre-identified projects are infrastructure components in the waterway infrastructure. Infrastructure components in the network are defined by the infrastructure design components that freight transport need to pass before reaching the next node, such as a dam, lock, bridge, etc. For the Netherlands, Inland Waterway Transportation (IWT) is a very important modality. In 2014, 5,200 seagoing vessels visited the Port of Amsterdam (Port of Amsterdam, 2014a) and over 29,000 visited the Port of Rotterdam (Port of Rotterdam, 2014). As not all loading of those seagoing vessels could be transported by roads, IWT is a flexible solution. The Port of Amsterdam had over 40,000 visits of inland waterway barges in 2014. The number of inland waterway visits of the Port of Rotterdam is unknown. In the future, this number of inland waterway visits should increase according to port visions of Port of Amsterdam and Rotterdam (Port of Amsterdam, 2014b). All together this inland waterway sector had generated a turnover of approximately 1.52 billion euros in 2011 (Bureau Voorlichting Binnenvaart, 2012).

Problem statement

The two infrastructure projects which are the main topic of this thesis include the sea lock IJmuiden (Figure 1.1) and the 3rd chamber at the Princess Beatrix lock (Figure 1.2). After identifying potential bottlenecks in corridors, detailed studies were conducted for the separate components in the network only (Rijkswaterstaat, 2014a) (Loman, 2011). By doing so, the impact on the performance of the entire network and the importance of connecting Europe has been rejected. While connecting Europe is one of the main objective of the European Commission (Directorate-General for Mobility and Transport, 2011). In addition, due to international freight flows, network studies should not be limited to a separate component or international corridor level.

Figure 1.1: IJmuiden lock complex

Figure 1.2: Princess Beatrix lock complex

Figure 1.3: Overview IWW the Netherland

Because of limited knowledge of impact of increasing link capacity at inland waterways, the research question can be defined as follows:

What is the impact of constructing additional locks at IJmuiden and Princess Beatrix for freight transportation to and from the hinterland via inland waterways in the Netherlands?

Additional locks will be created by constructing a larger sea lock at IJmuiden -which will replace the current Northern lock- and an additional 3rd chamber at the Beatrix lock complex will be constructed nearby Nieuwegein (Figure 1.3). Additional locks become necessary to meet the expected increased freight flow, providing that demand increases as the prognoses indicates (Slendebroek, 2011). In 2007 delays increased at IJmuiden up to 698 hours over 523 ships. While in 2008 a total delay of 969 hours was indicated over 795 ships (Vlugt, 2009). The delays for the Beatrix locks are more difficult to define, because of the fact that alternative routes are possible for smaller vessels. Apart from that, the lock is located approximately in the middle of the route between Rotterdam and Amsterdam. After the peak hours of the terminals in the morning, 4 to 5 hours, they arrive at the lock. In certain cases, waiting times are up to 1.5 to 2 hours per vessel (Bruinekool, 2010). At this moment it seems as if it is a peak hour problem; however, it was concluded that delays during off peak hours were also more than 30 minutes (Binnenvaartkrant, 2013). Note that 30 minutes is a given threshold value, indicated by the European Commission as a maximum delay time of locks.

1.1.1 Research relevance

Infrastructure investments are required in the waterway network to ascertain the position of inland waterway transport compared to the position of rail and road transport. Infrastructure investment at IJmuiden and Beatrix will initially improve port development and freight flow through the waterway network by decreasing delays. An additional lock at IJmuiden is essential to port development of Amsterdam since larger vessels (of the Panamax category) are unable to visit the Port of Amsterdam now (Loman, 2011). For the inland waterway network it becomes essential to increase capacity at the Beatrix lock since large waiting times might influence modal shift. Increased waiting times and delays will not result in a higher modal share of waterway freight transport. Especially with the expectations of volume growth of freight transport, waiting times will only increase further. As the delays differ for both locks, the impact of additional locks will differ also.

The need for infrastructure investments are detected by micro and macro simulation models. Existing simulation models and conducted studies will be evaluated to determine the need for a new simulation model. Scientific research is limited for simulating multiple locks in one model, therefore this thesis seeks to close the gap between the functioning of the studied network, existing simulation models and the conducted studies in the waterway network.

Infrastructure investments (e.g. Beatrix and IJmuiden) are (partly) financed by the Ministry of I&E. The IJmuiden lock will cost approximately 848 million euro (Boon, 2012) and the Beatrix lock will cost approximately 216 million euro (RTV Utrecht, 2014). These costs includes all costs from simulation to actual construction of the lock infrastructure. The Ministry of I&E should always seeks for a balance between minimal delays and minimal investments for the waterway network to function, given an expected freight flow.

1.2 Research scope and focus

This research focuses on the impact of IJmuiden and Beatrix in the inland waterway network in the Netherlands. Two scenarios are distinguished in this research, respectively before (i) and after (ii) constructing additional locks. With these scenarios the impact of separate links and freight flows will be measured, by making use of key performance indicators. The freight flows through IJmuiden and Beatrix are assumed to be OD (Origin-Destination) pairs starting at inland waterway terminals or sea ports, rejecting pre- and end haulage transport, because data of actual origin and destination is lacking. Within the two scenarios, before (i) and after (ii) constructing additional locks, the following assumptions are taken into account:

1. Ship passages divided into ship categories

Both locks differ in type and amount of passages of ships. Ships are divided in four main categories and freight carrying inland ships are subdivided based on data of Rijkswaterstaat. The four main categories are: (i) inland waterway shipping (freight-carrying), (ii) seagoing (freight carrying), (iii) non-freight carrying and (iv) recreational shipping. Freight carrying inland ships are categorized in fleet sizes from M1 to M12, tug-pushed and couple set, depending on their deadweight capacity. All freight carrying inland ships might carry different tons per trip. Furthermore, each fleet size has different waiting costs, as smaller fleet sizes are able to take alternative routes, while larger ships are prohibited to take one certain route though the main waterway network. Though in the recreational category, the amount of ships passing the infrastructure component is more important than their size. For seagoing and inland ships, which are freight carriers, size does matter. Appendix B elaborates on these categories.

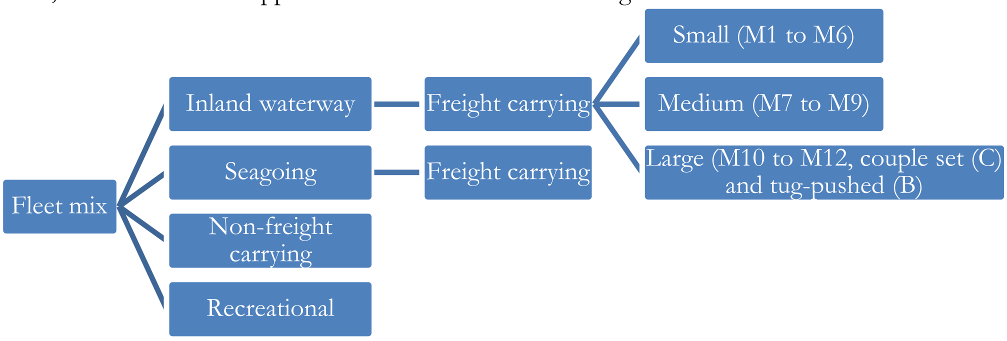


Figure 1.4: Categories and sub-categories of fleet mix (based on categories of Rijkswaterstaat)

2. Neglect effects of water level deviations and extreme weather conditions

In the simulation model the flow (resistance) rate of water is rejected (upstream/downstream), so deviations in ship velocity and ship resistance are not taken into account. This will also apply to water level. Due to seasonal influences, the water level deviates so that certain areas become less accessible. Finally, climate changes and weather influences might disrupt systems performance, which have also not been considered. The aim of this research is to discover the impact of additional capacity in comparison to flow resistance theories.

1.3 Report outline

As mentioned the Netherlands is striving to maintain its position as the 'Gateway to Europe' and infrastructural investments are necessary to maintain this position. Investments at IJmuiden and Beatrix are required to remove (potential) bottlenecks in the main freight waterway network, due to expand waiting times.

In the second section, the inland waterway network in the Netherlands is simplified into nodes, links and components. The main freight routes to and from both locks is illustrated and restrictions of the waterway network are specified. Based on (inter)national, regional and local details, a studied waterway network is determined for this research.

The third section will ascertain existing simulation models used to identify bottlenecks in the main freight waterway network ((inter)national, regional and local). Moreover, it elaborates on theory behind existing simulation models and concludes with input variables for the new simulation model. The existing simulation models will be compared with simulation models of other transport related research fields, such as port, road and rail. This was conducted because alternative simulation models might provide new insights and knowledge. All input variables that were analysed will create the outline of the new simulation model of the studied waterway network.

The fourth section will analyse results of a series of experiments of the simulation model and the last section of this thesis will end with a conclusion and discussion for further research.

2 Inland waterway network in the Netherlands and its hinterland

The inland waterway network of the Netherlands consists of links, nodes and components, with limited capacity. To identify a regional waterway network and to determine impact of increased capacity at IJmuiden and Beatrix, three levels are taken into account: national, regional and local. All levels provide input for the studied waterway network. First, this chapter elaborates on theory of freight waterway networks as the waterway network consists of nodes, links and components.

2.1 Freight waterway network exists of nodes, links and infrastructure components

Freight transport has to have certain volumes, otherwise no service network and infrastructure network is required. The outline of the framework for freight transport is illustrated in Figure 2.1 and is adapted from M. Zhang (Zhang, 2013). This framework illustrates the interference of the government on freight flows, service networks and infrastructure network. All three aspects: freight flow, service network and infrastructure network can be positively or negatively influenced by the government. For this research, the current infrastructure network will differ from the future infrastructure network due to the increased capacity at IJmuiden and Beatrix. The infrastructure network for the current and future situation is illustrated in the end of Chapter 2 into nodes, links and components. The service network will not change over time and freight flow in time will be analysed to identify the impact of the changes.

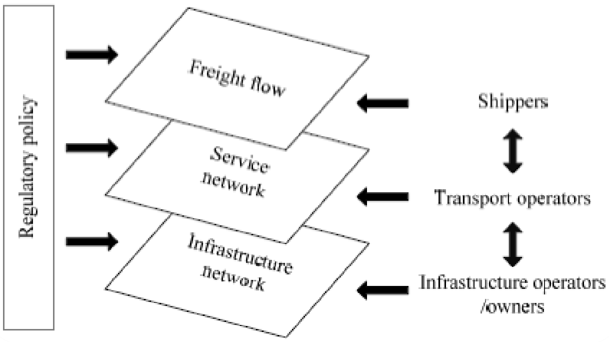


Figure 2.1: Three-layer framework of freight transport adapted from M. Zhang

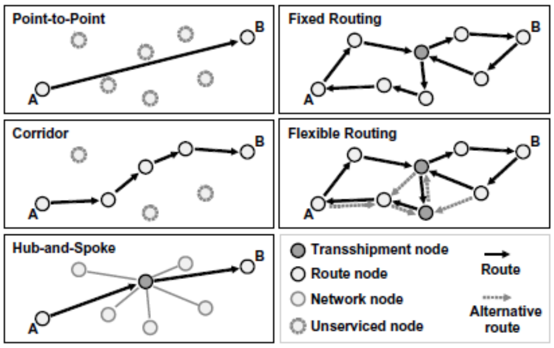


Figure 2.2: Network models, adapted from Woxenius (Woxenius, 2002)

All three levels (freight flow, service network and infrastructure network) are important to understand the interaction between the additional capacity at locks and the ability to use the network. Transport operators ensure the service network for freight flows from a certain origin to destination in the infrastructure network. An infrastructure network is usually represented in literature as nodes which are connected with links as illustrated in Figure 2.2 (Woxenius, 2002) (Hillier & Lieberman, 2009). The functions of nodes include transhipment, storage or transfer of goods (bulk and containers). For all modalities a certain capacity is needed at those links and nodes within the infrastructure network to plan transport to and from the hinterland (Zuidwijk, 2014).

When observing a link that connects nodes within the infrastructure network, it is an important fact that infrastructure components (might) affect the performance, for example at a lock, dam or bridge. Those infrastructure components and nodes have limited capacity compared to waterways. Waterways are limited by weather influences and its depths, so causing a maximum allowance of ship size. Weather influences are excluded from the scope of this research, which means only the draught of ships will be taken into account.
Many scientific papers have been written on strategic planning and coordination or the use of information for modalities during transportation at nodes (Horst & Langen, 2008) (Maia & Couto, 2013) (Konings, 2009). The performance at nodes and infrastructure components are essential for total network performance (Caris, Limbourg, Macharis, Van Lier, & Cools, 2014). Performance of nodes could be influenced by information systems, such that nodes, links and infrastructure components could be used safe and optimal.

2.2 Inland waterways of the Netherlands and its hinterland (macro – meso - micro)

To simplify current infrastructure into nodes, links and components, such that impact can be modelled, background information is required. Information about nodes and links is provided by a national overview of waterways in the Netherlands and its European hinterland. Additional information of components (IJmuiden and Beatrix) is provided using regional and local details. Not all nodes, links and components in the network are necessary to determine the impact of increased capacity at Beatrix and IJmuiden. Therefore the studied waterway network is based on national, regional and local infrastructure and freight flows as shown in Figure 2.3.

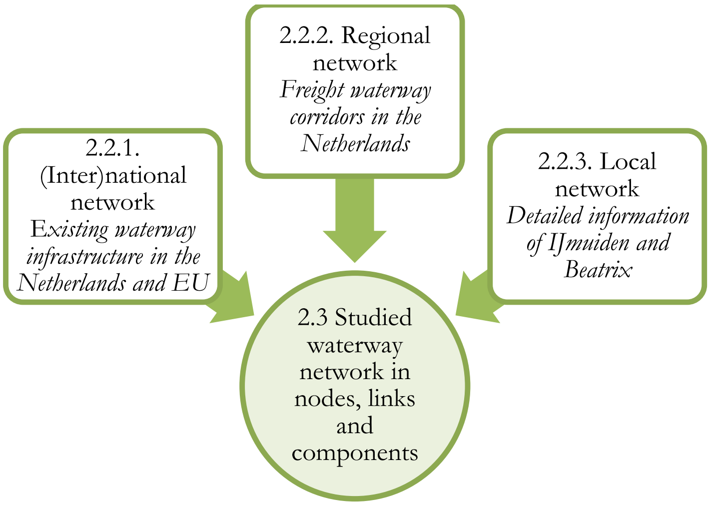


Figure 2.3: Studied waterway network exists of national, regional and local network details

2.2.1 (Inter)national network level – macro waterway network

As mentioned in the introduction the European Commission defined nine freight corridors throughout the EU infrastructure network. Not all nine corridors exists of waterways only, but also rail and road infrastructure is illustrated in Figure 2.4. Apart from infrastructure, not all nine corridors pass through the Netherlands. Only three corridors are aligned, respectively the North Sea Mediterranean corridor (European Commission, 2014d), Rhine-Alpine corridor (HaCon, 2014) and North Sea-Baltic corridor (Proximare Consortium, 2014). All three corridors are illustrated in Figure 2.5.

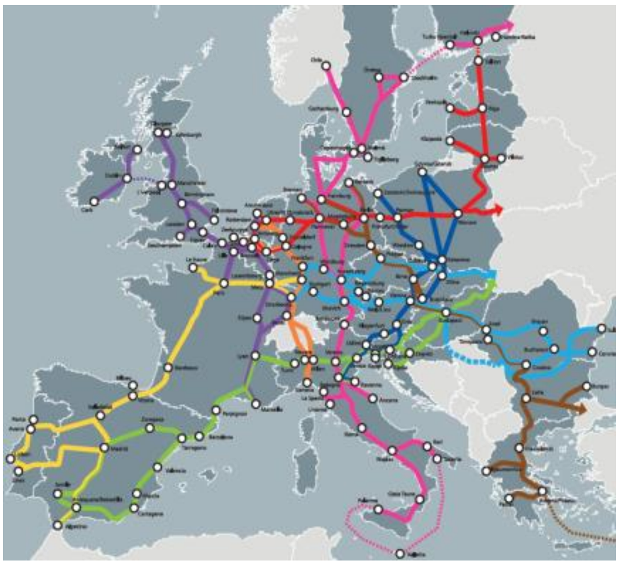


Figure 2.4: TEN-T corridor illustration (adapted from European Commission)

Figure 2.5: TEN-T corridor illustration, flows in the Netherlands (adapted from European Commission)

The corridor analyses were only conducted for main freight corridors through member states. However the Netherlands has a dense rail, road and water infrastructure network. Since this research focuses on waterway transport, only the waterway infrastructure network is illustrated in Figure 2.6. In this figure the main freight waterway routes are recognizable by their blue/purple colour with a large CEMT[1]-classification. Also waterways do not end in the Netherlands, but continues to neighbouring countries.

[1] CEMT (Conférence Européenne des Ministres de Transport) was developed in 1992 by the European Commission to identify ship classification for each waterway. The CEMT classification is based on standard dimensions of ships and push-towing vessels.

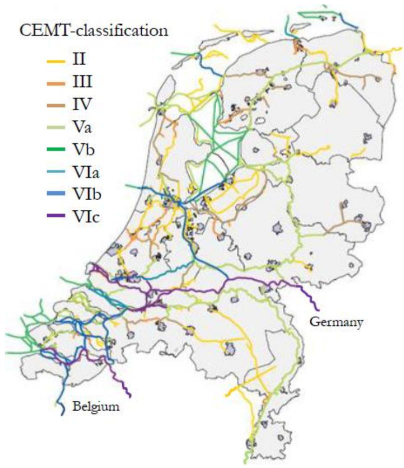


Figure 2.6: CEMT classification of the waterways in the Netherlands (adapted from Rijkswaterstaat)

Waterways have a CEMT classification to indicate what ship category (Appendix C) is able to use certain parts of canals or waterways. This classification is essential to identify limitations and alternative routes (Figure 2.2 fixed and flexible routing) of waterways in the Netherlands and beyond. Attractiveness of alternative routes is affected by increased travel distance and (additional) infrastructure components on that route. Alternative routes are -in most cases- inefficient since costs for transport operators and shippers will increase. In chapter 1, the total delays were identified for IJmuiden and Beatrix over an annual period to define the need for infrastructural investment. No attractive alternative route is available for seagoing vessels that visited the port of Amsterdam through the IJmuiden lock, whereas, for Beatrix, multiple routes are available depending on their CEMT classification.

2.2.2 Regional network level – meso waterway network

All three aligned corridors (the North Sea Mediterranean corridor, Rhine-Alpine corridor and North Sea-Baltic corridor) in the Netherlands consists of nodes, links and components as illustrated in Figure 2.7 and Figure 2.8. Note that only the main freight routes through the Netherlands are illustrated with CEMT-classification of VIa till VIc.

Figure 2.7: Overview of 3 corridors in the Netherlands (google.maps.nl)

Figure 2.8: Overview of 3 corridors in the Netherlands with its important nodes (google.maps.nl)

Zooming into the three aligned corridors, infrastructure components within the waterway network become visible. The North Sea-Baltic (illustrated in red) and Rhine-Alpine (illustrated in orange) corridors are combined into Figure 2.10, since the waterway network corridor is (almost) similar for both corridors.

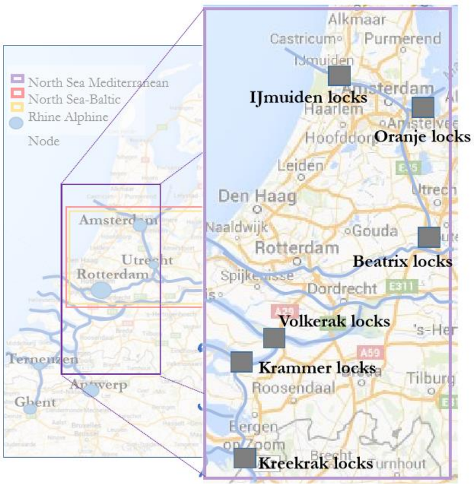


Figure 2.9: Infrastructure components for North Sea Mediterranean corridor (based on google.maps.nl and European Commission)

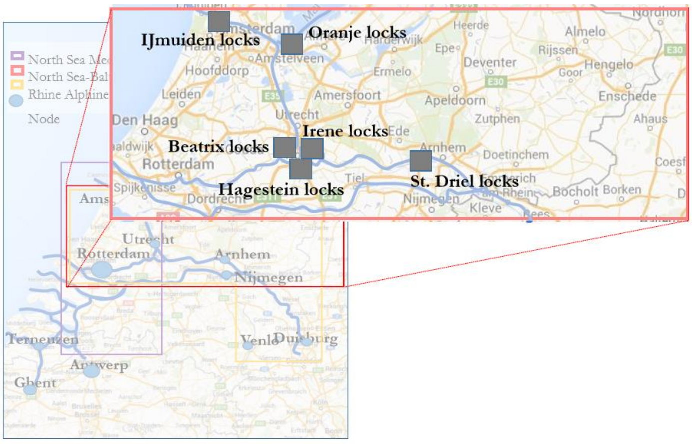


Figure 2.10: Infrastructure components for North Sea-Baltic and Rhine-Alpine corridors (based on google.maps.nl and European Commission)

2.2.3 Local network level – micro waterway network

All limitations and restrictions are indicated of all waterways in the Netherlands by a given CEMT-classification. While for infrastructure components, such as IJmuiden and Beatrix, additional background information is required. A lock can be seen as an obstacle on the link in the network (as illustrated in Figure 2.11), as the shipper needs to slow down to pass the lock. Thus, a lock can be determined as a network infrastructure component by the fact that it separates waterways due to a difference in water level or a difference in saltwater/freshwater. The total delay[2] for shippers can be defined as the waiting time of maximum 30 minutes plus the time of lockage[3].

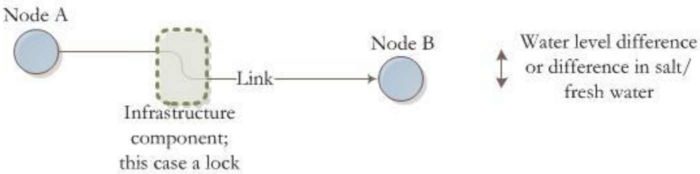


Figure 2.11: Network representation with nodes, links and components

Both Beatrix and IJmuiden have to deal with a difference in water level and IJmuiden only has to negotiate between salt and fresh water as it is a sea lock.

2.2.3.1 Detailed information of (inland waterway lock) Beatrix

The Beatrix locks consist of two chambers -also named as the *twin locks*- both with the same dimensions, a length of 225 m, a width of 18 m and a maximum permitted depth for vessels of 3.5 m. The Beatrix locks connect the Amsterdam-Rhine canal with the Lek river, which is the most important freight corridor between Amsterdam/north of the Netherlands and Rotterdam/Antwerp. This is the shortest freight route between Amsterdam and Rotterdam; approximately 20% of yearly passages of Beatrix is freight transport between these two cities. With the expected volume growth, waiting times will exceed the maximum waiting time of 30 minutes. This results in an increased amount of vessels waiting in a limited space before lockage. Consequently, expansion of the Princes Beatrix lock is necessary. According to the performed MKBA (Societal Costs-Benefit Analysis) a 3rd chamber at the Beatrix lock will have a positive outcome (Rijkswaterstaat, 2013).

Figure 2.12: Overview of Beatrix locks

[2] Note that total delay equals passing time of a ship for a certain infrastructure component in the waterway network.
[3] Lockage is the lock operation of the ship only once through the lock, thus to one direction.

2.2.3.2 Detailed information of (sea lock) IJmuiden

The sea lock IJmuiden exists of 4 chambers: (i) small lock, (ii) southern lock, (iii) mid lock and (iv) northern lock (see all specifications in Table 2.1). As can be seen from Figure 2.13, the IJmuiden northern chamber has been operating since 1929. Upgrades and maintenance have been carried out on the smaller locks. All chambers were originally constructed for sailing ships, as that was the way ships carried freight in that time. The northern chamber should be replaced, since it is reaching its life span of 100 years. Due to its age, complications and down times are increasing. Current complications will not only threaten safety of the city of Amsterdam, but also the frequently used freight route to the Port of Amsterdam and European hinterland corridors (Figure 2.5). Therefore, an early replacement (before end of life span) of the lock is inevitable.

Table 2.1: Specifications of current locks at IJmuiden (adapted from Wikipedia.nl and Port of Amsterdam)

	Small lock	Southern lock	Mid lock	Northern lock
Year of Construction	1886	1876	1896	1929
Length [in m]	110	104.8	200	400
Width [in m]	11	18.05	25	50
Depth [in m]	3.75	7.85	10	15

Two limitations are initially indicated by the use of the northern chamber. First, vessels have become larger over the past few years; however, the dimensions of the current locks are limited in terms of the type of vessel that can be used (CEMT classification). Next to that, in the last 100 years, the horse power of a vessel has become considerably larger, even larger than that of a Boeing 747. As a result the forces on the walls, bottom and doors of the lock become enormous. Moreover, the bottom plate becomes displaced causing a non-symmetric force pattern. Therefore the vessel tends to move to one side of the lock, causing steering problems within a non-symmetric shallow area. This phenomenon is not only a threat to maintenance costs of the lock, but also to the flow of freight (and maintenance time) to the Port of Amsterdam and further in the European hinterland. The second limitation of the northern lock is its tide dependence. Loaded deep draught vessels can only enter the lock as long as there is high tide. In the event of a new lock, vessels are able to enter the lock at any time of day.

Figure 2.13: An overview of IJmuiden lock (adapted from Min. I&E)

2.2.3.3 Sea lock IJmuiden and inland waterway lock Beatrix

Although both locks are an infrastructure component on a waterway link, the differences between the locks are:

1. Different geographical locations result in different type of freight flows.

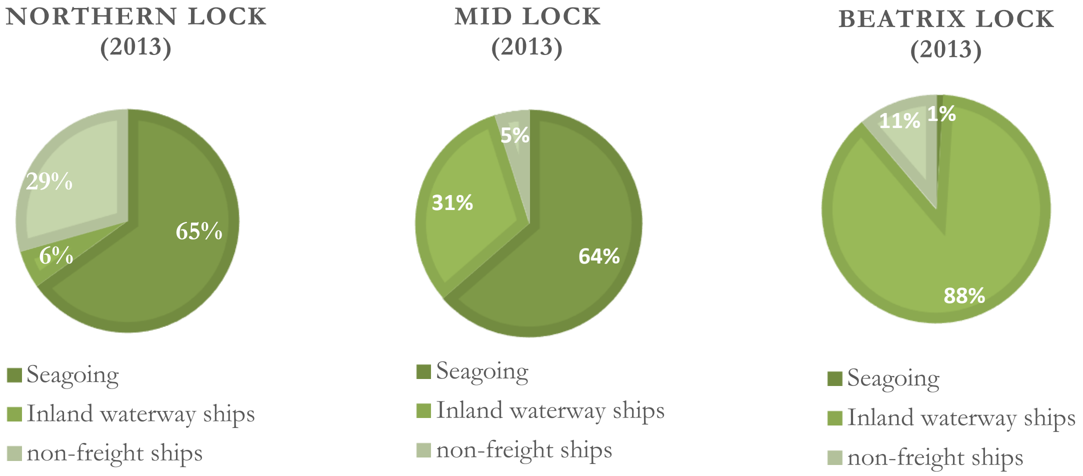
Both proportions between seagoing ships and IWT (Inland Waterway Transport) differ and the IWT share is larger for Beatrix compared to IJmuiden. At IJmuiden the share of seagoing vessels in the Northern lock is relatively larger, due to its access to sea. Table 2.2 demonstrates the shares of all three shipping purposes as defined in chapter 1.

Table 2.2: Throughput of IJmuiden and Beatrix lock for 2012 and 2013 (based on data of IVS 90-Rijkswaterstaat and Harbour master of the Port of Amsterdam)

	IJmuiden				Beatrix	
	2012 [#ships/year]		2013 [#ships/year]		2012 [#ships/year]	2013 [#ships/year]
	Northern	Mid	Northern	Mid	Total 'twin locks'	Total 'twin locks'
Seagoing vessels	CONFIDENTIAL					
Inland waterway ships						
Recreational ships						
Non-freight ships						
Total						

The table below illustrates the different shares for each ship category based on available data of 2013.

Table 2.3: Shares per ship categories of Northern, Mid and Beatrix lock (based on IVS 90-Rijkswaterstaat and Harbour master of the Port of Amsterdam)



a. Different freight flows result in different deadweight capacities

Large loaded vessels visit the area of the Port of Amsterdam (illustrated in Figure 2.14 in (a)/blue) and its surrounding ports by passing the sea lock IJmuiden (illustrated in Figure 2.14 with number 1). In Amsterdam they unload and travel back through the IJmuiden lock much of the time. (Un)loaded cargo is transported to the hinterland through either the Beatrix, Oranje or Irene lock (inbound goods). Of course freight flows go the other way around, with an origin in the hinterland and destination at one of the ports at the North Sea Canal (outbound goods), further explained in Appendix D.

Since IJmuiden encounters more seagoing ships compared to Beatrix, average deadweight capacity differs. For inland waterways, limitations of draughts of ships limit the loading degree of ships. In most cases[4], high loaded ships are transferred at the North Sea to smaller barges. To do so, their draught becomes acceptable for passing the IJmuiden lock. The actual amount of cargo or bulk that is transferred into smaller barges is only known by customs. Both ships (seagoing vessel and smaller barges where part of cargo is transferred into) require lockage and are registered at IJmuiden as unique passage. Customs control knows the exact transfer of cargo, though ships are not obligated to register their loading degree for lockage at IJmuiden. The following results differ for Beatrix and IJmuiden, since loading degree efficiency is registered by Rijkswaterstaat at Beatrix.

[4] Actual percentage is unknown, moreover experts are not able to estimate a percentage.

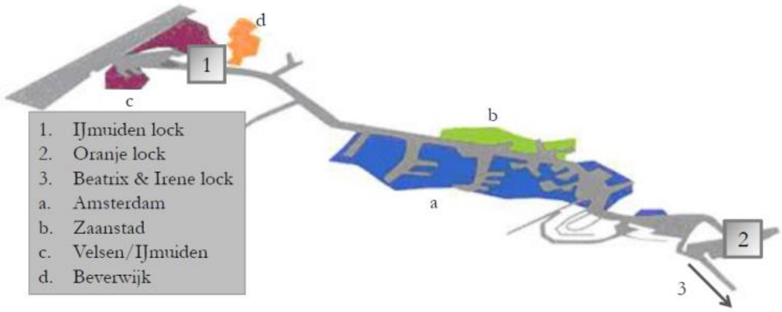


Figure 2.14: Overview ports in North Sea Canal region (based on NZKG)

b. Different freight flows result in different financial impact

Since fleets differ for both IJmuiden and Beatrix, financial impact differs as well. If the locks become unavailable for any reason, ships must wait until lockage is available again. Beatrix involves multiple routes through the waterway network, whereas the Port of Amsterdam is only accessible by IJmuiden. When larger ships (i.e. seagoing vessels) have to wait an hour, it has more financial impact compared to smaller ships (i.e. inland waterway ships).

