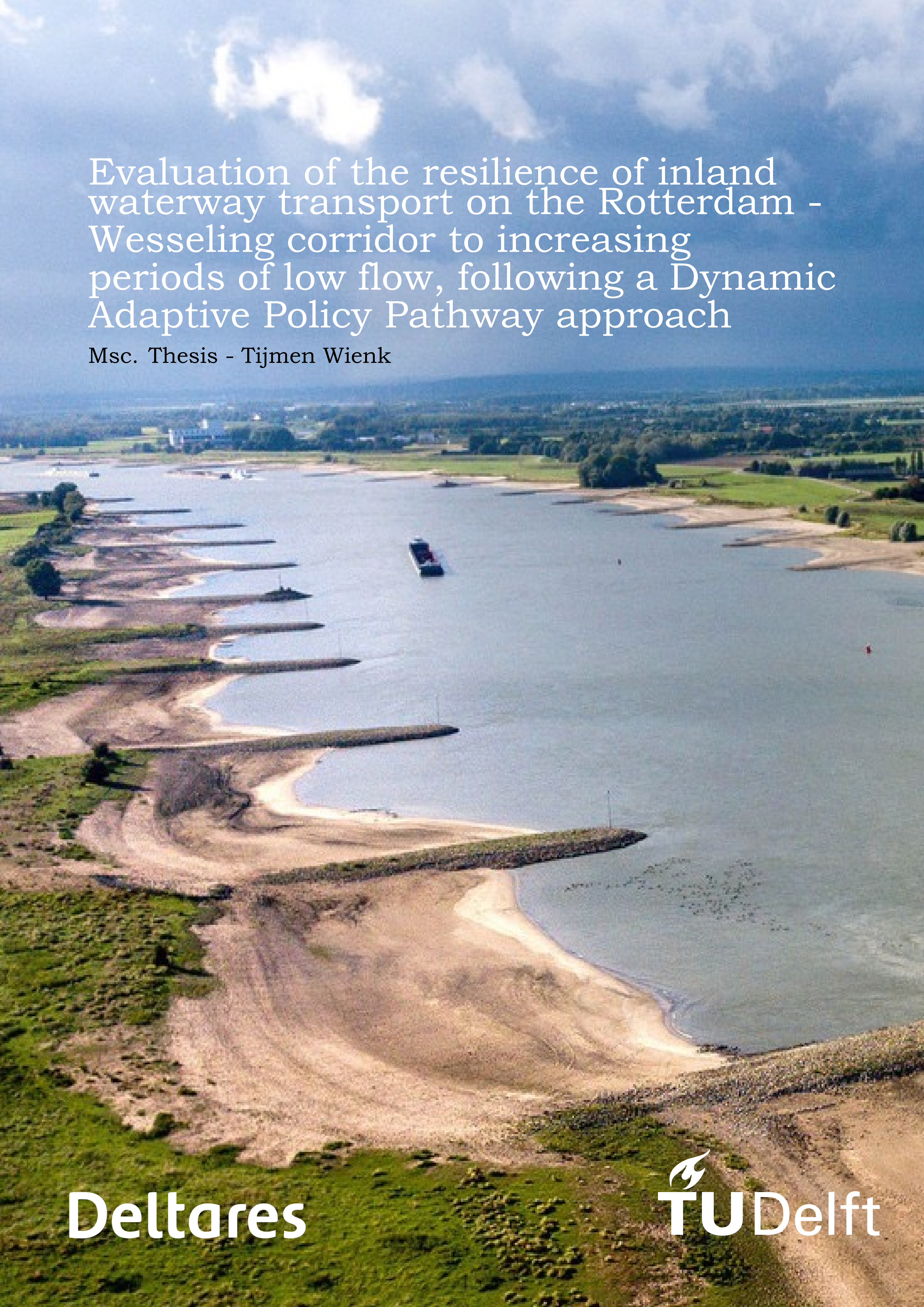
Evaluation of the resilience of inland waterway transport on the Rotterdam - Wesseling corridor to increasing periods of low flow, following a Dynamic Adaptive Policy Pathway approach

Msc. Thesis - Tijmen Wienk



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TU Delft

Evaluation of the resilience of inland waterway transport on the Rotterdam - Wesseling corridor to increasing periods of low flow, following a Dynamic Adaptive Policy Pathway approach

by

Wienk, Tijmen

Submitted to the Delft University of Technology in partial fulfilment of the degree of Master of Science in Hydraulic Engineering

Student number:	4388305	
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Supervisors:	Prof. dr. ir. Mark van Koningsveld	TU Delft
	Prof. dr. ir. P.H.A.J.M. van Gelder	TU Delft
	Dr. ir. Rolien van der Mark	Deltares
	Ir. F.R.S. Vinke	TU Delft

Preface

This research has been conducted to obtain the degree Master of Science in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of the Delft University of Technology.

The research has been performed in collaboration with Deltares, an independent institute for applied research in the field of water and subsurface. The motivation for this research originates from the ambition of Rijkswaterstaat to realize climate resilient networks by 2050. Deltares contributes to this ambition by conducting research in the fields of inland waterways and road networks and advises on the basis of the findings. Unfortunately, I haven't been to Deltares my entire research as working from home has been the urgent advice of the Dutch government since March 2020. This has meant that I never had the opportunity to meet my colleagues at Deltares, nor my supervisors at Delft University of Technology in person. Therefore, I would like to take this opportunity to express my thanks to the people that have guided me throughout this thesis.

To begin with, I would like to thank the chairman of my committee, Mark van Koningsveld, for his enthusiasm on the topic and the support throughout the process. Furthermore I would like to express my gratitude to Rolien van der Mark and Frederik Vinke for their daily availability to provide me with feedback and suggestions and motivate me during the ups and downs of the process. Lastly, I would like to thank Pieter van Gelder for his advice on the analysis of discharge time series and for his overall support.

Tijmen Wienk
Amsterdam, July 2021

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List of Abbreviations

IWW	Inland waterways
IWT	Inland waterway transport
ALD	Agreed low discharge
DAPP	Dynamic Adaptive Policy Pathways
ATP	Adaptive Tipping Point
IPCC	Intergovernmental Panel on Climate Change
KNMI	The Royal Netherlands Meteorological Institue
IVS	Informatie- en Volgsysteem voor de Scheepvaart (1990)
CEMT	Conférence Européenne des Ministres des Transports
RWS	Rijkswaterstaat
MAWD	Minimum available water depth
OpenCLSim	Open Source Complex Logistics Simulation
DES	Discrete-event simulation
ABS	Agent-based simulation

Abstract

Although inland waterways (IWW) are considered one of the most reliable transport modes, it is very vulnerable to climate change, more than other transport modes such as rail and road transport. The performance of inland waterway transport (IWT) strongly depends on the available water depth in the waterway, which is related to the river discharge. Due to climate change, it is expected that the number of days with low and extremely low discharges will occur more often during summer and autumn and that the absolute values of these low discharges will reduce.
On the other hand, inland waterway transport has the lowest fuel consumption per transported ton of cargo due to its high capacity and as a consequence, the lowest greenhouse gas emission per transported ton of cargo than other transport modalities. Besides, it generates less noise pollution and causes less congestion compared to rail and road transport. It is therefore essential to maintain the current inland waterway transport capacity and promote a modal shift of transport by road and rail to IWT. Adaptation measures can be implemented to make the inland waterway transport system more resilient to increasing periods of low flow and thus contribute to the desired modal shift. Therefore, main research question of this thesis is:

What is the maximum duration of a low flow period the inland waterway transport system can cope with on the Rotterdam - Wesseling corridor and when is this period expected to occur, following the Dynamic Adaptive Policy Pathways approach?

The Dynamic Adaptive Policy Pathway (DAPP) approach is used as a starting point for this research because the structure and steps cover objectives similar to the objective of this thesis. The essence of the DAPP approach is to develop an adaptive planning that can cope with deep uncertainties that a decision-maker has when the concerned time frame consists of many years in the future. The approach consists of seven steps: i. describe the system; ii. identify tipping points current policy; iii. identify tipping points alternative policies; iv. design and evaluate pathways; v. design the adaptive strategy; vi. implement the strategy; vii. monitor the strategy. Only the first four steps are performed in this thesis, as the last steps focus on the execution of the strategy.

This study considers the inland waterway transport of dry-bulk from Rotterdam to Duisburg and liquid-bulk transport from Rotterdam to Wesseling, both destinations are situated in Germany. The inland ports can be reached from Rotterdam via the River Waal that turns into the River Rhine at the Dutch-German border.

In step I, the objective of the inland waterway transport of dry-bulk and liquid-bulk is defined as to perform better than railway transport during periods of low flow. To assess if the objective is met, the system state is quantified by five performance indicators, which are: i. number of trips; ii. transported cargo; iii. transportation costs; iv. transportation costs per ton, and v. transportation costs per ton kilometer.

To perform step II and III of the DAPP approach, a simulation model has been set up in the form of a stress test to identify the tipping points according to the performance indicators. The model concept that is chosen for the simulation is based on the the OpenCLSim software package available at the GitHub of the Tu Delft Hydraulic Engineering department, which is a rule based planning tool for cyclic activities.
The simulation model uses water depth versus time relations as input, in which the water depth represents the minimum available water depth in the waterway. The stress test consists of multiple simulations in which the low water period duration builds up over the simulations and the water depth is kept constant during the low flow period. In total, three stress tests have been be performed with corresponding water depths to a low discharge of Q = 1020m^3/s, Q = 850m^3/s and Q = 700m^3/s.

From all five performance indicators, the *transportation costs per ton kilometer* is used to identify tipping points. This expression is frequently used in the transport sector to express performance and is therefore very suitable to compare IWT and railway transport. The annual average transportation costs per ton kilometer for railway transport in 2018 is used as a threshold value for the equally named indicator. If the value for inland waterway transport exceeds this threshold, the system no longer meets its objective and a tipping point is reached.

No tipping points were found for the dry-bulk supply chain, indicating it performs better than railway transport during low flow periods based on transportation costs per ton kilometer. This also implies that no adaptation measures are needed to contribute in achieving the supply chain objective.
The liquid-bulk supply chain however, experiences tipping points between 35 and 65 consecutive days of low flow. Two adaptation measures have been analysed for the liquid-bulk supply chain to improve its performance during low flow periods. The first is an adjustment of the maintenance criterion of the waterway. This means that skippers know exactly where the bottlenecks are located so that they can sail around them. This results in a larger available water depth. The second adaptation measure is the availability of a diverse fleet, which means that extra vessels are deployed during low flow but, are idle during high flow. Adjusting the maintenance criterion results in an extension of the tipping points and implementation of a diverse liquid-bulk fleet results in a situation where already tipping conditions occur after five days, based on the transportation costs per ton kilometer indicator.

Based on predicted discharges series with a daily time scale from 2001 to 2100 for the current climate and climate scenarios 'G' and 'W+', an estimation can be given on when the tipping conditions are expected to occur. As no tipping points were found for dry-bulk, it can be concluded that the supply chain is a more attractive transport modality than railway transport until 2100. For the liquid-bulk supply chain, it is expected to experience its first tipping point around 2030, but this can be extended to 2072 by adjusting the maintenance criterion.

Finally, the pathways are constructed in step IV. The stress test with a constant low flow of Q = $700 m^3/s$ is normative because, the corresponding tipping point for the current liquid-bulk supply chain is expected to occur around 2030, earlier than other tipping points. Therefore, the adaptive policy pathways are constructed for the Q700 stress test in Figure 1. The pathways display the opportunities on how and when to adapt to achieve the supply chains objective. However, to use it as an adaptive planning, it is recommended in the first place to analyse more adaptation measures. Secondly, this study considers only one performance indicator to determine tipping points for the current situation and adaptation measures. To analyse more adaption measures, it is highly recommended to define a performance indicator for each adaptation measure individually that express the objective of that measure. Because there are many actors in the system, different objectives play a role. Lastly, timing op tipping points are based on predicted discharge series generated for KNMI climate scenarios from 2006. To make a more reliable estimation, it is recommended to generate discharge series for the most recent climate scenarios available.

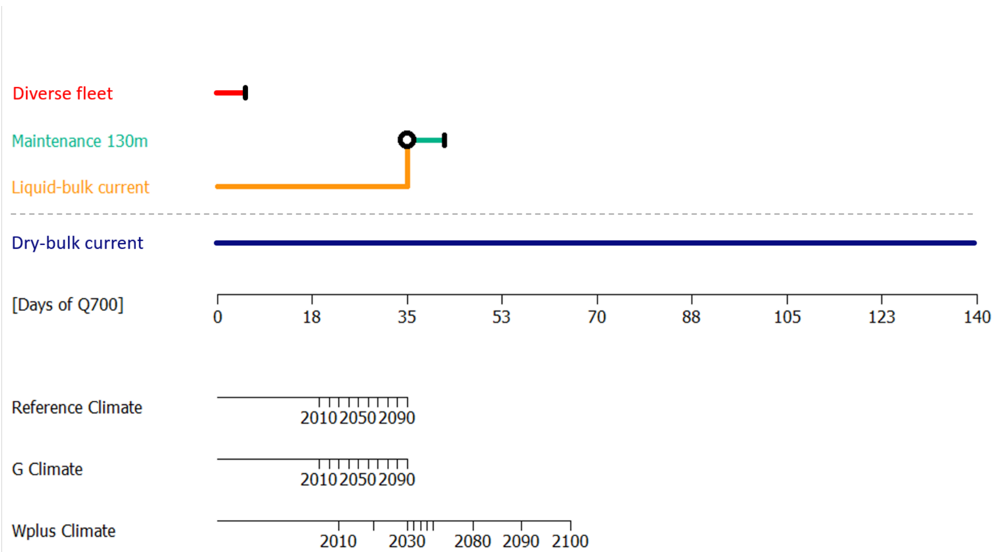


Figure 1: Pathways for Q700

1
Introduction

1.1. Context

The river Rhine has its source in Graubünden, Switzerland, and flows through Germany towards The Netherlands where it crosses the Dutch border at Lobith. Then, it splits at Pannerden into the branches Waal and Pannerdensch-Kanaal. With a total length of 1233 km, it is considered as one of the largest rivers of Europe and also one of most import waterways of Europe, as it is used to transport 63% of all cargo transported by inland waterways in Europe (Jonkeren, 2005).

Although inland waterways are considered one of the most reliable transport modes, it is very vulnerable to climate change, more than other transport modes such as rail and road transport (Christodoulou & Demirel, 2018). This is because the inland vessels are dependent on the river's water level, which is related to the discharge. The discharge fluctuates throughout the year and depends on precipitation and evaporation in the river basin area. Due to climate change, it is expected that the number of days with low and extremely low discharges will increase during summer and autumn. Besides, it is expected that the absolute values of these low discharges reduce in the future (Middelkoop et al., 2001). In other words; the water levels will be lower, and the number of days with low and extremely low water levels will increase.

The most recent example of such an extreme event is the drought in 2018 in the Netherlands. With an average precipitation deficit of a maximum of 309 mm nationwide, 2018 is in the top 5 of historical dry years, of which July 2018 was the driest month in history (Kramer et al., 2019). It was also one of the longest dry periods, forcing inland waterway vessels to reduce their load to decrease the draft (Schuetze, 2018). Periods with extremely low water levels have a large effect on the economy. For example in 2018 when several gas stations had to close as a consequence of the reduced load of tankers, which led to empty fuel stocks at the stations (Winters, 2018). In a study on the economical consequences of the drought in 2018, (Streng et al., 2020) calculated a negative impact of €295 million in the inland waterway transport sector in the Netherlands and even €2,4 billion for the IWT sector in Germany.

To reduce the impact of low water levels on the IWT and economy in the future, adaptation measures are needed. Even though many adaptation measures can be considered, not all of them are equally effective (Kievits, 2019). Also, due to the positive trend of inland waterway transport and the expected climate change, the lifespan of being effective is measure dependent (de Vries, 2013).

1.2. Relevance

It is essential to maintain the current IWT capacity and promote a modal shift of transport by road and rail to IWT, which is favourable for the sector itself but, it is also essential for the economy, society, and climate (Hassel & Menist, 2020). Research performed by Medda & Trujillo (2010) showed that inland waterway transport generates less CO2 emissions, congestion, and noise than road and rail transport.

Due to climate change, the modal shift and capacity of inland waterways are under pressure. Waterway managers like Rijkswaterstaat (RWS) and companies that depend on inland waterway transport such as freighters, shippers and other logistic companies, have to make decisions and investments based on trade-offs and predictions which are not available yet. Moreover, the river Waal is one of the essential branches of the Rhine in the Netherlands. It is responsible for 80% of the Rhine's total discharge during low discharges, and it connects the Port of Rotterdam to the hinterland. Considering the most recent extreme drought in 2018, it is crucial to know how and when to adapt to reduce the impact on inland waterway transport.

The most recent extreme drought in 2018 has a return period of 20 years when taking climate change into account (Kramer et al., 2019). This is a problem we face today and in the future. It is important to think ahead and use adaptive planning to deal with unexpected developments in climate change so the impact of low water levels on inland waterway transport can be reduced.

1.3. Gaps in knowledge

At this moment, many studies can be linked to the impact and consequences of climate change on inland waterway transport. Most of these studies focus on the situation for which low discharges prevail on the river Rhine. The welfare effects of drought are studied (Jonkeren, Ommeren, & Rietveld, 2007),(Jonkeren, 2005),(van Hussen et al., 2019), but also the impact on the loading factor of inland vessels (van Dorsser et al., 2020).

Deltares is working on a study on behalf of Rijkswaterstaat, called 'Climate Resilient Networks Rijkswaterstaat 2050' (in Dutch: Klimaatbestendige Netwerken Rijkswatersaat 2050). The part of this project that focuses on inland waterways, Deltares studied the navigable depth and width for different climate scenarios for the years 2050 and 2085. They indicated the location and size of bottlenecks that will occur during Agreed Low Discharge(ALD), which is the minimum discharge for 95% time of the year, but not when and for how long this is a bottleneck.

Measures to reduce the impact of low discharges are often mentioned in the literature. In a few studies, some are proposed as a possible option but are not analyzed by performing simulations (Bosschieter, 2005), (van Hussen et al., 2019), (Christodoulou & Demirel, 2018), (Scholten et al., 2017). The thesis by (Kievits, 2019), elaborates a little bit further on possible measures and predicts the impact they have on the amount of transported load in the year 2050 for two different climate scenarios.

The mentioned studies do not take the duration and timing of periods with low discharges into account. However, the duration of those periods affects the economy's impact and the type of measure to take. Since the droughts' duration and timing have not been considered yet, there is no indication of the lifespan of measures. Therefore it is difficult to make trade-offs between adaptation measures and assess different adaptive pathways.

1.4. Problem statement

The drought in 2018 caused many problems for inland waterway transport, which negatively impacted the economy. The discharge at Lobith was 156 days below the threshold value of 1020 m^3/s, forcing freighters to reduce the load of inland vessels. The estimated welfare loss on the Dutch economy caused by the drought in 2018 is even estimated to be €295 million (Streng et al., 2020). Taking climate change into account, summers will become dryer, and droughts will occur more often and take longer (Middelkoop et al., 2001). In other words, it is predicted that events similar to the drought of 2018 will occur more often. Although possible measures are known, little is known about their lifespan, and when to implement the adaptation measure because no one can tell exactly how the climate will change, the economic development will be or how other deep uncertainties will develop (Haasnoot et al., 2019). Therefore, it is difficult for decision-makers like Rijkswaterstaat, to make a trade-off between different options on how and when to adapt to more periods with low discharges in the future.

1.5. Scope

The scope of this study is limited to the hydrodynamic characteristics of the river Waal and the inland transport characteristics from Rotterdam to Duisburg and from Rotterdam to Wesseling (Figure 1.1). The scope is based on several reasons. First, this thesis will partially elaborate on the thesis performed by Kievits (2019), who developed a framework for the impact assessment of low discharges on the performance of inland waterway transport between Rotterdam and Duisburg. Secondly, there are no bottlenecks expected on the branch between Rotterdam and Gorinchem when the dry climate scenarios W_H and $W_{H,dry}$ for both 2050 and 2085 are taken into account (Van der Mark, 2019a). The same study already identified bottlenecks for the year 2050 and 2085 on the River Waal, depicted in Figure 1.1 by the solid blue line. In defining the bottlenecks, bedforms are not taken into account. These are short-term morphological developments that can differ from day to day, which is not relevant on the considered time horizon.

The time horizon for which the timing of tipping points will be determined lasts until the year 2100. For this time frame, discharge time series are available, generated by an HBV-model based on KNMI '06 climate scenarios. The discharges are generated for Lobith, so the water depths related to these discharges can be determined for the section downstream of Lobith.

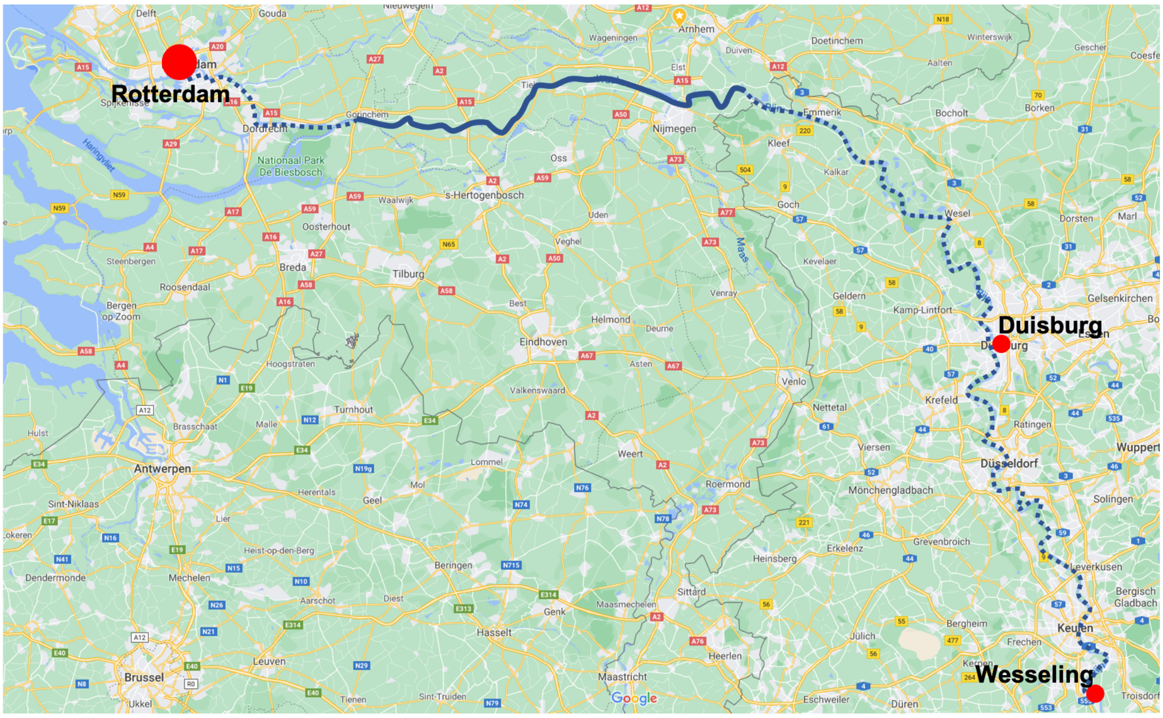
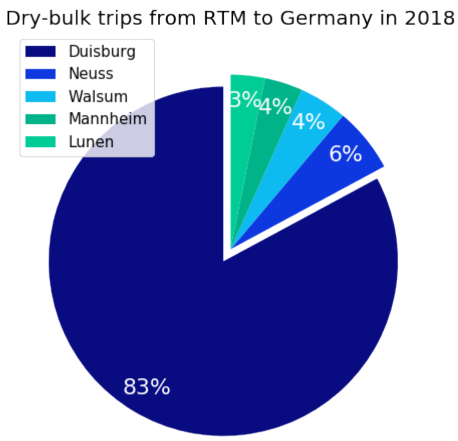
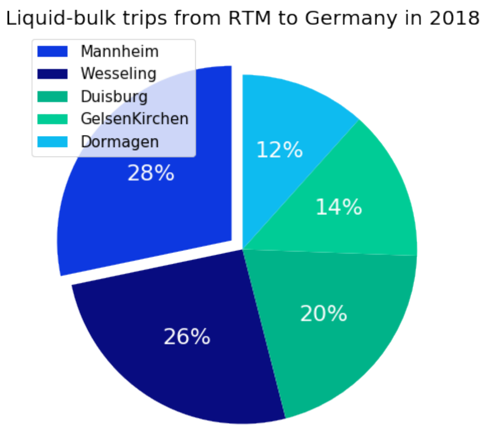


Figure 1.1: The considered corridor

This thesis will focus on the river Rhine, as this is one of the most important rivers of Europe for inland waterway transport (Jonkeren, 2005). The consequences of low water levels are more significant for dry bulk and liquid bulk than for container transport. Therefore, this research will only consider a dry and liquid bulk supply chain that navigate over the Waal branch. As there are many inland ports reachable by sailing over the River Waal, a selection has been made of two inland ports based on data analysis on the IVS90 data of 2018. The inland ports in Germany are compared on the share of total vessels with origin Port of Rotterdam and as destination an inland port in Germany. The Rotterdam - Duisburg corridor is considered for the dry bulk supply chain, as most departed vessels from Rotterdam have Duisburg as destination (Figure 1.2a). For liquid bulk vessels, most trips leave Rotterdam for Mannheim and Wesseling (Figure 1.2b). Because the share between these ports does not differ much and Wesseling is closer to the Waal branch, the Rotterdam - Wesseling corridor is considered during the liquid bulk supply chain research.



(a) Dry-bulk destinations



(b) Liquid-bulk destinations

Figure 1.2: Top 5 destinations in Germany for vessels departed from Rotterdam, IVS90

1.6. Research objective

This thesis aims to assess the performance of IWT during increasing periods of low flow and to determine which low flow condition the IWT-system no longer meets its objective. Consequently, the goal is to demonstrate that this condition can be affected by implementing adaptation measures and to define moments on a time scale up to the year 2100 when these conditions occur. To this end, the following research question is addressed:

What is the maximum duration of a low flow period the inland waterway transport system can cope with on the Rotterdam - Wesseling corridor and when is this period expected to occur, following the Dynamic Adaptive Policy Pathways approach?

1.6.1. Research approach

The Dynamic Adaptive Policy Pathway (DAPP) approach is used as a starting point for this research because the structure and steps of this approach cover objectives similar to the research objective. The essence of the DAPP approach is to develop an adaptive planning that can cope with deep uncertainties which, for example, a researcher or a decision-maker has when the concerned time frame consists of many years in the future (Haasnoot et al., 2019). No one can tell exactly how external factors such as the development of the world economy, climate change, population growth, or new technologies will unfold. This method helps with planning and makes it possible to make adjustments to the applied strategy if the future unfolds differently than expected.

DAPP is based on the Adaptation Tipping Point (ATP) approach, which focuses on a policy or measure individually and determines under which conditions the measure will fail. Eventually, when the tipping points of all the possible measures are identified, adaptive pathways are constructed to visualize the possibilities on how to reach the set objective in the concerned time frame. In Figure 1.3, the pathways for possible adaptation measures that reduce the impact of low water levels are constructed for a fictional case. The tipping points are indicated by the small vertical bars at the end of a pathway. For example, the measure 'small dredging' does not meet the requirements after approximately 85 years, the measure has reached its tipping point. To achieve the objective, one must adapt to a different path. The next option could be using smaller ships, however, as can be seen in the figure, this measure could also have been taken from the beginning. Making a trade-off between the adaptation measures and pathways will identify the most promising policies.

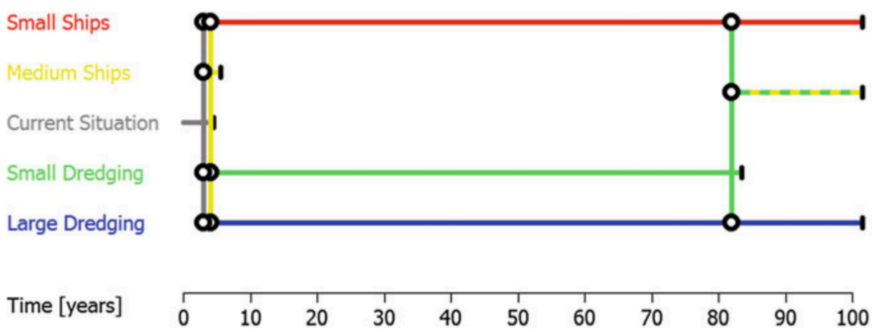


Figure 1.3: Generated pathways for a fictional case, (Haasnoot et al., 2019)

The DAPP approach consists of seven steps, which are:

1. Decision context
2. Assess vulnerabilities and opportunities and identify ATP's
3. Identify and evaluate options
4. Design and evaluate pathways
5. Design the adaptive strategy
6. Implement the strategy
7. Monitor the strategy

For this research, only step 1 till step 4 will be performed. From step 5, the method focuses on implementing the adaptation policy which will not contribute to achieving the research objectives and is therefore out of the scope of this thesis.

Step 1: Decision Context

The first step is to describe the system's characteristics and its objective, not to be confused with the research objective. To ensure the objective is met, performance indicators and thresholds have to be specified to assess the performance of the IWT-system. Furthermore, in this step it is also essential to determine a parameter representing the condition for which the performance of the IWT-system is measured. In further descriptions, the parameter is referred to as the 'conditional parameter'. This parameter is also used on the x-axis of the pathway visualization. Besides, uncertainties are identified that could change the prediction of how the future unfolds. One could think of different climate scenarios in which different uncertainties are considered. These scenarios are used to make an estimation of the moment of occurrence of tipping points.

In Chapter 2 the following research question is addressed, which covers step I of the DAPP approach:

1. What are the characteristics of the IWT-system between Rotterdam and Wesseling?

(a) What are the uncertainties of the system and which performance indicators describe the system's objective?

(b) How has IWT responded to low flow periods in the past?

(c) Which adaptation measures could be implemented in the IWT-system to better cope with low flow?

Step 2: Assess vulnerabilities and opportunities and identify ATP's

In the second step, the current policy is assessed by using the specified performance indicators and thresholds. A tipping point is reached when the indicator reaches its threshold during a specific condition. The condition at which a tipping point occurs, the tipping condition, is determined with a modelling approach. The model can be set up as a bottom-up or top-down approach. A bottom-up approach is a vulnerability assessment that identifies unacceptable outcome thresholds before assessing the timing of tipping points using scenarios. The top-down approach uses either multiple static scenarios or transient scenarios as inputs to identify unacceptable outcome thresholds (Haasnoot et al., 2019). This thesis will use a bottom-up approach to identify the conditions for which the system starts to perform unacceptably by applying a stress test.

To develop a simulation model that can be used to determine tipping points for IWT, in Chapter 3 the following research question is addressed first:

2. How can the performance of the inland waterway transport system during low flow periods be simulated?

Consequently in Chapter 4, the model is validated by concluding on the research question:

3. How does the simulation model perform compared to IVS90 data?

Finally, the model is used in the first section of Chapter 5 to determine tipping points of the current system and by doing so, completing step II of the DAPP approach. To this end, the following research question is addressed:

4. What is the tipping condition of the current inland waterway transport system before adaptation measures are implemented?

Step 3: Identify and evaluate options

The third step addresses possible adaptation measures that can be implemented to achieve the objective of the system. In the previous step, the tipping point of the current system is determined. In this step, the possible measures are assessed and their tipping points are identified. Finally when all tipping points are know, the timing of the tipping points can be determined according to transient scenarios.

The third step of the DAPP approach is completed in Chapter 5 by addressing the research question:

5. What is the effect of implementing adaptation measures on the tipping condition of the inland waterway transport system and when are the tipping conditions expected to occur?

Step 4: Design and evaluate pathways

In the final step, pathways can be constructed to visualize the tipping points of the current situation and the situation with implemented adaption measures, including the timing in different climate scenarios. In the last section of Chapter 5 the pathways are constructed and are used in Chapter 7 to conclude on the main research question:

What is the maximum duration of a low flow period the inland waterway transport system can cope with on the Rotterdam - Wesseling corridor and when is this period expected to occur, following the Dynamic Adaptive Policy Pathways approach?

1.6.2. Guide to reader

The outline of the report is presented in Figure 1.4, which gives an overview of the main research segments. In Chapter 2, the first research question is answered by conducting a literature study and a data analysis which resulted in a description of the considered system. This relates to step I of the DAPP approach. Chapters 3 and 4 answer the second and third research question regarding the model development and method used. Because no specific step of the DAPP approach considers model development, this Chapter is an intermediate step before step II of the DAPP approach can be executed, in which the developed model is applied. In Chapter 5 research question 4 and 5 are answered, regarding the results of this study. First, the performance of IWT during increasing periods of low flow is assessed on the basis of performance indicators. Then, tipping points are determined of the current IWT-system which is in accordance with step II of the DAPP approach. Consequently, step III is executed which considers the tipping points of the IWT-system with implemented adaptation measures. Finally, the timing of tipping points is estimated and the pathways are constructed in the last section of Chapter 5, completing step IV of the DAPP approach. Chapter 6 reflects the findings of this study that can be related to the performance indicators, tipping points an timing of tipping points. Finally, in Chapter 7, the conclusions are listed and recommendations for further research are given.

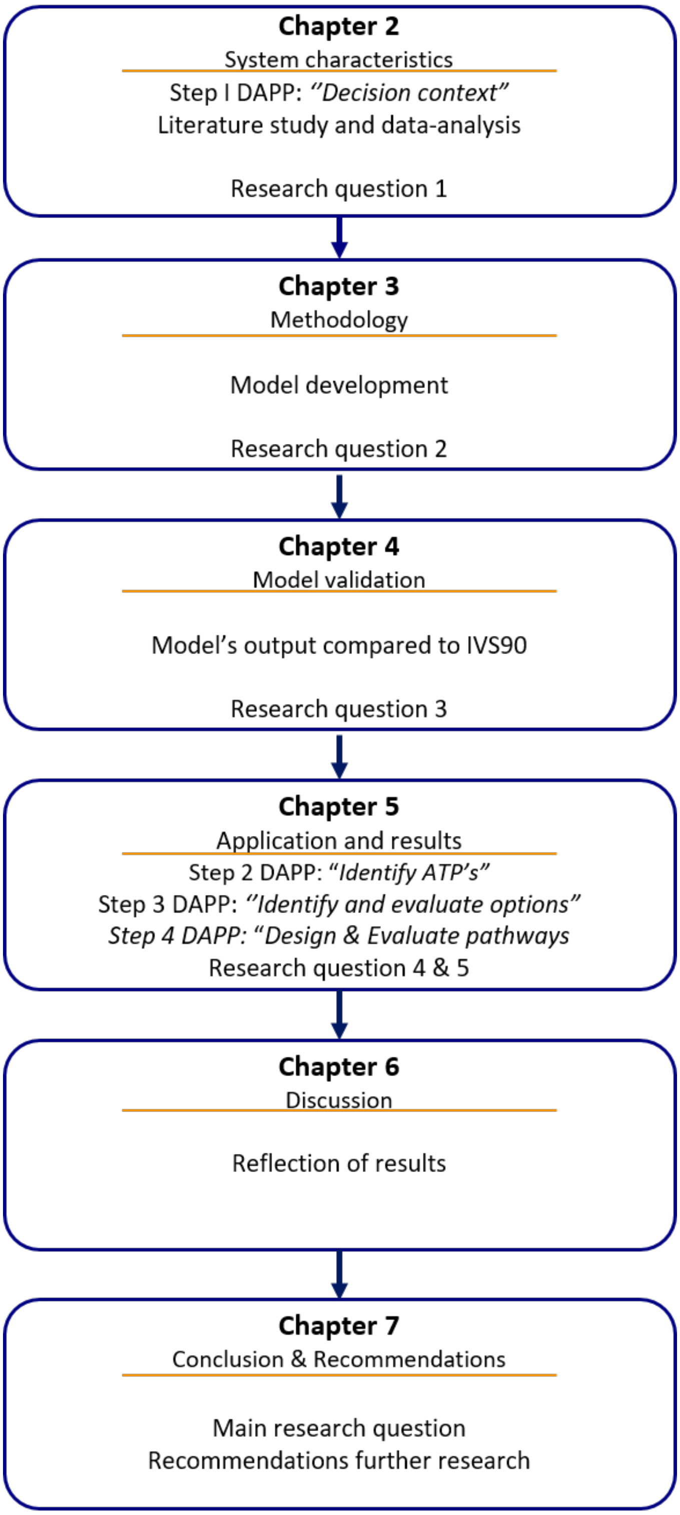


Figure 1.4: Thesis outline

2
Characteristics of the inland waterway transport system

This chapter covers Step I of the Dynamic Adaptive Policy Pathways approach and addresses the following research question:

1. What are the characteristics of the IWT-system between Rotterdam and Wesseling?
   (a) What are the uncertainties of the system and which performance indicators describe the system's objective?
   (b) How has IWT responded to low flow periods in the past?
   (c) Which adaptation measures could be implemented in the IWT-system to better cope with low flow?

In Step I, the setting of the system is described in terms of the system's characteristics, the objective of the system, uncertainties that have an effect on the system and opportunities that contribute to the objective. First, the uncertainties that affect the inland waterway transport system are described, together with its objective and performance indicators that represent this objective. Consequently, the behaviour of the inland waterway transport system between Rotterdam and Wesseling is analysed by performing a data-analysis on IVS90. Finally, opportunities in terms of adaptation measures are explained that can contribute to the objective of the system.

2.1. Uncertainties of the system

In general, a river has the primary function to supply fresh water, provide habitat and food for many of the earth's organisms, ensure flood safety for surrounding areas, and transport water, sediment and ice and provide routes for navigation (Hiemstra, 2018). All of these functions are affected by external factors, of which it is uncertain how those external factors develop in the future. Considering the objective of this research, only the effect of external factors on navigation are mentioned.

2.1.1. Climate change

The river Rhine is a combination of a rain-snow river but will become more rain-dependent due to climate change (Jonkeren, Rietveld, & van Ommeren, 2007). Precipitation in winter is expected to rise in increase in the upcoming years. Combined with temperature rise, a smaller part of this precipitation can be stored as snow in the mountains. Consequently, more rain has to be discharged by the rivers, resulting in higher average water levels and more occurrence of floods. In contrast to the summer, where lower average water levels are expected: the contribution of meltwater has decreased (less formation of snow during winter), a larger volume will evaporate due to the temperature rise, and in addition, less precipitation is expected. So during summer and autumn, the water levels in the River Rhine will become lower, and the duration of the period with lower water levels will increase (Middelkoop et al., 2001). Although the increase in water levels during floods will affect inland waterway transport, they are less disruptive than low flows because of their relatively low duration and frequency (Christodoulou & Demirel, 2018). During low water levels, inland waterway vessels use a reduced load factor to minimize their draft, and as a consequence, more vessels or more trips are needed and transportation costs increase (Christodoulou & Demirel, 2018). Furthermore, the navigable width of the channel reduces causing congestion and therefore an increase in travel time (Verschuren, 2020) Also, due to more trips and larger operational fleet size, (un)loading times at inland ports and waiting times at locks increase, resulting in extra delays of the vessels (van Hussen et al., 2019).

2.1.2. Climate scenarios

As no one can tell precisely how the future unfolds, it is uncertain to what extent climate change will develop and how large the impact will be on IWT. The Intergovernmental Panel on Climate Change (IPCC) provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. The Royal Netherlands Meteorological Institute (KNMI) represents the Netherlands in the IPCC and developed different climate scenarios to provide insight into climate change in the Netherlands. The scenarios are presented in a report and were published in 2006 for the first time. The so-called KNMI '06 climate scenarios. In 2014 a new report was published (KNMI '14), which is the most recent report available. The following report is expected to be presented in 2023.