2. Different locks with different managers and different operational policy

Due to the fact that both locks are managed by other stakeholders (IJmuiden is managed by the Harbour master of the Port of Amsterdam and Beatrix is managed by Rijkswaterstaat), differences occur in both databases. Both managers require different data from shippers and operate their lock differently. The IJmuiden lock is operations with making use of traffic management, as shippers need to register before lockage for an available time slot. For Beatrix registration for lockage is only necessary 2 kilometres before entering. Besides that, shippers might wait at sea, in front of IJmuiden, they are not necessarily waiting for an available time slot for lockage. They could also be waiting to transfer cargo into barges. The pricing strategy of carried cargo and limited capacity at the Port of Amsterdam could also be a cause. Due to unregistered waiting time of ships, it is hard to obtain related costs. Therefore this thesis will not relate costs to waiting and passing times.

3. Shift in route choice and port choice

For sea locks the financial impact (waiting costs per hour) is relatively larger compared to inland waterway locks, since no alternative routes are available and it might cause a shift in port choice. Figure 2.15 indicates the difference for IJmuiden and Beatrix. However the financial impact is not measured, due to the fact that occurrences of waiting is in most cases unregistered, the effects are visualised.

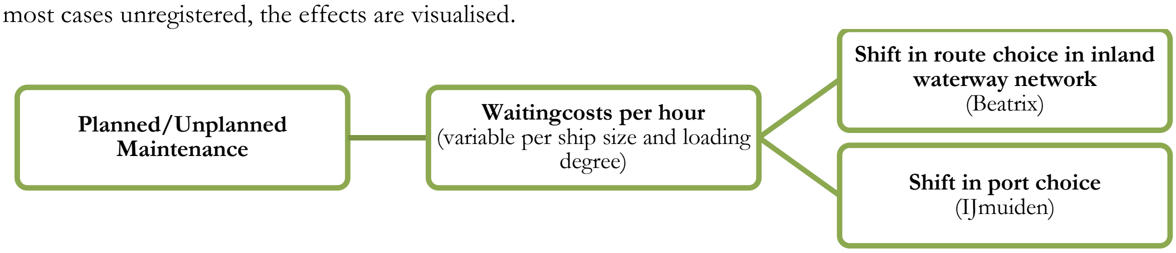
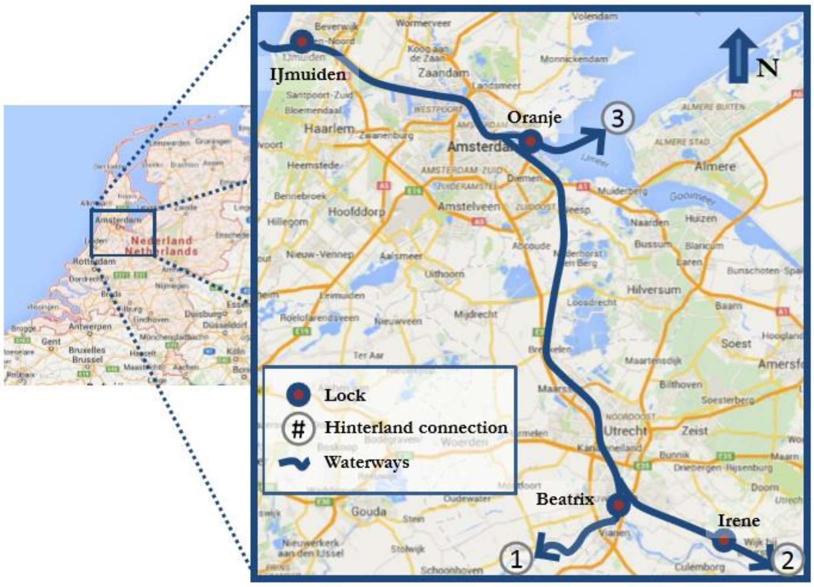


Figure 2.15: Different results for the inland waterway lock and sea lock

2.3 The studied waterway network in nodes, links and components

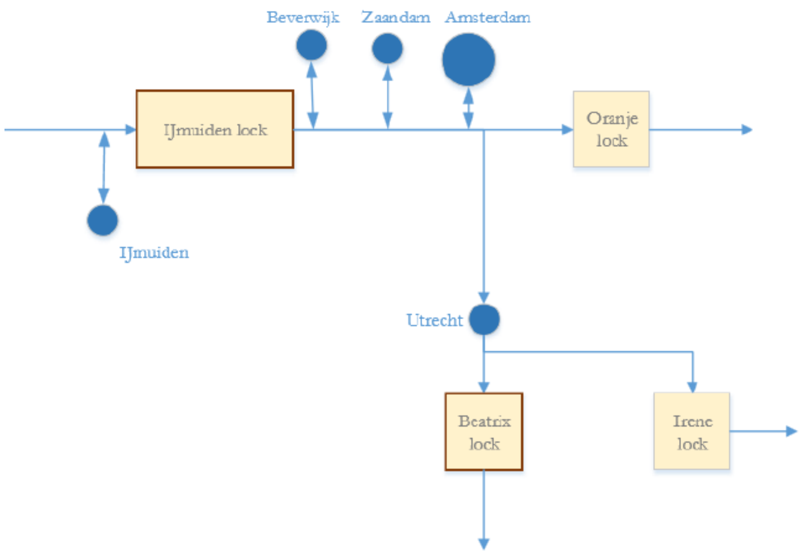
The regional waterway network under study is based on three levels, local, regional and national. IJmuiden as well as Beatrix are directly connected with Amsterdam, as large seagoing vessels enter the Netherlands through IJmuiden and are (un)loaded in most cases in the Port of Amsterdam. Therefore, Amsterdam can be defined as a transfer port. After transfer, freight is transported to the hinterland through either the Oranje, Irene or Beatrix locks (Figure 2.16 and Figure 2.17). Also from the hinterland, large flows are transported through one of the inland waterway locks to Amsterdam, where these smaller batches are consolidated for export. Smaller freight flows exist between other terminals in Zaandam, Beverwijk, IJmuiden and Utrecht.



The studied waterway network only focuses on a part of the waterway network in the Netherlands. Especially since two out of the four locks will have additional capacity after constructing additional chambers.

Three main (hinterland) routes through the waterway network are possible to travel to and from the Port of Amsterdam.

Figure 2.16: Overview of the studied waterway network in the Netherlands (based on google.maps.nl)



The studied waterway network is illustrated on the left, in Figure 2.17. The IJmuiden and Beatrix locks are highlighted with a borderline to illustrate additional capacity.

Figure 2.17: Overview of the study object for a regional dynamic impact model

The Irene lock is included in this research as this lock can be seen as an alternative route for Beatrix through the waterway network. In addition, (smaller) freight flows to and from Oranje and Irene and also to and from Oranje and Beatrix need to be taken into account.

Assumption for transhipments at IJmuiden

For this research it has been assumed that all transhipments at terminal IJmuiden are transferred on the sea side. Thus seagoing vessels do not have to pass the Northern lock before (un)loading at, for example, TATA Steel. In reality large steel packages are (un)loaded before passing the IJmuiden lock while scrap is (un)loaded after passing the lock. Since this share of scrap is relatively small, it has been assumed.

3 Simulation models to analyse network impact of increased (lock) capacity

The studied waterway network exists of multiple locks. By determining the impact of increased lock capacity in the studied waterway network, existing (waterway) simulation models are analysed. By explaining their theoretical background and shortcomings, the main aspects for a new models will be determined. The aim is to close the gap between simulation models and reality. To do so, lock variables are defined to explain chamber assignment. By defining these variables, key performance indicators and input variables have been ascertained for the new simulation model of the studied waterway network. Moreover, knowledge has been gathered from other transport related research fields that have overcome increased capacity in port, road and rail infrastructure, since limited scientific research has been conducted in regional waterway simulation models.

There are several models which are capable of modelling existing and future freight flows through the Netherlands. All existing freight simulation models and information systems, which are used to gather data are elaborated in appendix E. This analysis was conducted to identify shortcomings of existing waterway simulation models (national, regional and local) and to define an outline of the simulation model based on macro ((inter)national), meso (regional) and micro (local) simulation theories (as illustrated in Figure 3.1).

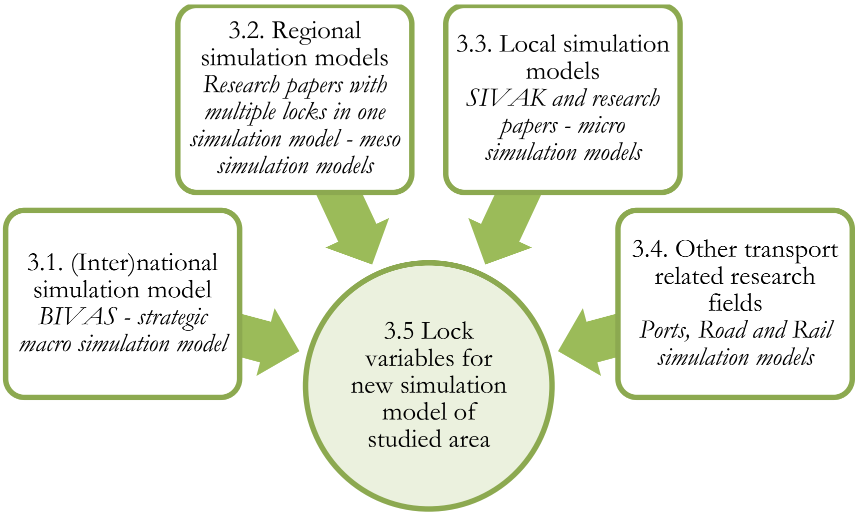


Figure 3.1: Deviation of existing waterway simulation models into three levels: national, regional and local

3.1 (Inter)national inland waterway simulation models - theory of a macro simulation model

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3.2 Regional inland waterway simulation models - theory of meso simulation models

Meso simulation models consists of multiple locks in one simulation model. Though not every lock in the Netherlands is simulated. There is a lack in research papers which include multiple locks into one simulation model. Only two research paper were available for this analysis.

The first research study that consists of a simulation model with a range of locks, was conducted for the upper Mississippi river. Single chamber locks transport tows through the network. The main finding of the article is that tows are too large to lock at once, so they need to be split into smaller groups of barges (Campbell, Smith, Sweeney, & Mundy, 2007). The simulation model focusses on 5 locks in particular and only simulates one-way traffic flow through those locks. After a few years the same bottleneck was not solved yet and more research was done in deterministic optimization of alternative scheduling regimes at those five locks. In this research they focussed on the following policy assignments of locks: (1) FIFO (First In First Out), (2) preference of ship arrivals and (3) maximum waiting time. Within the maximum waiting time the lock keepers were able to optimize the lock operation more (Smith & Nauss, 2012). The used simulation model was too specified to policy assignment and therefore not usable for this research.

A second research study is conducted for a real situation given that vessels travel from Rotterdam to Antwerp. Again one-way traffic is taken into account during simulation. Traffic is able to adapt their speed to determine minimal waiting times at locks (Hengeveld, Negenborn, & Lodewijks, 2012). Adapting speed of vessels is similar to scenario 4 as defined in CONFIDENTIAL IMAGE. As a results of speed adaptations, total waiting times decrease at locks while total travel costs increase. Note that the decrease of total waiting times is larger compared to the increase of travel costs. With this research benefits of speeds adaptations are proven, although two-way traffic and deviations in ships per lockage are not taken into account.

To summarise, both meso simulation models focus on a series of locks on a frequent used route. However both simulation models use one-way traffic only during simulation and assume no difference in the waterway infrastructure. The new simulation model of the studied area should be capable of simulating bi-directional locks and illustrate the impact of additional locks in the studied waterway network.

3.3 Local inland waterway simulation models - theory of micro simulation models

Many scientific research papers have been written on micro simulation models and lock variables. Micro simulation models focus on one lock only and different ship passages. Micro simulation starts after registration for lockage, so it includes approaching a lock and the lockage process itself. This section discusses lockage within a theoretical framework, supported with research papers. A theoretical framework is required to identify impact lock variables. Moreover limited meso simulation models are available, so existing micro simulation parameters are used to define the lock variables in the new simulation model of the studied waterway network. How these lock variables differ for each lock in the studied waterway network is explained in this section.

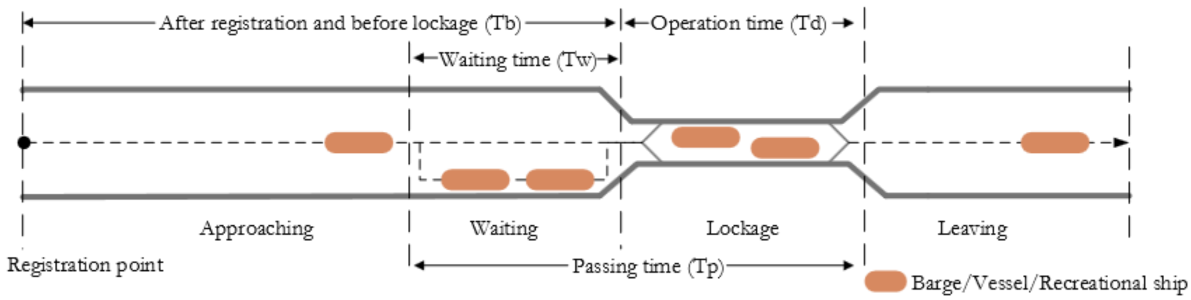

Figure 3.2: Passing process of ships through a lock, with indication of passing time (adapted from Groeneveld, et al.)

Approaching and waiting for lockage (T_b)

After ships are registered for lockage they have to overcome a certain distance before they actually arrive at the infrastructure component. The infrastructure component, in this case, a lock may exist of one or multiple chambers. Not all chambers need to have the same dimensions to operate. Though independent to ship size and lock dimensions a ship will enter the lock complex where it could encounter four scenarios, also indicated in **Error! Reference source not found.**:

1. Lock gates are already open, so the ship can travel directly into the lock chamber
$$f(entering) = Tentering\ lock$$
2. Lock gates are still closed, so the ship has to moor and wait for lock operation
$$f(entering) = Tmooring + Twaiting\ for\ lock\ operation + Tentering\ lock$$
3. Many ships are waiting, so the ship has to wait until the next available lock operation after mooring
$$f(entering) = Tmooring + N * Twaiting\ for\ lock\ operation + Tentering\ lock$$
4. Shipper communicates with lock operator for available time of arrival and adapts its speed (decelerates/accelerates) to the agreed time slot
$$f(entering) = T(distance\ to\ lock * velocity\ of\ ship)$$

These four scenarios provide insight into the plausible cases of arrival, operation and departure patterns. The arrival time can be affected by navigation speed to ensure waiting time is limited. By deceleration, environmental impact and fuel consumption will be limited.

Approaching and waiting for lockage in the studied waterway network

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The lockage process (T_d)

Once the shipper is able to enter the lock, independent to their scenario 1-4, the following process of passing through an infrastructure component is illustrated in CONFIDENTIAL IMAGE. For a service operator, cycle time of any lock operation is a recurring event (locking cycle). The complete locking cycle can be explained as follows:

$$Tc = Td(up) + Td(down) \quad \text{Equation 1}$$
$$Td = f(entering) + Tl + To \quad \text{Equation 2}$$
$$Tc = f(entering)up + f(entering)down \quad \text{Equation 3}$$

The total lockage cycle time can be interpreted by the equations 1-3, which is the sum of the time it takes to pass both directions (all symbols are further elaborated in Appendix H). One direction includes the time to enter f(entering), time to decrease/increase the water level (T_l) and time to leave (T_o) the chamber of the lock. The operation time can be subdivided into the time that is required to close the doors, to fill or empty the chamber and to open the doors. Those times are too specific and therefore are placed in the category of 'operation time' in Figure 3.2.

The lockage process has a certain lock capacity and can be expressed as follows:

$$Cs = (2 * \frac{nmax}{Tc}) \quad \text{[ships/time unit]} \quad \text{Equation 4}$$

$$Ct = Cs * Ts \quad \text{[tons/time unit]} \quad \text{Equation 5}$$

The capacity of ships per time unit (C_s) is equal to two times the amount of ships per lockage, divided by the total lockage time. The tons per time unit (C_t) indicate the amount of carried cargo per ship (C_s) divided by the time it takes to lock (T_s).

The lockage process (T_d) and lock capacity is influenced by lock variables

The lockage process with a certain lock capacity is influenced by lock variables. Lock variables are already a popular topic for years, for example to determine operation (T_d) and arrival times. This started in 1972 by Desai and in 1973 by Carroll and Bronzini (Dai & Schonfeld, 1998), who indicated that operational times are not exponentially distributed and arrival times are not Poisson distributed. Also other standard distributions have been tested without success. Nowadays, empirical distributions are used to describe means and variances of queuing models for locks and to describe operational times. For macro simulation models still exponential distributions are used since it approaches empirical data conforming Rijkswaterstaat (as was illustrated in **Error! Reference source not found.**). What can be learned from the past is the fact that chamber assignment differs for every infrastructure component, since service times are dynamic rates that might fluctuate during daytime also. Chamber assignment differs for every lock due to the fact that it is influenced by many variables (Verstichel, Causmaecker, b, & Berghe, 2011).

Not all lock variables that are indicated in the past can be used in the new simulation model, as the studied waterway network exists of multiple locks. The impact lock variables are described and when necessary mathematically expressed as follows by lock capacity variables (v_x in red) and external variables (ev_x in green):

$$Chamber\ Assignment = f(v1, v2, v3, v4, v5, v6, ev1, ev2)$$

Lock Capacity Variable 1 (v1): Chamber size

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Lock Capacity Variable 2 (v2): Maximum ship size

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Lock Capacity Variable 3 (v3): (average) Number of ships per lockage

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Lock Capacity Variable 4 (v4): (average) Deadweight capacity per ship

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Lock Capacity Variable 5 (v5): Unloaded/Loaded degree (loaded or empty)

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Lock Capacity Variable 6 (v6): Assignment policy

The sixth variable that will influence chamber assignment can be defined as the assignment policy. Policy for chambers can be FIFO (First-In First-Out) or LIFO (Last-In First-Out). In the literature FIFO policy is mentioned as a method that does not result in efficient use of infrastructure components (Campbell, Smith, Sweeney, & Mundy, 2007). This can be solved by making optimal usage of a lock assignment (dependent on ship demand for lockage). However, the ability of a shipper to wait for the next locking cycle for lockage becomes more complicated[5].

External Variable 1 (ev1): Inter arrival time of ships

The first external variable is defined as the inter arrival time (IAT) of ships, which influences the (possible) time to enter the lock. All ships operate with their own speed, which affect inter arrival times. If inter arrival times between ships are relatively small, then the amount of ships waiting for lockage increases. It can also be an indicator for the amount of ships that require lockage per time unit.

External Variable 2 (ev2): Interdependencies of locks

The inter arrival times of ships is influenced by the velocity of ships. Differences in velocity occur due to engine power, loading degree and ship size. Besides operational velocity, time of departure is an important aspect. Time of departure

[5] Gathered information in an interview with Mr. J. Vierhouten, former lockkeeper and currently operational nautical advisor at Rijkswaterstaat.

can be influenced by terminal operation or an already passed upstream or downstream lock. Therefore, all locks in the waterway network are connected. How large this interdependency is between different locks has not yet been described in literature and therefore hard to establish in static simulation models. As a result, this will be the focus for defining the impact of increased lock capacity.

External Variable 3 (ev3): enter/depart times of ship in/out of locks

Other detailed lock capacity variables as positioning of ships inside locks and engine power of ships (Verstichel, Causmaecker, Spieksma, & Berghe, 2014) are combined during this analysis. These small deviations are not modelled separately, since time to accelerate and decelerate causes service times to deviate for only a few minute(s). Verstichle et al. were the first researchers that were capable of obtaining a simulation model for both seagoing vessels as well as inland waterway barges. Due to ship dimensions, certain ships need to have a certain position inside the locks, which takes additional time. Besides that, specified knowledge is required for water management and water flow requirements of ships inside locks. This is not the aim of this research and is therefore rejected. In the end, both variables are combined to one variable what is defined as enter/departure time of ship in/out of locks.

Lock variables in the studied waterway network
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Passing times (T_p)
Passing times are gathered from micro simulation models. Micro simulations define certain different ship sizes and deadweight capacity that have to pass through a lock. Every ship will be simulated separately. Total passing time will be divided by the amount of ship passages or is expressed as follows for a single ship passage as operation time (T_d) plus the waiting time (T_w):

$$Tp = Td + Tw \qquad \text{Equation 7}$$

Passing times of ships in the studied waterway network (T_p)
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3.4 Simulation models to analyse increased capacity in other freight transport research fields

Due to limited scientific research in lock operations and waterway simulation models, a small study was conducted for optimization of port operations. In addition, rail and road simulation models were studied, as considering other simulation models could have advantages. In that way this research will not re-invent the wheel, but take advantage of existing knowledge.

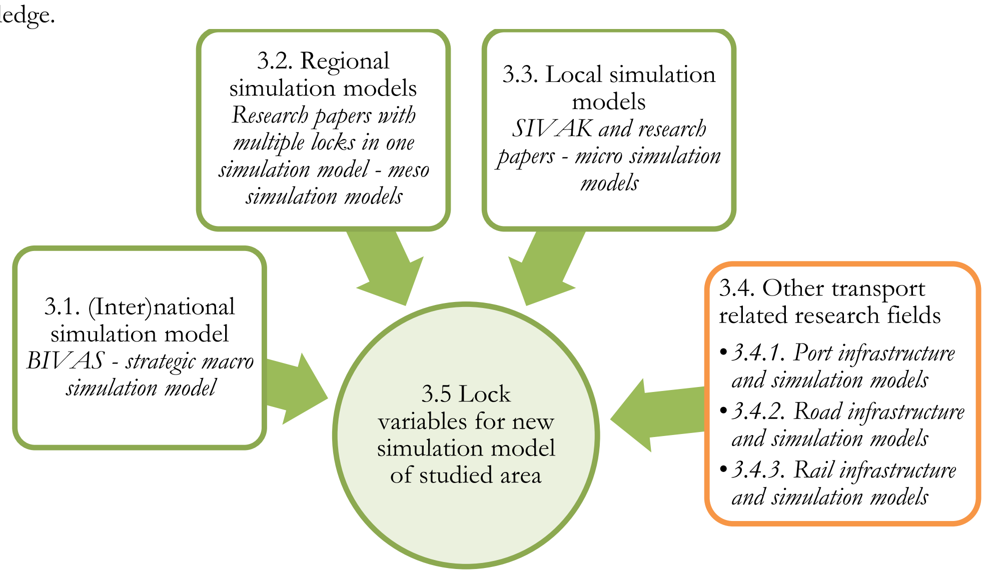

Figure 3.3: Besides waterway simulation models also other transport related research fields are analysed

3.4.1 Port infrastructure and simulation models

Port infrastructure and simulation models are evaluated since optimization of port operations is a popular topic for scientific papers, only storage yard operations result in 90 papers between 2004 and 2012 (Carlo, Vis, & Roodbergen, 2014). The port is mentioned to be a complex system since multimodal transport of incoming and outgoing freight flows needs to be on time for delivery (Kotachi, Rabadi, & Obeid, 2013). Moreover, it has been proven through tests that scheduling problems of container terminals are solvable with simulation optimization methods. Besides that, terminals are aligned as nodes in the studied waterway network and thereby directly connected to the inland waterways.

For port infrastructure, a distinction is made for handling materials or containers at five main terminal areas, namely *berth, quay, transport, storage yard* and *(terminal) gate*. All handling and operations within those five main areas are influential to terminal occupation rates and overall performance (Talley, Ng, & Marsillac, 2014). Overall performance is defined as the amount of cargo handled in a certain time span, where cargo could be any type of container or material.

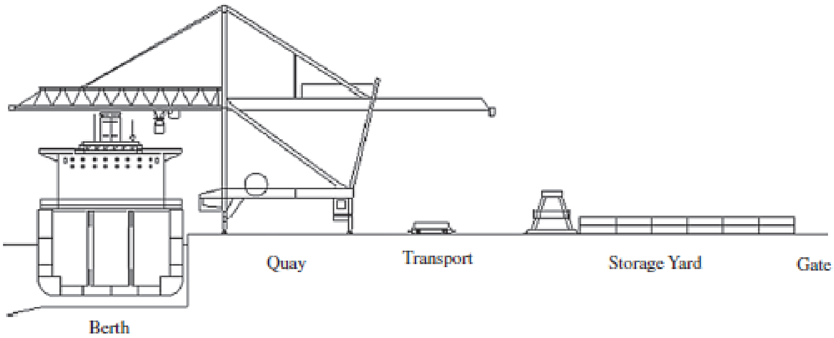

Figure 3.4: Main terminal areas (H. Carlo et al.)

Every terminal area could be modelled separately, though also an overview is provided of the entire terminal performance. Port operation depends on the performance of all logistic terminal operations in any area. Models could include terminal down times, finite capacity at yards, limited handling capacity of equipment, security and customs delays and so on (Kotachi, Rabadi, & Obeid, 2013). Thus meaning that separate areas could result in minimal delays, whereas port operation is tried to be optimal under certain circumstances. This phenomenon is also seen in one of the regional waterway simulation models in section 3.2. As if the single shippers were not optimized but the entire costs of the system did decrease.

The output of terminal area simulation might indicate (potential) bottlenecks. Bottlenecks might occur in handling equipment and/or in limited space for (temporarily) storage. Because of limited space and the high price of land use in ports, the optimal use of space is necessary and therefore the cheapest option. Optimal use of ports occurs as a minimum amount of handlings in any terminal area is required for any amount of handled cargo (Bichou, 2009) (Jiang, Lee, Chew, Han, & Tan, 2012). Moreover, queues are limited by (continuous) availability of handling equipment. Also for ports, variables are influential to ports' (optimal) performance and occupation rates. At a certain point, the decision should be made for expansion at one or multiple areas of the terminals when (potential) bottlenecks become unacceptable.

(Potential) bottlenecks in terminal areas are difficult to define by a certain threshold value for capacity expansion. In terms of decision-making for capacity expansion, the research is again limited. The decision to expand to other ports is clarified by seaport terminal awarding (Yip, Lui, Fu, & Feng, 2014). However it rejects terminal capacity for one location. In particular, the research focuses on optimal performance inside terminals by simulation models (Kia, Shayan, & Ghotb, 2002) (Fan, Wilson, & Dahl, 2012). Delays of flows of materials/containers throughout the port are incentives for decision-making. Terminal operators decide to expand their areas after a threshold value, which is difficult to prospect exactly since terminals vary in size, available equipment and throughput. A capacity increase might reduce marginal costs due to economies of scale and a reduction in congestion (Dekker, Verhaeghe, & Wiegmans, 2011). The optimal number of, in this case, berths are calculated with the queuing theory (Legato & Mazza, 2001), while decision-making processes of capacity expansion are related to dynamic programming.
For waterways not all components are modelled separately to decide for capacity expansion. Though this decision is based on the threshold value of 0.4 of the I/C ratio in BIVAS as defined in section 3.1. Since the decision is based on I/C ratios, optimization of (separate) areas in the system are not considered.

In short, shippers utilize their own trip and do not utilize system performance at, i.e. infrastructure components. While at port operations equipment might not be optimized since total port performance is more important. For the waterway network, overall performance is defined as the amount of ship passages in a certain time span, where ships could be any type of ship. Furthermore, optimization of separate areas is not considered.

3.4.2 Road infrastructure and simulation models

Road infrastructure is more restricted, compared to waterway infrastructure. Lanes and speed limitations result in a limited capacity at any link whereas this is not the case for waterways. Though, road also has multiple infrastructure components. A tunnel or bridge can be seen as a component in road infrastructure that might cause (potential) bottlenecks. A tunnel or bridge has a limited amount of lanes available, which means that no additional lanes could be constructed or opened in a certain time frame. For highways lanes can be opened temporarily e.g. during rush hour. Besides that traffic management regulations are able to influence the amount of vehicles per hour, this is already proven in simulation models before traffic management regulations were implemented. Speed adaptations in waterways has only been proven for waiting times as captured during a regional waterway simulation model. Nevertheless, the amount of ship passages are not proven to be increased in a time frame. By increasing the amount of ship passages per time unit, more cargo could be transported from one node to another node.

Existing road simulation models identify (potential) bottlenecks in passenger transport. Furthermore, choice in modality are essential components, which can be used in simulation models as OmniTrans. Four different levels are distinguished in road simulation models, namely (i) macroscopic, (ii) mesoscopic, (iii) microscopic, and (iv) hybrid models (Hoeven, Prins, Hout, & Vlist, 2012). A hybrid model is able to zoom-in and zoom-out at components to provide a comprehensive overview. All other levels of simulation are already discussed. However, a hybrid model in the maritime industry is not yet operational. Such a hybrid data collector in the maritime industry is Marine Traffic, which collects data on waterways, but also indicates the amount of vessels per continent by making use of AIS[6]. In comparison to road simulation models, Marine Traffic is not able to forecast future flows in infrastructure.

Existing road simulation models also identify future freight flows. Namely, V. Knoop et al. indicated the ability of traffic simulation models to prospect future flows within the micro, macro, meso and hybrid levels. Furthermore they identify new possibilities for traffic simulation models. Due to increased simulation areas, with limited time, a simulation is able to operate. Next to that, there are opportunities between (average) density of vehicles and (average) flows on links (Knoop & Hoogendoorn, 2013). In waterways, (average) density of ships and (average) flows on links are only visible for several years. For waterway simulation models future flows are also difficult to prospect since fleet sizes are still increasing.

Apart from simulation models, information systems are able to guide freight and passenger flows through the road infrastructure. By making use of GPS, TOMTOM® takes advantages of using GPS to define an estimated time of arrival and plan a shortest path to any node in the road network. AIS is currently used for waterway transport to track and trace ships and is used as a radar information system to identify information about ships size, origin and destination. AIS is publically available and it is therefore difficult for shippers to remain anonymously, for shippers this is an issue. For trucks using GPS, this is not an issue, since truck drives do not experience it as an obstacle. Most important, information systems such as AIS and GPS will support simulation models.

In short, road simulation models are able to model traffic management and policy changes. Not only policy changes but also zooming in and out of different levels is possible. By making use of GPS track and trace information systems, passenger and freight transport uses the road infrastructure network (almost) optimal by defining the shortest route and choosing appropriate alternative routes. Most important that these information systems are dynamic.

3.4.3 Rail infrastructure and simulation models

Rail infrastructure is even more restricted compared to road infrastructure. A freight train has to buy a certain timeslot for departures and, as a result, they are able to travel from origin to destination without unnecessary stops. Booking a time slot is possible for multiple countries if the trip involves international freight transport. By identifying a timeslot, a freight train is prohibited from departing outside that time slot. This is necessary due to strict regulations of minimal distance between freight trains and passenger train schedules. While waterway has more flexibility compared to the fixed time slots of railway traffic. For a ship, the exact time of departure does not have that impact as it has for a train. A freight train needs to choose alternative slots if the chosen slot cannot be taken. Therefore, any delay in the rail network might have major impact for one freight train.

Identical to road simulation models, rail simulation models combine passenger and freight transport into one model. Passenger and freight transport exists of fixed and variable train schedules. The real time location of trains is registered in a dynamic model to manage rail traffic through the network. Both real time and train schedules are used for future rail freight simulation models to determine available time slots and are used to define occupation rates of links in future years in the rail infrastructure network.

Especially freight rail transport contains a mix of fixed and variable scheduled trains. Fixed trains are shuttle trains and are booked a year in advance for its time slots, while variable freight trains are dependent on demand. Shuttle trains are used between an origin and destination with a certain frequency at any time unit. Trains on demand depend on their bundling possibilities. Shuttle trains take fixed capacity from rail network, whereas on demand trains use a variable capacity of the rail infrastructure.

In short, waterways are more flexible compared to rail infrastructure. Rail simulation models manage their capacity by divide scheduled trains into fixed and variable. This is beneficial for planning future train schedules and to spread trains

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[6] Automatic Identification System (AIS) used in Vessel Traffic Services (VTS)

over the rail infrastructure. For waterway transport this might be an option such that infrastructure components could be booked a period in advance such that fixed scheduled IWT can travel on time.

3.5 Requisite for increased lock capacity and the new simulation model

This section elaborates on the opportunities of waterway simulation models and lists all the point that are incorporated in the development of a new simulation model of the studied waterway network. First, in this section the requisite for increased lock capacity is founded using maximum flow, minimum cut theory. By doing so the need for capacity expansion is underpinned. Second, opportunities for waterway simulation models and aspects for the new simulation model requisites are defined based on existing waterway simulation models and simulation models of other transport related research fields.

3.5.1 Requisite for increased lock capacity in the studied waterway network

A theoretical framework is used to identify the need for increased capacity. Before additional capacity is required at any node, link or infrastructure component, they have to be identified as (potential) bottlenecks in the studied waterway network. Without the ability to exemplify potential bottlenecks, a capacity increase cannot be constructed. To construct the increased capacity of Beatrix and IJmuiden, a theoretical framework of maximum flow and minimum cut is used. This theory was originally formulated by Harris and Ross in 1954 and the aim is to identify maximum flow between any origin and destination (Ford & Fulkerson, 1954).

With the given nodes, links and components in the studied waterway network, a distinction is made for seagoing vessels and inland waterway barges due to differences in vessel size. Some seagoing vessels are not (always) able to pass the inland waterway locks of Beatrix, Irene and Oranje. To determine maximum flow from origin to destination, an algorithm of Ford-Fulkerson was used. This method starts with zero flow on each node/link/component and determines the maximum flow on each node/link/component based on their constraints (Kleinberg & Tardos, 2005) (Ford & Fulkerson, 1962). Note that the maximum flow is bounded by constraints, since maximum capacity is available at the nodes, links and components.

Maximum flow at nodes, links and components

Maximum flow at nodes (terminals) is examined based on maximum quay wall infrastructure and environmental limits of port areas. Maximum quay wall capacity for seagoing vessels is indicated as 20 million tons for IJmuiden and 125 million tons for Amsterdam (Ministry of I&E & Ministry of Interior and Kingdom Relations, 2013). By constructing an additional sea lock at IJmuiden, capacity will increase to 125 million tons, equal to the environmental limits of Amsterdam. In this case the number of passing ships is not causing (potential) bottlenecks, since smaller vessels are able to pass other locks at IJmuiden.

Maximum flow on links (waterways) is supposed to be dependent on certain ship passages on a waterway segment. The assumptions to estimate maximum capacity are examined in appendix I. Capacity at links exceeds capacity at terminals and the infrastructure components, therefore they are set to unlimited (∞) in Figure 3.5 and Figure 3.6.

Maximum flow at infrastructure components turns out to have the least capacity compared to nodes and links. For both inland waterway transport (Figure 3.6) and seagoing vessels (Figure 3.5) maximum flow is shown. This distinction is made due to the fact that both locks have different flows in terms of seagoing, inland waterway transport and non-freight as illustrated in Table 2.3.

Maximum flows in the studied network are illustrated in Figure 3.5 and Figure 3.6. Figure 3.5 illustrates IJmuiden as potential bottleneck for seagoing transport. Theoretically a capacity increase to 145 million tons[7] would be more sufficient, since no further increase of capacity in the future is required for seagoing vessels. Figure 3.6 indicates bottlenecks for inland waterway transport to and from the Port of Amsterdam. The actual deadweight capacity of the mid lock at IJmuiden is unknown and as a result illustrated by a question mark. Note that alternative routes are available for inland waterway transport through, i.e. the northern lock. Therefore it will not be assumed as a bottleneck for inland waterway transport. The three inland waterway locks are left with finite capacity. Beatrix has the lowest maximum deadweight capacity of 173 million tons per year and is identified as maximum flow and minimum cut through the network, together with the Northern lock for seagoing vessels.

[7] 145 million tons would be more sufficient, since 125 million tons pass through Amsterdam + 20 million tons in IJmuiden, adding up to 145 million tons. Note that it has been assumed that sea going vessels are not able to pass the mid lock (Appendix J).

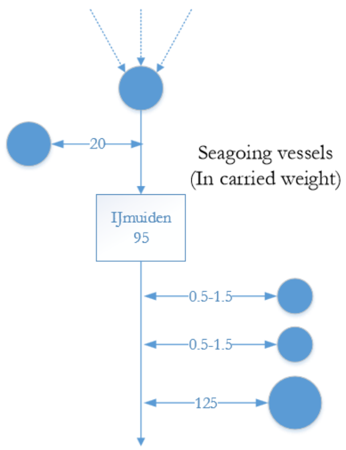


Figure 3.5: Maximum carrying weight given at links/nodes for seagoing vessels

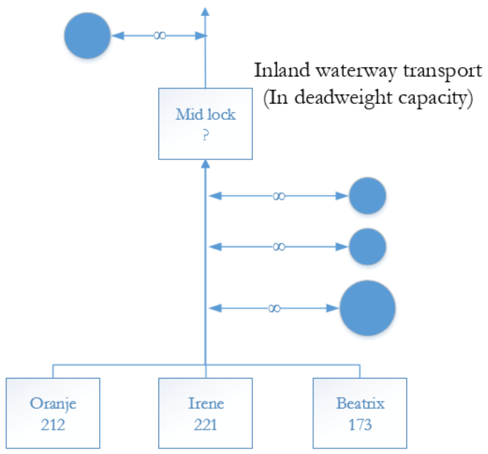


Figure 3.6: Maximum deadweight capacity[8] given at links/nodes for inland waterway transport

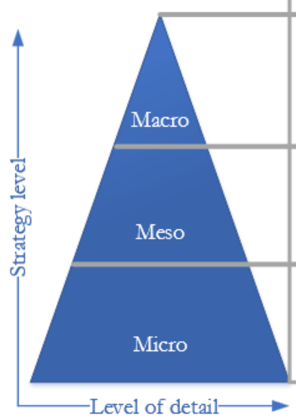
Increased capacity is required for Beatrix and IJmuiden
By identification of Beatrix and IJmuiden as (potential) bottleneck with making use of maximum flow, minimum cut, a capacity increase would improve the ability for larger flows through the studied waterway network. Note that in Figure 2.1 the aspect of service network is not applicable in this case, since the service network of all locks in the studied network are available 24 hours a day, 7 days a week.

3.5.2 Requisite for a new waterway simulation model

As the need for increased capacity for both IJmuiden and Beatrix is established, this section determines the necessity for a new simulation model. The section is divided into three subsections: shortcomings of current waterway simulation models, opportunities for waterway simulation models based on other freight transport research fields and the requirements for a new simulation model.

3.5.2.1 Shortcomings current waterway simulation models

Multiple freight waterway simulation models are used to provide an overview of national waterways or to determine the local information of a lock. All local, regional and national simulation models help identify the new waterway simulation model of the studied waterway network (as is also illustrated in Figure 3.1). To summarize all components that are discussed during these sections, Figure 3.7 shows the differences between certain simulation aspects.



	Amount of models	Amount of locks in model	Lock assignment variables	Time span	Level of detail
Macro	Differs per country	More than corridor only	Not applicable due to strategic overview	Year (even multiple years)	Average over all ship passages
Meso	>2	>2	5-10	Month/day	Ship categories
Micro	>25	1	>10	Day/hour	Every individual ship passage

Figure 3.7: Differences between macro, meso and micro waterway simulation models

Moreover, the following four main shortcomings (a-d) of existing waterway simulation models give cause for developing a new model:

a. ---------------CONFIDENTIAL INFORMATION---------------

b. ---------------CONFIDENTIAL INFORMATION---------------

[8] Capacity for inland waterway locks is assumed with certain vessel size.

c. ---------------CONFIDENTIAL INFORMATION---------------

d. The meso simulation model is only used once to model bi-directional ship passages: The existing simulation models are only used in a single direction or assume the same infrastructure network for the current and future situation. The new simulation model should be capable of modelling ship passages in both lock directions.

3.5.2.2 Opportunities for waterway simulation models

With the ability to investigate other freight transport related research fields, decision variables could have been defined. However no certain threshold value was examined. Only incentives of delays and large occupation rates give cause to increased capacity. Three other opportunities (e-g) for waterway transport are explained below:

e. Missing systems performance: Port operations are utilized for every area, but this is not the case for waterway transport. Every component in the waterway network is evaluated, but an overview is lacking. Apart from simulation models, systems performance is missing. Shippers plan their own route and reject others due to unplanned registration patterns at locks. Hence every shipper utilizes their own trip and neglects overall performance of the waterway network. Compared to port operations, advantages could be gained for improving waterway network performance. The new simulation model elaborates on lacking systems performance and identifies every ship passage, but does not adapt speed of ships (scenario 4 in CONFIDENTIAL IMAGE).

f. Waterway simulation models lag behind: As road and rail simulation models are able to dynamically interpret volume changes in the network, waterway simulation models are lagging behind. As a result, waterway transport might be at risk, since exact time of arrival cannot be prospected. This is especially important for the estimated time of arrival at nodes, but this might also increase the freight flows of waterway transport. (Macharis & Bontekoning, 2004) (Jong, et al., 2014). How this actually relates to future freight flows could be investigated in future research. In addition, the development of one new simulation model will not resolve the fact that waterway simulation models lag behind. More research is required.

g. Fixed and variable capacity modelling: For inland waterway transport, fixed and variable infrastructure are also an issue. Shuttle barges are used for large freight flows between OD pairs in the network, whereas on demand frequencies fluctuate over time. If fixed and variable capacity can be defined, more insight is provided into freight flows. Currently only terminal operators know what freight flows exist in the waterway network, although infrastructure operators are prohibited from maintaining the waterway network. This will not be included in the new simulation model as no data is available of fixed and variable capacity in the waterway network. Fixed and variable capacity could be a topic for future research.

To summarise, by defining the main shortcomings of waterway simulation models and opportunities of waterway simulation models, a foundation is developed for the simulation model that should be capable of illustrating the connection between IJmuiden and its hinterland connections over time (also illustrated in Figure 3.8). Fluctuations over time is most important, given the fact that rail and road simulation models are already able to simulate these fluctuations. Apart from other simulation models, it is necessary to predict arrival time of ships at their destination. Also, the simulation model should provide merely an overview and focus on the impact of ships and deadweight capacity per hour as captured as key performance indicators.

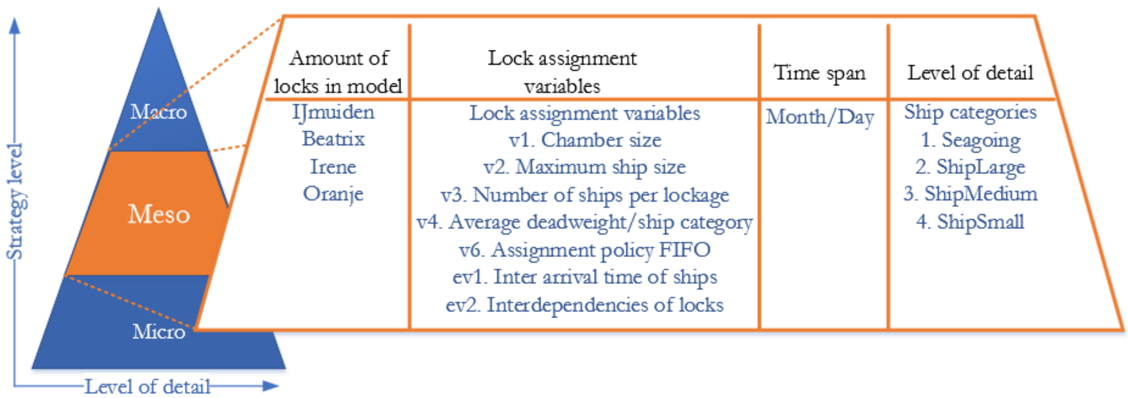


Figure 3.8: Requirements for a new simulation model based on existing simulation models

3.6 Outline of the new simulation model to measure impact in the studied waterway network

Section 3.1 to 3.5 are used to identify opportunities for lock simulation models. As a result of the gathered information, key performance indicators (KPI) are defined to evaluate the outcomes of the dynamic simulation model. Every KPI is created by a small recap of the theory and the shortcomings of existing simulation models. Based on the KPIs, the outline and input variables of the regional waterway simulation model are presented in this section.

3.6.1 Key Performance Indicators based on simulation models and theories

Based on the literature review, the exact threshold value needed to decide on additional capacity at infrastructure components is unknown. Rijkswaterstaat has decided to identify a threshold value based on an I/C ratio of 0.4., whereas the Ministry of I&E is expected to undertake further political steps at an I/C ratio of 0.6. Why these ratios differ is unknown. Only deadweight capacity is taken into account for I/C ratios, though actual occupation rates or filling degrees of chambers vary. For occupation rates and filling degrees, the amount of passages per hour might be an additional important indication. The amount of ship passages, as a function of time, is therefore an important indicator for the results of the simulation model.

KPI 1: Impact of the amount of ship arrivals per hour
KPI 2: Impact of the amount of deadweight capacity per hour

3.6.2 Waterway simulation model structure

Discrete event simulation is required to evaluate the KPIs. Since fluctuations occur over time, discrete event simulation is the right method to determine the impact of increased capacity at IJmuiden and Beatrix. Next to this, the research is conducted for the Ministry of I&E, whose policy makers aim for a real-time simulation model compared to a micro or macro simulation model. Moreover, this dynamic simulation model is necessary to visualize differences between BIVAS (the annual average simulation model) and the simulation model built for the studied waterway network.

Simio Simulation is used to simulate discrete events for determining the impact of additional lock capacity in the studied waterway network. In the past, Simio was used to simulate multiple transport and maritime purposes to support policy making. In addition, it involved many pre-defined objects which can be adapted by users. In this case Simio is appropriate, due to the fact that pre-defined objects and many scenarios can be developed to identify the impact with and without additional locks. In addition, Simio can visualize simulation models easily by importing Sketch-Up 3D models. As an entity travelling through the network, the following illustrates a ship travelling through the current and future network:

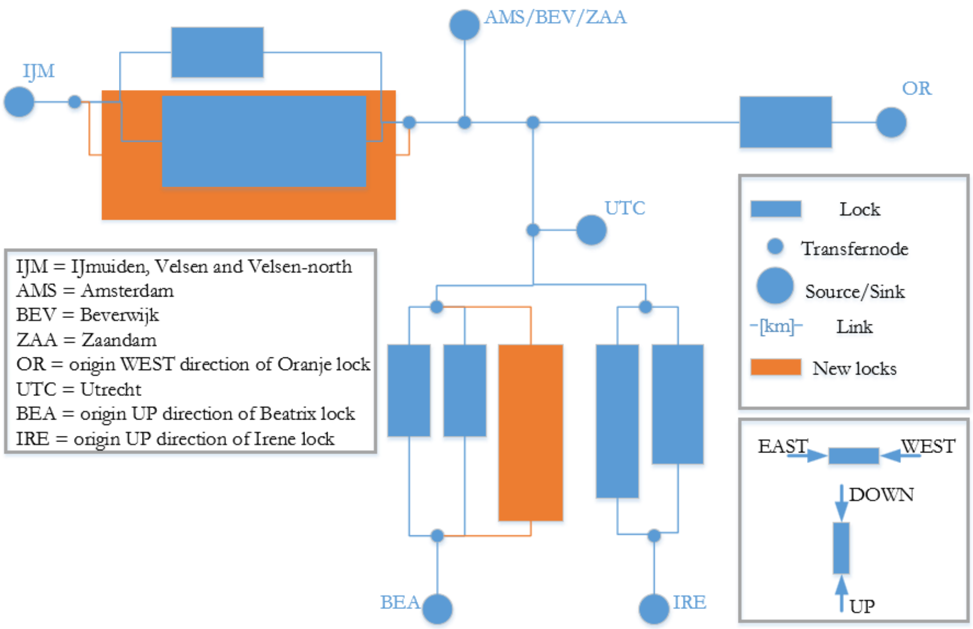


Figure 3.9: Studied waterway network with its nodes, links and components

In Simio Simulation, the same aspects are identified as in the studied waterway network (Figure 3.9). The aspect in the simulation model are nodes (origins/destination of ships), links (waterways), infrastructure components (locks) and entities (ships). From a node, an entity (ship) has to overcome a lock illustrated as a infrastructure component. An origin and destination node could be any node in the studied waterway network (Figure 3.9). When a ship passes the infrastructure component, it will continue its trip to its destination node or to a next infrastructure component (also illustrated in the flow chart of CONFIDENTIAL IMAGE). No stops in between are simulated due to the unknown stops of shippers, likewise shown in Figure 3.10.

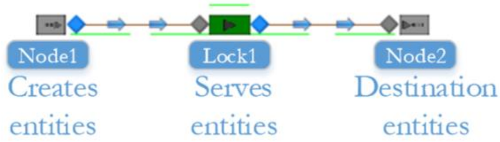


Figure 3.10: Node - Lock - Node representation in Simio Simulation

In Simio Simulation, locks are more complex to model. Many pre-identified objects are available in Simio Simulation, but bidirectional locks are not available. This means that this infrastructure component must be constructed from the beginning in Simio. As freight flows occur in both directions in waterways, locks should be capable of serving ships in both directions (bidirectional servers). Apart from that, the lock should be capable of serving either zero, one, two, or three[9] ships at once. This differs for each lock in the network, as capacity of the lock fluctuates over time. Even when a lock has no ships for lockage, it requires sufficient time to level the water to begin lockage from the other direction (respectively east-west or up-down).

After consulting Simio Simulation experts, it has been decided to adapt a vehicle into a lock. A vehicle is able to carry multiple ships (zero, one, two, three, etc.) at once. By assuming locks as vehicles, travel time of paths equals time to level out the water, as the water level functions as an elevator. Figure 3.11 and Figure 3.12 illustrate this phenomenon. As a result of being lifted as if in an elevator, the ships can be computed by arrival and departure time. In additional, fluctuations in lock capacity can be modelled. Aside from the benefits of functioning as an elevator, one disadvantage is acknowledged. In reality, ships are loaded and unloaded at the same transfer node in Figure 3.11. In Simio Simulation, this is not possible as the vehicle is (un)loading ships at the same time. This solution though has limited impact on service time, as is verified in chapter 4.

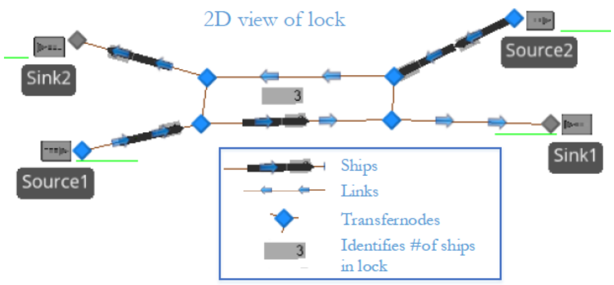


Figure 3.11: 2D view of lock in Simio Simulation

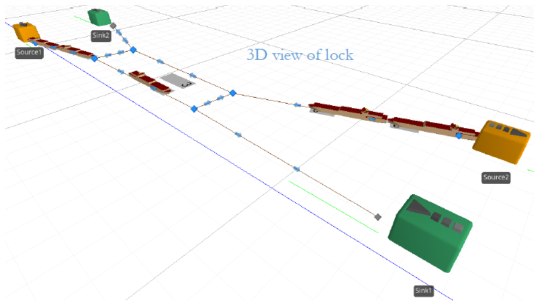


Figure 3.12: 3D view of lock in Simio Simulation

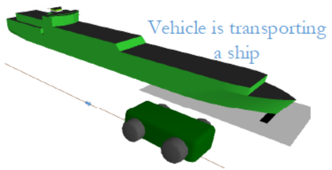


Figure 3.13: Representation of lock vehicle transporting a ship inside a lock

The representation of a lock in Simio Simulation is shown in Figure 3.11 and Figure 3.13. The vehicle, carrying a ship, is illustrated in Figure 3.13 as it follows the length of the lock with a certain velocity. The velocity is equal to the average time it takes to level out the water based on the annual average data of BIVAS. The distance the vehicle has to cover is equal to lock dimensions in the studied waterway network. Additional time will be added to (un)load the ships in the locks.

3.6.3 Assumptions and input variables of nodes, links and components in the new simulation model

For the assumptions and variables of the regional waterway simulation model, all components in Simio Simulation are elaborated on using the discussed theory in section 3.3. In that section, chamber assignment was established with the following equation:

$$Chamber\ Assignment = f(v1, v2, v3, v4, v6, ev1, ev2, ev3)$$

All variables v1 (chamber size), v2 (maximum ship size), v3 (average number of ships per lockage, v4 (deadweight capacity of ships), v6 (FIFO assignment), ev1 (inter arrival time) and ev2 (interdependencies of locks) are included in the regional waterway simulation model. Assumptions are divided into 4 categories as is done in Simio, respectively (1) node, (2) links, (3) lock and (4) ship entity, where variables regarding their implementation in the regional waterway simulation model are explained in more detail.

[9] A maximum of 3 ships per lockage (Nmax) were encountered through existing ship passages by extracting data of IVS 90.

3.6.3.1 Nodes in the waterway simulation model (origin/destination)

Freight flows differ for each origin node to destination node in the studied waterway network. As Amsterdam is a larger port with multiple terminals, e.g. compared to Utrecht.

Freight flows were specified based on ship data registration in IVS 90. IVS 90 ship passages are specified from yearly passages into monthly passages. These monthly passages are further specified to one week for simulation. The decisions and exact data of ship passages are shown in Figure 3.14 and in appendix K. In the end, it was chosen to completely specify data of ship passages from 1 April 2013 to 7 April 2013. In this research it was decided to simulate a peak day, due to the fact that ship arrival patterns over months and days[10] will remain approximately the same in the future[11] (Appendix L). During weekends the ship passages are relatively lower compared to weekdays. Even within weekdays deviations occur, since Tuesday, Wednesday and Thursday have relatively larger ship passages per day. As not all shippers are able to continue their trip during night time, it can be assumed that these patterns remain as they are in the future. This will be elaborated on later in this chapter.

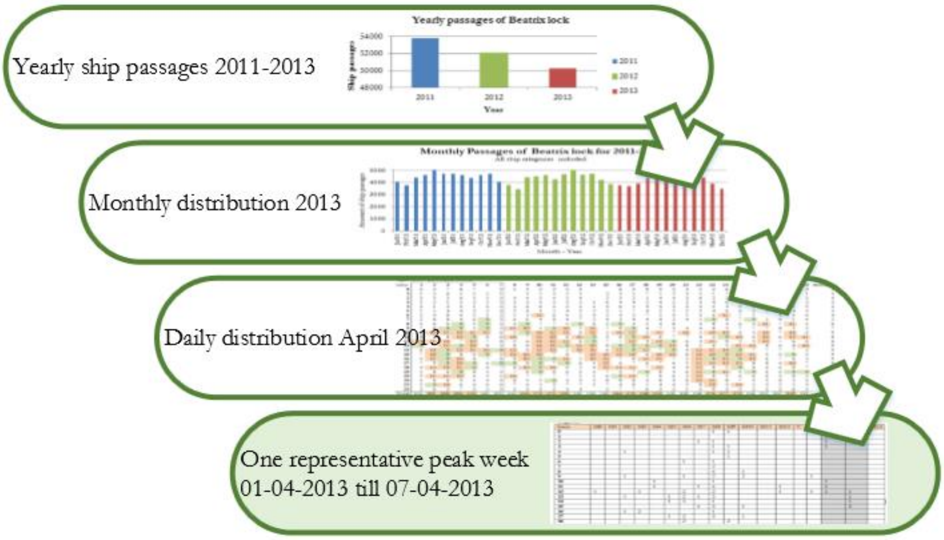


Figure 3.14: IVS 90 data specification

Specified freight flows in the studied waterway network result in ship departure patterns to and from each node in the studied waterway network. The OD patterns (as illustrated in CONFIDENTIAL IMAGE) are based on one week of ship passages in the studied network. One week is used to define OD patterns throughout the network as this will be representative for ship distribution. One week is also manageable in terms of the number of ships.

Table 3.1: OD matrix simulation model (based on extracted data of 01-04-2013 to 07-04-2013)

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Freight flows are further specified into ship departures, per node per hour in the studied waterway network. These ship departure tables, which examine departures of ships at each node, are adapted from IVS 90. Those departures are available for one peak day out of the week from 1 April 2013 to 7 April 2013. Table 3.2 displays the number of ship departures at all nodes in the studied network. It is assumed that all ships are correctly registered by lock keepers and passed an infrastructure component in the same hour as they were registered for lockage.

Table 3.2: Ship departure table of nodes in the studied waterway network (origins)

Time (hour)	Departure (events/hour)

[10] Fluctuations remain over the months, because of seasonal influences and fluctuations remain over days, because of week-weekend days

[11] Based on knowledge of J. Vierhouten and C. Willems – Rijkswaterstaat

Starting Offset	Ending Offset	Source IJM	Source AMSIJM[12]	Source AMS hinterland	Source OR	Source BEA	Source IRE	Source UTC
Day 1, 00:00:00	Day 1, 01:00:00		C					
Day 1, 01:00:00	Day 1, 02:00:00		O					
Day 1, 02:00:00	Day 1, 03:00:00		N					
Day 1, 03:00:00	Day 1, 04:00:00		F					
Day 1, 04:00:00	Day 1, 05:00:00		I					
Day 1, 05:00:00	Day 1, 06:00:00		D					
Day 1, 06:00:00	Day 1, 07:00:00		E					
Day 1, 07:00:00	Day 1, 08:00:00		N					
Day 1, 08:00:00	Day 1, 09:00:00		T					
Day 1, 09:00:00	Day 1, 10:00:00		I					
Day 1, 10:00:00	Day 1, 11:00:00		A					
Day 1, 11:00:00	Day 1, 12:00:00		L					
Day 1, 12:00:00	Day 1, 13:00:00							
Day 1, 13:00:00	Day 1, 14:00:00							
Day 1, 14:00:00	Day 1, 15:00:00							
Day 1, 15:00:00	Day 1, 16:00:00							
Day 1, 16:00:00	Day 1, 17:00:00							
Day 1, 17:00:00	Day 1, 18:00:00							
Day 1, 18:00:00	Day 1, 19:00:00							
Day 1, 19:00:00	Day 1, 20:00:00							
Day 1, 20:00:00	Day 1, 21:00:00							
Day 1, 21:00:00	Day 1, 22:00:00							
Day 1, 22:00:00	Day 1, 23:00:00							
Day 1, 23:00:00	Day 2, 00:00:00							
	Total							

Limited freight flows occur for small nodes in the studied waterway network. These small nodes are combined, as throughput is limited. Also, with a limited amount of nodes, simulation is simplified. Zaandam, Beverwijk and Amsterdam are combined, and IJmuiden, Velsen, Velsen-North and North Sea are assumed as one node. Utrecht is still an individual node, since relatively smaller ships visit the node compared to Zaandam, Beverwijk or Amsterdam.

Actual freight flows might be larger for departures from nodes in the studied waterway network, since IVS 90 is assumed to be valid. In fact, the actual passing times of ships are unknown; a ship is able to pass the infrastructure component one hour earlier or later compared to the data that was registered by lock keepers. This phenomenon is true for every passing ship, thus, an alternative peak scenario has been assumed, where one additional ship is created every hour and named IVS 90+1 (Table 3.3). For an alternative scenario the +1 is taken into account for every hour, independent to the number of ship arrivals per hour. This uniform approach is assumed because a stochastic approach involves too many uncertainties. To determine the stochastic number of ship passage for the next hour the following data is required:

- The average time it takes between ship data registration and actual lockage. This involves velocity and distance to the lock to determine the average time. Moreover the average time will not be sufficient enough as large standard deviations occur for ship arrivals as shown in CONFIDENTIAL IMAGE.
- The arrival pattern and inter arrival times cannot be assumed to be Poisson or normally distributed. Poisson is explored in micro simulation literature and a normal distribution requires more ship arrivals per hour.

Due to these uncertainties +1 is taken into account, since even with two ship arrivals per hour, one ship passage could be locked in the next hour.

Table 3.3: IVS 90+1 - New ship table (based on IVS 90)

Time (hour)		Departure (event/hour)						
Starting Offset	Ending Offset	Source IJM	Source AMSIJM	Source AMS hinterland	Source OR	Source BEA	Source IRE	Source UTC
Day 1, 00:00:00	Day 1, 01:00:00		C					
Day 1, 01:00:00	Day 1, 02:00:00		O					
Day 1, 02:00:00	Day 1, 03:00:00		N					

[12] Though they are related, AMS IJM and AMS hinterland are two different sources, due to the fact that both create another proportion of ship types through the network.