KNMI'06 & KNMI'14

KNMI describes four scenarios for a time horizon around 2050 and 2085. They form the boundaries in which the climate in The Netherlands probably will develop according to the most recent insights. Each scenario combines two main factors by the two time horizons, change in global temperature rise and the air circulation pattern.
At this moment, there are two climate reports available, of which KNMI '14 is an updated version of KNMI '06. It would be a logical choice to use the most recent climate scenarios for this study as it is based on the latest insights and thus should contribute to more reliable results. However, comparing the available river discharge data based on KNMI '06 and the available data based on KNMI'14, it turned out that the climate scenarios reported in 2006 are more helpful for this research. See also the next sub-section. KNMI climate scenarios are based on regular assessments of the scientific basis of climate change provided by IPCC. The most recent IPCC report on which KNMI '14 is based has only minor differences compared to the IPCC report used for KNMI '06. Therefore, the general climate change described by KNMI'14 strongly corresponds to the climate described in the KNMI'06 report. This also indicates that the general climate change indicators are robust (Klein Tank et al., 2015). However, there are a few differences. First of all, the notation for each of the four scenarios is slightly different. It is a minor detail, but important to prevent confusion. Secondly, the time horizon after 2050 for which values are predicted seem to differ between the two reports. For both reports, the models used for the predictions have performed calculations until 2100. However, to determine values for natural variations that describe a particular climate, 30-year averages are calculated (Klein Tank et al., 2015). Following this time frame of a 'climate', 2085 is the ultimate time horizon in a time frame of 30 years. In Table 2.1, the main differences between the two reports are shown. In essence, KNMI'14 scenarios cover a broader range of climate parameters and indicators than KNMI'06, and both reports show plausible scenarios of climate change in The Netherlands. Some predictions from KNMI'06 seem a little bit less possible from the latest insights; however, according to KNMI, the report of 2006 can still be used for specific applications.

KNMI '06			KNMI '14		
	2050	2100		2050	2085
G	+1.0	+2.0	G_L	+1.0	+1.5
G+	+1.0	+2.0	G_H	+1.0	+1.5
W	+2.0	+4.0	W_L	+2.0	+3.5
W+	+2.0	+4.0	W_H	+2.0	+3.5

Table 2.1: Differences between KNMI'06 and KNMI'14

2.2. System objective

Because cargo can be transported in large volumes, IWT has the lowest fuel consumption per transported cargo unit and, therefore, the lowest greenhouse gas emissions than other transport modalities. In terms of capacity, it is predicted that the inland waterway network will not face any problems in the coming 50 years (de Vries, 2013). It is not only important for the sector itself to promote IWT but also for the economy, society and climate. Unfortunately, climate change is endangering the position of inland shipping, in particular, because the sector has to compromise on reliability during low flow periods. Therefore, objective on the inland waterway transport of the considered dry-bulk and liquid-bulk supply chain is defined here as to perform better than railway transport during low flow periods. In this report, the term 'IWT-system' refers to the considered dry-bulk and liquid-bulk supply chain.

2.2.1. Performance indicators & Targets

An essential segment of the Dynamic Adaptive Policy Pathways Approach is the determination of adaptation tipping points, which should not be confused with adaptation turning points. The difference between a turning point and a tipping point lies in the nature of the threshold to be reached (Riquelme-Solar et al., 2015). The threshold value is a specific target of the performance indicator that can be reached until the considered system does not meet its objective anymore. Adaptation tipping points have a threshold value related to formal policy objectives, and this implies changes may have a discrete character much like state transformations in physical systems (Riquelme-Solar et al., 2015). Adaptation turning points are based on threshold values that include social preferences, stakes and interest, and turning points will only occur after coordination between all actors after a growing realization that climate change results in conditions they all consider unacceptable. In other words; a moment when they experience all the same problem.

The inland waterway transport sector knows many actors such as river managers, shippers, skippers, customers, port authorities and other IWT companies. Each actor has its own objective and therefore experiences different key performance indicators and targets. In other words, a situation that causes a problem for one actor in the system does not have to be a situation for which other actors experience any problems. This makes it difficult to describe the quantitative state of the supply chains by one performance indicator and assign a threshold for it that indicates a problematic situation occurs when determining adaptation tipping points. The analysis in chapter 5 will determine which is most suitable to express the objective of the considered supply chains:

- Number of Trips
- Transported cargo
- Total transportation costs
- Transportation costs per ton
- Transportation costs per ton kilometer

2.3. IWT during low flow

Vessels that use the Dutch inland waterways have to report information about their trip to the IVS (*in Dutch: Informatie- en Volgsysteem voor de Scheepvaart*) database when they pass locks, bridges, and other specific traffic locations along the waterway. In Figure 2.1, the so-called IVS-posts on the river Waal are marked with a red circle. The IVS database , is maintained by Rijkswaterstaat to have a clear overview of the full shipping activity on the waterways and is used by local water managers, ports and in some cases the data is shared for research.

In the first quarter of 2019, Rijkswaterstaat updated the old system, IVS90, which was outdated and not performing well anymore. The current system is called IVS Next and is more suitable for the future. For this research, Rijkswaterstaat has shared IVS-data from 2013 and 2018 that is gathered on the Waal (see also Figure 2.1). The data is very useful to analyse the activity on the Waal and its behaviour during specific periods.

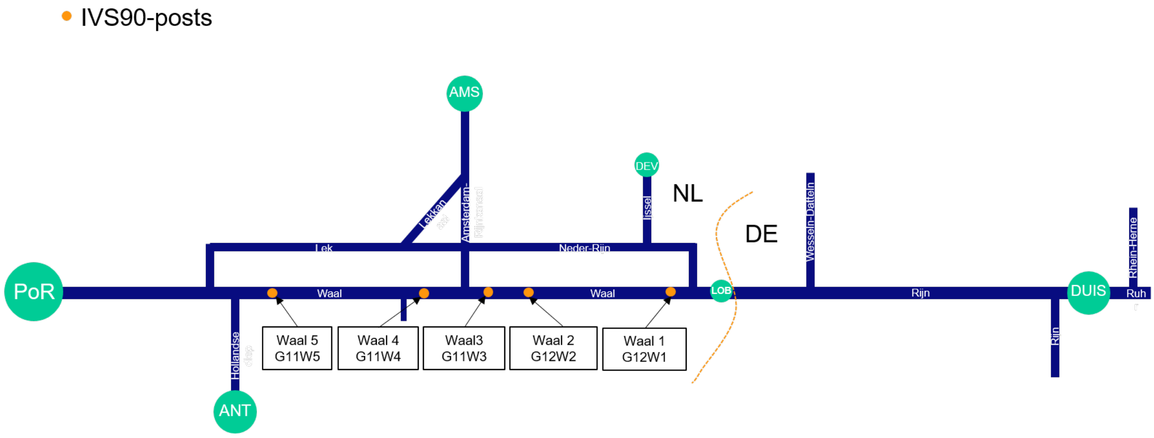
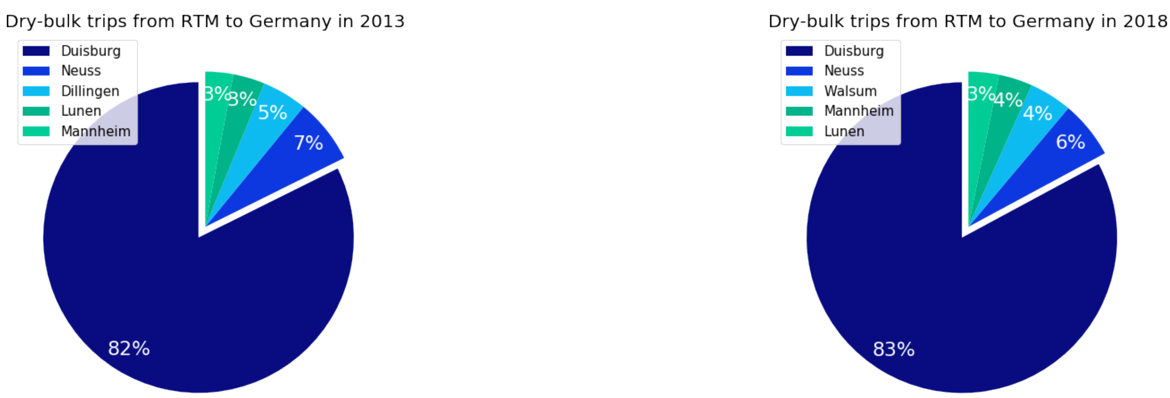


Figure 2.1: Schematisation of IVS-posts on the Waal

Most frequently called inland ports in Germany

An analysis of the data is performed to delineate this research's scope further and gain insight into the inland waterway transport activity that falls within the scope. First, the IVS data is used to determine which inland ports in Germany most often serve as a destination for vessels departing from Rotterdam. Because container vessels are out of this research scope, only dry-bulk and liquid-bulk transport are considered. For this analysis, the number of vessels that have passed IVS-post 'Waal 5' and have as departure city Rotterdam and as destination country Germany, are filtered from the data-sets. Then, the vessels are grouped based on their destination port in Germany. To results of the analysis of 2013 and 2018 are compared to check if there is a difference between a relatively wet and relatively dry year. As can be seen in Figure 2.2a, the top destination for dry-bulk vessels that have departed from Rotterdam is Duisburg. In addition, there is no diverting to another port during a 'dry' year with low water levels like in 2018 (Figure 2.2b).

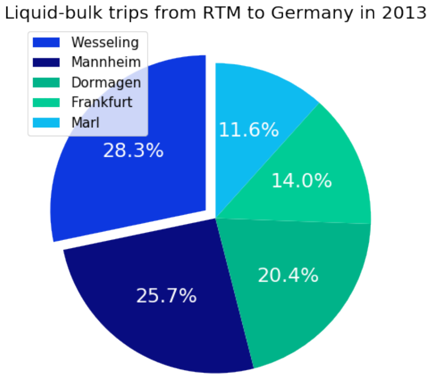


(a) Share of total trips to Germany in 2013

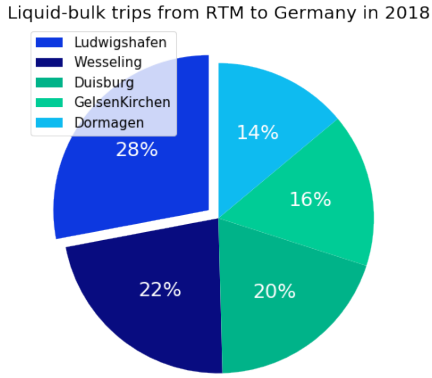
(b) Share of total trips to Germany in 2018

Figure 2.2: Top 5 most frequently called inland ports by dry-bulk vessels in Germany departed from Rotterdam, IVS90

For liquid-bulk however, there is no such dominant destination as Duisburg is for dry-bulk. In 2018, the top destination is the second most called port in 2013. Given the small difference between the shares, it is probably due to a difference in demand at that time.



(a) Share of total trips to Germany in 2013



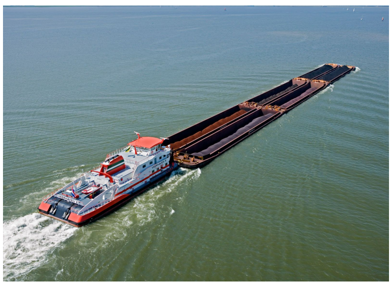
(b) Share of total trips to Germany in 2018

Figure 2.3: Top 5 most frequently called inland ports by tankers in Germany, departed from Rotterdam, IVS90

Active fleet on the corridor

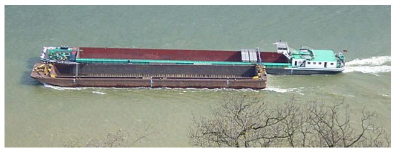
In 1954, the Conférence Européenne des Ministres des Transports (CEMT) accepted an international classification system for inland waterways. The classification system's starting point was to classify each waterway by the largest vessel that could pass safely, considering five types of vessels mostly used at that time. Due to the upward trend of increasing ship size and capacity, CEMT-classes are not representative of the current fleet anymore, according to Rijkswaterstaat Koedijk (2020). Therefore they updated and extended the CEMT-classification method by adding new vessel sizes and labelled each class with representative names (RWS-classes). To see the full classification, reference is made to Appendix A.

There are three different vessel types used for inland transport which are motor vessels, push-barges and convoys (Figure 2.4).



(a) Push-barge unit with 6 barges (B-class)

(b) Motor vessel (M-class)



(c) Convoy of motor vessel with one barge alongside (C-class)

Figure 2.4: Vessel types used for inland waterway transport

Push-barge units consisting of 6 barges (RWS-class: BII-6) is the most preferred class to transport dry-bulk from Rotterdam to Duisburg due to its high capacity. The downside of this class is that the large dimensions cause safety issues when the water level drops below N.A.P. +8.50 meter at Lobith (Staatscourant, 2020). Dry-bulk is then transported by push-barge units consisting of 4 barges (RWS-class: BII-4), a combination with smaller dimensions and less capacity. Because the vessels have less capacity and sail with a reduced load factor due to the low water levels, more trips are needed to transport the same amount of cargo. If the water level drops even more, also BII-4 vessels are taken out of operations. To compensate for the capacity loss during low flow periods, motor vessels and convoys are deployed van Hussen et al. (2019). The use of motor vessels and convoys leads to increased ship movements, which leads to congestion of the network (Verschuren, 2020). The effect of an increase in the number of trips during low flow periods can also be seen in the IVS-data of 2018, Figure 2.5. For this analysis, all trips that have passed IVS-post 'Waal 5' and have as destination Rotterdam or Duisburg are filtered from the data-set and, consequently, are summed on a daily frequency. A significant increase in the number of trips is visible when the water discharge at Lobith drops.

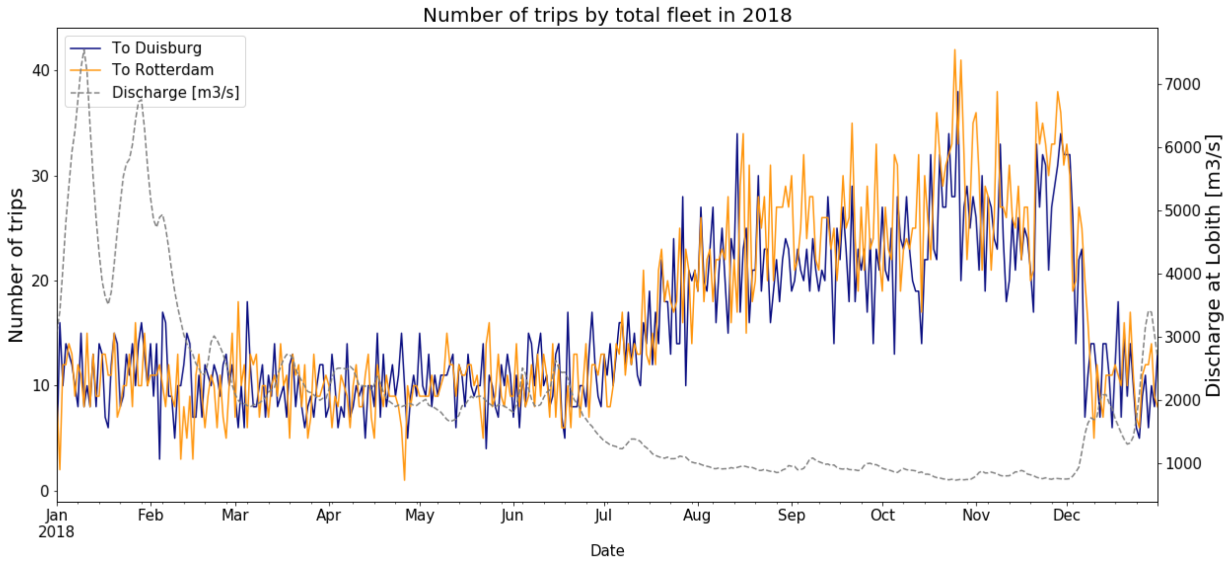


Figure 2.5: Increase of trips during low flow, IVS90

As mentioned, the fleet size and operational RWS-classes on the corridor depend on the available water depth in the waterway. To have more insight into which vessel classes are used to transport dry-bulk to Duisburg, the number of passages by each RWS-class at the IVS-post 'Waal 5' has been extracted from the data. Then, if the number of passages is divided by the cycle time of one vessel, an estimation can be given on the fleet size:

$$Fleet\ size = \frac{Number\ of\ trips\ by\ RWS_{class}}{Cycle\ time} \tag{2.1}$$

And:

$$Cycle\ Time = loading\ time\ +\ sailing\ full\ +\ unloading\ time\ +\ sailing\ empty \tag{2.2}$$

The cycle time is assumed to be two days for every vessel that ships cargo between Rotterdam and Duisburg, based on a sailing full speed of 2.25 m/s and a sailing empty speed of 4.5 m/s.

For the fleet size analyses, four different discharges values at Lobith are considered. The choice for these values is explained in Chapter 3. A discharge of 2500 m^3/s corresponds to water levels for which no bottlenecks occur and thus there are no restrictions for push-barges, and vessels use their maximum loading capacity. The other discharges can be classified as low, very low and extremely low, corresponding to 1020 $m3/s$, 850 $m3/s$, 700 $m3/s$ respectively.

The effect of different water discharges on the fleet composition described at the beginning of this paragraph is also reflected in the IVS-data of 2018, Figure 2.6. First of all, the bar diagram shows that there are 7 BII-6L units in operation during a discharge of 2500 $m3/s$ at Lobith but, no vessels are active when the discharge drops, confirming the fact that they are taken out of operations for safety reasons. Secondly, more BII-4 push-barge units become active when the discharge at Lobith decreases, as an alternative for the larger BII-6L units. However, when the discharge is extremely low (Q=700m^3/s), this RWS-class is also taken out of operations for safety reasons. Thirdly, the data shows a significant increase in fleet size of C4 convoys, which are motor vessels with three barges alongside. Apparently, more and more motor ships take barges alongside as the discharge decreases, especially for extreme low discharges. Lastly, the data shows that a few motor vessels are used to transport dry-bulk during low and very low discharges but that it is not the preferred ship type, probably because of their low capacity. However, when extreme conditions prevail, even motor vessels are frequently used to transport dry-bulk.

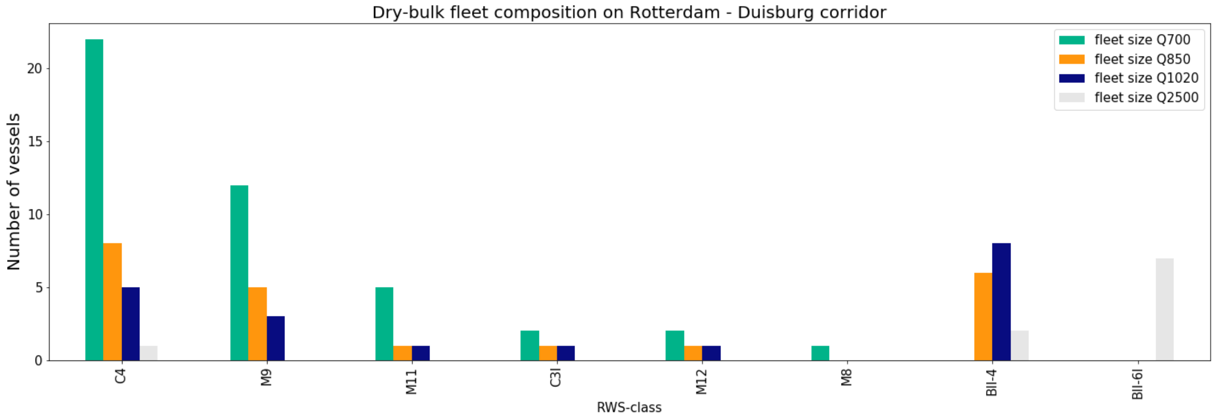


Figure 2.6: Dry-bulk fleet composition between Rotterdam and Duisburg, IVS90

The same analysis can be applied to the liquid-bulk supply chain to get an insight into the RWS-classes that are operational on the Rotterdam - Wesseling corridor. The IVS data gathered at IVS-post 'Waal 5' is filtered on tanker vessels and trips that sail from Rotterdam to Wesseling and vice versa. Then, the set is re-sampled to a weekly frequency because of less daily activity of this supply chain. Compared to dry-bulk, where the number of trips fluctuates around ten trips per day, liquid-bulk fluctuates around ten trips per week. In Figure 2.7 the total trips per week in 2018 of tanker vessels are plotted together with the discharge at Lobith. Starting from half June, the same reaction to the low flow period is visible by an increase in the total number of trips. However, halfway through the drought, suddenly, the number of trips drops in both directions.

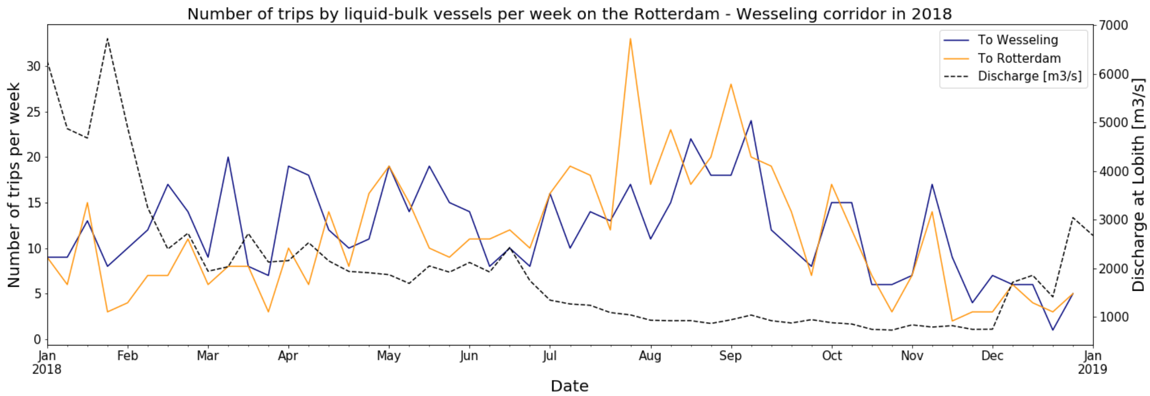


Figure 2.7: Number of trips by liquid-bulk vessels on the Rotterdam - Wesseling corridor in 2018, IVS90

To determine the fleet size of the operational RWS-classes for liquid-bulk vessels, equation 2.1 is applied in which a cycle time of 2.4 days is assumed. This is based on the distance between Rotterdam and Wesseling and a speed of 2.25 m/s and 4.5 m/s for sailing full and sailing empty, respectively. The results are plotted in a bar-diagram in Figure 2.8. The first thing that one notices is that for liquid-bulk, only motor vessels are used (M-type), as it is not possible to transport liquid-bulk in barges. Secondly, the most dominant RWS-class to transport liquid-bulk from Rotterdam to Wesseling is M8, followed by M9 and M12 vessels. Compared to the dry-bulk fleet, different flow regimes seem not to affect the fleet size of M8, M9 and M12 vessels. If the fleet size in- or decreases, it is in the order of 1 vessel, which is not a significant change that can be related to different flow regimes. A reason for the equal fleet size could be explained by the fact that motor vessels are the preferred vessels during low flow, and there are no alternatives for liquid-bulk like convoys(C4) are for dry-bulk.

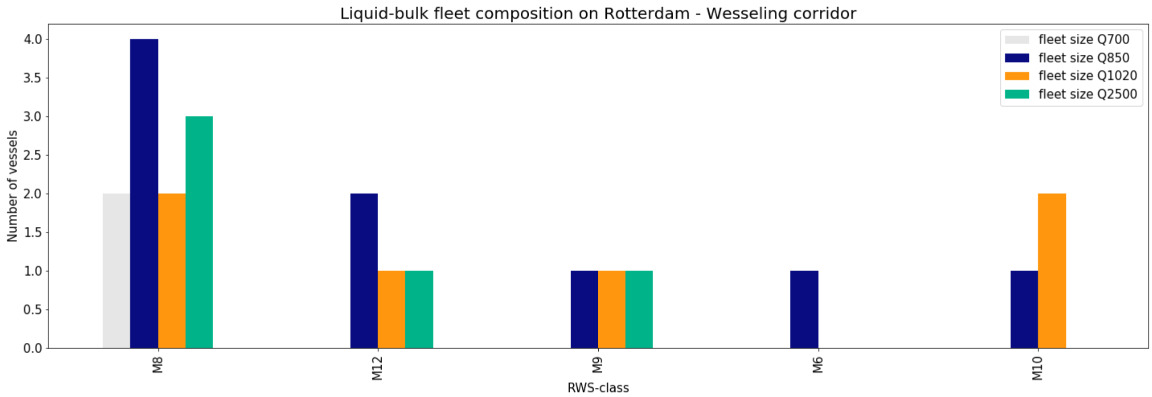


Figure 2.8: Liquid-bulk fleet composition between Rotterdam and Wesseling, IVS90

Transported cargo on the corridor

In this study, only dry-bulk and liquid-bulk transport are considered because these supply chains are more vulnerable to low water levels than container and break-bulk transport. Moreover, The Central Commission for the Navigation of the Rhine reported that dry-bulk and liquid bulk have by far the largest share types of cargo transported from Rotterdam to the hinterland (CCR, 2019). As a consequence of a reduced load factor of vessels, less cargo is transported per trip, and more trips are made to compensate for the loss of transported cargo. However, if the low water conditions prevail for a longer period or the water levels drop significantly, cargo loss cannot be compensated completely. The total transported volume decreases. During the drought of 2018, several gas stations in The Netherlands had to close as a consequence of the reduced load of tankers which led to empty fuel stock at the stations (Winters, 2018). Also, industrial companies in Germany who strongly depend on supply by inland waterway vessels had to reduce their production as the vessels could not deliver enough raw materials to keep production at 100% (Streng et al., 2020).

The effect of a decrease in transported cargo during a low flow period can also be seen in the IVS-data of 2018. For this analyses, the data of the same IVS-post is used as is used for the trip analyses in the previous paragraph. In Figure 2.9 the total weight of transported dry-bulk is plotted for the supply chain from Rotterdam to Duisburg and vice versa. First of all, there is a large difference in transported weight between both directions. This can be explained by the fact that large steel factories, such as Thyssenkrupp, are located in Duisburg, and they require large volumes of iron ore and coal as raw materials for their production. These are supplied from overseas to Rotterdam, where is it loaded on inland vessels to transport to Duisburg. Then the dry-bulk vessels sail back empty, resulting in a low transported weight downstream (orange line). Secondly, a decrease in transported weight upstream is visible during the dry period, starting in June and ending at the beginning of December.

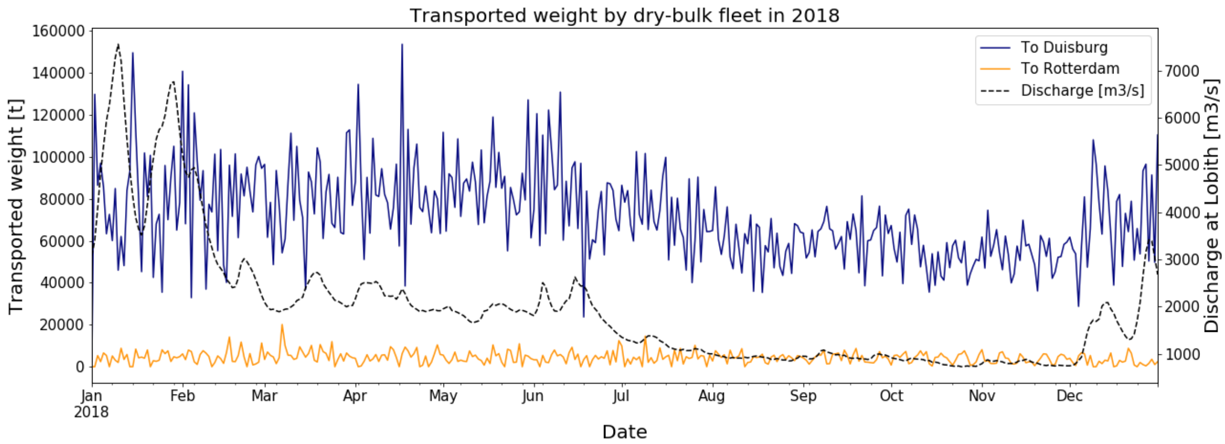


Figure 2.9: Transported dry-bulk weight on the Rotterdam - Duisburg corridor in 2018, IVS90

As mentioned earlier, during water levels for which push-barges can sail safely, units with six barges are preferred for dry-bulk transport to Duisburg as they have the largest capacity. When performing a more detailed analyses on the transported weight data, it can be seen in Figure 2.10 that BII-6 push-barge units have the largest share in transported weight, followed by C4 convoys and BII-4 units.

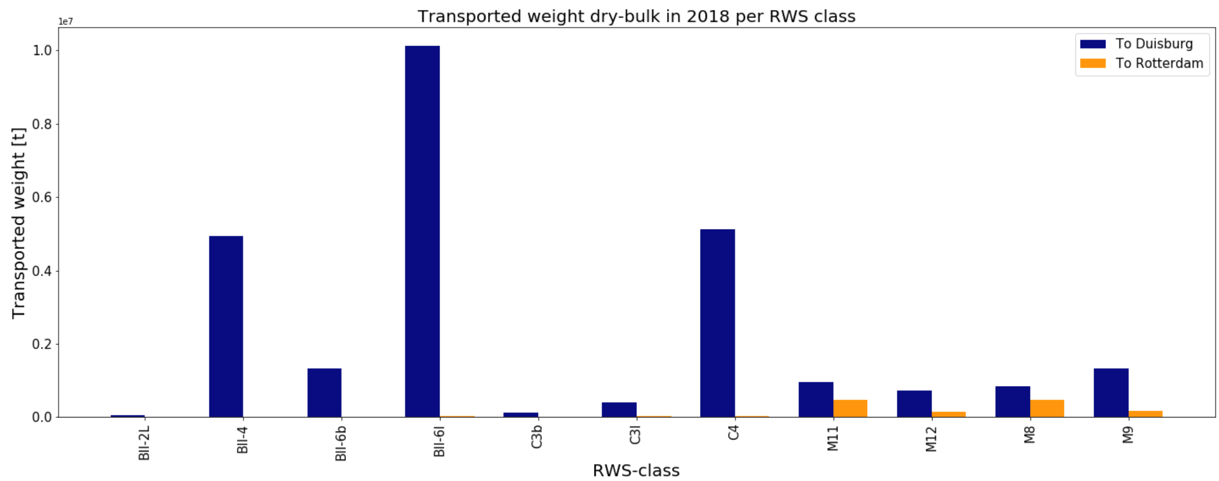


Figure 2.10: Transported dry-bulk weight on the Rotterdam - Duisburg corridor in 2018 per RWS-class, IVS90

Although the weekly number of tanker trips to Wesseling has slightly increased during the first half of the low flow period, the weekly transported cargo dropped significantly, as shown in Figure 2.11. Apparently, the applied load factors were so low that more trips could not compensate for the loss in transported cargo. In the downstream direction, from Wesseling to Rotterdam, the weekly transported cargo was not affected at the beginning of the drought but dropped in the period after. Liquid-bulk transport to Wesseling shows a significant decrease in weekly transported cargo during the drought of 2018 as can be seen in Figure 2.11.

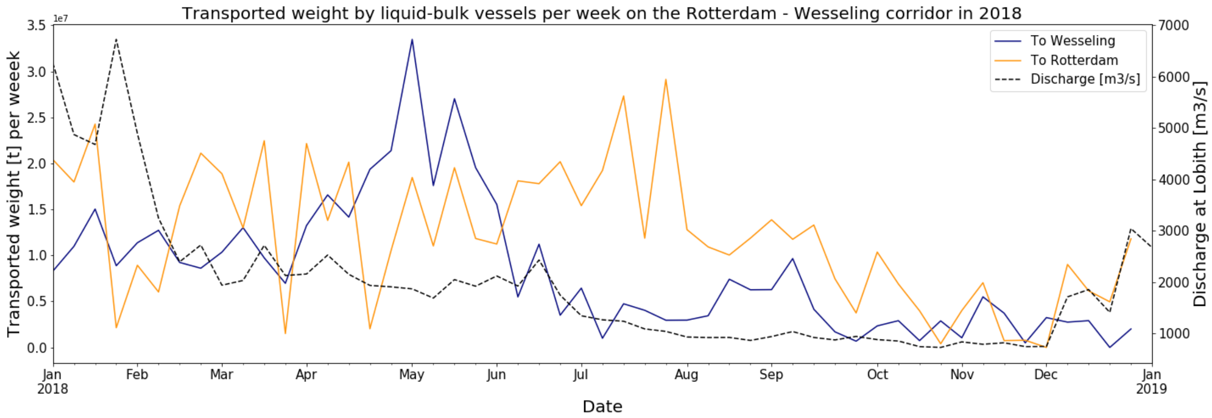
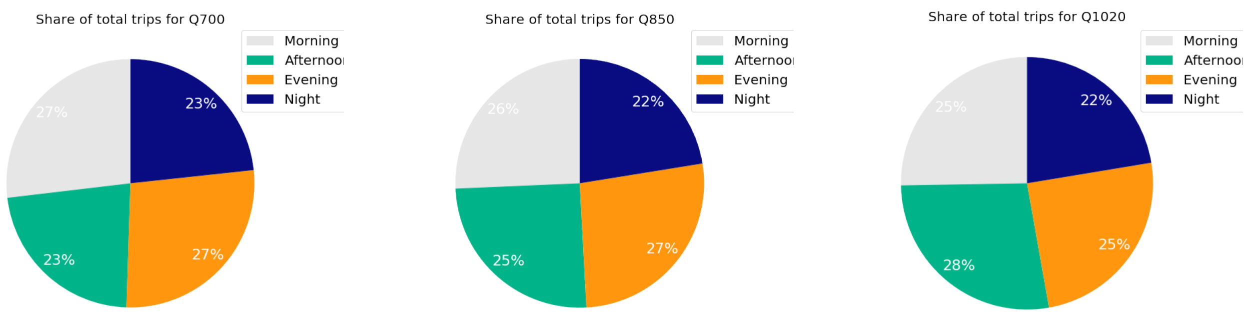


Figure 2.11: Transported liquid-bulk weight on the Rotterdam - Wesseling corridor in 2018, IVS90

Operational hours

Several studies on the impact of climate change on inland waterway transport propose an adaptation measure to increase the transport capacity during low flow periods by increasing the operational hours of vessels (Bosschieter, 2005, Krekt et al., 2011, Van Der Mark, 2021). The available crew size limits the number of operational hours of inland vessels. According to Bosschieter (2005), most vessels have a single crew which limits the vessels to 14 operational hours, sailing on a daily-trip basis or 18 operational hours, sailing on a semi-continuous basis. Increasing the operational hours to 24 hours increases the transport capacity of the fleet. In the same report, she states that there is an upward trend in the number of vessels that operate continuously, equivalent to 24 operational hours. To make this adaptation measure effective, companies at the departure and arrival ports should then also operate on a continuous basis. In 2011, six years after Bosschieter (2005), Krekt et al. (2011) wrote that at that time, only 25% of the companies operate around the clock. Thus much improvement can be made on this aspect to increase capacity during low flow periods. At this moment, ten years after the statement of Krekt et al. (2011), IVS90 data shows that the fleet's activity during low discharges at Lobith is more or less equally spread over 24 hours, indicating that vessels sail on a continuous basis. In Figure 2.12, the share of the number of trips that pass IVS-post 'Waal 5' are shown. The trips are counted for three different flow regimes at Lobith and are divided into morning, afternoon, evening and night passages.



(a) Intensity spread during Q = 700 $m3/s$ (b) Intensity spread during Q = 850 $m3/s$ (c) Intensity spread during Q = 1020 $m3/s$

Figure 2.12: Activity of dry-bulk vessels during the day in 2018, IVS90

2.4. Adaptation measures

Due to climate change, IWT will be affected more often by low flow periods. Adaptation measures can be implemented to make the IWT-system more climate resilient. Many reasonable adaptation measures can be found in literature, of which most of them can be divided into four sub-categories. Although numerous measures are proposed, not all of them are equally effective or realistic. In fact, implementing only one adaptation measure from one of the four sub-categories will not be sufficient to have a significant effect on the low flow problem (Van Der Mark, 2021). The following sub-categories can be defined:

- Infrastructural
- Fleet / Maritime
- Logistics
- Information provision

One could also think of dividing based on which actor should take the initiative or make the investment to realise the adaptation measure. If we look at the sub-categories, infrastructural measures are often taken by the government/river managers(e.g. Rijkswaterstaat), fleet / maritime measures by skippers and other private inland waterway transport companies, logistic measures by shippers and information providers by skippers and Rijkswaterstaat. To make IWT climate-resilient, every actor should do something; the government(Rijkswaterstaat), inland waterway transport companies and shippers.

This study considers two adaptation measures that will be simulated taking the time frame of the research into account. The considered adaptation measures in the study are chosen by predicted effectiveness in literature and on the condition: every actor should do something.

- Adjust maintenance criterion (government - infrastructural)
- Flexible fleet availability(shipping companies - fleet)

Adjust maintenance criterion

Rijkswaterstaat maintains the navigation channel of the river Waal at a minimum width and minimum available water depth criterion during the agreed low discharge(ALD). The agreed low discharge is the discharge at Lobith, for which the discharge falls below for twenty days a year (<5% days per year). At ALD, a minimum agreed water level(ALW) of 2.80 m should be available downstream of Lobith, and the minimum navigable width of the channel must be 150 m. Currently, the ALD is set to 1020 m^3/s at Lobith. However, this criterion is hardly met. In fact, during the extreme drought of 2018, the discharge was 156 days(42% days per year) below ALD van Hussen et al. (2019). During extreme low flow periods, such as the drought of 2018, it is almost impossible to dredge the required volumes to maintain the width and depth criterion. Rijkswaterstaat and dredging companies can adapt to these situations by adjusting the width criterion to a smaller width (Van Der Mark, 2021). During low flow periods, the navigation channel could be dredged at specific locations to maintain a minimum available water depth of 2.80 meters at a width of, for example, 130 meters instead of 150 meters. This adaptation measure implies that the dredging criterion should be adjusted.

Diverse fleet

During high water levels, most dry bulk is transported by push barges to Duisburg, but during low water periods, push barges become inactive. To compensate for the reduction in fleet capacity, more motor vessels and convoys are deployed. These smaller vessels have less capacity but can better cope with low flow due to their smaller size. The bottleneck in shifting cargo to smaller vessels is the fleet size. Therefore, more available motor vessels during low flow periods can increase the performance of the inland waterway transport system. However, due to the economy of scale, smaller vessels are less effective during high flow periods, and large push units become the preferred option. This can lead to motor vessels become idle during periods without. Therefore, it is important for this adaptation measure that the smaller extra vessels use cases are available.

2.5. Conclusion

This chapter addressed Step 1 of the Dynamic Adaptive Policy Pathway approach, which is a description of the considered system. Following the DAPP approach, the uncertainties that affect the system have been brought to light and the objective of the inland waterway system has been set with corresponding performance indicators. Consequently, the fleet characteristics on the corridor and its reaction to low water levels have been analyzed by performing an IVS90 data analysis. In the last section of the chapter, the most promising adaptation measures, according to literature, that contribute to obtaining the objective of the system have been explained.

This resulted in information to answer the research question:

1. What are the characteristics of the IWT-system between Rotterdam and Wesseling?

The objective of the IWT-system, is to maintain and increase its share in modal shift by being the most attractive transport modality. This objective can be quantified by the performance indicators: i. number of trips; ii. transported cargo; iii. transportation costs; iv. transportation costs per ton, and v. transportation costs per ton kilometer.

The IVS90 analysis showed that during low water water levels the number of trips between Rotterdam and Duisburg increase. In Figure 2.6, it can be seen that the active fleet size on the corridor depends on discharge in the waterway. As the discharge drops, push-barges become inactive and more motor vessels and convoys are deployed to compensate for the capacity loss of the fleet. This is the main reason why Figure 2.5 shows a rise in number of trips during the low flow period. Although the ship movements have increased significantly during the drought of 2018, the loss in capacity couldn't be compensated, which led to a reduction of the transported cargo. This can be explained by the reduced load factor of active vessels during low water levels. Furthermore, it was shown that during low water levels inland ships operate on a continuous basis because the share in number of trips are almost equal during the morning, afternoon, evening and night.

Adaptation measures can be implemented to become more climate resilient and improve the performance of inland waterway transport. They can be divided into the sub-categories: i. infrastructural, ii. fleet, iii. logistics and iv. information provision. However, one could also think of a division by which actor should implement the adaptation measure: i. waterway managers, ii. shippers, iii. skippers. Although many adaptation measures can be found in literature, this study only considers two adaptation measures: adjusting the maintenance criterion which is a infrastructural measure and should be implemented by waterway managers and the deployment of a diverse fleet which is a logistic measure and should by implemented by shippers.

3
Modeling IWT and river hydrodynamics

As is explained in section 1.6, step II of the Dynamic Policy Pathways approach considers the determination the tipping points of the current IWT-system by using a model. This chapter is an intermediate step before step II can be executed and describes how inland waterway transport between Rotterdam and Wesseling can modeled, taking into account the characteristics determined in chapter 2.

To this end, the following research question in answered in this chapter:

How can the performance of the inland waterway transport system during low flow periods be simulated?

The simulation model is set up as a bottom-up approach, which is comparable with a stress test. In a stress test, the amount of stress applied to the system changes over the modelling time. During the modelling or simulation time, the system's performance is measured until it no longer meets the set requirements. At this point, the amount of stress the system can cope with is known. Examples of the well-known stress test are the tensile strength test of steel (Huh et al., 2009) and internal risk analyses in the financial sector (Grennepois, 2017).

If we translate this to the DAPP-method, the stress is called the condition or, conditional parameter, and the point where the applied stress makes the system fail is called the tipping condition. As stated in chapter 1, one of the objectives of this research is to determine which low flow condition the IWT-system no longer meets its objective. Therefore the condition or stress applied to the system is the duration of a stationary low flow period, which will increase over the modelling time. When the applied duration becomes too large, it is expected that the system will no longer meet its requirements and a tipping point is reached.

In figure Figure 3.1, the main segments of the stress test are shown in chronological order to eventually be able to construct adaptive pathways in Step IV of the DAPP approach.

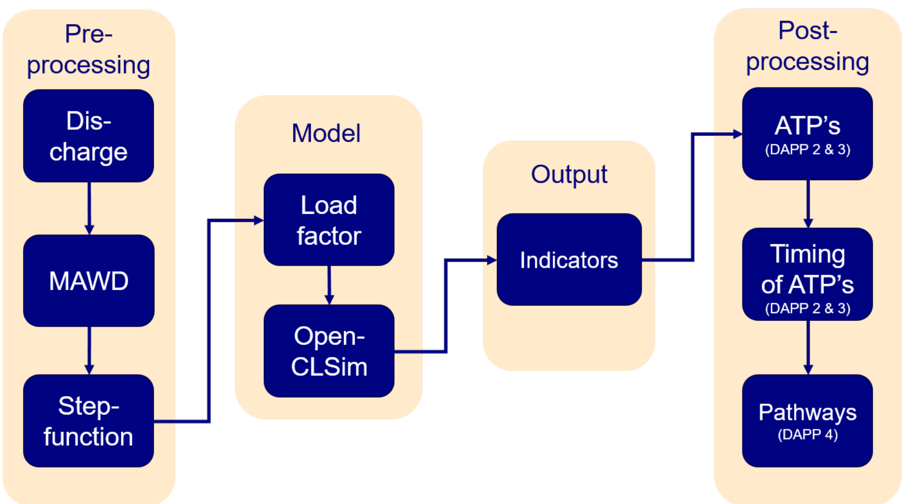


Figure 3.1: Steps to construct Pathways

One of the most important segments is the actual simulation of inland waterway transport during low flow periods, denoted by 'OpenCLSim'. In 2019, Kievits (2019) developed a model that is able to simulate inland waterway transport between Rotterdam and Duisburg during low flow periods. In his graduation thesis, he assessed the performance of the IWT network for the annual discharge series at Lobith in 2018 and for two predicted discharge series in the year 2050, taking two climate scenarios into account (Kievits, 2019). This model already showed the possibility of simulating inland waterway transport and is therefore used as a starting point for the simulation segment of the stress test in this study.

This chapter continues with an explanation of the application of segments categorized in Figure 3.1 by 'Pre-processing' and 'Model. The segment categories 'Output' and 'Post-processing' concern data analyses and results, which are mentioned in chapter 5.

3.1. River discharge

The load factor of vessels is positively correlated to the minimum available water depth, which is positively correlated to the discharge. In other words, if the discharge decreases at Lobith, the minimum available water depth in the waterway decreases and consequently, the load factor decreases if the water depth is smaller than the maximum draft of the vessel. A reduced load factor is one of the main consequences of low water levels that negatively affect the performance of the inland waterway transport system. Therefore, a stationary discharge must prevail during simulation. In this way, the only increasing stress in the system is the duration of a low flow period and not a changing load factor that affects the performance of the IWT-system as well.

However, the discharge at Lobith fluctuates over time. As it is expected that during a lower stationary discharge, tipping points in the system are reached earlier, three different flow regimes are considered. This will contribute to a broader range of results that can be related to historical data. As a consequence, three stress tests are performed, one for each flow regime. The flow regimes in this research correspond to the flow regimes used by Deltares in the Climate Resilient Networks project that is carried out for Rijkswaterstaat, part of the Dutch Ministry of Infrastructure and Water Management (De Jong, 2019).

- Q = 700 m^3/s: Extreme low discharge
- Q = 850 m^3/s: Most prevailing low discharge during the drought of 2018
- Q = 1020 m^3/s: ALD (Agreed Low Discharge)

3.2. Minimum available water depth

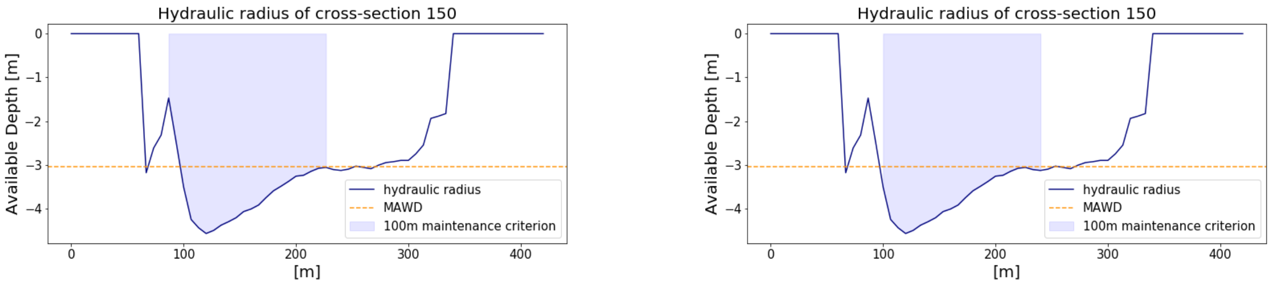
The minimum available water depth in the waterway determines the load factor of vessels. If the MAWD is larger than the maximum draft of a vessel, a load factor of 1.0 (100%) can be applied and the vessel will not experience any depth-related bottlenecks during its trip. If the MAWD is smaller than the maximum draft, then the water depth is a bottleneck for inland vessels and a reduced load factor has to be applied. Furthermore, the available width in the waterway reduces as well when the discharge decreases. A small available width can cause safety issues and congestion (Verschuren, 2020). To keep the depth and width related bottlenecks as low as possible, Rijkswaterstaat has a maintenance criterion to keep the minimum available water depth at 2.80 meters at a minimum available of 150 meters during ALD (Q = 1020 m^3/s at Lobith). However, this criterion is hardly met. For example, during the extreme drought of 2018, the discharge was 156 days below ALD (van Hussen et al., 2019).

To determine the minimum available water depth for the three different flow regimes, a method developed by Deltares is applied in which SOBEK output data is translated to a more dense grid. SOBEK is a computational 1D-flow flow model that can simulate complex flows in, e.g. rivers, deltas and irrigation systems by solving the complete De Saint Venant (1871) equations (Delatres, 2020). The *Rijntakken-model* is a SOBEK-model of the Rhine-branches in the Netherlands, in which cross-sections of each branch are defined. This model is therefore used to calculate the water levels in the Waal that correspond to the three different stationary flows at Lobith. For every river kilometre of the Waal, SOBEK calculates the corresponding water level. However, local shallows smaller in size than one kilometer form already bottlenecks for inland waterway transport. The method developed by Deltares translates the SOBEK results to a grid with higher density to identify local shallows. The cells are considerably smaller across the width than the length to sufficiently visualize variations across the width, see Figure 3.2.

Figure 3.2: Sobek output at river kilometre (white dots) to a more dense 2d-grid, Van der Mark (2019b)

The SOBEK output is translated to the 2D-grid by interpolating between river kilometre points in the longitudinal direction and adding the same value to the cells across the width. By applying this simplification across the width, water level changes in this direction are neglected (Van der Mark, 2019b). Then, to come to water depth values, the bed level is subtracted from the water level grid. The bed level values are available in the same 2D-grid, which were gathered by multi-beam measurements by Deltares.

Consequently, determining the minimum available water depth in every cross-section of the water depth grid leads to a minimum value for the complete waterway. This determination can be approached in two different ways; the first approach is based on the minimum depth within the official navigation channel of which its borders are defined by coordinates. The second is based on the minimum water depth available at a width of 150 meters. In Figure 3.3 the available water depth in a cross-section of the Waal is plotted.



(a) Available water depth in navigation channel

(b) Available water depth at 150 meters width

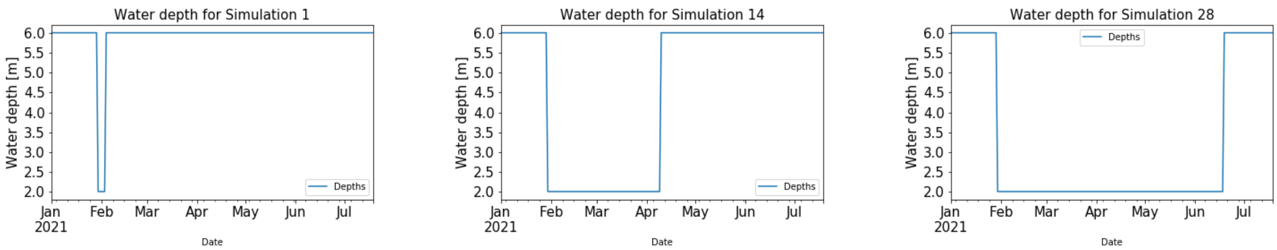
Figure 3.3: Two approaches to determine the minimum available water depth

The data is extracted from the water depth grid for Q = 1020 m^3/s. In Figure 3.3a also the position of the official navigation channel is plotted based on its coordinates. It can be seen that a local shallow is located inside the navigation channel. The second approach is applied in Figure 3.3b, where a minimum water depth is available at a width of 150 meters in the cross-section.

By comparing the two figures, it can be concluded that applying the first approach leads to results that do not display the available water depth in the system correctly. Therefore, an algorithm developed by De Jong (2020a) that applies the second approach is implemented in the model.

3.3. Step-function

One stress test consists of multiple simulations that are executed one after the other. Every simulation uses as input water depth versus time relations in which the water depth represent the minimum available water depth in the waterway. The water depth of the low flow period in these relations corresponds to the stationary flow regimes explained in section 3.1 and are calculated with the method explained in section 3.2. The applied stress to the system is increased by enlarging the low flow period in the subsequent simulations. In Figure 3.4 some of the input step functions are shown and it can be seen that the low flow period increases in the subsequent simulations.



(a) Water depth vs. time relation input for simulation 1

(b) Water depth vs. time relation input for simulation 14

(c) Water depth vs. time relation input for simulation 28

Figure 3.4: Input step-functions

In order to determine the amount of stress (=low flow period) the inland waterway system can cope with, the output of each simulation is compared. To make a reliable comparison, the water depth versus time relations must be created such that the IWT system experiences the same circumstances except for the applied stress. To this end, every simulation starts with a 30 day high water period for which vessels do not experience bottlenecks and after this period the low flow period occurs. In other words; The low flow periods start on the same day in every simulation. This can also be seen in Figure 3.4, where every low flow period starts on the 31st of January. Secondly, the duration of the low water period of the last simulation is set to 140 days, as this the maximum number of consecutive days that a more or less stationary discharge prevailed at Lobith. This is obtained by analysing a data-set with historical discharges at Lobith that ranges from 1901 to 2020. Thirdly, to reduce the modelling time of the stress test, the low flow period increases every simulation by five days. This means that in total, 28 simulations will be performed for one stress test. In addition, to make a reliable comparison between simulations, the total simulated days must be the same for every simulation. Also, the high water period after the low water period be sufficiently long for the IWT-system to recover and return to equilibrium. Therefore this period is set to 30 days. This means that, to simulate a low flow period of 140 days, the minimum of total days of each simulation must equal 30+140+30 = 200 days.

3.4. Load factor

The largest minimum available water depth in the corridor is normative for the weight inland vessels can transport at once (De Jong, 2020a). If the water depth is sufficient, vessels can sail at total capacity and the design draft is reached. However, when the available water depth is smaller than the design draft, skippers have to load less cargo to reduce their draft. To this end, a load factor is determined by the model before every trip and it is based on the actual water depth:

$$Actual\ depth = Available\ depth - Under\ keel\ clearance\ (UKC) \tag{3.1}$$

The applied under keel clearance is a safety margin to prevent grounding and mainly depends on the type of cargo and the river bed (van Dorsser et al., 2020). Smaller clearance is used for dry-bulk and sandy river beds, where a larger clearance is applied when transporting chemicals and the river bed consists of rocks. The applied under keel clearance actually is to what extent the skipper is willing to take a risk, as the consequence of grounding on a rocky river bed is larger. Although rules of thumb can be found in the range of 20cm and 40cm, (Borremans, 2015), during extreme low water periods, freight transport prices increase and skippers seem to take more risks (van Dorsser et al., 2020). Therefore, under keel clearance values cannot be described by rules of thumb when modelling extreme low water levels. At that point, the ukc is determined by each skipper individually. An IVS90 analysis performed by De Jong (2020b), shows under keel clearance values ranging from -50cm to +50cm relative to the minimum available water depth during extreme low water depths (0.0 to 2.0m) on the Waal. Clearances smaller than zero are sometimes applied by experienced skippers who are familiar with the waterway and now exactly the locations of local shallows so that they can sail around them. Because in this study extreme low water periods are modeled, the median values of applied under keel clearances found by De Jong (2020b) in 2018 are used(Table 3.1).

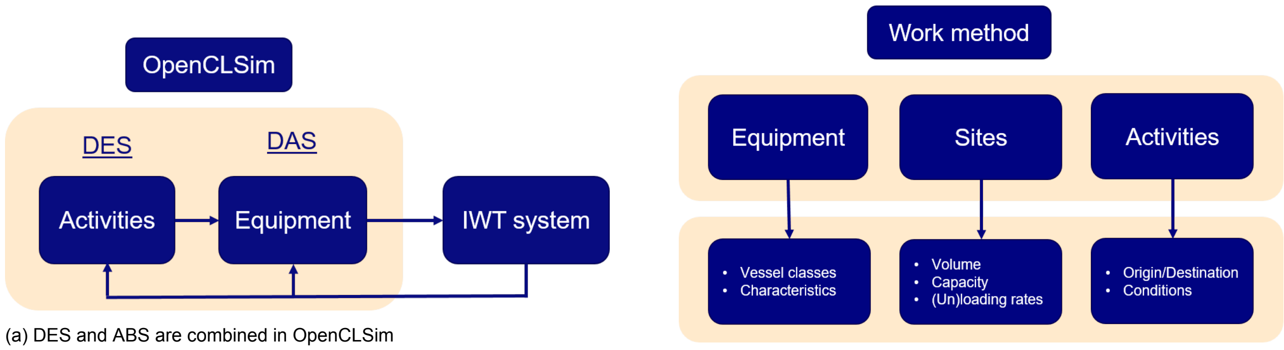
Cargo	**Q1020**	**Q850**	**Q700**
Dry-bulk	20cm	0.10cm	0.0cm
Liquid-bulk	20cm	0.15cm	0.0cm

Table 3.1: Median ukc values in 2018, (De Jong, 2020b)

A method developed by van Dorsser et al. (2020) in 2020 is implemented in the model to calculate the load factor. This method is more accurate during extreme low water levels than the method used in BIVAS or the one suggested by Bosschieter (2005). To create the load factor model, van Dorsser et al. (2020) applied linear regression models to data obtained by field observations and information collected from 124 load certificates of individual ships. These certificates contain the relation between water depth, loading draft and the ships' dead-weight (van Dorsser et al., 2020). The fitted regression models are combined in one general model that only requires the type of vessel, length, and beam to calculate the load factor.

3.5. OpenCLSim

The model is written in the Python programming language, and its core is formed by the Open Source Complex Logistics Simulation (OpenCLSim) package. The OpenCLSim package aims to facilitate rule-based planning of cyclic activities and in-depth comparison of different system concepts. This package has been, in turn, developed in a Simpy environment, that offers a framework for process-based discrete-event simulation (DES). OpenCLSim covers two simulation principles: DES and agent-based simulation (ABS), see Figure 3.5a. Discrete events are activities in order of execution within a simulation with a start and stop condition and a fixed duration. Considering the inland waterway transport cycle, the discrete events are loading, sailing loaded, unloading and sailing empty. These discrete events are performed by equipment such as vessels and cranes at berths. All necessary equipment can be seen as an independent entity, also called an 'agent'. In ABS modelling, the behaviour of each agent depends on the interactions with other agents. OpenCLSim uses a predefined work method to set out the conditions of the discrete events that take place. The work method consists of all the necessary equipment, locations (sites) between which the discrete events take place, and activities that describe the process of the equipment, see Figure 3.5b. The components of the work method (sites, equipment, activities) require input variables that enable the model to simulate the IWT's logistics (Kievits, 2019).



(a) DES and ABS are combined in OpenCLSim

(b) The work method and its components

Figure 3.5: The components of OpenCLSim. (Figure taken from (Kievits, 2019))

3.5.1. Simulation concept

The Simpy environment uses a container principle, which can be seen as virtual boxes that can contain a volume of material. The containers have a predefined capacity and an initial volume of material in it. When the simulation runs and start conditions of activities are met, material is put in or get from containers. Furthermore, containers representing the vessels can move between the sites. As mentioned before, the activities are stopped when a stop condition is met. This concept is shown in Figure 3.6 for various time-steps. For time T = 0, the figure shows a full stockpile (i.e. full container) at the terminal, an empty stockpile at the destination and an unloaded vessel (i.e. empty container). As the simulation commences, the vessel is loaded by the berth equipment, and by doing so, the level of the stockpile container decreases and the level of the vessel container increases. The load factor determines to which level the vessel's container is loaded. This process regards the discrete event 'loading'. After the vessel has been loaded, it starts to sail to the destination, regarding the discrete event 'sailing full'. At this point, the stockpile resource becomes available for the next vessel. After a few time-steps, the first vessel arrives at the destination stockpile and the discrete event 'unloading' starts. As soon as all the material has been moved from the vessel container to the stockpile, the vessel sails back to its origin, regarding the discrete event 'sailing empty'. During the simulation, the discrete-events of every defined equipment agent and site locations are logged. This results in large dataframes containing timestamps, the prevailing discrete-event at that time, the level of the container during the event and the position in the network where the event takes place. The simulation ends when a stop condition is met, which can be a predefined simulation time or when a predefined volume of cargo is transported. In this research, the stop condition of the simulation is time-based, being a simulation time of 200 days.

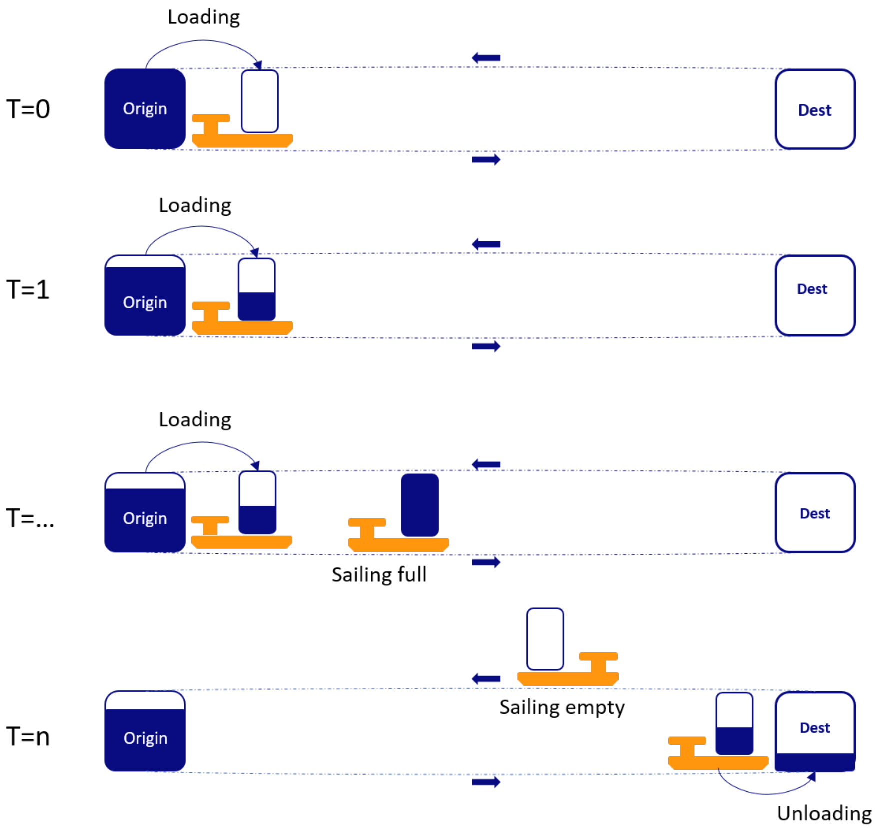


Figure 3.6: Simulation concept, figure is a sketch, will be updated

3.5.2. Input variables - Equipment

Vessels

Equipment is needed to carry out the discrete events of the inland waterway transport cycle. Dry-bulk is transported from Rotterdam to Duisburg by push-barges, motor vessels and convoys depending on the flow regime and, liquid-bulk is transported from Rotterdam to Wesseling only by motor vessels(tankers). Therefore, the equipment that is related to the events sailing loaded and sailing empty are the different types of inland vessels. The inland vessels that are defined in the model follow from the fleet analysis performed in Chapter 2. Leading to a dry-bulk fleet composition of BII-6, BII-4, C4, M9(Va) and M12(VIa) vessels. In the model, only M8 vessels are considered for the tanker fleet. The input parameters related to the vessel equipment that describe the characteristics of each vessel are given in Table 3.2 and are explained below:

Input parameter	BII-6	BII-4	C4	M9(Va)	M12(VIa)	M8-tanker
Ship type [-]	Barge	Barge	Barge+Dry	Dry	Dry	Tanker
Fleet size [-]	9	11	2	11	6	20
Capacity [t]	16.000	7.500	5.000	2.050	4.300	2050
Length [m]	77	77	77	135	135	77
Beam [m]	11.40	11.40	11.40	11.40	17.0	11.40
UKC [cm]	0-2	0-20	0-20	0-20	0-20	0-20
Sailing speed full [m/s]	2.25	2.25	2.25	2.25	2.25	2.25
Sailing speed empty [m/s]	4.50	4.50	4.50	4.50	4.50	4.50

Table 3.2: Vessels input variables before validation

Ship type
The load factor for each trip is determined by applying the method developed by van Dorsser et al. (2020) as explained in section 3.4. This method requires the ship type as input, which are known as: tankers, dry-bulk ships, container ships and dumb barges. Because a convoy(C4) consists of 1 dry-bulk ship and 3 dumb barges no single exploitation type can be assigned before hand. Validation of the load factor will determine which exploitation type is the most suitable for a C4-convoy.

Fleet size
The fleet size describes the number of available vessels of each RWS-class. The active part of this fleet size depends on the prevailing flow regime in the system, as can be seen in the fleet analyses performed in Chapter 2.3. When the load factor is sufficient, vessels can transport enough cargo to meet the demand. This means that it is possible that not every vessel in the fleet is needed and are therefore idle. More vessels of the fleet become active when the load factor is insufficient and the current fleet size cannot meet the cargo demand. When the maximum fleet capacity is reached and the extra vessels cannot compensate for the decrease in load factor, the volume of transported cargo decreases. The active fleet size is determined by data analysis performed in Chapter 2.3 and depends on which flow regime is being simulated. In section 4.1 the number of trips are validated, which is related to the fleet size.

Capacity
The amount of transported cargo by each vessel depends on its maximum capacity in combination with the applied load factor (van Dorsser et al., 2020). When there are no water depth related bottlenecks in the system the vessels can load their maximum capacity. When the water depth is insufficient, less cargo than the maximum capacity is loaded, depending on the applied load factor. The capacity of each vessel before validation is the capacity defined by Kievits (2019). Validation of the transported cargo will determine if these values should be adjusted.

Length & Beam
The length and beam of each vessel serve as input for the load factor calculations together with the exploitation type. To determine the load factor for push-barge units such as BII-6 and BII-4, the length and beam of one dumb barge are required as input instead of the the dimensions of the complete unit.

UKC
The load factor is based on the minimum available water depth minus the under keel clearance. For more detail on the applied ukc, reference is made to section 3.4.

Sailing speed
The sailing speed of each vessel varies between the upper limit when sailing empty and a lower limit when sailing full. It is assumed that the sailing empty and sailing full speed limits for each vessel type are equal, 4.5m/s and 2.25m/s respectively. The model calculates the sailing speed by considering the load factor and a linear interpolation between the limits.

Berths

The discrete events 'loading' and 'unloading' are carried out by berth equipment. The berths represent the cranes at the terminals in inland ports and its characteristics consist of the available resources and loading/unloading-rates. The number of resources represent the number of berths and thus how many vessels can be handled at the same time at the terminal. If all resources are in use and a vessel arrives, a waiting time is induced until a resource becomes available. The values of these input parameters are assumed equal to the validated values from Kievits (2019) for dry-bulk.

Name	Location	Loading [t/h]	Unloading [t/h]	Resources
From dry-berth	Rotterdam	4.500	-	6
From liquid-berth	Rotterdam	4.500	-	6
To dry-berth	Duisburg	-	2.700	6
To liquid-berth	Wesseling	-	2.700	6

Table 3.3: Berth input variables before validation

3.5.3. Input variables - Sites

The discrete events take place between origins and destinations, called the sites. These sites represent the terminals at inland ports between which the cargo is transported. In this model, four sites are defined; two at the origin and two at the destinations. Sites, or terminals, require three input variables, which are the coordinates of the location, its storage capacity and the initial volume of the stored cargo. The capacity values for dry-bulk and liquid-bulk are assumed equal and are based on the validated values by Kievits (2019).

Names	Location	Capacity [t]	Initial Volume [t]
EECV Terminal	Rotterdam	50.000.000	0
Vopak Terminal	Rotterdam	50.000.000	0
Thyssenkrupp Terminal	Duisburg	60.000.000	0
Godorf Terminal	Wesseling	60.000.000	0

Table 3.4: Sites input variables

3.5.4. Input variables - Activities

The activities connect the equipment and sites and describe the discrete events. The activity will begin as soon as the predefined start is fulfilled and it will stop when the stop event is met. These activities describe the actual transport processes in the IWT system (Kievits, 2019). The cycle of discrete events, which include the activities, is repeated for every vessel when the start condition is met. Activities can run simultaneously, as long as they do not exceed the number of resources. The required input parameters for activities can be found in Table 3.5. Because activities do not require numeric input data but only defined parameters from equipment and sites, the general parameter is given. The simulation is visualized in Figure 3.7, where also the activity parameters and resources are indicated.

Parameter	
Origin	*[site]*
Destination	*[site]*
Loader	*[berth]*
Mover	*[vessel]*
Unloader	*[berth]*
Start event	*[condition]*
Stop event	*[condition]*

Table 3.5: Activity input parameters

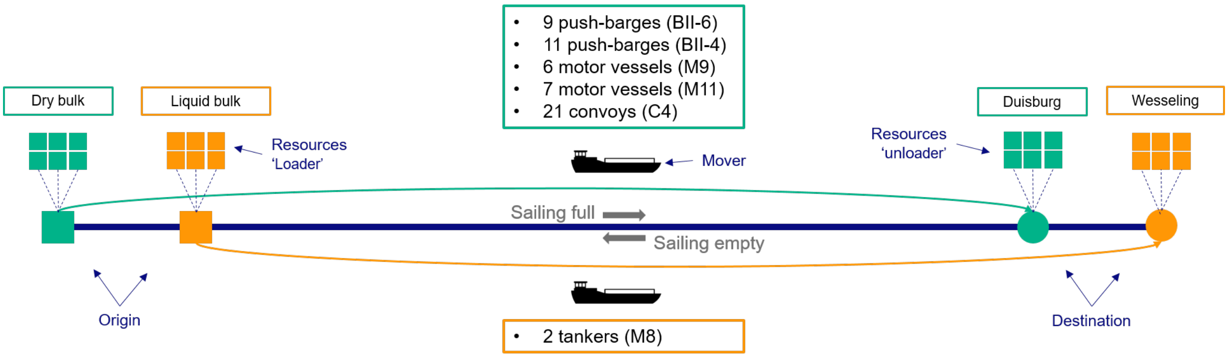


Figure 3.7: Simulation overview

3.6. Conclusion

This chapter described segments of the developed model that is used to simulate inland waterway transport between Rotterdam and Wesseling. The objective of the model is to assess the performance of the IWT-system for enlarging periods of low flow. First, segments related to the available water depth in the waterway were explained. Consequently, the actual simulation of IWT in OpenCLSim was described. By doing so, this chapter has addressed the following sub-question:

How can the performance of the inland waterway transport system during low flow periods be simulated?

The model is set up as a bottom-up approach, which is comparable with a stress test. In this study, the applied stress to the system is an enlarging period of low flow. To exclude the effect of changing water depths on the performance of IWT, during the low flow periods a stationary discharge prevails. Three stress tests will be performed, with a discharge of Q = 700m^3/s, Q = 850m^3/s and Q = 1020m^3/s respectively, to gain a broader range of results. A stress test consists of 28 simulations, in which the low flow period increases with five days, resulting in low flow period of 140 consecutive days in simulation 28.

The minimum available water depth in the waterway that corresponds to the prevailing discharge is determined at a width of 150m in each cross-section. The data used for the water depth related calculations is gathered by Deltares where they have performed SOBEK simulations to obtain water levels on the River Waal. Consequently, the bed level data is subtracted which results in water depth values.

When the available water depth in the waterway is known, the load factor can be determined. The load factor is determined for each vessel, based on its length, beam and ship type.

The actual simulation of inland waterway transport is developed in a Simpy environment in the Python programming language. Simpy uses a container principle, which can be seen as virtual boxes that can contain a volume of material. OpenCLSim is the main package used, which combines Discrete-event simulation (DES) and Agent-based simulation. The simulation uses a work method which consists of equipment to carry out discrete events, sites between which events take place, and activities that describe the actual processes. The simulation covers the dry-bulk transport from Rotterdam to Duisburg and the liquid-bulk transport from Rotterdam to Wesseling. For both supply chains, terminals at the origin and destination (i.e. sites) are defined between which dry-bulk vessels and tanker vessels are active. During simulation the discrete-events loading, sailing full, unloading and sailing empty are performed that represent that transport cycle. The discrete events are logged for each equipment and site with timestamps and the amount of cargo that is loaded or shipped at that timestamp during the event. This results in large output dataframes which can be post-processed to express the performance of IWT-system in performance indicators as defined in chapter 1.

4
Validation

The model described in Chapter 3 is validated on three parameters that are of importance to assess the IWT-system on the basis of the performance indicators mentioned in section 2.1. The DAPP approach does not consider a specific step for model validation so, this chapter can be seen as an intermediate step before step II can be executed, in which the developed model is applied to determine tipping points.
In the first section of this chapter reference data from IVS90 is selected that has been gathered during stationary flow periods in 2018. Consequently, the load factor is validated followed by the number of trips and transported cargo for the three considered flow regimes. Lastly, the parameters are validated during a high water period. By doing so, the following research sub-question can be answered:

How does the simulation model perform compared to IVS90 data?

4.1. Validation

The model is already validated for fluctuating discharge series, but not for the use case with step functions (Kievits, 2019). Furthermore, a new supply chain is added and extra vessels are defined. To validate the model, the output data is compared to IVS-data on three main parameters: load factor, number of trips and the transported cargo. It is important that the validation of the parameters is carried out in this order to exclude effects on a parameter by the other; if the load factor is validated, an incorrect value of number of trips can only by caused by an incorrect fleet size. Otherwise it could be the case that if the number of trips are incorrect, this could also been caused by a different load factor which leads to more trips. After the load factor and trips are validated, the transported cargo can be validated. If the transported cargo shows deviation from IVS-data, we can exclude that this is caused by an incorrect load factor or number of trips. Then this is probably caused by incorrect defined capacities of vessels. Only the load factor, number of trips and transported cargo are validated because this is those are the most relevant output data for this research.

The model's output is assumed to be validated when the mean values fall within a 10% range of the IVS data. Because the consecutive days that a stationary flow prevails in 2018 are selected with a 10% discharge range, it is expected that the load factor can deviate within the same bandwidth due to the linear correlation between water depth and load factor.

4.1.1. Reference data

The model's output is validated by a comparison with IVS-data from 2018. Because the model's input is not a annual discharge series of 2018, periods from the IVS-data have to be selected that correspond to stationary flow periods as is the case during simulations. Therefore the first step of validation is to search for stationary flow periods in the discharge series of 2018 and then to extract the IVS-data that corresponds to the same period. To find periods of stationary flow in the discharge data of 2018, the number of consecutive days are counted when one of the three flow regimes prevails with a 10% margin around that specific discharge value.

For example, to find a stationary period of Q = 1020 m^3/s the number of consecutive days are counted which have a discharge between Q = 920 m^s/s and Q = 1120 m^3/s. Because the input step functions consist of low and high water levels, also consecutive days for Q = 2500 m^3/s are counted to gather data for the validation of the model's output during high water levels. Now the periods of consecutive days that the flow regimes prevail are known(Figure 4.1), the IVS-data that corresponds to these period is extracted from the IVS90-data set to compare with the model's output.

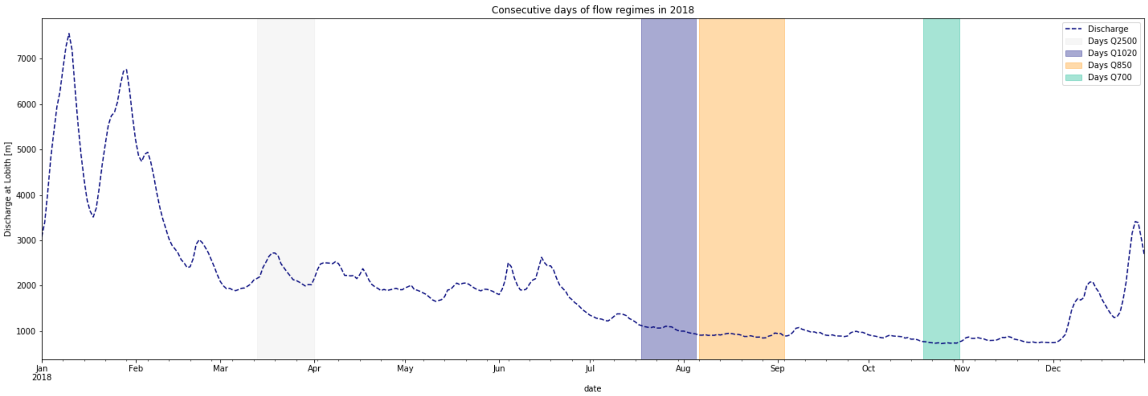


Figure 4.1: Consecutive days in 2018

To compare the model's output with the IVS data, simulations are performed where the low flow period is as long as the number of consecutive days found in the discharge data, shown in Table 4.1.

Flow regime	**Range [m^3/s]**	**Consecutive days**
Q2500	2250-2750	19
Q1020	920 - 1120	18
Q850	765 - 935	28
Q700	630 - 770	12

Table 4.1: Consecutive days in discharge data of 2018

4.1.2. Load factor

The load factor is validated first to exclude effects of a deviating load factor on the number of trips and transported cargo. The validation is carried out for each defined vessel and for every flow regime with its corresponding water depth in Table 4.2.

	MAWD
Q1020	2.39 m
Q850	2.01 m
Q700	1.79 m

Table 4.2: Available water depth

First, the load factor data that correspond to the same periods that are depicted in Figure 4.1 are extracted from the 2018 IV90 data. Although the load factor is not a parameter that is reported in IVS90 data, it can be calculated for each trip by dividing the transported cargo by the maximum load capacity. The next step is to produce output data by performing simulations with a stationary low flow period with equal length to the extracted data from the IVS90 data set. To validate the model's output, the mean values over the full low flow period are calculated of the reference data as well as of the model's output. As an example, the validation of the load factor of a BII-4 push-barge unit during a discharge of Q = 1020 m^3/s is shown in Figure 4.2. The blue solid line corresponds to the load factor extracted from the IVS90 dataset and the blue dashed line indicates its mean value. The light blue area shows the 10% range around the mean value to indicate values for which the model's output is assumed to be validated. The model's output is plotted by the solid orange line, with its mean value indicated by the orange dashed line. As can be seen, the load factor of a BII-4 push-barge unit falls within the 10% range of IVS data and is therefore assumed to validated. Important to mention is that the values are validated for the low water level period and the high water values are ignored in this validation step. The high water values are validated in subsection 4.1.5.