Day 1, 03:00:00	Day 1, 04:00:00		F					
Day 1, 04:00:00	Day 1, 05:00:00		I					
Day 1, 05:00:00	Day 1, 06:00:00		D					
Day 1, 06:00:00	Day 1, 07:00:00		E					
Day 1, 07:00:00	Day 1, 08:00:00		N					
Day 1, 08:00:00	Day 1, 09:00:00		T					
Day 1, 09:00:00	Day 1, 10:00:00		I					
Day 1, 10:00:00	Day 1, 11:00:00		A					
Day 1, 11:00:00	Day 1, 12:00:00		L					
Day 1, 12:00:00	Day 1, 13:00:00							
Day 1, 13:00:00	Day 1, 14:00:00							
Day 1, 14:00:00	Day 1, 15:00:00							
Day 1, 15:00:00	Day 1, 16:00:00							
Day 1, 16:00:00	Day 1, 17:00:00							
Day 1, 17:00:00	Day 1, 18:00:00							
Day 1, 18:00:00	Day 1, 19:00:00							
Day 1, 19:00:00	Day 1, 20:00:00							
Day 1, 20:00:00	Day 1, 21:00:00							
Day 1, 21:00:00	Day 1, 22:00:00							
Day 1, 22:00:00	Day 1, 23:00:00							
Day 1, 23:00:00	Day 2, 00:00:00							
	Total							

3.6.3.2 Links in the waterway simulation model (waterways)

Traffic flows in the studied network are controlled by the weight of links in order to decide how flows are transported throughout the network. It is assumed that flows are weighted by the amount of ship passages over a time span of a week (1 April 2013 to 7 April 2013). This means that routing is based on data that is provided out of IVS 90. Travelling costs and shortest paths are rejected, since it has been assumed that ships need to travel an OD pair in spite of link costs and distance. For example, ships still need to travel through Irene to go to Germany, despite its relatively larger distance. Therefore, routing has been assumed in rather simple terms, since shortest paths and costs of paths are not relevant for this research.

Table 3.4: Weights based on OD matrix (origin based weights)

	AMS/ZAA/BEV	IJM	OR	UTC	BEA	IRE	Total ship production
AMS/ZAA/BEV	Confidential						100%
IJM							100%
OR							100%
UTC							100%
BEA							100%
IRE							100%

Current traffic flows will differ from the future studied waterway network (with additional locks). As with the new lock at Beatrix, shippers are able to load up to 4 meters. Many shippers are already loaded for 4 meters when traveling thought the studied waterway network, though they travel now through the Irene lock. As a result of being rerouted, an additional travel time of 4.5 hours is assumed[13]. By constructing an additional lock at Beatrix, on average 440 ships will be rerouted through the waterway network per year (Roelse & Wortelboer, 2004). These ships are divided by the percentages of weekly volumes, which are presented in Figure 3.14. The exact freight flow shares through Beatrix and Irene are defined in chapter 4.

Next to traffic flow weights, lengths of links also differ, but they are equal for the current and future infrastructure. Lengths of links were calibrated on Google maps to approach travel distance from one node to the other. Figure 3.15 illustrates the length of links (in kilometres) in the studied network. The length of links are assumed to be constant, however, in reality, a small deviation in distances appear as waterways are not straight.

[13] 4.5 hours of delay is assumed with an average velocity of 12 km/h and its additional distance of 54 km.

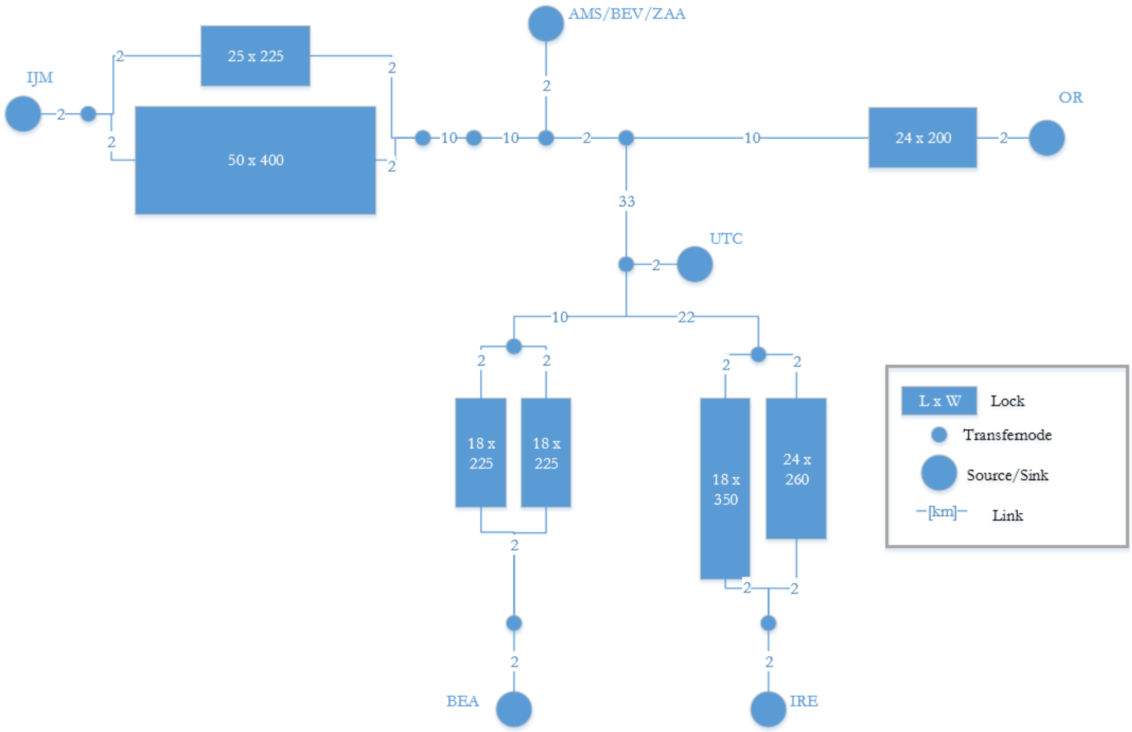


Figure 3.15: Current distances of links between all locks in the studied waterway network

3.6.3.3 Locks in the waterway simulation model

Locks diverge in chamber size (v1) and, thus, for the number of ships per lockage (v3) in the studied waterway network. Chamber size of each lock has already been illustrated in Figure 3.15. Every lock is adapted to its dimensions and additional locks will be adapted to their future chamber size. Moreover, the amount of ships per lockage (v3) will differ for the current and future infrastructure networks. The amount of ships during lockage is shown in Table 3.5.

Table 3.5: Nmax for the current and future waterway network

Lock	Current [# ships per lockage]	Future [# ships per lockage]
IJmuiden – Northern	1.16	2.01
IJmuiden – Mid	1.26	1.60
Beatrix	1.80	2.80

Various lock dimensions will result in divergent service times of locks, which are acquired from BIVAS (the national waterway simulation model). Service times are independent of the number of ships during lockage (v3) and therefore assumed to be constant. This is contributed to the fact that the water level must always be level and that takes time. As a matter of fact, service times will differ for an empty and fully loaded chamber. However, small deviations in time are not taken into account in this simulation model. Due to differences in lock dimensions and service times, vehicle speed to cover the distance will vary. An overview of all vehicle speeds is given in Table 3.6.

Table 3.6: Input data of locks for Simio Simulation

Lock	Lock dimension [m]	Service times in BIVAS [min][14]	Vehicle speed [m/s]
Beatrix lock	225	13	0.288
Irene lock	350	13	0.489
	260	13	0.333
Oranje lock	200	11	0.333
IJmuiden (Mid) lock	225	13	0.288
IJmuiden (Northern) lock	400	13	0.512
New Beatrix lock	270	11	0.409
New Northern lock	500	11	0.758

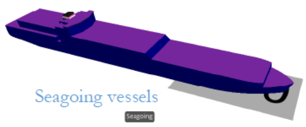
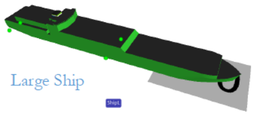
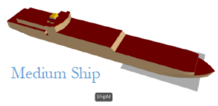
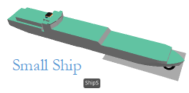
[14] Service times excluding additional waiting times and time to enter/depart after the water levels.

The last lock variable for the new simulation model is the lock assignment policy. In micro simulation models, FIFO assignment (v6) was discovered to be inappropriate. Despite of the fact that scientific papers prove that FIFO is not a proper lock scheduling problem, no other lock assignment policies have been considered suitable.

3.6.3.4 Ship entity in the waterway simulation model

In the beginning of this research, 4 main categories were considered: (i) inland waterway barges, (ii) seagoing vessels, (iii) non-freight carrying ships and (iv) recreational ships. During simulation, only inland waterway barges and seagoing vessels are taken into account; recreational and non-freight carrying ships take limited capacity from waterways. In most cases, non-freight carrying ships are tugs, which are used to steer larger ships inside locks. Due to their limited impact on capacity, they are rejected in the model. For seagoing vessels, one ship category was created, while for inland waterway barges, three subcategories were defined (Large, Medium and Small). Ship sizes for those four categories (Seagoing, Large, Medium and Small) differ in deadweight capacities (v4) of the categories. Every category might have differences in loading degrees. As mentioned, differences in loading degrees could have many reasons and are complex for IJmuiden (v5). Therefore velocities are assumed to be constant. All proportions of ship categories are illustrated in Table 3.7.

Table 3.7: Ship type categories and visual appearance of ship types

	Seagoing vessels (Seagoing)	Inland waterway barge Large (ShipL)	Inland waterway barge Medium (ShipM)	Inland waterway barge Small (ShipS)
				
Ship category	All types of seagoing	M10-M12, B (push barge)	M7-M9	M1-M6
Velocity [km/h]	12	12	12	12
Enter/ depart [min]	Enter: 6 Departure: 6	Enter: 5 Departure: 5	Enter: 4 Departure: 4	Enter: 3 Departure: 3

Entities depart from origin nodes in the simulation model. For every node, the type of ship can be merged, as Amsterdam is able to handle larger ships, e.g. seagoing vessels compared to Utrecht. Therefore ship entities that are created by nodes deviate in proportions (Table 3.8).

Table 3.8: Ship Type deviation for AMS hinterland and AMS-IJM/IJM-North Sea (based on IVS 90 data extraction)

	AMS hinterland		AMS IJM	
	Ship Type	Proportion [%]	Ship Type	Proportion [%]
1	Seagoing	Confidential	Seagoing	
2	ShipL		ShipL	
3	ShipM		ShipM	
4	ShipS		ShipS	

To summarise, the simulation model consists of four types of elements: nodes, links, locks and ship entities. All elements are based on real ship registration data (IVS 90) and assumptions are made where data is lacking. An alternative case was developed with different ship registration data (IVS 90+1), as the accurateness of IVS 90 is debatable. Apart from that, several impact variables are determined to be different for the current and future studied waterway network, e.g. without and with additional lock capacity. Firstly, the weight of links from additional locks will change, as rerouting will take place. Secondly, the average number of ships per lockage (Nmax) will increase by constructing additional (larger) locks. Thirdly, the entrance and departure time inside the locks will decrease depending on their ship category. Thus, IVS 90 and IVS 90+1 result in changes within, while impact variables result in changes between the current and future studied waterway network.

4 Analysis and results of the new waterway simulation model

The studied waterway network was simplified in a simulation model to analyse the impact of increased lock capacity. This section validates and verifies the simulation model. To determine the impact of increased lock capacity, a series of experiments were used to analyse the studied waterway network, i.e. (i)without and (ii)with additional locks.

4.1 Validation and verification of the new waterway simulation model

Verification and validation is an evaluation process to check if the model is appropriate for the simulation, which is discussed in this section.

4.1.1 Validation: "Is this the right model?"

Validation should determine whether the model meets the freight flows through the studied waterway network. Requirements will be compared to real data of passing ships. The data slightly differs, as the simulation model is programmed based on the FIFO (First In First Out) principle and only average service times are used. The number of ships passing the lock is exactly the same as the database IVS 90. Despite small deviations between the average number of ship passages, the results are accurate enough to use the simulation model for experiments.

Table 4.1: Validation of the number of ship passages in the studied waterway network and the new simulation model

Lock	Beatrix		IJmuiden	
IVS 90/simulation	IVS 90[15]	Simulation model[16]	IVS 90[27]	Simulation model
Day 1 ship passages	Confidential			
Day 2 ship passages				
Day 3 ship passages				
Day 4 ship passages				
Day 5 ship passages				
Day 6 ship passages				
Average				

4.1.2 Verification: "Is this model right?"

Verification should determine whether the model is acting as it should. Verification is done by evaluating the lock operation, as it is assumed to be a vehicle that follows a certain path. Lock operations are verified by a simple hand calculation to determine the minimal system time for ships. These hand calculations are compared in Simio by determining experiments with *n* runs. A run is a repetition of the same experiment. For this research *n* replications is chosen to be ten. Ten replications are appropriate for this simulation model as the time increase for a run is limited and an average of 10 runs is accurate as small deviations occur.

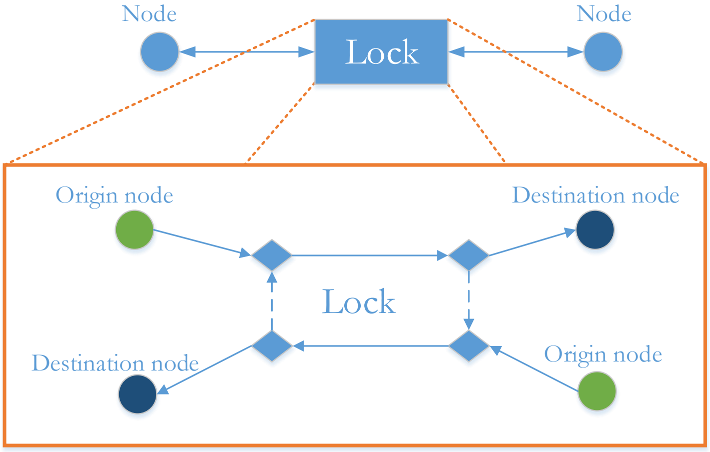


Figure 4.1: node-lock-node representation for verification lock operation

For verification of the lock operation a simple node-lock-node situation is assumed as is illustrated in Figure 4.1. In this situation minimal system time is calculated for ships. The minimal system time could be captured by a summation of passing time on links and passing time of locks.

$$Minimum\ system\ time = Time\ on\ link + Passing\ time\ lock$$

[15] The ship passages are elaborated in appendix K

[16] The number of ship passages for the simulation model shows less deviations compared to the number of ship passages in IVS 90 data. This is due to the fact that the simulation models is modelled with a smaller deviation in the number of ship passages to ensure it models a relative peak day.

Passing time of locks was defined in section 3.3 as operation time plus waiting time. As this verification requires minimal system time it assumes a waiting time at locks of zero minutes. By assuming a waiting time of zero, every entering ship is able to lock directly independent to maximum lock capacity. The hand calculation of minimal time in system is calculated by the following assumptions:

Table 4.2: Assumptions for hand calculations and simulation model to verify results

Time on links			Time in lock		
Origin node to lock	10	[meter]	Time to enter lock	4	[minutes]
Lock to destination node	10	[meter]	Time to level water in lock	7	[minutes]
Velocity ship	3.3333	[m/s]	Time to leave lock	4	[minutes]
Total time on links: 0.1 minutes			Total time in lock: 15 minutes		
Minimal time in system: 15.01 minutes					

Both, the hand calculations (Table 4.2) and Simio Simulation model (Figure 4.2) show approximately equal outcomes based on the minimal time in system. The minimum time in system in Simio Simulation is 0.2558 hours * 60 = **15.35 minutes**.

Replications		Responses	
Required	Completed	AverageTimeInSystem (Hours)	MinimumTimeInSystem (Hours)
10	10 of 10	0,325972	0,255762

Figure 4.2: Minimum time in systems conforming the Simio Simulation model

As the results of both calculations are approximately the same, the system is verified and ready for the experiments to determine the impact of additional locks in the studied waterway network.

4.2 Series of experiments on the studied waterway network and its simulation variables

As a result of successful verification and validation, the simulation model could be applied to a series of experiments to determine the impact of additional capacity at IJmuiden and Beatrix. For all experiments, 24 hours of ship departure patterns at nodes is taken into account with a number of ten runs.

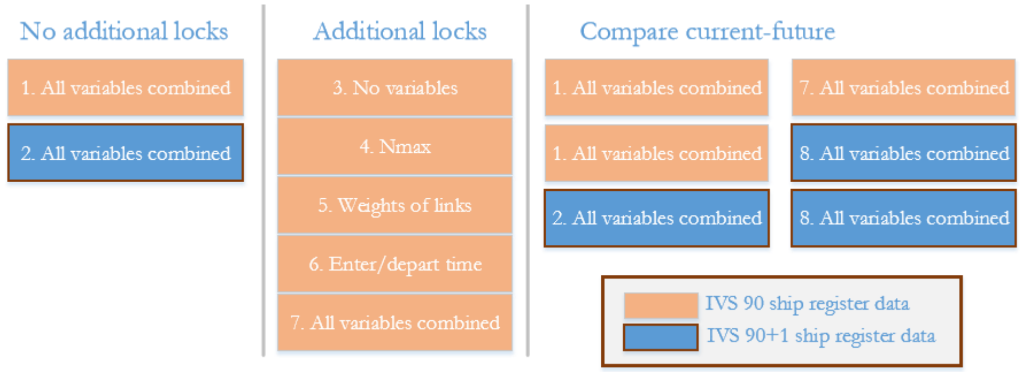


Figure 4.3: Series of experiments on the studied waterway network

A series of experiments was used to determine the impact of increased lock capacity in the studied waterway network and the method to measure the impact is illustrated in Figure 4.3. As the studied waterway network differs between the current (without additional locks) and future (with additional locks) situation, the experiments are also based on this difference in infrastructure network. The first set of experiments (current case) determines the ship arrival pattern for both Beatrix and IJmuiden without additional locks. Since the current case uses IVS 90 data, an alternative base case was developed (IVS 90+1[17]). Also, for this alternative case (IVS 90+1), the ship arrival patterns of Beatrix and IJmuiden were determined. For the future case, additional locks are constructed in the simulation model, which is the second set of experiments. In the future case, the impact variables (shown in Table 4.3) are tested in terms of ship arrival patterns. To do so, the impact variables are evaluated separately as well as a combination of all variables. The last set of experiments are used to determine the total impact of constructing additional locks in the studied network, as IVS 90 is valid or invalid (IVS 90+1). This results in three scenarios for ship arrival patterns at Beatrix and IJmuiden. The variables for the series of experiments of the current and future case are shown in Table 4.3

[17] IVS 90+1 indicates the ship data registration of IVS 90 per hour + 1 extra ship for each hour. Therefore it is named IVS 90+1

Table 4.3: Differences between current and future case for determination a series of experiments

Variables	Current case	Future case
(New) Lock infrastructure	No additional locks – IVS 90	Additional locks
Number of ships per lockage (Nmax)	1.16 (Northern); 1.26 (Mid); 1.80 (Beatrix)	2.01 (Northern); 1.60 (Mid); 2.80 (Beatrix)
Weights of links	OD matrix (56% to Beatrix; 44% to Irene)	OD matrix adapted to rerouting (62% to Beatrix; 38% to Irene)
Time to enter and leave lock	Seagoing: 12 minutes Ship Large: 10 minutes Ship Medium: 8 minutes Ship Small: 6 minutes	Seagoing: 10 minutes Ship Large: 8 minutes Ship Medium: 6 minutes Ship Small: 4 minutes
Ship departure at nodes	IVS 90 IVS 90+1	IVS 90 IVS 90+1

4.2.1 Current cases - experiments without additional locks to define the base case

The first two experiments are defined as the base cases, since the waterway network currently operates without additional locks. Below is a short description of each experiment. The second experiment consists of extra ship passages, as chapter 3 indicates the inconsistency in registration at locks.

Table 4.4: Current case experiments (1-2)

Experiments	Additional locks	Nmax	Weights of links	Enter/depart times	Ship departure
Experiment 1	NO	current	current	current	IVS 90
Experiment 2	NO	current	current	current	IVS 90+1

Experiment 1: Current case with no additional variables
This experiment is considered as a reference case during this series of experiments. No additional locks are operational in the waterway network and other variables are set to the current situation. This experiment is required so that other experiments and impact variables can be compared.

Experiment 2: Current case with alternative ship departures at nodes
The base case might or might not be valid, due to the complexity of registration at locks. IVS 90 +1 can therefore also be a conceivable scenario. By simulating the extreme peak scenarios, the locks in the studied waterway network are occupied with more ships.

Only experiment 1 is used to determine the impact of the separate impact variables Nmax, weights of links and entrance/departure times. Experiment 1 is chosen as base case, as it involves fewer assumptions than IVS 90+1. The actual ship arrival pattern is probably in between experiment 1 and experiment 2. Apart from that, if variables are able to decrease existing ship arrival peaks in experiment 1, they will probably decrease peaks for experiment 2.

4.2.2 Future cases - experiments with additional locks to define the impact of impact variables

The second series of experiments are defined as the future case, due to the fact that the waterway network operates with additional locks at IJmuiden and Beatrix. A description of each experiment is given below.

Table 4.5: Future case experiments (3-8)

Experiments	Additional locks	Nmax	Weights of links	Enter/depart time	Ship departure
Experiment 3	YES	current	current	current	IVS 90
Experiment 4	YES	future	current	current	IVS 90
Experiment 5	YES	current	future	current	IVS 90
Experiment 6	YES	current	current	future	IVS 90
Experiment 7	YES	future	future	future	IVS 90
Experiment 8	YES	future	future	future	IVS 90+1

Experiment 3: Future case with no additional variables
In the future case, the new locks are operational in the network. The northern lock is replaced by the new IJmuiden lock and an additional lock is constructed at Beatrix. For ship entities that are able to pass the Beatrix lock, one additional lock is available for passage, while the IJmuiden chamber size is adapted to the future waterway network. This experiment merely defines the impact of additional locks and no additional effects of constructing new locks are taken into account.

Experiment 4: Future case with additional number of ships during lockage
Since additional locks will be constructed in the waterway network, the amount of ships per lockage will increase. Given that both locks are larger compared to the base cases, the effects are only measured for ships passages; lock occupation rates are excluded from this analysis.

Experiment 5: Future case with alternative routes through the studied waterway network
Additional locks at Beatrix will especially result in alternative routes through the waterway network. As the allowed depth for ships increases in the future case from 3.5 to 4 meters.

Experiment 6: Future case with decreased (un)loading times of ships into locks
As a result of the increased widths of locks, ships are able to enter and depart the lock more smoothly. Under these circumstances, entrance and departure times will decrease for every ship category. Note that, by decreasing entrance and departure times, the overall service times of lockage are decreased.

Experiment 7: Future case with all additional variables set in the future situation and with current ship departure tables (IVS 90).

Experiment 8: Future case with all additional variables and with new rate tables
This experiment is modelled with all future variables (experiment 4-6) and with IVS 90 +1 (experiment 2). In addition to the future case, all variables together are influential to overall performance of the waterway network. Even with the possibility that IVS 90 +1 might be valid; the network with its additional locks should be capable of locking all created entities.

4.2.3 Comparison of current and future cases – experiments with and without additional locks

When additional locks are constructed in the studied waterway network, a combination of the impact variables is encountered. These variables cannot be implemented separately. Therefore, to compare current and future cases, a combination of all impact variables is taken into account for the future cases. For the current case, a base and alternative base case were already developed. All three scenarios depend on the current case and whether IVS 90 is valid or invalid. The results will probably be in between of experiment 1 and 2, since IVS 90 is valid for multiple hours, but not for all. Whether the number of hours from IVS 90 is valid is unknown due to non-consistent registration at locks.

- Scenario 1: experiment 1 (original case) is compared with experiment 7 (future case)
- Scenario 2: experiment 1 (original case) is compared with experiment 8 (future case with IVS 90+1)
- Scenario 3: experiment 2 (original case with IVS 90+1) is compared with experiment 8 (future case with IVS 90+1)

Table 4.6: Scenario 1-3 explanation of current and future cases regarding ship departure patterns at nodes

	Current case experiment	Future case experiment
Scenario 1	Experiment 1 (IVS 90)	Experiment 7 (IVS 90)
Scenario 2	Experiment 1 (IVS 90)	Experiment 8 (IVS 90+1)
Scenario 3	Experiment 2 (IVS 90+1)	Experiment 8 (IVS 90+1)

4.3 Output of the current and future case experiments on the studied waterway network

All experiments are modelled in the simulation model. The results will be presented for IJmuiden and Beatrix for both the current and future cases. Subsequently both current and future cases will be compared.

Divergent ship arrival patterns occur in both directions as Beatrix (up-down direction) and IJmuiden (east-west direction) are bi-directional locks. Arrival patterns deviate during the 24 hours of simulation. The aim is to minimize mutually divergent arrival patterns of both directions. Not only equal distributions are desired for directions, but the arrival patterns should also be equally distributed over a time span of 24 hour. By considering an equal distribution arrival pattern, the ability to wait for lockage is set to a minimum. This is with the given condition that equal distributed arrival patterns of ships are able to pass the infrastructure components within that hour. After all, larger ship passages occur during the day compared to night; equally distributed patterns are not entirely possible, though in the most optimal case, ship passages are equally distributed over a 24 hour period. All locks are used 24 hours a day, so every hour is available for ship passage.

The aim is to minimize fluctuations of ship arrival patterns <u>for the separate directions</u> and <u>the sum of the directions</u> of ship passages. By minimizing fluctuations, the waiting times are minimized for lockage and lock occupation rates are maximized. A minimization of waiting time for shippers is desired in terms of costs and large lock occupation rates are beneficial for energy saving. Especially empty lockage operations are undesired, thus meaning that lockage takes place without any ship inside of the lock, while on the other side ships are waiting. This phenomenon is elaborated in Appendix L with two illustrations.

A minimization of fluctuations is illustrated in Figure 4.4 and Figure 4.6. It has been assumed that Beatrix is able to lock 11 ships per hour for passage, while IJmuiden is able to lock 6 ships per hour. If only one direction is considered, the amount of ships is specified to 8 ships per hour for Beatrix and 5 ships per hour for IJmuiden (Table 4.7). The following rejects differences in ship categories. The maximum number of ship passages for both directions and single directions are created out of the IVS 90 analyses as described in Figure 3.14. This number will differ for the future situation, as the number of ships per lockage is increased; ship sizes are also expected to increase. Therefore the maximum allowance of ship passages remains the same for evaluation.

Table 4.7: Maximum number of ships per hour for the current and future case for locks in the studied waterway network (based on IVS 90 data)

	Beatrix		IJmuiden	
	One direction [# ship per hour]	Both directions [# ship per hour]	One direction [# ship per hour]	Both directions [# ship per hour]
Current (no additional locks)	8	11	5	6
Future (additional locks)	10	15	6	7

Minimizations of fluctuations in arrival patterns are clarified in Figure 4.4. This is compared to Figure 4.6, where an unequal distribution of ship arrivals for a time frame of 24 hours is illustrated for one direction of the IJmuiden locks. The limit of 5 ship passages per hour is shown by the red lines.

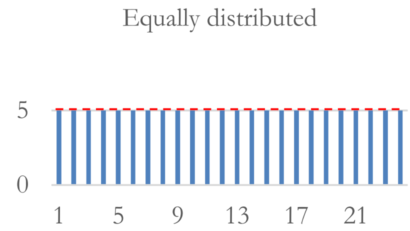


Figure 4.4: Desired arrival pattern as outcome of the simulation model

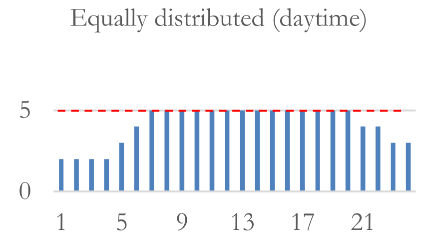


Figure 4.5: Desired arrival pattern as outcome of the simulation model, assuming there are more ship arrivals during daytime

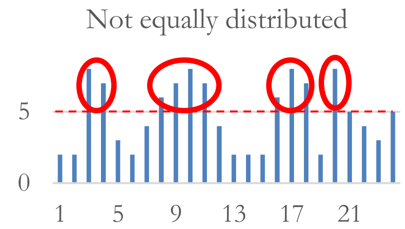


Figure 4.6: Undesired arrival pattern as outcome of the simulation model (in red peak arrivals)

Fluctuations of ship arrival patterns are not valid for one direction only, since both directions are influenced. In addition, both directions (the sum of the single directions) should also be within the threshold value of maximum ship arrivals as defined above for Beatrix and IJmuiden. This phenomenon is shown in Figure 4.7.

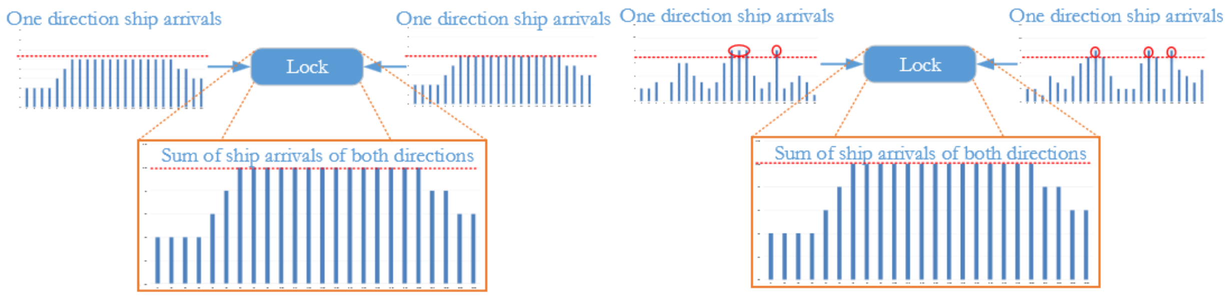


Figure 4.7: Ship arrival illustration of one direction and the sum of both directions

4.3.1 Output of current cases – Determine the base case for Beatrix and IJmuiden

For the current case, experiments 1 and 2 are analysed for both IJmuiden and Beatrix without additional locks in the waterway network. The base case is experiment 1 if IVS 90 is considered completely valid. Though, in reality, it appears that IVS 90 could also be IVS 90+1. To illustrate the differences between additional ship departures in the studied waterway network, these two experiments are compared. Initially, Beatrix is analysed for the up (north) and down (south) direction of ship passages. The blue arrival patterns represent the down direction, parallel to the green arrival patterns, which represent the up direction. Following that, the analysis is conducted for IJmuiden.