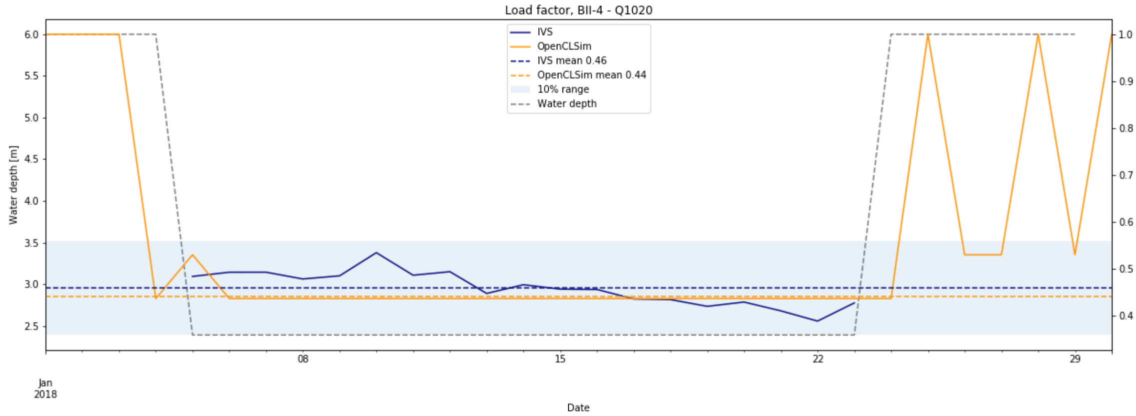
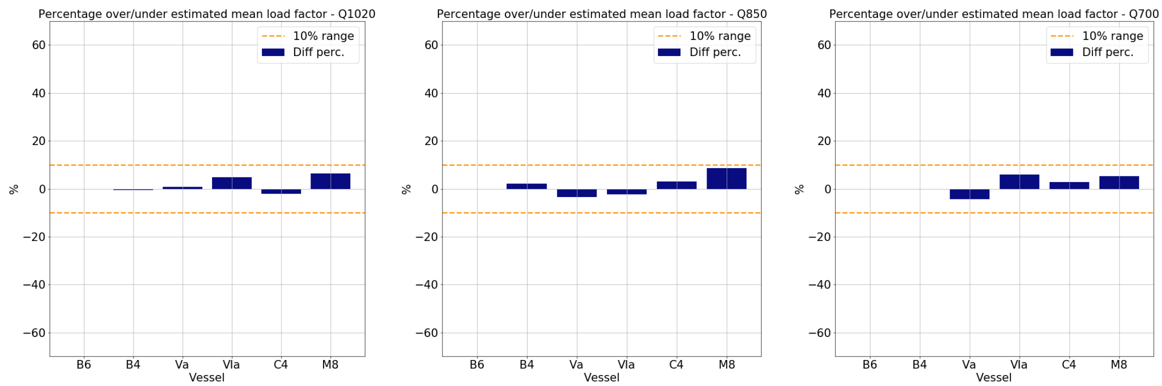


Figure 4.2: Load factor validation of BII-4 during Q1020

This process is repeated for every vessel and every flow regime. The results for Q1020 are plotted in a bar diagram in Figure 4.3a, for Q850 in 4.3b and for Q700 in Figure 4.3c. The dashed orange lines indicate the 10% bandwidth of the mean value extracted from IVS data. When analysing the validation results, it can be seen that the model determines load factors that are within the 10% margin for every vessel during each flow regime. There is no deviation in load factor for BII-6 push units. Because of its inactivity the load factor equals zero in IVS90 data as well as in the model's output. Concluding, the method developed by van Dorsser et al. (2020) in combination with the under keel clearance values determined by De Jong (2020b) in Table 3.1 and the estimated water depth available at 150m width performs really well.



(a) Load factor Q1020 (b) Load factor Q850 (c) Load factor Q700

Figure 4.3: Load factor validation results.

4.1.3. Fleet size

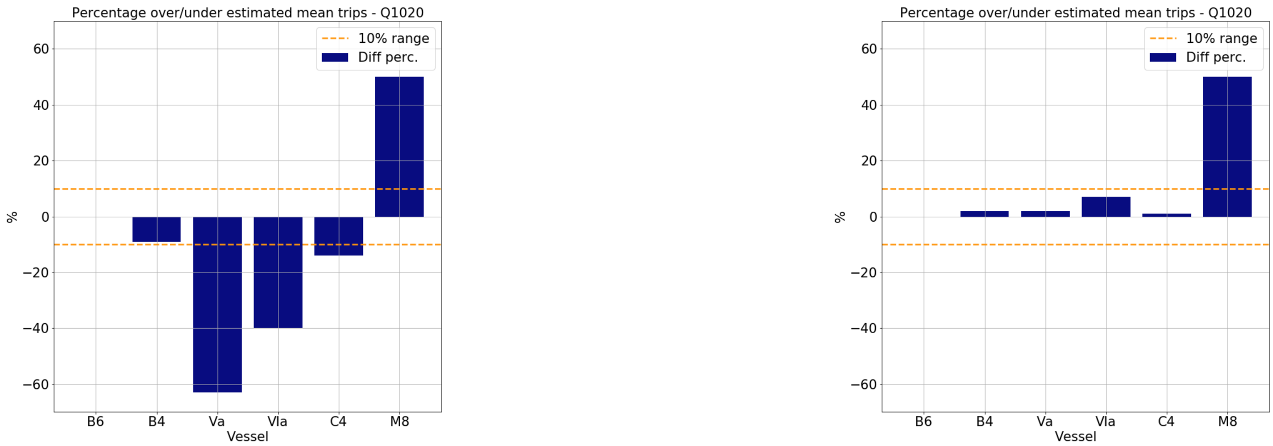
The active fleet size is determined in Chapter 2.3 by analysing IVS90 data and assuming the cycle time of each RWS-class (=vessel type) to be equal to two days. These values are used as input for the first simulation runs and are validated by applying the same method as the load factor validation. Because the fleet size cannot directly by extracted from IVS data, the number of trips made during the periods depicted in Figure 4.1 are compared to the number of trips performed by the model. Assuming that the number of trips only depends on the active fleet size. First, the number of trips for Q = 1020m^3/s are validated, then Q = 850m^3/s and finally Q = 700 m^3/s.

RWS-class	Q1020	Q850	Q700
BII-6	0	0	0
BII-4	8	6	0
C4	5	8	22
Va	3	5	12
VIa	2	2	2
M8-tanker	2	4	2

Table 4.3: Active vessels during the flow regimes found in section 2.3

Q1020

The bar diagram in Figure 4.4a shows the percentage deviation of the model's output compared to IVS90 data during Q1020 simulations. The mean number of trips of Va vessels by the model is under estimated with more than 60% compared to IVS data in a period of equal length during Q = 1020m^3/s.



(a) mean number of trips deviation from IVS90 before validation - Q1020

(b) Mean number of trips deviation from IVS90 after validation - Q1020

Figure 4.4: Number of trips validation results Q1020

Because the load factor is already validated, the small number of trips is not caused by a higher load factor during simulation which would lead to less trips. Therefore, it is assumed that the difference in number of trips is caused by a difference in active vessels. The under estimation of Va trips can also be seen in the plot in Figure 4.5. The dashed orange line represent the mean value of the model's output, which lies below the mean value of IVS90 data represented by the dashed blue line. It is important to mention that the plot of the individual RWS-class has have been drawn for every vessel in each flow regime, before the bar diagrams are plotted. Due to the extensiveness of the output, it is chosen to only show the bar diagrams and occasionally show the results of an individual vessel as an example (Figure 4.2 and Figure 4.5).

The mean number of trips by the VIa and M8 are under and over estimated by 40%. This indicates that the initial value of active VIa vessels size is too small and the active fleet size of M8 tankers is too large. The

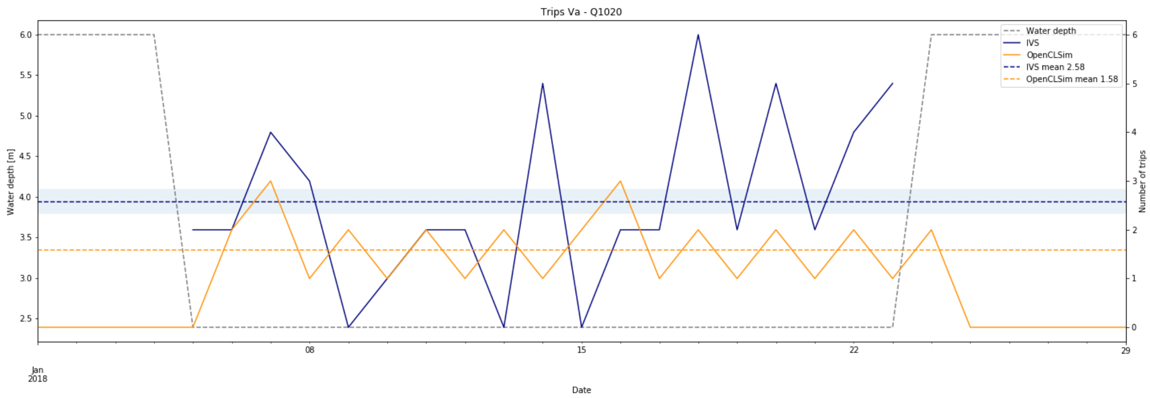


Figure 4.5: Under estimation of mean trips by Va fleet during Q1020

mean number of trips by the C4 convoy seems to be slightly under estimated as well. To improve the model's output, the fleet sizes are adjusted in a second validation run by taking the percentage deviation into account. Reasoning that the mean value of the model's output should change by this percentage in order to equal the mean value of IVS90 data. The starting point for the adjusted fleet size is the initial fleet size multiplied by the percentage factor. The outcome is rounded up because it can result in a fleet size with a value after the decimal point. For example the Va fleet size:

$$
\begin{aligned}
&Initial\ fleet\ size\ *\ percentage\ deviation\ =\ RoundUp(fleet\ size)\ =\ adjusted\ fleet\ size \qquad (4.1)\\
&5\ Va\ vessels\ *\ 60\%\ =\ RoundUp(4.8)\ =\ 5
\end{aligned}
$$

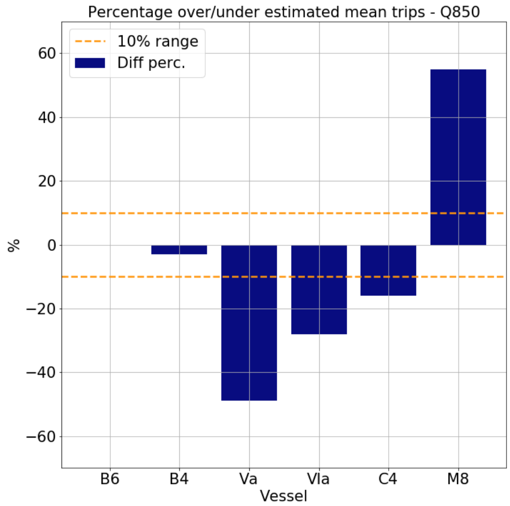
By applying Equation 4.1 to the VIa and C4 fleet, the adjusted fleet sizes become three VIa vessels and six C4 convoys. For the M8 tanker fleet however, it is chosen to keep the fleet size at two tankers, despite the over estimation by the model. It is assumed that there are always two tankers active during Q = 1020m^3/s based on the fleet analysis in section 2.3. This leads to fleet sizes that perform on average trips within a 10% range of IVS90-data except for M8 tanker vessels. The results are shown in Figure 4.4b.

RWS-class	Initial size IVS	Fleet size model
BII-6	0	0
BII-4	8	8
C4	5	6
Va	3	5
VIa	2	3
M8 -tanker	2	2

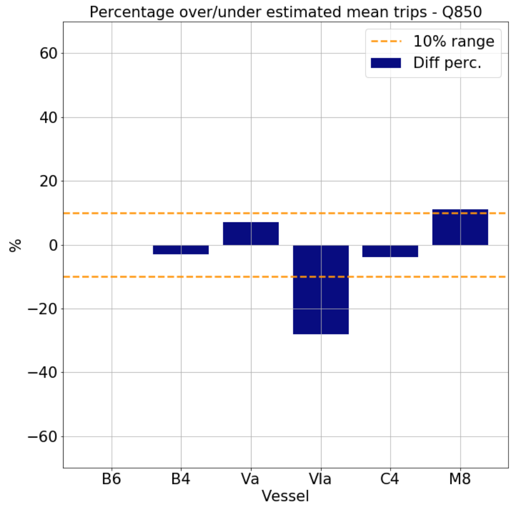
Table 4.4: Validated fleet sizes Q1020

Q850

The validation results of the mean number of trips during Q = 850m^3/s are depicted in Figure 4.6. At first, the simulation is run with the active fleet size as given in Table 4.3. This resulted in an output of mean number of trips of both push-barge units performed by the model that are in the 10% range of IVS-data, see Figure 4.6a. The other RWS-classes are over and under estimated by the model. Apparently, a fleet size of five Va vessels perform on average less trips during a period of Q = 850m^3/s than the fleet does according to IVS-data. The mean number of trips by the VIa motor vessels exceed the 10% range, indicating that the defined fleet size in the model is smaller than the active VIa fleet between Rotterdam and Duisburg. Besides, the C4-convoy mean number of trips are slightly under estimated by the model and M8-tankers trips are over estimated.



(a) Number of trips deviation from IVS before validation



(b) Number of trips deviation after second iteration

Figure 4.6: Number of trips validation results Q850.

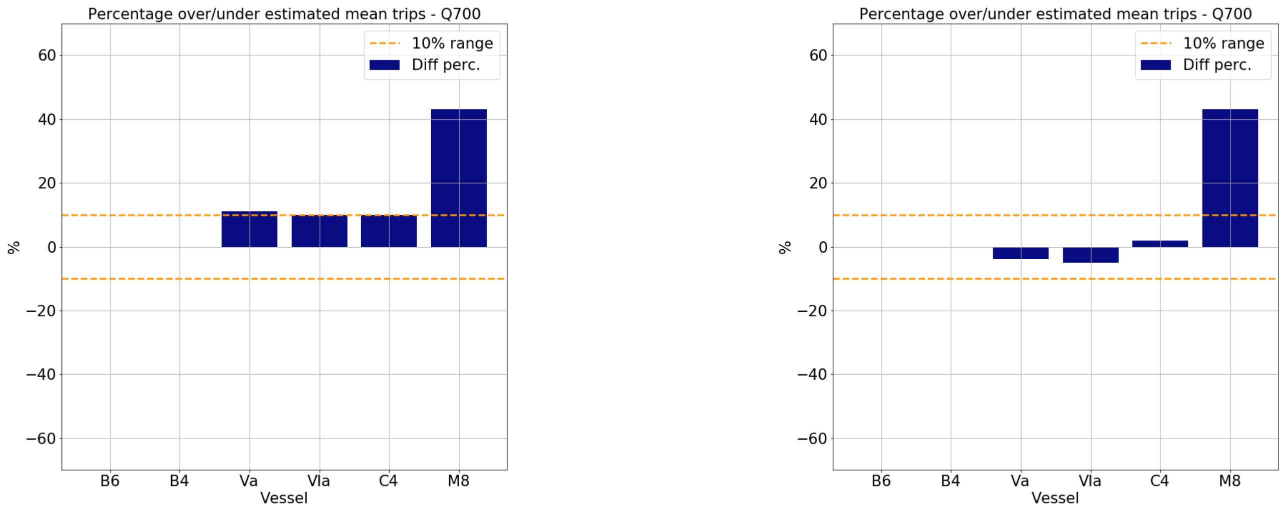
The fleet sizes are adjusted by applying Equation 4.1 to the initial values. As a consequence, the mean number of trips by the Va fleet has significantly improved, in contrast to the VIa fleet, which has not changed because the fleet size is kept equal. Furthermore, the active C4 convoys perform on average trips within the 10% range of IVS90-data. Also the number of trips by M8 tankers has significantly improved (Figure 4.6b). Although they are still slightly over estimated, the fleet is assumed to be validated.

RWS-class	Initial size IVS	Fleet size model
BII-6	0	0
BII-4	6	6
C4	8	9
Va	5	7
VIa	2	2
M8 -tanker	4	2

Table 4.5: Validated fleet sizes Q850

Q700

In Figure 4.7a, the percentage deviation in mean number of trips during Q = 700 m^3/s can be seen. As expected, for both push-barge units, there is no deviation in the model compared to IVS90 data as in both cases no push-barge units are active during Q = 700m^3/s. The dry-bulk motor vessels of RWS-class Va and VIa show a small over estimation by the model. In the next validation simulation these fleet sizes are decreased according to formula 4.1.



(a) Number of trips deviation from IVS before validation

(b) Number of trips deviation after validation

Figure 4.7: Number of trips validation results Q700.

Although the mean number of trips by the C4 convoys falls just within the 10% margin, in the next validation run, the fleet size is reduced by the same formula from 22 vessel to 20 vessels for better performance. It is noticeable that the M8 tankers have a significant deviation from IVS90 data. This is mainly caused by a large irregularity in IVS trips during Q700 and a small time frame over which the mean is calculated. Because on one day during the Q700 period IVS data shows that two trips are carried out by M8 vessels and that this was also found by the analysis performed in section 2.3, it is assumed that 2 vessels is correct. This can also be seen in Figure 4.8, where the IVS data and simulation output is plotted.

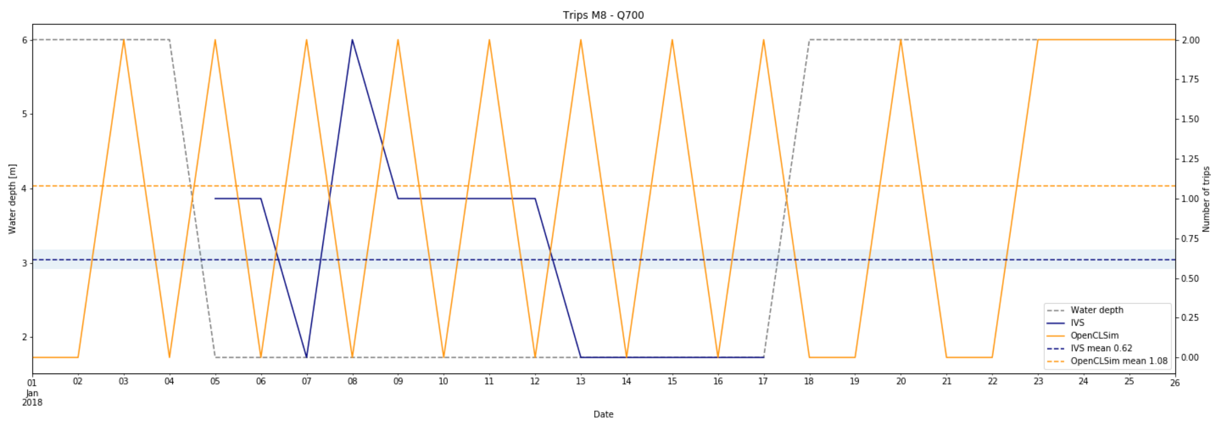


Figure 4.8: Number of trips validation for Q700, M8 tanker

4.1.4. Transported cargo

The transported cargo is the third parameter to be validated. The same method is applied that has also been used for the previous parameters. Deviations in transported cargo between the reference data and the model's output that are more than 10% cannot be linked to the load factor or number of trips because there are already validated. First, the transported cargo by each RWS-class during Q = 1020m^3/s is validated.

Q1020

Dry-bulk

Figure 4.9 shows large deviations in transported cargo between IVS data during a reference period and the model's about except for the BII-6 and VIa fleet. Because the model is already validated for the load factor and number of trips during Q = 1020m^3/s, the large under estimation cannot by caused by those two parameters.

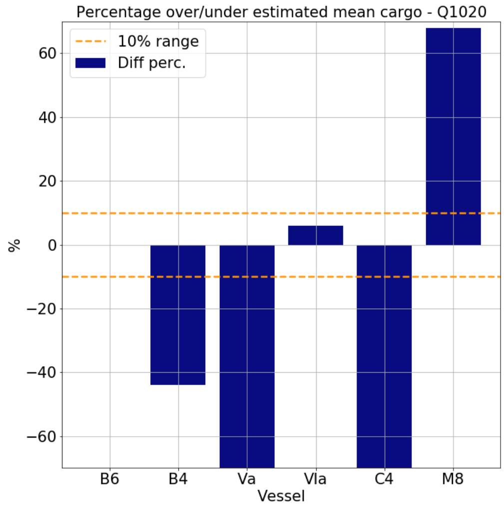


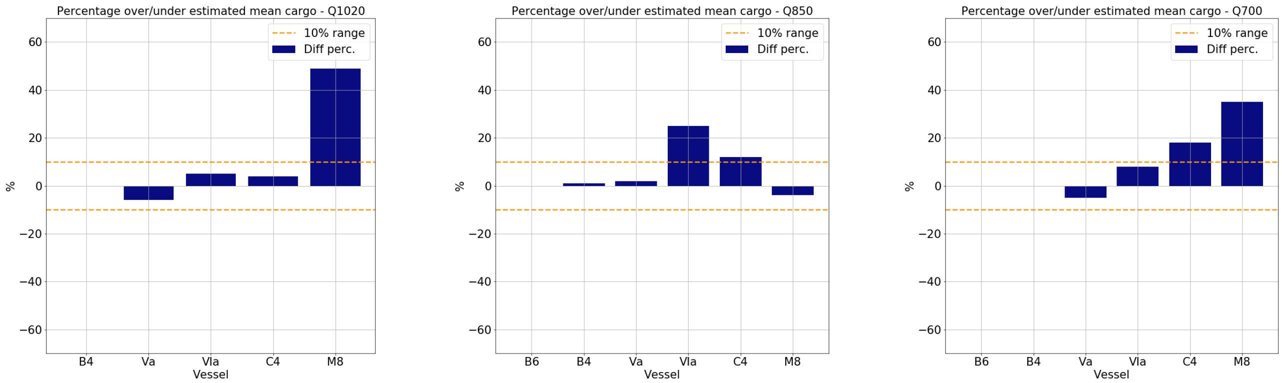
Figure 4.9: Mean cargo deviation from IVS90 before validation

The maximum load capacity each RWS-class can transport has, of course, a large effect on the transported weight during simulations. Rijkswaterstaat provides the maximum load capacity in a range for each RWS-class (Koedijk, 2020). For the first simulation run, the maximum capacity values determined by Kievits (2019) are used and for new added vessels the lower limit of the capacity range by RWS is used. However, the output data in Figure 4.9 shows that this leads to under estimation of the transported cargo for dry-bulk. The maximum capacity input variables are validated by performing a data analysis on IVS90, see Appendix C. In the second validation simulation run, the median value of maximum load capacity extracted from IVS90 are used as input variables. The capacity ranges by Rijkswaterstaat and the input variables for the first and second run are compared in Table 4.6.

RWS-class	Rws-capacity range [t]	Initial capacity [t]	Median capacity IVS90 [t]
BII-6	12.000 - 18.000	16.000	16.800
BII-4	7.051 - 12.000	7.500	10.800
C4	>7.251	5.000	10.800
Va	2.051 - 4.000	2.051	3.900
VIa	>4.001	5.601	5.550
M8-tanker	2.051 - 3.300	2.051	1.650

Table 4.6: Maximum capacity input variables

The validation results with the median maximum capacity gathered from IVS90 data, are shown in Figure 4.10 and a significant improvement is noticeable for Q1020 simulations(Figure 4.10a. In contrast to the M8 tanker vessel, which deviation from IVS90 data has decreased but still exceeds the 10% margin. As mentioned in the previous section about the fleet size validation, the model's number of trips by M8 tankers is larger than the number of trips according to IVS data during Q1020. This contributes to a larger volume of transported cargo by the model. The maximum load capacity is vessel dependent and does not change when the water level changes. Therefore, the same input variable for maximum load capacity has to be used for all flow regimes. The results for Q850 and Q700 can be seen in Figure 4.10b and 4.10c, respectively. Although most vessels perform within the 10% margin of error, some exceed the upper 10% limit. One thing to notice is that the M8 tankers perform better during Q850 than during Q1020 and Q700 in terms of transported cargo. This is because also the number of trips during Q850 are within the margin of error. The opposite is true VIa motor vessels during Q850, which transport more cargo in the model compared to IVS because also more trips are performed by the model compared to IVS as can be seen in Figure 4.6b.



(a) Mean cargo deviation from IVS after validation, Q1020

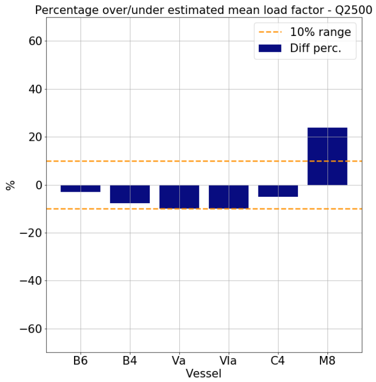
(b) Mean cargo deviation from IVS after validation, Q850

(c) Mean cargo deviation from IVS after validation, Q700

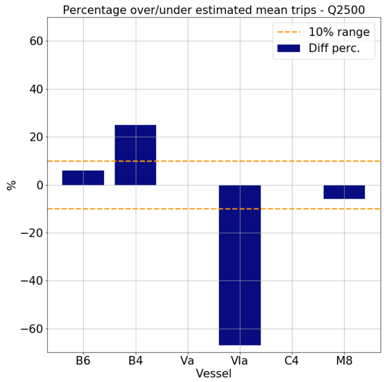
Figure 4.10: Cargo validation results

4.1.5. High water level

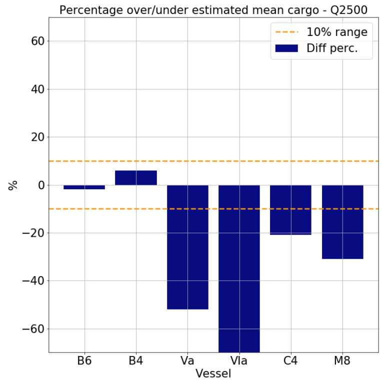
In this section, the model's output during the high flow regime of Q = 2500m^3/s is validated by a comparison with IVS90 data from a reference period in 2018. First, the load factor is validated, then the mean number of trips and consequently the transported cargo. The load factor is determined by the method developed by van Dorsser et al. (2020) and uses as input vessel dependent fixed values; length, beam and exploitation type. This means that there are no uncertainty parameters that can be adjusted to improve the model's load factor output. Besides, the water level during high flow is chosen such, that no bottlenecks occur for vessels that are active during this picture. Therefore it is expected that the model produces load factors equal to 100%.



(a) Load factor deviation from IVS after validation



(b) Mean trips deviation from IVS after validation



(c) Mean cargo deviation from IVS after validation

Figure 4.11: Validation results Q2500

Load factor

In Figure 4.11a the percentage deviation between the model's load factor output and IVS90 data are depicted. First of all, the load factor shows good results for the active dry-bulk fleet which are BII-6, BII-4 and C4 units. Secondly, the percentage deviation for the motor vessels Va and VIa are expected to be equal to 0, because these ships are modeled as in active during high water levels according to the fleet analysis in 2.6. Inactive in ships in IVS as well as in the model should results in both load factors to be 0% and thus no deviation between them.

By studying the plot in Figure 4.12, in which the IVS data and the model's output during high flow are plotted, it can be seen that indeed the model's load factor equals 0.0. However, the load factor in IVS(solid blue line) shows a peak, but is zero for the largest part during this period. This peak causes the mean to deviate from zero and also a deviation between IVS and model. Following the fleet analyses in section 2.3 and that the IVS load factor is for the largest part equal to zero, it is assumed that the model's output is correct for Va. The same conclusion holds for VIa, which plot can be seen in Appendix B, Figure B.1.

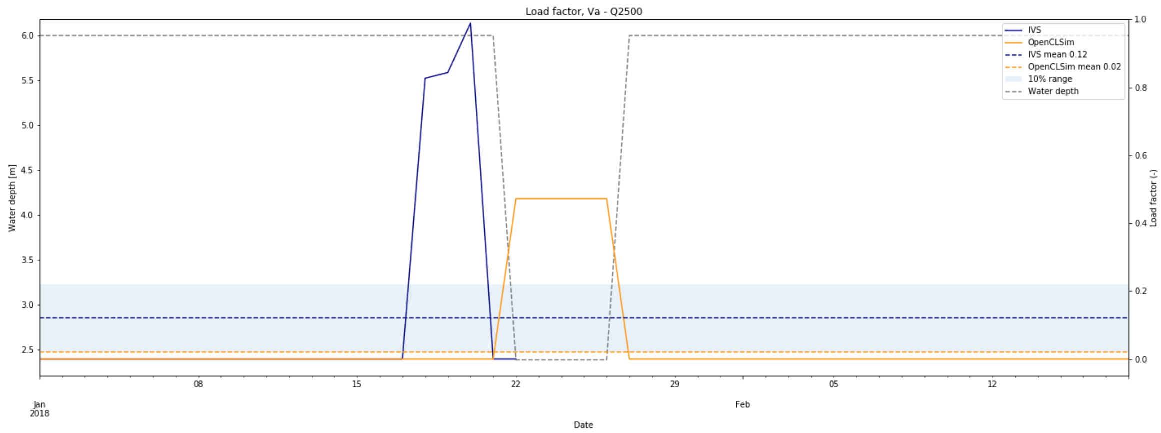


Figure 4.12: Va load factor validation during Q2500

Thirdly, the load factor for M8 tanker vessels show a large percentage deviation, in contrast to the expectation that an active vessel has a load factor around 1.0 in IVS as well as in the model. When studying the plot in Figure 4.13, the model produces load factors equal to 1.0 as expected for vessels that do not experience depth related bottlenecks. However, the IVS90 data shows load factors between 0.6 and 0.8 during the high water period. Reasons for liquid-bulk tankers to not load at maximum capacity although there are no depth related bottlenecks, could be for balancing the ship, according to expert judgement.

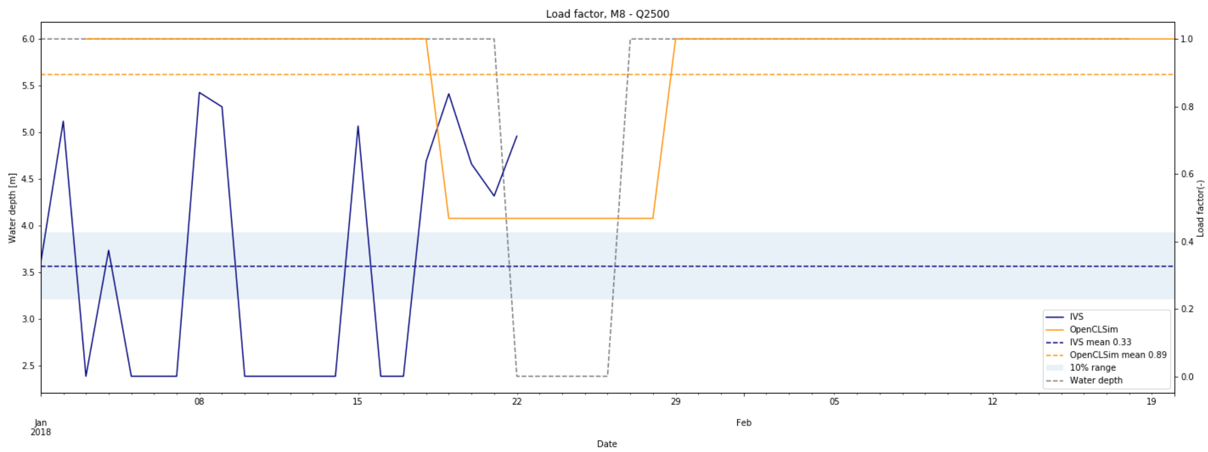


Figure 4.13: Load factor validation for Q2500, M8 tanker

Number of trips

The number of trips during the high water period show good results for all vessels except for BII-4 push-unit and VIa motor vessels(Figure 4.11b). When studying the plot of number of trips performed by BII-4 depicted in Figure 4.14, it can be seen that the mean values of both IVS and the model slightly differ from each other. However, the model's output follows almost the same pattern as the IVS data with peaks and troughs overlapping each other. It is therefore assumed that the model performs correctly on the number of trips for BII-4 push units.

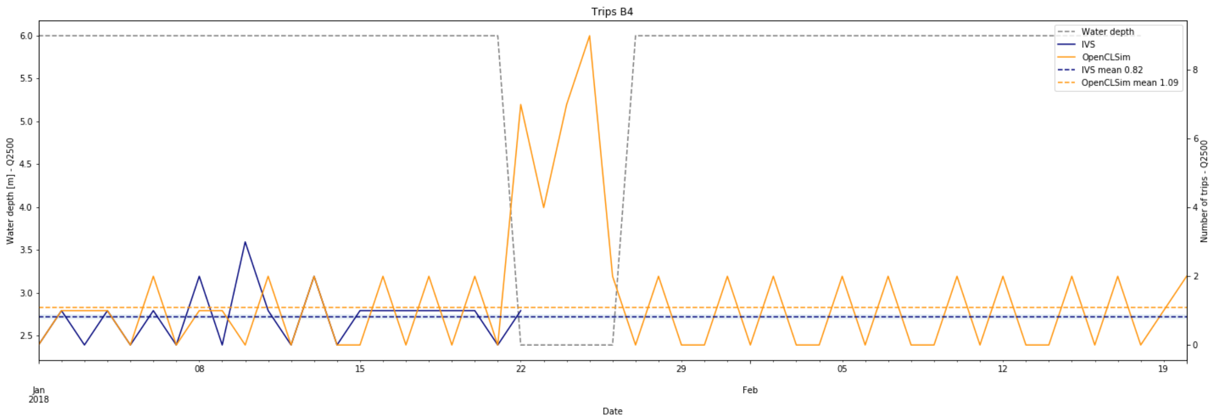


Figure 4.14: Number of trips validation for Q2500, BII-4 push barge

For the number of trips by VIa motor vessels the same reasoning can be applied as in the section about the load factor validation above. No VIa trips are performed by the model during high water levels, which is also concluded by the fleet size analyses in section 2.3. However the IVS plot in Figure 4.15, shows two peaks of 1 trip in a period of 22 days. This causes a large difference in mean values. Because no trips are visible for the largest part of the high water period according to IVS, it is assumed that the model produces the correct number of trips for VIa vessels during the high water period.

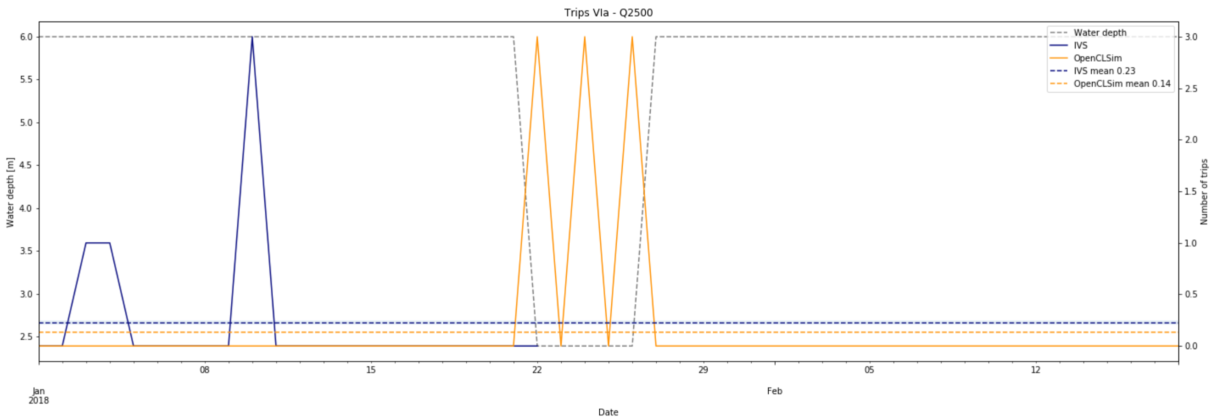


Figure 4.15: Number of trips validation for Q2500, VIa motor vessel

Transported cargo

The validation results of the transported cargo during high water levels are depicted in Figure 4.11c. The first thing to mention is that, again, the inactive motor vessels show large deviations from IVS90 data for the same reasons as explained in the previous sections. Besides, by comparing the absolute values of transported cargo in a bar diagram, it can be seen that the transported cargo by the motor vessels Va and VIa in both cases is almost equal to zero(Figure 4.16). This supports the assumption that the transported cargo by the model is in compliance with IVS90-data for the dry-bulk motor vessels.

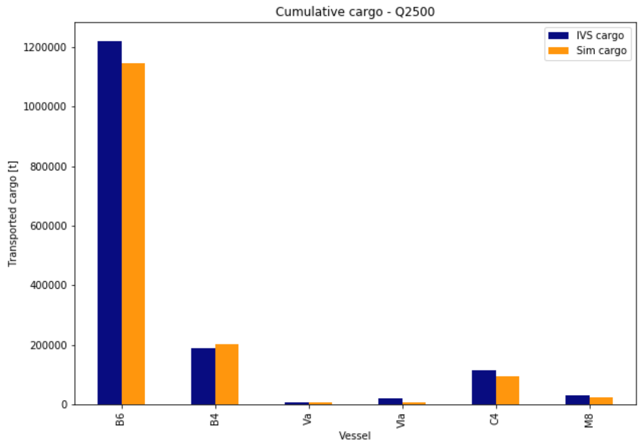


Figure 4.16: Transported cargo during Q2500 in absolute values

Although the load factor and mean number of trips for C4 convoys are within the margin of error, the mean transported cargo is under estimated by the model. The maximum load capacity is determined during the validation of Q1020 and is a fixed value which does not depend on the prevailing flow regime. Therefore, the deviation in transported cargo by C4 convoys cannot be adjusted and is assumed to be validated. In addition, the corresponding plot in Figure 4.17, shows many similarities between the model's output and IVS90 data.

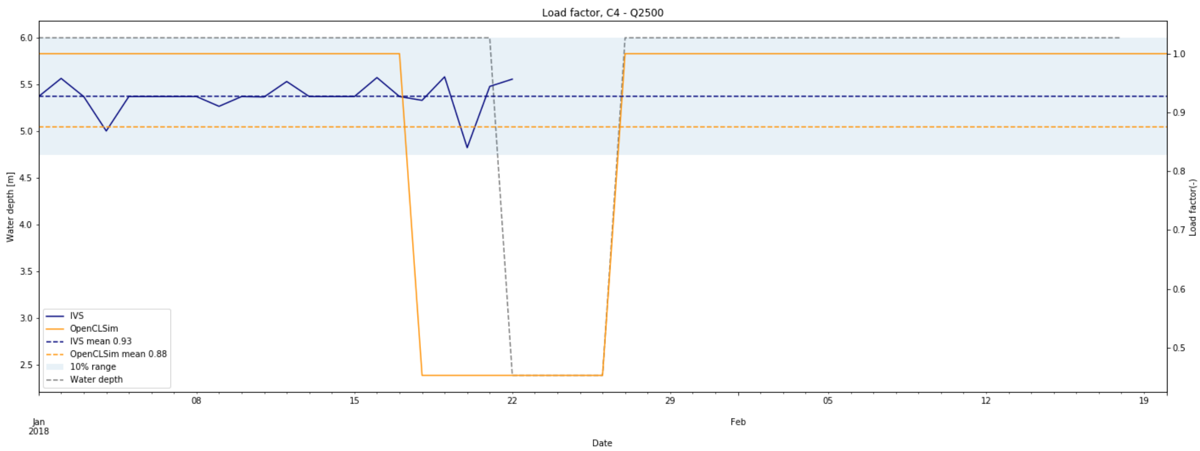


Figure 4.17: Load factor validation for Q2500, C4 convoy

Finally, the M8 tanker fleet transports less cargo during simulation than during a reference period in IVS90 data even though the load factor is highly over estimated by the model. A reason for the under estimation of transported cargo could be the relatively low maximum load capacity for an M8 vessel that was found by the IVS-analysis in section 4.1.4.

4.2. Conclusion

This chapter considered the validation of the simulation model by considering the load factor, number of trips and transported cargo. The model's output is compared with IVS90 reference data input parameters were adjusted when needed. By doing so, the following research question was has been addressed:

How does the simulation model perform compared to IVS90 data?

The load factor, number of trips and transported cargo are validated in this order to exclude deviations of each parameter to have an significant effect on each other. The validation is performed for each considered flow regime during low flow and for the high water period that occurs before and after the low flow period. It was found that the model calculates load factors for all vessels within a 10% range compared to IVS90-data, during all flow regimes. This result excludes the load factor to have an effect on the number of trips and transported cargo output. Consequently, the deviation to IVS90 in number of trips is analysed. It was concluded that the active fleet sizes determined in section 2.3, were slightly under estimated during Q1020 and Q850 and a bit over estimated during Q700. After a second validation run with adjusted fleet sizes, the number of trips performed by the model were within the 10% margin, except for the M8 tanker vessels during Q1020 and Q700 and the VIa vessels during Q850. Finally the transported cargo was validated. It was found that the initial input variables that describe the maximum load capacity were on the low side. In a second validation run, the median value of maximum load capacity, according the IVS90 data, was used as new input variables. This resulted in a significant improvement of the model in terms of transported cargo during all flow regimes. However, during Q1020 and Q700 transported cargo by M8-tankers is still over estimated by the model. This can be related to the over estimated number of trips by M8-tankers during the same flow regimes.

The table below shows an overview of the input values that have been considered during the validation.

	Active vessels before validation			**Active vessels after validation**				**Capacity [t]**	
RWS-class	Q1020	Q850	Q700	Q1020	Q850	Q700	Q2500	Before	After
BII-6	0	0	0	0	0	0	9	16.000	16.800
BII-4	8	6	0	9	6	0	2	7.500	11.200
C4	5	8	22	6	9	20	1	5.000	11.200
Va	3	5	12	5	8	11	0	2.050	3.900
VIa	1	2	2	3	3	6	0	4.300	5.550
M8-tanker	2	4	2	2	2	2	2	2.050	1.650

Table 4.7: Validated input variables

5
Results

The model that has been described in Chapter 3 and 4 is applied in this chapter to perform step II en III of the Dynamic Adaptive Policy Pathways approach. Step II considers tipping points of the current IWT-system, where step III considers tipping points of the IWT-system with implemented adaptation measures. The chapter starts with assessing the performance of the network during increasing periods of low flow on the basis of performance indicators.The performance indicators are first analysed for one flow regime individually before the performance during the different flow regimes is compared to each other. In the section that follows, the research question that relates to the tipping points for the dry-bulk and liquid-bulk supply chain will be addressed.

What is the tipping condition of the current inland waterway transport system before adaption measures are implemented?

Consequently, it is analysed if the system becomes more resilient to low water periods if adaptation measures are implemented. For the liquid-bulk supply chain, the availability of a more diverse fleet is implemented in the model. Then, the maintenance criterion is adjusted from 150 meters width to 130 meters width, as has been explained in section 2.4. This adaptation measure affects the dry-bulk as well as the liquid-bulk supply chain because it leads to an increase in available water depth, which has a positive effect on the load factor during low water water levels. Finally, when all tipping conditions are known, the timing of the tipping conditions is estimated in three climate change scenarios. The analyses of adaptation measures is explained in section 5.3 and the timing is estimated in section 5.4. Both sections contribute to the following research question:

What is the effect of implementing adaptation measures on the tipping condition of the inland waterway transport system and when are the tipping conditions expected to occur?

In the last section, step IV of the DAPP approach is completed by constructing the pathways that visualize the answers on the addressed research question in this chapter.

5.1. Performance indicators

The dry-bulk supply chain is mentioned first and consequently the liquid-bulk supply chain. The indicators are plotted in a bar diagram, in which each bar represents the cumulative value of all RWS-classes for one simulation. As mention in Chapter 3, the duration of the low flow period increases over the number of simulations. All simulations together form the stress test of the system of the concerned flow regime. On the x-axis of the bar diagrams, the number of days that low water levels prevailed during the simulation is indicated. When reading the plot from left to right, the number of low water level days increases. The contribution of each RWS-class to the cumulative value of the performance indicator is visualized by assigning different colors to each class.

5.1.1. Dry-bulk

In this section, the performance indicators are analysed for Q1020. The same reasoning can be applied to the Q850 and Q700 stress test so, to prevent recurrence, the results of of Q850 and Q700 can be found in Appendix E.

Trips

The bar diagram containing the cumulative trips for the Q1020 stress test is depicted in Figure 5.1. The first thing to notice is that the cumulative number of trips shows an increasing trend, where the number of trips has more than doubled between the first simulation containing 5 days of low flow and the last simulation containing 140 days of low flow. An increase in number of trips during low water levels is also expected according to the IVS analysis in Figure 2.5. This automatically leads to an increase in cumulative trips when comparing different duration of low flow periods, which is visible in the bar diagram. The trends of the individual RWS-classes do also show behaviour that can be expected. To start with the BII-6 push-units(dark blue), of which the number of trips decreases when the duration of the low water periods increases. BII-6 units are only active during high water levels and the high water level period decreases over the simulation runs. Furthermore, it can be seen that most BII-6 trips are compensated by BII-4 push units(moderate blue) as their cumulative trend slightly increases. This effect is the consequence of safety regulations that during Q = 1020 m^3/s sailing with 6 push barges is not allowed and units of 4 push barges have to be formed (Staatscourant, 2020). Finally, the share in number of trips by motor vessels, the green colors, and C4-conoys show an increasing trend, which is also confirmed by the IVS-analyses in Figure 2.6 and literature (van Hussen et al., 2019). Reference is made to Appendix E for the bar diagram plots of trip indicators for Q850 and Q700. The same reasoning for Q1020 as explained in this paragraph holds for the other flow regimes. The only difference is that during Q700 also BII-4 units become inactive which results in a larger contribution of C4 convoys as compensation than is the case during Q1020 and Q850.

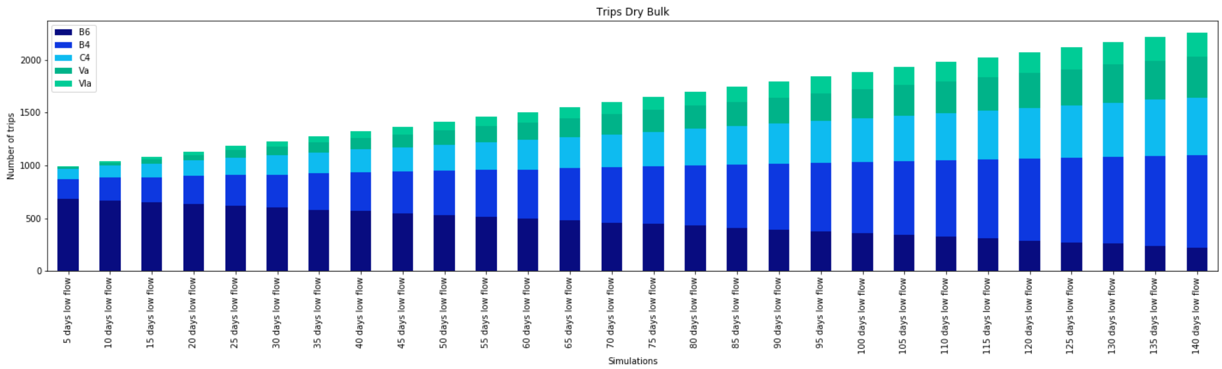


Figure 5.1: Number of trips per RWS-class for Q1020

Transported cargo

The bar diagram containing the cumulative transported cargo for the Q1020 stress test is depicted in Figure 5.2. Although the cumulative number of trips show an increasing trend as can be seen in the paragraph above, the cumulative transported cargo shows an decreasing trend over the simulations. Apparently, the extra deployed vessels during Q1020 and extra trips, cannot compensate for the cargo loss of the total fleet caused by the reduction in load factor. If we look at the RWS-classes individually, the trends are in compliance with the trends in number of trips. The transported cargo by BII-6 decreases, as the dark blue bar decrease in size and also the number of trips decrease. In contrast to BII-4 units, that transport more cargo over the simulations because also more trips are performed by this class. The same holds for the motor vessels Va and VIa an the C4 convoys. Reference is made to Appendix E for the bar diagram plots of the transported cargo indicators for Q850 and Q700. The same reasoning for Q1020 as explained in this paragraph holds for the other flow regimes.

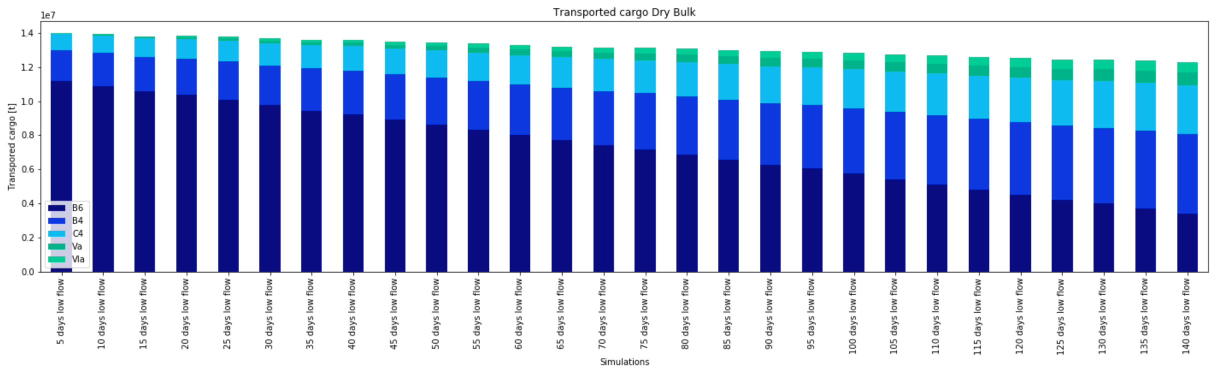


Figure 5.2: Transported cargo per RWS-class for Q1020

Total transportation costs

The bar diagram containing the cumulative transportation costs for the Q1020 stress test is depicted in Figure 5.3. The calculation of the transportation costs is based on cost figures determined by Panteia (Meulen & Ree, 2017), which are also implemented in the well-known BIVAS tool. The transportation costs depend on operational hours [h] and sailed distance [km] and are calculated according to the same structure as is proposed by Meulen & Ree (2017). The cost figures can be found in Appendix D.

$$Transportation\ costs = labor\ costs[h] + material\ costs[h] + variable\ costs[h+km] + handling\ costs[h] \tag{5.1}$$

In which:

$$Material\ costs = depreciation[h] + interest[h] + insurance[h] + maintenance[h](50\%) + harbor\ fees[h] + others[h] \tag{5.2}$$

$$Variable\ costs = fuel[h] + maintenance[km](50\%) \tag{5.3}$$

$$Handling\ costs = load\ costs[h] + unload\ costs[h] \tag{5.4}$$

The cumulative transportation costs show is slightly increasing trend over the simulations. At first, a large increase in transportation costs was expected due to the significant rise in number of trips. When looking at the RWS-classes separately, the total transportation costs do increase over the simulations, except for BII-6.

This can all be related to the in- and decrease in number of trips. The BII-6 units become less active over the simulations, which leads to a reduction of material, variable and handling costs for this particular fleet. In contrast to the BII-4 push units, which become more active over the simulations. This leads to a rise in operational hours, sailed distance and fuel consumption and thus in labor, material and variable costs. The share of handling costs in the total costs however, is not as large as it is for BII-6 units because the BII-4 units are mostly active during low water and sail with a reduced load factor. Less cargo is loaded into the barges unloaded from the barges so a large cut is made on the handling costs. This holds also for the RWS-classes Va, VIa and C4. Concluding, the cumulative transportation costs rise less than expected due to a more inactivity of BII-6 units over the simulations and a reducing share of handling costs for vessels active during low water levels. Nonetheless, transportation costs between Rotterdam and Duisburg for dry-bulk rise when low flow periods increase. Reference is made to Appendix E for the bar diagrams for Q850 and Q700 as the same reasoning can be applied.

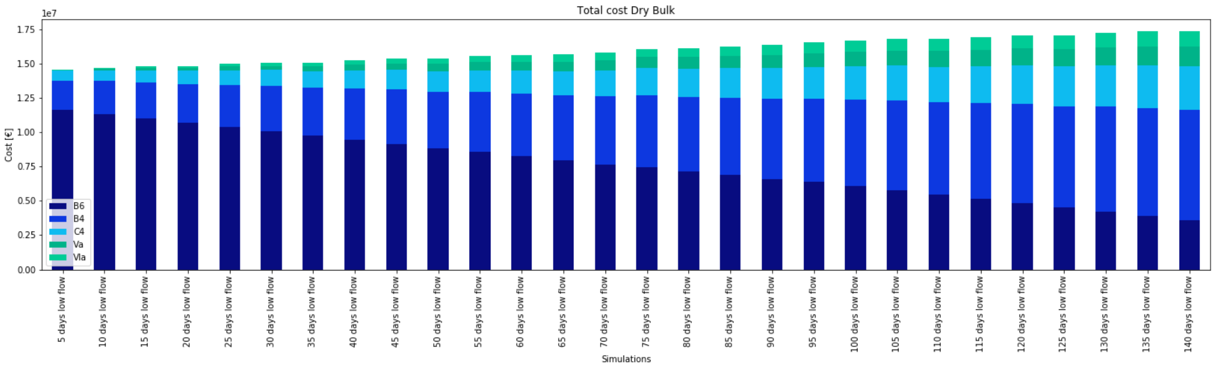


Figure 5.3: Transportation costs per RWS-class for Q1020

Cost per ton

The bar diagram containing the cumulative transportation costs per ton cargo for the Q1020 stress test is depicted in Figure 5.4. The transportation costs per ton cargo are determined by dividing the total transportation costs of the specific RWS-class by the total transported cargo. This comes down to dividing the values of each RWS-class from Figure 5.3 by the values from Figure 5.2:

$$Cost\ per\ ton = \frac{Transportation\ cost}{Transported\ cargo} \tag{5.5}$$

It is expected that the cost per ton will show a clear upward trend as the low water period increases because more trips have to be carried out to transport an equal amount of cargo. Furthermore, applying the economy of scale reasoning, it also expected that the vessels with largest capacity are most beneficial options. However, studying the bar diagram, the cumulative values of each simulation show a very small upward trend over 28 simulations and looking at the RWS-classes separately, the transportation cost per ton does not seem to change over the simulations except for BII-4 push units.

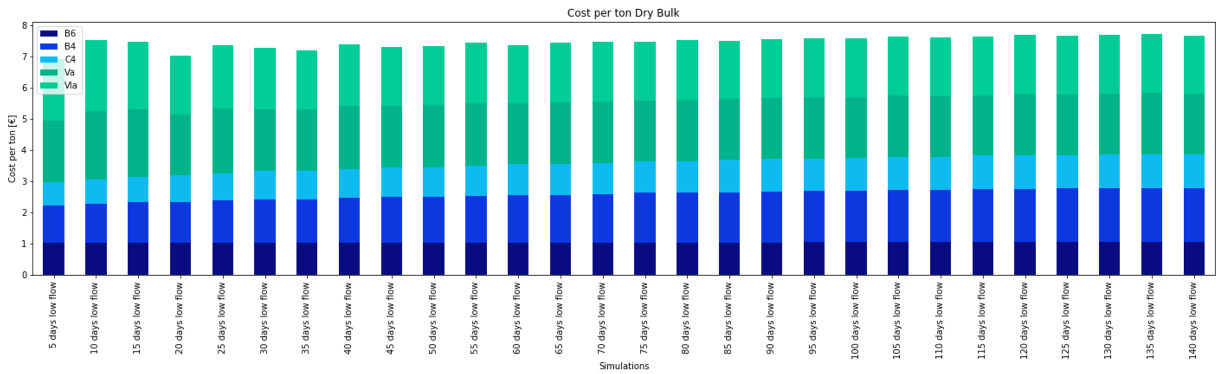


Figure 5.4: Cost per ton per RWS-class for Q1020

In Figure 5.5, the transportation cost per ton cargo trend of each RWS-class is plotted. The first thing to notice is that this plot indicate the vessels with the largest capacity are the most beneficial vessels to transport cargo, which is in compliance with the economy of scale. The BII-6 push units are cheaper in cost per ton than BII-4 units and the both push units are in turn cheaper than the motor vessels. Also the motor vessels themselves show that a VIa vessel, that has a larger capacity than a Va vessel, is more beneficial to transport cargo than a Va vessel. It is also noticeable that there can be two different developments of the trend lines be distinguished: constant and upward.

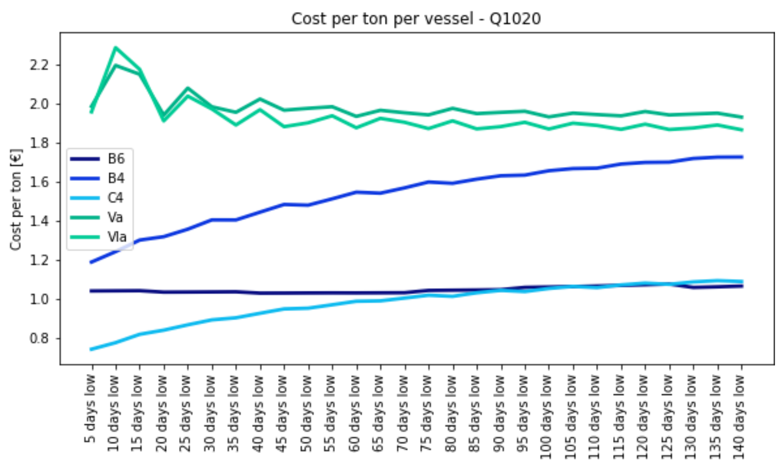


Figure 5.5: Cost per ton per RWS-class for Q1020

First, the cost per ton trend line of BII-6 push units show a constant trend line, meaning the cost per ton value does not change over the simulations. This can be explained by the fact that BII-6 push units are only active during high water levels. Because the water level is kept constant and no depth related bottlenecks occur, the load factor is always 1.0 and thus the circumstances for BII-6 units are equal for every simulation. The only thing that changes is the time these vessels are active. But, as the cost per ton is calculated as a mean value over the full period according to equation 5.5, the duration of the high water period has no effect on the outcome. The same holds for the motor vessels Va and VIa, which are only active during the low flow period. During this period, the load factor is, admittedly, smaller than 1.0 but it remains constant. So also for these vessels the circumstances don't change. In contrast to the BII-4 and C4 vessels, which show an increasing trend in the transportation costs per ton cargo over the 28 simulations. The difference between these vessels and the ones mentioned before is that some of the vessels are active during high water levels as well as during low water levels. It can also be seen that for the first simulations BII-4 and C4 vessels are a beneficial vessel type to transport cargo due to their high capacity during high water levels. However, when the duration of low water levels increase and thus the vessels have to sail with reduced load factors, they become more expensive. Reference is made to Appendix E for the bar diagrams for Q850 and Q700 as the same reasoning can be applied.

5.1.2. Liquid-bulk

The same indicators as mentioned in the section above are used the analyse the performance of tankers that transport liquid-bulk from Rotterdam to Wesseling. Despite from the destination, the main difference between the modeled dry-bulk and liquid-bulk supply chain is the composition of the fleet. Liquid-bulk can only be transported by motor vessels and the modeled fleet consists of just two vessels of the same type: M8. Besides, the two vessels are active during the full simulation period(i.e. 200 days), thus during high water levels and low water levels. Because of the uniformity of the fleet, the same behaviour as the BII-4 and C4 units from the dry-bulk fleet is expected. These vessels are also active during high water levels as well as during low water levels.

This section explains the results of Q1020 simulations for the liquid-bulk fleet. The results for Q850 and Q700 can be found in Appendix E because the same reasoning can be applied and the results only differ in absolute values.

Trips

The bar diagram containing the cumulative trips for the Q1020 stress test is depicted in Figure 5.6. In contrast to the dry-bulk supply chain, the fleet size does not change during low water levels which effects the number of trips. However, the bars show an increasing trend in the total number of trips performed by the M8-tankers as the duration of the low flow period becomes larger. During this low flow period, the tankers apply a reduced load factor which enables them to sail with a higher velocity. The higher velocity contributes to a reduction of the cycle time which leads to more trips in the same amount of time.

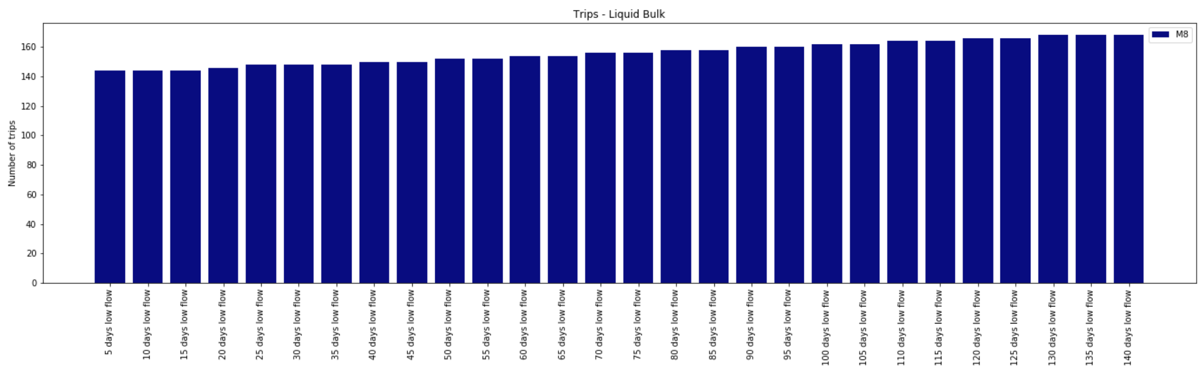


Figure 5.6: Number of trips by tankers for Q1020

Transported Cargo

The bar diagram containing the cumulative transported cargo for the Q1020 stress test is depicted in Figure 5.7. A clear downward trend of the transported cargo can be seen as the duration of the low flow period increases over the simulations. The reduced load factor has a significant effect of the transported cargo by the M8 tankers. The increase in number of trips cannot compensate for the loss in cargo per trip.

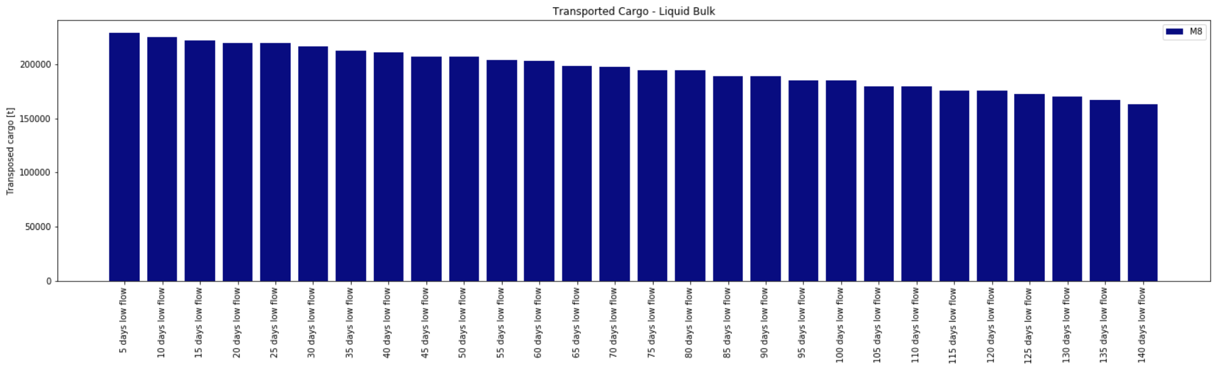


Figure 5.7: Transported cargo by tankers for Q1020

Total transportation costs

In Figure 5.8, the total transportation costs are plotted in a bar diagram. The cumulative value of the tanker fleet slightly fluctuates over the simulations but the general trend is more or less constant. As stated in equation 5.1, the transportation costs consist of labor, material, variable and handling costs, of which the first three rise with the increase in number of trips which leads to a larger sailed distance and operational hours by the total fleet. However, because no extra vessels are deployed and the number of trips slightly increase, the rise of labor, material and variable costs has no significant effect on the total transportation costs. In contrast to the handling costs, which decreases due to the fact that less cargo is loaded and unloaded. Moreover, if the value of the total transportation costs of the first simulation is compared with the value of the last simulation, a small reduction is visible. This means that the reduction in handling costs(loading/unloading) outweighs the rise in labor, material and variable costs.

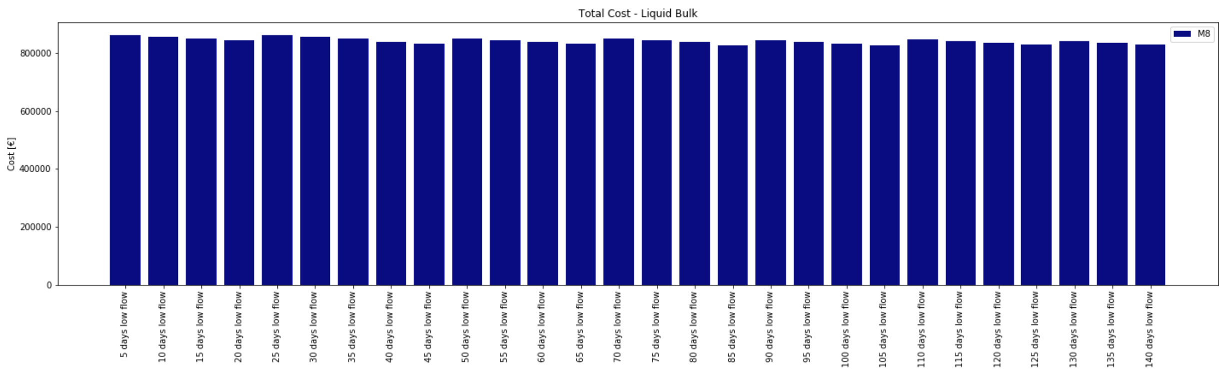


Figure 5.8: Transportation costs by tankers for Q1020

Cost per ton

The bar diagram containing the transportation cost per transported ton cargo for the Q1020 stress test is depicted in Figure 5.9. The upward trend indicates an increase in transportation costs per ton of cargo which is an consequence of the transported cargo trend and transportation cost trend in Figure 5.7 and 5.8, respectively. This can be explained as follows; considering the almost constant trend of transportation costs over the simulation, each time the low flow period increases, less cargo is transported for which each time equally transportation costs are incurred by the liquid-bulk fleet.

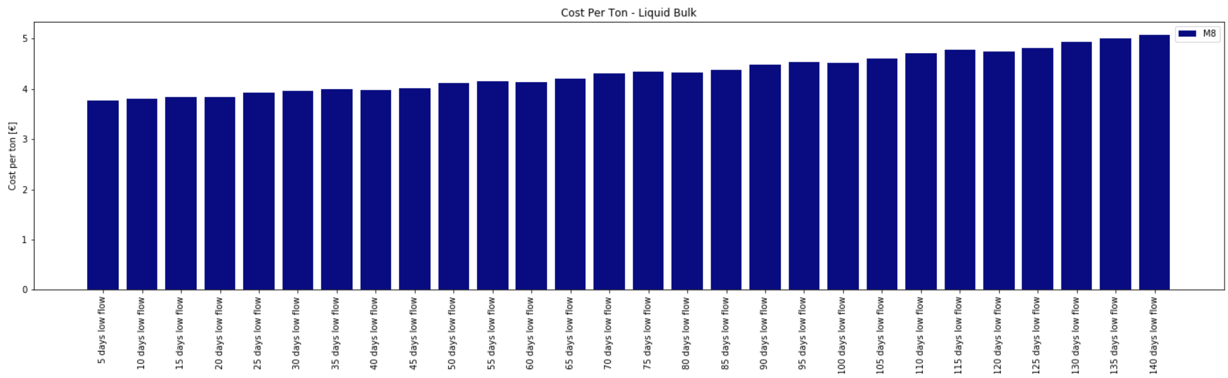


Figure 5.9: Cost per ton by tankers for Q1020

5.2. Current situation

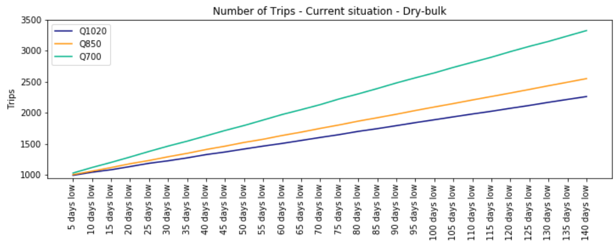
This section elaborates on the performance indicators mentioned in the previous section. In this phase, the values of the indicators for the different flow regimes are plotted. This adds an extra dimension to the analysis compared to section 5.1 because, the effect of different water levels becomes visible instead of only the low water level duration. Furthermore, the tipping condition of the current situation of both the dry-bulk supply chain as well as the liquid-bulk supply chain will be determined.

Dry-bulk

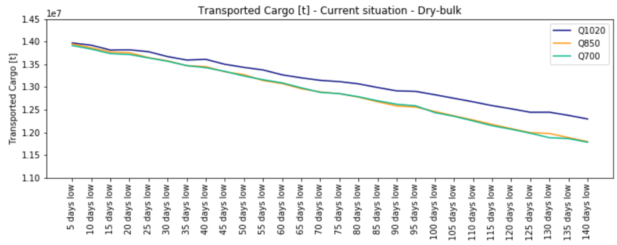
The performance indicators of the dry-bulk fleet are plotted in Figure 5.10. Instead of comparing the RWS-classes amongst each other as has be done in section 5.1, in these plots the different flow regimes are compared. So, the plotted lines represent the performance of the full dry-bulk fleet during three different flow regimes, where the solid dark blue line corresponds to Q1020 simulations, equal to the bar diagrams trends in section 5.1. The solid orange and green line represent the flow regimes Q850 and Q700 respectively.

In Figure 5.10a, the total number of trips is plotted for every flow regime. As explained in the previous section, when the duration of the low flow period increases, also the total number of trips rises. This effect holds for every flow regime as can be seen in the plot. In addition, not only the duration of the low flow period affects the number of trips, but also the prevailing flow regime. Comparing the different flow regimes in one simulation, for example the last simulation containing 140 days of low flow, it can be seen that when the discharge at Lobith decreases, the number of trips increases. In terms of network performance, a certain threshold in the number of trips can be reached where the system will no longer meets its objective. The threshold for number of trips can be related to, for example, congestion of the network (Verschuren, 2020) or to much CO2 emissions as these are consequences of more vessel movements. Considering an upper threshold in number of trips, one could say that if the low water level periods increase and the water level itself decreases, the situation of the inland waterway transport system becomes more severe. However, the number of trips is not used as an indicator to determine tipping points for this study. A congestion analyses of the inland waterway or an emission analyses are out of the scope of this research.

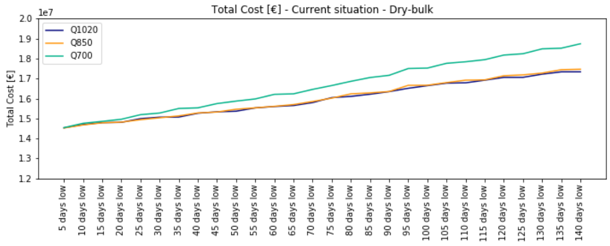
In Figure 5.10b, the total transported cargo is plotted for every flow regime. When studying the flow regimes individually, it can be seen that the active fleet cannot compensate for the reduced load factor and thus less cargo is transported. However, comparing the flow regimes Q850 and Q700, the same weight of cargo is



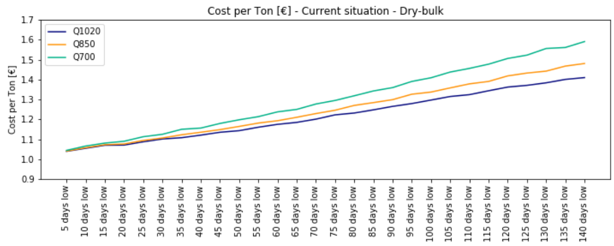
(a) Number of trips for all flow regimes, dry-bulk



(b) Transported cargo for all flow regimes, dry-bulk



(c) Transportation costs for all flow regimes, dry-bulk



(d) Cost per ton for all flow regimes, dry-bulk

Figure 5.10: Indicators for all flow regimes

transported. The extra trips during Q700 do compensate for the inactivity of BII-4 and a reduced load factor relative to Q850 simulations. This is mainly caused by the significant increase in number of trips performed by the C4-convoys, which can be seen in the bar diagram for Q700 in Appendix E. Considering the transported cargo as a performance indicator, a lower limit can be set as threshold value. The threshold value for transported cargo could be related to the stock of industries at the destination site. If less cargo is transported, the stock at industries decreases and the production has to be reduced with economic consequences van Saase & Streng (2020). Taking this consequence into account, it can be said that the situation of the inland waterway transport system becomes more severe when the duration of low water periods increases and the corresponding discharges reduce. However, this indicator is not used for this study to determine tipping points, as this would focus more on the consequences of the low water levels for a specific company, which is out of the scope.

In Figure 5.10c, the total transportation costs are plotted for every flow regime. The reasoning for an upward trend in transportation costs over the simulations as explained in section 5.1 also holds for the Q850 and Q700 flow regimes. The transport costs for Q850 and Q1020 are approximately the same for each simulation. Taking into account the rise in number of trips relative to Q1020, the labor, material and variable costs are larger for Q850 than they are for Q1020. In contrast to the handling costs, which are related to the transported cargo and thus are smaller for Q850 than they are for Q1020. Concluding, the rise and reduction in the cost items cancel each other out, which leads to approximately equal transportation costs for Q1020 and Q850. The upward trend in total transportation costs do indicate that transportation becomes more expensive as low water periods increase. However, this does not necessarily have to be a negative effect. For example, transporting more cargo automatically leads to larger transportation costs. To assess the performance of the IWT system only by transportation costs is therefore not sufficient. To express the performance of the IWT-system in terms of costs, they should be related to the volume transported cargo for those costs. A common expression is the cost per transported ton cargo, which is depicted in Figure 5.10d. All flow regimes follow an upward trend for the same reasons as explained in the previous section. The first thing to notice is that the costs per ton do not show equal values for flow regimes, which is the case for Q1020 and Q850 in transportation costs. According to the transportation costs, the dry-bulk supply chain performance is equal for Q850 and Q1020, which is, obviously not the case. The costs per ton, therefore, is a more suitable indicator to express the performance of the IWT-system. The cost per ton can be seen as the average cost over the full simulation period to transport 1 ton from Rotterdam to Duisburg. An upper limit of the cost per ton can be set as a threshold value to indicate for which value the system does not longer meet its requirements. Considering an upper limit, the upward trend in Figure 5.10d shows that the more severe the low water level periods become in terms of duration and the water level itself, the worse the system starts to perform. It becomes more and more expensive to transport 1 ton from Rotterdam to Duisburg.

Tipping condition

The indicator transportation costs per ton is often used to express the performance of a transport system because the transported cargo and transportation cost on their own do not tell the complete story. Furthermore, it also gives the possibility to compare different transport modalities to each other. Besides the transportation costs per ton indicator, an other frequently used parameter is the transportation costs per ton kilometer:

$$Cost\ per\ ton\ kilometer = \frac{Transportation\ cost\ /\ Transported\ cargo}{Distance\ traveled} = \frac{Cost\ per\ ton}{Average\ distance\ traveled} \quad (5.6)$$

Because the average distance traveled between Rotterdam and Duisburg is constant for each simulation (i.e. 240 km), the transportation costs per ton kilometer show the same trend of transportation costs per ton but, differ in absolute value. As stated in Chapter 2, the objective of the inland waterway transport system is to be the most attractive transport modality. In a study performed by *Kennisinstituut voor Mobiliteitsbeldel*(KiM), the transportation costs for different modalities are analyzed Visser (2020). It was found that for the transport of dry-bulk by rail, the yearly average transportation costs per ton kilometer are 1,2 euro cent/tonkm. Because this value is found in literature, no extra research or analyses have to be made to determine a threshold value for railway transport. Taking into account the scope of this research and the supply chains objective, it is chosen to use transportation costs per ton kilometer as performance indicator to base the tipping points on. Dry-bulk transport by road is not considered for this case, because of the large differences in capacity it is almost impossible to shift dry-bulk transport from waterways to road.

The threshold value can be used to apply the Dynamic Adaptive Policy Pathway approach as explained in Chapter 3 and determine a tipping condition for the dry-bulk supply chain between Rotterdam and Duisburg. In Figure 5.11, the transportation costs per ton kilometer is plotted for all flow regimes, together with the threshold value that equals the transportation costs per ton kilometer for dry-bulk railway transport. The values are calculated according to equation 5.6.

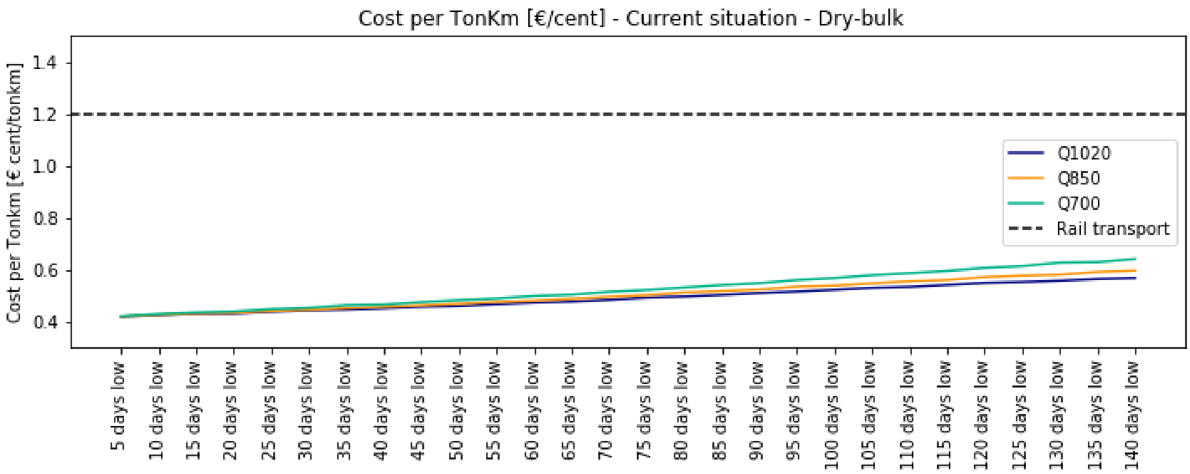
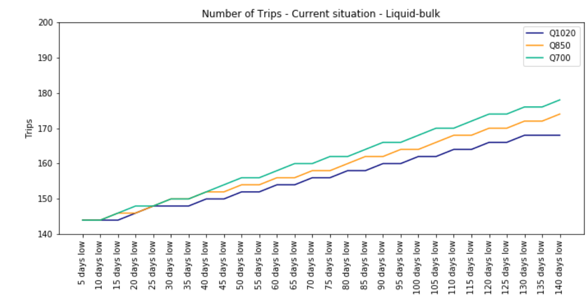


Figure 5.11: Tipping conditions dry-bulk

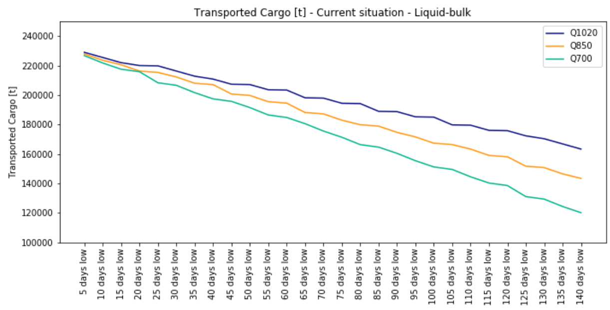
Comparing the transportation costs per ton kilometer for all flow regimes with railway transport, it can be concluded that no tipping condition is reached, because the transportation costs per ton kilometer for dry-bulk are always lower than for railway transport. This means that, according to this indicator, inland shipping is the most attractive transport mode between Rotterdam and Duisburg, even if the low water periods become more severe.