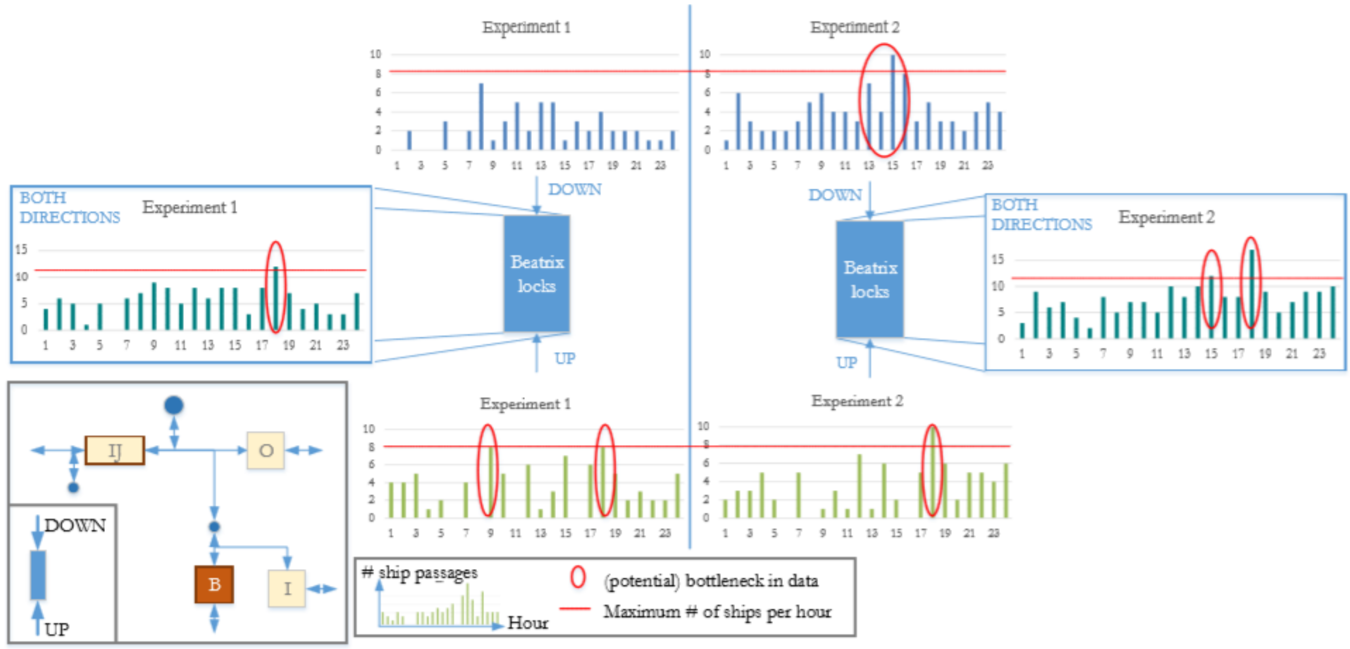


Figure 4.8: Beatrix lock with ship arrival patterns for both directions over a period of 24 hours (current case - experiments 1 and 2)

The following observations are made for the current case concerning Beatrix (Figure 4.8):

- Experiment 1: Both directions show significant peaks during daytime. Where the down direction shows many ship passages at the hour of 8, the up direction shows many ship passages at the hour of 9. The following indicates empty lockage in the other direction and back again. However, if both directions show sufficient (equal) ship passages over the hours 8 and 9, the occupation rate of lockage will be larger. This experiment is set as a base case and other experiments are compared to experiment 1.
- Experiment 2: IVS 90+1 is considered to increase existing peaks in arrival patterns; however, this phenomenon seems to have limited impact, which conforms to the simulation model. Existing peaks in experiment 1 hardly increase; though hours before and after a peak indicate more ship passages. The following is indicated for both directions. Apart from that, the peak ship passages are moved to the afternoon for the down direction. This means that throughout the studied waterway network more ships are clustered towards the Beatrix locks. The following is explained as multiple terminals indicate a larger number of ship departures at the time slot 9 till 12 hour. Before they reach the Beatrix lock, it illustrates the peak of the hours of 13-16 for the Beatrix down direction.

The same analysis is conducted for the IJmuiden lock, as an additional lock will be constructed in the future. Experiment 1 and 2 represents the current situation, i.e. without additional locks in the studied waterway network. For IJmuiden, the results are shown horizontally, as ship passages occur in the east (red) and west (purple) instead of up and down.

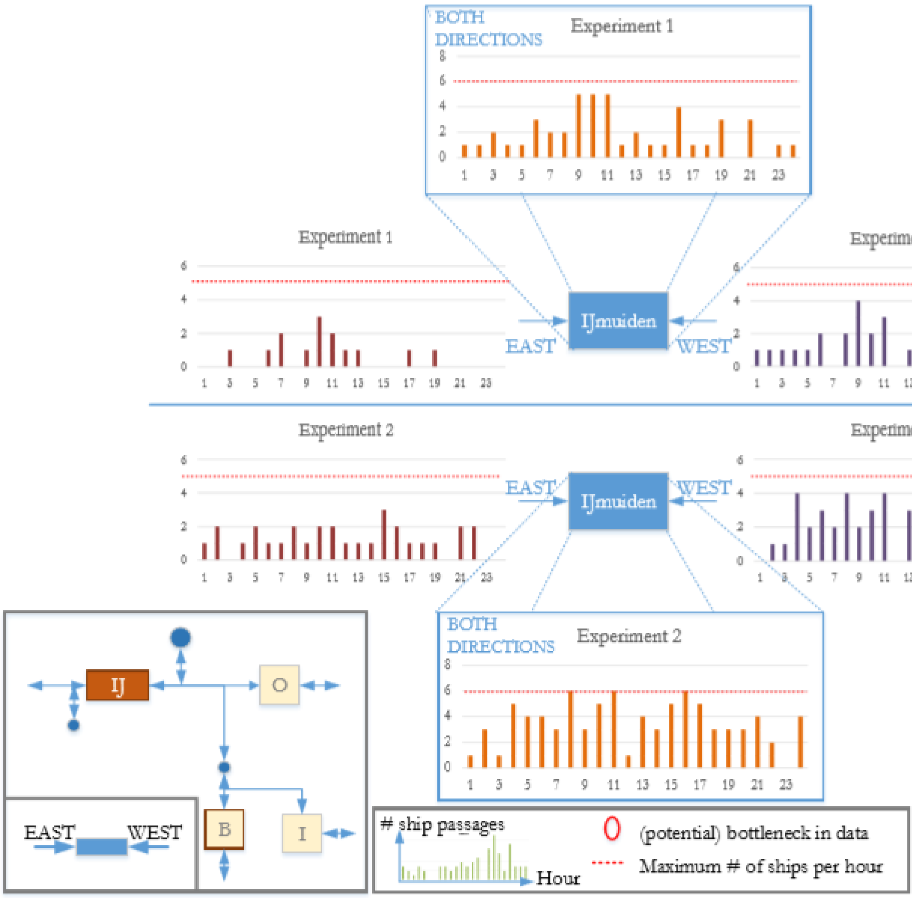


Figure 4.9: The IJmuiden lock with ship arrival patterns for both directions over a period of 24 hours (current case - experiments 1 and 2)

The following observations are presented for the current case concerning IJmuiden (Figure 4.9):

- Experiment 1 is set as the original situation and is used to compare other experiments in the future case. The east direction shows a limited amount of ship passages, compared to the west direction. This occurs also in the real data. For the west direction, the daytime ship arrivals are also larger compared to night time.
- Experiment 2 illustrates IVS 90+1 with more ship arrivals in a time frame of 24 hours. The arrival patterns do not examine additional peaks, but rather a more distributed arrival pattern. The reason for this is that ship arrivals are more equally distributed with additional ship passages, as each hour has one additional ship. Therefore, the impact of IVS 90+1 is evaluated positively to equal distributed ship arrival patterns.

After observing both directions of IJmuiden, the limited number of ship passages for the east direction is difficult to evaluate. As the number of ship passages is still limited, the future analysis for IJmuiden is only considered with regard to the west direction and for the sum of both directions.

4.3.2 Output of future cases – Determine the impact of variables on Beatrix and IJmuiden

The base and impact variables in the future cases for IJmuiden and Beatrix are compared; experiment 1 is compared to experiment 3 to 7. First, the sum of both directions is analysed followed by the down and up directions separately. Both down and up direction are taken into account, due to the fact that distribution patterns contribute to the total arrival pattern at Beatrix. This is different for the IJmuiden lock, as the east direction shows limited ship passages.

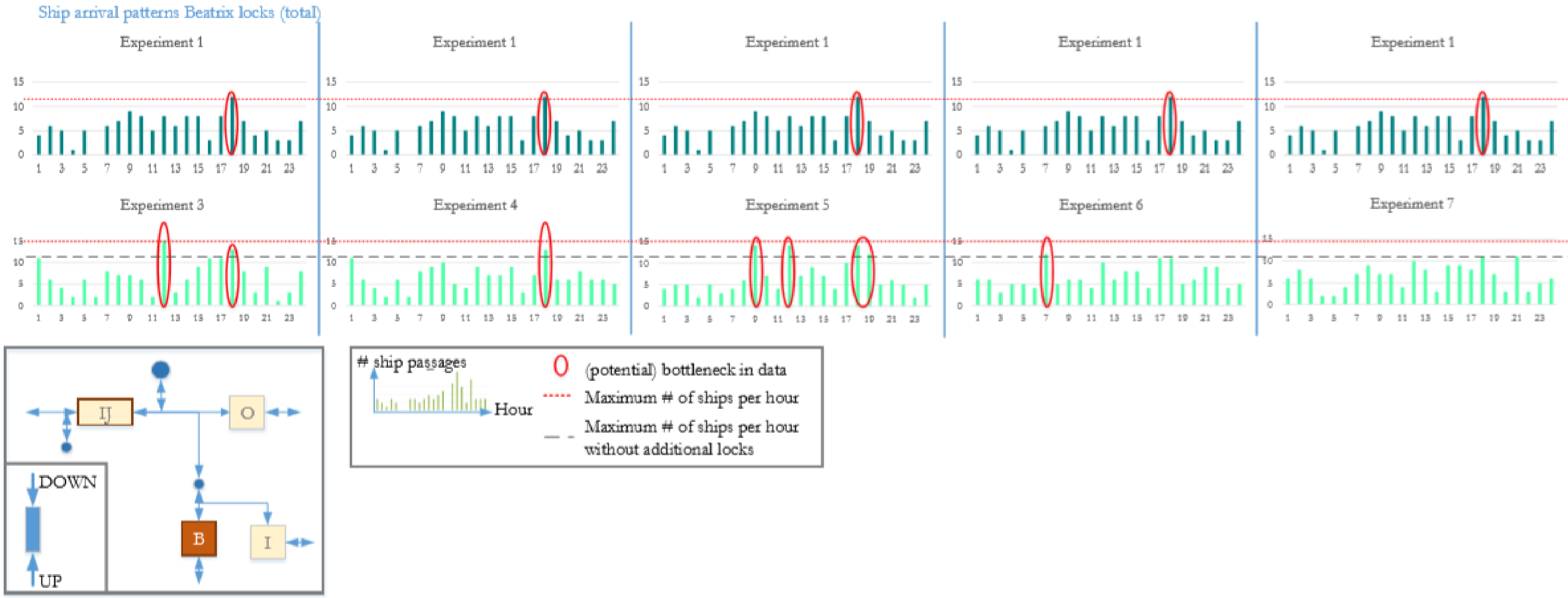


Figure 4.10: Beatrix lock (up and down directions) with ship arrival patterns for current and future cases over a period of 24 hours

Remarks for Figure 4.10:

- Experiment 1 and 3: New infrastructure causes differences in arrival patterns and an additional peak at hour 12. The peak at hour 18 remains the same.
- Experiment 1 and 4: The future case is less equally distributed compared to the base case.
- Experiment 1 and 5: Rerouting results in a more distributed ship arrival pattern and larger ship arrival peaks.
- Experiment 1 and 6: Decreased lock entrance/departure times shows a peak in the early morning, while the peak in the late afternoon does not exceed the maximum number of ship arrivals anymore.
- Experiment 1 and 7: All variables combined result in a more equal distribution pattern for ship arrivals. Apart from that, ship arrivals do not exceed the red line limit.

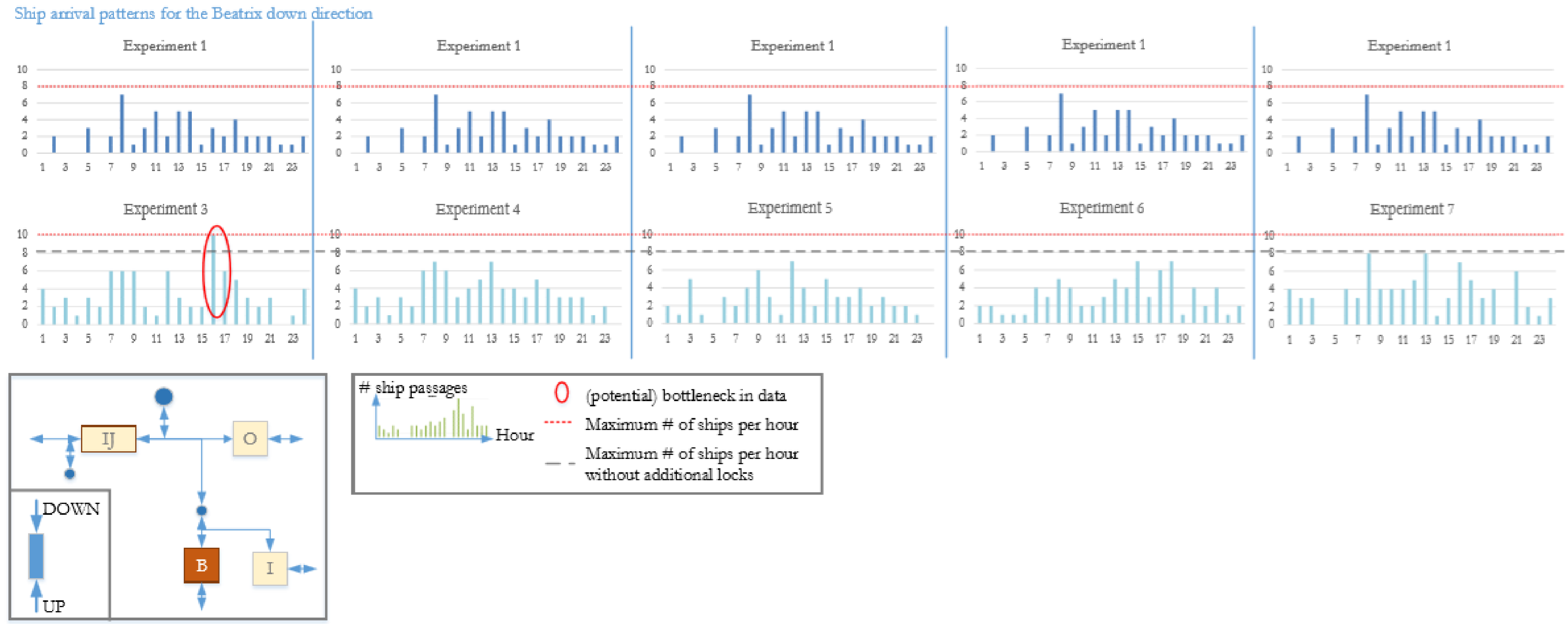


Figure 4.11: Beatrix lock (down direction) with ship arrival patterns for current and future cases over a period of 24 hours

Remarks for Figure 4.11:

- Experiment 1 and 3: Experiment 1 shows one large peak (hour 6), while experiment 3 shows a larger peak at hour 16.
- Experiment 1 and 4: The future case displays more ship passages compared to the current case, but the future case never exceeds the limit of ship passages per hour.
- Experiment 1 and 5: Both ship arrival patterns are completely different.
- Experiment 1 and 6: In the future case, peaks become slightly smaller in the early morning compared to the current case. Also, arrival patterns tend to increase in the (late) afternoon.
- Experiment 1 and 7: All variables combined result in larger peaks, but they do not exceed the threshold value. The ship arrival patterns in the future situation become less equally distributed.

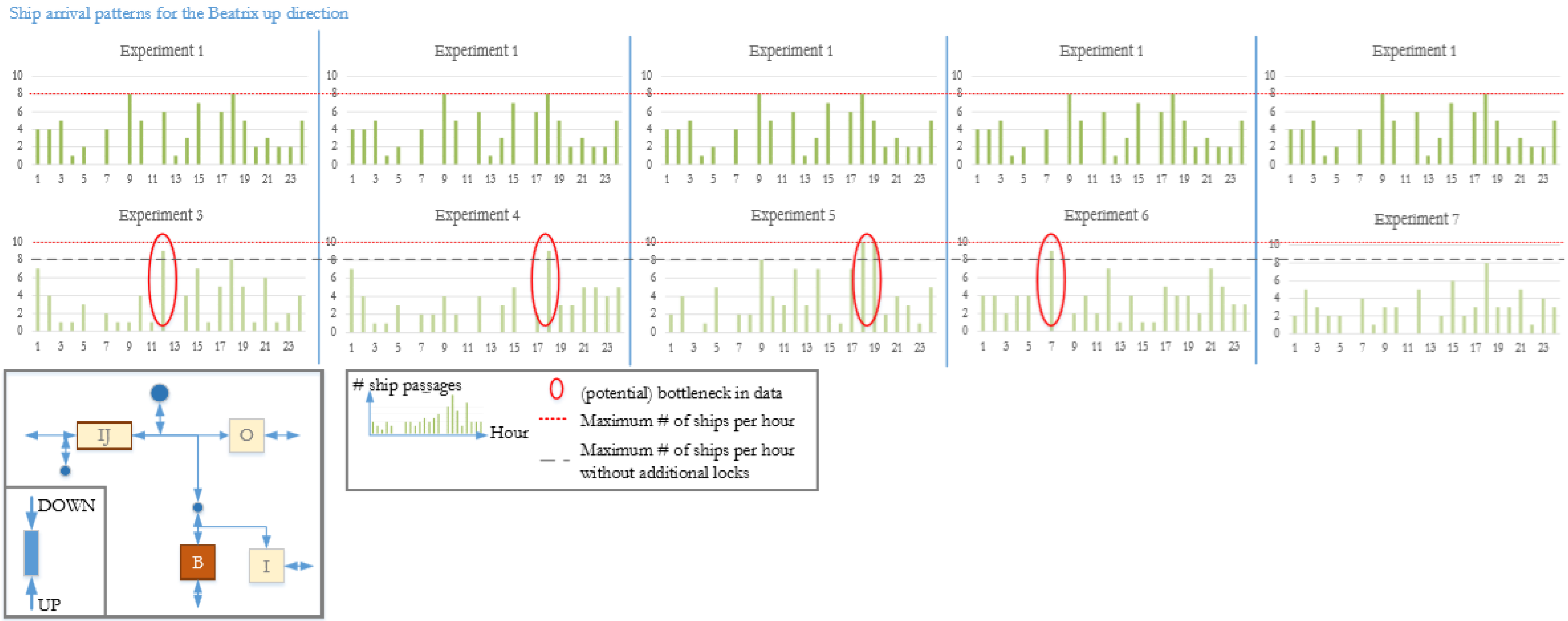


Figure 4.12: Beatrix lock (up direction) with ship arrival patterns for current and future cases over a period of 24 hours

Remarks for Figure 4.12:

- Experiment 1 and 3: The future case seems less equally distributed and in one hour the ship passages exceed the limit of 8 ship passages.
- Experiment 1 and 4: The future case again exceeds the limit of 8 ship passages.
- Experiment 1 and 5: Rerouting results in a less equal distribution pattern in the future case, where ship passages exceed the limit at hour 18 and 19.
- Experiment 1 and 6: Both experiments have different outcomes and peaks. The current case shows highly fluctuations in ship arrivals, while those are decreased in the future case. Although, in the future case, one peak is examined in the morning (hour 7).
- Experiment 1 and 7: All variables combined result in less ship arrivals, which solve most peaks (except at hour 18).

Total ship arrival patterns for IJmuiden
The differences between the future and current cases are also examined for IJmuiden. First, the total ship passages are evaluated followed the west direction of ship arrivals. The west direction is chosen since the number of ship passages is larger; the east direction has limited ship passages and hardly any peaks. This makes it difficult to measure the impact.

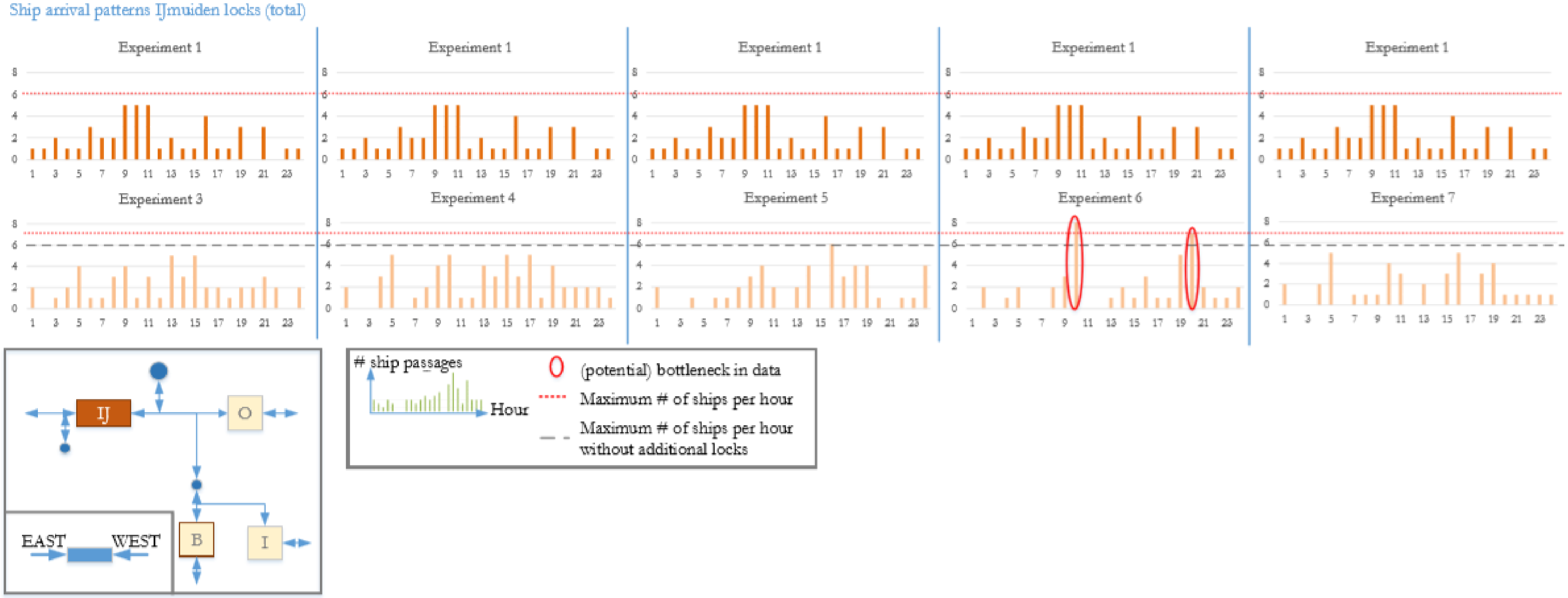


Figure 4.13: IJmuiden lock (east and west direction) with ship arrival patterns for current and future cases over a period of 24 hours

Remarks for Figure 4.13:

- Experiment 1 and 3: With new infrastructure, the peaks are postponed to the afternoon (from hour 9-11 to 13-15).
- Experiment 1 and 4: In the future case, peaks are larger and take longer. Ship arrivals are also greater, but peaks do not exceed the limit of 6 ship arrivals.
- Experiment 1 and 5: Rerouting appears to have large deviations in ship arrivals.
- Experiment 1 and 6: The peak for the future case is at hour 10 and 20. It is unknown why those peaks occur with decreased arrival and departure times.
- Experiment 1 and 7: All variables combined result in less ship arrivals and existing peaks remain in the ship arrival pattern.

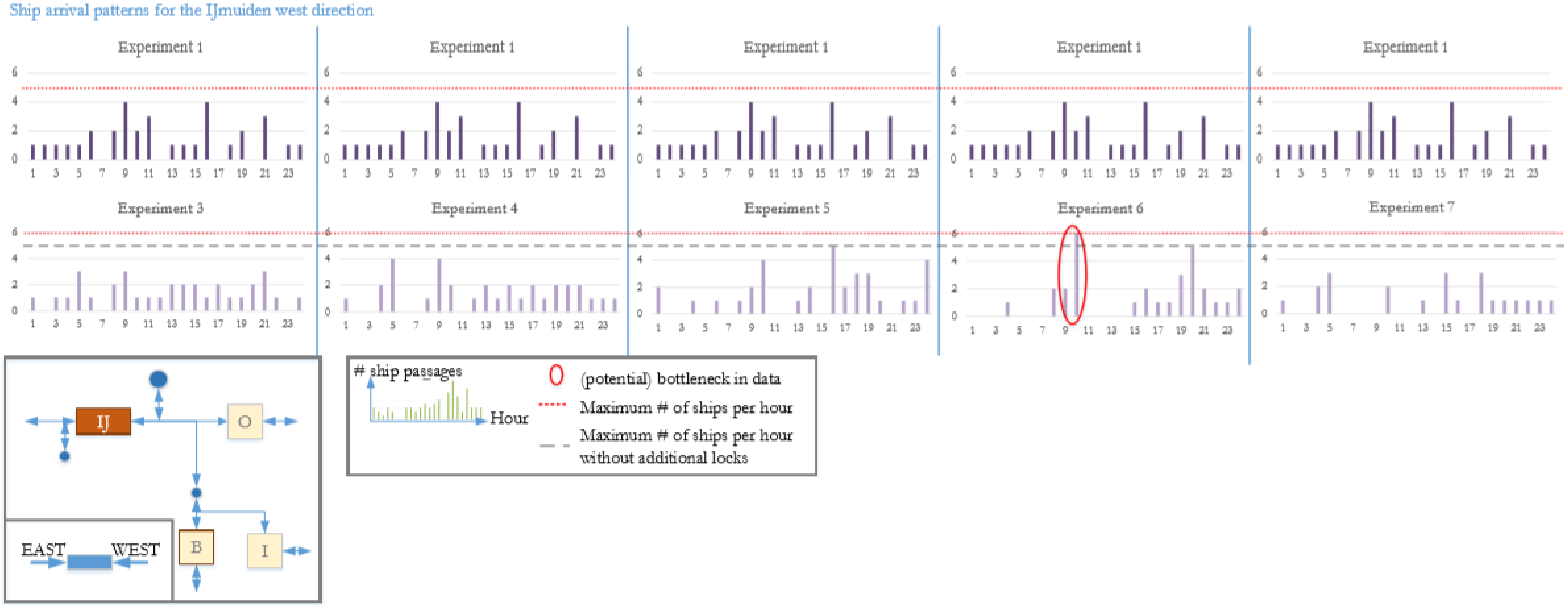


Figure 4.14: IJmuiden lock (west direction) with ship arrival patterns for current and future cases over a period of 24 hours

Remarks for Figure 4.14:

- Experiment 1 and 3: The future case with an additional lock at IJmuiden; the arrival pattern of ships is more equally distributed. An additional lock creates a positive effect for decreasing existing peaks and the ship arrivals are more equally distributed over a period of 24 hours.
- Experiment 1 and 4: Ship passages do not exceed the limit of 5 ship passages per hour. The peaks for the future case are remarkable in the early morning. Both arrival patterns show similarities.
- Experiment 1 and 5: For the current and future cases, peaks remain and it becomes even larger at hour 16. Many 'zero' ship arrivals occur in experiment 6.
- Experiment 1 and 6: Again the future case determines a larger peak compared to the current case. The ship arrivals in the future case are clustered.
- Experiment 1 and 7: All variables combined appears to result in less ship arrivals. Less ship arrivals could be caused by the new larger lock with its increased passing time as more ships are able to enter the lock at once. Besides that, the larger lock is able to lock larger seagoing vessels. Larger seagoing vessels are able to carry more freight at once and therefore less freight vessels are required. At last, in the simulation model the new depth of the lock is taken into account, as ships do not have to transfer part of their freight into smaller barges.

To summarise the observations of Beatrix and IJmuiden, the following table illustrates the differences in equal ship arrival distribution patterns *(named as Equal in Table 4.8)* and peaks in ship arrival patterns *(named as Peak in Table 4.8)* for all impact variables. The variables are evaluated separately based on the current case (experiment 1) and future case (experiment 3-7) analyses. Table 4.8 shows the results by making use of +, +/-, - and 0. For each indicator a value is determined for equally distributed ship arrival patterns and peak arrivals. The equal distributed pattern uses averages and standard deviations to determine plus, plus-minus, minus and zero. Peak arrivals uses the number of peaks in ship arrival patterns to determine the impact. The indicators are further explained in Appendix M.

- A plus (+) indicates a positively effect for ship arrival (peak) patterns and/or equal distributions.
- A plus-minus (+/-) indicates a moderately positive effect for ship arrival (peak) patterns and/or equal distributions. Moderately positive indicates some improvements and some deteriorations for certain hours, whil it does not exceed the maximum number of ship arrivals per hour.
- A minus (-) indicates a negative effect for ship arrival (peak) patterns and/or less equal distributions.
- A zero (0) indicates almost no effect for ship arrival (peak) patterns and/or equal distributions.