Liquid-bulk

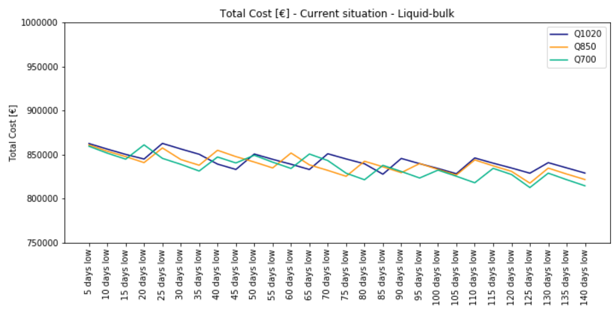
The performance indicators of the liquid-bulk fleet are plotted in Figure 5.12. The number of trips by the liquid-bulk fleet for different flow regimes shows the same behaviour as the dry-bulk fleet: an upward trend when for increasing low water level periods and a decreasing discharge (Figure 5.12a). The transported cargo in Figure 5.12b by the M8 tankers reduces as well for the same reason as for the dry-bulk fleet. In Figure 5.12c the total transportation costs are plotted. In contrast to the behaviour of the other indicators, it shows a different behaviour than the dry-bulk fleet. An important difference with the dry-bulk fleet is that the liquid-bulk is uniform: only two M8 tankers are active during high and low water. The transportation costs have a small decreasing trend for all flow regimes. When the low water periods become larger, less cargo is transported and thus the handling costs decrease. In contrast to the other cost items, which rise due to more traveled distance and operational hours(more ship movements). The downward trend indicates that for a uniform fleet the handling costs are normative. Furthermore, the transportation costs are approximately equal for all flow regimes, because no significant extra costs are made by the deployment of extra vessels(uniform fleet). The transportation costs per ton are plotted in 5.12d and the same behaviour as for dry-bulk is visible. In addition, it shows again that the transportation costs per ton is a more suitable indicator than the transportation costs. Because, studying only the transportation costs would indicate that the performance of the liquid-bulk supply chain between Rotterdam and Wesseling is equal for all flow regimes.



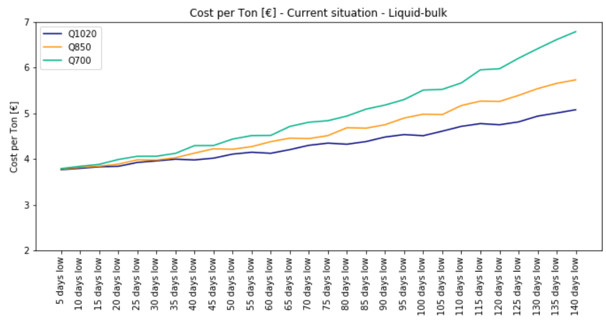
(a) Number of trips for all flow regimes, liquid-bulk



(b) Transported cargo for all flow regimes, liquid-bulk



(c) Transportation costs for all flow regimes, liquid-bulk



(d) Cost per ton for all flow regimes, liquid-bulk

Figure 5.12: Liquid-bulk indicators

Tipping condition

The indicator transportation costs per ton kilometer is also used to determine the tipping condition for the liquid-bulk supply chain. According to the analysis performed by KiM, (Visser, 2020), the yearly average transportation costs per ton kilometer for liquid-bulk railway transport is 1,5 euro cent/tonkm. In Figure 5.13, the transportation costs per ton kilometer is plotter for the liquid-bulk supply chain together with the threshold value, which equals the ton kilometer costs for railway transport. In contrast to dry-bulk, the liquid-bulk fleet experiences tipping points, indicated by the triangles on the x-axis.

The transportation costs per ton kilometer for Q1020 exceed the threshold value when a low water level period of 65 days is simulated. In other words: during a low flow period of 65 days and Q = 1020m^3/s the liquid-bulk supply chain does not meet its objective anymore. After 65 days of Q = 1020m^3/s railway transport becomes more beneficial than inland waterway transport. For the Q = 850m^3/s flow regime, the tipping point already occurs at 50 days. If the conditions become even more severe and Q = 700m^3/s, the threshold is reached and exceeded if the discharge prevails for 35 days. The shift of the tipping condition to a shorter period of low flow demonstrates the negative effect the duration of low flow periods has on the performance of the IWT system.

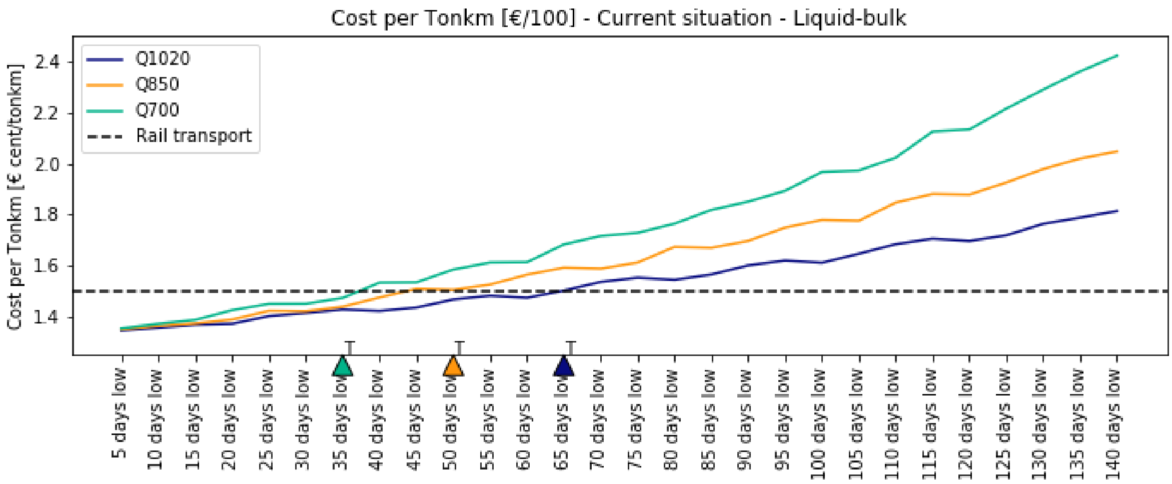


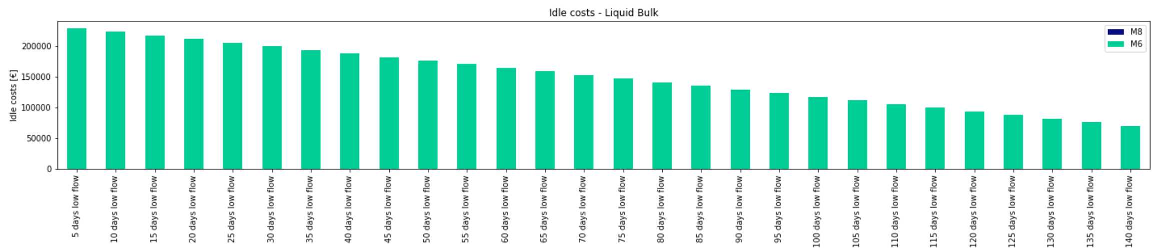
Figure 5.13: Tipping conditions liquid-bulk

5.3. Adaptation measures

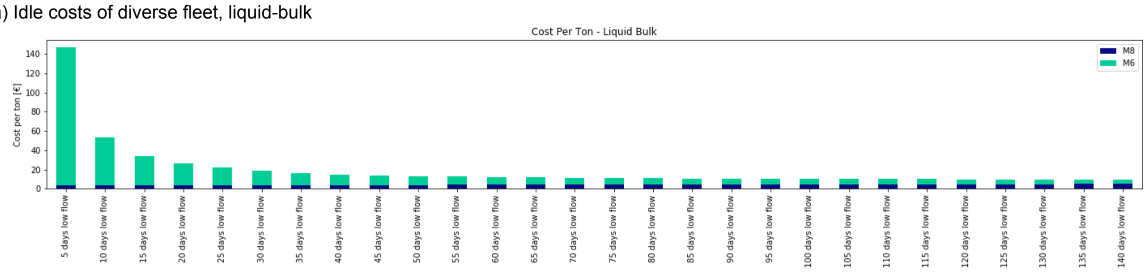
Adaptation measures can be implemented to improve the performance of the inland waterway transport system. The performance of the system or, definition of success, can be expressed in many indicators and can be different for every actor on the system as mentioned in Chapter 2. In the previous section, five indicators are analysed and finally transportation costs per ton kilometer was chosen the to be used for the determination of tipping points. Adaptation measures aim to extent the tipping points which indicates a better performance of the IWT-system. However, the dry-bulk supply chain does not experience any tipping points which implies no adaptation measures are needed as the system is already climate resilient according to transportation costs per ton kilometer, in contrast to liquid-bulk. A big difference between dry-bulk and liquid-bulk supply is the fleet composition. Where the liquid-bulk fleet is uniform, consisting of two M8 tankers, the dry-bulk fleet is diverse: size and type of active fleet adapt to the prevailing flow regime. The fact that the dry-bulk fleet is diverse and is already climate resilient, based on cost per ton kilometer, the first adaptation measure to improve the liquid-bulk supply chain is the availability of extra vessels during the low water period. Secondly, the maintenance criterion is adjusted which should result in a more beneficial available water depth.

5.3.1. Diverse fleet

To model the diverse fleet for liquid-bulk, a few assumptions are made. First, the two M8 tankers that were already active during high and low water in the current scenario, are also active in the diverse fleet scenario. Secondly, during low water levels, two M6 tankers become available instead of M8 tankers. It is assumed that due to a smaller draft, M6 tankers perform better during low water levels. The third assumption is that during high water periods, the M6 tankers are idle and therefore generate extra costs. The idle costs consist of insurance, interest, depreciation and harbor fees. In Figure 5.14a, the idle costs of the M6 tankers over the Q1020 simulations can be seen, following a decreasing trend. The cost per ton per RWS-class of the diverse fleet are plotted in Figure 5.14b. The peak in the first simulation is caused by large idle costs in combination with a small volume transported cargo, because the M6 vessels are only five days active. As the idle time reduces and M6 tankers start to transport more cargo, the costs per ton drop significantly.



(a) Idle costs of diverse fleet, liquid-bulk

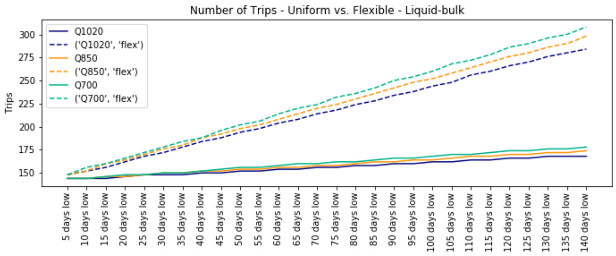


(b) Cost per ton diverse fleet, liquid-bulk

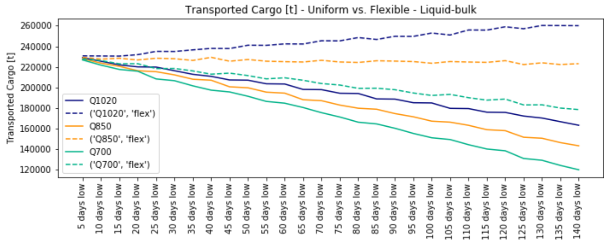
Figure 5.14: Idle costs of diverse liquid-bulk fleet

To analyse the impact of a diverse fleet, the indicators of the uniform fleet are compared with the indicators of the diverse fleet in Figure 5.15. The total number of trips performed by the diverse fleet are considerably larger than for a uniform fleet, which is, of course, because two extra vessels are added on top of the already active uniform fleet. If the number of trips would have an upper threshold value, than an uniform fleet has a negative effect on the performance of the IWT-system.

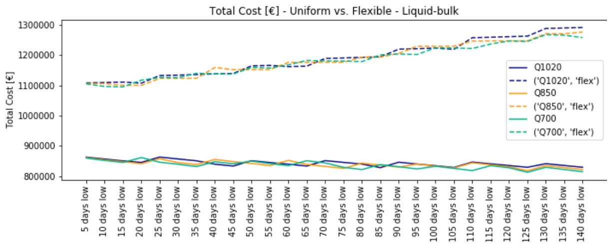
Comparing the diverse fleet with the uniform fleet on the transported cargo, it can be seen that a diverse fleet is able to transport more cargo during low water levels than a uniform fleet. This can be explained by the extra capacity added to the fleet. So, a diverse fleet has a positive effect on the performance of the network in transported cargo. The increasing line for Q1020 indicates that the diverse fleet transports more cargo if low flow periods increase than during a period of equal length without any depth related bottlenecks. In real-life, this would only be the case if the demand is larger during low water levels than during high water levels and the fleet can handle this demand. In compliance with Figure 5.14a, the total costs of diverse fleet are larger than a uniform fleet due to idle costs and more operational hours because of the two extra added vessels. The cost per ton indicator displays larger costs for a diverse fleet than for a uniform fleet. This will be further analysed according the cost per ton kilometer indicator in Figure 5.16.



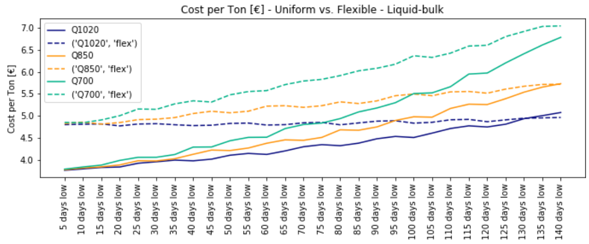
(a) Number of trips for all flow regimes, liquid-bulk



(b) Transported cargo for all flow regimes, liquid-bulk



(c) Transportation costs for all flow regimes, liquid-bulk



(d) Cost per ton for all flow regimes, liquid-bulk

Figure 5.15: Uniform vs. diverse liquid-bulk fleet indicators

The cost per ton kilometer indicator is displayed together with the threshold value of railway transport. The plot shows different results than were expected beforehand. In the first place, the transportation costs per ton kilometer are rising as the low flow periods increase, where it was expected that transportation costs per ton kilometer would become more beneficial if low flow periods would prevail for a certain number of days. One reason could be that M6 tankers are less efficient during low water levels, because they still have to apply a large load factor. Secondly, the diverse fleet has higher transportation costs per ton kilometer than a uniform fleet for each simulation during the Q700 stress test. For Q850 and Q1020, an intersection with the uniform fleet is visible for the last simulation. This means that for 130 consecutive days of flow Q = 850m^3/s or Q = 1020m^3/s a diverse fleet is more beneficial than a uniform fleet. At this point, the idle costs are compensated by extra transported cargo compared to a uniform fleet. Finally, the diverse fleet does not shift tipping points as it is more expensive than railway transport for all simulations. This implies the system does not meet its object from 5 days of low flow and on wards, if only a diverse fleet would be available. Concluding, a uniform fleet contributes to more transported cargo during low water levels, which is in favour of industries at the destination site. In fact, as mentioned in section 2.4, the diverse fleet measure should be initiated by the industries and not by the government. However, this implies higher transportation costs.

	Current situation	**diverse fleet**
Q1020	65 days	5 days
Q850	50 days	5 days
Q700	35 days	5 days

Table 5.1: Tipping conditions for a diverse fleet

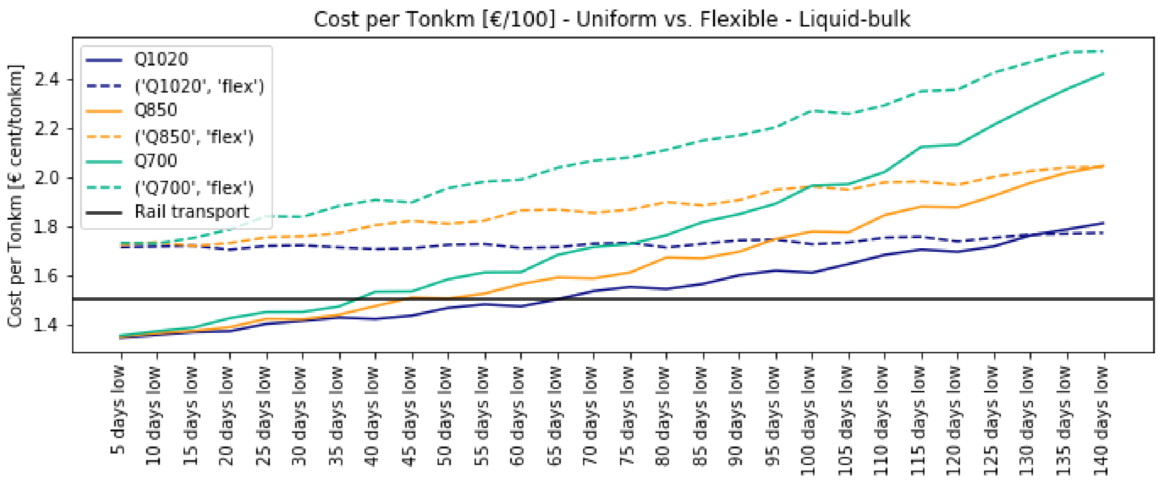


Figure 5.16: Cost per ton kilometer for uniform and diverse fleet

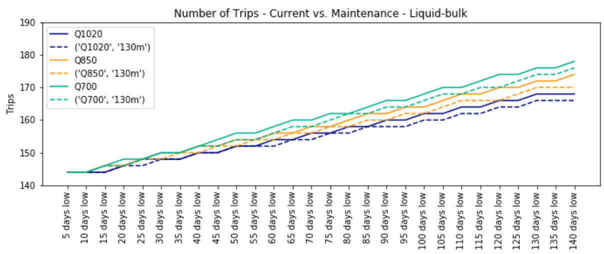
5.3.2. Adjust maintenance criterion

Currently, the river Waal is maintained by a criterion that guarantees a minimum depth of 2.80 meters at 150 meters width. However, during low flow periods this criterion is hardly and the minimum available water depth in particular cross-sections is less than 2.80 meters. By adjusting the maintenance criterion to a guaranteed depth at 130 meters width, the inland vessels can load to larger available water depths. This entails that the bottlenecks that are located outside the 130 meters width must be known by the skippers, so that they can sail around them. For example by indicating the bottlenecks with buoys in the navigation channel. The maintenance criterion can be modeled by adjusting the width input variable for the 'minimum available water depth' algorithm. This algorithm determines the minimum available water depth in every cross-section at a given width. For more details on the minimum available water depth and the adaptation measure, reference is made to section 3.2 and section 2.4 respectively. Instead of a minimum width of 150 meters, the maintenance criterion is reduced to a width of 130 meters. The corresponding water depths are shown in Table 5.2. Because the available water depth in the waterway is larger, dry-bulk as well as liquid-bulk will be affected by this adaptation measure. Although dry-bulk transport does not experience tipping points based on the transportation costs per ton kilometer, the performance can still be improved. Because the adaptation measure will not lead to improved tipping conditions, the effect on the performance indicator can be found in Appendix F.

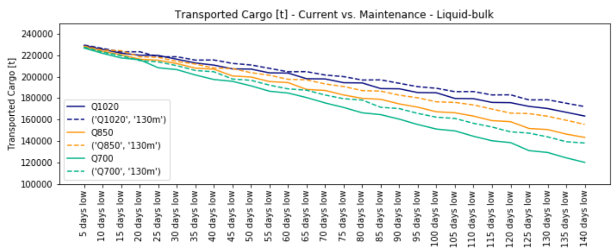
	MAWD 150m	**MAWD 130m**
Q1020	2.39 m	2.59 m
Q850	2.01 m	2.20 m
Q700	1.79 m	1.91 m

Table 5.2: Available water depth for different maintenance criteria

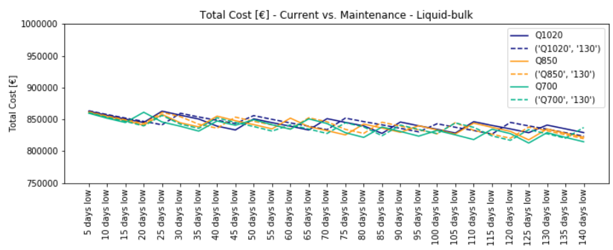
In Figure 5.17a and 5.17b it can be seen that less number of trips are performed when the maintenance criterion is adjusted and more cargo is transported. The adjusted maintenance criterion leads to larger available water depths which on turn leads to larger load factors and thus more transported cargo. The maintenance criterion seem to have no effect on the total transportation costs. Considering the transportation costs per ton in Figure 5.17d, adjusting the maintenance criterion leads to a reduction and a better performance of the IWT, because for the same transportation costs more cargo is transported.



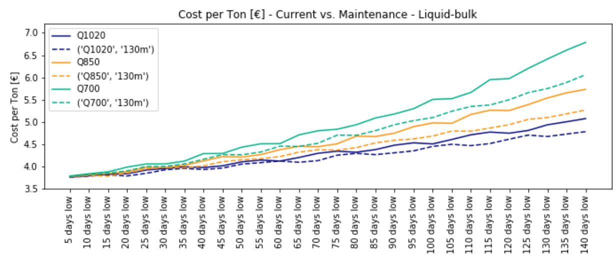
(a) Number of trips for all flow regimes, liquid-bulk



(b) Transported cargo for all flow regimes, liquid-bulk



(c) Transportation costs for all flow regimes, liquid-bulk



(d) Cost per ton for all flow regimes, liquid-bulk

Figure 5.17: Maintenance of 150m width vs. 130m width, liquid-bulk

The improved performance of the IWT of liquid-bulk between Rotterdam and Wesseling by adjusting the maintenance criterion is also confirmed when analysing the transportation costs per ton kilometer in Figure 5.18. The dashed-lines indicate the values for the adjusted maintenance criterion, which are lower for every flow regimes compared to the current situation indicated by the solid lines. Moreover, the tipping conditions have shifted to the right on the y-axis, indicating the system can cope with longer low flow periods. The comparison of the tipping points with the current situation can be seen in Table 5.3

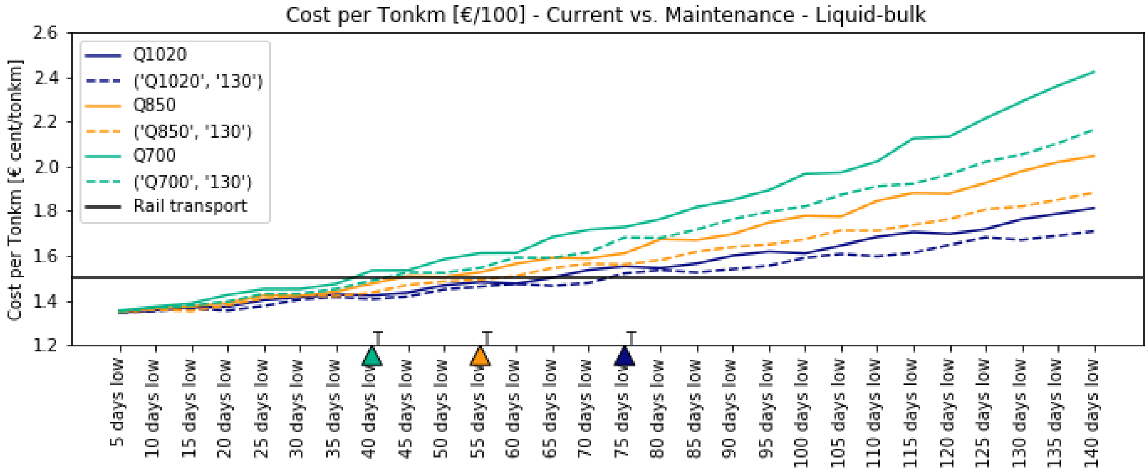


Figure 5.18: Cost per ton kilometer for maintenance of 150m width vs. 130m width, liquid-bulk

	Current situation	Maintenance criterion
Q1020	65 days	75 days
Q850	50 days	55 days
Q700	35 days	40 days

Table 5.3: Tipping conditions for an adjusted maintenance criterion

5.4. Timing of tipping conditions

This section covers the timing of tipping conditions considering three different climate scenarios. The timing of a tipping condition is determined by its occurrence in transient scenarios developed by Haasnoot et al. (2015). There are 20 discharge series available for the discharge at Lobith on a time scale from 2001 to 2021 for every climate scenario. The discharge series are transformed to series that display the number of consecutive days that a certain flow regime prevails. This results in 9 categories: three flow regimes in three climate scenarios. Each category consists of 20 series that contain the number of consecutive days of the specified flow regime (Figure 5.19).

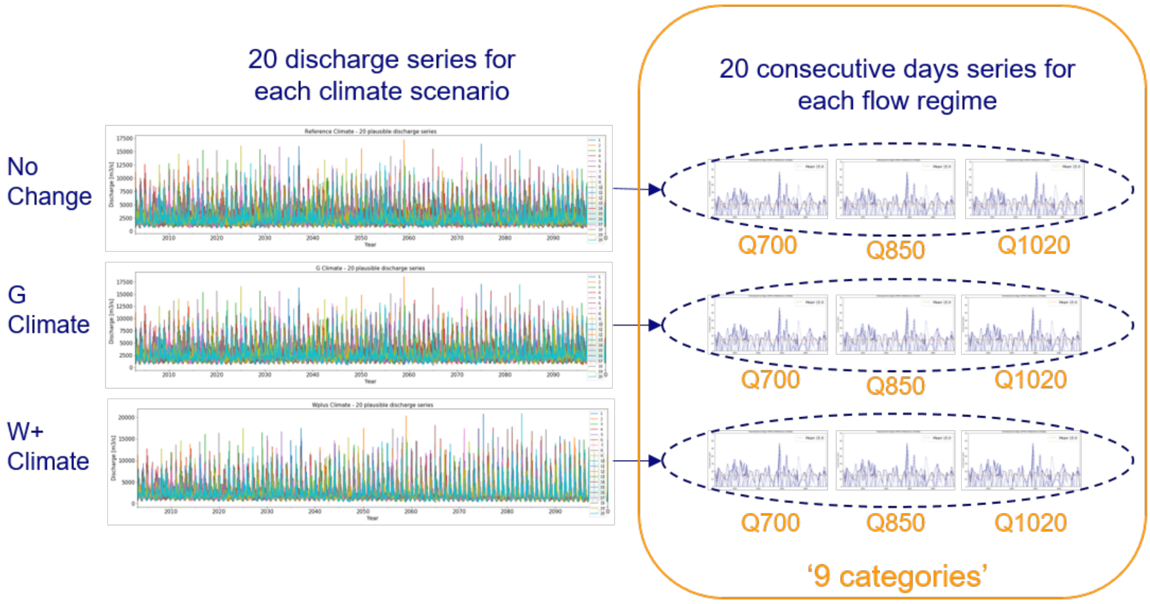


Figure 5.19: Tranformation of discharge series

The consecutive days for every flow regime in each climate scenario, the categories, are plotted in Figure 5.20. In addition, the mean number of consecutive days over 20 series of every category is indicated by a dashed orange line.

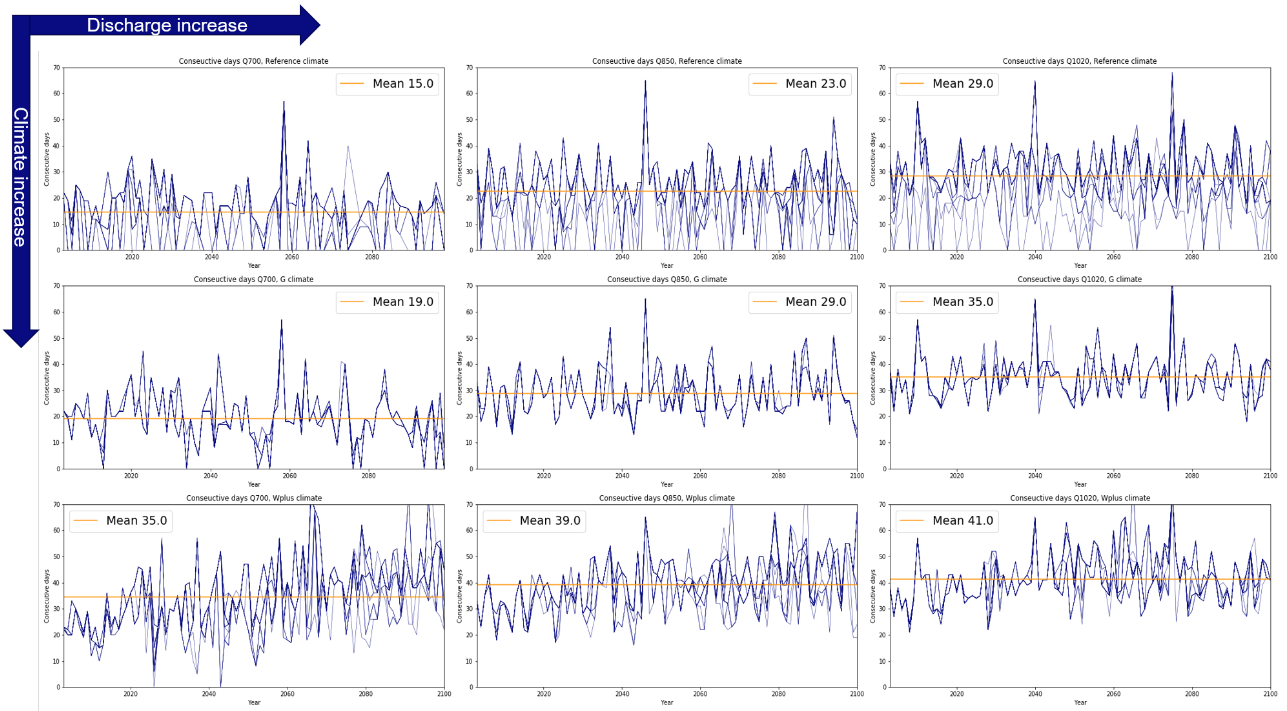


Figure 5.20: Consecutive days of flow regimes for every climate scenario

The expected climate change mentioned in Chapter 2 and by the KNMI reports is confirmed by analysing the mean values and plots of every category: the duration of low flow periods will prevail for a longer period of time and will occur more often. For all three flow regimes, the mean number of consecutive days increases when the climate change becomes more severe, see Table 5.4. When reading Figure 5.20 from the top to the bottom, the climate changes becomes more severe. It can be seen that the blue plotted lines are fluctuating around a higher trend line compared to the plots above the bottom row, indicating the consecutive days will occur more often.

Climate/ Flow regime	**No climate change**	**G climate**	**W_{plus} climate**
Q1020	29 days	35 days	41 days
Q850	23 days	29 days	39 days
Q700	15 days	19 days	35 days

Table 5.4: Mean number of consecutive days

The timing of a tipping condition is determined for the 9 categories, three flow regimes in three climate scenarios. The timing of a tipping condition is assumed to be valid if the tipping condition occurs for three years in a row in the consecutive days series. The first year that this happens is stored, resulting in a list of tipping conditions for each category. The list can consist of 20 'timings' maximum, because each category consists of 20 series. Consequently, the median value of the list is assigned as the timing of the tipping condition.

Dry-bulk

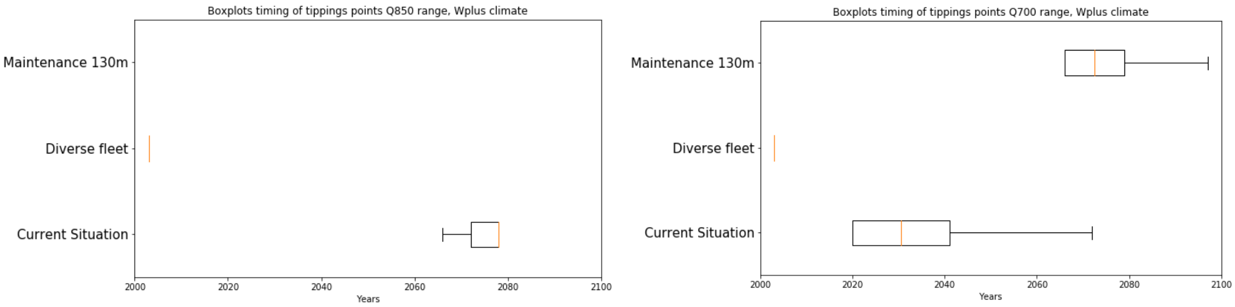
In section 5.2, no tipping conditions were found for the inland waterway transport of dry-bulk between Rotterdam and Duisburg. This means that, when considering the transportation costs per ton kilometer, the IWT-system can cope with 140 consecutive days of flows ranging between Q = 700 m^3/s and Q= 1020m^3/s, because this was the maximum simulated low flow period. Moreover, a period of 140 days of low flow does not occur in any of the climate scenarios according to the analysis in Figure 5.20. This means that, based on the cost per ton kilometer indicator, the inland waterway transport of dry-bulk between Rotterdam and Duisburg is climate resilient until 2100.

	No climate change		**G climate**		**Wplus climate**	
	ATP	Timing	ATP	Timing	ATP	Timing
Q1020	>140 days	>2100	>140 days	>2100	>140 days	>2100
Q850	>140 days	>2100	>140 days	>2100	>140 days	>2100
Q700	>140 days	>2100	>140 days	>2100	>140 days	>2100

Table 5.5: Timing of tipping conditions dry-bulk

Liquid-bulk

In the previous section, it was found that the inland waterway transport of liquid-bulk between Rotterdam and Wesseling experiences tipping points in the current situation but also when adaptation measures are implemented. For all flow regimes, the transportation costs per ton kilometer indicator exceeds the value for railway transport and therefore it does not meet the objective to be the most beneficial modality in terms of transportation costs per ton kilometer. The consecutive days analysis on the 9 categories depicted in Figure 5.20 results in timing of tipping points for Q850 and Q700 in the W$_{plus}$ climate scenario. For the other categories no timings are found, which means that the tipping conditions are not expected to occur. The box plots containing the timing conditions for tipping points corresponding to Q850 and Q700 are depicted in Figure 5.21 below and the corresponding median in Table 5.6.



(a) Timing of tipping conditions for Q850 (b) Timing of tipping conditions for Q700

Figure 5.21: Timing of tipping conditions liquid-bulk

	Current situation		**Maintenance criterion**		**Diverse fleet**	
	ATP	Timing	ATP	Timing	ATP	Timing
Q1020	65 days	No occurrence	75 days	No occurrence	5 days	2003
Q850	50 days	2078	55 days	2100	5 days	2003
Q700	35 days	2030	40 days	2072	5 days	2003

Table 5.6: Timing of liquid-bulk tipping conditions

5.5. Dynamic Adaptive Policy Pathways

This section covers step IV of the Dynamic Adaptive Policy Pathways approach. At this stage, all the previous steps have been executed, which has resulted in adaptive tipping conditions for the current situation of inland waterway transport of liquid-bulk and an prediction for the timing of the tipping conditions(Table 5.6). The inland waterway transport of dry-bulk between Rotterdam and Duisburg in the current state does not experience tipping points, considering the transportation costs per ton kilometer indicator. The outcomes can be visualized by constructing pathways that contain the tipping condition, as well as the timing of the tipping condition. In total, three different pathway schemes have been drawn, one for each stress test corresponding to the flow regimes.

Q1020

The pathways for Q1020 are depicted in Figure 5.22 and contains the results of the liquid-bulk transport as well as the dry-bulk transport. The core of the pathways is formed by the x-axis that indicates the number of consecutive days that the flow regime prevailed during simulations. The solid dark blue line represents the pathway for dry-bulk in the current situation. Because no tipping points were found, the line continues to 140 days of Q = 1020m^3/s. The liquid-bulk transport has a tipping condition in Q1020 at a low water level period of 65 days, indicated by the solid orange line. This already visualises that current liquid-bulk supply chain can cope with less consecutive days of Q = 1020m^3/s than dry-bulk. Moreover, adjusting the maintenance criterion to 130 meters width results in a more resilient liquid-bulk supply chain, but still the dry-bulk supply chain can cope with more consecutive days of Q = 1020m^3/s. A diverse fleet does not contribute to a more resilient liquid-bulk supply chain, based on transportation costs per ton kilometer. The implementation of this measure would lead to a tipping point already at five consecutive days, which is indicated by the relatively short pathway.

Consequently, the timing of tipping conditions in three different climate scenarios are shown at the bottom of the pathway scheme. To start with the 'Reference Climate'(i.e. no climate change). Following the time scale, it can be seen that a flow of Q = 1020m^3/s is expected to prevail for 35 consecutive days in 2010. Because the transient scenarios are on a time horizon from 2001 to 2100, the analysis can give values of years in the past. If 35 days would have been a tipping condition, than this timing would indicate that the system is failing today and adaptation measures are needed. However, the actual tipping condition for the current situation of liquid-bulk in Q1020 is at 65 consecutive days. According to the analysis in section 5.4, the condition is not expected to occur for three years in a row in any of the climate scenarios. This is depicted in the pathway scheme by the time scales of each scenario ending before 65 days on the x-axis. This also implies that adjusting the maintenance criterion will not contribute to extending the timing of the tipping points of the current situation of liquid-bulk, because the current situation is climate resilient until 2100. However, implementing the adaptation measure can still contribute to improved performance of the IWT-system.

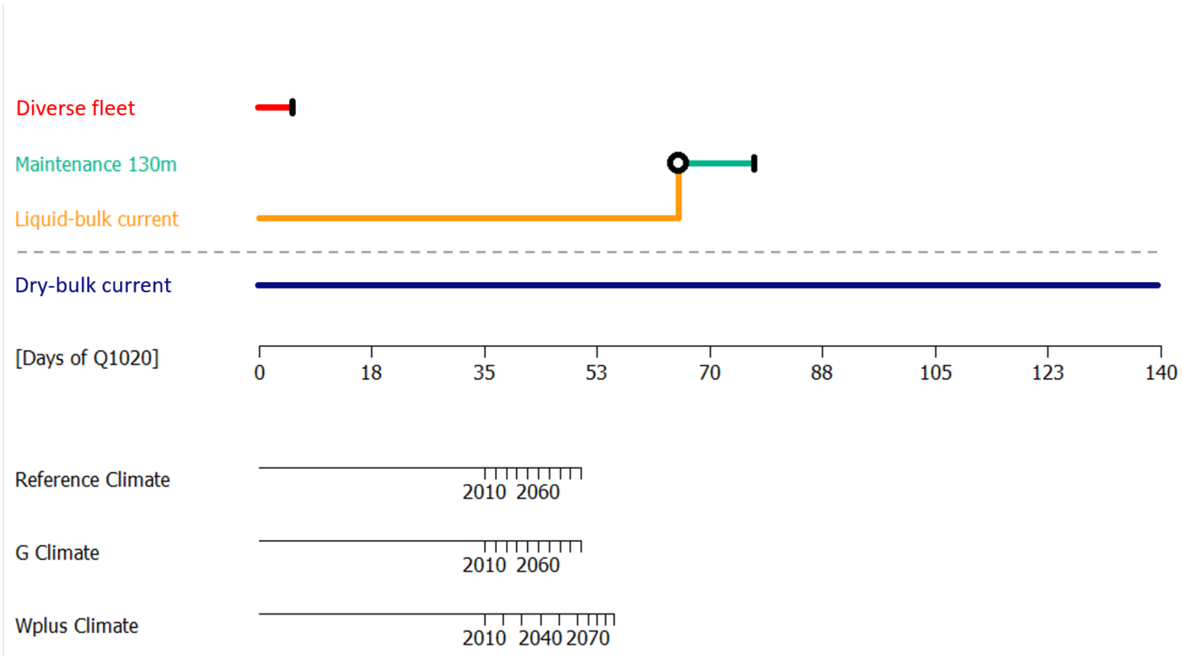


Figure 5.22: Pathways for Q1020

Q850

The tipping condition of the inland liquid-bulk transport in the current situation was found at 50 consecutive days of Q = $850m^3/s$ and inland dry-bulk transport does not experience a tipping point for this flow regime. The pathways that correspond to the Q850 stress test can be seen in Figure 5.23 and it is clearly visible that again current liquid-bulk supply chain experiences its tipping point significantly sooner than the dry-bulk supply chain. The tipping point can be extended by adjusting the maintenance criterion to 130 meters width. The deployment of a diverse liquid-bulk fleet will not contribute to a more resilient supply chain for low flow periods of Q = $850m^3/s$ if only the transportation costs per ton kilometer are considered. Then, a tipping point already occurs after five days of low flow

This pathway scheme also visualises the effect of climate change. If the climate follows the current trend or develops more towards a 'G-climate scenario', the tipping point of the current liquid-bulk transport will not experience its tipping point before 2100. However, if the climate develops towards a 'W$_plus$-climate scenario', the tipping point is estimated to occur around 2078. Moreover, if the maintenance criterion would be adjusted, the liquid-bulk supply chain does not even experiences its tipping point before 2100 in a 'W$_plus$ climate'.