Table 4.8: Overview of impact variables for ship arrival patterns (equal distributions and peaks) of Beatrix and IJmuiden lock

		New locks (exp. 3)		Nmax (exp. 4)		Weights of links (exp. 5)		Enter/depart time (exp. 6)		Combined variables (exp. 7)	
		Equal	Peak	Equal	Peak	Equal	Peak	Equal	Peak	Equal	Peak
Current case (exp. 1)	Beatrix total	+/-	-	+/-	-	+/-	-	+	0	+/-	+
	Beatrix down	+/-	-	+	+/-	+	+/-	+/-	+/-	+/-	+/-
	Beatrix up	-	-	+/-	-	+/-	-	+/-	-	+/-	+/-
	IJmuiden total	+	+/-	+/-	+/-	-	+/-	-	-	-	+
	IJmuiden west	+	+	+	+/-	+/-	+/-	-	-	+/-	+

- Experiment 3 (no additional impact variables): Beatrix appears to have (moderately) positive effects on equal distribution of ship arrival patterns (with the exception of Beatrix up) and negative effects on peak ship arrival pattern, while the placement of an additional lock seems to be almost sufficient for IJmuiden.
- Experiment 4 (Nmax): Nmax does not necessarily have positive distributed effects, only on the patterns of Beatrix down and IJmuiden west. It even indicates a negative influence of ship arrival patterns with more peaks for Beatrix up and Beatrix total. This is the case as the number of ship arrivals at hour 17/18 still exceed the maximum number of ship arrivals per hour even though an additional lock is constructed.
- Experiment 5 (weights of links): weights of links can be considered as an impact variable for Beatrix. Especially Beatrix shows divergent ship arrival patterns for both directions. This impact variable is very important for Beatrix to observe as the equal distributed ship arrival pattern shows positive impact, while peak arrivals shows negative impact. Thus the number of ship arrivals increase due to a large lock such that shippers are able to pass with large draughts. This results in larger standard deviations and averages as the new rerouted ships tend to arrive at peak hours or even cause new peaks. For IJmuiden, the impact is measured as moderately positive or negative for IJmuiden total in terms of equal ship arrival patterns.
- Experiment 6 (decrease in entrance/departure times): entrance and departure times have diverse effects. For Beatrix, the ship arrival patterns become (moderately) positive for equal distribution of ship arrival patterns, while the impact is less positive for peak arrivals. In general the average lock time will decrease with decreased entrance/departure times of ships in/out of locks. For IJmuiden, the effect on equal ship distribution and peaks is rather negative. Why this is the case is unknown, micro simulation is required to elaborate on this phenomenon.
- Experiment 7 (all variables combined): all variables combined will not directly result in positive changes in arrival patterns of ships at locks. Overall, the effects of the combined variables compared to experiment 1 become moderately positive or positive in terms of distribution and peaks in ship arrival patterns, with the exception of negative impact of equal distribution ship arrivals for IJmuiden total.

Table 4.9: Overview of impact variables for ship arrival patterns of Beatrix and IJmuiden lock with correlations

		New locks (exp. 3)		Nmax (exp. 4)		Weights of links (exp. 5)		Enter/depart time (exp. 6)		Combined variables (exp. 7)	
		Equal	Peak	Equal	Peak	Equal	Peak	Equal	Peak	Equal	Peak
Current case (exp. 1)	Beatrix total	+/-	-	+/-	-	+/-	-	+	0	+/-	+
	Beatrix down	+/-	-	+	+/-	+	+/-	+/-	+/-	+/-	+/-
	Beatrix up	-	-	+/-	-	+/-	-	+/-	-	+/-	+/-
	IJmuiden total	+	+/-	+/-	+/-	-	+/-	-	-	-	+
	IJmuiden west	+	+	+	+/-	+/-	+/-	-	-	+/-	+

All separate variables (experiment 4 till 6) cannot be evaluated separately as the impact of all variables combined is completely different. The following is shown in Table 4.9 in orange. For all separate variables the peaks in ship arrival patterns were evaluated negative or moderately positive, but all variables combined results in (moderately) positive impact for peaks in ship arrival patterns. Thus meaning that number of existing peaks is declined and/or existing peaks do not exceed the maximum number of ship arrivals. Next to the orange squares, also a grey square is shown. The grey square shows that rerouting results in more ship arrivals at Beatrix. More ship arrivals are in this case negative or moderately positive for equal ship distribution patterns (with the exception of Beatrix down) and peak arrivals. Rerouting attracts more ship arrivals and it also attracts more ships at peak moments. This can be explained by managing the number of ships in the studied waterway network as shown in Figure 4.15. It appears that approximately 60% of the number of ships are in the system during daytime (from hour 9 till 17). So for example if 10 ships would reroute due to an additional lock at Beatrix, 6 out of the 10 ships will reroute during daytime. This results in almost every hour, one additional ship. Even within this time frame of 8 hours during daytime, shippers' preference is noticeable. For shippers upstream/downstream benefits occur, such that shippers are able to save on fuel costs. Those benefits are that large that ships are clustered in the network.

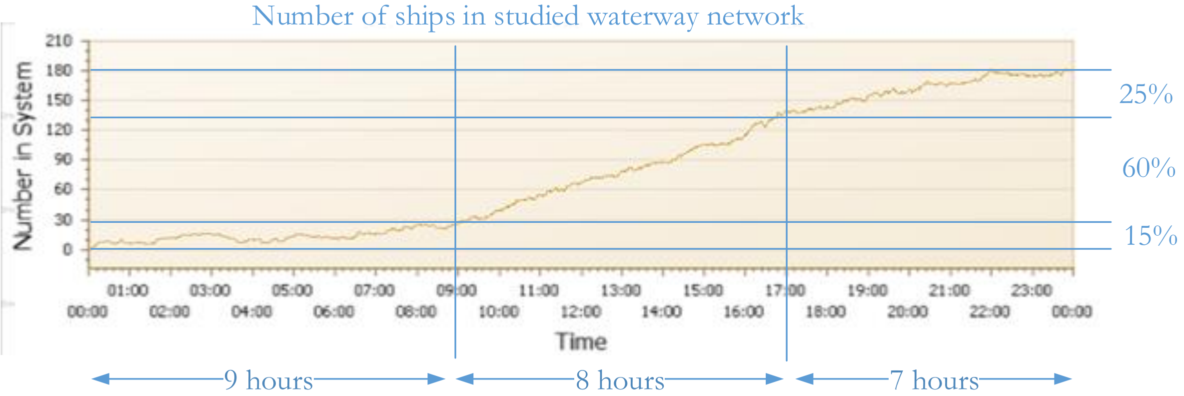


Figure 4.15: Number of ships in the studied waterway network conforming the simulation model

Apart from measuring the impact of all separate variables, more remarkable observations are shown in Table 4.9. In green, decreased enter and departure times of ships in or out of the IJmuiden locks appears to have negative impact on peak arrivals and for equal distribution patterns. The negative peaks and non-equal distribution patterns might be solved using traffic management. Therefore, the effects might not be as negative as the simulation illustrates. The same applies for the purple square.

In short, in the future case, traffic management at IJmuiden is possibly able to solve determined peaks and non-equally ship arrival patterns in the simulation model. Though for Beatrix this is not the case, as peaks remain and vary between different time frames. Beatrix will remain or become again a (potential) bottleneck despite a third chamber. A third chamber is able to facilitate lockage for a larger amount of ship passages per hour, but when additional ship arrivals occur during the determined peaks, this might result in queues. The reason that peaks remain is based on upstream and downstream traffic flow through the waterway network. For shippers, upstream and downstream is very important, as a substantial amount of fuel can be saved. The amount is unknown and not part of this research. It is important to acknowledge the ability of shippers to plan their route on water flow (upstream/downstream) benefits. These deviations occur again due to IVS 90+1. Apart from that, impact variables cannot be observed separately, as the combined variables have different impact on equal distributed ship arrival patterns and peak arrivals.

4.3.3 Compare output current and future - Impact of increased lock capacity on the studied network

As the results of individual impact variables in the future case are unpredictable, the following experiments are compared in a more detailed analysis. This is done to determine the impact of increased lock capacity in the studied waterway network with and without additional ship departures for the current and future situation. Only the combination of variables is taken into account, since the impact variables will be implemented as combined impact variables and will not be implemented separately.

For both Beatrix and IJmuiden, all three scenarios are determined.

- Scenario 1: experiment 1 (original case) is compared with experiment 7 (future case)
- Scenario 2: experiment 1 (original case) is compared with experiment 8 (future case with IVS 90+1)
- Scenario 3: experiment 2 (original case with IVS 90+1) is compared with experiment 8 (future case with IVS 90+1)

The results are illustrated in ship arrival patterns in Figure 4.16 and Figure 4.17.

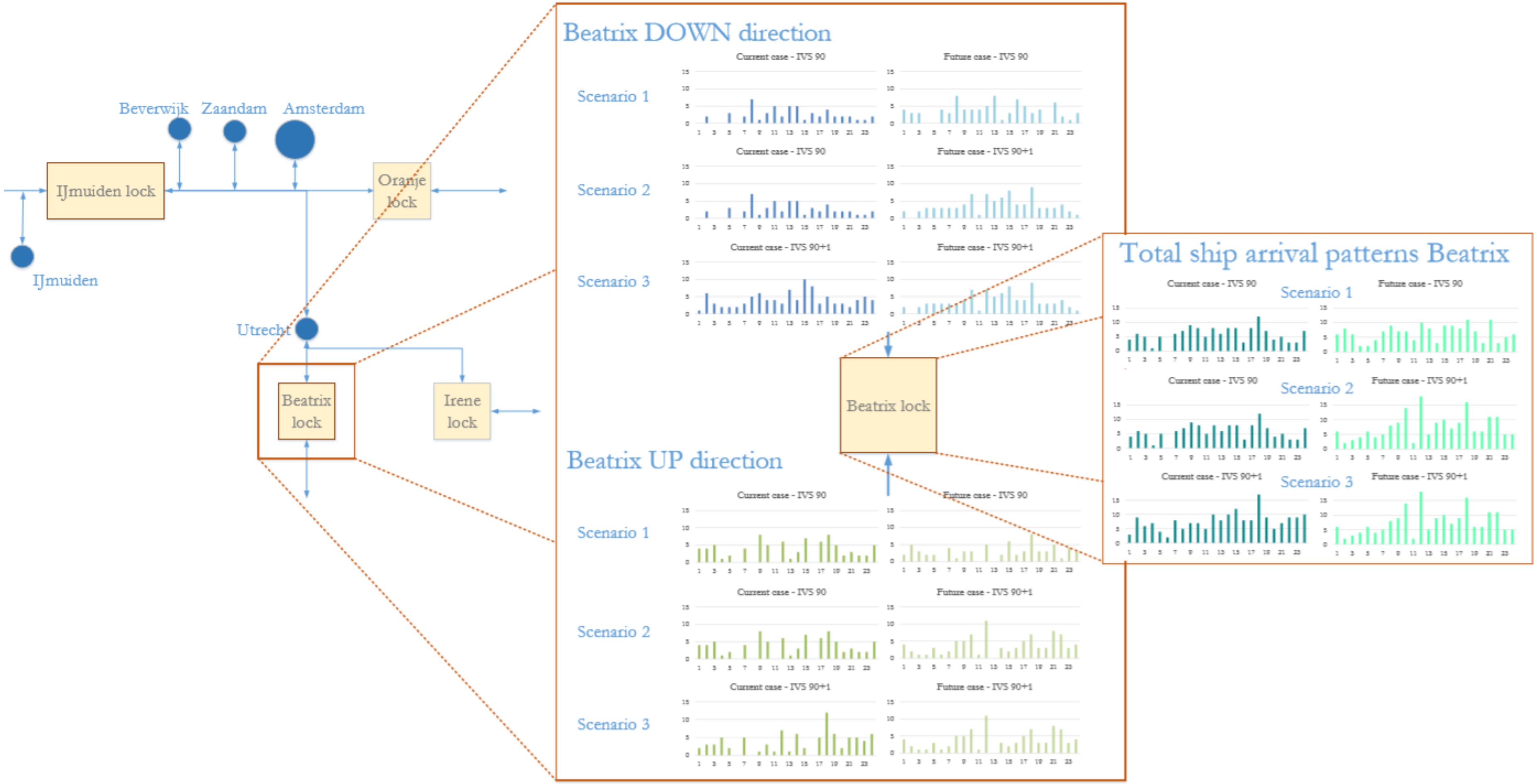


Figure 4.16: Various current and future scenarios to evaluate impact on Beatrix in the studied waterway network

Both scenario 2 and 3 might result in a (potential) bottleneck even with an additional third chamber. Current and future ship arrival patterns and peak arrivals are completely different and therefore difficult to compare and prospect. Scenario 1 for the future case is evaluated positively, as ship arrival patterns are more distributed and show less peak arrivals, while scenario 2 and 3, for some hours, can be evaluated positively and/or negatively as ship arrival patterns are less/more distributed and show less/more peak arrivals. When ship passages increase as future freight flows determine, the arrival patterns might be completely different. In this simulation model, only one type of alternative freight flow pattern is evaluated and it has significant influence in ship arrival patterns. This is especially since the alternative freight flow pattern is assumed to be equally distributed over 24 hours. As almost 60% of ship arrivals occur during daytime (Figure 4.15 and Appendix N), this equal distribution of freight flow pattern might not be completely valid. Therefore, the impact of an additional lock at Beatrix is limited, as peak arrivals and non-equal distribution patterns remain (or even become larger) in the studied waterway network.

To determine the impact of increased lock capacity, also three scenarios are defined for IJmuiden (illustrated in Figure 4.17)

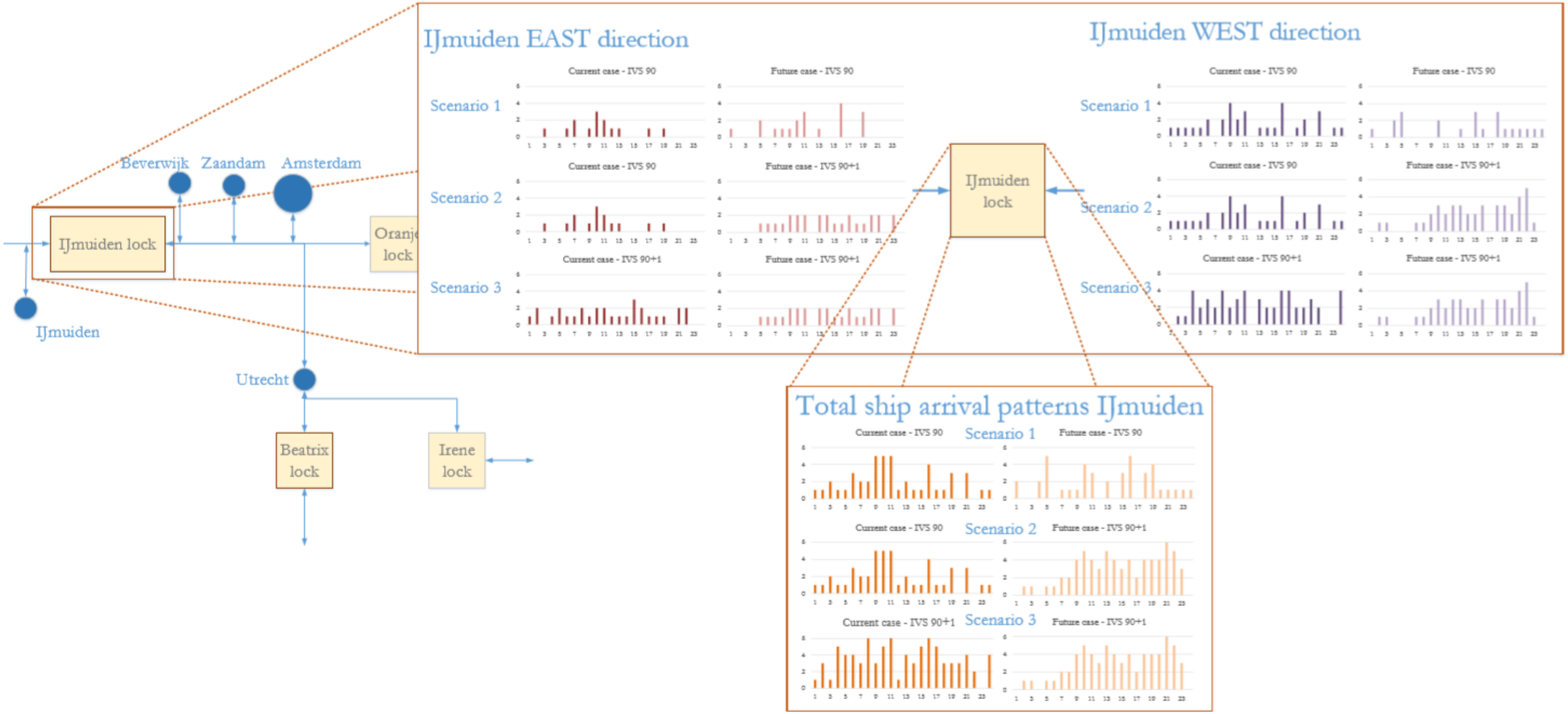


Figure 4.17: Various current and future scenarios to evaluate impact on IJmuiden in the studied waterway network

Scenario 1 shows positive impact on equal distributed ship arrival patterns and peak arrivals with a replacement of the current Northern lock. In the EAST direction, one peak occurs, but this can easily be captured by spreading ship passages with traffic management. Scenario 2 and 3 are less positively evaluated in terms of impact. Larger peaks occur for both scenarios 2 and 3, especially during daytime and (late) evening. Occupation rates of the future case tend to be larger, even with a larger lock. It is unknown how the number of ship passages will develop as ships do not need to unload part of their cargo at sea in the future case due to the enlarged depth of the new lock. Larger ships are especially able to enter and depart the new Northern lock more easily and it becomes tide independent. Therefore, impact of increased lock capacity at IJmuiden is larger compared to the Beatrix lock. Though, the number of ships hardly exceeds the maximum number of ships per hour. As the maximum number of ships is hardly exceeded the need for an additional lock is solely based on the current dimensions of the Northern lock and the exceeding life span.

As the Key performance indicator indicated, impact cannot solely depend on ship passages. This means it will be a combination between deadweight capacity and the number of ship passages. The number of ship passages captured in the simulation model is used to determine the total deadweight capacity per hour. Though total deadweight capacity, in tons, fluctuates as deadweight capacity of ship categories fluctuates. To determine the upper and lower bound of deadweight capacity Appendix O will elaborate on the upper and lower bound. Figure 4.18 will therefore make a distinction between average, lower and upper bound for deadweight capacity per hour.

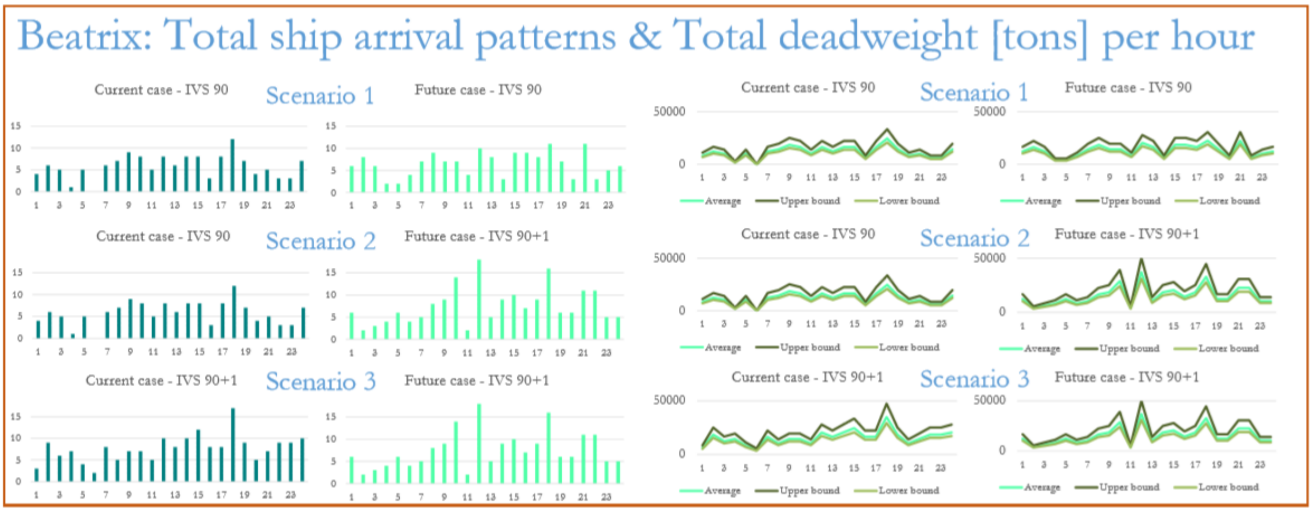


Figure 4.18: Deadweight tons per hour for the Beatrix lock for each of the three scenarios

The amount of deadweight capacity for Beatrix will be larger for scenario 1, while a small increase is determined for scenario 2 and 3 after hour 12. Deadweight capacity also fluctuates after hour 12 in scenario 2 and 3. For IJmuiden, the patterns for scenario 1 is less equal compared to Beatrix. Apart from that, deadweight capacity fluctuates less for scenario 2 and 3 for IJmuiden as is shown in Figure 4.19.

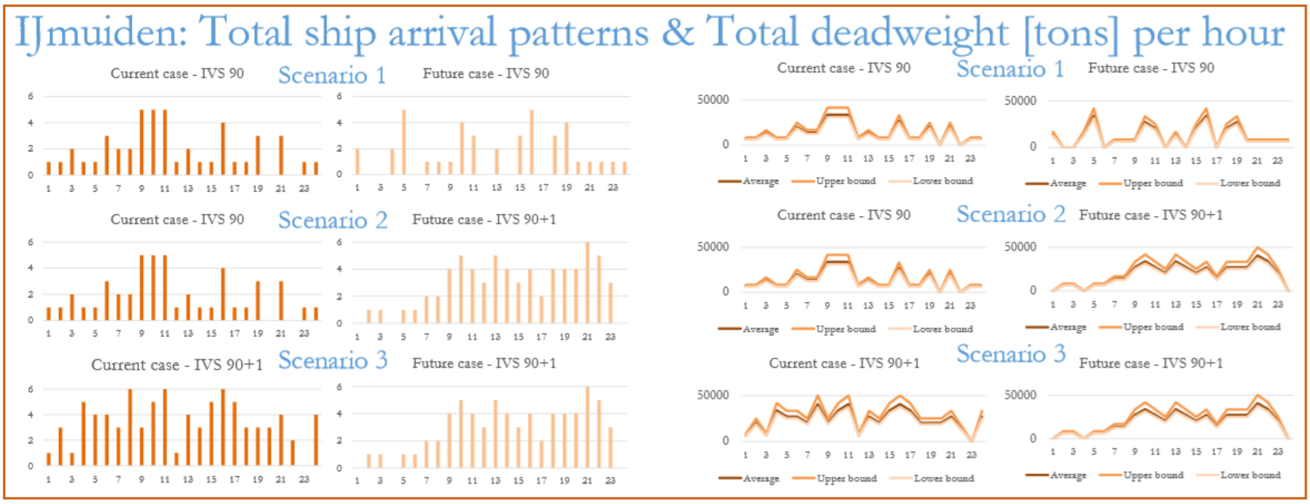


Figure 4.19: Deadweight tons per hour for the IJmuiden lock for each of the three scenarios

In short, the impact variables (Nmax, rerouting and the decrease in lock entrance/departure times) cannot be measured separately, since the total arrival pattern shows hardly any similarities. If the impact variables are combined, three possible scenarios are acknowledged. The scenario that is valid depends on the real ship passages in the waterway network now and in the future. Even with additional locks in the studied waterway network, ship arrival patterns and peak arrivals might cause (potential) bottlenecks at IJmuiden and Beatrix. Despite the possibility that both locks remain a (potential) bottleneck, the need for additional locks is also proven, since ship arrival patterns will exceed the maximum amount of ship arrivals per hour. The potential of using additional locks more properly will be a challenge for the future.

5 Conclusion and recommendations

In this research, the impact of additional locks (Beatrix and IJmuiden) on inland waterway freight transport is evaluated. This is important for the Netherlands' position as 'Gateway to Europe', as it is highly profitable for the Dutch Ministry of Infrastructure and the Environment (Ministry of I&E). Only a part of the waterway infrastructure network is used to determine the impact of additional locks as those locks are directly connected in the studied waterway network. For that matter, the studied waterway network originates from the (inter)national, regional and local waterway infrastructure network. Existing nodes, links and infrastructure components of all infrastructure network levels are examined to determine the studied waterway network. In addition, with the construction of additional locks, the current and future studied waterway network will differ. Within the studied waterway network, the planned additional locks at IJmuiden and Beatrix resulted in the following research question:

What is the impact of constructing additional locks at IJmuiden and Princess Beatrix for freight transportation to and from the hinterland via inland waterways in the Netherlands?

Evaluating additional capacity in the studied network for IJmuiden and Beatrix is more difficult than was initially acknowledged. The differences between the sea lock IJmuiden and inland waterway lock Beatrix are explained by the fact that IJmuiden acts as access to the sea and Beatrix acts as a main hinterland connection of the Port of Amsterdam. Thus, with the construction of an additional Beatrix lock, another lock becomes available for passing ships. For IJmuiden, the new lock will replace the current northern lock, which means that the number of operational infrastructure components remains the same in the future. If the new IJmuiden lock becomes unavailable due to any reason, large ships would not be able to enter or leave the Port of Amsterdam, as there is not an alternative lock; other locks at IJmuiden can only be used by smaller seagoing vessels. Apart from that, the IJmuiden lock is managed with the use of traffic management, to manage ship arrivals over time.

Currently, evaluating the need for additional lock capacity is done in macro-, micro-, and meso waterway simulation models. The macro simulation model of the Netherlands, BIVAS, is used to identify (potential) bottlenecks. The input data, which is used to identify (potential) bottlenecks, appears to be inaccurate and based on annual averages. For annual averages no distinction is made for fluctuations in ship passages per month, day and hour. In addition to that, inconsistencies in the ship register data occur as the register differs for every ship and every lock in the network. The importance of measuring input data accurately is crucial for macro simulation models, as the ship register data is used to identify (potential) bottlenecks to indicate (future) infrastructure investments. Moreover, after observing BIVAS, missing data (black spots) are revealed. For example, the IJmuiden lock appears to be managed by the Harbour Master of the Port of Amsterdam and, therefore, data appears to be managed differently compared to all the other locks in the Netherlands. This means that IJmuiden is not connected in any simulation model with its hinterland. After identifying a (potential) bottleneck, micro simulation is used to verify the outcome of the macro simulation model. Micro simulation models simulate one lock and focus on chamber assignment outcomes for the (new) lock. In contrast to macro and micro simulation models, meso simulation models are able to model multiple locks at once. As the studied waterway network consists of multiple locks, meso simulation is appropriate, though limited simulation models are available. The available meso simulation models present one-directional traffic on a corridor; however, this research presents bi-directional traffic. This means not only one corridor, but multiple freight flows from multiple nodes. In addition, the new meso simulation will model fluctuations in ship passages and connects IJmuiden with its hinterland.

Since limited research is available to evaluate the need for additional lock capacity in waterway simulation models, other transport related research fields (port, road and rail infrastructure and simulation models) are analysed. It appears that transport related research fields are more advanced than waterway simulation models, as they are able to simulate the impact of traffic management and policy changes. For example, port simulation models simulate every terminal area in the system separately as well as the system as a whole, so the terminal is optimized. In the waterway network every shipper acts only what is beneficial for him or her; the system does not yet perform as a whole. Shippers' incentives to optimize their own route are better when high or low tide occurs (depending on their destination), by this fuel costs can be decreased drastically. The benefits of high/low tide are that beneficial, such that arriving at a certain time at infrastructure components is common for many shippers. Ship arrivals are therefore concentrated for certain time frames during daytime. Additional locks could be a solution for this peak in ship arrivals. Next to that, traffic management could also be a solutions, as it is used in road infrastructure.

As a result of the shortcomings of existing waterway simulation models and since other transport related research fields are more advanced, a new meso simulation model was developed. The new simulation model takes bi-directional ship arrival patterns and the impact variable of constructing additional locks into account. Both aspects in the new meso simulation model are based on existing simulation models. The impact variables will vary for both the current case (without additional locks) and the future case (with additional locks) to determine the impact of increased lock capacity in the studied waterway network. The following impact variables are examined: the average number of ships per lockage (Nmax), weights of links, and the entrance and departure times of ships. Also, within the current and future case, one impact variable is determined, since ship register data is not managed properly. An additional base and future case is developed with different ship departures at nodes. Finally, 3 scenarios are developed to illustrate the impact of additional locks in the studied waterway network as the determined freight flows appears to be inaccurate. The desired outcome of impact is measured in ship arrival patterns and peak arrivals, which are aimed to be equally distributed over the simulation period of 24 hours and the amount of peaks is aimed to be minimized. A minimal occurrences of peaks is desired since the risk of waiting is limited. Equal ship arrival distributions and minimal peak arrivals are desired for both separate directions and the sum of both directions at locks.

It appears that the new locks (IJmuiden and Beatrix) will not necessarily be positive for equal distributed ship arrival patterns and peak arrivals in the studied waterway network. Ship arrival patterns will not necessarily be more equally distributed and peak arrivals will not necessarily be limited. Moreover, the ship arrival patterns and peaks will not necessarily be positively influenced with additional locks. Also, the ship arrival patterns and peaks are different compared to the current case. The measured impact in the studied waterway network is as follows for the separate and combined impact variables:

- The first impact variable, Nmax, is observed to have a (moderately) positive impact on ship arrival patterns and peaks with the exception of Beatrix up direction and Beatrix total. The peak arrivals for Beatrix up and Beatrix total remain as the departure pattern remains the same for the up directions, even with a larger Nmax, the number of ship arrivals exceed the maximum number of ship arrivals per hour.
- The second impact variable, weight of links, appears to have a moderately positive impact on equal distributed ship arrival patterns. The peak arrivals are less positively evaluated, as the number of peaks increase in the future case. An increase in peaks can be explained due to an increase in ship arrivals, since this route becomes more attractive for larger ship sizes and larger draughts.
- The third impact variable, decreased entrance and departure times, have a moderately positive impact for Beatrix. The effect for IJmuiden, however, appears to be rather negative for ship arrivals patterns and peak arrivals. By changing the entrance and departure times, the passing times of ship is influenced. The negative impact for IJmuiden is hard to define as the ship arrivals operate conform a random arrival pattern, therefore micro simulation is required.
- All impact variables combined will result in a (moderately) positive impact on ship arrival patterns and peak arrivals. It is important to note that, even if all separate impact variables are evaluated negatively, the combined variables will not necessarily be negative for equal distributed ship arrival patterns and peak arrivals for both locks in the studied waterway network.

Evaluating ship arrival patterns appears to be complicated as ship data registration demonstrates many flaws. Therefore, to define ship arrival patterns of both IJmuiden and Beatrix, 3 scenarios are developed. The first indicates a positive outcome, while the second and third scenario outcomes are moderately positive for equal distributed ship arrival patterns and peak arrivals. Even with the new lock, the maximum number of ship arrivals per hour will be reached or even exceeded. The increased lock capacity is limited for IJmuiden as the new lock will replace the current lock. What is important, is that IJmuiden utilizes its ship arrivals per hour more efficiently as traffic management has already been implemented. Moreover, increased lock capacity for Beatrix makes it possible to accommodate relatively more ship passages per hour, but traffic is not managed.