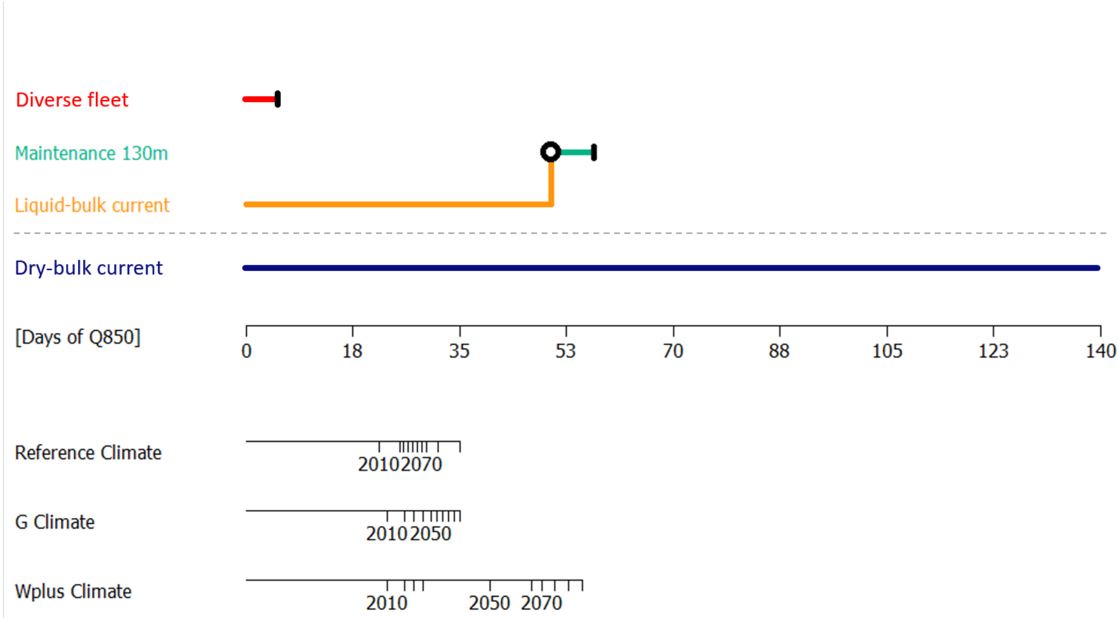


Figure 5.23: Pathways for Q850

Q700

The pathways corresponding to the Q700 stress test are shown in Figure 5.24 in which, again, the path for dry-bulk continues to 140 consecutive days, because also no tipping points were found during the Q700 flow regime for this type of transport. Inland transport of liquid-bulk between Rotterdam and Wesseling no longer meets its requirements after 35 consecutive days of Q = $700m^3/s$. Taking climate change into account, this tipping condition is expected to occur around 2030 if the climate develops towards the W_{plus} scenario and can be extended to 2078 if the maintenance criterion is adjusted to 130 meters width. In a moderate climate change and no climate change, the tipping point of the current liquid-bulk transport is not expected to occur before 2100. The deployment of a diverse liquid-bulk fleet will also not contribute to a more resilient supply chain for low flow periods of Q = $700m^3/s$ if only the transportation costs per ton kilometer are considered. Then, a tipping point already occurs after five days of low flow.

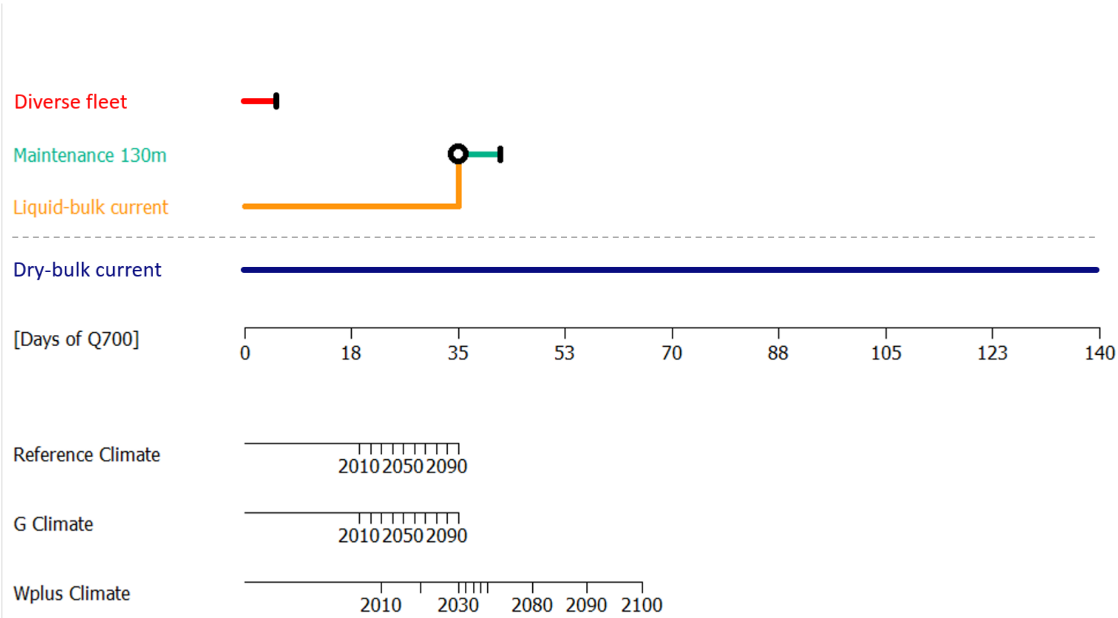


Figure 5.24: Pathways for Q700

5.6. Conclusion

This chapter covered step II, III and IV of the Dynamic Adaptive Policy Pathway approach and addressed two research questions. The chapter started with analysing the performance indicators individually before the performance during different flow regimes was compared to have a good understanding of the model's output. Consequently, in the next section the tipping points of the current IWT-system were determined (step II), followed by the tipping points for two adaptation measures(step III). In the last section, the pathways were constructed that visualize the results of this study(Step IV).

The indicator number of trips shows the same response to low water periods as is expected from previous studies and the IVS90-analyses performed in section 2.3. The indicator demonstrates that the situation deteriorates for dropping discharges and an increasing period of low water levels, because for both situations the number of trips rise. This means that the number of trips is positively correlated with the duration of low flow and negatively correlated with the prevailing discharge.

The indicator transported cargo displays a reduction in transported cargo when longer periods of low flow prevail and the discharge reduces. Furthermore, it was found for dry-bulk that, the deployment of extra C4 convoys during Q700 can compensate for the relative cargo loss during Q850. It can be concluded that the transported cargo is negatively correlated with the duration of a low flow period and positively correlated with the river discharge.

Then, the indicator transportation costs shows an increasing trend when low water periods prevail for longer periods of time, but also for lower discharges (positively and negatively correlated). The rising trend in transportation costs can be related to a larger active fleet. In contrast to the transported cargo, this indicator shows equal values for Q1020 and Q850 where it was expected that a lower flow regime would cause higher transportation costs.

Although transported cargo and transportation costs imply that the IWT-system performance equally during particular flow regimes, the transportation costs per ton indicator shows that there are differences in the performance of the IWT-system when discharges drop. This indicator is in compliance with the expectation that it becomes more and more expensive to transport one ton of cargo if discharges drop and low flow periods prevail for a longer period of time. In the transport sector also the indicator transportation costs per ton kilometer is often used to express the performance of a modality, in which the cost per ton is divided by the average traveled distance. This makes it an ideal indicator to compare different transport modalities. Values for this indicator can be found in literature, which means no extra analyses have to made to determine the threshold value for railway transport. The average transportation costs per ton kilometer in 2018 to transport dry-bulk by rail was 1,2 euro cent and to transport liquid-bulk by rail was 1,5 euro cent. Taking the scope op this research into account and the supply chains objective, it was chosen to use these threshold values.

In the second part of this chapter, the tipping points for dry-bulk and liquid-bulk are determined, addressing the following question:

What is the tipping condition of the current inland waterway system before adaptation measures are implemented?

The tipping conditions are determined according to a threshold value for the cost per ton kilometer indicator. Because the objective is to increase the share in modal shift, the cost per ton kilometer costs for railway transport are set as the threshold value. Considering the inland waterway transport of dry-bulk between Rotterdam and Duisburg, no tipping points were found. For each flow regime and simulation, the cost per ton kilometer are lower than for railway transport. However, liquid-bulk transport experiences tipping points at 65 days of Q1020, 50 days of Q850 and already at 35 days during Q700.

The last section of this chapter considered the question:

What is the effect of implementing adaptation measures on the tipping condition of the inland waterway transport system and when are tipping conditions expected to occur?

According to the performance indicator transportation costs per ton kilometer, the dry-bulk supply chain does not experience any tipping conditions. This implies that no adaptation measures are needed and the supply chain always meets its objective. In contrast to the liquid-bulk supply chain between Rotterdam and Wesseling for which adaptation measures are analysed. A diverse fleet for liquid-bulk has a negative effect on the transportation costs per ton kilometer as tipping points already occur after 5 days of low flow for all flow regimes. This is caused by higher total transportation costs as more vessels are active. However, the adaptation measures contributes to more transported cargo compared to the current situation. The adjustment of the maintenance criterion results in a larger available water depth on the corridor. Implementing this adaptation measures results in more resilient liquid-bulk transport based on the transportation costs per ton kilometer. The tipping points for all flow regimes are extended with 5 to 10 days. Moreover, this adaptation measure leads to more transported cargo during low flow periods.

The timing of tipping points are determined in three different climate scenarios: no climate change, moderate climate change and warm climate change. Discharge series for Lobith are available for the climate scenarios on a time horizon from 2001 to 2100. To determine the timing of tipping points, the discharge series are transformed to series of consecutive days that discharge X prevails and are depicted in Figure 4.1. Then, the timing of a tipping condition is found when the tipping condition occurs for three years in a row. Because the dry-bulk does not experience tipping points, it can be concluded that the IWT-system between Rotterdam and Duisburg meets its requirement up to 2100 despite climate change, based on cost per ton kilometer. Liquid-bulk transport between Rotterdam and Duisburg does not experience tipping points up to 2100 in the current and moderate climate. In a warm climate change, the supply chain is expected to experience the tipping condition of Q700 in 2030 and the tipping condition corresponding to Q850 in 2078 if no adaptation measures are implemented. If the maintenance criterion is implemented, the tipping condition of Q700 is expected to occur in 2072. The tipping condition of Q850 shifts from 2078 to 2100, indicating the liquid-bulk transport supply chain is resilient to flows of Q = 850 m^3/s if the maintenance criterion would be adjust from 150m width to 130m width.

6
Discussion

In this chapter, the results found by this study are discussed. This includes the limitations of the model and an explanation on how to interpreted the results, related to the key concepts of the Dynamic Adaptive Policy Pathways approach: performance indicators, tipping points and the timing of tipping points.

6.1. Discussion

6.1.1. Performance indicators

The activities of vessels start if the predefined start condition is met and stop if the stop condition is met, both related to a moment in time. Within this time frame, the vessels perform as many trips as possible. This means that the number of trips is time limited and not limited by the cargo demand. According to the validation results of the dry-bulk fleet, the number of trips performed by the model corresponds with IVS90 data. However, more trips are performed by the model for liquid-bulk than actually are performed according to IVS90 data. The active fleet size meets already the cargo demand in Wesseling by performing less trips than are possible within a given time frame. Therefore, the number of trips for liquid-bulk transport to Wesseling are limited by the cargo demand, but are modeled as time limited.
Except from the model-aspect, the number of trips also depend on active fleet size. As mentioned in Chapter 2, when the river discharge reduces, the dry-bulk fleet size increases to compensate for the capacity loss due to inactivity of push barge units and reduced load factors. As a result, the number of trips increase during low flow periods. However, the liquid-bulk fleet is uniform, meaning that the fleet consists of one type and has a fixed size. This would imply that the number of trips are equal for each flow regime but, the performance indicator for liquid-bulk shows a small increase in number of trips if the discharge reduces. This can be explained by a higher sailing speed of M8 tankers for decreasing flow regimes, due to a smaller load factor. Considering the time limitation, M8 tankers perform more trips in a given time frame for larger sailing speeds.

The transported cargo by an individual vessel depends on its loading capacity and the minimum available water depth on the corridor. The loading capacity of vessels was determined by performing a data analysis on IVS90, which resulted in an improvement of the model's performance for dry-bulk. The loading capacity for M8 tankers from this analysis resulted in a minimal value of 1.825 tons, where common values for this type of vessels are in the range op 2.050 tons - 3.300 tons. For consistency in the methodology, it was chosen to use the minimal value for M8 tankers. Besides, a relatively low loading capacity is beneficial for the transported cargo, considering the over estimation in number of trips.

The transportation costs follow from key-figures which are used in BIVAS and are applied to the active vessels during simulation. This means that no idle costs are taken into account for inactive vessels. As a consequence, the performance indicator 'total transportation costs' can be an under estimation of the real transportation costs. However, it is questionable to what extent vessels are inactive. For example, BII-6 and BII-4 units become inactive when the discharge drops where the active fleet size of C4-convoys increases. It is very likely that the barges that become available by the inactivity of BII-6 and BII-4 are used to form C4-convoys and thus the barges are not idle. Nonetheless, the pusher-boats seem to have no other function.
In addition, motor vessels can operate on the spot market meaning that they are only rented when needed. For these vessels, it is assumable that they operate on different corridors when smaller fleet size can meet the cargo demand on the considered corridor. Idle costs do not play a role for the liquid-bulk fleet in the current

situation because, the fleet size is fixed at two vessels that are always active, despite discharge changes. In the analysis of a diverse fleet for liquid-bulk as adaptation measure, idle costs are taken into account.

The transportation costs per ton are determined by the cumulative value of the transportation costs divided by the cumulative value of the transported cargo, both over the full simulation period. Therefore, the transportation costs per ton should not be interpret as the value during low flow period, but as an average value over the simulation time. The same methodology is applied by Meulen & Ree (2017) and Visser (2020), where they calculated the transportation costs per ton by dividing the total transportation costs in 2018 by the total transported cargo in 2018. The same interpretation holds for the transportation costs per ton kilometer, which describes the average transportation costs to transport one ton of cargo over a distance of one kilometer on the considered corridor.

6.1.2. Tipping points

The tipping points are based on the performance indicator 'transportation costs per ton kilometer' and are determined by setting the value for rail transport as a threshold. If the threshold value is exceeded, a tipping point has been reached. A few side notes have to be made to correctly interpret the tipping points.

First of all, the threshold value for rail transport is the average value in 2018 determined by Visser (2020). If the analysis was performed on a different year, there is a chance that this would have resulted in an other value for rail transport, which affects the tipping points determined in this study. In addition, the transportation costs per ton indicator is quite sensitive. The indicator follows a gradual increase over the simulations which means that small difference in the threshold value results in a large difference in tipping points.

Tipping points strongly depend on the supply chains objective defined at the beginning of this study and the corresponding performance indicator. However, it difficult to define an objective that considers every actor on the system, because each actor has an other definition of success. For example, if the study would have been performed from a German industry point of view, an operational objective could have been the stock level at the destination site. Then, the performance indicator transported cargo would be more suitable, which can results in other tipping points than have been found in this study.

Because of the high dependency on the supply chains objective and its sensitivity, the tipping points are not presented as an advice nor as a recommended adaptation strategy. The tipping points are determined to demonstrate the effect of increasing periods of low flow on the performance of inland waterway transport.

Furthermore, the periods of consecutive days that followed from the discharge series do not take the discharge before and after this period into account, which can result in too positive results for the timing of tipping points. The step-functions used as input for the model contain a high water period before and after the low water period. In the historical discharge series however, before and after a period of, for example Q = $700 m^3/s$, already a low discharge prevails. So in reality, IWT is already limited in performance before and after a low flow period, which implies that tipping points are reached earlier.

6.1.3. Timing of tipping points

The timing of tipping tipping points are based on plausible discharge series that were derived by the application of a rainfall-generator and the HBV-model for climate scenarios defined in 2006 (Haasnoot et al., 2015). Applying these models to the 2014 climate scenarios, will probably result in different plausible discharge series and thus also affect the timing of tipping points in this study.

7
Conclusion and recommendations

This chapter concludes on the research by addressing the main research question:

What is the maximum duration of a low flow period the inland waterway transport system can cope on the Rotterdam - Wesseling corridor and when is this period expected to occur, following the Dynamic Adaptive Policy Pathways approach?

The research comprises of several sub-questions of which the conclusions contribute to finding an answer to the main research question. This section follows the same order in conclusions as the sub-questions are handled throughout this thesis. After the main research questions has been addressed, recommendations for further research are given.

7.1. Conclusion

This thesis aimed to assess the performance of IWT during increasing periods of low flow and to determine for which low flow condition the IWT-system no longer meets its objective. Consequently, the goal was to demonstrate that this condition can be affected by implementing adaptation measures and to define moments on a time scale up to the year 2100 when these conditions occur. To this end, the first four steps of the Dynamic Adaptive Policy Pathways were used. This gained insight into the resilience of the inland waterway transport between Rotterdam and Wesseling to increasing periods of low flow.

The first research question that was addressed:

What are the characteristics of the IWT-system between Rotterdam and Wesseling?

An analysis performed on IVS90 data from 2018 showed how IWT has responded to low water levels in the past. It can be concluded that during low water levels, push-barge units become inactive for safety reasons and that this loss in capacity is compensated by the deployment of extra motor vessels and convoys. In addition, during low water levels, a reduced load factor is applied which leads to extra trips to compensate for the loss in transported cargo by an individual vessel. This results in an increase in number of trips on the considered corridor during low water levels. If the maximum fleet capacity is reached, in combination with a reduced load factor, the volume of transported cargo decreases, as was the case in 2018. Adaptation measures can be implemented to the IWT-system to better cope with low flow periods. The measures can be linked to infrastructure, logistics, fleet and information provision. However, they can also be classified by considering which actor on the system makes the investment to implement the adaptation measures: river managers (Rijkswaterstaat), shippers, industries and inland waterway companies.

Consequently, the second research question was addressed:

How can the performance of the inland waterway transport network during low periods be simulated?

In 2019, Kievits (2019) developed a model that is able to simulate inland waterway transport between Rotterdam and Duisburg during low flow periods. This model already showed the possibility of simulating the performance of inland waterway transport by performance indicators. It is therefore used as a starting point for the simulation model in this study. The IWT-system is a modeled in the Python programming language in a Simpy environment. The model concept that is chosen for the simulation is based on the OpenCLSim software package available at the GitHub of the TU Delft Hydraulic Engineering department, which is a rule bases planning tool for cyclic activities. The model is able to simulate the inland dry-bulk transport from Rotterdam to Duisburg and liquid-bulk transport from Rotterdam to Wesseling. The simulation model is set up as a stress test to assess the performance of IWT during increasing periods of low flow. One stress test consists of twenty-eight simulations, each simulation containing a longer prevailing low flow period. The low flow period is constant and corresponds to Q = $700m^3/s$, Q = $850m^3/s$ or Q = $1020m^3/s$, depending on the stress test. Finally, the number of trips, transported cargo, total costs, cost per ton and cost per ton kilometer are calculated by post-processing the output data. This gives insight on how the system performs during increasing periods of low flow.

The following research question was addressed in Chapter 4:

How does the simulation model perform compared to IVS90 data?

This research question considered the validation of the load factor, number of trips and transported cargo by the model. The model's output was compared to IVS90 data that correspond to stationary flow periods occurred in 2018. It was found that the model calculates load factors for all vessels within a 10% margin of the IVS90 data for all flow regimes. Consequently, the deviation in number of trips was analysed. After two iterations, the number of trips performed by the model were within a 10% margin of the IVS90 data, except for the M8 tankers. During Q1020 and Q700 , the number of trips by M8 tankers are over estimated by the model. Finally, the transported cargo was analysed and adjustments have been made to the initial capacity of all vessels. After implementing the median values of the maximum capacity found in IVS90 data, the transported cargo was significantly improved. Only the transported cargo by M8 tankers is over estimated by the model for Q1020 and Q700, which can be related to the deviation in number of trips during the same flow regimes.

The following research question considered the performance indicators and the determination of tipping points:

What is the tipping condition of the current inland waterway system before adaptation measures are implemented?

Based on the research conducted in chapter 5, the most suitable performance indicator for determining tipping points was selected to be the *transportation costs per ton kilometer*. One of the most advantages of this indicator is its independency of the transport modality. This makes the indicator very suitable to compare the performance of different modalities. The values are calculated by dividing the transportation costs per ton with the average traveled distance. Because the distance is constant in the simulations, transportation cost per ton and per ton kilometer show the exact same trends and behaviour but, differ in absolute value. The annual average transportation costs per ton kilometer for railway transport in 2018 for dry-bulk and liquid-bulk were, respectively, 1,2 euro cent/tonkm and 1,5 euro cent/tonkm according to Netherlands Institute for Transport Policy Analysis(*in Dutch: Kennisinstituut voor Mobiliteitsbeleid*).

For the inland waterway transport of dry-bulk from Rotterdam to Duisburg, no tipping points were found. The transportation costs per ton kilometer for IWT are lower than for railway transport in each simulation. This implies that, according to this indicator, inland shipping is the most attractive transport mode between Rotterdam and Duisburg, even if the low water periods become more severe.

Liquid-bulk transport between Rotterdam and Wesseling experiences tipping point for all three considered flow regimes. The costs per ton kilometer for Q1020 exceed the threshold value when a low water level period of 65 days is simulated. In other words: during a low flow period of 65 days and Q = $1020m^3/s$ the liquid-bulk supply chain does not meet its objective anymore. After 65 days of Q = $1020m^3/s$ railway transport becomes more beneficial than inland waterway transport in terms of transportation costs per ton kilometer. For the Q = $850m^3/s$ flow regime, the tipping point already occurs at 50 days. If the conditions become even more severe and the discharge equals Q = $700m^3/s$, the threshold is reached and exceeded at 35 consecutive days. The shift of the tipping conditions to a shorter period of low flow demonstrates the negative effect the duration of low flow periods has on the performance of the liquid-bulk supply chain.

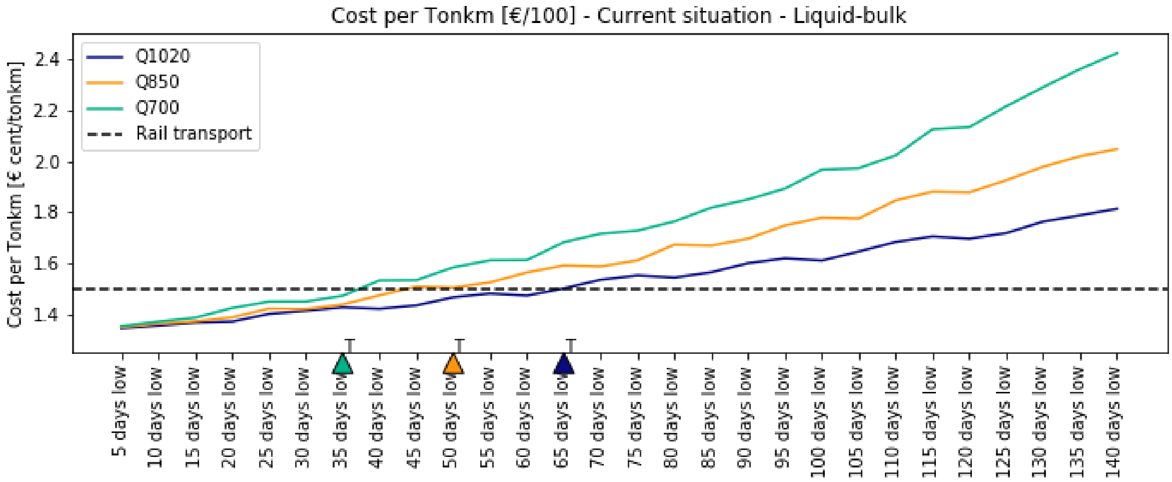


Figure 7.1: Tipping conditions liquid-bulk

Finally, the following research question was addressed in chapter 5:

What is the effect of implementing additional adaptation measures on the tipping condition of the inland waterway transport system and when are the tipping conditions expected to occur?

In section 2.4, adaptation measures were analysed for the IWT-system to better cope with low flow. Because no tipping points were found for dry-bulk when considering the performance indicator 'transportation costs per ton kilometer', the adaptation measures have been applied to the liquid-bulk transport between Rotterdam and Wesseling. First of all, the effect of a diverse fleet was compared with the performance of the uniform fleet. Implementing this adaptation measure resulted in larger transportation costs per ton kilometer than for a uniform fleet and thus affects the tipping condition negatively. However, the diverse fleet is able to transport more cargo during low flow periods than a uniform fleet. Secondly, the maintenance criterion was adjusted from 150m width to 130m width. As a consequence, the minimum available water depth on the corridor becomes larger and vessels can apply a more beneficial load factor. Implementing this adaptation measure has a positive effect on the tipping conditions as the transportation costs per ton kilometer are smaller for each simulation and flow regime compared to the current system. The tipping points are extended with five to ten days.

For the timing of tipping points, three climate scenarios were considered: no climate change, moderate climate change and warm climate change. Plausible discharge series are available for each scenario and are translated to series that display the number of consecutive days of discharge Q = $700 m^3/s$, Q = $850 m^3/s$ and Q = $1020 m^3/s$. According to these series, the tipping conditions for Q1020 are not expected to occur for three years in a row in each climate scenario. Therefore, no timing to the tipping conditions is assigned. In contrast to the tipping conditions for Q850 and Q700, which can be seen in Table 7.1.

	Current situation		**Maintenance criterion**		**Diverse fleet**	
	ATP	Timing	ATP	Timing	ATP	Timing
Q1020	65 days	No occurrence	75 days	No occurrence	5 days	2003
Q850	50 days	2078	55 days	2100	5 days	2003
Q700	35 days	2030	40 days	2072	5 days	2003

Table 7.1: Timing of liquid-bulk tipping conditions

To conclude on the main research question, the dynamic adaptive policy pathways are constructed for the stress test Q700 as the corresponding tipping points are expected to occur earlier than the tipping conditions for Q850 and Q1020. Although no tipping points were found for dry-bulk considering the transportation costs per ton kilometer indicator, the pathway is added to the figure. This pathway is separated from the liquid-bulk pathways by a dashed line, because, of course, one cannot adapt from liquid-bulk to dry-bulk.

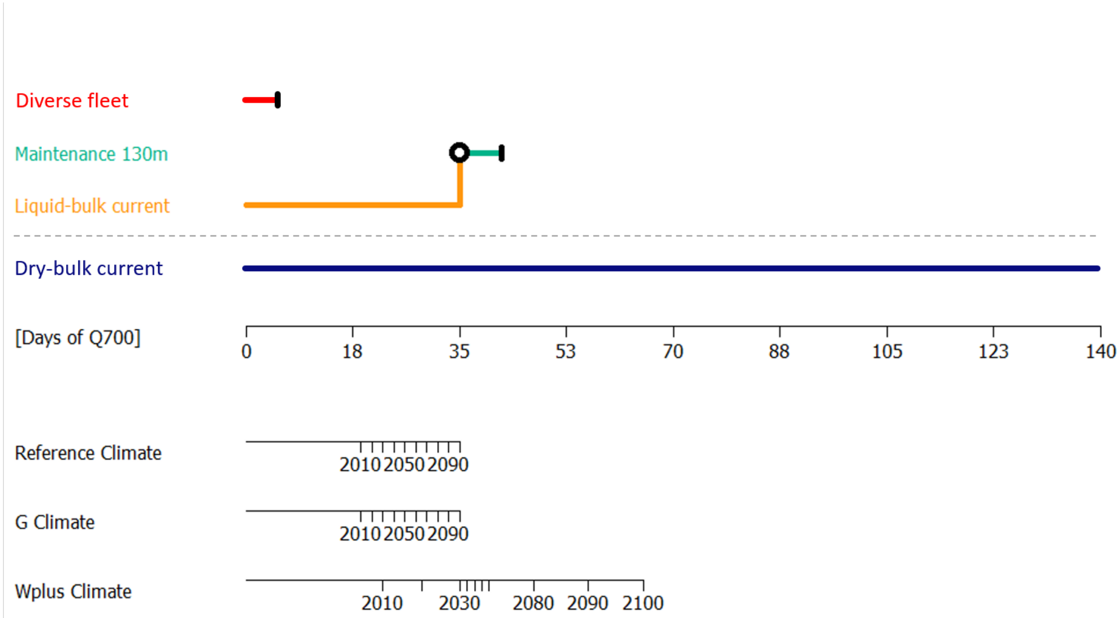


Figure 7.2: Pathways for Q700

The dynamic adaptive policy pathways in Figure 7.2 show that the current inland transport of liquid-bulk experience a tipping point after 35 consecutive days of Q = $700m^3/s$ according to the transportation costs per ton kilometer indicator. This tipping condition is expected to occur beyond 2100 if the climate develops towards a moderate climate or if the current trend is proceeded. However, if the climate develops towards a warm climate change, this situation is already expected to occur in 2030. For the liquid-bulk supply chain to become more resilient to low flow periods, one can adapt by adjusting the maintenance criterion to 130 meters width. This results in the inland waterway transport of liquid-bulk between Rotterdam and Wesseling to be resilient to low flow periods until the year 2078, based on transportation costs per ton kilometer, if the climate develops towards a warm climate change (W+ scenario).

7.2. Recommendations

This study focused on the impact of increasing consecutive days of low flow on the inland waterway transport, in contrast to other studies that mainly focused on the impact of low flow periods that have occurred in the past or on expected climate change-induced discharge series. The performance of the IWT-system during increasing consecutive days is assessed on the basis of performance indicators by performing stress tests with a simulation model. The basis of the model was developed by Kievits (2019) for his MSc. graduation and is improved on several recommended aspects mentioned in his thesis. This section covers recommendations to further improve the model and to gain more insight in the low flow problem for IWT.

This study has shown the application of step I to step IV of the Dynamic Adaptive Policy Pathways approach to the low flow problem faced by inland waterway transport. The essence of the DAPP approach is to develop an adaptive planning for systems that experiences high uncertainties in the future however, the results of this study are not yet sufficient to base an adaptive strategy on. Therefore, it is recommended to assess more adaptation measures that contribute to an improved performance of IWT during low flow periods and reconsider the performance indicator 'transportation costs per ton kilometer' to appoint tipping points. Although it is useful to consider multiple performance indicators to get an overview of the impact of an adaptation measure, the performance indicator to determine tipping points should be measure dependent. In other words, tipping points cannot be determined by one performance indicator for each adaption measure. To effectively select a performance indicator, it is recommended to define the main objective of the measure and take into account the actor that has to take the initiative to implement the measures, as mentioned in section 2.4.

The timing of tipping points followed from discharge series that cover three climate scenarios on a time scale from 2001 to 2100. The discharge series were derived with a rainfall generator and the HBV-model that used as input data based on climate scenarios from 2006 (Haasnoot et al., 2015). To give a more reliable estimation on the timing of tipping points, it is recommended to derive new discharge series for the most recent available climate scenarios.

One of the performance indicators is the total transportation costs that followed from key-figures defined by Panteia, (Visser, 2020). Although commonly accepted in the sector, it was found that some key-figures for push-barge units are on the high side compared to expected values. This can contribute to an over estimation of the transportation costs and it is therefore recommended to analyse the key-figures in more detail for other RWS-classes defined in this model.
The transportation costs consist of fixed costs, regarding loading and unloading of vessels and variable costs, regarding time and distance dependent costs. The loading and unloading costs are determined by a time hourly rate, depending on the vessel's type. This means that the total loading and unloading costs strongly depend on the loading and unloading capacity of the berth equipment. However, for each modeled vessel equal capacity of berth equipment is assumed and this value is on the high side. To gain more reliable results on the fixed costs, it is recommended to revise the modeled capacity of the berth per commodity and vessel type. In addition, no idle costs are included in the transportation costs of the dry-bulk fleet. A first analysis to the impact of including idle costs for a diverse liquid-bulk fleet showed that this can have a significant effect on the tipping points. However, it is questionable if vessels are idle when not deployed on the considered corridor or if they are operational on other corridors. Taking also into account that the active fleet size adapts to the prevailing flow regime, further research to the behaviour of the fleet size and deployment of vessels on other corridors can lead to interesting insights and an improvement of the calculation of transportation costs. It is recommended to combine AIS data with IVS Next in this analysis to track the activity of inland vessels on other corridors.

To further develop the user experience of the simulation model, the modeling of the fleet size in combination with their activities in terms of start and stop conditions is at this moment a time consuming task and use case dependent. It is recommended to develop a tool in the form of a Python script that can automatically generate start-stop conditions and activities for predefined vessel classes and fleet sizes. This would a user friendly addition to the OpenCLSim package which makes it also more efficient to use.

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A

RWS-classes

Inland vessels classification table (Koedijk, 2020)

CEMT-Klasse	Motorvrachtschepen (Motorvessels)							Duwstellen (Barges)			
	RWS Klasse	Karakteristieken maatgevend schip**				Classificatie		RWS Klasse	Karakteristieken maatgevend duwstel**		
		Naam	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte
			m	m	m	t	m			m	m
	M0	Overig				1-250	B<=5,00 of L<=38,00				
I	M1	Spits	5,05	38,5	2,5	251-400	B=5,01-5,10 en L>=38,01	BO1		5,2	55
II	M2	Kempenaar	6,6	50-55	2,6	401-650	B=5,11-6,70 en L>=38,01	BO2		6,6	60-70
III	M3	Hagenaar	7,2	55-70	2,6	651-800	B=6,71-7,30 en L>=38,01	BO3		7,5	80
	M4	Dortmund Eems (L < = 74 m)	8,2	67-73	2,7	801-1050	B=7,31-8,30 en L=38,01-74,00	BO4		8,2	85
	M5	Verl. Dortmund Eems (L > 74 m)	8,2	80-85	2,7	1051-1250	B=7,31-8,30 en L>=74,01				
IVa	M6	Rijn-Herne Schip (L <= 86 m)	9,5	80-85	2,9	1251-1750	B=8,31-9,60 en L=38,01-86,00	BI	Europa I duwstel	9,5	85-105
	M7	Verl. Rijn-Herne (L > 86 m)	9,5	105	3,0	1751-2050	B=8,31-9,60 en L>=86,01				
IVb											
Va	M8	Groot Rijnschip (L <=111 m)	11,4	110	3,5	2051-3300	B= 9,61-11,50 en L=38,01-111,00	BII-1	Europa II duwstel	11,4	95-110
	M9	Verlengd Groot Rijnschip (L >111 m)	11,4	135	3,5	3301-4000	B= 9,61-11,50 en L>= 111,01	BIIa-1	Europa IIa duwstel	11,4	92-110
								BIIL-1	Europa II Lang	11,4	125-135
Vb								BII-2l	2-baksduwstel lang	11,4	170-190
VIa	M10	Maatg. Schip 13,5 * 110 m	13.50	110	4,0	4001-4300	B=11.51-14.30 en L=38.01-111.00	BII-2b	2-baksduwstel breed	22,8	95-145
	M11	Maatg. Schip 14.2 * 135 m	14.20	135	4,0	4301-5600	B=11.51-14.30 en L>= 111.01				
	M12	Rijnmax Schip	17,0	135	4,0	>= 5601	B>= 14.31 en L>= 38.01				
VIb								BII-4	4-baksduwstel (Incl. 3-baks lang)	22,8	185-195
VIc								BII-6l	6-baksduwstel lang (Incl 5-baks lang)	22,8	270
VIc								BII-6b	6-baksduwstel breed (Incl. 5-baks breed)	34,2	195

Figure A.1: RWS classification table (1/2)

Duwstellen (Barges)			Koppelverbanden (Convoys)							Doorvaart-hoogte*
	Classificatie		RWS Klasse	Karakteristieken maatgevend koppelverband**				Classificatie		
Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte	Incl. 30 cm schrikhoogte
m	t	m			m	m	m	t	m	m
1,9	0-400	B<=5,20 en L= alle	C1l C1b	2 spitsen lang 2 spitsen breed	5,05 10,1	77-80 38,5	2,5 2,5	<= 900 <= 900	B<= 5,1 en L=alle B=9,61-12,60 en L<= 80,00	5,25* 5,25*
2,6	401-600	B=5,21-6,70 en L=alle								6,1
2,6 2,7	601-800 801-1250	B=6,71-7,60 en L=alle B=7,61-8,40 en L=alle								6,4 6,6 6,4
3,0	1251-1800	B=8,41-9,60 en L=alle								7,0* 7,0*
			C2l	Klasse IV + Europa I lang	9,5	170-185	3,0	901-3350	B=5,11-9,60 en L=alle	7,0*
3,5 4,0 4,0	1801-2450 2451-3200 3201-3950	B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L=111,01-146,00								9,1* 9,1* 9,1*
3,5-4,0	3951-7050	B=9,61-15,10 en L>=146,01	C3l	Klasse Va + Europa II lang	11,4	170-190	3,5-4,0	3351-7250	B=9,61-12,60 en L>=80,01	9,1*
3,5-4,0	3951-7050	B=15,11-24,00 en L<=146,00	C2b C3b	Klasse IV + Europa I breed Klasse Va +Europa II breed	19,0 22,8	85-105 95-110	3,0 3,5-4,0	901-3350 3351-7250	B=12,61-19,10 en L<=136,00 B>19,10 en L<=136	7,0* alleen voor klasse IV koppelverband 9,1*
3,5-4,0	7051-12000 (7051-9000)	B=15,11-24,00 en L=146,01-200	C4	Klasse Va + 3 Europa II	22,8	185	3,5-4,0	>=7251	B>12,60 en L>=136,01	9,1*
3,5-4,0	12001-18000 (12001-15000)	B=15,11-24,00 en L>=200,01								9,1*
3,5-4,0	12001-18000 (12001-15000)	B>=24,01 en L=alle								9,1*

Figure A.2: RWS classification table (2/2)

B

Validation plots

Load factor VIa - Q2500

By studying the plot in Figure B.1, in which the IVS data and the model's output during high flow are plotted, it can be seen that the model's load factor equals 0.0 during the high water period. The load factor in IVS(solid blue line) shows a peak, but is zero for the largest part during this period. This peak causes the mean to deviate from zero and also a deviation between IVS and model. Following the fleet analyses in section 2.3 and that the IVS load factor is for the largest part equal to zero, it is assumed that the model's output is correct for VIa.

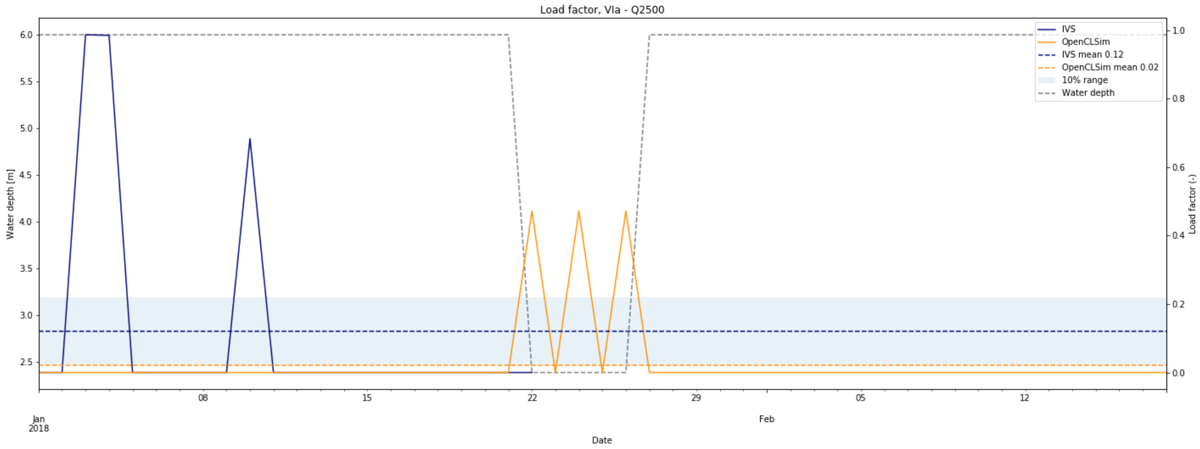


Figure B.1: Load factor validation for Q2500, VIa motor vessel

C
Maximum load capacity

During the validation of the transported cargo it was found that initial values of the vessel's maximum load capacity was on the low side. To improve the model's output, the maximum load capacity is extracted from IVS90 data. The data set is filtered on vessels that sail between Rotterdam and Duisburg and Rotterdam and Wesseling during Q = 1020m^3/s. Consequently, the median value of the maximum load capacity of each RWS-class is used.