For Beatrix and IJmuiden, constructing additional locks in the waterway network will also attract additional ship passages. The new ship passages were in the current situation not able to pass the infrastructure component, until the situation changed with constructing a new lock. In most cases the new ship passages have larger dimensions (length, width and draught). At most, the new ship type has the incentive to arrive at peak moments or creates additional peaks in ship arrival patterns. In general, additional traffic volumes would, occur at peak hours, as already 60% of passages take place during daytime peaks between 08.00 and 17.00. Next to that, the infrastructure investment of an additional lock at Beatrix could be postponed by traffic management. For IJmuiden this is not the case as the lock has reached it life span. So both locks involve different argumentation for additional capacity.

To conclude, the impact of increased lock capacity is limited as the potential ship arrivals per hour are not utilized, which causes non-equal distribution ship arrival patterns and peak arrivals. Thus, increased lock capacity in inland waterway freight transport is only positive for the short-term if volumes during daytime do not exceed the maximum number of ship passages per hour. In the long-term, structural changes, such as traffic management are also required.

5.1 Future research

The results of this study reveal many opportunities for future research:

1. Traffic management at infrastructure components might be a solution for non-equally distributed ship arrival patterns and peak arrivals. Apart from the benefits that traffic management indicates, the disadvantages should be taken into account as well. The extent of these advantages and disadvantages could be a challenging topic for future research. By implementing traffic management, the differences between fixed and variable (e.g. on-demand) transport should be taken into account. Especially since shuttle freight services are able to book a time slot for lockage, though for non-shuttle services this might become complicated. (Un)loading at

surrounding ports at infrastructure components will also be difficult, as time of arrival at infrastructure components is known only half an hour in advance.
Furthermore, the inland waterway sector consists of many entrepreneurs, who need to be persuaded by the possibilities of traffic management. Schuttevaer (Dutch shippers' organization) has stated that they are willing to cooperate to implement traffic management at infrastructure components and to help convince inland waterway operators. Thus, the potential of traffic management is acknowledged by the sector itself, as shippers are able to prospect their arrival time at terminals and minimize passing times at infrastructure components.

2. Ship register data are not properly registered and used. Information systems are useful to determine the actual time of lockage and might be able to better prospect freight flows through the waterway network. In addition, more data can be gathered for current occupational rates of locks.

   Additional unanswered questions include:
   What is the exact arrival/depart time at locks?
   What is the maximum capacity at locks and how long does lockage take?
   When does the lockage process start?
   What is the actual waiting time for ships at peak hours?
   What are the related costs to waiting?
   What is the environmental impact of adapting speed (scenario 4 in CONFIDENTIAL IMAGE)?

   To answer those questions, the Ministry of I&E and Rijkswaterstaat should cooperate; it would contribute to data input for policy-making and therefore beneficial for both organisations.

Waterway freight transport has a substantial amount of potential to stimulate intermodal transport. However, waterway freight transport has to improve certain aspects to utilise the current and future infrastructure network more optimally. If the inland waterway operators, Rijkswaterstaat and the Ministry of I&E, do not cooperate properly, the potential of inland waterway transport cannot be realised. Not only is the stimulation of intermodal transport at risk, but also the position of the Netherlands as the 'Gateway to Europe'.

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Appendix A: International impact of increased lock capacity

All origins and destinations for each lock (IJmuiden and Beatrix) are itemized for 2013. As mentioned for IJmuiden only passing ships are used as indication of freight patterns. This is done since loading is transferred to lighter barges before ships are able to pass lock IJmuiden. The origin (Figure A.1 and Figure A.2) and destination (Figure A.3 and Figure A.4) of passing ships is divided for continents whereas the European Union is subdivided into Member States. Note that these percentages indicate ships passages and does not indicate the deadweight capacity of ships. Thus meaning that larger ships -with a larger deadweight capacity- will pass the Northern lock less often compared to several smaller short sea ships – with a relative smaller deadweight capacity- per ship.

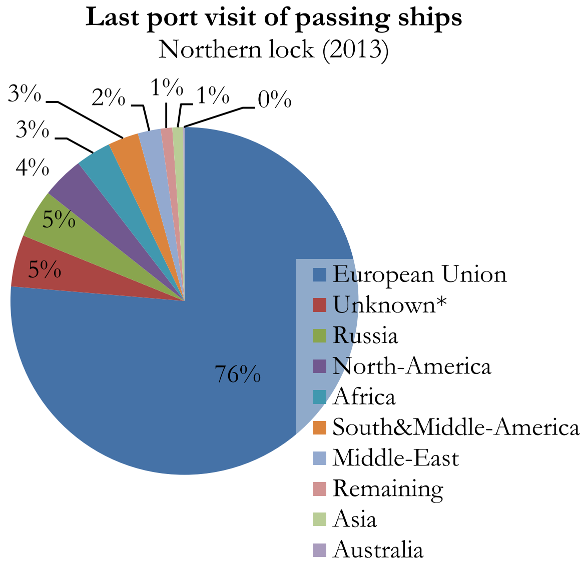


Figure A.1: Last port visits of passing ships of the Northern lock in 2013 (indication of origin of ships)[18*]

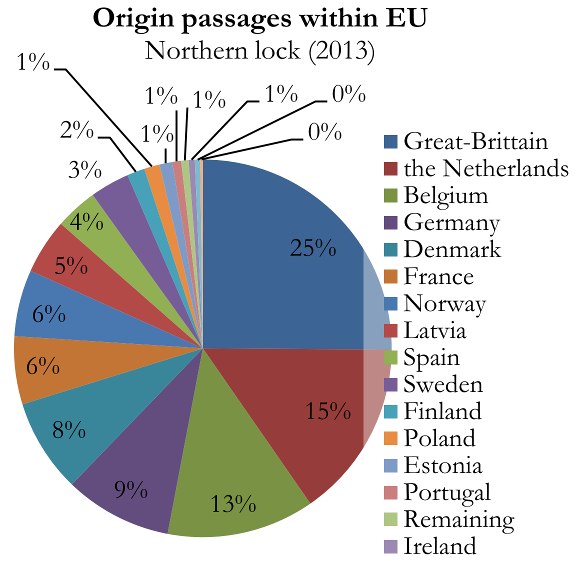


Figure A.2: Last port visit of passing ships of Northern lock in 2013 within the European Union (indication of origin of ships for Member States)

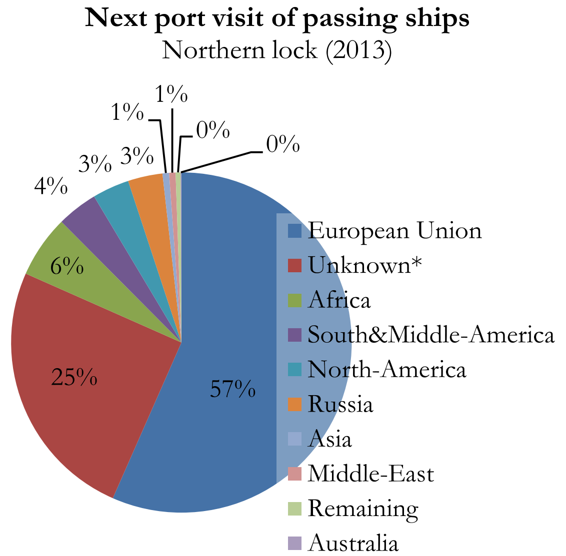


Figure A.3: Next port visits of passing ships of the Northern lock in 2013 (indication of destination of ships)

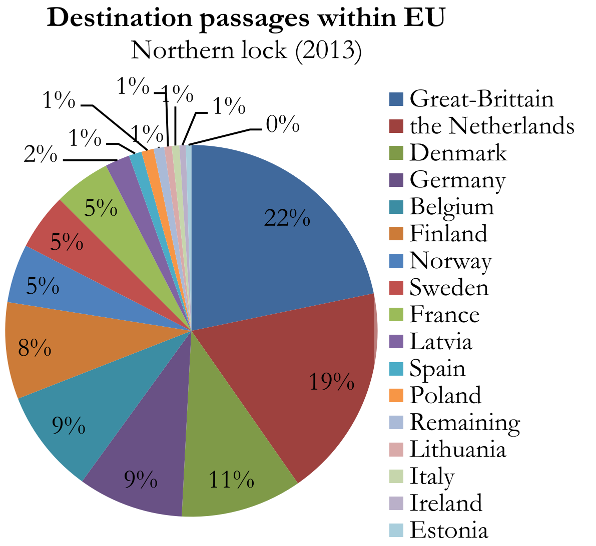


Figure A.4: Next port visits of passing ships of Northern lock in 2013 within the European Union (indication of destination of ships to Member States)

[18*] The unknown category is a lack in the database and registration policy of passing ships. Data of IJmuiden is extracted from the Harbour master of the Port of Amsterdam.

For the Ministry of I&E, Figure A.1 until Figure A.4 are very important since the origins and destinations of ships are indicated. Therefore Member State and European added value are used to politically support decision-making for an additional lock at IJmuiden. With these freight flows the impact for different continental and European flows is indicated. By constructing an additional larger lock, all freight flows to and from the indicated continents and countries are able to expand. Besides that additional origins and destinations are able to pass the new sea lock IJmuiden.

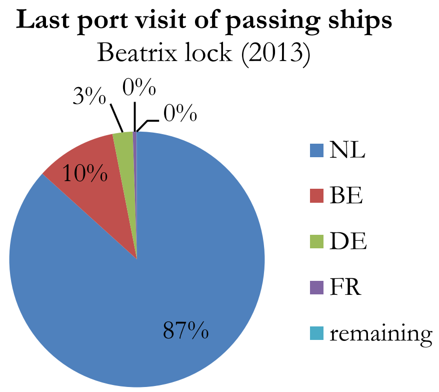


Figure A.5: Last port visits of passing ships of the Beatrix lock in 2013 (indication of origin of ships)

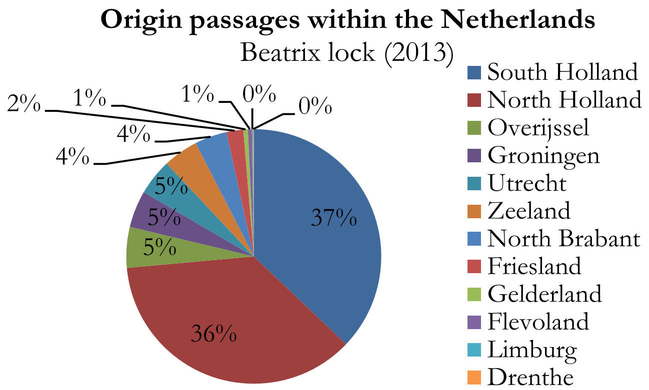


Figure A.6: Last port visit of passing ships of Beatrix lock in 2013 within the Netherlands (indication of origin of ships of provinces)

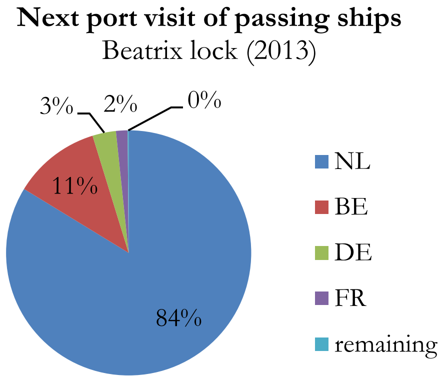


Figure A.7: Next port visits of passing ships of the Beatrix lock in 2013 (indication of destination of ships)

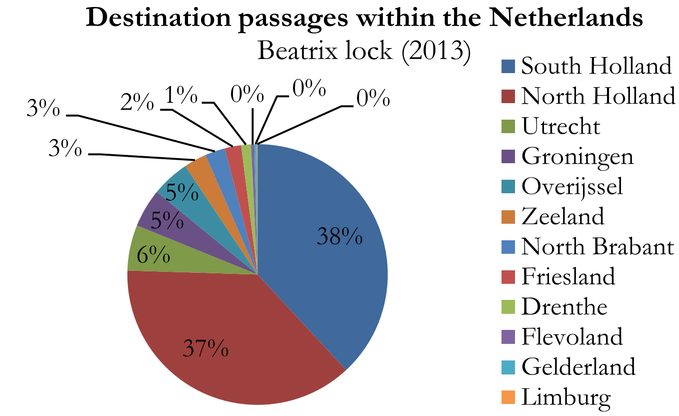


Figure A.8: Next port visit of passing ships of Beatrix lock in 2013 within the Netherlands (indication of destination of ships of provinces)

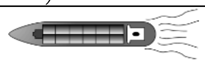
Appendix B: Ship categories

The type of ship categories and subcategories are shown for each main category. The distinction of using four categories is based on this deviation of Rijkswaterstaat.
(In Dutch only)

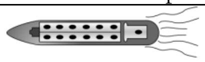
1. BINNENVAART

VRACHT- EN TANKVAART

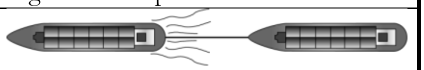
0. scheepstype niet te bepalen (bijv. bij mist)



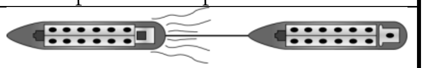
1. motorvrachtschip
3. containerschip



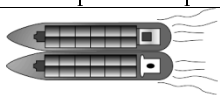
2. motortankschip
4. gas-tankschip



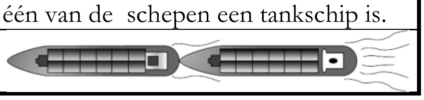
5. slepend motorvrachtschip
11. sleep-vrachtschip



6. slepend motortankschip
12. sleep-tankschip

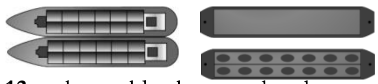


7. motorvrachtschip, met één of meer vrachtvaartuigen langszij
8. combinatie als **7.**, waarbij tenminste één van de schepen een tankschip is.



9. motorvrachtschip, met één of meer vrachtvaartuigen duwend
10. combinatie als **9.**, waarbij tenminste één van de schepen een tankschip is.

11. sleep-vrachtschip
12. sleep-tankschip



13. gekoppelde sleepvrachtschepen
14. combinatie als **13.**, waarbij tenminste één van de schepen een tankschip is.
15. vrachtduwbak
16. tankduwbak
17. vrachtduwbak geladen met containers
18. gas-tankduwbak

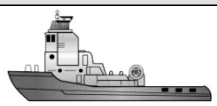
DUWEENHEDEN

Uitsluitend vrachtduwbakken
21. duwboot met één vrachtduwbak
22. duwboot met twee vrachtduwbakken
23. duwboot met drie vrachtduwbakken
24. duwboot met vier vrachtduwbakken
25. duwboot met vijf vrachtduwbakken
26. duwboot met zes vrachtduwbakken
27. duwboot met zeven vrachtduwbakken
28. duwboot met acht vrachtduwbakken
29. duwboot met meer dan acht vrachtduwbakken
Per scheepstype worden de tonnages van de bakken bij elkaar opgeteld.

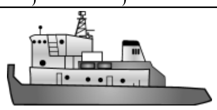
Met minimaal 1 (gas-)tankduwbak
31. duwboot met één tankduwbak c.q. gas- tankduwbak
32. duwboot met twee duwbakken w.v. ten minste één (gas-)tankduwbak
33. duwboot met drie “
34. duwboot met vier “
35. duwboot met vijf “
36. duwboot met zes “
37. duwboot met zeven “
38. duwboot met acht “
39. duwboot met meer dan acht duwbakken w.v. ten minste één (gas-)tankduwbak
Per scheepstype worden de tonnages van de bakken bij elkaar opgeteld.

2. BINNENVAART

NIET UITSLUITEND VRACHTVERVOEREND

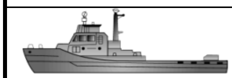


40. sleepboot losvarend
41. sleepboot behorend bij één of meer sleepschepen. De sleepboot kan ook langszij zijn vastgemaakt.
42. sleepboot assisterend bij schip, gekoppelde schepen (c.q. bakken) of ander drijvend object.

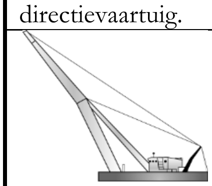


43. duwboot losvarend

44. passagiersschip, veerboot, rondvaartboot, rode kruisschip e.d.



45. dienstvaartuig: Politie, Rijkswaterstaat (peil-, meet-, directievaartuig, e.d.), Havendienst. Ook particulier directievaartuig.

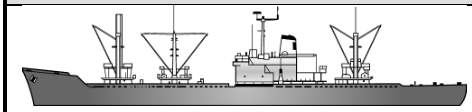


46. werkvaartuig: bok, zuiger, baggermolen, kabellegger, bergingsvaartuig, betonningsvaartuig

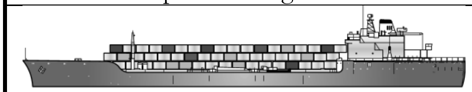
47. gesleept object, anders dan de code **1.** t/m **18.** (bijv. pijpleiding, brugdeel, e.d.).
48. vissersvaartuig
49. overige binnenvaartuigen en drijvende objecten, nog niet genoemd, incl. bunkerboten en parlevinkers.

3. ZEEVAART

VRACHT- EN TANKVAART

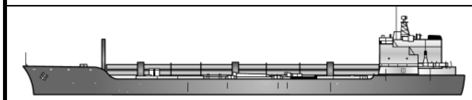


50. vrachtschip voor stukgoed

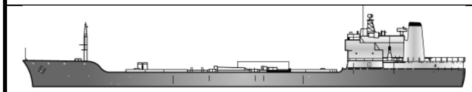


51. containerschip, ro-ro vrachtschip, lash-schip

52. bulkcarrier



53. tanker voor olie en andere vloeibare lading

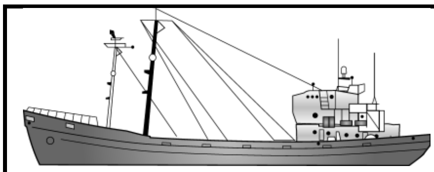


54. tanker voor samengeperste gassen

NIET UITSLUITEND VRACHTVERVOEREND (also category 2)

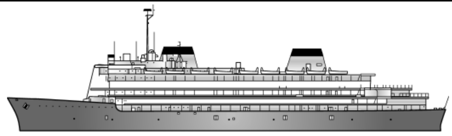
60. zeesleepboot, bevoorradingsschip: losvarend

61. zeesleepboot, bevoorradingsschip: slepend



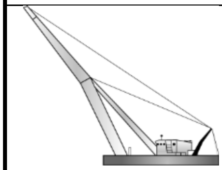
62. vissersvaartuig (geen binnenvisser, geen mosselvisser)

63. veerboot, ro-ro schip (niet uitsluitend vracht vervoerend)



64. passagiersschip

65. zeegaand dienstvaartuig, patrouilleboot, loodsdienst, peil- en meetvaartuig, andere tenders, e.d.



66. zeegaand werkvaartuig: bok, zuiger, kabellegger, bergingsvaartuig, betonningsvaartuig, etc.

67. gesleept zeegaand object: boor- kraaneiland, dood schip, e.d.

68. marinevaartuig (ook Koninklijke landmacht)

69. overige zeegaande vaartuigen en drijvende objecten: weerschip, opleidingsvaartuig, e.d.

4. RECREATIEVAART

80. motorjacht, ook snelvarend

81. speedboot

82. zeiljacht varend op (hulp) motor
83. zeilend jacht

84. vaartuig voor sportvissers

85. zeil- c.q. motorschepen met een lengte van meer dan 20 m, in gebruik als recreatievaartuig o.a. bruine vloot, charterschepen, omgebouwde beroepsvaartuigen, e.d.

89. overige recreatievaartuigen: roeiboot, kano, rubberboot, zeilplank, e.d.

Rijkswaterstaat, February 2001

Appendix C: CEMT classification of ships

Inland waterway ships

Inland AVV[19]	Length	Width	DWT (+/-)
M0	<38	<5	1-250
M1	38,5	5,05	251-400
M2	50-55	6,6	400-650
M3	55-70	7,2	650-800
M4	67-73	8,2	800-1050
M5	80-85	8,2	1050-1250
M6	80-85	9,5	1250-1750
M7	105	9,5	1750-2050
M8	38-111	9,6-11,5	2050-3300
M9	>111	9,6-11,5	3300-4000
M10	38-111	11,5-14,3	4000-4300
M11	>111	11,5-14,3	4300-5600
M12	>38	>14,3	>5600
B	100-120	11-22	3950
C	100	19-22	3350

Classification	Type
0	Small ships
I	Spits
II	Kempenaar
III	Dortmund-Eems canal ship
IV	Rhine-Herne canal ship
V	Large Rhine ship and push-towing barges
VI	Push-towing barges
VII	Push-towing barges

Seagoing vessels

Cargo ship	Length	Width	DWT (+/-)
V0	60-80	11-12	1200-2300
V1	80-95	11-13	2300-4000
V2	107-110	17-19	5000-7500
V3	115-122	19-20	5300-6400
V4	139-144	19-22	6200-6700
V5	152-162	20-22	8600-10000
V6	168-169	20-22	21000-23000
V7	185-204	29-32	18000-22000
V8	>213	>32	>26000

V0 never through Northern lock
Maximum of V2 through Mid lock

Tanker	Length	Width	DWT (+/-)
T0	92-100	15-17	4200-5300
T1	115-120	15-20	7500-8000
T2	128	20	13000
T3	134	20	13000-14000
T4	145	20-23	15000-17000
T5	160-170	23	25000
T6	175-185	27-32	40000-50000
T7	228	32	70000
T8	244	42	105000

T0 never through Northern lock

Maximum of T2 through Mid lock

Bulkcarrier	Length	Width	DWT (+/-)
B1	181	30	35000
B2	210	36	60000
B3	224-225	32	75000
B4	229	32-36	85000
B5	240-250	38-43	100000
B6	290	40-45	180000

Passenger ship	Length	Width	DWT (+/-)
P1	176	23	5100-5500
P2	252	32	8800

Worker	Length	Width	DWT (+/-)
W1	84-94	15-17	5300
W2	152	21	7500

Only through Mid lock

Only through Northern lock

[19] Adapted from Expertise and Innovation Centre Inland Waterway Transport (EICB)

Appendix D: North Sea Canal throughput

The Amsterdam port region consists of four small ports with terminals. As are given in yellow, purple, green and blue in Figure D.1: Overview ports in North Sea Canal region. In 2014 total transhipment of the North Sea Canal ports was 97.4 million ton, which was an increase of 1.7% compared to 2013. North Sea Canal ports consist of ports of Amsterdam, Beverwijk, IJmuiden and Zaandam. Total transhipment of all ports is illustrated in Table D.1.

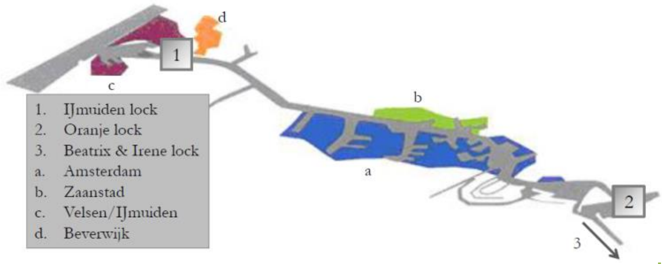


Figure D.1: Overview ports in North Sea Canal region

Table D.1: Transhipment of ports within the North Sea Canal port region in 2013 (adapted from Port of Amsterdam)

	Transhipment [mln ton]	In terms of percentage (to 2013)
Amsterdam	79.7	+1.4%
IJmuiden	17.3	+3%
Beverwijk	0.2	-9%
Zaanstad	0.2	+17%

To establish throughput, ship passages are required in both directions. For both the Northern and Mid lock ship passages are extracted to show the differences between WEST and EAST direction passages.

Appendix E: Existing waterway simulation models and information systems

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Appendix F: Data collection points in the Netherlands

Figure F.1: Overview of locks in the Netherlands. These locks collect data for existing simulation models as BIVAS and BasGoed

The inland waterway network exists of multiple routes through the waterway network and all routes have a certain distance. By separating freight flows and the details of those flows, the branched network can be defined as the input of the model. The freight flows are measured at certain data collection points, as they are illustrated in Figure F.1 in red dots. Through those dots many routes through the waterway network are available, dependent to the CEMT classification of ships. Especially since certain flows tend to increase or decrease in the future, the routes are crucial. (Dienst Verkeer Scheepvaart, 2010).

In the Netherlands there are multiple routes possible to take to go from a certain origin to a certain destination. Not all locks in the Netherlands are essential for modelling freight transport of IWT, as freight is concentrated on the main routes. Therefore only the main freight routes are included in this research. Besides that not all locks are equipped with an obligatory reporting centre. In the reporting centre the ship is obliged to fill in forms to determine its origin, destination, transported goods, etc. Not all locks, especially the smaller locks, do not have a reporting centre. Data collected by reporting centres is used to fill the central database (IVS 90) with the mentioned data. The locks which include a counting point of the transport data is illustrated in Figure F.2.

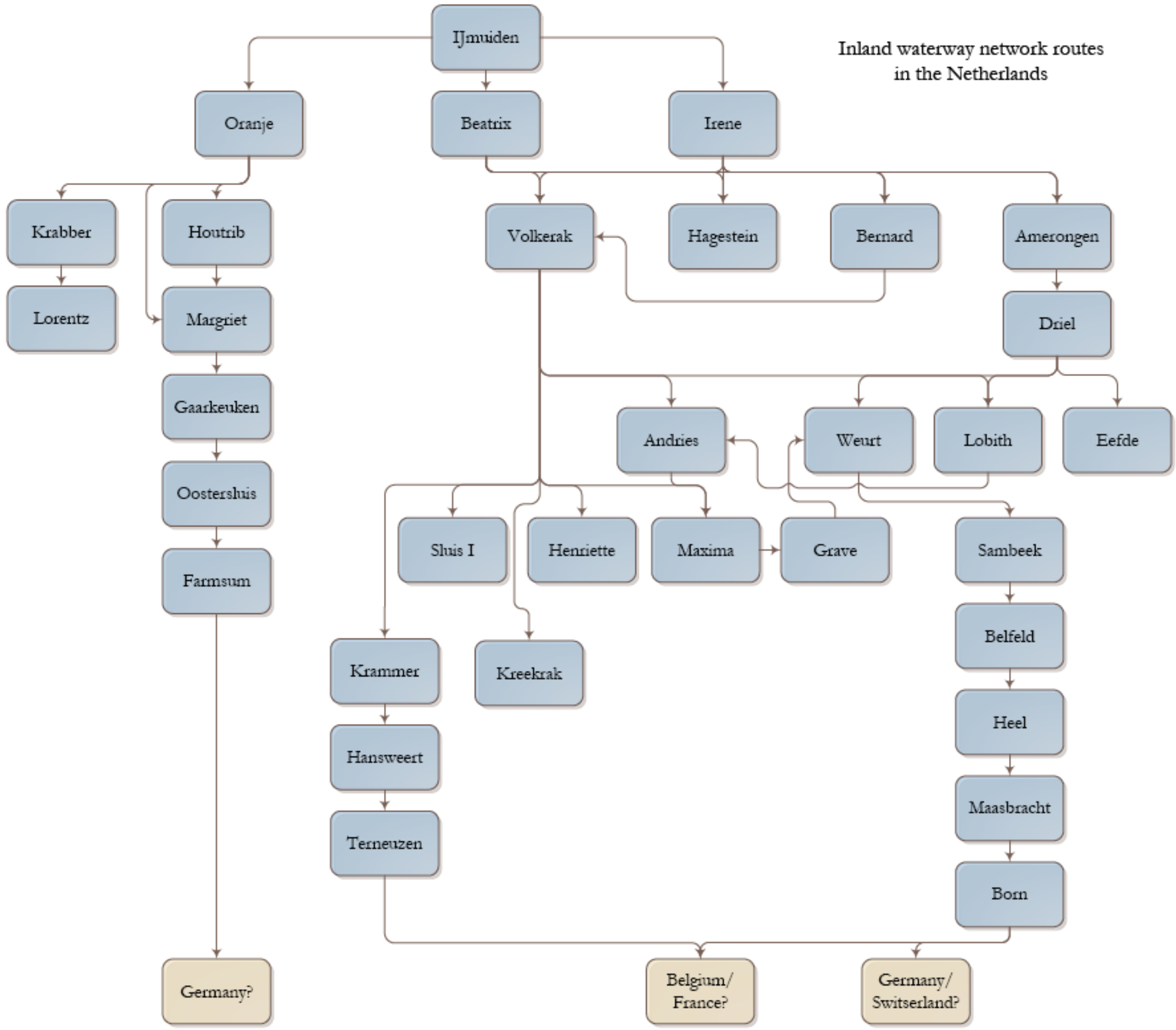

Figure F.2: Inland Waterway network routes in the Netherlands through the main freight routes

The possible connections between locks is illustrated, instead of the distance. Certain links that are illustrated become unattractive, due to an increase in distance. Depending on navigation speed there is a breakeven point between alternative route, so additional distance and waiting time. An example is explained for alternative route from IJmuiden to Volkerak. The shortest path from IJmuiden to Volkerak is through Beatrix, however when waiting time exceeds 60 minutes an alternative route through Irene lock becomes attractive.

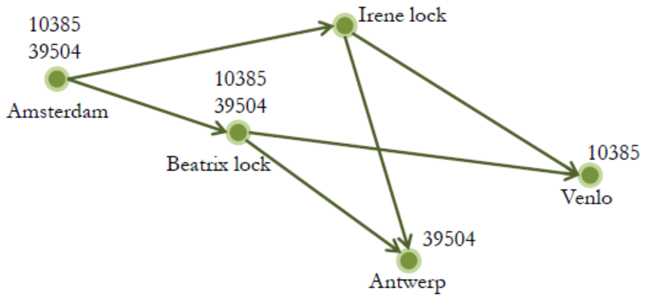

Figure F.3: Example of branched network, with routes through the network, to illustrate the required data

Figure F.4: OD representation of network

The ship ID is used to determine the branched network. From every lock this ship passes, the ID is registered. The origin is the loading point and the destination is given for its unloading point (Figure F.4). Therefore this research rejects pre- and end-haulage transport. Adjacent to the type of goods, the amount of tons per ship is registered as well. The reason for this is to ascertain the amount of empty trips through the lock. Lastly, a distinction is made for ship size.

Appendix G: Ship categories for Beatrix lock (2011-2013)

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Appendix H: List of symbols of micro lock simulation

List of symbols

T_c = (Average) total cycle time of a lock, so after a locking cycle the lock is in its initial state again. The lock has been performed an upstream and downstream lockage.

T_d = Locking time in one direction, also mentioned as the passing time of ships which equals waiting time and operation time of ships. Locking time in one direction is in this report explained by lockage.

T_i = Time for ship(s) to enter the chamber during lockage (so in one direction either upstream or downstream)

T_l = Time to close/open the gates and attain an increase/decrease of the water level during lockage (so in one direction either upstream or downstream)

T_o = Time for ship(s) to leave the chamber during lockage (so in one direction either upstream or downstream)

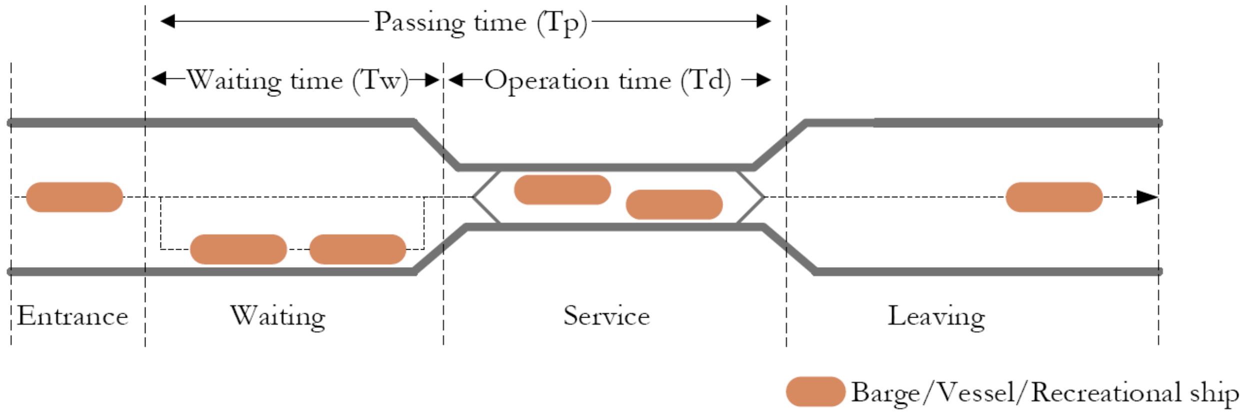
T_w = Waiting time for ship(s) to enter the chamber and waiting time for ships until the last ship has left the chamber.

C_s = Average capacity of the lock as the number of ships per time unit (time unit can be per year, month or week)

C_t = Average loaded capacity in tonnes per time unit, as deadweight capacity which is used by Rijkswaterstaat to identify intensity and capacity of locks

N_{max} = Average number of ships over a large number of maximum capacity locking operations depending on positioning of ships inside locks

T_s = Average load in tonnes per ship passing the lock as mentioned to be loading degree of ships



Appendix I: Assumption of maximum capacity at waterway links

To contribute on limited capacity of waterways, several variables are identified in theory and illustrated in Figure I.1 (Groenveld, Verheij, & Stolker, 2006). All variables that influence capacity of inland waterways are illustrated.

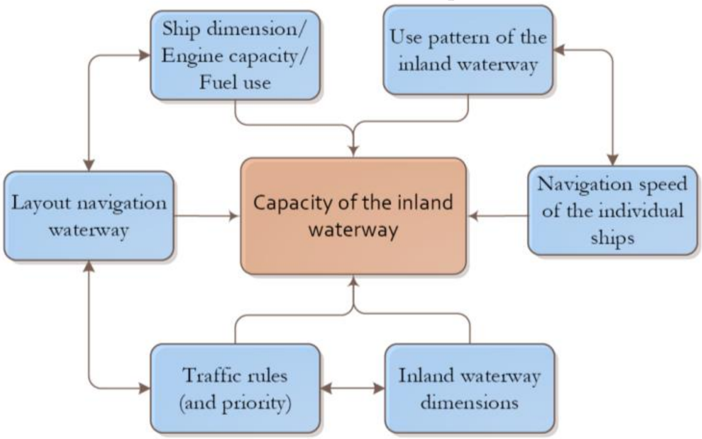


Figure I.1: Factors that influence the inland waterway capacity adapted from Groeneveld, et al.

Ship dimensions were already covered by the CEMT classification of waterways, while the use pattern of the inland waterways depends on supply and demand of goods, what in following text is explained as OD pattern (Origin-Destination pattern). Also navigation speed of ships interferes with availability of capacity at infrastructure components. In this research layout of waterways are rejected whilst speed changes need to be taken into account. Waterways are not straight, but rather curved. Those curves reduce navigation speeds of ships. Ships carrying dangerous goods are already tracked by making use of GPS/AIS more careful in the waterway network by Rijkswaterstaat. This is necessary due to their additional safety and/or environment risks. This research will not highlight transport of dangerous goods further on.

Navigation speed of ships might result in a cluster of multiple ships in a particular area. The same phenomenon is noted at highways for trucks (Tympakianaki, Spiliopoulou, Kouvelas, & Papamichail, 2014). Therefore it might affect the actual capacity of waterways, which cannot be defined as unlimited (Liu & Hyman, 2012). For this research it has been assumed within the classification of VIa that three M8 ships are able to pass at once a waterway segment due to waterway widths. M8 ships have a length of 110 m and a width of 11.4 m (Hove & Doorn, 2010). Based on the following assumptions:

- On average deadweight capacity of M8 ships is 2051-3300 tons, so on average 2500 tons per ship is assumed. This is supposed since not all M8 ships are already equipped with the largest deadweight capacity.
- Assuming three M8 ships passing a waterway segment and assumed that the following occurs at a maximum of 4 times per hour. Four times per hour is assumed since ships needs to maintain one's distance. At the North Sea Canal maximum length and width of ships is larger, since classification VIb is able to pass compared to Amsterdam-Rhine Canal.

Thus the maximum capacity of waterways is:

$$2500\ tons * 3\ ships\ passing\ at\ once\ a\ segment = 7{,}500\ tons$$
$$7{,}500\ tons * 4\ times\ per\ hour = 30{,}000\ tons\ per\ hour$$
$$30{,}000 \frac{tons}{hour} * 24 \frac{hour}{day} * 365 \frac{days}{year} = 262.8\ million\ tons\ per\ year$$

Summarized a maximum capacity of waterways of 262.8 million tons in deadweight capacity per year is assumed.

Appendix J: Identify (potential) bottlenecks using max flow min cut

Before additional capacity is required at any link or node, a theoretical framework is used to identify the bottlenecks at infrastructure components of the regional waterway network. Without the ability to identify potential bottlenecks, a capacity increase cannot be constructed. To construct the increased capacity of Beatrix and IJmuiden, a theoretical framework of maximum flow and minimum cut is used. This theory was originally formulated by Harris and Ross in 1954 and the aim is to identify maximum flow between any origin and destination (University Munchen, 2005).
As described, a freight waterway network consists of links (waterways) and nodes (terminals). With the given nodes and links in the regional waterway network, a distinction is made for seagoing vessels and inland waterway barges due to difference in vessel size. Some seagoing vessels are not (always) able to pass the inland waterway locks of Beatrix, Irene and Oranje.

Assume a network graph $G = (N, L)$ with links (waterways) $(l \in L)$ and nodes (terminals) $(n \in N)$, such that origin (o) and destination (d) can be determined as terminals: $o, d \in N$. Each link has a non-negative capacity, $c(l) \geq 0$. Capacity of a link is related to maximum capacity of infrastructure components such as locks. A flow on a link can be defined as $0 \leq f(l) \leq c(l)$, which means that flows on a link $l \in L$ are not able to exceed capacity. Maximum capacity of infrastructure components in the regional waterway network. (Aharoni, Berger, Georgakopoulus, & Perlstein, 2011)

The flow conservation law is applied for the flow $f(l)$ from origin to destination. Outflow from an origin terminal is equal to total flow size that enters the destination terminal.

Table J.1: Overview of locks in study object in terms of maximum capacity (based on data of Rijkswaterstaat)

	Capacity [mln tons per year]	Intensity [mln tons per year]	Supply/Demand [mln tons per year]	Passages per year [#]	Lock dimensions [meter]
Beatrix lock	173	102.5	38	50,300	18 x 225 18 x 225
Oranje lock	212	57.0	23	62,000	24 x 200
Irene lock	221	68.8	35	34,200	18 x 350 24 x 260
IJmuiden	? ?	90[20]	97.7[21]	15,300 8,500	50 x 400 (Northern) 25 x 225 (Mid)

To determine maximum flow from origin to destination, an algorithm of Ford-Fulkerson was used. Note that the maximum flow is bounded, since maximum capacity is available at the links. Infrastructure components turn out to have less capacity compared to waterways. Appendix D illustrates assumptions that are made to calculate maximum capacity of waterways. For both inland waterway transport (Figure 3.6) and seagoing vessels (Figure 3.5) maximum flow is shown. This distinction is made due to the fact that both locks have different flows in terms of seagoing, inland waterway transport and non-freight as illustrated in Table 2.3. Large seagoing vessels transfer load into smaller barges before passing the IJmuiden lock. Next to the transfer into smaller barges, both locks are managed by different operators. Different operators manage their data differently for loading and deadweight capacity. Therefore two different maximum flows, minimum cuts are determined.

[20] Rough estimate since data is registered differently compared to the other (inland waterway) locks.
[21] 97.7 million ton is total throughput of the North Sea Canal region.

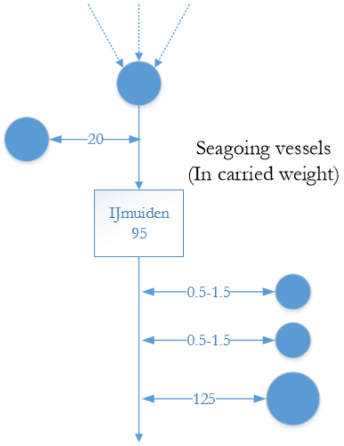


Figure J.1: Maximum carrying weight given at links/nodes for seagoing vessels

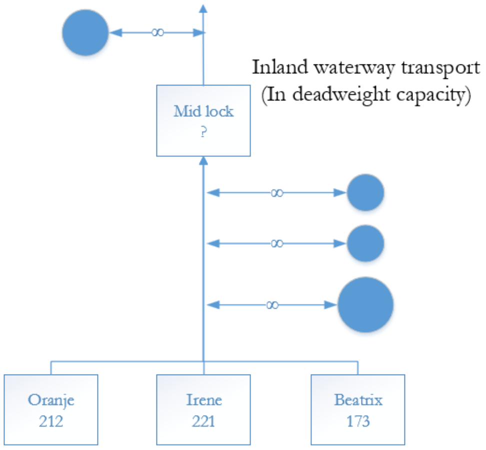


Figure J.2: Maximum deadweight capacity[22] given at links/nodes for inland waterway transport

Capacity of sea going vessels
Carrying weight is given in Figure 3.5 instead of maximum deadweight capacity, since deadweight capacity of ship passages is not registered by the port master of Amsterdam. As mentioned in section 2.2.3.3, in most cases, cargo is transferred into smaller barges before entering the sea lock IJmuiden. Besides that, seagoing vessels require more quay wall infrastructure and have more environmental effects compared to inland waterway barges. Maximum quay wall capacity for seagoing vessels is indicated as 20 million tons for IJmuiden and 125 million tons for Amsterdam. By constructing an additional sea lock at IJmuiden, capacity will increase to 125 million tons, equal to the environmental limits of Amsterdam. In this case the number of passing ships is not causing (potential) bottlenecks, since smaller vessels are able to pass other locks at IJmuiden. Theoretically a capacity increase to 145 million tons[23] would be more sufficient, since no further increase of capacity in the future is required for seagoing vessels.

Capacity inland waterway transport
Figure 3.6 indicates bottlenecks for inland waterway transport to and from the Port of Amsterdam. With the assumption of unlimited capacity availability of nodes for inland waterway transport, each node has been set to unlimited (∞). Between those nodes assumptions are made to identify capacity at links (Appendix I). Capacity at links exceeds capacity at the infrastructure components, therefore they are also set to unlimited (∞).
The actual deadweight capacity of the mid lock at IJmuiden is unknown and as a result illustrated by a question mark. Note that alternative routes are available for inland waterway transport through, i.e. the northern lock. Therefore it will not be assumed as a bottleneck for inland waterway transport. The three inland waterway locks are left with finite capacity. Beatrix has the lowest maximum deadweight capacity of 173 million tons per year and is identified as maximum flow and minimum cut through the network, together with the Northern lock for seagoing vessels.

Increased capacity is required for Beatrix and IJmuiden
By identification of Beatrix and IJmuiden as (potential) bottleneck with making use of maximum flow, minimum cut, a capacity increase would improve the ability for larger flows through the regional waterway network. Note that in Figure 2.1 the aspect of service network is not applicable in this case, since the service network of all locks in the studies network are available 24 hours a day, 7 days a week.

[22] Capacity for inland waterway locks is assumed with certain vessel size.
[23] 145 million tons would be more sufficient, since 125 million tons pass through Amsterdam + 20 million tons in IJmuiden, adding up to 145 million tons. Note that it has been assumed that sea going vessels are not able to pass the mid lock.

Appendix K: Monthly/daily passages of Beatrix, IJmuiden, Irene and Oranje lock

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Step 3: Normative month is extracted into ship passages per hour

April 2013 - BEATRIX LOCK

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
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22																															
23																															
Total																															

Step 4: One (representative) week is chosen for extraction of data for daily volume distribution
The first week 1-7 April 2013 is chosen, since in that week highest and lowest monthly average is situated in that week. This week is used for every lock in the study object.

Step 5: All seven days of that week are extracted into ship categories

Beatrix 1-7 April 2013

1-apr-13

hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	C	B	NOFR	RECR	SEA
0																		
1																		
2																		
3																		
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2-apr-13

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3-apr-13

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5-apr-13

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6-apr-13

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7-apr-13

hour																		
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23																		

Step 6: Deadweight capacity per passing ship per hour
The next tables distinguish the deadweight capacity of passing ships. To do so the Non-freight and Recreational ships are outside the scope. The aim of this table is to illustrate the relationship between:

1. The amount of ships passing in one hour
2. The amount of deadweight capacity passing in one hour

Assumptions to define deadweight capacity per hour is based on seagoing vessels categories, described in appendix B.

	#Ships/hr	DWT per hour	DWT/ship
1-apr-13			
2-apr-13			
3-apr-13			
4-apr-13			
5-apr-13			
6-apr-13			
7-apr-13			
Average/day			
Average/hr			

	1-apr-13			2-apr-13			3-apr-13			4-apr-13			5-apr-13			6-apr-13			7-apr-13		
hour	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#freight ships/hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship
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IJmuiden – Northern lock
Step 1: yearly volumes of 2011-2013

Step 2: Monthly distribution of volumes 2011-2013 to identify one normative month (+2% annual average)

Step 3: Normative month is extracted into ship passages per hour

April 2013 - IJMUIDEN NORTHERN LOCK

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
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Step 4: One (representative) week is chosen for extraction of data for daily volume distribution

Step 5: All seven days of that week are extracted into ship categories

Northern lock IJmuiden 1-7 April 2013

1-apr-13

hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	C	B	NOFR	RECR	SEA
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Step 6: Deadweight capacity per passing ship per hour

The next table distinguish the deadweight capacity of passing ships. To do so the Non-freight and Recreational ships are outside the scope. The aim of this table is to illustrate the relationship between:

3. The amount of ships passing in one hour
4. The amount of deadweight capacity passing in one hour

Assumptions to define deadweight capacity per hour is based on seagoing vessels categories, described in appendix B.

	1-apr-13			2-apr-13			3-apr-13			4-apr-13			5-apr-13			6-apr-13			7-apr-13		
hour	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship	#Ships /hr	DWT per hour	DWT/ ship
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	#freight ships/hr	DWT per hour	DWT/freight ship
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2-apr-13			
3-apr-13			
4-apr-13			
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6-apr-13			
7-apr-13			
Average/day			
Average/hr			

#ships per hour	
#ships	Frequency
0	
1	
2	
3	
4	
5	

deadweight capacity per hour			
	lower bound	upper bound	Frequency
<10,000			
10,000-20,000			
20,000-30,000			
30,000-40,000			
40,000-50,000			
50,000-60,000			
60,000-70,000			
70,000-80,000			
80,000-90,000			
90,000-100,000			
100,000-110,000			
110,000-120,000			
>120,000			

deadweight capacity/ship/hour			
	lower bound	upper bound	Frequency
<10,000			
10,000-20,000			
20,000-30,000			
30,000-40,000			
40,000-50,000			
50,000-60,000			
60,000-70,000			
70,000-80,000			
80,000-90,000			
90,000-100,000			
100,000-110,000			
110,000-120,000			
120,000-130,000			
130,000-140,000			
140,000-150,000			
>150,000			

The tables above summarize the frequency that a certain ships per hours occurs during this week (1-7 april 2013)

IJmuiden – Mid lock
Step 1: yearly volumes of 2011-2013

Step 2: Monthly distribution of volumes 2011-2013 to identify one normative month (+2% annual average)

Step 3: Normative month is extracted into ship passages per hour

April 2013 - IJMUIDEN MID LOCK

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
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Step 4: One (representative) week is chosen for extraction of data for daily volume distribution

Step 5: All seven days of that week are extracted into ship categories

Middensluis IJmuiden 1-7 April 2013

1-apr-13

hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	C	B	NOFR	RECR	SEA
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Irene
Step 1: yearly volumes of 2011-2013

Step 2: Monthly distribution of volumes 2011-2013 to identify one normative month (+2% annual average)

Step 3: Normative month is extracted into ship passages per hour

April 2013 - IRENE LOCK

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
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Step 4: One (representative) week is chosen for extraction of data for daily volume distribution

Step 5: All seven days of that week are extracted into ship categories

Irene 1-7 April 2013

1-apr-13

hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	C	B	NOFR	RECR	SEA
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Oranje
Step 1: yearly volumes of 2011-2013

Step 2: Monthly distribution of volumes 2011-2013 to identify one normative month (+2% annual average)

Step 3: Normative month is extracted into ship passages per hour

April 2013 - ORANJE LOCK

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
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Step 4: One (representative) week is chosen for extraction of data for daily volume distribution

Step 5: All seven days of that week are extracted into ship categories

Oranje 1-7 April 2013

1-apr-13

hour	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	C	B	NOFR	RECR	SEA
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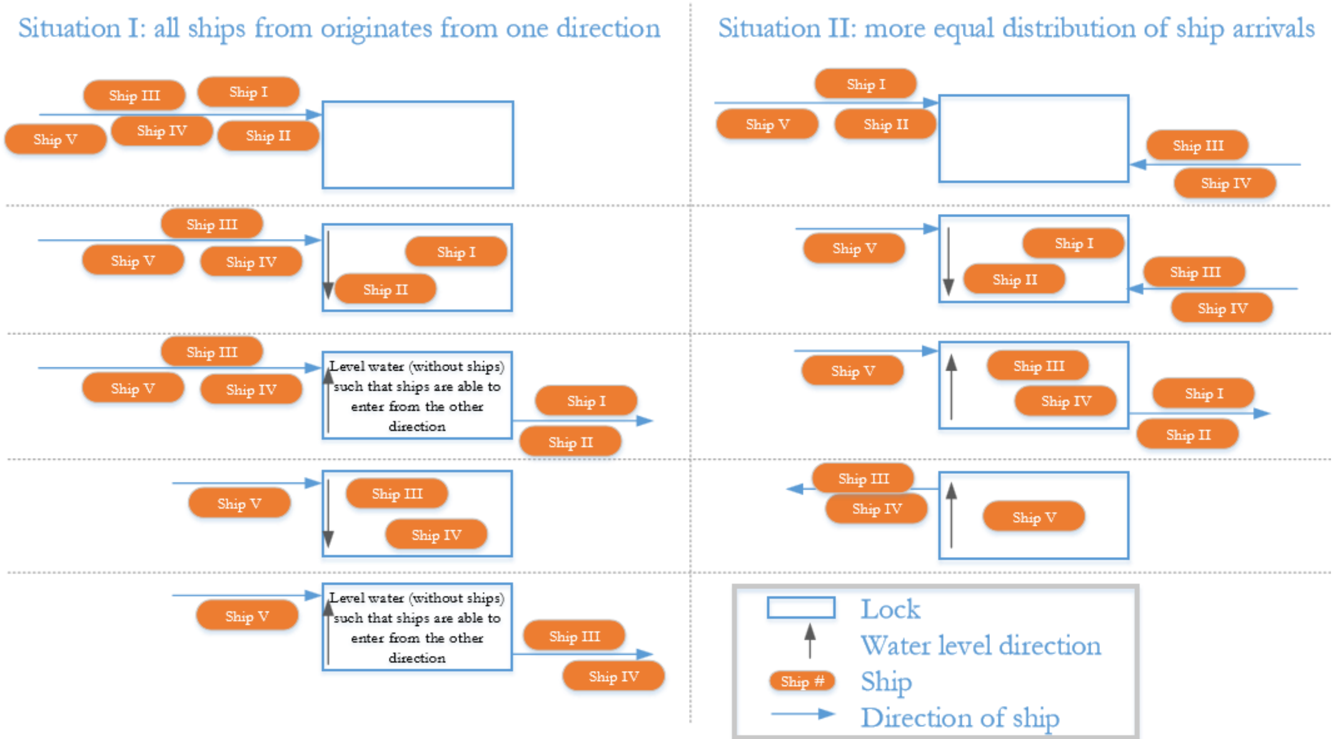
Appendix L: Benefits of ship arrivals from both directions

This illustration shows the benefit of ship arrivals from both directions, compared to situation I where all ship arrivals are located from one direction. With ship arrivals from both directions, less lock operations are required and lock occupation rates are larger.



A smaller number of lockage is required for locking 5 ships. Besides that the average occupation rate is larger for the second situation.

Appendix M: Indicator for equally distributed ship arrival patterns and peak arrivals

For this research qualitative indicators are used to determine the impact of the separate variables in the future case experiments. To qualify the indicators the equal distributed ship arrival patterns and peak arrivals are compared. For qualification the results are based on the number of the phenomenon during the simulation period. Both equal distributed arrival patterns and peak arrivals are explained in more detail below.

1. Equally distributed ship arrival patterns

Equally distributed ship arrival patterns are based on average and standard deviations of the number of ship arrivals in experiment 1 and the future case experiments. The average and standard deviations of the experiments could be larger, smaller or the same. The average number of ship passages per hour is preferred to be larger in the future case experiments, while the standard deviations is preferred to be smaller in the future case experiments. The combinations of both the average and standard deviation will result in the +, - and +/- as shown in the main text.

Average number of ship arrivals per hour	Standard deviation between ship arrivals per hour
(+) indicates a positive effect	(+) indicates a smaller standard deviation and therefore positive
(-) indicates a negative effect	(-) indicates a larger standard deviation and therefore negative
(0) indicates the same average number of ship arrivals	(0) indicates the same standard deviation

Average	Standard deviation	Result in Table 4.8
+	+	+
+	-	+/-
+	0	+
-	+	+/-
-	-	-
-	0	-
0	+	+
0	-	-
0	0	0

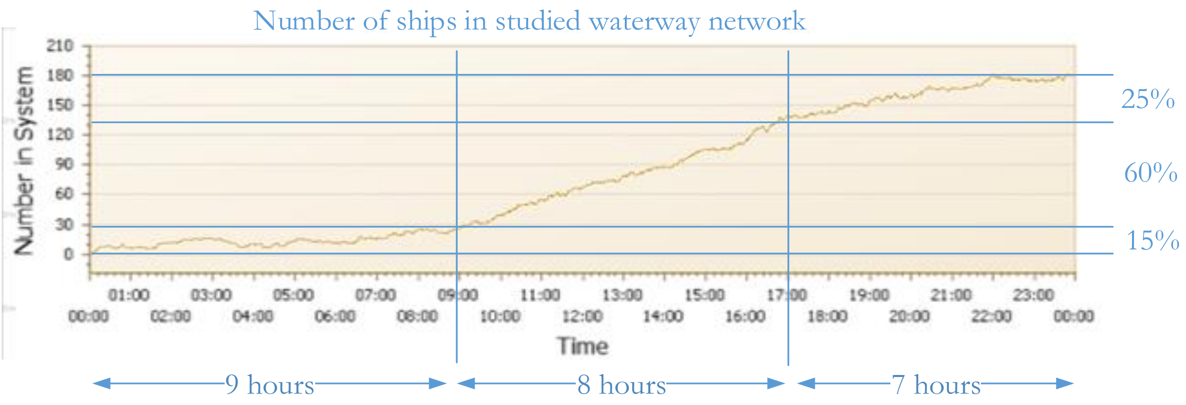
2. Peak arrivals

Peaks are only defined as peaks when they exceed the maximum number of ship arrivals per hour. The number of peaks might increase or decrease in the future case experiments. Plus-minus indicates that there are currently no peaks in the ship arrival patterns, such that the ship arrivals will exceed the maximum. Though the ship arrivals might approach the maximum number of ship arrivals per hour. For an increase of decrease in the number of ships approaching the maximum, no subcategory is defined.

Minus (-)	Indicates more peaks compared to experiment 1, so a negative effect Indicates the same number of peaks, though the peak is larger, so a negative effect
Plus (+)	Indicates less peaks, so a positive effect
Plus-Minus (+/-)	Indicates a situation where the number of ship passages does not exceed the maximum number of ship passages per hour, but they intent to reach the maximum number of ship arrivals per hour.
Zero (0)	Indicates the same amount of peaks and with the same height of the peak. Thus results in zero effects.

Appendix N: Daytime passages

The amount of passages, over the 24 hours simulation period, are not equally distributed as already mentioned in the main text. The following figure illustrates the different numbers of ships in the new simulation model. It appears that during daytime (1/3 of the simulation period) already 60% of the ship passages occur.

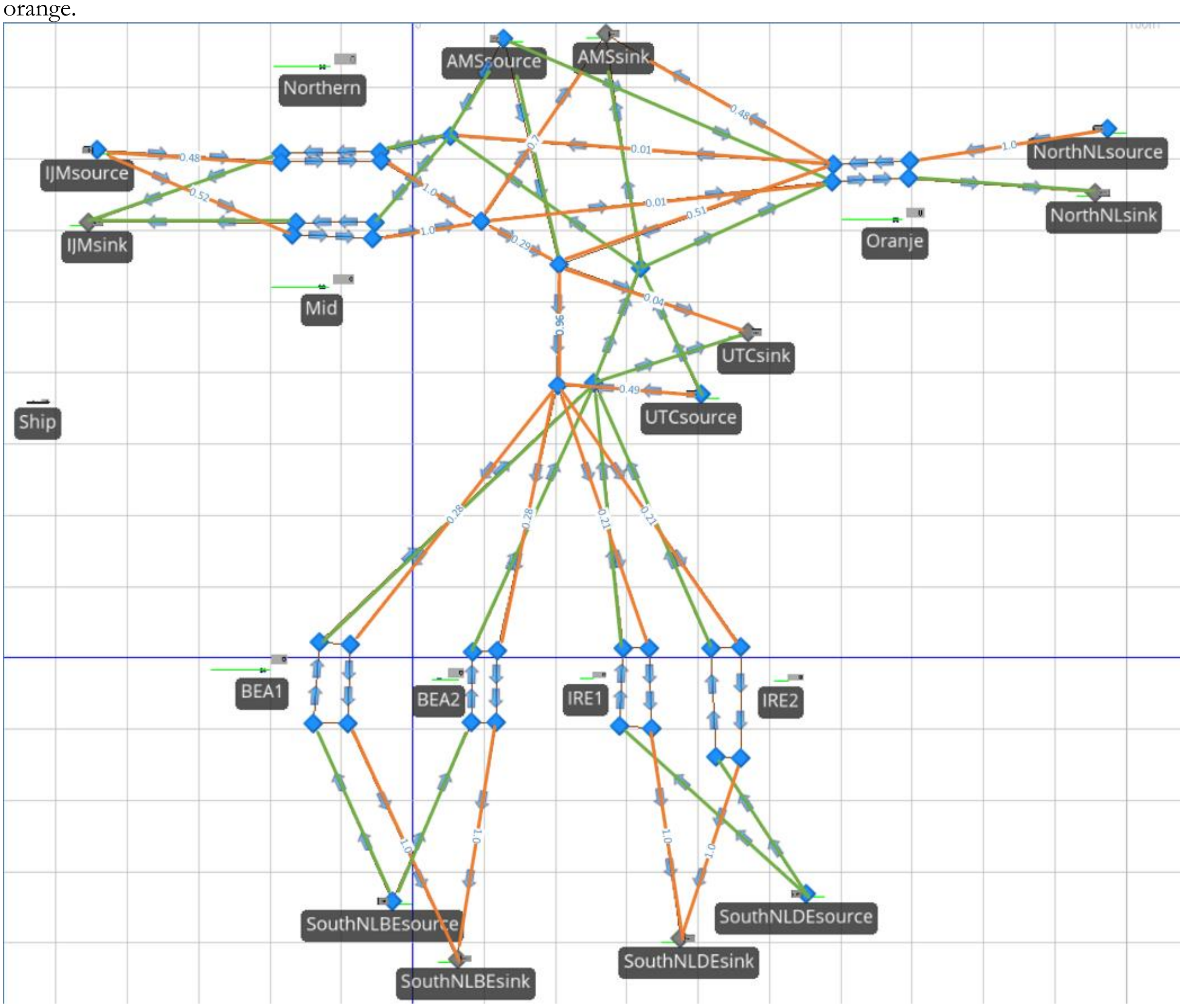


When freight flows increase, the number of ships in the system will also increase. The change that additional ships will be travelling through the network during daytime is larger compared to night time/evening.

Appendix O: Deadweight capacity

The deadweight capacity is given for the three scenarios for the current and future case. How these deadweight capacities were captured is shown in the next two pages for both Beatrix and IJmuiden. To determine the deadweight capacities per hours, an average, upper and lower bound is given.

Overview of the new simulation model of the studied waterway network with the link directions given in green and orange.



Inland waterway lock Beatrix, deadweight capacity for each average-upper-lower scenario

Current case – IVS 90				**Current case – IVS 90+1**				**Future case – IVS 90+1**				**Future case – IVS 90**			
#ships	average	upper	lower	#ships	average	upper	lower	#ships	average	upper	lower	#ships	average	upper	lower

Average			Upper			Lower		
Ship	DWT	ratio	Ship	DWT	ratio	Ship	DWT	ratio
Seagoing								
L								
M								
S								

Sea lock IJmuiden, deadweight capacity for each average-upper-lower scenario

Current case – IVS 90				**Current case – IVS 90+1**				**Future case – IVS 90+1**				**Future case – IVS 90**			
#ships	average	upper	lower	#ships	average	upper	lower	#ships	average	upper	lower	#ships	average	upper	lower

Average			Upper			Lower		
Ship	DWT	ratio	Ship	DWT	ratio	Ship	DWT	ratio
Seagoing								
L								
M								
S								