Maximum load capacity

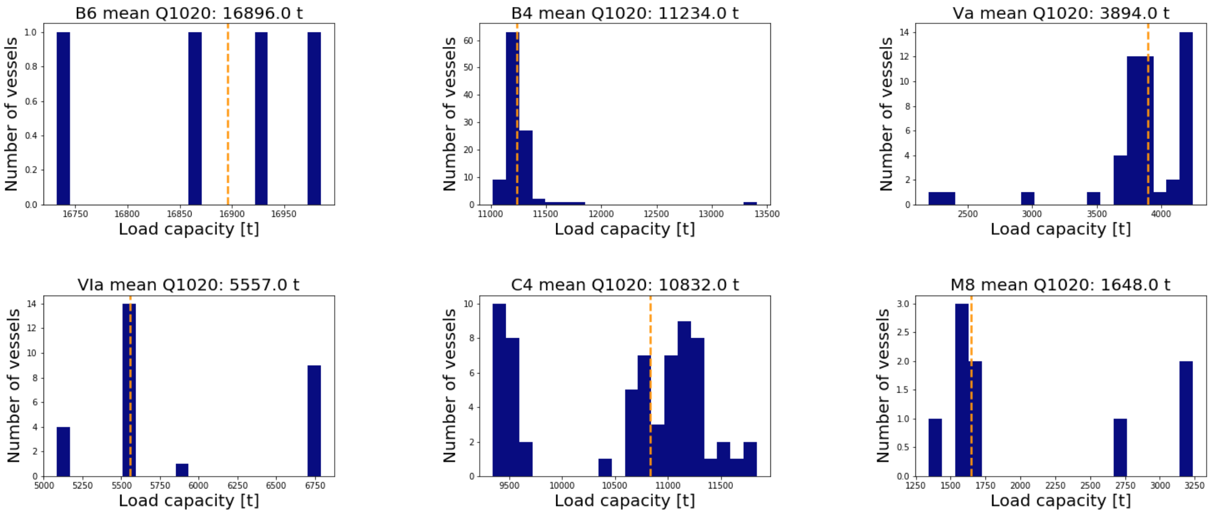


Figure C.1: Maximum load capacity, IVS90

D
Cost figures

Sailing loaded		BII-6	BII-4	M8	M12	C4	M8 tanker
Cost item	rate						
Labor	[€/h]	94,19	83,90	57,83	62,55	79,32	58,39
Depreciation	[€/h]	112,38	85,92	25,68	36,34	35,08	45,83
Interest	[€/h]	8,51	6,21	2,58	4,14	3,26	4,10
Insurance	[€/h]	13,66	13,47	10,49	13,39	10,31	13,41
Maintenance	[€/h]	12,89	10,20	2,56	3,24	6,11	2,39
Harbor fees	[€/h]	17,49	11,77	3,39	5,43	10,47	3,08
Other	[€/h]	28,66	23,17	4,22	5,65	15,62	2,93
Maintenance	[€/km]	1,40	0,95	0,38	0,56	1,29	0,38
Fuel max	[€/h]	281,97	192,39	79,42	69,04	85,98	44,93
Fuel min	[€/h]	155,46	145,12	54,33	52,35	68,09	34,10
Loading/Unloading	[€/h]	302,34	244,83	166,13	107,10	140,0	129,12

Table D.1: Cost figures sailing full

Sailing empty		BII-6	BII-4	M8	M12	C4	M8 tanker
Cost item	rate						
Labor	[€/h]	92,23	82,90	47,64	62,97	45,02	47,64
Depreciation	[€/h]	114,57	82,78	31,53	49,45	45,72	31,53
Interest	[€/h]	11,48	7,90	3,02	4,99	6,07	3,02
Insurance	[€/h]	22,51	18,42	11,34	13,56	16,61	11,34
Maintenance	[€/h]	13,25	10,19	2,51	3,09	6,42	2,51
Harbor fees	[€/h]	16,22	10,92	3,30	5,74	10,31	3,30
Other	[€/h]	26,17	21,26	3,85	5,24	13,49	3,85
Maintenance	[€/km]	1,.32	0,96	0,38	0,54	1,37	0,38
Fuel max	[€/h]	281,97	192,39	79,42	69,04	85,98	44,93
Fuel min	[€/h]	155,46	145,12	54,33	52,35	68,09	34,10
Loading/Unloading	[€/h]	302,34	244,83	166,13	107,10	140,0	129,12

Table D.2: Cost figures sailing empty

E
Indicator bar diagrams

E.1. Indicator plots for Q850 - Dry-bulk

The number of trips by the total dry-bulk fleet shows an upward trend when the duration of a low flow period of Q = 850m^3/s increases. The share of BII-6 reduces, due to inactivity during the low flow period. It can be seen that BII-4 push units compensate for this inactivity, because the trend of BII-6 plus BII-4 is more or less constant.

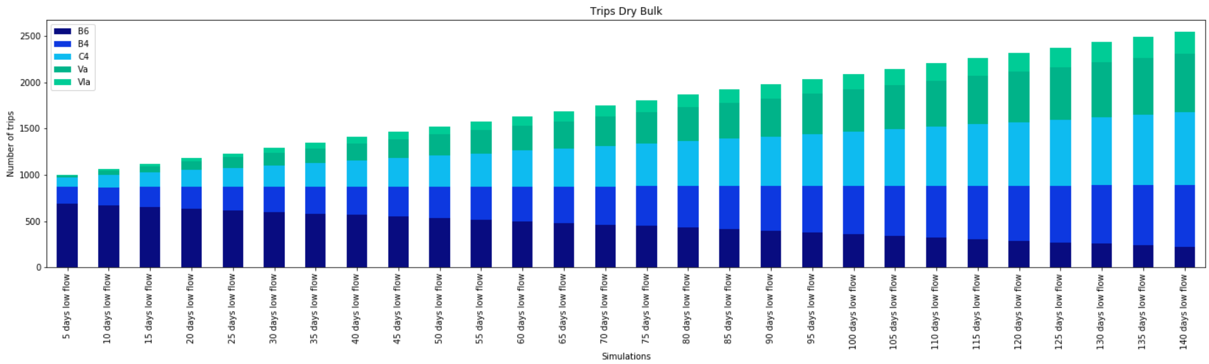


Figure E.1: Number of trips per RWS-class for Q850

The total transported cargo by the dry-bulk fleet decreases over the simulations. This implies that the extra number of trips cannot compensate for the capacity loss during the low flow period, otherwise the trend would have been constant.

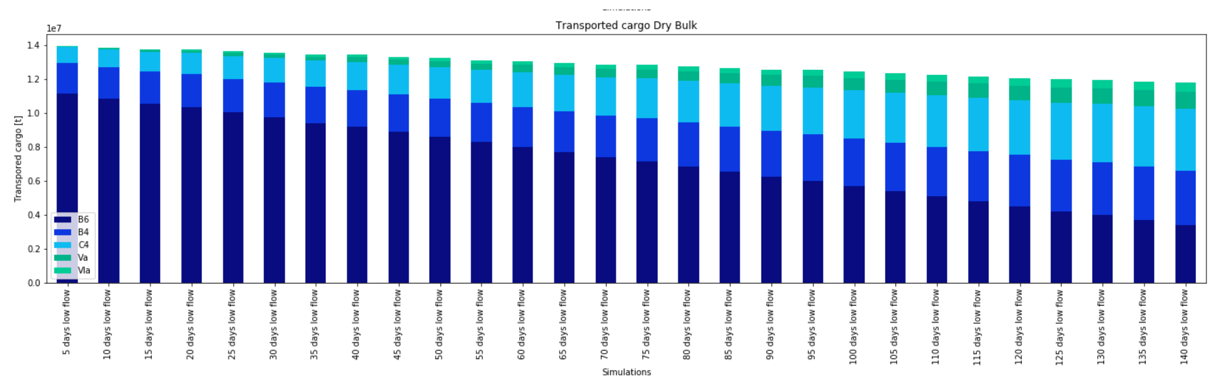


Figure E.2: Transported cargo per RWS-class for Q850

The total transportation costs rise for increasing period of low flow. This can be explained by the extra trips that are performed which results in more labor, material and variable costs. Because less cargo in transported the costs related to loading and unloading reduce. Apparently the reduction is smaller than the rise in labor, material and variable costs, as the trend is still upward.

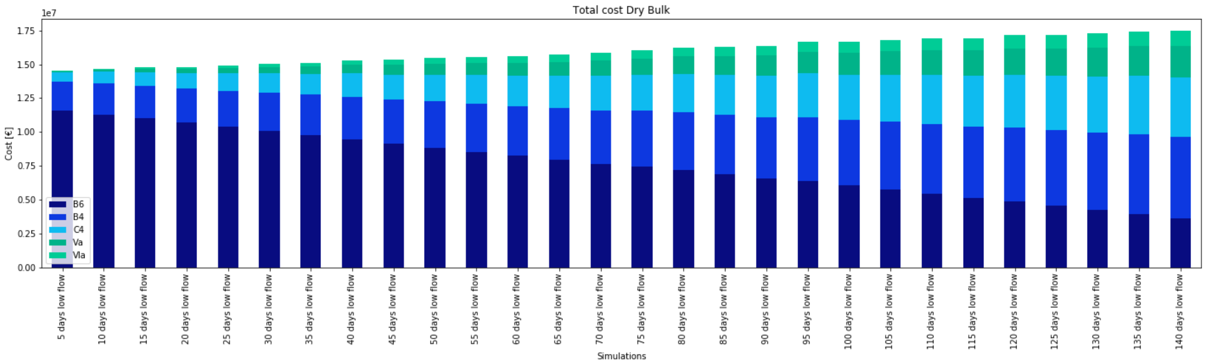


Figure E.3: Transportation costs per RWS-class

The total transportation costs per ton shows a slight upward trend, implying that it becomes more expensive to transport one ton of cargo from Rotterdam to Duisburg if the low flow period prevails for a longer period of time.

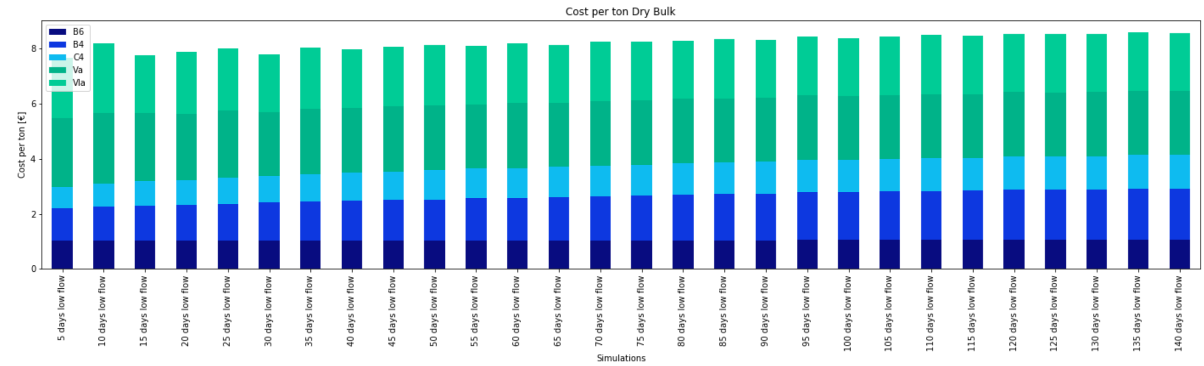


Figure E.4: Transportation costs per ton per RWS-class

E.2. Indicator plots for Q850 - Liquid-bulk

The number of trips by the liquid-bulk fleet increase if the the duration of the low flow periods increases. However, in contrast to the dry-bulk fleet, no extra vessels are deployed during the low flow period. More trips are performed by the tankers because the vessels can sail with higher speeds when less cargo is loaded and thus more trips can are performed in periods of equal length.

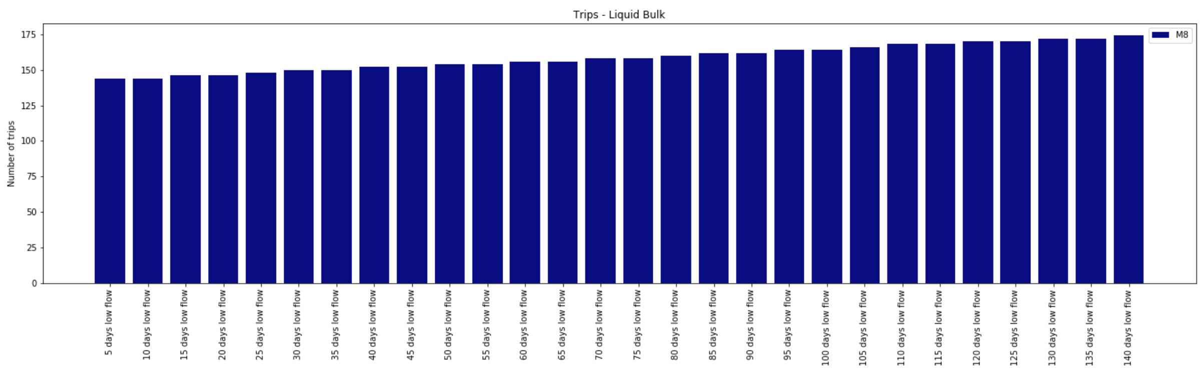


Figure E.5: Number of trips per RWS-class for Q850

Although more trips are performed by the model, less cargo is transported when the low flow period prevails for a longer time. This can be explained by the reduced load factor that is applied during the low flow period.

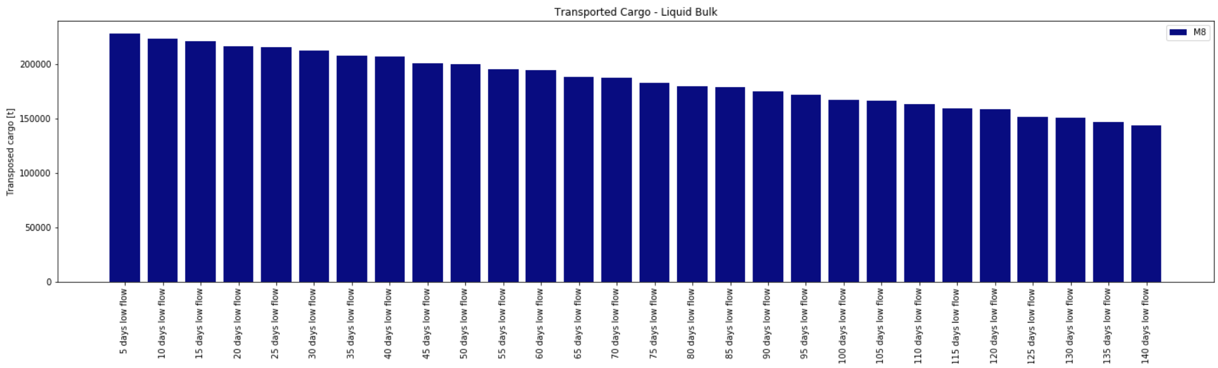


Figure E.6: Transported cargo per RWS-class for Q850

The transportation costs for the liquid-bulk fleet has a more or less constant trend. Because only a few extra trips are performed, the extra labor, material and variable costs slightly increase. The costs related to loading and unloading reduce because less cargo. Moreover, if the value of the total transportation costs of the first simulation is compared with the value of the last simulation, a small reduction is visible. This means that the reduction in handling costs(loading/unloading) outweigh the rise in labor, material and variable costs.

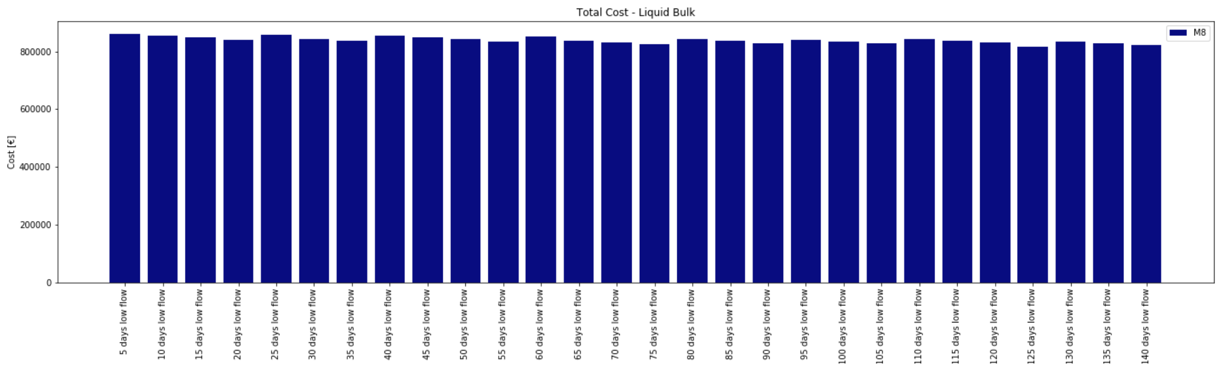


Figure E.7: Transportation costs per RWS-class

The transportation costs per ton shows an increasing trend over the simulation. This can be explained by looking at the bar diagrams for transported cargo and total transportation costs. Significant less cargo is transport for almost equal transportation costs, which results in higher costs to transport one ton of cargo if the low flow period prevails for a longer period of time.

E.3. Indicator plots for Q700 - Dry-bulk

The number of trips by the total dry-bulk fleet shows an upward trend when the duration of a low flow period of Q = 700m^3/s increases. The share of BII-6 and BII-4 reduces, due to inactivity during the low flow period. It can be seen that C4 convoys trips increase significantly to compensate for the loss of capacity by the push units.

The total transported cargo by the dry-bulk fleet decreases over the simulations. This implies that the extra number of trips by the motor vessels and convoys cannot compensate for the capacity loss during the low flow period, otherwise the trend would have been constant.

The total transportation costs rise for increasing period of low flow. This can be explained by the extra trips that

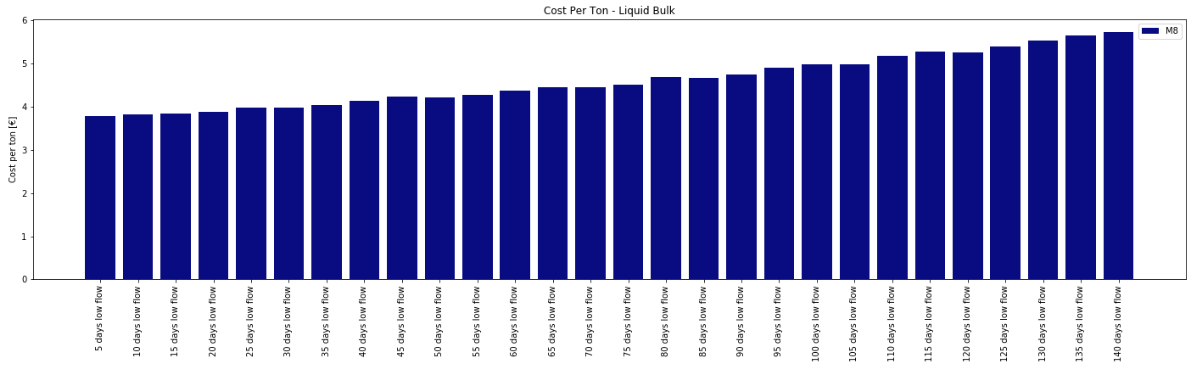


Figure E.8: Transportation costs per ton per RWS-class

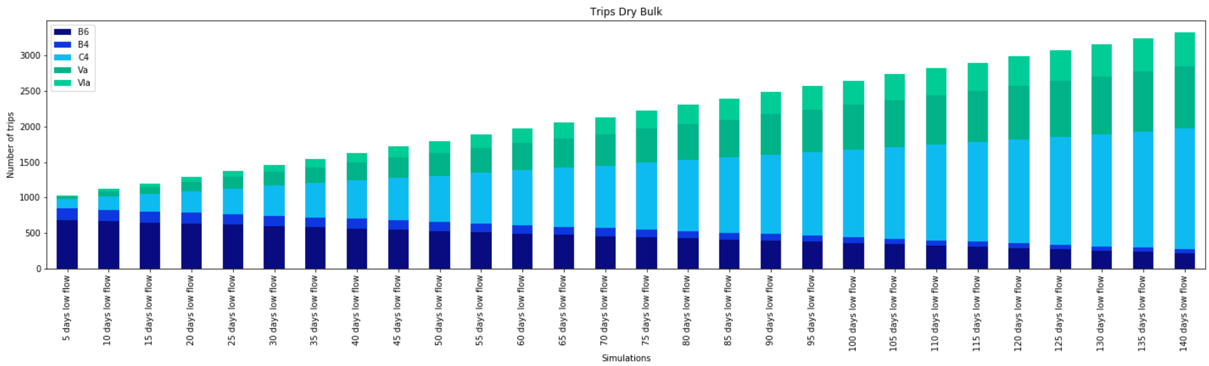


Figure E.9: Number of trips per RWS-class for Q700

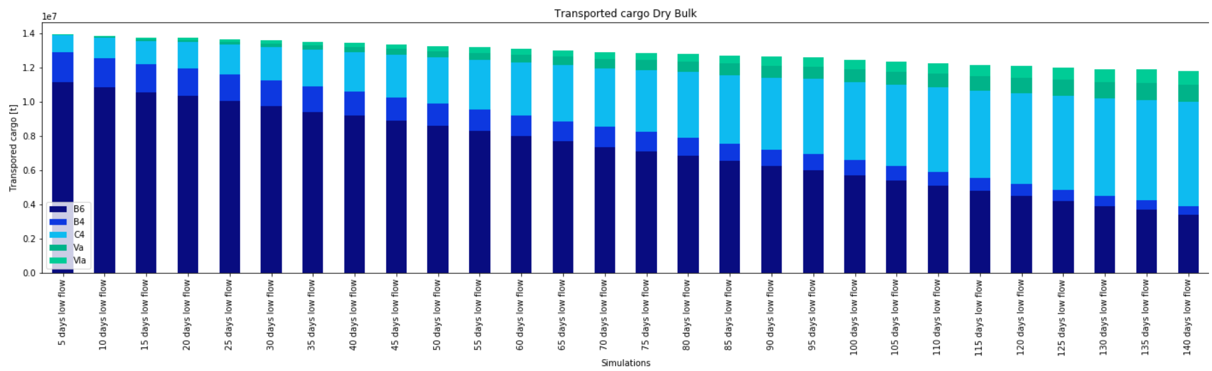


Figure E.10: Transported cargo per RWS-class for Q700

are performed which results in more labor, material and variable costs. This is clearly visible for C4 convoys. Because less cargo in transported the costs related to loading and unloading reduce. Apparently the reduction is smaller than the rise in labor, material and variable costs, as the trend is still upward.

The total transportation costs per ton shows a slight upward trend, implying that it becomes more expensive to transport one ton of cargo from Rotterdam to Duisburg if the low flow period prevails for a longer period of time.

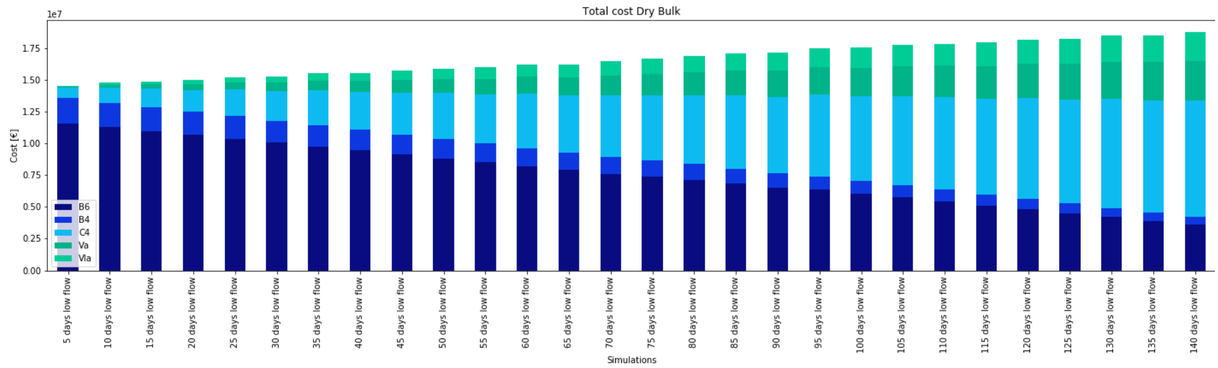


Figure E.11: Transportation costs per RWS-class

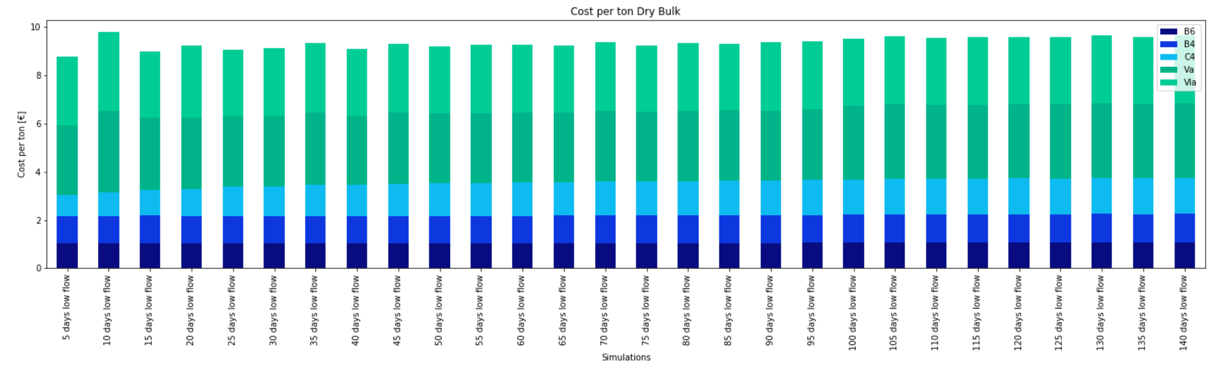


Figure E.12: Transportation costs per ton per RWS-class

E.4. Indicator plots for Q700 - Liquid-bulk

The number of trips by the liquid-bulk fleet increase if the the duration of the low flow periods increases. However, in contrast to the dry-bulk fleet, no extra vessels are deployed during the low flow period. More trips are performed by the tankers because the vessels can sail with higher speeds when less cargo is loaded and thus more trips can are performed in periods of equal length.

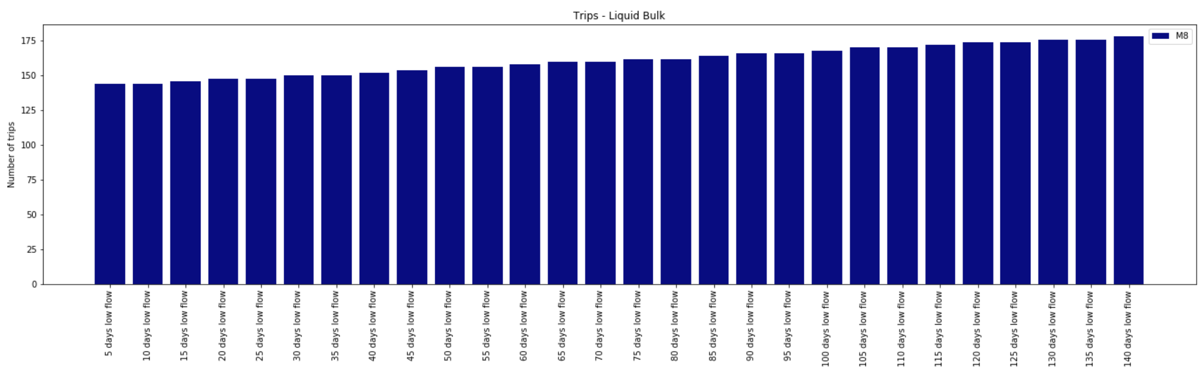


Figure E.13: Number of trips per RWS-class for Q850

Although more trips are performed by the model, less cargo is transported when the low flow period prevails for a longer time. This can be explained by the reduced load factor that is applied during the low flow period.

The transportation costs for the liquid-bulk fleet has a more or less constant trend. Because only a few extra

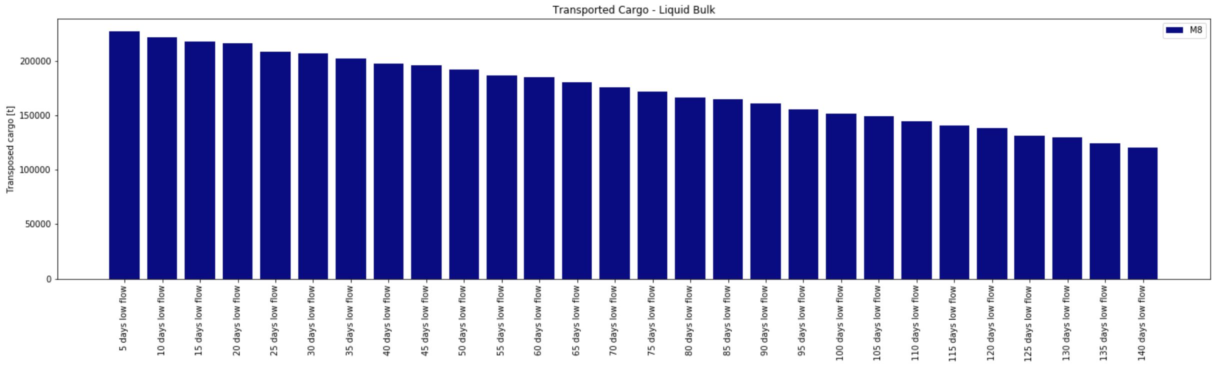


Figure E.14: Transported cargo per RWS-class for Q850

trips are performed, the extra labor, material and variable costs slightly increase. The costs related to loading and unloading reduce because less cargo. Moreover, if the value of the total transportation costs of the first simulation is compared with the value of the last simulation, a small reduction is visible. This means that the reduction in handling costs(loading/unloading) outweigh the rise in labor, material and variable costs.

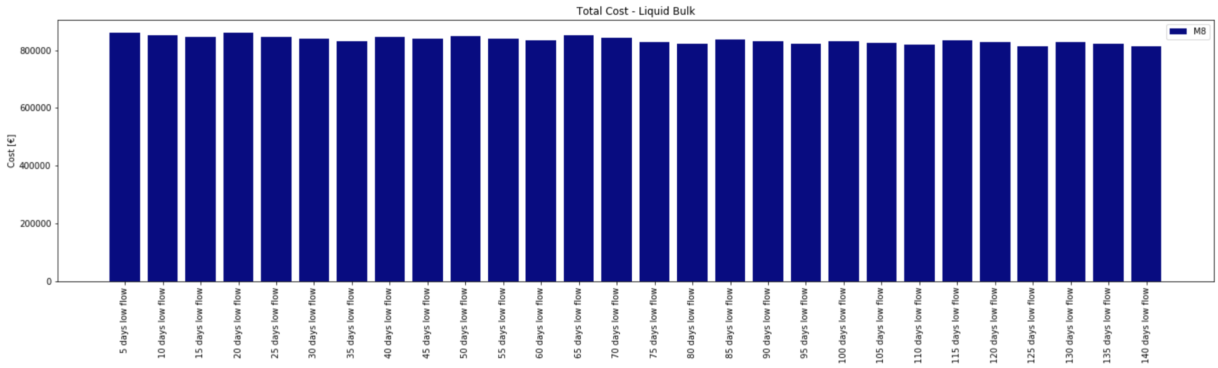


Figure E.15: Transportation costs per RWS-class

The transportation costs per ton shows an increasing trend over the simulation. This can be explained by looking at the bar diagrams for transported cargo and total transportation costs. Significant less cargo is transport for almost equal transportation costs, which results in higher costs to transport one ton of cargo if the low flow period prevails for a longer period of time.

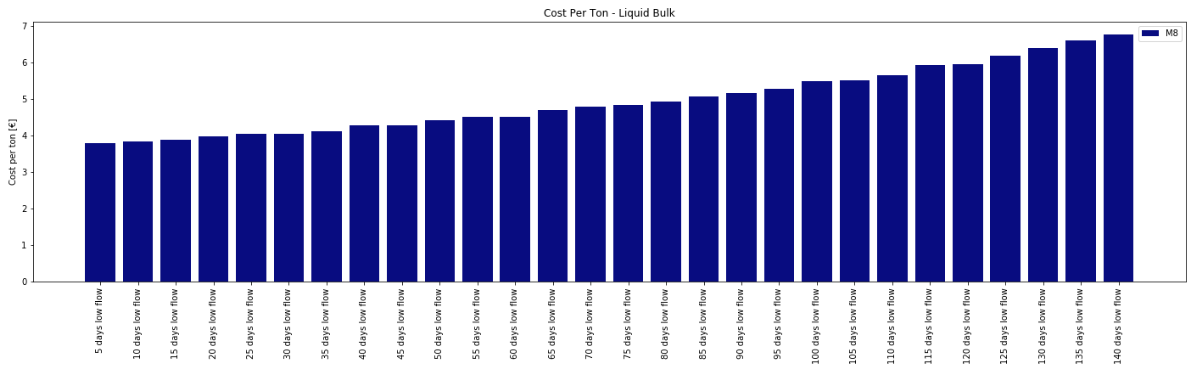
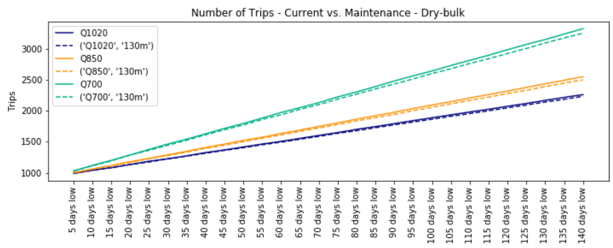


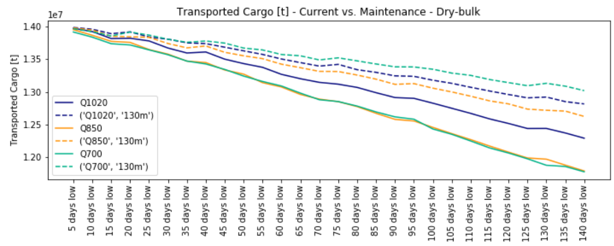
Figure E.16: Transportation costs per ton per RWS-class

F Maintenance criterion dry-bulk

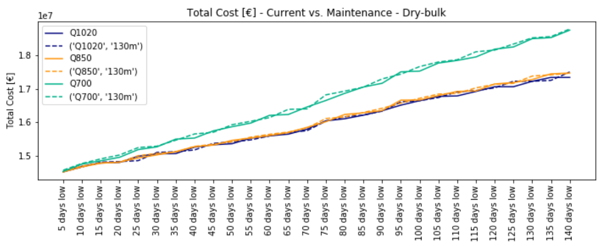
The performance of the dry-bulk transport between Rotterdam and Duisburg slightly improves by adjusting the maintenance criterion from 150 meters to 130 meters. The adaptation measure has no effect on the number of trips and total transportation costs. However, due to the improved water depth as a consequence of this measure vessels can apply a larger load factor, resulting in more transported cargo from Rotterdam to Duisburg(Figure F.1b). The transportation costs per ton are lower for all flow regimes when the maintenance criterion is implemented. This also holds for the transportation costs per ton kilometer and as can be seen in Figure 5.18, the dry-bulk supply chain does not experience any tipping points as expected.



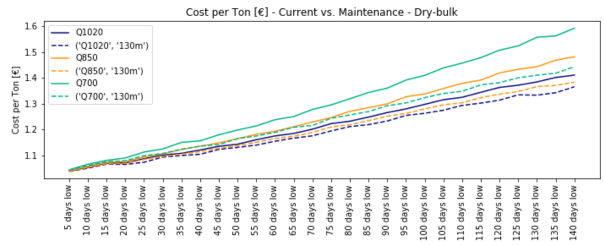
(a) Number of trips for all flow regimes, dry-bulk



(b) Transported cargo for all flow regimes, dry-bulk



(c) Transportation costs for all flow regimes, dry-bulk



(d) Cost per ton for all flow regimes, dry-bulk

Figure F.1: Maintenance criterion 150m vs. 130m performance dry=bulk

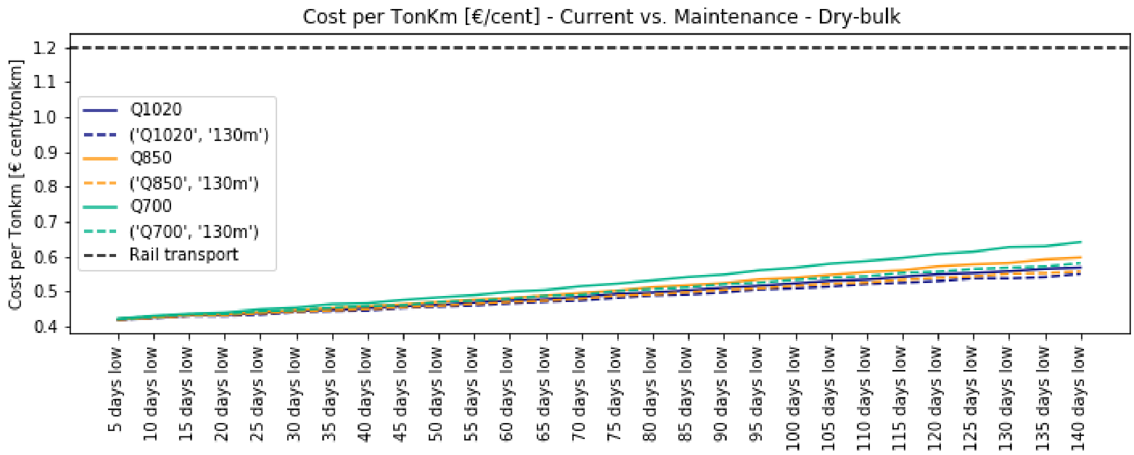


Figure F.2: Cost per ton kilometer for maintenance of 150m width vs. 130m width, dry-bulk

G
Code archive

The simulation model has been developed with the 1.0.0 version of Open Complex Logistics Simulation (OpenCLSim) package. The package is available at the GitHub of the TU Delft Hydraulic Engineering department. A link to this package can be found in Figure G.1

The simulation model has been used to measure the performance of IWT expressed in number of trips, transported cargo and transportation costs, during increasing periods of low flow. A link to the simulation in the GitHub repository that has been used for stress-testing the current situation in section 5.2, can be found in Figure G.2. The simulation with a diverse liquid-bulk fleet that has been used in subsection 5.3.1 can be found in Figure G.3. For the simulation of an adjusted maintenance criterion in subsection 5.3.2, reference is made to Figure G.4.

Figure G.1: Link to OpenCLSim package on the TU Delft Github

Figure G.2: Link to the simulation of the current situation

Figure G.3: Link to the simulation of a diverse liquid-bulk fleet

Figure G.4: Link to the simulation with an adjusted maintenance criterion